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AN UNDERPINNING METHODOLOGY TO DERIVE STAND-OFF DISTANCES FROM A WIND FARM

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At present, the scientific basis for setting the stand-off distance threshold is unclear resulting in diverse approaches nationally and internationally. Annoyance effects from wind turbine for the non infrasonic component have been published. Health effects including nausea, dizziness, and headaches have been reported and assumptions for linking those effects to the infrasonic component are being increasingly suggested. The noise spectra generated by a wind farm has two components; an infrasonic component and a non-infrasonic component. For all the components - the sound power level, the rate of decay with distance, and finally the effects for a given sound pressure level on a nearby resident are different. The non-infrasonic component decays at a rate with distance representative of a spherical sound source. The infrasonic component decays at a rate with distance much lower than a spherical sound source and close to the decay rate of a cylindrical propagation condition. Explanations for the reasons of a much lower rate of attenuation for the infrasonic component are given. These effects in combination inform the methodology proposed to determine noise stand-off distances from a wind farm.

1. Introduction

In the last thirty years the size of wind turbines has increased from 15m diameter to over 80m diameter. This means that the sound spectra has shifted towards lower frequencies and also generates higher amplitude. Combined with the increase in size and number, health problem complaints attributed to wind farms has emerged world wide. It is not the purpose or objective of this paper to debate the issue of health effects, but rather to link acoustic principles that when combined together help in understanding the reason(s) for reported noise and health complaints attributed to wind farms. The approach used is based on the formulation that adverse health effects are related to a time exposure of sound level and/or vibration level above a given threshold leading to annoyance and health effects. Annoyance effects from wind turbines for the non-infrasonic component have been published. Health effects including nausea, dizziness, and headaches have been reported and assumptions for linking those effects to the infrasonic component are being increasingly suggested.

While annoyance curves have been derived from many studies over a relatively long period of time for road, rail and aircraft noise indicators, relatively few studies have been made for annoyance arising from wind farm noise. Health effects associated with noise exposure are well documented for sound pressure levels within the audio range but they are less so for low and infrasonic frequencies. It is postulated that such adverse effects are associated with a level above the detection threshold in a similar way that the temporary threshold shift leads eventually to a permanent threshold shift. This mechanism is very different for a single tone compared to broadband tonality. The condition for an adverse health effect (*AHE*) is an exposure for a given duration of a received sound level and/or vibration level that is above the threshold of sensitivity, Eq. (1):

$$AHE = \int_0^t \text{human sensitivity}\left(\textit{sound pressure level}, \textit{vibration}\right) \qquad (1)$$

A temporary (raised) threshold shift may occur when sound exposure exceeds the thresholds for a given time. In such a case the threshold is a function of the received sound level over the duration. The received sound pressure level and vibration level are defined by Eqs. (2) and (3):

$$\begin{aligned} \text{sound pressure level(dB)} = \sum_{i=1}^{N} \{ & \text{turbine sound power level}_i \left(B, \textit{rpm}, \textit{spacing}, \textit{freq}\right) \\ & + \text{spreading law}_i \left(\textit{distance}\right) \\ & + \text{directionality}_i \left(\textit{angle}\right) \\ & + \text{attenuation from air}_i \left(\textit{freq}, \textit{humidity}\right) \\ & + \text{atmospheric effect}_i \left(\textit{temperature gradient}\right) \\ & + \text{attenuation outdoor/indoor}_i \left(\textit{freq}\right) \\ & + \text{vibroacoustic coupling to house}_i \left(\textit{vibration}\right) \\ & + \text{room acoustic resonance}_i \left(l, w, h\right) \} \end{aligned} \qquad (2)$$

Where *N* is the number of wind turbines
i denotes that the term applies to the *i*th turbine
B is the blade size (m)
Spacing is the distance between wind turbines
freq is the frequency (Hz), narrow or broadband in dB(Z)
distance is the distance (m) from turbine to receiver
angle is the angle from the turbine axis to the measurement point
temperature gradient includes wind shear, wind speed, wake turbulence, Pasquill stability
vibration is the transmitted vibration(s) in the ground from turbine to receiver
l,*w*,*h* are the room dimensions where the sound pressure level is measured

$$\begin{aligned} \text{vibration(dB)} = \sum_{i=1}^{N} \{ & \text{turbine vibration level}_i \left(B, \textit{rpm}, \textit{spacing}, \textit{freq}\right) \\ & + \text{spreading law}_i \left(\textit{dist from wind farm}\right) \\ & + \text{directionality}_i \left(\textit{angle}\right) \\ & + \text{attenuation from soil}_i \left(\textit{freq}, \textit{humidity}, \textit{soil}\right) \\ & + \text{vibrational coupling to house}_i \left(\textit{freq}, \textit{room}(l, w, h)\right) \end{aligned} \qquad (3)$$

Where *N* is the number of wind turbines
i denotes that the term applies to the *i*th turbine
B is the blade size (m)
spacing is the distance between wind turbines
freq is the frequency (Hz), narrow or broadband in dB(Z)
angle is the angle from the turbine axis to the measurement point
l,*w*,*h* are the room dimensions where the vibration level is measured

The above equations present the methodology proposed to determine noise stand-off distances from a wind farm. The human sensitivity component of the equation in (1) is described in terms of thresholds at infrasonic and low frequencies.

2. Determination of thresholds at infrasonic and low frequencies

In recent years there have been claims that infrasound from wind turbines cause nausea, headaches, dizziness and sleep disturbance. At this stage the linkage between these effects and infrasound from wind turbines have not been scientifically established and infrasound thresholds associated with these effects are not determined. The following available data was gathered to assess vibro-acoustic energy for low frequency and infrasound: (a) maximum levels for human exposure, (b) audiology thresholds of detection, (c) annoyance thresholds, (d) thresholds of physiological effect, (e) thresholds of pain, and (f) equaphone curve for very low frequencies.

Figure 1 presents various thresholds of detection of low frequency sound and infrasound available in the literature Fidell et al.[1], Hodgdon et al.[2], Johnson[3], Moller et al.[4], Tokita et al.[5],Watanabe et al.[6], Yeowart et al.[7]. These thresholds of detection have been superimposed with equaphone curves to illustrate the convergence of the curves towards infrasonic frequencies.

There is an observed difference of 20dB or more between the minimum and maximum detection threshold as shown in Figure 1. Using the precautionary principle, the lowest observed effect is selected. The minimum at any frequencies of those detections curves is used for the onset of the detection thresholds of low frequency and infrasonic frequencies. Thresholds for onset of annoyance, oppressive feeling, objectionable feeling, onset physiological effects as well as the detection thresholds for various limits proposed for infrasound and low frequencies limits such as the Danish EPA 20dBA limit and 85dBG limit and the low frequency limit proposed by Sloven[8] for annoyance are recorded.

Johnson[3] explained that infrasound is detectable down to 2Hz , but loses tonal quality at 16Hz. Johnson found that annoyance from infrasound is a definite problem as the threshold of annoyance is very much the same as the threshold of audibility. As can be seen from Figure 1, the presence of sound can produce annoyance before being detected, and further, it can be seen that between the 20Hz to the 50Hz region, the annoyance is very close to the level judged as oppressive by Tokita[5] while at 8 Hz the oppressive level corresponds to a level found by Johnson as a level with biological significance.

Fidell et al.[1] reviewed the effect of infrasound and low frequency sounds from 1Hz to 70Hz for detection, pressure fullness in ears, temporary threshold shift, aural pain and maximum tolerable level and from 2Hz to 100Hz for loudness, annoyance, interference with task performance, visceral sensation and blurred vision. The sound pressure level for the effect reported was found to vary as a function of the duration of the exposure by as much as 9dB between one hour exposure to 8 hour exposure. Most of the experiments reported do not mention the duration of the sound exposure for the effect reported. The thresholds proposed in this paper do not take into account the duration of the sound exposure for the onset of the effect. It may be a significant modification of the thresholds of annoyance since a resident may be exposed to long sound exposure duration. Harris[9] has proposed maximum sound pressure levels for low frequency sound exposure for three different sound exposure durations. Figure 1 collates the detection thresholds, the annoyance/oppressive thresholds and the pain/physiological effects threshold. It must be noted that the thresholds for the onset of headaches, nausea or dizziness have not been researched and are not included. The proposed detection thresholds of the outer hair cells by Salt et al.[10] are not referenced as yet. The thresholds proposed in Figure 1 can be modified as new evidence is published.

On the basis of these thresholds, an estimate is able to be made of the sound level pressure for a given frequency for the onset of both the detection of the sound and the annoyance effect. In order to determine at what distance from the wind farm these effects may occur, the linear sound power level of the wind farm needs to be known and the correct attenuation of low and infrasonic frequencies with distance need to be established.

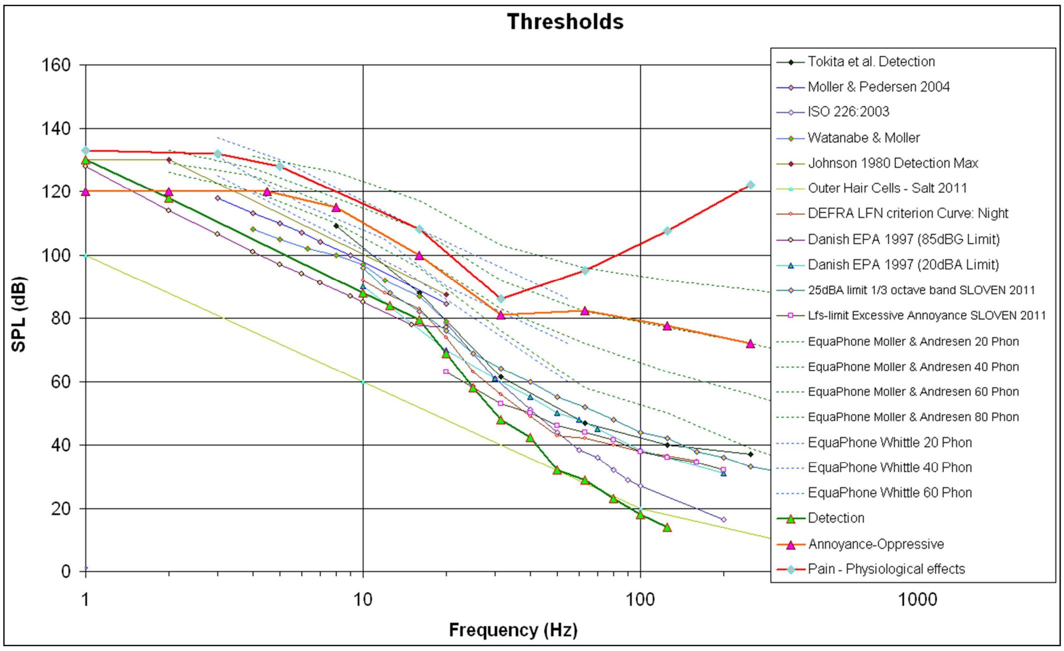

Figure 1. Threshold of detection (Green), Threshold of Annoyance-Oppressive (Orange) and Threshold of Pain-Physiological effects (Red)

3. Propagation of infrasound and low frequencies

Wavelength is inversely proportional to frequency, as a result for infrasound the wavelength reaches hundreds of metres which is significant for the attenuation of sounds. Several effects are combined which are frequency dependant influencing the propagation of sound. The first is the absorption of sound which depends on frequency and humidity, the second is the geometrical spreading which is function of distance and again linked to frequency. The sound source has a directivity which yet is frequency dependant, finally the atmospheric effect from temperature gradient also affect propagation with a frequency dependence. The main mechanism by which sounds attenuate is by the air viscous force which is proportional to velocity or frequency. When sounds travels through a medium, its intensity diminishes with distance. The first effect of the dissipation of sound is due to geometric effect associated with energy being spread over an increasing area and not to any loss of total energy. The weakening of a sound wave energy is also due to absorption and scattering. Scattering is the reflection of sound in directions other than its original direction of propagation while absorption is frequency dependant. The attenuation of noise in dB follows the slope given by *20Log(R)* where R corresponds to the distance between the sound source and the distance corresponding to the attenuation. Shepherd et al. [11] state that the attenuation at very low frequencies would not be 6dB but only 3dB per distance doubling due to atmospheric refraction and channelling of sound in the lower atmosphere.

Larom[12] studied the attenuation of infrasound according to distance to understand why elephants were so specific in the timing of their vocalisation and to understand if there was a correlation between elephant vocalisation and weather effects. Vocalisation took place mostly during temperature inversions which result in calls being heard on a surface multiplied by tenfold. The peak pressure of elephant vocalisation is about 15Hz and at that frequency the elephant threshold of hearing was about 67dB. Under normal weather conditions the surface for which an elephant could be heard by his peers was 30km^2 corresponding to a radial distance of about 3km. The slope of the corresponding attenuation is *14.3Log(R)*. However, at sunset and the beginning of the evening, while the temperature inversion is taking place, Larom found that corresponding surface for which an elephant could be heard by his peers was increased from 30km^2 to 300km^2. The increase in the surface for which the vocalisation is heard is increased by ten, thus increasing the possibility of mating proportionally. The corresponding attenuation of sound is decreased from *14.3Log(R)* to *12.4Log(R)*. Propagation and harmonics have been identified and described as ‘heightened noise zones’ by Bakker et al.[14] in evidence presented at the Turitea, New Zealand, wind farm hearing.

Propagation depends on the component frequencies within the sound emission. Wind turbines are essentially very large propellers. Metzger[13] reviewed the expression of the fundamental frequency for a propeller. Multiple harmonics will stem from the fundamental frequency as the nth multiple of that frequency with decreasing amplitude. As shown in Eq. (2) the fundamental frequency (the first and highest peak of the graph) is govern by the rotational speed and therefore function of the wind speed. As a function of the RPM for a wind turbine propeller at 20 RPM the fundamental frequency is expected to be 1Hz and the harmonics, 2Hz, 3Hz, 4Hz, 5Hz 6Hz and visible up to 7Hz.

Doolan[15] reviewed the directivity curve of each contributing element of the wind turbine sound generation mechanism and concluded that the trailing edge generation mechanism was the main noise generation for the wind turbine and exhibited similar directional characteristics to aircraft propeller noise. Doolan found that the blade tower interaction generated a supplementary noise source as a very low frequency pulse.

Style et al.[16] investigated the seismic propagation of vibration produced by wind turbines to check the interference that wind farms may have on a seismic monitoring station located in Eskdalemuir. The harmonic signals are related to overtones of the blade-passing frequency of the turbine and that the vibration in the 0.5 to 5Hz band could be detected beyond 10km from the wind turbine. Styles found that a wind farm composed of a number of turbines produces a noise proportional to the square root of the number of turbines because they are not all working in phase and they are not operating at the same frequency because of the small variations in rotation speed and wind conditions across the wind farm and the vibration from the different turbines interacted between each other. In air, a similar interaction is expected, for a specific frequency it is expected that a modal pattern is a function of distance and that interaction between the different wind turbines will complicate further these modal patterns[14].

The mode of vibration below 1Hz is the strongest. This is highly relevant since the measurement of very low frequencies requires specific instrumentation. Frequencies below 1Hz are those that are related to motion sickness (Griffin[17]) and the effects of motion sickness have been reported in many publications in the last couple of years (Nissembaum[18], Davidsen[19]). Evans[20] reported for sound pressure level between 100dB and 125dB for frequencies ranging from 2Hz to 5Hz movement of the eardrum in response to the pressure change of pressure build-up in the middle ear and resulted in headaches and for 125dB to 137dB for 2 Hz to 5Hz, Evans reported lethargy and drowsiness, post exposure headaches and fatigue.

The vibration propagation is important since when those vibrations arrive into a residence, the residence becomes the resonant chamber in the same way a violin is the resonant chamber from the string vibration. In other words, the resulting sound field within the residence is the interaction between the potential modes of resonance of the residence and the source of vibration. The vibration of 3Hz which is so well propagated to 5.9km may would induce vibration of 3Hz within a residence at 5.9km but will also resonates to a room tune with vibration mode which are multiple of 3Hz. The vibration mode within a residence may further be enhanced by the propagated acoustic pressure wave tuned to the same harmonics. The coupling may enhanced greatly the sound within a residence, as the airborne wave coupled with the vibration wave may interact in a complex manner and be further combined with a standing wave resonance within a room. The blade tower interaction expressed in Doolan[15] gives rise to a further low frequency pulse. Hubbard and Shepherd[11] have investigated the prediction in amplification given interaction of the multiple wind turbine and gave an equation to quantify this amplification according to the number of wind turbines. They found the sound pressure level can be calculated for a given harmonic at a given distance. Using this equation, Ceranna[21] found that for the 2Hz harmonic of a 600KW turbine at 1km the sound pressure level should be 58.5 dB and the same 2Hz harmonic generated by an array of 11 wind turbine would generate 68dB at 1km. This relationship shows that the turbines can be regarded as uncorrelated. The propagation of infrasound given by Hubbard and Shepherd[11] appears to follow closely the cylindrical propagation with an attenuation as function of distance R of *10Log(R)*.

4. Prediction of the distance from a wind farm for the onset of annoyance threshold

In the previous section, the onset of annoyance threshold is proposed, the propagation of infrasound is reviewed and the sound spectrum for a wind turbine is reviewed. The sound power levels are usually given in dBA, the sound power level of a wind turbine is a function of its rotational speed and therefore the wind speed and its diameter. In order to establish the distance for which physiological effect and annoyance should be anticipated from the infrasonic harmonics, the narrow band measurements of a wind turbine or from a wind farm are needed. Sound propagation for infrasound increases under temperature inversion condition. Spherical propagation from a single point source has -6dB reduction in relative intensity per doubling of distance. However from a single point source to multiple sound sources, as is the case for a wind farm, the propagation slope may be modified toward cylindrical or line source propagation with only -3dB reduction per doubling of distance. The argument presented in this paper is based on ‘single point source’ propagation.

The corresponding threshold at 10 Hz for annoyance and physiological effects are extracted from Figure 1 and now using the propagation slopes given by Larom[12] and using a sound power level likely to reach 155dB at a harmonic, the resulting distances for physiological effects range from 280m to 780m for temperature inversion condition. Using a similar procedure, for annoyance, the resulting distance ranges from 1400m to 4400m. Since the thresholds are changing rapidly between the 10Hz and 30Hz the next derivation is to express the distance relating to 20Hz to 30Hz band. Assuming the sound power level for a modern wind turbine to be about 117dB in the range between 20Hz to 30Hz and taking the assumption of a 3dB increase from the wind turbine to a wind farm the resulting sound power level is assumed to be 120dB. In Figures 2 and 3, the distances (termed the ‘stand-off distance) associated with the onset of expected annoyance and corresponding onset of expected physiological effects are shown for a wind turbine with a sound power level of 120dB. The sharp harmonics generated by the blades of the wind turbine are assumed to generate a sound power level about 120dB. Low frequency absorption also results in sound being strongly affected by temperature gradient and weather effects. This result in the sound propagation being for the frequency range to follow a slope for sound propagation ranging from 14.3 LOG R for a day time sound propagation to 12.4 LOG R when a temperature inversion occurs. The bounding of those expected minimum and maximum slopes are only valid for those frequencies and for reference the commonly used 20 LOG R for normal audio frequencies together with the 10 LOG R for the line source are also added for comparison. In Figure 1 the threshold for oppressive feeling – annoyance is reported at 80dB and the threshold for physiological effect and pain is reported at 90dB. By taking the precautionary approach it would be expected the onset of such effects to be lower for a percentage of population.

Figures 2 and 3 therefore show the onset of the effect 5dB below the reported data until those thresholds are reassessed and confirmed on a larger population sample. Figure 3 shows that the onset of annoyance for the frequency range from 20Hz to 30 Hz is expected to be about 75 dB and that for the given sound power level of 120 dB at the corresponding frequency range and the corresponding propagation slopes, the 75 dB received level at those frequencies are expected between 1300m to 4400m. Using a similar approach the received sound pressure level of 85 dB linear at frequencies ranging from 20Hz to 30 Hz would intersect the propagation slopes for those frequencies at distances ranging from 280m to 750m. The distances of 280m to 750m would correspond to the expected onset of physiological effects.

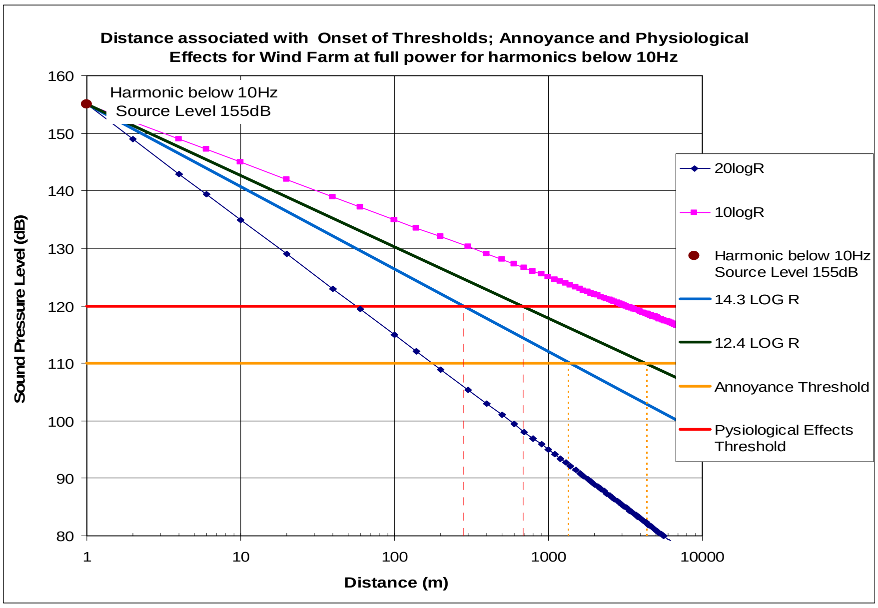

Figure 2. Distance for which the threshold of annoyance and physiological effects threshold are anticipated for one wind turbine generating a source level of 120dB in the frequencies below 10Hz.

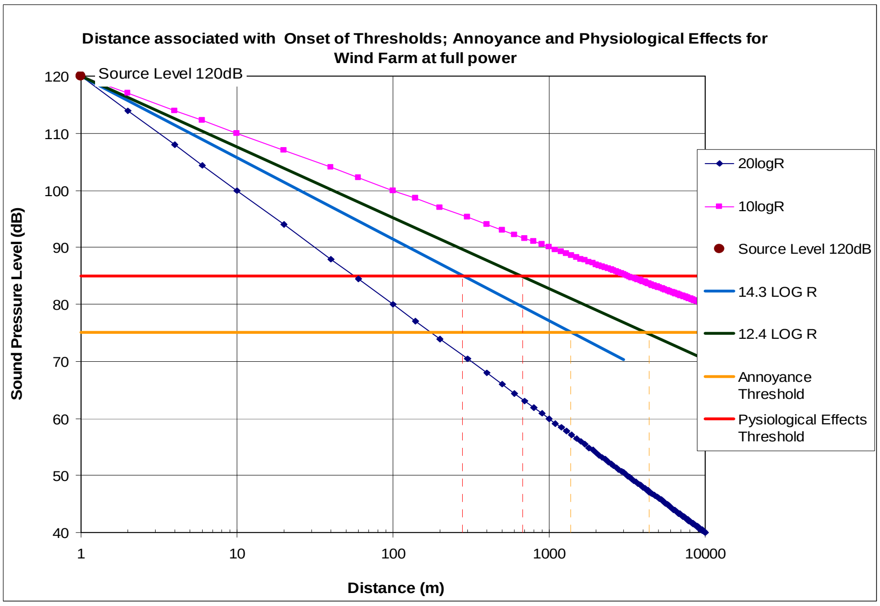

Figure 3. Distance for which the threshold of annoyance and physiological effects threshold are anticipated for one wind turbine generating a source level of 120dB in the frequencies 20Hz to 30Hz.

5. Conclusion

This paper proposes a methodology to assess the effect of wind turbine low frequencies and infrasonic frequencies on nearby human receptors. The method includes objective calculations and subjective responses. Thresholds for detection of low frequency and infrasound, annoyance and physiological effects are proposed. The interactions of several wind turbines will result in complex sound fields given the different effects involved such as harmonics generations, directivity of the sound field, difference in rotational speed between wind turbine, interference, beating effects and modulation may result. The diurnal effect temperature inversion, variability in wind speed, will add to the complexity in the assessment of the impact of low frequency and infrasound. Modulation of low-and infrasonic frequencies is influenced by the interaction of several wind turbines. Frequency analysis measured in the presence of wind turbines has three separate components: (a) the basic blade rate infrasound, (b) a secondary unsteady component of blade lift induced noise, and (c) the broadband ambient from turbine and wind-flow noise. The propagation of sound for low frequency and infrasonic frequency has been reviewed and the slope for the attenuation of sound below 100Hz is proposed to range from *14.3Log(R)* to *12.4Log(R)* when a temperature inversion takes place.

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