SERI/TP-217-3261
UC Category: 60
DE88001113

A Proposed Metric for Assessing the Potential of Community Annoyance from Wind Turbine Low-Frequency Noise Emissions

N.D. Kelley

November 1987

Presented at the Windpower '87
Conference and Exposition
October 5-8, 1987
San Francisco, California

Prepared under Task No. WE721201
Program No. 8

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401-3393

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

NOTICE

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A02

A PROPOSED METRIC FOR ASSESSING THE POTENTIAL OF COMMUNITY ANNOYANCE FROM WIND TURBINE LOW-FREQUENCY NOISE EMISSIONS

N.D. Kelley
Solar Energy Research Institute
Golden, Colorado 80401

ABSTRACT

Given our initial experience with the low-frequency, impulsive noise emissions from the MOD-1 wind turbine and their impact on the surrounding community, the ability to assess the potential of interior low-frequency annoyance in homes located near wind turbine installations may be important. Since there are currently no universally accepted metrics or descriptors for low-frequency community annoyance, we performed a limited program using volunteers to see if we could identify a method suitable for wind turbine noise applications. We electronically simulated three interior environments resulting from low-frequency acoustical loads radiated from both individual turbines and groups of upwind and downwind turbines. The written comments of the volunteers exposed to these interior stimuli were correlated with a number of descriptors which have been proposed for predicting low-frequency annoyance. The results are presented in this paper. We discuss our modifications of the highest correlated predictor to include the internal dynamic pressure effects associated with the response of residential structures to low-frequency acoustic loads. Finally, we outline a proposed procedure for establishing both a low-frequency "figure of merit" for a particular wind turbine design and, using actual measurements, estimate the potential for annoyance to nearby communities.

INTRODUCTION

Experience with wind turbines has shown that it is possible, under the right circumstances, for low-frequency (LF) acoustic noise radiated from the turbine rotor to interact with residential structures of nearby communities and annoy the occupants. Currently there are no universally accepted metrics or descriptors for community annoyance from low levels of LF noise. It is important from both a design and an operational perspective that the potential for such annoyance from wind turbines be quantified as much as possible. This is not a straightforward task, given the highly subjective nature of human response to noise in this frequency range. Given the lack of guidance in this area, we performed a limited experiment in which several volunteers were asked to describe their impressions of three electronically simulated, interior, LF noise environments related to the operation of wind turbines. We correlated the volunteers' responses with a series of currently available LF noise descriptors and identified two that we believe to be the most efficient. The spectral definitions of these descriptors were then modified to include the influence of an intervening residential structure and the levels adjusted for a reference propagation distance.

BACKGROUND

The modern wind turbine radiates its *peak* sound power (energy) in the very low frequency (VLF) range, typically between 1 and 10 Hz. This is a direct consequence of its small rotor solidity and relatively low rotational (shaft) speed (17.5-300 rpm). Other common rotating machinery employing lifting blades (such as the large fans and blowers associated with forced-draft cooling towers and ventilation systems) generally radiate their peak sound powers at frequencies greater than 60 Hz. This higher frequency is due to a combination of high rotor solidity and much faster shaft speeds.

Our experience with the low-frequency noise emissions from a single, 2-MW MOD-1 wind turbine demonstrated that, under the right circumstances, it was possible to cause annoyance within homes in the surrounding community with relatively low levels of LF-range acoustic noise. An extensive investigation of the MOD-1 situation [1,2] revealed that this annoyance was the result of a coupling of the turbine's impulsive LF acoustic energy into the structures of some of the surrounding homes. This often created an annoyance environment that was frequently confined to ***within the home itself***.

LOADING OF RESIDENTIAL STRUCTURES BY LOW-FREQUENCY ACOUSTIC EMISSIONS

Impulsive Loading

A significant amount of scientific investigation has gone into documenting the response of residential structures (and resulting community annoyance) to high-energy noise events such as aircraft flyovers and short-duration, impulsive events such as sonic booms and quarrying and mining explosions [3,4]. We found that the periodic loading by the MOD-1 impulses excited a range of structural resonances within the homes measured. Figure 1 schematically illustrates the radiated acoustic frequency spectrum associated with the various types of wind turbine emission characteristics. If there was no small-scale turbulence in the turbine inflow, the acoustic spectrum would resemble the monotonic falloff in the blade passage harmonics indicated by the "steady and long-period loading curve." The curve then rises again as the processes

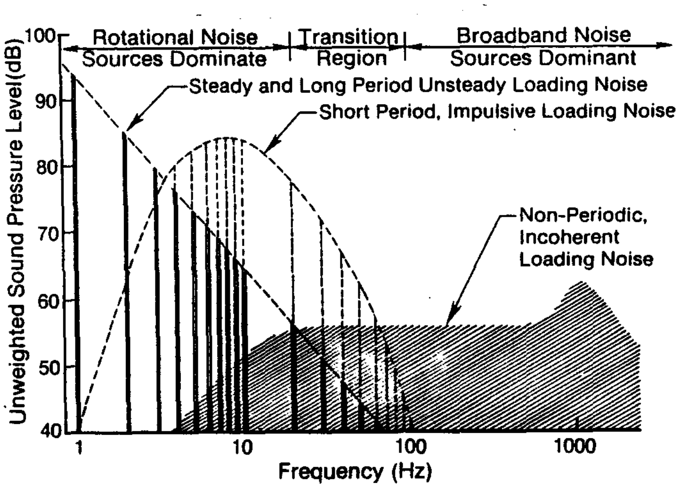


Figure 1. SCHEMATIC REPRESENTATION OF AN AVERAGED RADIATED SOUND PRESSURE SPECTRUM FROM A WIND TURBINE

responsible for the nonperiodic, incoherent, or broadband (high-frequency) radiation become dominant above 100 Hz. However, there are always some short-period aerodynamic load fluctuations as a result of the rotor encountering atmospheric turbulence, indicated by the dashed region of Figure 1. This region can expand to higher frequencies and contain considerable energy if impulses are present. A blade passing through the downstream wake of the support tower or intersecting its own wake can result in repetitive, transient aerodynamic loads that can produce LF impulsive radiation that is *periodic at the blade passage frequency* (BPF).

The acoustic-mechanical response of a residential structure to acoustic loads is schematically diagramed in Figure 2. The ranges of the various structural and acoustic resonances and the typical wind turbine acoustic spectrum have been superimposed. The dashed region, corresponding to the short-period and impulsive radiation range, overlaps with the structural resonances almost perfectly. Figure 2, therefore, illustrates the coupling mechanisms between the structure and the LF noise excitation. The temporal dynamics of this coupling are shown in Figure 3. The upper curve traces the outdoor acoustic pressure field and the lower one the internal one, as we see in the 31.5-Hz octave frequency band. The pair of turbine-generated impulses, about 8 ms in duration each, produce a strongly resonant pressure field in the house oscillating at the room fundamental of 14 Hz, lasting about 1.8 s. Thus, the action of the house has been to stretch the initial impulse duration over 100 times. The auditory time constant has been estimated to be on the order of 70-100 ms, thus, at least in theory, raising the possibility of audible detection inside the home but not necessarily outside. Hubbard and Shepherd [5] have isolated the Helmholtz response and measured enhancements up to 5 dB. They also found significant sound pressure level variations up to 20 dB when acoustic interactions were present. We have determined a typical indoor/outdoor LF acoustic transfer function using measurements from two homes near the MOD-1 turbine. The impulsive-source curve of Figure 4 illustrates this empirically derived function.

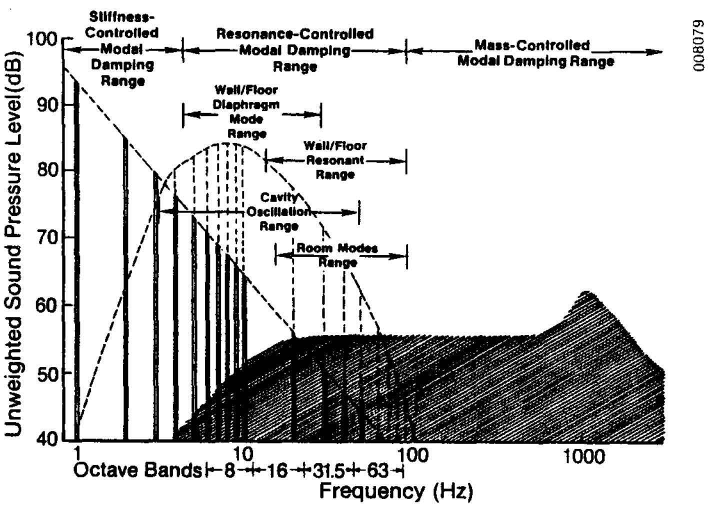


Figure 2. SCHEMATIC SOUND SPECTRUM OF FIGURE 1, WITH RESIDENTIAL VIBRATION AND ACOUSTIC MODES ADDED

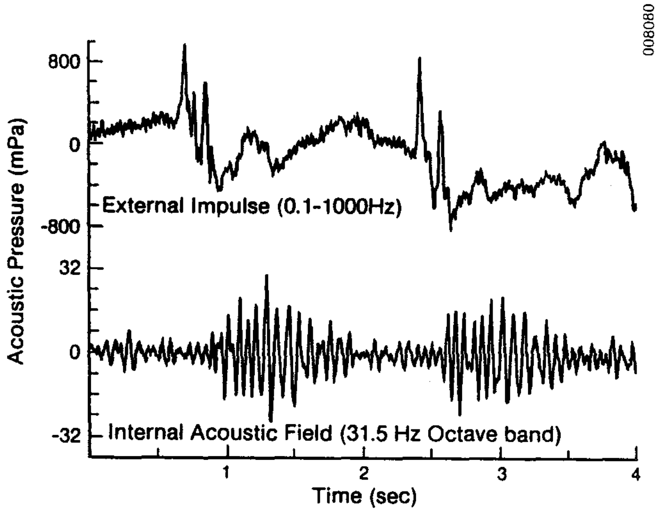


Figure 3. TRANSIENT RESPONSE OF AN INTERNAL PRESSURE FIELD TO EXTERNAL IMPULSIVE EXCITATION

Nonimpulsive Acoustic Loads

Even when an impulsive-type emission characteristic is not present (the MOD-1 did not always generate impulses), a varying level of LF acoustic energy is emitted (see the dashed region of Figure 1) as a result of the turbulent inflow. Because of the low damping present in residential structural modes in the 5-100 Hz range of Figure 1, we needed to find a well-documented source of nonimpulsive, LF acoustic excitation and indoor response for comparison. We were fortunate to obtain a series of measurements made simultaneously inside and outside five homes within a few kilometers of a gas turbine peaking generator [6]. The homes were acoustically excited by broadband LF emissions from a resonating exhaust stack. The nonimpulsive curve of Figure 4 traces the mean of the measured indoor/outdoor response for several rooms of the homes. The two curves of Figure 4 indicate that internal overpressures up to 10 dB can be expected in the 3-10 Hz

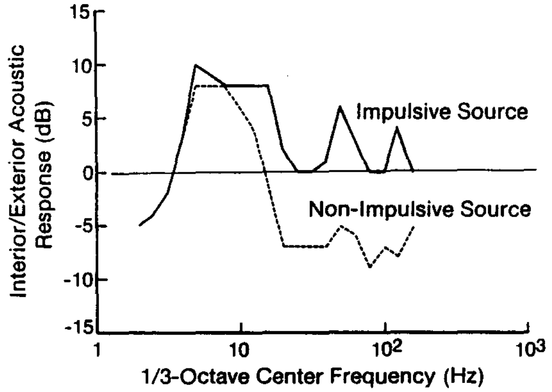


Figure 4. A TYPICAL INDOOR/OUTDOOR ACOUSTIC TRANSFER FUNCTION MAGNITUDE FOR IMPULSIVE AND NONIMPULSIVE LF ACOUSTIC LOADS

range for both impulsive and nonimpulsive acoustic loads. Above 10 Hz, significant overpressures occur in the 40-63 Hz and 80-125 Hz 1/3-octave bands under impulsive loads. Typically, 5-7 dB of attenuation occurs in the 10-160 Hz band range for a nonimpulsive source excitation.

EXPERIMENTAL PROCEDURE

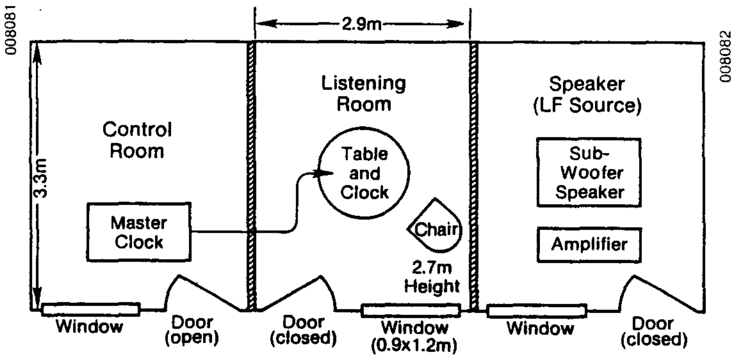
Our objective in the limited experiment reported on here was to simulate a series of LF noise environments that would be likely to exist within a small room of a home (a small bedroom, for example) as a result of the LF acoustic loading caused by wind turbine emissions. Our experience has shown that interior LF annoyance is more likely to occur and be more severe in rooms with small dimensions and at least one outside wall facing the wind turbine. This was also true of the annoyance related to the gas turbine peaking generator; i.e., the most serious annoyance occurred near the sides of the houses facing the LF source. We synthesized three interior LF noise environments that would be expected as a result of the acoustic loading of a residential structure from the following kinds of emissions:

- A single, large, multimegawatt turbine or an array of smaller turbines that *are not* producing periodic impulses *(a periodic random source)*;
- A nearby single turbine operating at a shaft speed of 30 rpm and producing impulses at the blade passage frequency *(a periodic impulsive source)*;
- An upwind *array* of turbines that are individually producing unsynchronized impulses at their blade passage frequencies *(a random impulsive source)*.

In addition to these three basic environments or *stimuli classes*, the periodic random source was repeated but with a "pink" noise masking level of 40 dBA.

Physical Setup

The physical layout of the testing environment is diagramed in Figure 5. A very low frequency or subwoofer speaker system and its high-powered amplifier were placed in a room adjoining the listening area. The subwoofer had a minimum frequency cutoff of about 5 Hz. This arrangement allowed only the dominant LF noise to be transmitted to the listening-room environment via the walls. It also filtered out the higher frequency sounds associated with the nonlinear response of the speaker cone (a "whooshing" sound), which was particularly evident during large excursions. The electronic equipment responsible for developing the subwoofer's "drive" signals was located in the control room. A master time code generator was also located here, and a repeater or slave unit was placed on the table in the listening room for the evaluator to time-index his or her comments. Table 1 lists the physical and acoustic properties of the listening room. The concrete slab floor minimized tactile (feeling) transmission of LF vibration to the evaluator. Since we were trying to simulate the quiet environment typical of a family home, we did not ask the staff on the other side of the partition to refrain from talking during the evaluation process. As a result, the evaluators occasionally noted hearing conversations from the offices adjacent to the rear wall of the listening room. The background noise was dominated by the sound of air moving through the ventilation system which produced an average background noise level of 35 dBA, typical of a quiet home.



Concrete Slab Floors Covered with 1.6cm Resilient Carpeting

Figure 5. PLAN VIEW SCHEMATIC OF PHYSICAL ARRANGEMENT OF TESTING FACILITIES

Table 1. PHYSICAL AND ACOUSTIC PROPERTIES OF LISTENING-ROOM ENVIRONMENT

Dimensions	2.9 x 3.3 x 2.7 m ($25.8\ m^3$ or $254\ ft^3$)
Walls	Movable partitions, composition material, nominally supported
Floor	Concrete slab covered with 1.6 cm of resilient carpet
Background Noise Level	35 dBA dominated by ventilation system noise; no attempt to reduce or mask voices generated on other side of rear wall

Evaluation Procedure

A series of sequences was developed for each type of LF noise environment in which the levels and intensities were systematically varied. We found that the corresponding, unweighted acoustic 1/3-octave band pressure levels over the range of 2-160 Hz could be repeated to better than 0.3 dB for each test level. The three simulated characteristic wind-turbine-emission environments are *schematically* diagramed in Figure 6. The averaged 1/3-octave band pressure level spectra for each of the source characteristics, and the incremental level changes are shown in Figures 7, 8, and 9. The room background spectra are indicated with dashed lines.

Seven volunteer evaluators took part in the experiment. The group consisted of three women and four men who ranged in age from the early twenties to the early sixties. All claimed to have an adequate hearing acuity. In this choice of a very limited number of participants, we attempted to obtain what we believed to be a small, random sample of the general population.

During the evaluation, the evaluator sat at the table indicated in Figure 5 on which a record log was furnished. The evaluators were asked to write down their impressions of what they were currently experiencing along with the time indicated on the clock. The evaluation sequence began with the periodic random simulation, stepped up through the six intermediate levels, and then back down again to the background level. No indication was given to the evaluators of the stimuli classes or their incremental steps. The initiation and completion times of each incremental step in a simulation were logged for later comparison with the evaluator's opinions. The dwell or integration time at each incremental stimuli step was held at 2 minutes plus or minus a 20% *random* variation to prevent the evaluator from anticipating changes in the testing sequence. The five levels of the periodic impulsive simulation were then sequenced, and this was followed by the five levels of the random impulsive stimuli. Finally, 2 minutes after the conclusion of the random impulsive simulation, the 40 dBA pink noise masking was activated from two speakers in the room's ceiling and the random periodic stimuli sequence was repeated. The entire four-pass process required about 45 minutes to complete.

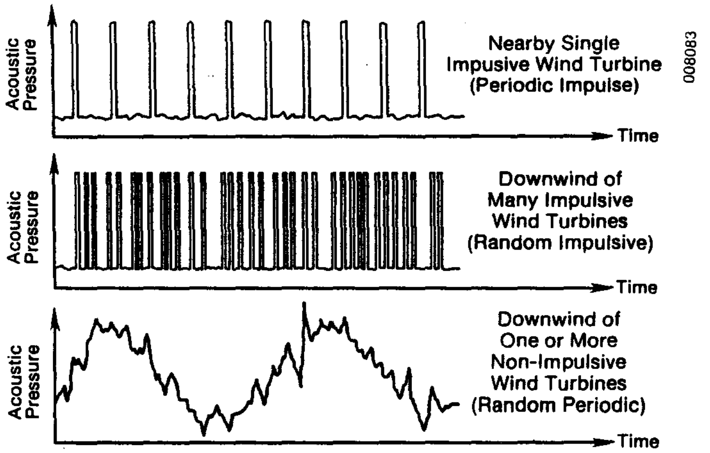


Figure 6. SIMULATED ACOUSTIC EMISSION CHARACTERISTICS OF WIND TURBINES

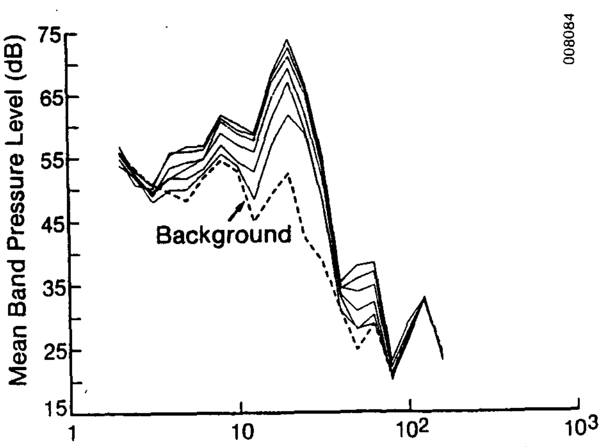


Figure 7. PERIODIC RANDOM STIMULI SPECTRA

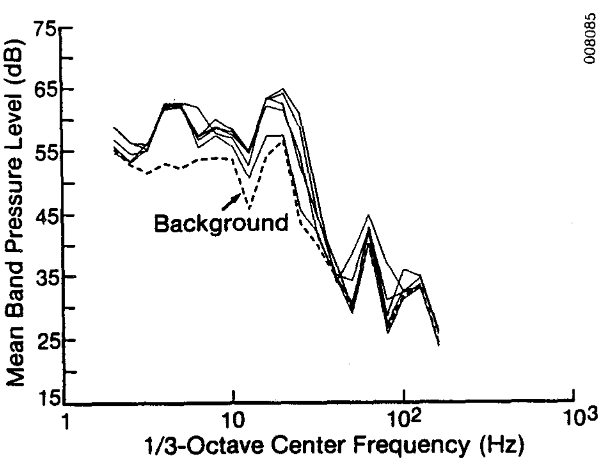


Figure 8. PERIODIC IMPULSE STIMULI SPECTRA

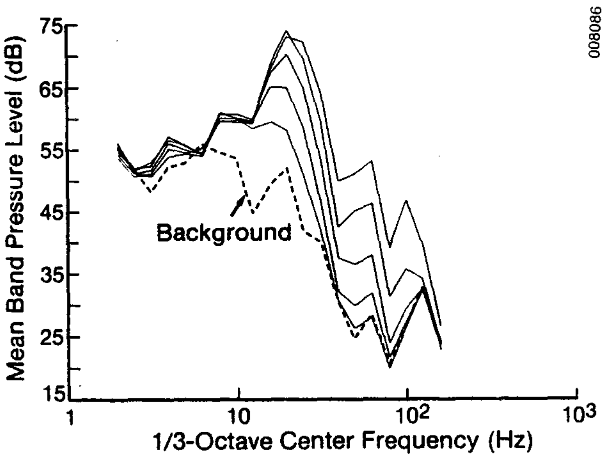


Figure 9. RANDOM IMPULSIVE STIMULI SPECTRA

Data Reduction

The evaluators' responses were quantified by means of a six-level ranking in terms of the following four annoyance categories:

(1) Loudness or noise level

(2) Overall degree of annoyance and displeasure

(3) Any sensations of vibration or pressure

(4) The sensing of any pulsations.

Table 2 lists the subjective ranking criteria. The ranked responses were then correlated by linear regression with a series of low-frequency noise descriptors or metrics. These particular metrics or spectral weighting factors have been suggested as measures of LF annoyance by a number of investigators, and they include the following:

- The ISO (International Organization for Standardization) proposed G_1 weighting [7]
- The ISO proposed G_2 weighting [7]
- The LSPL or low-frequency sound pressure level weighting [8]
- The LSL or low-frequency sound level weighting [8]
- The ISO/ANSI (American National Standards Institute) C-weighting [9]
- The ISO/ANSI A weighting [9].

Figure 10 plots these weighting windows over a frequency range of 2-100 Hz. The ISO G_1 and G_2 curves have been proposed for assessing subjective human responses to acoustic noise in the infrasonic range (less than 20 Hz). The ISO/ANSI A- and (usually) C-weighting curves are standard on sound level measuring equipment. As Figure 10 shows, the C-weighting passes much lower frequencies than does the most common noise description, the A-weighting scale. The LSL and LSPL metrics have been proposed by Tokita et al. [8] for assessing residential interior environments. The LSL metric "reflects three low-frequency noise influences: structural, physiological, and psychological complaint stimuli" [8]. The LSL metric has been proposed as an appropriate descriptor for evaluating residential interior environments that contain both infra- and low-frequency audible acoustic components.

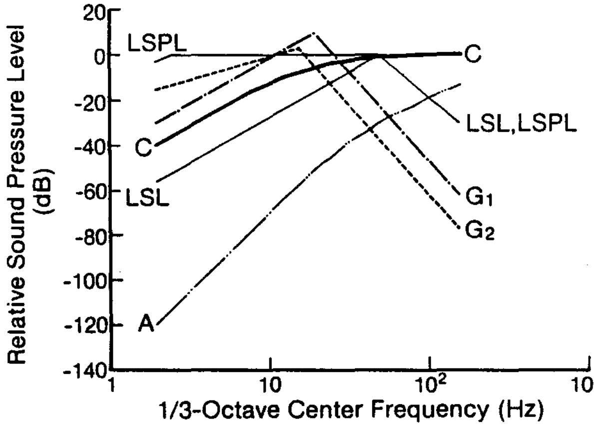


Figure 10. LOW-FREQUENCY NOISE METRICS SPECTRAL WEIGHTINGS

RESULTS

The ranked responses to the four annoyance categories were correlated with the four stimuli sequences by regression and are summarized in Table 3. Immediately

Table 2. SUBJECTIVE RANKING CRITERIA FOR LOW-FREQUENCY (LF) NOISE ENVIRONMENTS

	Stimuli Response Rating					
Rank	**0**	**1**	**2**	**3**	**4**	**5**
	Perception					
Noise level (loudness)	Can't hear	Barely can here	Weak, but definitely audible	Moderate loudness	High noise level, loud	Very high noise level, very loud
Annoyance/ displeasure	None	Barely aware of presence	Definitely aware of presence	Moderate distraction/ some irritation	Very annoying, irritating	Extremely annoying, uncomfortable
Vibration/ pressure	None	Feel presence	Definitely feel vibration/ pressure	Moderate vibration/ pressure feeling	Very noticeable	Severe vibration
Pulsations	None	Barely feel pulses	Definite pulses or bumping	Moderate booming or thumping	Heavy booming or thumps	Very heavy pulses, booms, thumps
	Acceptable		???????		Clearly unacceptable	

Table 3. CORRELATION COEFFICIENTS OF EVALUATOR ANNOYANCE RATINGS OF LF NOISE STIMULI VERSUS SIX NOISE METRICS

Metric	Noise Level	Annoyance/ Displeasure	Vibration/ Pressure	Pulsations	Mean
G_1	0.898 *(0.033)*	0.933 *(0.018)*	0.709 *(0.170)*	0.819 *(0.115)*	0.840 *(0.084)*
G_2	0.873 *(0.071)*	0.879 *(0.053)*	0.701 *(0.157)*	0.769 *(0.148)*	0.806 *(0.107)*
LSPL	0.898 *(0.035)*	0.924 *(0.034)*	0.711 *(0.155)*	0.831 *(0.107)*	0.841 *(0.083)*
LSL	0.935 *(0.021)*	0.958 *(0.014)*	0.732 *(0.174)*	0.860 *(0.097)*	0.871 *(0.077)*
C	0.940 *(0.030)*	0.947 *(0.008)*	0.725 *(0.167)*	0.841 *(0.098)*	0.863 *(0.076)*
A	0.384 *(0.464)*	0.269 *(0.413)*	0.413 *(0.137)*	-0.077 *(0.719)*	0.247 *(0.433)*

obvious is the superiority of the five metrics that pass significant low frequencies in comparison with the A-weighted scale. These results, limited as they are, seem to confirm that (1) people do indeed react to a low-frequency noise environment and (2) A-weighted measurements are not an adequate indicator of annoyance when *low frequencies are dominant.* Table 4 ranks the efficiency of each metric for the stimuli population in terms of the correlation coefficient and stimuli-to-stimuli class standard deviation. These rankings, with the exception of the last two, contain two of the six metrics. We simply do not have a sufficient number of statistical degrees of freedom to differentiate further. Actually, the only statistically significant difference is between the five LF metrics and the A-weighted scale. This experiment would have to be repeated with a much larger number of evaluators (population) to confirm Tables 3 and 4 in terms of their individual matrix elements.

ESTABLISHING AN INTERIOR ANNOYANCE SCALE

The rankings of the evaluators' comments were summarized for each of the four stimuli, and three annoyance-level classes were determined for each. The perception-threshold level is defined as the corresponding LSL- and C-weighted band levels for an evaluation ranking of 1. The annoyance-threshold level classification was arbitrarily assigned a ranking of 2.5, and the unacceptable-annoyance level classification was given a value of 4 or greater. The LSL- and C-weighted metrics corresponding to the annoyance classification rankings are listed in Table 5 for the four stimuli evaluated. As the table shows, three of the four stimuli have similar threshold-perception LSL- and C-weighted values. It is interesting to note that, even though many individual impulsive sources are present, the net effect of a *random summing* of these contributions invokes a response similar to that from a periodic random source. It is also evident that the threshold is considerably lower for a single or a few distinct impulsive sources. This is reflected by the general source characteristics listed at the bottom of Table 5. For all practical purposes, the annoyance level criteria for the C-weighted scale are 10 dB higher than those for the LSL-weighted band pressure level (BPL).

PREDICTING AN INTERIOR LSL OR C LEVEL

To assess the potential of interior LF noise annoyance in nearby communities, we must estimate the LSL or C metric levels from available acoustic measurements of the turbine design. Generally, this will be an averaged, unweighted (linear) 1/3-octave band spectrum over a 5-100 Hz range and, when adjusted for propagation losses, it can be considered representative of the external acoustic load present at the home being evaluated. We noted earlier that the structural dynamic response of houses alters both the temporal and spectral characteristics of the external acoustic excitation and that the alteration characteristics depend on whether the source is impulsive or not. To predict an interior LSL- or C-level (PLSL or PC), we must *spectrally* apply the appropriate

Table 4. APPROXIMATE EFFICIENCY RANKING OF THE SIX METRICS AS DESCRIPTORS OF INTERIOR, LF NOISE ANNOYANCE

Rank	Metric	r[a]	Stimuli Class Variance Coefficient
1	LSL	0.871	8.8%
1	C	0.863	8.8%
2	LSPL	0.841	9.8%
2	G_1	0.840	10.0%
3	G_2	0.806	13.3%
4	A	0.247	175%

[a] Correlation coefficient.

indoor/outdoor acoustic transfer function magnitudes plotted in Figure 4 to the measured 1/3-octave band spectrum. Using these functions, we have replotted the original frequency weighting characteristics of the LSL and C metrics in Figure 11 for both impulsive and nonimpulsive sources. Table 6 lists the corresponding weighting factors for the transfer function magnitudes of Figure 4.

A limited verification of this procedure is shown in Figure 12. The predicted or PLSL values are plotted against the measured value for a bedroom excited by the MOD-1 impulses. The remaining rooms were in various homes excited by the gas turbine for which annoyance was reported. Figure 13 plots the observed interior LSL values in relation to the LSL annoyance criteria thresholds. While complaints were received from the residents of all four homes in which these rooms were located, we do not have sufficient information to completely verify the vertical stratification other than that it was above the perception level.

ESTABLISHING A REFERENCE EXTERNAL ACOUSTIC LOADING

The method of estimating a representative internal PLSL or PC value requires a suitable measure of the external acoustic loading spectrum. Since most homes are located

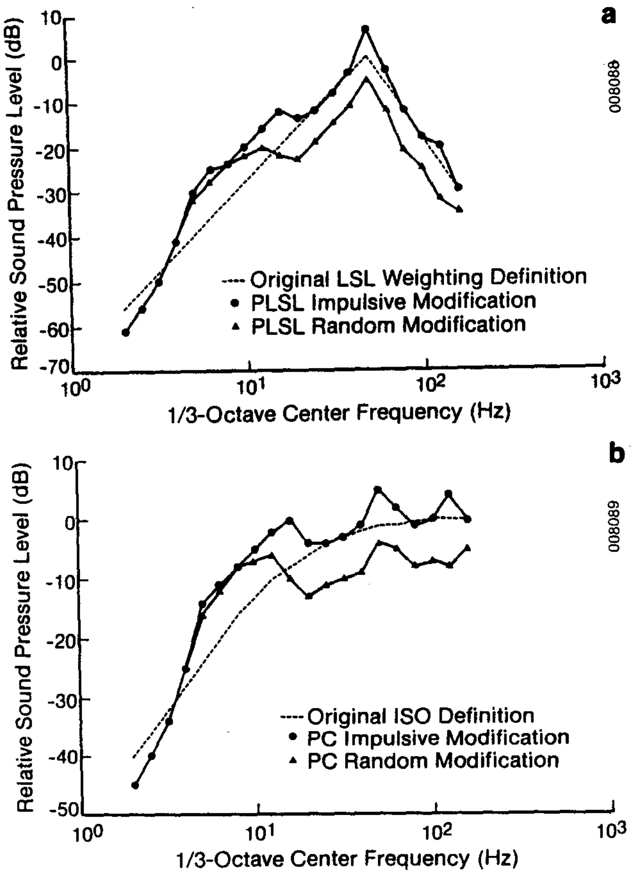


Figure 11. (a) PLSL SPECTRAL WEIGHTING; (b) ISO AND MODIFIED C SPECTRAL WEIGHTING

Table 5. INTERIOR LF ANNOYANCE-LEVEL CRITERIA EMPLOYING THE LSL AND C METRICS

	Threshold Perception		Annoyance Threshold		Unacceptable Annoyance	
Stimuli Class	LSL (dB)	C (dB)	LSL (dB)	C (dB)	LSL (dB)	C (dB)
Nonimpulsive, periodic random	58	68	65	75	68	77
Periodic impulsive source	53	63	57	67	60	68
Random periodic source	59	67	68	76	70	78
Periodic random w/40 dBA mask	59	68	65	75	67	79
Considering Only General Source Characteristics						
Nonimpulsive source	58	68	65	75	68	78
Impulsive source	53	63	57	67	60	68

Table 6. INDOOR/OUTDOOR TRANSFER FUNCTION WEIGHTING FACTORS

1/3-Octave Band Center Frequency (Hz)	Impulsive Transfer Function Magnitude LSL (dB)	Impulsive Transfer Function Magnitude C (dB)	Nonimpulsive Transfer Function Magnitude LSL (dB)	Nonimpulsive Transfer Function Magnitude C (dB)
2.0	-61	-45	-61	-45
2.5	-56	-40	-56	-40
3.15	-50	-34	-50	-34
4.0	-41	-25	-41	-25[a]
5.0	-30	-14	-32	-16
6.3	-25	-11	-28	-12
8.0	-24	- 8	-24	- 8
10.0	-20	- 5	-22	- 7
12.5	-16	- 2	-20	- 6
16.0	-12	0	-22	-10
20.0	-14	- 4	-23	-13
25.0	-12	- 4	-19	-11
31.5	- 8	- 3	-15	-10
40.0	- 3	- 1	-11	- 9
50.0	+ 6	+ 5	- 5	- 4
63.0	- 3	+ 2	-12	- 5
80.0	-12	- 1	-21	- 8
100	-18	0	-25	- 7
125	-20	+ 4	-32	- 8
160	-30	0	-35	- 5

[a] Recommended minimum 1/3-octave spectral range.

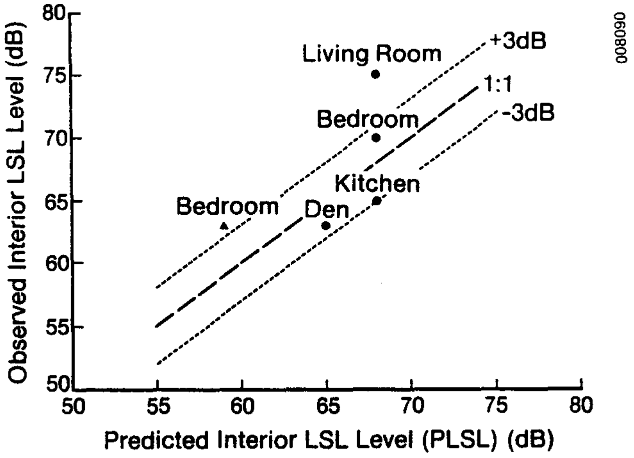


Figure 12. PREDICTED VS. OBSERVED INTERIOR LSL LEVEL COMPARISON

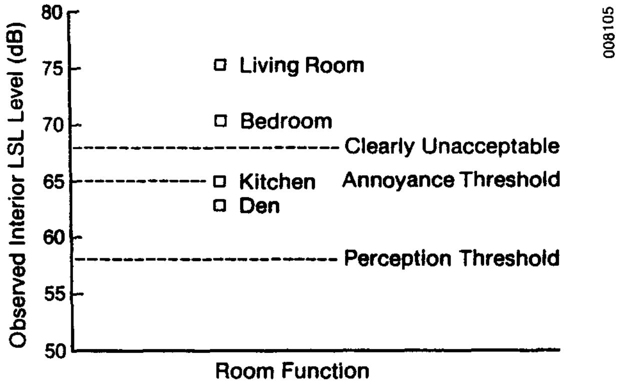


Figure 13. OBSERVED INTERIOR LSL VALUES FOR NONIMPULSIVE SOURCE

some distance from the nearest wind turbine(s), a method must be devised to provide a reference spectrum that takes into account situations in which atmospheric refraction and terrain reflection increase the acoustic levels above those expected from spherical divergence alone. We recommend using a reference distance of 1 km (0.6 mile) for calculating a "figure of merit" PLSL or PC level for a given wind turbine installation. To account for worst-case terrain/atmospheric focusing, we also recommend that 15 dB be added to the PLSL or PC values calculated at the 1 km distance. As an example, Table 7 lists the predicted or PLSL values for a home located 1 km from the MOD-1 and MOD-2 wind turbines [10].

SUGGESTED PROCEDURE FOR ESTIMATING THE INTERIOR LF ANNOYANCE POTENTIAL OF A GIVEN TURBINE DESIGN

The results of this paper are summarized below as a recommended procedure for establishing a low-frequency figure of merit for a given wind turbine design.

(1) Obtain a series of representative, unweighted, averaged 1/3-octave band pressure spectra over a range of 5-100 Hz for a range of operating conditions. Make the measurements at a distance from the turbine where a sufficient signal-to-noise ratio for this frequency range can be reasonably obtained. Use recording periods of at least 2 minutes but not more than 10 minutes.

Table 7. PREDICTED INTERIOR LSL (PLSL) VALUES AT 1 km FROM THE MOD-1 AND MOD-2 WIND TURBINES

Turbine	PLSL (dB)	PLSL+15 (dB)
MOD-1 Turbine (Severe impulsive characteristic)		
35 rpm operation	65	80
23 rpm operation	54	69
MOD-2 Turbine (Nonimpulsive characteristic)		
17.5 rpm operation	41	56

(2) Establish whether the turbine exhibits impulsive radiation characteristics.

(3) Determine the equivalent near-field PLSL- or PC-weighted level by using the contents of Table 6 for impulsive or nonimpulsive sources to weight the linear 1/3-octave band spectra.

(4) Calculate the equivalent PLSL or PC levels at the reference distance of 1 km by assuming spherical divergence (-6 dB per doubling of distance).

(5) Add 15 dB to the results of step (4). This result is the figure of merit for the worst-case, low-frequency-range acoustic emissions associated with the wind turbine design. This level or these levels can now be compared with Table 5 to assess the interior annoyance potential.

ACKNOWLEDGEMENTS

This work has been supported by the U.S. Department of Energy under contract no. DE-AC02-83CH10093. The author wishes to thank the seven SERI staff members who took the time to serve as evaluators for this project. Acknowledgment is also given for the excellent technical support rendered by Ed McKenna, David Jager, James Pruett, and Richard Garrelts. Engineering Dynamics, Inc., was responsible for the design and construction of the very low frequency (subwoofer) speaker system.

REFERENCES

1. Kelley, N.D., H.E. McKenna, and R.R. Hemphill, "A Methodology for Assessment of Wind Turbine Noise Generation," *J. Solar Engineering*, Vol. 21 (1981), pp. 341-356.
2. Kelley, N.D., H.E. McKenna, R.R. Hemphill, C.L. Etter, R.L. Garrelts, and N.C. Linn, *Acoustic Noise Associated with the MOD-1 Wind Turbine: Its Source, Impact, and Control*, SERI/TR-635-1156, Golden, CO: Solar Energy Research Institute (February 1985), 262 pp.

3. Carden, H.D., and W.H. Mayes, *Measured Vibration Response Characteristics of Four Residential Structures Excited by Mechanical and Acoustical Loadings*, NASA/TN-D-5776, Hampton, VA: NASA Langley Research Center (1970), 59 pp.

4. National Research Council, Comm. on Hearing, Bioacoustics, and Biomechanics Assembly of Behavioral and Social Sciences, CHABA Working Group 84, *Assessment of Community Response to High-Energy Impulsive Sounds*, Washington, D.C.: National Academy Press (1981), 31 pp.

5. Hubbard, H.H., and K.P. Shepherd, *The Helmholtz Resonance Behavior of Single and Multiple Rooms*, NASA/CR-178173, Hampton, VA: NASA Langley Research Center (September 1986), 26 pp.

6. Robin Towne, Assoc., Environmental Study of Low-Frequency Noise and Vibration, A Report to the Portland General Electric Co., Portland, OR: Robin Towne, Assoc. (1974), 144 pp.

7. International Organization for Standardization (ISO), Draft Proposal for "Acoustics Methods for Describing Infrasound," ISO/DIS 7196, Geneva, Switzerland: ISO.

8. Tokita, Y., A. Oda, and K. Shimizu, "On the Frequency Weighting Characteristics for Evaluation of Infra and Low-Frequency Noise," *Proc. 1984 Conf. on Noise Control Engineering*, G.C. Maling, Jr., ed., Poughkeepsie, NY: Inst. of Noise Control Engineering (1984), pp. 917-920.

9. American National Standards Institute (ANSI), "American National Standard Specification for Sound Level Meters," ANSI S1.4-1983, New York, NY: ANSI (1983).

10. Kelley, N.D., H.E. McKenna, E.W. Jacobs, R.R. Hemphill, and N.J. Birkenheuer, *The MOD-2 Wind Turbine: Aeroacoustical Noise Sources, Emissions, and Potential Impact*, SERI/TR-217-3036, Golden, CO: Solar Energy Research Institute (to be published).