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Assessing low frequency noise from industry – a practical approach

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ABSTRACT

The potential adverse impacts of Low Frequency Noise (LFN) from industry and wind farms are often raised by the community as issues of concern. Whilst levels of LFN may be an occupational hazard in certain industries such as defence, aeronautics and music, it rarely constitutes an off-site hazard. It does however increase the level of annoyance and approval bodies must ensure controls are in place to provide adequate levels of community protection and address public concern.

This paper presents a practical alternative approach developed by the authors that could be used to assess the effects of LFN within approval frameworks in a manner that is consistent with contemporary science.

The approach was developed from a critique of existing wide band methods used to assess LFN including overall C-weighted thresholds and the C minus A delta approach currently used in New South Wales, Australia [1]. Several issues were identified from the critique including:

- The C minus A delta approach has a high potential to identify false positive results when assessed against more contemporary standards;
- There is a need for a robust, yet practical methodology; and
- An approach based on knowledge of the noise spectrum is needed.

In summary, the critique found that LFN assessment levels need to be based on the frequency spectrum. However, such comprehensive spectral analysis is complex for compliance assessment purposes and therefore both a preliminary screening measure and industry specific simplified measures could be proposed to minimise the need to progress to full spectral analysis in all circumstances.

INTRODUCTION

In the Australian state of New South Wales, one of the issues that is being raised more frequently in the public arena relates to the impacts of Low Frequency Noise (LFN). This increase in interest appears to have followed a period of ongoing concern from some community members about the potential health effects of wind farms much of which relate to

LFN and infrasound. These same concerns are now being raised more commonly on industrial projects such as open cut coal mines.

Given the increased interest and community concern about LFN, and the potential implications of controls on industry, it is clear that a robust and contemporary methodology for the assessment of excessive levels of LFN is needed. The present paper presents a critique by the authors of the existing wide band methods including the approach in NSW; identifies deficiencies in the current guidance material; and develops a potential alternative method that is underpinned by a substantial body of current scientific support.

There are differences in the definition of the range of frequencies that comprise LFN however for the purposes of environmental noise identification, the range of 10 – 160 Hz is used in this present paper. Infrasound is considered to be that which is less than 20 Hz.

CURRENT ASSESSMENT OF LOW FREQUENCY NOISE

Since 2000, industrial activities in NSW have been generally assessed against the requirements of the NSW Industrial Noise Policy (INP) [1]. This document contains a recommendation whereby if annoying noise characteristics are identified, then the objective level should be modified by way of a penalty. Excessive LFN is one of those characteristics and if triggered, a 5 dB penalty is recommended.

The definition of excessive LFN in the INP is given by:

> *Measure/assess C- and A- weighted levels over same time period. A correction to be applied if the difference between the two levels is 15 dB or more.*

The current methodology is technically not a measure of excessive LFN, but rather an indicator of an unbalanced spectrum. In Australia, this method had been used successfully to identify locomotives with a high LFN content when measurements were undertaken at 15 metres. However, this method has deficiencies and often returns false-positive results when assessed against more contemporary standards, particularly when measurements are made at significant distances [2, 3].

Before examining an alternative contemporary methodology, it is worth examining the limitations of the existing method and alternate methods that have been considered.

METHODS OF ASSESSING LFN AND THEIR LIMITATION

The following provides a discussion on some of the more commonly used broadband methods of assessing LFN and the limitations of these approaches.

dB(C) minus dB(A) as an Indicator of LFN

A range of studies undertaken up to 38 years ago [4, 5 & 6] considered that the difference between C- and A-weighted noise levels could be adopted as a predictor of annoyance, as this difference is an indication of an unbalanced spectrum biased towards the low frequencies.

The work of Kjellberg et al [6] examined existing noise in work places (offices, laboratories, industry etc) with 508 subjects and concluded that correlations between a C minus A delta and annoyance were of limited value, but when the difference exceeds 15 dB, an addition of 6 dB to the A-weighted level is a simple rating procedure. However, over time it has been found that this methodology was not appropriate in all circumstances, for example when either the noise levels are low or the measurements are made at large distances from the source [3].

The observation that a C minus A delta is inappropriate as an assessment tool was recognised by Leventhall [7] who in a summary of this early work, concluded that "*Attempts to assess low frequency noise by conventional wide-band noise methods often fail, so illustrating the inadequacy of these methods for low frequencies.*"

Limitation of method

Two key limitations of the C minus A delta method are as follows:

Frequency content, level and audibility

The approach does not provide information about the specific frequency content, level (amplitude) and audibility of the LFN signal. For example, in noise catchments where the dB(A) levels are not high (i.e. in the order of 40 dB(A) or less), it is possible that the C minus A weighting delta method can result in a LFN penalty being applicable arising from frequencies below the threshold of hearing.

Differential attenuation due to atmospheric absorption

As can be seen in Figure 1, differential attenuation of frequencies by atmospheric absorption alone results in the flat spectrum of Pink Noise (equal energy per octave) returning a C minus A delta of 15 dB at around 3 km. In practice this can occur at much shorter setbacks due to other factors such as screening by obstacles and to a lesser extent ground effects which ISO 9613.2 [8] predicts will slightly preference attenuation of higher frequencies.

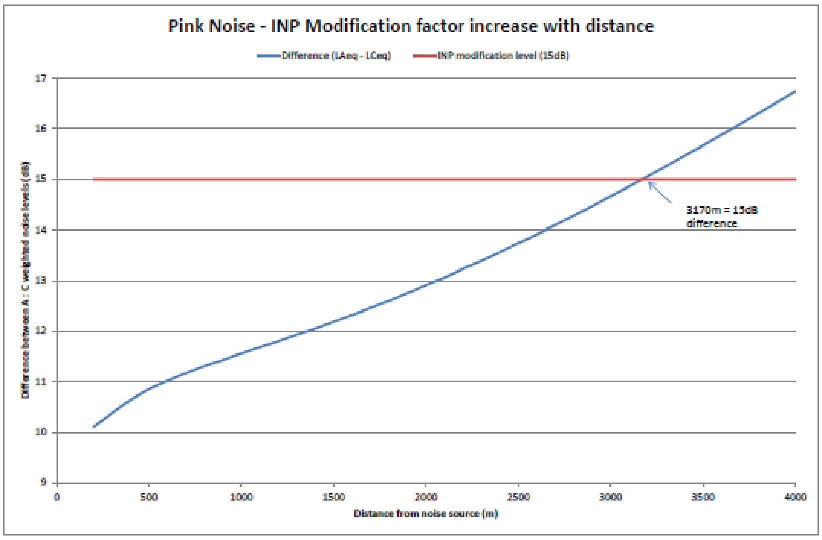

Figure 1. Differential attenuation of broadband noise at 15 ^{0}C and 50 % humidity.

Overall C-weighted Level as an Indicator of LFN

In 2009, the NSW Department of Planning and Environment commissioned a proposal for an alternative to the current approach (published as [2]). The objectives recommended in this report were based on overall C-weighted level of Leq 65 dB(C) daytime and Leq 60 dB(C) night-time and were drawn largely from the work by Hessler [9] on emissions from gas turbines. Characteristically, gas turbines have significant emissions in the lower end of the LFN range, i.e. nominally dominant low frequency energy from 16 Hz to 63 Hz. For gas turbines with these typical spectrums, the levels proposed by Broner [2] provide an appropriate level of protection regardless of the distance setback.

Limitation of method

Whilst the overall dB(C) level method proposed by Broner [2] was considered a more reliable LFN indicator than the C minus A delta method, there was some potential for industries with a spectrum that had more energy towards the higher end of the LFN range to cause adverse community complaint whilst complying with the recommended criteria. Additionally, most noise sources greater than about 50 dB(A) will also exceed 60 dB(C) as a result of overall broadband level, not LFN content. In such cases, application of a penalty would undermine an assessment process that is based on a dB(A) criterion. Consequently, it was determined that the issues identified by Leventhall [8] could also apply to this method as presented in the following examples.

SUMMARY OF LIMITATIONS OF SIMPLIFIED METHODS

Both the C minus A delta and overall C-weighted approaches have potential limitations. Some examples of these limitations are outlined below.

Example 1: Tonal LFN at 20 Hz at a level of say 70 dB could give a C minus A of greater than 40 dB and an overall C weighted level of greater than 60 dB(C). Both of these descriptors would indicate the potential for a LFN impact. However, 70 dB @ 20 Hz is below the human hearing threshold in ISO 226 [10] and therefore would be unlikely to represent an impact.

Example 2: Tonal LFN at 160 Hz at a level of say 50 dB could give a C minus A of just less than 15 dB and an overall C weighted level as low as 50 dB(C). Both of these descriptors would indicate that there is no low frequency impact. However, the level of 50 dB @ 160 Hz would likely exceed internal annoyance indicators for LFN, such as that proposed by the UK Department for Environment, Food and Regional Affairs (DEFRA) [11] when assuming a modest transmission loss across a façade of minus 10 dB @ 160 Hz.

G WEIGHTING

G weighting has a close relation to the human perception to infrasound, however this was not the specific focus of this review. This weighting has relevance in respect to the assessment of a subset of LFN, but has not gained universal acceptance as a measure of annoyance. As can be seen from Figure 2 below, the curve is defined to have a gain of zero dB at 10 Hz. Between 1 Hz & 20 Hz the slope is approximately 12 dB per octave. The cut-off below 1 Hz has a slope of -24 dB per octave, and above 20 Hz the slope is -24 dB per octave.

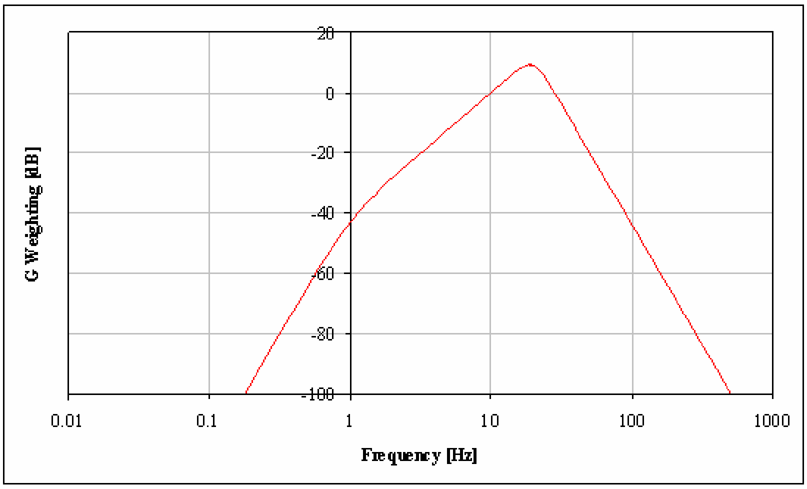

Figure 2. The G weighting curve.

Spectrum Based Analysis

LFN criteria and approaches applied in Europe, are typically based on one-third octave assessment curves generally from 10 Hz to 160 Hz, as opposed to overall C-weighted noise levels and/or 'C minus A' approaches. As eluded to above, DEFRA also conducted a review of European LFN criteria as part of the development of an assessment approach for LFN designed to assist UK Environmental Health Officers when undertaking investigations of alleged LFN nuisances.

The DEFRA approach presents a criterion curve, reproduced below in Table 1, with threshold levels from 10 Hz to 160 Hz. These levels can be relaxed by 5 dB if the sound only occurs for the daytime period. They can also be relaxed by 5 dB if the sound is steady and not fluctuating.

Table 1. UK Department for Environment, Food and Regional Affairs fluctuating criterion values. Reproduced from [11].

Fluctuating Criteria													
Hz	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
dB	92	87	83	74	64	56	49	43	42	40	38	36	34

Note: The criterion values may be raised by 5 dB for the daytime period or where the noise is steady

Limitation of Method

DEFRA [11] states:

> "*The procedure is intended to assist in the evaluation of existing problems. It is not intended as a means of predicting when disturbance might occur, for example in a planning situation, and would not be reliable to use as such. This is because disturbance by LFN depends on a number of factors, such as the character of the sound, whose effects are neither well understood, nor readily predictable. Levels of sound above criteria based on the average threshold of hearing are frequently found to be acceptable and levels falling marginally below can occasionally cause disturbance, so no generic approach appears to be possible*".

The underlined phrase suggests that the DEFRA LFN criteria are likely to be conservative if used in a predictive/planning sense. For that reason, the significance of exceedance of the DEFRA fluctuating curve (base curve) would likely be less than the significance of exceedance of the steady/daytime curve (i.e. plus 5 dB). Additionally, it is also recognised that the sample size for the DEFRA study was not large.

Leventhall [7] recognised the potential increased annoyance associated with a fluctuating LFN signal. The DEFRA approach also recognises this in the relaxation of the base curve for a steady state signal. However, for an assessment approach to include consideration of fluctuations, an objective measure to determine fluctuation strength is needed together with practical means to determine the presence of fluctuations under field conditions. The authors proposed approach adopts an alternative and simplified method based on the magnitude of the exceedance above the base curve.

OTHER COUNTRIES

Figure 3 compares the DEFRA fluctuating curve (identified as UK) with other curves used in Europe and Japan to assess LFN impacts.

Below 50 Hz the curves are typically below the hearing threshold and are reasonably closely grouped. Above 50 Hz the curves move apart with a range of 20 dB at 125 Hz and with some curves below and above the hearing threshold. Note that the Danish curve is derived at each one-third octave from the Danish LFN criteria $Lp_{LF(10\text{–}160\ Hz)}$ 20 dB(A) and is therefore an approximate interpretation.

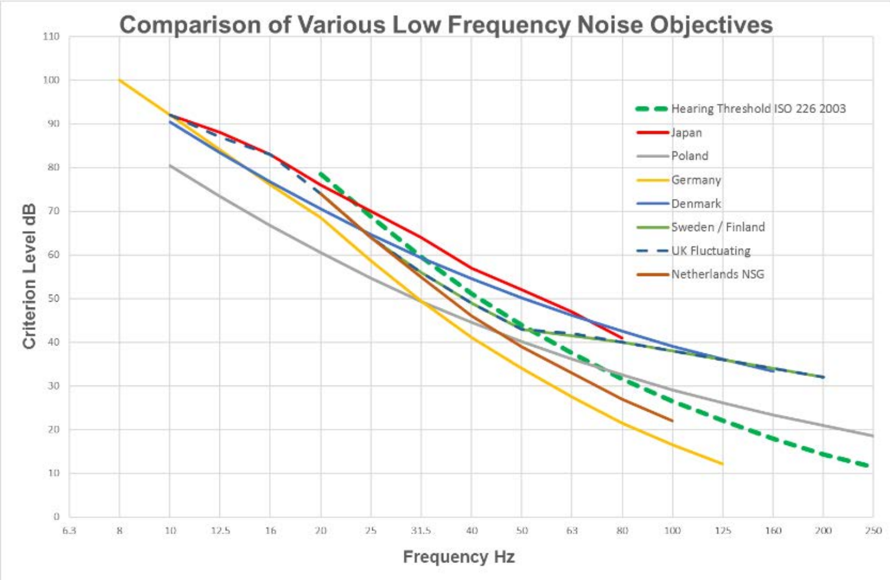

Figure 3. UK Department for Environment, Food and Regional Affairs fluctuating curve compared to other jurisdictions.

DEVELOPING A CONTEMPORARY ALTERNATIVE APPROACH

Noise criteria in NSW typically apply external to a building and in the free field. This is typically more than 3 metres from a reflective vertical surface in the INP [1], or includes a façade correction as required in the Road Noise Policy [12] and Rail Infrastructure Noise Guideline [13]. The use of internal criteria would raise a number of complexities including the need to access buildings for compliance assessment purposes.

Therefore, if a spectral based assessment approach is to be proposed for use as an external measure of LFN, there would need to be reasonably conservative assumptions made about the relationship between indoor and outdoor noise levels, that is, the attenuation (noise reduction) effect of the façade. It is commonly accepted that typical residential buildings provide lower reductions for noise in the low frequency range than in mid to high frequencies.

Façade Noise Reduction

There is a considerable body of scientific literature examining overall façade noise reductions using A-weighted decibels, however this reveals very little in terms of how the façade performs in the low frequency range. Literature specific to the low frequency range is sparser.

Some recent work undertaken in Australia [14] found indoor to outdoor differences in noise near a wind farm in Australia relative to two wind vectors at the house (presumably microphone height) being 0 m/s and 1.1 m/s with windows open as shown in Figures 4a and 4b. The operating conditions of the wind farm were not available to the investigators.

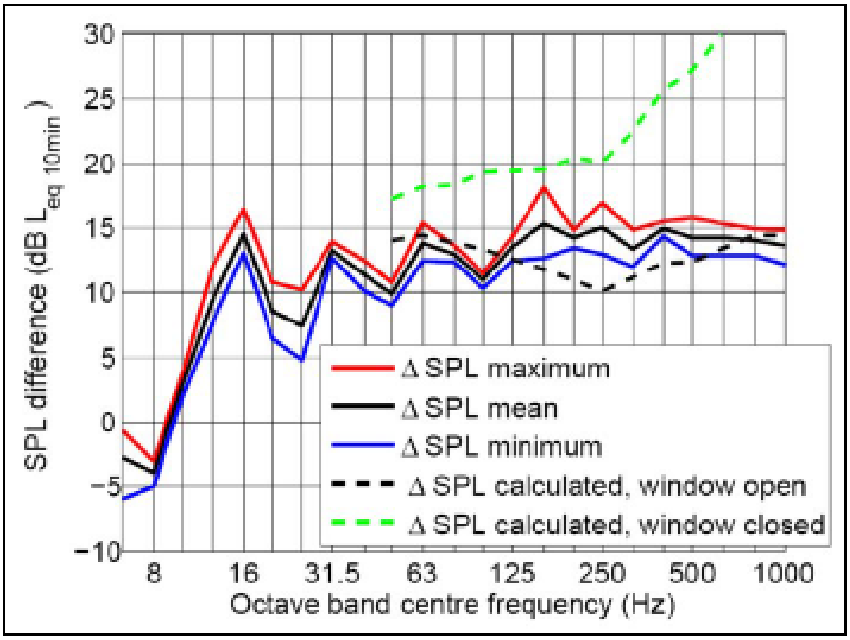

Figure 4a. Sound pressure level (SPL) difference from outdoors to indoors near a wind farm for wind speeds of 0 metres per second [14].

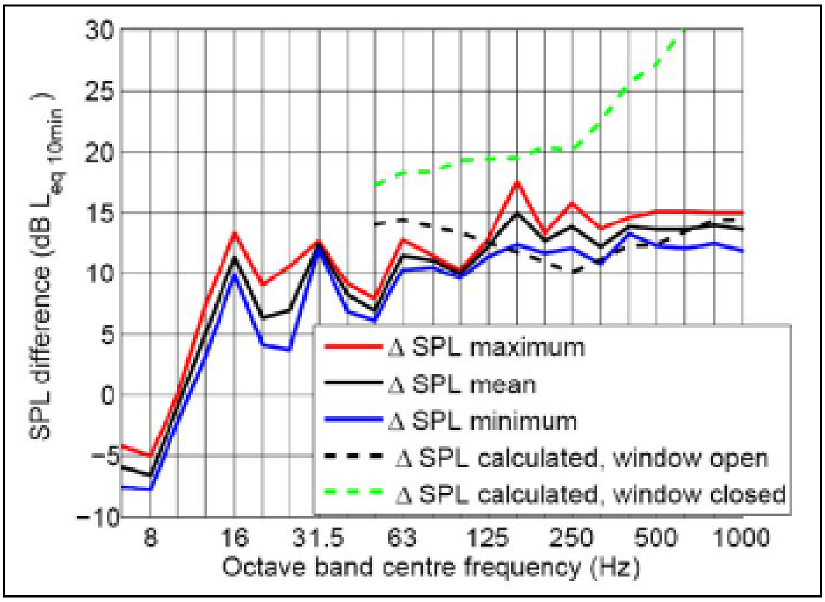

Figure 4b. Sound pressure level (SPL) difference from outdoors to indoors near a wind farm for wind speeds of 1.1 metres per second [14].

Denmark introduced LFN requirements for wind farms in 2012 whereby it required that 20 dB(A), band limited to 10 Hz to 160 Hz, not be exceeded inside a residence. The limits apply for 6 m/s and 8 m/s and are based on predicted noise levels following a prescribed approach. Part of this approach necessarily includes façade noise reduction values from 10 Hz to 160 Hz.

Figure 5 is an extract from Hoffmeyer and Jakobsen [15] presenting a summary of average results from façade transmission loss studies in Denmark, the Netherlands, Great Britain and United States. Details about whether windows were open or closed were not provided.

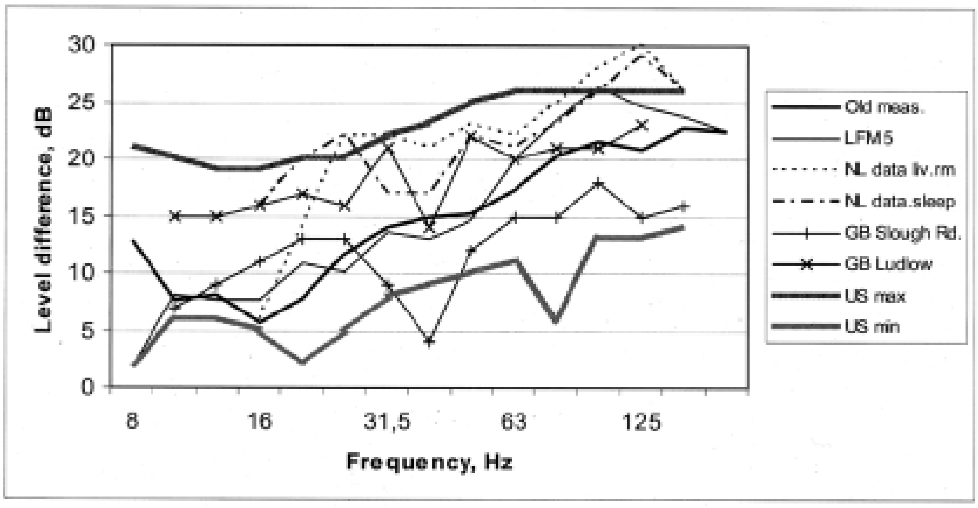

Figure 5. Summary of average results from façade transmission loss studies in Denmark, the Netherlands, Great Britain and United States [15].

The present authors are aware that some of the data presented in the Hoffmeyer and Jacobson [15] paper were considered uncertain (US and GB data) and that data from the Netherlands studies, as presented in Figure 5 above, were not adjusted to account for a façade mounted external microphone location. These factors were considered by the present authors with respect to the outside to inside façade noise reduction values proposed. The present authors are also aware of some dissenting professional views on the Hoffmeyer and Jacobson [15] paper that were published in the Journal of Low Frequency Noise [16, 17].

Additionally, Jakobsen [18] presented data from the 'old' and 'new' Danish Studies reported in [15] comprising measurements undertaken in 14 Danish residences using three internal measurement positions. Figure 6 presents the results of all measurements of outdoor/indoor level difference and a selected 'level difference curve' (solid dark line) that is exceeded by 67 per cent of the measurements, which is used in the Danish Regulation of Low Frequency Noise from Wind Turbines. Details about whether windows were open or closed were not provided.

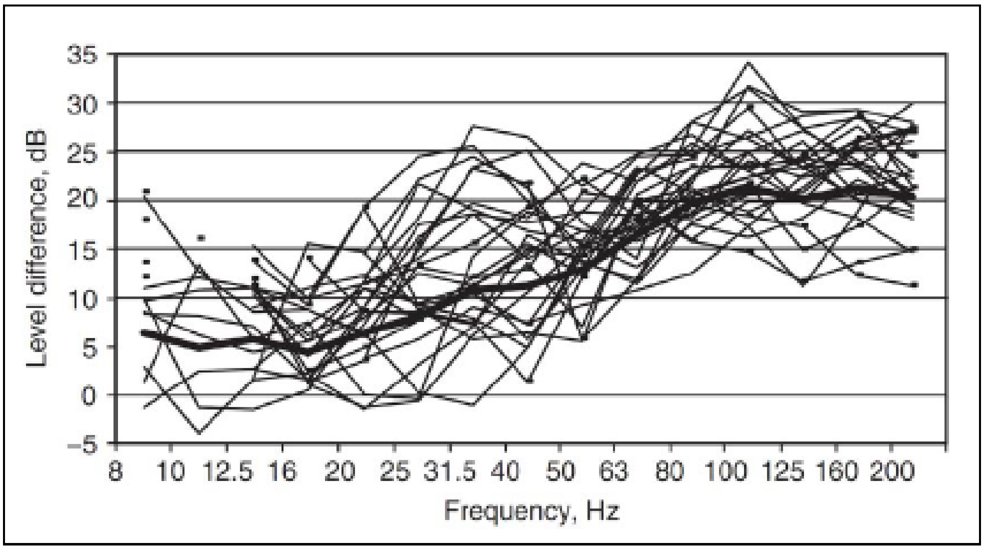

Figure 6. Outdoor/indoor level difference and 'level difference curve' – Danish Regulation of Low Frequency Noise [18].

Shindo, et al [19] reported outdoor/indoor differences in the very low frequency range [20] by considering various configurations of construction and window frame/sash arrangements. Figure 7 presents the result of these measurements. Details about whether windows were open or closed were not provided.

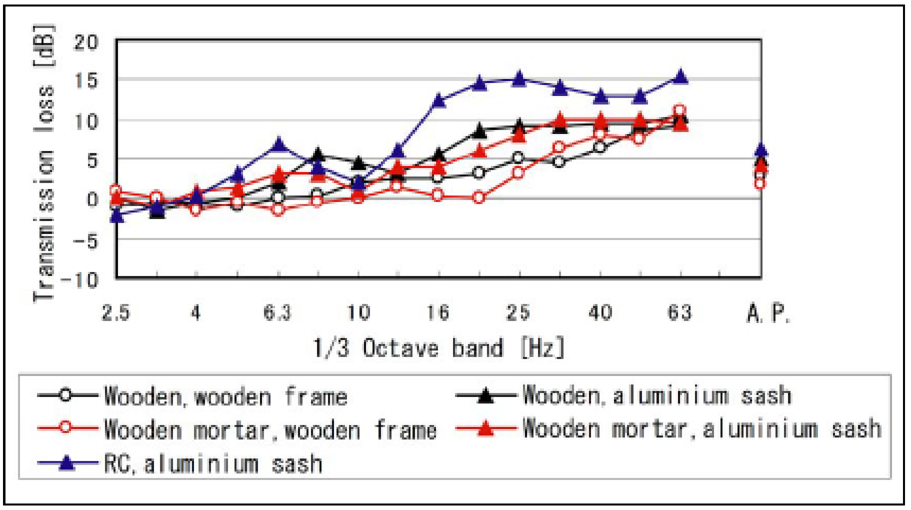

Figure 7. Outdoor/indoor sound pressure level differences for various window sash configurations [20].

Kelley [21] also reported transmission loss across five typical American homes exposed to noise from a gas-fired turbine in the low frequency range for both impulsive and non-impulsive noise as shown in Figure 8. Details about whether windows were open or closed were not provided. Kelly indicates that "*Typically, 5 – 7 dB of attenuation occurs in the 10 – 160 Hz band range for a non-impulsive source excitation*".

While in some circumstances it is clear that LFN can be amplified from outside to inside due to structural resonance and room configuration, in most cases modest reductions occur.

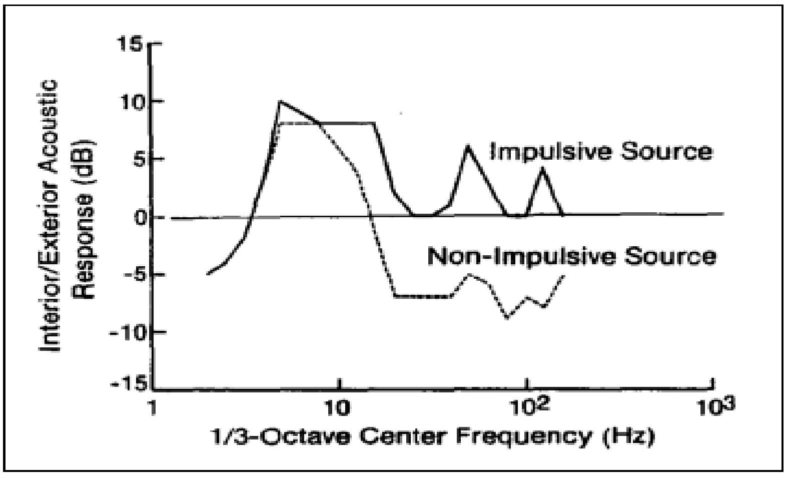

Figure 8. Indoor/outdoor attenuation in five typical American homes near a gas fired power station, non-impulsive source [21].

Assumed Façade Noise Reductions

The authors acknowledge that the measurement procedure used to establish indoor/outdoor level differences vary in the studies examined. To account for this, the correction factors outlined below in Table 2 have been established based on the lowest tenth percentile façade noise reduction data from the above reference studies and practical policy application considerations. They can be used to adjust the DEFRA criteria [11] from an internal noise objective to an external noise objective.

Table 2: Assumed façade noise reductions (10 – 160 Hz).

Default Low Frequency Façade Reductions													
Hz	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
dB	0	-2	-3	-3	-5	-5	-5	-7	-8	-8	-10	-10	-10

Note: These adjustments would be positive when correcting criterion values and negative when adjusting measured values

ALTERNATIVE ASSESSMENT APPROACH

The features of an alternative assessment approach could include:

1. A simple initial screening tool,
2. A frequency based confirmation tool; and,
3. An effective and simple rating tool.

Initial Screening Tool

The use of a C minus A delta of 15 dB or greater as an initial screening approach would be integral as this provides a simple approach to determine whether LFN may be an issue and also safeguards against loud broadband noise triggering an adjustment based only on exceedance of frequency based thresholds.

Frequency based confirmation tool

The frequency based confirmation tool could adopt the DEFRA thresholds as corrected to an external assessment location using adopted façade noise reduction values in Table 2 to arrive at the values presented in Table 3.

Table 3: Third octave low frequency noise adjustment thresholds.

Externally Modified Criteria													
Hz	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
dB	92	89	86	77	69	61	54	50	50	48	48	46	44

Effective and simple rating tool

An effective and simple rating tool could include the following provisions:

- Where a C minus A of 15 dB or greater is measured/predicted, either a 5 dB positive adjustment is applied to measured or predicted A weighted noise levels, or external one-third octave band measurements or predictions are undertaken from 10 Hz to 160 Hz and compared to the frequency specific criteria in Table 3.
- Where any of the 1/3 octave noise levels in Table 3 are exceeded by up to 5 dB and cannot be mitigated, a 2 dB positive adjustment to measured/predicted A weighted levels applies for the evening/night period.
- Where any of the 1/3 octave noise levels in Table 3 are exceeded by more than 5 dB and cannot be mitigated, a 5 dB positive adjustment to measured/predicted A weighted

levels applies for the evening/night period and a 2 dB positive adjustment applies for the daytime period.

Notes to Approach

The above approach is based on the DEFRA base curve for a fluctuating signal, however rating adjustments to objective noise levels have been graduated based on the magnitude of the exceedance above the curve and when (day/evening/night) it occurs. The use of the base curve and the graduated adjustment is considered a practical and simplified alternative to complex measures and assessment of fluctuation and strength.

Where the transmission loss of a building is known, or can be more reliably estimated, then this may be used to produce a building specific Table 2, which may then be used to modify Table 3. This may be particularly relevant where a dwelling has been treated as part of a negotiated noise agreement.

In recognition of the simplicity and considerable merit of the method proposed by Broner [3], premise specific dB(C) values could be developed for compliance assessment purposes. However, this should only occur were it is demonstrated that noise imissions at a receiver location have a known and repeatable spectral composition. Under these conditions a surrogate dB(C) value can be developed as a measure of compliance against the third octave thresholds in Table 3. For example, it may be calculated that a specific open cut coal mine will be compliant with the DEFRA objectives if a level of 56 dB(C) or less is being measured.

Current wind farm assessment approaches in NSW [22] acknowledge that wind farms have well known spectral emissions (and imission at typical offset distances), and for these facilities a value of 60 dB(C) has been adopted as a surrogate LFN compliance measure. Where the regulator has doubt, then it may require a full spectral analysis in the low frequency domain.

CONCLUSION

A thorough literature review of LFN management practices has been undertaken and it is concluded that a frequency based component should be included in any LFN assessment approach. The criteria thresholds developed by DEFRA are based on contemporary science and could be considered as the frequency based component of an alternative assessment approach. The authors also recognise that any LFN assessment tool must be practical, and should incorporate a number of complementary initiatives including the use of a C minus A delta of 15 dB as a screening tool; developing a default table of façade noise reductions to allow for the derivation of external measurement criteria; and an approach that allows for the development of simplified compliance techniques through the use of a surrogate site specific dB(C) level. Graduated adjustments or rating values to objective noise levels based on the magnitude of the exceedance above the criteria curve are considered a practical and simplified alternative to complex measures and assessment of fluctuation strength.

Preliminary assessment has shown that such an alternative approach is both pragmatic and repeatable. Most importantly it has the potential to reduce incidents of applying a correction to noise levels where it is not justified based on increased annoyance due to LFN.

Acknowledgements

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