

Practical formulas for quantifying the uncertainty of impact sound insulation measurements caused by the diffuse field assumption

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ABSTRACT

In conventional approaches for experimental impact sound insulation assessment, such as the approach of ISO 10140-3, it is (implicitly) assumed that the sound field that is generated by the impacted structure is diffuse. A diffuse field is by definition a random field: it represents a conceptual ensemble of rooms with the same volume and total absorption, but otherwise any possible arrangement of boundaries and small objects that scatter incoming sound waves. Adopting a diffuse sound field model in the assessment procedure therefore inherently introduces uncertainty on the resulting quantities, such as the normalized impact sound pressure level. When determining such quantities in one particular room, this uncertainty can be important, especially at the lower frequency end of the spectrum. In this work, closed-form expressions are derived for quantifying the uncertainty on experimentally determined impact sound pressure levels and related single-number ratings that is due to the diffuse field assumption when measurements are carried out in one particular room. The practical use of the formulas is demonstrated with two examples: a bare concrete floor and a concrete floor with floating screed.

Keywords: Impact sound, laboratory measurements, uncertainty quantification

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1. INTRODUCTION

In noise control engineering, structure-borne sound refers to sound that is generated by direct mechanical excitation of a structure, such as (a part of) a building, a car body or an aircraft fuselage [1]. In buildings, structure-borne noise sources include impacts due to walking people and service equipment. With urbanization accelerating on a global scale, protecting people against such noise sources has become a major concern. At the same time, new types of floor systems are being developed. For economical and ecological

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reasons, these are usually made of lightweight materials such as timber, which makes it challenging to achieve a sufficiently high level of impact sound insulation.

The experimental impact sound insulation assessment of floor systems, e.g., by means of a rating, is crucial in this context. However, such a rating faces difficulties, as the sound that is radiated by a particular floor type depends on the excitation, the floor dimensions and boundary conditions, and the acoustic properties of the receiver room. For this reason, standardized assessment procedures are used, in which the excitation is fixed, the floor is tested in a laboratory with suppressed flanking transmission and a sufficiently large floor opening, and the radiated sound field is taken as diffuse and normalized to a reference absorption value. An example of such a procedure can be found in ISO 10140-3 [2], in which the standard tapping machine [3] is used as excitation device, and the frequency-weighting procedure of ISO 717-2 [4] is employed for generating a single-number rating.

A diffuse field is by definition a random field: it represents a conceptual ensemble of rooms with the same volume and total absorption, but otherwise any possible arrangement of boundaries and small objects that scatter incoming sound waves. Adopting a diffuse sound field model in the experimental assessment procedure therefore inherently introduces uncertainty in measured results: these will be different for different rooms with the same nominal properties (total volume and total absorption area). This uncertainty is known to be inversely related to the modal overlap factor of the room [5]. Since the modal overlap factor increases with frequency, the mean total energy of the random ensemble of test facilities will be close to the total energy in any particular member of the ensemble at high frequencies. This implies that at high frequencies, e.g., above the Schroeder frequency [6], diffuse fields behave essentially as deterministic, and they are indeed treated as such in the experimental rating procedures described above. At low frequencies however, the uncertainty that is inherent in the diffuse field model is larger because of the lower modal overlap. This implies that considerable variation can occur when the normalized impact sound pressure level of a given floor is measured in two different laboratories with low modal overlap at low frequencies.

It would be very interesting if one could quantify the related uncertainty, as this would allow to assess how well a measurement result obtained in one test facility would carry over to other test facilities with similar receiver room volume (and obviously, similar test opening dimensions and floor damping). The purpose of the present paper is therefore to deliver closed-form expressions for the diffuse-field variance of experimentally determined normalized impact sound insulation levels and single-number ratings. The derivation of these practical formulas will be based on insights from fundamental physics [7] that have led to an expression for the variance of the total energy in a diffuse field [8–10]. The practical use of the novel expressions that are derived in the present paper will be illustrated in detail.

2. VARIANCE OF BAND-INTEGRATED SOUND PRESSURE LEVELS IN A DIFFUSE SOUND FIELD

In this section, a practical formula will be derived for computing the variance (due to the diffuse field assumption) of the spatially-averaged sound pressure level in a diffuse sound field that has been obtained by integration over a certain frequency band. This is performed in several steps: first existing results on harmonic and band-averaged variance of the total sound energy are discussed, and subsequently a new formula for the variance of the sound pressure levels is derived

2.1. Variance of the total harmonic sound energy

In a sound field that is composed of plane waves, such as a diffuse sound field, the time-averaged squared sound pressure amplitude $p^2(\mathbf{x})$ at location \mathbf{x} relates to the energy density $e(\mathbf{x})$ via

$$e(\mathbf{x}) = \frac{p^2(\mathbf{x})}{\rho_a c^2}, \quad (1)$$

where ρ_a denotes the density of air, and c the sound speed. Consequently, in any sound field that is composed of plane waves, such as a diffuse field, the spatially averaged squared sound pressure level

$$p_{\text{av}}^2 := \frac{1}{V} \int_V p^2(\mathbf{x}) d\mathbf{x}, \quad (2)$$

where V denotes the room volume, relates to the total time-averaged acoustic energy E in the room via

$$E = \int_V e(\mathbf{x}) d\mathbf{x} = \frac{p_{\text{av}}^2 V}{\rho_a c^2}. \quad (3)$$

Based on the generalized definition of a diffuse field in terms of the Gaussian Orthogonal Ensemble [11], Langley and Brown [12] derived the relative variance of the total sound energy (or, equivalently, the spatially-averaged squared sound pressure) of a diffuse field under harmonic loading with a deterministic amplitude. The result of this derivation reads

$$\frac{\text{Var}[E]}{\hat{E}^2} = \frac{\text{Var}[p_{\text{av}}^2]}{(\widehat{p_{\text{av}}^2})^2} \approx \frac{\alpha - 1}{\pi m} + \frac{1}{(\pi m)^2}, \quad (4)$$

where the hat denotes an ensemble average, m is the modal overlap factor of the room

$$m := \omega \eta n, \quad (5)$$

ω the (angular) frequency, n the modal density (i.e. the number of modes per radial bandwidth), η the damping loss factor, and α a loading factor. The damping loss factor can be determined from the reverberation time T or the absorption A by [13, Eq. 6.59]

$$\eta = \frac{6 \ln(10)}{\omega T} = \frac{cA}{4\omega V} \quad (6)$$

where \ln denotes the natural logarithm, c the sound speed and V the room volume. In the second equality, Sabine's reverberation formula was employed. The approximation in Equation 4 is accurate when $m \geq 0.2$. In the present setting, the diffuse sound field originates from a vibrating structure via an area coupling, in which case $\alpha \approx 2$ [8, Sec. III.D]. The modal density n can be approximated to that of a room with rigid walls, i.e. [5]

$$n = \frac{V\omega^2}{2\pi^2 c^3}. \quad (7)$$

2.2. Variance of the total band-averaged sound energy

In technical acoustics, it is customary to integrate energetic quantities over frequency bands, such as octave bands or 1/3-octave bands. For example, the acoustic energy E can be integrated over a frequency band $[\omega_l, \omega_u]$ to yield the band-integrated energy E_B :

$$E_B := \frac{1}{2\pi} \int_{\omega_l}^{\omega_u} E(\omega) d\omega, \quad (8)$$

where the factor $1/(2\pi)$ is necessary when $E(\omega)$ has units J/Hz; it should be omitted when the units are Js/rad. Since ensemble averaging is an additive operation, the mean band-averaged energetic quantities can be immediately obtained by integration:

$$\hat{E}_B := \frac{1}{2\pi} \int_{\omega_1}^{\omega_u} \hat{E}(\omega) d\omega \quad (9)$$

For the relative variance, the derivation that has led to Equation 4 has been extended to yield [15]:

$$\frac{\text{Var}[E_B]}{\hat{E}_B^2} \approx \frac{\alpha - 1}{\pi m B^2} \left(2B \arctan(B) - \ln(1 + B^2) \right) + \frac{1}{(\pi m B)^2} \ln(1 + B^2), \quad (10)$$

where the bandwidth parameter B is defined as

$$B = \frac{\omega_u - \omega_1}{\omega \eta} \quad (11)$$

in which ω represents the nominal (or center) frequency of the band. For 1/3-octave bands, $B \approx 0.23/\eta$, while for octave bands, $B \approx 0.71/\eta$. When the bandwidth tends to zero, the above mean and variance expressions reduce to the harmonic ones [15]. In the derivation of Equation 10, it has been assumed that damping and the load spectrum (which in the present application, boils down to the vibration spectrum of the radiating structure) be constant over the considered frequency band [15]. This implies that, in order for Equation 10 to hold with good accuracy, the frequency band of integration should be sufficiently narrow. Similarly, although Equation 10 has been derived for the special case $w(\omega) = 1$, it will also hold with good accuracy for any $w(\omega)$ that does not vary widely within the frequency band of integration.

The prediction of the variance of the band-integrated energy over wide frequency bands is an open problem. In this work, a practical solution is investigated, which consists of dividing the wide band into several narrower bands that are (i) sufficiently narrow such that Equation 10 holds with good accuracy, and (ii) sufficiently wide such that the band-integrated energies belonging to different bands are approximately statistically independent. Condition (i) requires that for each of the smaller bands j , the following approximation be accurate:

$$\hat{E}_{B,j} \approx \frac{\omega_{u,j} - \omega_{l,j}}{2\pi} \hat{E}(\omega_j) \quad (12)$$

where ω_j is the center frequency of band j , and $\omega_{l,j}$ and $\omega_{u,j}$ represent the lower and upper frequency limits of band j . A possible indicator for condition (ii) is the relative covariance between the squared amplitude of the point pressure frequency response function at the upper and lower limits of the frequency band, which can be estimated as [16]:

$$c(B_j) \approx \frac{1}{1 + B_j^2} \quad (13)$$

where B_j is defined as in Equation 11. When $c(B_j) \ll 1$, it is reasonable to assume that condition (ii) holds with good accuracy.

When both conditions are satisfied, the mean and variance of the band-integrated energy for the narrower bands can be estimated from Equation 9 and Equation 10, thanks to condition (i). Thanks to condition (ii), the mean and variance of the integrated energy over the wide band that was subdivided into narrower bands are then obtained as

$$\hat{E}_B = \sum_j \hat{E}_{B,j} \quad \text{and} \quad \text{Var}[\hat{E}_B] = \sum_j \text{Var}[\hat{E}_{B,j}]. \quad (14)$$

2.3. Variance of the band-integrated sound pressure level

The spatially averaged squared sound pressure is usually represented on a logarithmic scale, as the sound pressure level L_p :

$$L_p := 10 \log \frac{p_{av,B}^2}{p_0^2}, \quad (15)$$

where \log denotes the logarithm with base 10, and the reference value is chosen as $p_0 = 2 \cdot 10^{-5}$ Pa. The subscript B is employed to emphasize that it usually concerns band-averaged quantities. As discussed above, the total sound energy and the spatially averaged squared sound pressure have the same relative variance. Furthermore, they are lognormally distributed in good approximation [17]. If this also holds for the band-averaged quantities, then the sound pressure level is normally distributed, with mean value

$$\hat{L}_p = 10 \log \frac{\widehat{p_{av,B}^2}}{p_0^2} - \frac{C}{2}, \quad (16)$$

and variance

$$\text{Var}(L_p) = \frac{10C}{\ln 10} \quad \text{where} \quad C := 10 \log \left(1 + \frac{\text{Var}[E_B]}{\hat{E}_B^2} \right), \quad (17)$$

and \ln denotes the natural logarithm. It can be noted that the ensemble mean of the sound pressure level is not simply the level of the ensemble mean of the squared sound pressure, but the error by neglecting the additional term will be smaller than 1 dB as long as the relative variance of the band-averaged energy will be smaller than 0.6.

In practice, \hat{L}_p is usually obtained by averaging the squared sound pressures not over the entire room volume, but only over the central part of the room, away from the room boundaries. Due to interferences between incoming and reflected waves at the room boundaries, the mean energy density will be larger near the room boundaries than in the central zone of the room. This effect has been quantified by Waterhouse [18]. From his analysis, it follows that

$$\hat{L}_{p,\text{central}} = \hat{L}_p - 10 \log \left(1 + \frac{\pi c S}{4\omega V} \right) \quad (18)$$

where S is the total surface area of the room. The variance of $L_{p,\text{central}}$ is however still given by Equation 17.

3. VARIANCE OF SINGLE-NUMBER RATINGS

In this section, it is illustrated how the above theory can be used for practical uncertainty assessment regarding the single-number ratings for impact sound insulation that appear in the ISO 717-2 standard [4]. It is furthermore assumed that impact sound pressure levels have been measured in the laboratory according to ISO 10140-3. This implies, amongst other things, that an ISO tapping machine has been used as impact device to excite the floor, that the absorption in the receiver room is normalized to an equivalent absorption area of $A = 10 \text{ m}^2$ (resulting in *normalized* sound pressure levels L_n) and that the measurements have been performed in 1/3-octave bands. The methodology is readily generalized to other ratings, either standardized or not.

It may be noted that ISO 717-2 explicitly mentions the format in which the uncertainty on a single-number rating should be expressed (as an interval centered around the rating value), but otherwise does not provide any interpretation of this uncertainty (e.g., in terms of a probabilistic confidence interval), nor the sources of uncertainty that should be included in the stated value (such as the diffuse field assumption). Here, the uncertainty will be expressed as a 95 % confidence interval, and the source of uncertainty that is included is the diffuse field assumption. As discussed earlier, a deterministic diffuse field can only be achieved in a room with very large (theoretically infinite) volume. So the fact that measurements are performed in a room of finite volume yet the generated sound field is taken to be diffuse, generates uncertainty (in terms of limited reproducibility) on the experimental results.

3.1. Weighted normalized impact sound pressure level

The procedure for obtaining the weighted normalized impact sound pressure level $L_{n,w}$ can be summarized as follows. First, compare the measured sound pressure levels due to tapping machine excitation $L_n(f_j)$ with reference values $L_{ref}(f_j)$ for all 1/3-octave bands from $f_j = 100$ Hz till $f_j = 3150$ Hz. Then, shift the reference curve with an increment ΔL_{ref} until the sum of all unfavorable deviations (i.e., measured values larger than reference values) equals 32.0 dB. In other words, determine ΔL_{ref} such that

$$\Delta L_{ref} = -\frac{32 \text{ dB}}{N} + \sum_{j \in \mathbb{S}} \frac{L_n(f_j) - L_{ref}(f_j)}{N}, \quad (19)$$

where \mathbb{S} denotes the set of 1/3-octave bands in which the measured $L_n(f_j)$ is larger than the shifted reference curve:

$$\mathbb{S} := \left\{ j \mid L_n(f_j) - L_{ref}(f_j) - \Delta L_{ref} > 0 \right\}, \quad (20)$$

and N is the number of elements of \mathbb{S} . Normally, ΔL_{ref} need be rounded to the closest higher integer, however, when uncertainty is being expressed, this rounding is not necessary² [4]. The value of the shifted reference curve at 500 Hz equals $L_{n,w}$:

$$L_{n,w} = L_{ref}(500 \text{ Hz}) + \Delta L_{ref}. \quad (21)$$

Since all $L_n(f_j)$ are normally distributed (see Section 2.3), so is $L_{n,w}$. When assessing measurement accuracy, the measured values (in this case $L_n(f_j)$) are usually taken as the nominal (expected) values $\hat{L}_n(f_j)$, resulting in $\hat{L}_{n,w}$. The computation of the variance however is complicated by the fact that the set \mathbb{S} is a random set as it depends on ΔL_{ref} , in other words, the number N of elements of \mathbb{S} , can be different for different members of the considered random ensemble of diffuse sound fields. An approximate solution is obtained by fixing \mathbb{S} to the set that is used for determining the expected values:

$$\mathbb{S} \approx \hat{\mathbb{S}} := \left\{ j \mid \hat{L}_n(f_j) - L_{ref}(f_j) - \Delta \hat{L}_{ref} > 0 \right\}. \quad (22)$$

The variance of $L_{n,w}$ is then obtained as follows:

$$\text{Var}(L_{n,w}) = \text{Var}(\Delta L_{ref}) = \frac{1}{N^2} \sum_{j \in \hat{\mathbb{S}}} \text{Var}(L_n(f_j)). \quad (23)$$

²To be more precise, ISO 717-2 requires that ΔL_{ref} be rounded to the same accuracy of the $L_n(f_j)$ values, i.e., 0.1 dB, in case uncertainty is accounted for.

The variances of the measured sound pressure levels $L_n(f_j)$, due to the diffuse field assumption, can be obtained as discussed in Section 2.3, i.e., through Equation 17 and Equation 10. The $L_n(f_j)$ in the above expression are assumed uncorrelated for each band. This assumption and its assessment have been discussed at the end of Section 2.2.

3.2. Unweighted linear impact sound level

ISO 717-2 contains a second, alternative single-number rating procedure for impact sound insulation. The reason is that this additional weighting procedure seems to be more representative for the A-weighted impact levels as caused by walking for all types of floor [4, App. A]. The rating is defined as a correction C_I to the $L_{n,w}$ that was discussed in the previous section:

$$L_{n,w} + C_I = L_{n,\text{sum}} - 15 \text{ dB} \quad \text{where} \quad L_{n,\text{sum}} = 10 \log \left(\sum_{j \in \mathbb{S}'} \frac{p_{\text{av}}^2}{p_0^2} \right), \quad (24)$$

although in this case, the set \mathbb{S}' is defined differently, i.e., it contains all 1/3-octave bands from 100 Hz to 2500 Hz. If the spatially averaged squared sound pressures are independent for all 1/3-octave bands, then the variance of $L_{n,w} + C_I$ that is due to the diffuse field assumption can be obtained by using the results of Sections 2.2 and 2.3:

$$\text{Var}(L_{n,w} + C_I) = \text{Var}(L_{n,\text{sum}}) = \frac{100}{\ln 10} \log \left(1 + \frac{\text{Var}[E_{\mathbb{S}'}]}{\hat{E}_{\mathbb{S}'}^2} \right) \quad (25)$$

$$= \frac{100}{\ln 10} \log \left(1 + \frac{1}{\hat{E}_{\mathbb{S}'}^2} \sum_{j \in \mathbb{S}'} \text{Var}[E_{B,j}] \right) \quad (26)$$

The relative variances that appear in the final expression, can be obtained by evaluating Equation 10 for all 1/3-octave bands involved.

4. EXAMPLES

As examples of the foregoing methodology, an uncertainty assessment is performed on two test results that are publicly available. It concerns a concrete base floor of 140 mm thickness, which is tested in uncovered condition and with a floating screed on top. The floor with floating screed is made up of the following layers (from top to bottom):

- 60 mm reinforced screed with density $1900 \frac{\text{kg}}{\text{m}^3}$;
- 0.2 mm polyethylene (PE) foil;
- 6 mm of extruded polyethylene with closed cell structure and density $30 \frac{\text{kg}}{\text{m}^3}$ (commercial product name Carro-Foam 6+);
- 60 mm insulating screed with expanded polystyrene grains and density $200 \frac{\text{kg}}{\text{m}^3}$ (commercial product name Iso-Bel 200)
- 140 mm reinforced concrete base floor.

The floors were tested in the acoustic laboratory of the Belgian Building Research Institute (BBRI). The surface area was $260 \text{ cm} \times 442 \text{ cm}$ and the receiver room had a volume of 102.21 m^3 .

Fig. 1 displays the normalized impact sound pressure levels that have been measured in 1/3-octave bands on the base floor only and on the base floor with floating screed on top. The 95 % confidence intervals, that have been obtained with Equation 17 and Equation 10 and the parameters $\alpha = 2$, $A = 10 \text{ m}^2$ and $V = 102.21 \text{ m}^3$, are displayed as well. The confidence intervals give an idea of how well the measurement results would carry over to any other laboratory, if only the room geometry would be different.

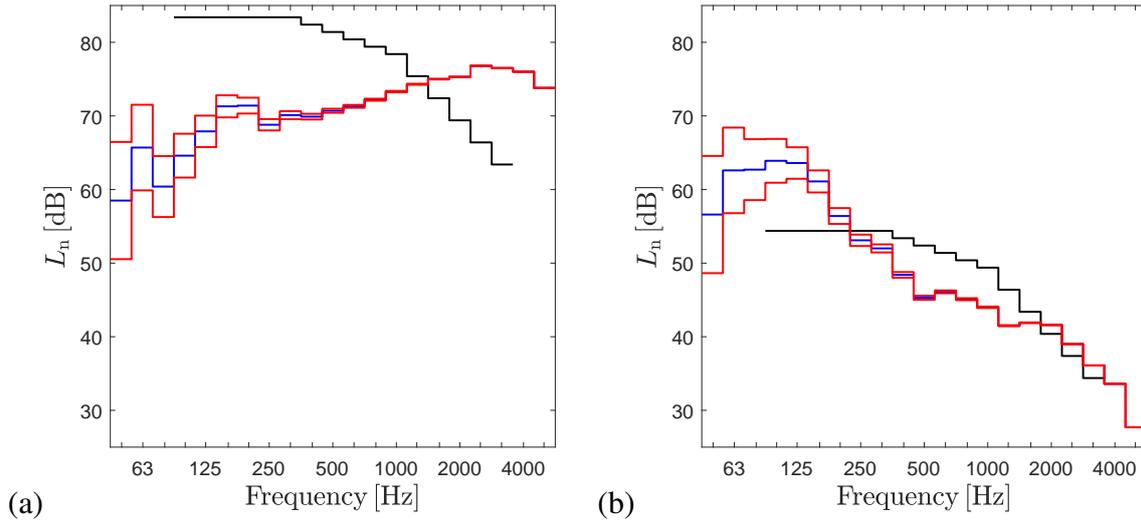


Figure 1: Normalized impact sound pressure levels for (a) a concrete base floor, and (b) the same base floor with floating screed on top. Blue curves: measured (nominal, mean) values \hat{L}_n ; red curves: 95 % confidence interval $\pm 2\text{Std}(L_n)$ due to the diffuse field assumption; black curves: shifted reference curves $L_{\text{ref}} + \Delta\hat{L}_{\text{ref}}$.

Inspection of Fig. 1a allows to anticipate that the diffuse field uncertainty of the weighted normalized impact sound pressure level $L_{n,w}$ will be very low for the base floor itself, as the measured levels exceed the shifted reference values only at high frequencies, where the diffuse field uncertainty is very low. Inspection of Fig. 1b on the other hand reveals that the diffuse field uncertainty of $L_{n,w}$ will be higher when the floating screed is present, because then the shifted reference values are exceeded at low frequencies, where the diffuse field uncertainty is much higher.

This is confirmed in Table 1, where the single-number ratings and their 95 % confidence intervals are listed. It can also be noted that the alternative weighting $L_{n,w} + C_I$ yields higher uncertainties for these two examples. The maximum width of the 95 % confidence interval is 2.6 dB, which is obtained for the unweighted linear impact sound level of the floor with floating screed.

Finally, it would be interesting to re-compute the uncertainties for the smallest rooms that are allowed by the standard, i.e., with a room volume $V = 50 \text{ m}^3$. The result of this calculation is provided in Table 2. The differences between both tables indicate the loss in accuracy that would be incurred when the diffuse-field radiation of impact sound would be assessed in a room of 50 m^3 instead of 102 m^3 , all other parameters such as test opening dimensions being constant. For the $L_{n,w} + C_I$ rating of the floor with floating screed for example, the width of the 95 % confidence interval would increase from 2.6 dB to 3.6 dB.

floor	$\hat{L}_{n,w} \pm 2 \text{ Std}(L_{n,w})$	$\hat{L}_{n,w} + \hat{C}_1 \pm 2 \text{ Std}(L_{n,w} + C_1)$
bare concrete	81.4 \pm 0.02 dB	69.3 \pm 0.1 dB
with floating screed	52.4 \pm 0.6 dB	53.5 \pm 1.3 dB

Table 1: Single number ratings and their uncertainties, expressed as 95 % confidence intervals, due to the diffuse field assumption.

floor	$\hat{L}_{n,w} \pm 2 \text{ Std}(L_{n,w})$	$\hat{L}_{n,w} + \hat{C}_1 \pm 2 \text{ Std}(L_{n,w} + C_1)$
bare concrete	81.4 \pm 0.02 dB	69.3 \pm 0.2 dB
with floating screed	52.4 \pm 0.8 dB	53.5 \pm 1.8 dB

Table 2: Single number ratings and their uncertainties, expressed as 95 % confidence intervals, due to the diffuse field assumption when the tests would have been performed in a room with a volume of 50 m³.

5. CONCLUDING REMARKS

In this article, closed-form expressions have been derived for estimating the uncertainty associated with the assumption that the radiated sound field in an impact sound insulation measurement is diffuse. For the individual 1/1-octave or 1/3-octave values, Equation 17 is the main result. Evaluation of this and the related expressions reveals that, when the absorption in the room is fixed to a reference value (e.g., 10 m²), the uncertainty depends only on the room volume and the frequency.

For the standardized single-number ratings $L_{n,w}$ and $L_{n,w} + C_1$, the main results are Equation 23 and Equation 26, respectively. Two examples have been worked out, first for a concrete base floor and then for the same floor with a floating screed on top. Since the performance of the bare floor is determined mainly at the high frequencies, the uncertainty of the diffuse field assumption for the radiated sound field on the single-number ratings is negligible. On the other hand, when a floating screed is added, the low-frequency sound radiation determines the performance and the uncertainty of the single-number ratings due to the diffuse field assumption becomes more important.

It should be noted that the variance expressions that have been derived here represent *only* the uncertainty which is inherent in the diffuse field assumption of the radiated sound field. In cases where this is not the dominant source of uncertainty, as for the bare concrete floor that has been investigated here, other sources of uncertainty need be accounted for, such as the dimensions of the test opening and the floor damping, in order to get a correct idea of the reproducibility of the test results.

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