A Simple Criterion for Low Frequency Noise Emission Assessment

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There are many sources of Low Frequency Noise (LFN) in the environment and complaints about the effect of higher level LFN in the form in the form of "rumble", a "feeling of pressure" and the resultant headaches and nausea have been known for decades. A number of different European methods have been suggested for assessment of LFN, all based on measured indoor noise levels. The administrative procedures used in individual countries to enforce any LFN criteria are quite different but they are all generally based on the assumption that the annoyance due to LFN is dependent on the relative SPL when compared to the threshold of audibility. In terms of simplicity of application, the determination of an overall noise level that could be used for assessment of LFN would be the optimum approach rather than requiring any detailed spectrum analysis and calculations. Ideally, LFN criteria should be set indoors where the LFN complaints normally occur. However, in planning terms, it is much easier to set criteria for the outside of residences. In this paper, we therefore propose criteria for the prevention of LFN complaints for both residential and commercial permisies based on the measured overall C-weighted SPL. We also consider the impact of LFN SPL fluctuations.

1. INTRODUCTION

Complaints about the effect of higher level Low Frequency Noise (LFN) in the form of rumble, a "feeling of pressure" and resultant headaches and nausea have been known for decades (eg Broner 1978, Leventhall 2003). Human hearing becomes gradually less sensitive as frequency decreases, so for humans to perceive LFN i.e. to perceive frequencies below 100 Hz, the sound pressure level must be relatively high when compared to that for mid frequency noise, eg 500 – 3000 Hz. As the frequency decreases toward the infrasonic range (frequencies less than 20 Hz and a subset of LFN), the sensation of hearing changes to one of a feeling of ear pressure and envelopment for those noises which exceed the hearing threshold.

Figure 1 shows the spectra measured in a Boardroom and Office affected by a LFN source near to a commercial building. The occupants of this building were quite annoyed by the LFN and complained of headaches and nausea. It can be seen that the increase in Sound Pressure Level (SPL) when the source is turned on is quite significant at low frequencies. In particular, there was an increase of the order of 20 dB at the 16 Hz and 31.5 Hz octave bands and of the order of 10 dB at the 63 Hz octave band. The degree of low frequency excess can be determined using the LFNR (Low Frequency Noise Rating) Curves (see Broner and Leventhall, 1983). These curves are shown in Figure 1. The Board Room noise has a Low Frequency Noise Rating (LFNR) of about 40 at frequencies above 125Hz. Therefore, as the LFNR 40 curve is exceeded below 125Hz, in this instance, the low frequency noise complaint would be considered justified.

The overall SPL's in the Office and Board Room are shown in Table I below. The (C-A) level difference for these occupancies were 36 dB and 32 dB respectively.

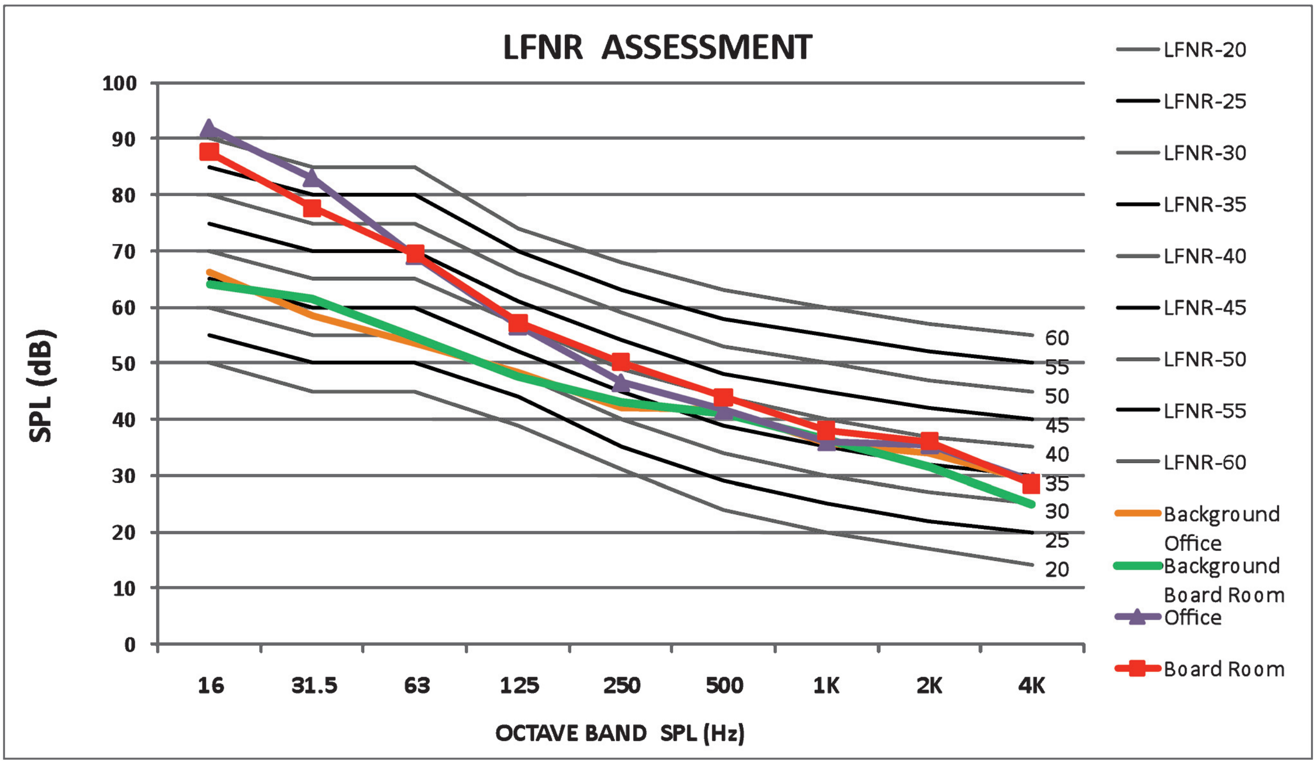

Figure 1 *Spectra Measured in a Commercial Building Where the Occupants Suffered from LFN*

Table 1 Overall SPL's in the board room and office

Location	dBA	dBC	dBZ
Office	49.1	85.2	92.5
Board Room	49.1	80.7	88.1
Background Office	43	61	67.3
Background Board Room	42.5	61.4	66.3

2. TYPICAL LOW FREQUENCY NOISE SOURCES

There are many sources of LFN in the environment eg Leventhall and Kyriakides, 1976. These range from boilers, pumps, fans, cooling towers, ventilation plant and gas turbines to wind farm turbines (eg Bryan 1976, Broner 1978). At larger distances from many industrial plants, the noise character will be that of LFN due to the relatively large attenuation of high frequency energy as compared to LFN (note that the LFN level also decreases due to geometrical spreading). Transportation noise sources such as aircraft and diesel trains also are sources of LFN. Helicopters generate LFN and blade slap in particular. Also LFN can be generated at pubs/band venues and concerts where the bass sound is considered as wanted sound by patrons, but can be very annoying to neighbours.

Typical low frequency noise sources include:-

- Open Cycle Gas Turbines
- Boilers
- Forced Draft and Induced Draft Fans
- Shakers on hoppers
- Vibratory screens
- Compressors
- Wind farms

The noise sources listed above generate low frequency noise due to the operation of various items of plant or equipment e.g.:-

- **Power Station** - Open Cycle Gas Turbines / Forced Draft Fans generate low frequency noise due to combustion and turbulent air flow.
- **Industrial Sites** - Boilers generate low frequency noise through combustion noise / Forced Draft Fans generate turbulent airflow
- **Mine Sites / Quarries** - Shakers on hoppers / vibratory screens generate low frequency noise due to excitation of the structure, large FD/ID fans associated with exhaust stacks may generate LFN..
- **Wind Farms** – Wind Turbine Generators with the rotors downwind of the tower were noted for LFN with the passage of the blades through the tower's wind shadow (resulting in pulses at about one per second which were analysed as infrasound). However, current generation wind turbines have the rotors "upwind" of the turbine tower, thus avoiding this problem. Turbine blade rotation may result in a "swishing" sound, which is at higher frequencies, but with a low frequency modulation. This should not be confused with LFN (eg Leventhall 2004).

It should be realised that just because these sources exist at a site, it does not necessarily mean that a LFN problem will occur. There are many plants/facilities with LFN sources in them and where LFN is not a problem in the surrounding community. Whether or not LFN becomes a problem will depend on the level of the LFN, whether it is fluctuating and other individual circumstances.

It can be said that the effects of LFN are broadly similar to those of high frequency noise in the sense that any unwanted sound is potentially annoying. However, LFN exhibits itself in the form of "rumble" and "pressure" and while not at all loud in the normal sense of the word, LFN can exacerbate the annoyance reaction when compared to higher frequency noise, especially when the noise is perceived to be "fluctuating" or "throbbing".

3. LFN PERCEPTION AND ASSESSMENT

3.1 PERCEPTION AND ANNOYANCE

Based on empirical and laboratory studies, it can be shown that the primary effect due to LFN appears to be annoyance and that this affect is greater than would be expected based on the A-weighted level alone, e.g. Berglund et al. 1996, Broner 1978, 1980, Broner and Leventhall 1983, Bryan 1976.

It seems that for sound with "tonal" low frequency content below 50 Hz and for infrasound (< 20 Hz), particularly where the sound level is perceptibly fluctuating or throbbing, annoyance and loudness are treated differently and that this difference may increase with time (Hellman and Broner, 2004). As the loudness adapts more rapidly with time than the annoyance (i.e. the perceived loudness decreases more rapidly with time than the perceived annoyance), the effect is to effectively increase the annoyance with time i.e. it seems that we can adapt to the loudness element more readily than to the annoyance. This effect would be more pronounced for the lower frequency infrasound where, at levels above the hearing threshold, the sound is not so much heard but is rather perceived as a feeling and sensation of pressure.

The perception of annoyance is particularly dependent on the degree of amplitude modulation and spectral balance e.g. Bradley (1994) and Bengtsson et al (2002). As a result, it is considered that there is a significant limitation in the long term averaging of LFN noise levels, as this approach results in the loss of information on fluctuations e.g. Broner and Leventhall, (1983) and Blazier and Ebbing, (1992), Leventhall (2003).

3.2 WHICH NOISE METRIC?

Assessment and prediction of annoyance due to LFN is not simple. When assessing noise, the most common method is to use the A-weighting. Based on empirical evidence and many documented cases (Broner and Leventhall, 1983, Leventhall 2003, Moorhouse et al 2005), it is very clear is that the A-weighted SPL alone is not successful in assessing the response to LFN (and to infrasound). The major reason for this is that A-weighting network significantly decreases the contribution of low frequency energy in a sound due to the reduced loudness sensitivity of our hearing at low frequencies.

Although the A-Weighting network is commonly used for most applications, the 'C' Weighting is more appropriately used for assessment of higher noise level generating noise sources and for some entertainment noise level measurement. This is because the C-weighting includes nearly all of the low frequency energy in a signal and so would be more appropriate for situations where the transmission of bass noise or significantly high levels of LFN from plants or equipment can be a problem in the community. In addition, because until recently there was no accepted Standard for the Linear network (dBZ), if we wanted to use a noise measure that didn't significantly affect the low frequency content of a signal when we were measuring it, we would have to choose the C-weighting network.

It can be deduced from the above, that a simple method of indicating how much LFN there is in a sound would be to subtract the A-weighted SPL from the C-weighted SPL. But there are two questions viz. what (C-A) difference is necessary, and, is this difference the same at all sound levels?

3.3 ASSESSMENT BASED ON (C-A)

As indicated above, the (C-A) difference can indicate how much LFN is present in a sound. Empirical evidence shows that where the imbalance is such that the difference between the Linear and A-weighted Sound Pressure Levels is at least 25 dB, the sound may cause annoyance. Broner and Leventhall (1983) and DIN 45680-1997 suggested that a difference of 20 dB can result in an unbalanced spectrum which could lead to LFN annoyance. Similarly, the Alberta EUB (2007) require the (C-A) difference to exceed 20 dB to determine the presence of a LFN problem.

Others have suggested that a difference of only 15 dB was a good rule of thumb to identify a potential infrasound LFN problem situation e.g. Kjellberg et al (1997). In New South Wales (Australia), the Industrial Noise Policy (INP 2000) allows the determination of either an intrusiveness or amenity criterion when considering land use planning. It recommends that a 5 dB modifying factor be added to the outdoor A-weighted measured/predicted sound pressure level when the 'C' weighted sound pressure level minus the 'A' weighted sound pressure level difference is 15 dB or greater.

Based on a review of the literature, it is recommended that a minimum (C-A) difference of 20 dB is necessary to indicate the presence of a LFN problem. However, a greater difference may be permissible at low A-weighted levels, as the (C-A) difference for low levels of background noise may exceed 20dB without causing complaints

In general, the (C–A) level difference is only an appropriate **starting** metric for indicating when a potential LFN problem may become a significant source of annoyance to the public. However, its predictive ability is of limited value (see also Leventhall 2003) and, as can be seen from the above, higher (C-A) differences are suggested as being necessary to indicate a LFN problem.

What would be most suitable is a simple overall criterion below which annoyance due to LFN is not expected to occur regardless of the (C-A) difference (or above which annoyance could be anticipated).

In addition, if it is necessary to utilise a (C-A) SPL difference at all, it is recommended that a (C-A) difference of at least 20 dB be used to indicate the presence of a potential LFN noise problem.

Below we review overall noise level criteria for LFN which will be able to assist in determining if a complaint due to LFN should be considered for further investigation.

4. INDOOR LOW FREQUENCY NOISE LEVEL ASSESSMENT

LFN from external noise sources has the ability to pass through 'light weight' residential and commercial building structures with minimal acoustic attenuation and can strongly impact on the internal noise environment. To assess the impact of LNF, a range of noise criteria have been developed.

The G-weighting (ISO7196, 1995) was specifically designed for the assessment of infrasound, falling off rapidly below 1 Hz and above 20 Hz at 24 dB/octave (see Figure 2). Between 1 Hz and 20 Hz, it follows a slope of 12 dB/octave, thus each frequency is weighted in accordance with its relative contribution to the perception. A G-weighted level of 95 – 100 dBG is close to perception level whilst levels below 85 – 90 dBG are not normally significant for human perception. Note this weighting has a limited application in practice and care should be taken not to put too much reliance on this metric as it may divert attention away from problems at higher frequencies (in the range 20 – 100 Hz). In practice, for commonly occurring noise levels, LFN noise in the range 30 – 80 Hz is more likely to be a problem in terms of annoyance. e.g. Broner 1983, Leventhall 2003.

Broner and Leventhall (1983) recognised the problem of spectrum imbalance for the assessment of LFN complaints. They noticed that complaints of LFN were invariably associated with sound that had most energy at low frequencies and that had reducing high frequency content as the frequency increased. This type of sound is typically found indoors as a result of the high frequency filtering effect that a building façade has on the noise when it enters a building with closed windows. They suggested that when the A-weighted SPL was greater than 30 dBA, the overall Linear SPL should be limited to the sum of the A-weighted SPL plus 30 dB to minimise annoyance. Thus for sound at 35 dBA, the

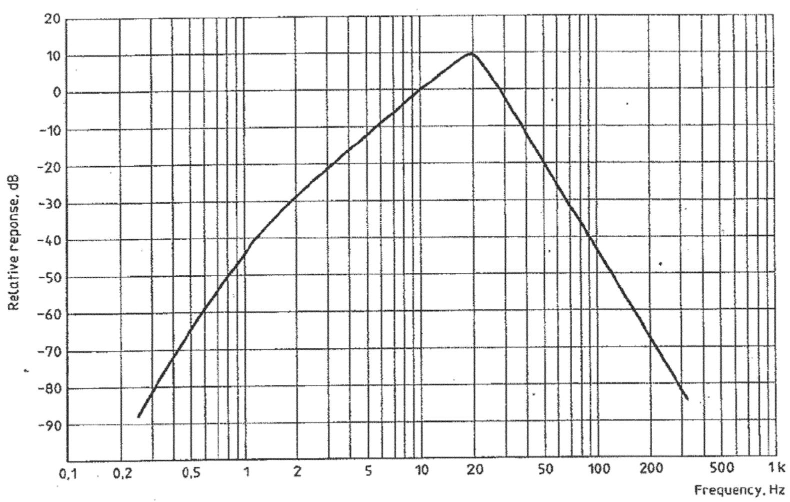

Figure 2 The G weighting (after ISO 7196:1995)

recommendation was a LFN limit of 65 dB Linear (note that this criterion is approximately equal to a [C-A] difference of 20 dB). They further suggested a 3 dB penalty for noise that was fluctuating or throbbing.

A number of different European methods have also been suggested for assessment of LFN, all based on measured indoor noise levels (note that these are specifically for the assessment of LFN following a complaint). These are the Danish, Swedish, German, Polish and Dutch methods (Poulsen 2003, Leventhall 2003 and Moorhouse et al 2005 all compare all of these). The administrative procedures used in the individual countries to enforce the criteria are quite different but they are all generally based on the assumption that the annoyance due to LFN is dependent on the relative SPL when compared to the threshold of audibility. The Dutch curve is really intended to predict audibility rather than acceptability so is somewhat lower than the other curves. Figure 3 shows a comparison of the various criteria curves (T. Poulsen 2003). Each of these methods is based on the measurement of the noise in either octave or third octave bands so that a comparison of the measured data with the criterion can be made. Further, it is noted that these methods are generally designed for the assessment of "steady" sounds (the measurement criterion is in terms of the equivalent continuous sound level so that the fluctuations and excursions in level over time are averaged out), and will therefore not correctly assess the impact of annoyance due to those cases of LFN which do have a considerable fluctuating or throbbing characteristic. This is because the averaging process removes the level fluctuations which are a major source of the perceived annoyance due to LFN.

Note that only the German DIN 45680 (1999) uses a (C-A) difference as a test for the potential presence of a LFN problem, in this case, a difference of greater than 20 dB.

Moorhouse et al (DEFRA 2005) reviewed the existing European criteria for assessment of LFN when measured indoors at a complainant's house. They proposed that if the L_{eq} was taken over a time when the LFN was said to be present exceeded the proposed reference curve (which is shown in Table II), the LFN would be assessed as one which *could* cause disturbance. They proposed two "relaxations" of their criterion reference curve. One was 5 dB if the noise occurred only during the day, the other 5 dB relaxation was to be applied if the noise was steady in character (a

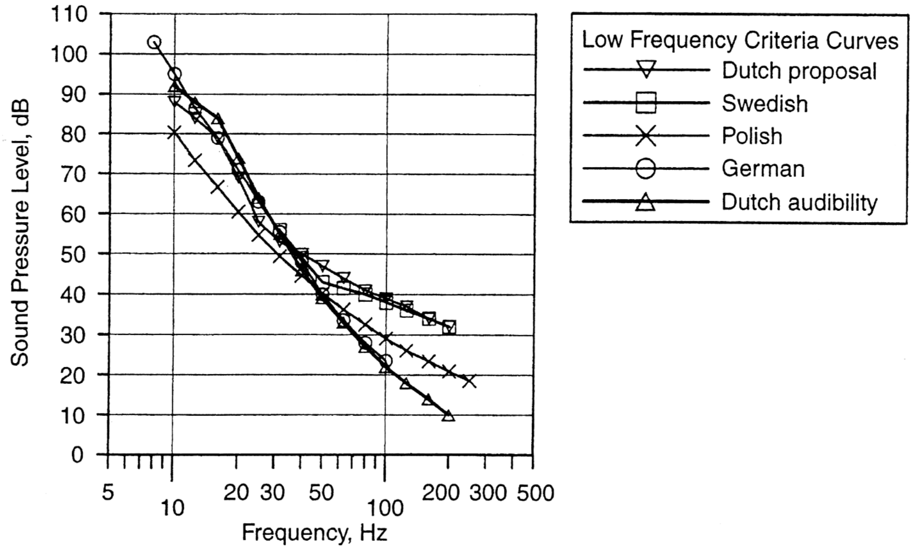

Figure 3 European Low Frequency Noise Criteria (after Poulsen 2003)

Table II Threshold Curves for Low Frequency Noise

Standard	**Sound Pressure Level (dB) 1/3 Octave Band Centre Frequency (Hz)**														
	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200
DEFRA 2005 Reference Criterion Curve			92	87	83	74	64	56	48	48	42	40	38	38	34
DIN 45680:1997-3		103	92	87	79	71	63	56.5	48	40.5	38.5	28	23.5		
ISO 7029:2000 Median minus 4 dB (10% of 60 year old males)					74	62	55	46	39	33	27	22	18	14	10
ISO 389-7 1996					78	68	59	50.5	43.5	37.5	31.5	26.5	22	18	14.5
ISO 226 - 2003					78.5	68.7	59.5	51.1	44	37.5	31.5	26.5	22.1	17.8	14.4

LFN was considered steady if the $L_{10} - L_{90} < 5$ dB or if the rate of change of the sound pressure level (Fast time weighting) was less than 10 dB per second). We note that the DEFRA reference curve adds to approximately 80 dBC so that if a noise spectrum followed this curve exactly, the night time residential criterion according to this approach could be as high as 80 dBC in the worst case.

Roberts (2008) also recognised the impact of amplitude modulation on the perceived annoyance due to LFN and recommended a subtraction of 5 dB from the nominated threshold reference curve in that instance. For initial screening purposes, he suggested the use of a (Z-A) difference greater than 15 dB but this was independent of the measured A-weighted noise level.

For comparison purposes, other

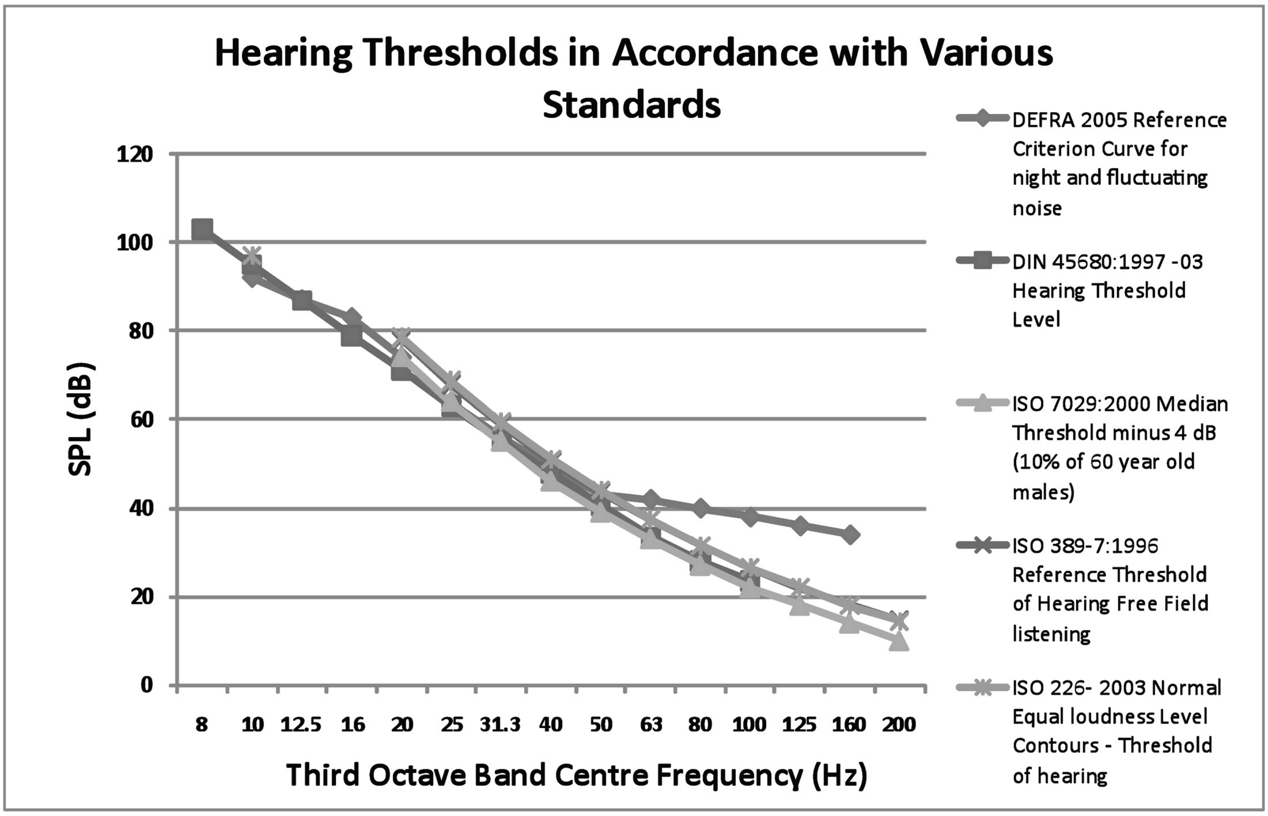

Figure 4. Threshold Curves for Low Frequency Noise Based on Different Standards

"threshold" curves based on different International Acoustics Standards are also included in Table II. Figure 4 shows the same data in graphical form. It can be seen that there is a general agreement for frequencies below 50 Hz with some divergence above.

5. OUTDOOR LOW FREQUENCY NOISE LEVEL ASSESSMENT

It has been known for many decades that gas turbines, boilers, forced draft fans and other sources can produce low frequency noise which can cause feelings of annoyance in sensitive people, due to nausea, headache and uneasiness and vibration induced rattle. In terms of simplicity of application, the determination of an overall noise level that could be used for assessment of LFN would be the optimum approach rather than requiring any detailed spectrum analysis and calculations (as are required in some European countries – see above). Much of the data concerning an acceptable external overall criterion for LFN comes from research associated with power station noise. However, any criteria so developed would certainly apply to **any** LFN problem regardless of the source due to the spectral and fluctuating characteristic of the consequent LFN.

Concern about the impact of LFN on residential communities was already raised by Hoover in 1973 who, recognised that if homes were located within 1000 feet of an open cycle gas turbine (OCGT) installation, then the Sound Pressure Level (SPL) in the 31.5 Hz octave band needed to be no more than 65 – 75 dB at 400 feet. Hoover suggested a guideline that the SPL in the 31.5 Hz octave band should never exceed 70 dB (L_{eq} 67 dBC) or even 65 dB (L_{eq} 62 dBC) outside a house when ambient levels were in the range 48 – 53 dB.

ANSI B133.8 -1977 recognised that for installations where frame structures are occupied by people near to gas turbine installations, the A-weighted sound level alone does not adequately define permissible low frequency sound emissions. Indeed, ANSI B133.8 Appendix B recommends the selection of a maximum C-weighted level outside the nearest occupied framed structure and suggests the upper limit should be selected not to exceed 75 – 80 dBC. The range of values was given due to

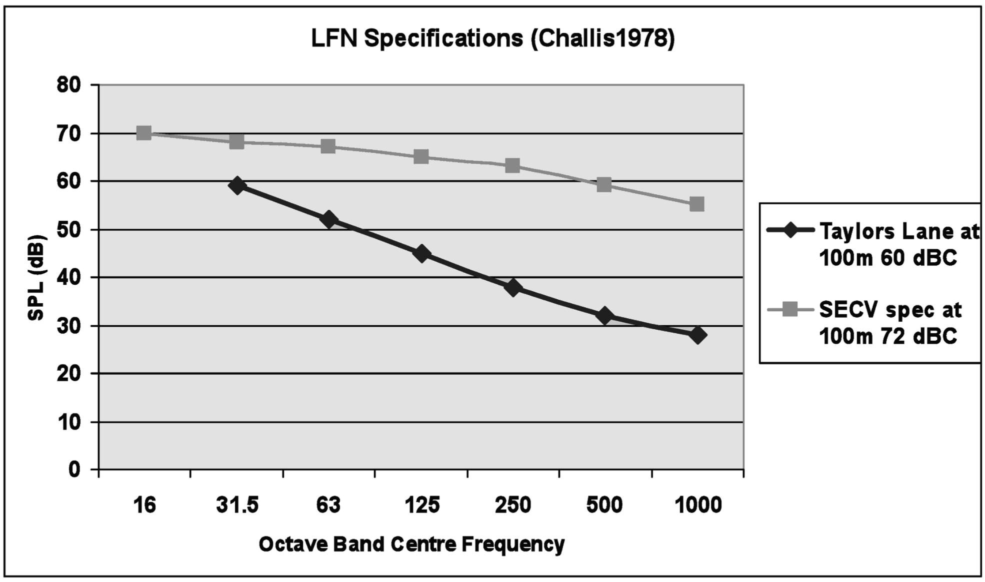

Figure 5. LFN specifications by utilities quoted by Challis

uncertainty as to the sound level required to induce a structural vibration in a frame structure.

Challis and Challis (1978) also recognised that even though a level of 40 dBA might seem to be moderate, gas turbine emissions could have SPL's as high as 96 dB at 16 Hz and 110 dB at 10 Hz, which are both audible, causing strong negative community response. Challis and Challis (1978) also identified a number of English and Australian Utilities that had specified criteria, basically NR curves, but with significantly reduced noise levels below 63 Hz, specifically for 8Hz, 16 Hz and 31.5 Hz Octave Bands.

These utilities had experienced LFN problems and came up with their criteria for neighbouring residences based on the experience of others.

As an example, Figure 5 below shows the specification for two utilities for stack emission at 100 metres (after Challis and Challis 1978). These two criteria are quite different and vary from L_{eq} 72 dBC to L_{eq} 60 dBC.

In discussing low frequency gas turbine noise, Newman and McEwan (1980) quoted a British Gas Corporation criterion for specifying noise control for gas turbines viz. 60 dB in the 31.5 Hz octave band at the nearest dwelling. This would be equivalent to L_{eq} 57 dBC. This value was said to have been determined by review of the noise levels which complainants found satisfactory.

In 2001, Hessler noted that low frequency noise was only a problem for OCGT plants and he recommended that "a level of 70 dBC at the closest residence is normally low enough to prevent perceptible vibration but that a slightly lower level of 65 dBC is needed in quiet, rural environments where the residual ambient noise level is low".

In 2005, Hessler described the low frequency noise problems that have occurred in the USA due to incorrect siting of gas turbine power plants close to residential areas. Typically, neighbours expressed complaints of low frequency rumble noise, vibration rattle, nausea and headaches in some people. At low frequencies, apart from the spectral imbalance issue, a major factor in causing annoyance is the significant temporal level fluctuations that may occur.

Hessler considered that his experience since 1971 had shown that the recommendation of ANSI B133.8 was "woefully inadequate" for protecting residential areas against low frequency noise problems and that the problem continued to occur for combustion turbine open cycle plants. He therefore proposed C-weighted Sound Pressure Levels supplementary to the A-weighted site criteria as follows:

Table III Maximum Allowable dBC Levels at Residential Areas to Minimise Infrasound Noise and Vibration Problems

	For Normal Suburban/Urban Residential Areas, Daytime Residual Level, L_{90}>40dBA	**For Very Quiet Suburban or Rural Residential Areas, Daytime Residual level, L_{90}<40dBA**
For Intermittent Daytime Only or Seasonal Source Operation	70	65
Extensive or 24/7 Source Operation	65	60

These levels contained no factor of safety or margin of error and Hessler cautioned that these levels should be considered the maximum allowable. Hessler (2008) has since clarified that his criteria are all in terms of the C-weighted L_{eq}.

Similarly, Annex D of ANSI S12.9 – 2005/Part 4 deals with sounds with strong low frequency content and for essentially continuous sound where the C-weighted sound level exceeds the A-weighted sound level by at least 10 dB. Annex D provides a means for calculating an adjustment to the sound exposure level based on the summation of the time – mean – square sound pressures in the 16, 31.5 and 63 Hz octave bands. ANSI recognises that generally, annoyance is minimal when octave band sound pressure levels are less than 65 dB at these octave bands (equivalent to L_{eq} 67 dBC) and that to prevent the likelihood of noise-induced rattles, the low frequency sound pressure level should be less than 70 dB (ANSI does not make clear at which octave bands this applies to but it is presumably at the 16, 31.5 and 63 Hz octave bands – this would be equivalent to L_{eq} 72 dBC).

The Oregon State Noise Control Regulations for industrial and commercial noise sources also quote low frequency allowable octave band sound pressure levels for the 31.5 Hz and 63 Hz octave bands as 65 dB and 62 dB respectively for the night time period 10 pm – 7 am [this would be equivalent to L_{eq} 65 dBC] (the limits are 68 dB and 65 dB for the daytime period 7AM – 10 PM respectively [equivalent to L_{eq} 68 dBC]).

In a recent paper, Hale (2009) described a power plant that was to be located in an area where the proposed project location was in an unincorporated jurisdiction that had enacted C-weighted daytime and night time noise limits of 50 dBC and 45 dBC respectively. In response to objections by both commissioners and the local community, the original power plant location was abandoned and a new site selected. The project sought and obtained a noise variance for a 65 dBC noise limit at the plant boundary. The local consultant indicated that the C-weighted SPL's due to the plant did not comply because of 16 Hz tones. However, the local community indicated the operating plant could not be heard in the community and Hale concluded that the plant design was adequate for compliance with the noise variance limit and that no noise impacts to sensitive locations would occur.

6. RESIDENTIAL CRITERIA VS COMMERCIAL CRITERIA

It is clear from the above that:

- High levels of LFN are necessary for perception.
- Most cases of LFN annoyance occur when an unbalanced spectrum occurs with a decreasing level as frequency increases.
- LFN needs to be above threshold for a nuisance to occur but there is a very small percentage of the population that may be more sensitive to LFN than most ie they have relatively low LFN thresholds and tolerance.
- Continuous audible LFN can be a noise nuisance in the same way as can be any other noise.

Ideally, LFN criteria should be set for indoors where the LFN complaints normally occur. However, in planning terms, it is much easier to set criteria for the outside of residences where artefacts of the measurement do not play such a big role and where there is no need to enter a person's premises after start-up to confirm compliance with an outdoors noise level specification. Similarly, an overall noise level criterion is much preferred to one relying on an octave band or third-octave band analysis and calculation.

We would therefore propose that to prevent low frequency noise complaints, the simplest approach is to limit the overall noise level outside **the residential locations** to the following:

For the **daytime** or when the LFN source operates only intermittently (for 1 - 2 hours):

Desirable: L_{eq} 65 dBC
Maximum: L_{eq} 70 dBC.

For the **night time** or for where the LFN operates continuously (24/7), it is proposed that the criteria for residential locations should be:

Desirable: L_{eq} 60 dBC
Maximum: L_{eq} 65 dBC.

The impact of LFN level fluctuations also needs to be considered as when they occur, the annoyance is exacerbated due to the significant change in perceived loudness with change in SPL at LFN. Thus, if the dBC level is fluctuating at least +/- 5 dBC (ie 10 dBC overall fluctuation), the above criteria should be reduced by 5 dBC.

Should there be a different set of criteria for **commercial office/industrial locations**? For commercial office/industrial situations, there would appear to be an expectation that acceptable LFN noise levels could be higher than for residential areas. In most circumstances, office/commercial structures are much more solid than a framed residential house. In addition, it could be expected that there would be greater tolerance to low frequency noise from LFN sources such as OCGT peaking plants, if these plants are operated for only *short* time periods during the normal working day or after normal working hours when employees are not normally present. On the other hand, LFN due to incorrectly balanced HVAC systems may be continuous, but not necessarily at as high a SPL.

Thus, for **day operations** or where the LFN source only operates intermittently (say 1 – 2 hours), it is proposed that the criteria for offices/commercial structures should be:

Desirable: L_{eq} 75 dBC
Maximum: L_{eq} 80 dBC

For **night time** operation or for where the LFN operates continuously (24/7), it is proposed that the criteria for offices/commercial structures should be:

Desirable: L_{eq} 70 dBC
Maximum: L_{eq} 75 dBC

Again, a "penalty' of 5 dBC to the proposed criteria is recommended where the measured LFN SPL is fluctuating at least +/- 5 dBC.

The above criteria are expected to protect 90 - 95% of the population. There will always be someone who might be more sensitive than the majority of the population. In such a circumstance, a detailed investigation by an acoustic consultant who is familiar with LFN problems might be warranted.

On the other hand, an exceedance of the recommended criteria by 2 – 3 dBC should not necessarily result in LFN complaints if the noise source is not continuous.

7. LOW FREQUENCY NOISE MITIGATION

It should be realised that the cost of noise mitigation where LFN problems occur can be quite substantial, particularly as a retro-fit. The problem is that LFN has a very large wavelength eg at 50 Hz, the wavelength is 6.86 metres at Standard temperature and pressure conditions. In contrast, the wavelength at 1000 Hz is 0.343 metres, $1/20^{th}$ the length. This phenomenon has a very real impact on what is possible and practical for controlling LFN as compared to higher frequency noise. For example, the façade of a

Criteria for Assessment of LFN

	Sensitive Receiver	Range	Criteria Leq (dBC)
Residential	Night time or plant operation 24/7	Desirable	60
		Maximum	65
	Daytime or Intermittent (1 – 2 hours)	Desirable	65
		Maximum	70
Commercial/ Office/ Industrial	Night time or plant operation 24/7	Desirable	70
		Maximum	75
	Daytime or Intermittent (1 – 2 hours)	Desirable	75
		Maximum	80

house or building might reduce high frequency noise (1000 Hz) by the order of 30 – 35 dB while at 50 Hz the same façade might only provide 5 – 10 dB noise level reduction. This means that when a LFN impinges on a house façade, it "punches straight through". The higher frequencies are successfully reduced by a facade so that what is left is potentially a sound balanced to the low frequencies and this type of sound is potentially found annoying by some people.

With respect to silencers, the same difficulty in treating LFN relative to higher frequencies occurs. To achieve a 5 dB reduction at 1000 Hz, will require acoustic splitters that are not as wide or long as would be required for low frequencies. To achieve a 5 dB reduction at say 31.5 Hz in an exhaust silencer, could require acoustic splitters of the order of 1000 mm thick and 5 – 10 metres long. The cost of such installations, especially as a retro-fit, could be in the order of $10 – 20 million.

It is therefore always better to consider any potential LFN emission when in the planning stage of developments with LFN sources. The cost for noise mitigation is always much less when incorporated during the initial design of a plant than as a later retro-fit to fix a LFN problem.

8. RECOMMENDATION

Ideally, LFN criteria should be set for indoors where the LFN complaints normally occur. However, for the purpose of planning, it is much easier to set criteria for outside residences.

Based on a review of many case histories and the literature, the author recommends the following criteria:

If the measured LFN SPL is fluctuating at least +/- 5 dBC, then a "penalty' of 5 dBC to the proposed criteria (ie a reduction in the proposed limit) is recommended.

When measuring the noise, all energy down to 10 Hz should be considered and a minimum sampling duration of 3 – 5 minutes should be used so as not to average out the LFN fluctuations which are characteristic of many LFN problems. This is further to ensure that the low frequency sound level is sampled accurately.

The noise levels to be recorded are the maximum and minimum C-weighted SPL's using the Fast time weighting, the L_{C10} and L_{C90} levels (the C weighted SPL's exceeded for 10% and 90% of the recording time) for the purpose of providing an indication of the level fluctuation of the LFN. The same metrics are to be recorded using the A-weighting instead of the C-weighting.

REFERENCES

Alberta Energy and Utilities Board, Noise Control Directive 038 Feb 16, 2007.

ANSI B133.8 – 1977 Gas Turbine Installation Sound Emissions Reaffirmed 1989 and 2001.

ANSI S12.9-2005/Part 4 Quantities and Procedures for Description and Measurement of Environmental Sound – Part 4: Noise Assessment and Prediction of Long-term Community Response.

AS IEC 61672.1 – 2004 "Electroacoustics – Sound Level Meters Part 1: Specifications".

Bengtsson, J., Persson-Waye K., Kjellberg, A. (2002) "Sound Characteristics in Low Frequency Noise and their Relevance for Performance Effects" *Inter-Noise 2002*, Paper 298.

Berglund B. et al. (1996) "Sources and Effects of Low Frequency Noise" *J. Acoust. Soc. America*, 99, 2985 – 3002.

Blazier, W.E., Ebbing, C.E (1992) "Criteria for Low Frequency HVAC System Noise Control in Buildings", *InterNoise 92*, Toronto, Canada, 761 – 766.

Bradley, J.S. (1994) "Annoyance Caused by Constant Amplitude and Amplitude modulated Sounds Containing Rumble" *Noise Control Eng.*, 42, 203 – 208.

Bryan M.E. (1976) "Low Frequency Noise Annoyance" in *Infrasound and Low Frequency Vibration* edited by W. Tempest, Academic Press, London 65 – 96.

Broner N. (1978): "The Effects of Low Frequency Noise on People – A Review" *Journal of Sound and Vibration* 58(4), 483-500.

Broner N. (1980) "A Criterion for Low Frequency Noise Annoyance" 10th ICA Sydney, Paper C1-4.4.

Broner N., Leventhall H.G. (1983) "Low Frequency Noise Annoyance Assessment by Low Frequency Noise Rating (LFNR) Curves" *Journal of Low Frequency Noise and Vibration* 2(1) 20-28.

Challis L. A., Challis A.M. (1978) "Low Frequency Noise Problems from Gas Turbine Power Stations" *InterNoise 78*, 475 – 480.

DIN 45680 (1997) "Messung und Bewertung tieffrequenter Gerauschimmissionen in der nachbarschaft (Measurement and Evauation of Low Frequency Environmental Noise)".

Hale M. E. (2009) "Controlling Power Plant Noise with a Stringent C-weighted Noise Limit", *Inter-Noise 2009*, Ottawa, Canada, August 23 – 26.

Hellman R.P., Broner, N. (2004) "Relation Between Loudness and Annoyance over time: Implications for Assessing the Perceived Magnitude of Low-Frequency Noise Presented at the *Acoust. Soc. of Amer. 75th Anniversary Meeting*, New York, May.

Hessler G. F. Jr (2001) "Beware Low-Frequency Gas-Turbine Noise" *Power*, July/August

Hessler G. F. Jr (2005) "Proposed Criteria for Low Frequency Noise from Combustion Turbine Power Plants", *Noise-Con 2004*, Baltimore, Maryland, July 12 – 14, 922-931.

Hessler G. F. Jr (2005) "Proposed Criteria for Low frequency industrial Noise in Residential Communities" *Journal of Low Frequency Noise, Vibration and Active Control* 24, No.2, 97-105.

Hessler G. F. Jr (2008) Email communication, March.

Hoover R.M.(1973) "Beware Low-Frequency Gas-Turbine Noise" *Power, May*.

ISO 226- 2003 "Acoustics – Normal Equal-Loudness – Level Contours".

ISO 398-7 (1996) Reference Zero for Calibration of Audiometric Equipment – Part 7 Reference Threshold of Hearing Under Free-field and Diffuse Field Listening Conditions".

ISO7196-1995 (E) "Acoustics - Frequency Weighting Characteristics for Infrasound Measurements".

Kjellberg, A. et al (1997) "Evaluation of Frequency-Weighted Sound Level Measurements for Prediction of Low

Frequency Noise Annoyance" *Envt. Intl.*, 23, 519 – 527.

Leventhall H. G. (2004) "Notes on Low Frequency Noise From Wind Turbines with Special Reference to the Genesis Power Ltd Proposal, near Waiuku NZ" Prepared for Genesis Power/Hegley Acoustic Consultants.

Leventhall H. G., Kyriakides K. (1976) "Environmental Infrasound: its Occurrence and Measurement" in *Infrasound and Low Frequency Vibration* edited by W. Tempest, Academic Press, London, 1 - 18.

Leventhall H.G.et al (2003) "A Review of Published Research on Low Frequency Noise and Its Effects", Dept of Environment, Food and Rural Affairs (DEFRA), Research Project Report

http://www.defra.gov.uk/environment/quality/noise/research/lowfrequency/documents/lowfreqnoise.pdf

Moorhouse A. et al (2005) "Proposed Criteria for the Assessment of Low Frequency Noise Disturbance" University of Salford, Prepared for DEFRA, February, Contract No NANR45.,

Newman J.R., McEwan K.I. (1980) "Low Frequency Gas Turbine Noise" *Transactions of the ASME*, 102, 476-481.

New South Wales Industrial Noise Policy. Environmental Policy Branch, NSW Environment Protection Authority January 2000.

Oregon Department of Environmental Quality, Noise Control Regulations for Industry and Commerce OAR 340-035-0035 http://www.deq.state.or.us/regulations/rules.html

Poulsen T. "Comparison of Objective Methods for Assessment of Annoyance of Low Frequency Noise with Results of a Laboratory Listening Test" *J. Low Frequency Noise, Vibration and Active Control*, Vol. 22(3), 2003, pp. 117-131.

Roberts C. (2008) "A Guideline for the Assessment of Low-Frequency Noise" *Acoustics Bulletin*, Sep Oct 2008, 31 – 36.

BLANKETING A NOISY BRIDGE

Contractors working for the Washington Department of Transportation will soon begin work on a pilot project to absorb traffic noise from the I-5 express lanes in Seattle by installing special panels. During the next few months, Penhall Co. construction crews will hang more than 700 of these panels from the ceiling at the south end of the Ship Canal Bridge. The noise panels are a lightweight material similar to a blanket and are used in a variety of places, such as classrooms and movie theaters, to absorb noise. Since a ceiling treatment like this is not typically used on transportation structures, the DOT said it will install a test section on the ceiling above the lower deck of the I-5 Ship Canal Bridge and monitor it for at least three years to evaluate its effectiveness. The 500-foot test section will consist of about 700 4-foot-by-8-foot panels. The state says the location is good because it includes noise on a double-deck structure and also noise moving over water. The state hopes those who live near the test section will notice less noise. In 2005, the Legislature earmarked $7 million to evaluate noise reduction options in the heart of Seattle next to the Ship Canal Bridge. The state has also been trying to reduce noise by building noise walls and testing quieter concrete and asphalt. The state also closes the I-5 express lanes at night to reduce the reverberating noise from the structure.