PRACTICAL ACOUSTIC DESIGN – THE APEX METHOD

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1 INTRODUCTION

The problem with some types of acoustic assessment is that the process of the calculation can obscure the effect of the elemental performance on the global performance parameter. Similarly it can be difficult to perceive the effect of the performance in some frequency bands on global performance parameters such as that required under Building Regulations, $D_{nT,w}$ + C_{tr}. The acoustic designer is then left with the opportunity for a process of trial and error with alternative design options, to determine which are the controlling factors in the design. The processes and explanations in this paper are aimed at offering insight into the factors that may be limiting the design or measured performance.

The first example is for calculation of the required façade sound insulation to achieve internal noise level limits. The Standard that describes the appropriate calculation methodology is intended to determine the overall mean façade performance, as this is what some European countries have prescribed in their regulations, rather than achieving particular internal noise levels. The approach presented for the calculation is undertaken differently to achieve this different purpose of determining indoor ambient noise levels. This is described as designing for sound levels, and is illustrated by determining the sum of the parts that contribute to the overall parameter sought.

The second example is described as designing for sound level differences. In this, the composing portions of the level difference are ascertained, such that the relevant parts of a composite element or components the frequency spectrum that degrade the overall performance can be identified separately.

2 DESIGNING FOR SOUND LEVELS – SOUND INSULATION AGAINST OUTDOOR SOUND

A common task for acoustic consultants is to design façade elements to achieve upper limits for noise penetration into a room. The method for the analysis of noise ingress through façade elements is described in BS EN 12354-3 [1]. Firstly the methods and terms of that Standard are reproduced, and then the proposed method of carrying out the calculation for design insight is presented.

2.1 Background: external noise ingress

Equation (2) from EN 12354-3 is reproduced below:

$$R'_{tr,s} = L_{eq,1,s} - L_{eq,2} + 10\log\left(\frac{S}{A}\right) - 3 \quad (1)$$

Where the terms have the following meanings:
$R'_{tr,s}$ is the apparent sound reduction index where the source of noise is traffic, in dB.
$L_{eq,\ 1,s}$ is the average equivalent sound pressure level on the outside surface of the building element, in dB; this includes the reflecting effect of the façade element itself and other adjacent elements.
$L_{eq,2}$ is the average equivalent sound pressure level in the receiving room, in dB.
S is the area of the façade element, in m.
A is the equivalent sound absorption area in the receiving room, in m^2.

It is noted that $R'_{tr,s}$ gives values which are comparable to those measured under laboratory conditions, and neglecting flanking transmission for an element $R'_{tr,s} \approx R$. We are generally more inclined to express the performance in terms of the standardised level difference, as:

$$D_{2m,nT} = R' + \Delta L_{fs} + 10\log\left(\frac{V}{6\,T_0 S}\right) \quad (2)$$

Where the terms have these meanings:
$D_{2m,nT}$, is the difference between the level 2 m in front of the façade and the level in the room, standardised to the reference reverberation time T_0.
V is the volume, in m^3.
S is the area of the element, in m. It can be seen that the Sabine relation is used to substitute for the absorption, $A \approx 0.16.V/T \approx V/6T$.

ΔL_{fs} is the façade shape level difference. It is given by the difference between the freefield incoming sound field in the absence of the façade, $L_{1,in}$, and the level measured just in front of the surface of the façade, $L_{eq,1s}$ by the relation:

$$\Delta L_{fs} = L_{1,in} - L_{eq,1s} + 6 \quad (3)$$

It may be noted that ΔL_{fs} has the value of zero for a plain façade. The other relevant term here is the sound level 2 m in front of the façade, $L_{1,2m}$; for a plain façade with $\Delta L_{fs} = 0$, the relation between these quantities is:

$$L_{1,in} = L_{1,2m} - 3 = L_{eq,1s} - 6 \quad (4)$$

The level 2 m in front of a plain façade, $L_{1,2m}$ is often referred to as a “façade level”. It is clearly essential to use the appropriate external noise level in whichever calculation method is adopted. Rearranging equation 1 to calculate the standardised internal level due to a single element, making the substitution for the Sabine relation for internal noise levels, assuming a plain façade with ΔL_{fs} =0 such that $L_{1,2m} = L_{eq,1s} - 3$:

$$L_{eq,2,nT} = L_{1,2m} - R' + 10.\lg\left(\frac{6T_0 S}{V}\right) \tag{5}$$

Which may be simplified by substituting for a reference reverberation time of 0.5 seconds and with further approximations to:

$$L_{eq,2,nT} = L_{1,2m} - R' + 10.\lg\left(\frac{S}{V}\right) + 5 \tag{6}$$

A further part of the design jigsaw is an expression for the façade sound insulation of a small element, with laboratory-measured element normalised level difference data, $D_{n,e}$, for which the internal level is similarly given by:

$$L_{eq,2,nT} = L_{1,2m} - D_{n,e} + 10.\lg\left(\frac{N_{vent}}{V}\right) + 15 \tag{7}$$

Where:
N_{vent} is the number of vents with element normalized level difference $D_{n,e}$.

2.2 Apex method: combining partial level contributions

The internal noise level may now be considered as the sum from contributions from all relevant elements, in all relevant octave bands. The contribution from each facade portion or element may be considered as a partial level contribution to the overall level calculated. This is best illustrated by the following example. Consider the simple case of external noise incident on a façade that is composed of a masonry wall, a window, and a trickle vent with the following performance data.

Room volume, V /m^3	50.0					
Wall area, S /m^2	6.0					
Window area, S/m^2	4.5					
Reverberation Time, T /s	0.5					
Acoustic performance data / octave band		125 Hz	250 Hz	500 Hz	1 kHz	2 kHz
Wall, R		41	46	52	58	64
Window, R		23	22	30	36	37
Trickle vent, $D_{n,e}$		36	34	31	34	38

Table 1: Geometry and acoustic performance data for example calculations

When carrying out the calculation, it is suggested that the source noise octave band levels are first A-weighted. As we are only interested in the A-weighted result, all calculated values will then be in a relevant and comparable metric. Similarly, if octave band data is summed to give A-weighted values without first inspecting the A-weighted octave band values, essential insight into the performance requirements for relevant elements cannot be discerned. In the following example the standardised road traffic spectrum is used as the source noise, with the façade and element performance from Table 1:

Octave centre frequency	dB(A)	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz
Façade noise, $L_{1, 2m}$ /dB(A)	60	46	50	53	56	54
Eqn 6: Wall partial L_2	4	0	0	-3	-6	-15
Eqn 6: Window partial L_2	25	17	22	17	15	11
Eqn 7: Ventilator partial L_2	24	8	14	19	20	14
Combined internal noise / dB(A)	27					

Table 2: Calculated partial levels from each component, with a single trickle vent

It may be noted that the octave band values may be summed to give a value for each component, and then the values for each component may be summed to give the global result. Similarly, the values in each octave band may be summed to give octave band totals, from which the global result is calculated. All the values shaded in Table 2 are simply summed logarithmically to determine the global internal level. As they are all A-weighted, the relative contributions can be seen directly.

Inspection of Table 2 reveals that the contribution of the masonry wall is negligible, and that the most significant contributions to the overall internal level are from the window in the 250 Hz octave band, followed by contributions from the vent in 1 kHz and 500 Hz bands. This information would not be so readily available if the average sound reduction for the whole façade were first calculated before determining the effect of each component. Therefore if a lower internal level is required with the above set of components, glazing with a higher performance in 250 Hz band would be required, after which the vent performance in the 1 kHz and 500 Hz bands would be the next most limiting factors. As the balance between internal levels in different frequency bands is a function of the external incident noise spectrum, the same balance of components proposed may not be suitable in another situation where the overall noise level is similar but with different spectral levels.

Consider also if the number of vents required is not one but four, the calculated results are shown in Table 3. This is more representative of a design in the UK that relies on trickle vents for a natural ventilation solution. It can be seen that the noise through the trickle vents dominates the overall levels, and a higher performance of the trickle vent would be required in the 500 Hz and 1 kHz octave bands if lower internal levels are sought.

Octave centre frequency	dB(A)	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz
Partial $L_{2, wall}$	4	0	0	-3	-6	-15
Partial $L_{2, window}$	25	17	22	17	15	11
Partial $L_{2, vent}$	30	14	20	26	26	20
Combined internal noise / dB(A)	31					

Table 3: Calculated partial levels from each component, with four trickle vents

It may be useful to note that in Annex D.2 of EN 12354-3 the level difference provided by an unattenuated opening is given by:

$$D_{n,e} = -10\log\left(\frac{S_{open}}{10}\right) \quad \textbf{(8)}$$

This relation should be used with caution, as it is found that most small elements for which there is laboratory data have smaller normalized element level difference performance values, $D_{n,e}$, compared to the calculated value for the free area using the relation above. The equivalence between equations (6) and (7) is evident by consideration of an open area that may either be treated as an area with a sound reduction of zero, or a small element with $D_{n,e}$ as above.

If use is made of equation (8) for noise ingress through an open area, there is no advantage to calculating the octave band values - there is no frequency information in this assessment of the sound transmission performance of an open area, so that the combined sum of the octave band sound levels is the same as equation (7) applied to the A-weighted source level, i.e.:

$$L_{Aeq,2,nT} = L_{A,1,2m} + 10\log\left(\frac{S_{open}}{V}\right) + 5 \quad \textbf{(9)}$$

In the above examples the source noise spectrum used was that from the standard for road traffic, as described in ISO 1793-3 [2], and as used in the C_{tr} spectrum adaption term for single figure noise indices. As such, the same results would be calculated using single figure acoustic performance data in terms of $R_w + C_{tr}$ for the facade components, and $D_{n,e,w} + C_{tr}$ for the vent. However, if the external noise level has a different spectral composition, calculation with single figure values will involve an error that may be difficult to quantify without also carrying out the octave band calculation.

The most significant change in external noise source levels is generally found from $L_{AF,max}$ events. The spectral content of noise from events that cause the highest $L_{AF,max}$ levels tends to be weighted much more significantly towards the higher frequencies rather than the lower frequencies. The benefit of this for the designer is that it is easier to attenuate the higher frequency noise. Hence exactly the same calculations as above can be carried out for the spectrum of noise associated with the $L_{AF,max}$ events in question, and the performance of the elements determined to achieve the internal level requirements.

It is noted that this can lead to a problem: the highest $L_{AF,max}$ event externally does not necessarily lead to the highest $L_{AF,max}$ event internally, as the internal level is a function of the spectral content of the external level. Therefore if there is a criterion that no $L_{AF,max}$ events should exceed an internal threshold, such as required in some proprietary hotel brand specifications, then there is no alternative but to carry out the calculation for all of the most significant $L_{AF,max}$ events, until the designer is satisfied that the intended performance can be achieved.

3 DESIGNING FOR LEVEL DIFFERENCES

Another common application for the acoustic consultant is designing and testing to achieve a level difference requirement between two rooms. The same approach is suggested in arranging the calculation and interpreting the results, only this time the levels to combine are level differences rather than levels. It is fairly intuitive for the acoustic practitioner to add decibel values together logarithmically - we know that 10 plus 10 gives 13, or that 10 plus 16 gives 17, but adding level differences is not so common. A level difference may be considered as a negative value, so that combining a level difference of 10 and 10 gives an overall result of 7, or adding a level difference of 10 and 16 gives a result of 9. In this way level differences may be combined in the same way as levels, with the results summed negatively. This is demonstrated in the equation below, but the perception of the meaning of the equations is equally valuable, as demonstrated in the following examples.

Consider a common design problem, where there is a level difference performance requirement between two rooms, with a variety of sound transmission paths between them. One method to assess the performance would be to calculate the composite performance of the combination of elements, but in doing so it would be easy to miss the partial effect of each element. The method suggested is to calculate the partial level difference for each element, and then combine the effect of all the elements by adding the partial level differences to determine an overall level difference for direct sound. Level differences may be summed using the following equation:

$$D_{global} = -10\log\left(10^{(-D_{partial,1}/10)} + 10^{(-D_{partial,2}/10)} + \dots + 10^{(-D_{partial,n}/10)}\right) \quad \mathbf{(10)}$$

A common situation in which level differences are averaged is in converting third octave sound reduction data to octave band data. The equation above can be modified to account for averaging the level differences in the same way that averaging sound levels is carried out.

3.1 Background: sound transmission between rooms

The relation for direction sound transmission between two rooms is according to EN 12354-1 [3]:

$$R' = L_1 - L_2 + 10\log\left(\frac{S}{A}\right) \quad \mathbf{(11)}$$

And the standardized level difference being:

$$D_{nT} = L_1 - L_2 + 10\log\left(\frac{T}{T_0}\right) \quad \mathbf{(12)}$$

Combining these yields the standardised level difference as a function of the geometry and receiving room conditions:

$$D_{nT} = R' + 10.\lg\left(\frac{T}{T_0}\right) - 10\log\left(\frac{S}{A}\right) \quad \mathbf{(13)}$$

Which is simplified with the Sabine relation and the reference reverberation time of T_0 = 0.5 secs to:

$$D_{nT} = R' + 10\log\left(\frac{0.32V}{S}\right) \approx R' + 10\log\left(\frac{V}{S}\right) - 5 \quad \mathbf{(14)}$$

Using this equation, the partial level difference due to each contributing frequency band of each element can be calculated, or a term for a normalized flanking level difference due to a raised access floor or suspended ceiling can also be added, by considering the definition:

$$D_{n,f} = L_1 - L_2 - 10\log\left(\frac{A}{A_0}\right) \quad (15)$$

Substituting into equation (12) yields:

$$D_{nT} = D_{n,f} + 10\log\left(\frac{A}{A_0}\right) + 10\log\left(\frac{T}{T_0}\right) \quad (16)$$

Which is simplified with the Sabine relation, the reference reverberation time of T_0 = 0.5 sec and the reference absorption area of A_0 = 10 m^2 to:

$$D_{nT} = D_{n,f} + 10\log\left(\frac{0.32V}{10}\right) \approx D_{n,f} + 10\log(V) - 15 \quad (17)$$

It should be noted that equation (17) is only strictly valid if the receiving room has the same proportions in terms of length of separating partition and depth from the separating partition as that tested in the laboratory, otherwise adjustments should be made as described in EN 12354-1. However, it is frequently found in practice that the laboratory conditions are representative of the site conditions considered, such that equation (17) can be used without adjusting.

3.2 Apex method: combining level differences for transmission between rooms

In the following worked example, consider two rooms separated by a partition containing a glazed screen and built off a raised access floor. It is noted that calculating the composite values from the weighted averaged values such as R_w is not mathematically or physically correct, but is usually approximately so. Strictly, the combined partial (ie global) level difference in each frequency band should be calculated, and then the curve-fitting procedure of ISO 717-1[4] used to determine the weighted single figure value. However, it is entirely correct if using pseudo-receiving room parameters such as R_w + C_{tr} or R_{living}, as demonstrated by the discussion in the following section.

Element	Area / m^2	R_w or $D_{nf,w}$ / dB	Partial $D_{nT,w}$	Global $D_{nT,w}$
Partition	8	40	43	40
Glazed screen	2	34	43	
Raised access floor	-	48	50	

Table 4: Calculated partial level differences from each element, and the global level difference

Consideration of the partial level differences gives interesting possibilities. Firstly, degradation between laboratory and site conditions may be attributed to each element independently, as part of the calculation of partial level difference. For example, a greater degradation may be assumed for dry lined partitions compared with masonry partitions, and this may be useful where a wall is composed of a mixture of partition types. Glazed screens themselves are likely to perform similarly in situ as in the laboratory, although sealing around the perimeter may be considered separately. The contribution of a flanking path through the ventilation system may be considered, or through doors and lobbies. Consideration of the calculation in this way allows the designer to quantify the contributing level difference from various elements within the overall context.

4 THE FREQUENCY DEPENDENCE OF SINGLE FIGURE INDICES FROM PARTIAL WEIGHTED LEVEL DIFFERENCES

The Building Regulations performance parameter, $D_{nT,w} + C_{tr}$ is described as a *pseudo receiving room level difference*, because it determines the A-weighted noise level in the receiving room for the assumed spectrum of source noise. The single figure level difference $D_{nT,w} + C_{tr}$ is the actual difference between the A-weighted level of traffic noise in the source room, and the A-weighted level in the receiving room.

The single figure result can be understood by inspecting the process of calculating the single figure value in terms of the weighted spectral level differences, which is described in ISO 717-1. The level difference in each frequency band is calculated, and then weighted according to the index type with the relevant reference spectrum. This is achieved by simply adding the reference curve value to the standardised level difference in that frequency band, to give a "*partial weighted level difference*"; the global result is then simply the logarithmic sum (the negative sum as they are level differences) of all the level differences. Hence review of the partial weighted level differences reveals immediately those frequency bands contributing most significantly to the global result. Level differences may be summed using the following equation (which is the same as Eqn (10)):

$$D_{global} = -10\log\left(\sum_{i=1}^{n} 10^{\left(\frac{-D_{partial,i}}{10}\right)}\right) \qquad \textbf{(18)}$$

The components of the parameter $D_{nT,w} + C_{tr}$ are defined in ISO 717-1 with the descriptor X_{A2} denoting the sum of the frequency band level differences, X_i, and C_{tr} spectral term, L_i:

$$X_{A2} = -10\log\sum 10^{\frac{L_i - X_i}{10}} \qquad \textbf{(19)}$$

The term in equation (19), $\{X_i - L_i\}$, by comparison with equation (18), is the partial weighted level difference. The sum in Eqn (19) can be understood as simply the logarithmic sum of the partial weighted level differences in each frequency band. In Eqn (19), the term X_{A2} is simply the term $\{D_{nT,w} + C_{tr}\}$: there is no need to subtract the value of $D_{nT,w}$ to calculate the value of C_{tr} alone, the value of the parameter $\{D_{nT,w} + C_{tr}\}$ is calculated directly by the logarithmic sum of the component parts.

The power of this analysis is that the most significant frequency band contributors to the global level difference $\{D_{nT,w} + C_{tr}\}$ can be identified immediately by inspection of the partial weighted level differences. This analysis can be similarly used for design purposes, and allows extension to include flanking sound: the calculated frequency components of flanking sound can be included by adding those partial weighted level differences in exactly the same way - the contribution of all relevant level difference paths and frequency bands can be considered by adding the level differences in this way.

Equation (14) illustrates the relation for calculating the direct sound transmission between two rooms in a frequency band. When using this equation to calculate a pseudo receiving room parameter, the *partial level differences* due to the direct sound from each contributing element can be calculated by simply summing the *partial level differences* in terms of $R_w + C_{tr}$. This method is equally applicable, for pseudo receiving room level difference parameters, for the global result as it is for frequency components. Indeed, it is valid to combine the most significant frequency components from one element with the global value from another component – all partial level differences can be summed in this way.

5 CONCLUSION

Acoustic design methods that offer insight into how the performance of elements or frequency bands contribute to the overall result have been presented. These methods offer the ability to design rather than just analyse common situations and are illustrated with examples. The concepts of *partial levels*, *partial level differences* and *partial weighted level differences* are used to aid understand and insight into how the overall result is derived from the contributing parts. These concepts can used in further applications to enable the designer to control the most significant elements of the design, and to interpret test data more effectively.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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