Association
of Australian
Acoustical
Consultants

Please address correspondence to:
AAAC Secretary
Level 14, 120 Edward Street
Brisbane QLD 4000
T 07 3120 6800 F 07 3210 3900
E info@aaac.org.au

1 June 2015

Select Committee on Wind Turbines
PO Box 6100
Parliament House
Canberra ACT 2600

**Attention: Dr Richard Grant**

Dear Sir,

**REVIEW OF THE ACOUSTIC GROUP REPORT**
**"THE RESULTS OF AN ACOUSTIC TESTING PROGRAM CAPE BRIDGEWATER WIND FARM"**

A review of The Acoustic Group report titled, "The results of an acoustic testing program Cape Bridgewater Wind Farm" (the Study) has been conducted.

The overall conclusion drawn from the review is that the Study provides no new credible scientific evidence, and further, no scientific evidence to support the media reporting positively of the Study.

The Study measures infrasound at the blade pass frequency and multiples of the blade pass frequency. The level of infrasound is similar to the levels measured previously by others and is well below the threshold of human perception.

The Study suggests that there is a "pattern" of high severity disturbance associated with four turbine operating modes. When all data are considered, there are limitations, contradictory and limited data and the results do not support the description of a "pattern".

The Study includes a hypothesis that "sensations" felt by the participants might be related to the measured level of infrasound. The hypothesis is based on a very limited subset of the data, with any data excluded from the analysis if it did not fit the theory. When all data are considered, the evidence does not support the hypothesis.

**Measured Infrasound**

Figure 49 of the report indicates that the level of infrasound at the blade pass frequency and multiples of blade pass frequency are in the order of 45 to 71 dB re 20μPa. This is not new and has previously been measured by others at similar levels.

The established threshold of human perception at these frequencies is in the order of 110 dB re 20μPa at 5Hz (Watanabe and Møller, 1990) and even higher at lower frequencies. That is, although the infrasound can be detected by instruments, it cannot be perceived by humans.

Since the Study, researchers have simulated the character and level of infrasound measured at wind farms to determine any reported symptoms or sensations. The research, conducted by Colin and Kristy Hansen (Hansen et al, 2015), Renzo Tonin and Associates (Tonin and Brett, 2015) and Channel Island Acoustics (Walker and Celano, 2015), indicates that there is no reported symptoms or sensations to this level, or indeed higher levels, of infrasound.

**Sensation Pattern**

The Study claims to have *"found a pattern of high severity of disturbance to be associated with four different operating scenarios of the wind farm being:*

- *when the turbines were seeking to start (and therefore could drop in and out of generation)*
- *an increase in power output of the wind farm in the order of 20%*
- *a decrease in the power output of the wind farm in the order of 20%, and*
- *the situation when turbines were operating at maximum power and the wind increased above 12m/s".*

There is no statistical analysis supporting this claim. For the claim to be made, an expert in statistics should have been retained to design the experiment and to analyse the data in a scientific manner.

The "pattern" is based on the analysis of "sensation" classified as "severity category 4" or "5". Of the 522 occurrences where a resident identified a severity category 4 or 5, the Study identifies the conditions as fitting into one of the above categories on 194 occasions. That is, the pattern is based on 37% of the occurrences being classified as one of the four operating scenarios or an average of less than 10% per operating scenario. To provide context, 63% of the occurrences were not classified in any of the four operating scenarios.

Contrary to this pattern, there are many occasions when sensations were recorded when the wind turbines were shut down. For example, during the shutdowns on 22 May and 24 May 2014, the occupants of House 88 identified 9 separate occasions when the sensation level was classified as category 4. That is, at a time when the turbines were not operating, the sensation was classified as a "substantial impact (disruptive)", which is described as "quality of life diminished due to change in character of the area".

Although the Study states, "For one resident, sensation, noise and vibration were observed with the wind farm shutdown", levels of sensation were recorded at all three houses during periods of shutdown. For example, at House 87 on 13 June, sensation was classified by the occupants as category 4 when turbines were not operating and at House 89 on 15 and 22 May, sensation was classified as category 2 when turbines were not operating. On 21 May at 6:10am when turbines were shut down, a resident of House 89 recorded the diary entry, "Sudden awakening (awakening with a start/adrenalin surge to gut)".

Conversely, a resident of House 89 stated, "During the second week, the Wind Facility was in shutdown for eleven days, due to work being undertaken on power lines" … "During the shutdown we slept." However, although the turbines were shutdown during the day, they were restarted on most nights.

Based on the above, there does not appear to be any establishment of a pattern without ignoring contradictory occurrences.

## Sensation and Infrasound

The Study conducts an analysis of the level of infrasound recorded during category 5 sensations compared with category 2 sensations. However, only a very narrow band of category 5 sensations were included in the analysis. The report states that there were 81 occasions when category 5 sensations were recorded but only 31 are included in the analysis. For example, data were excluded if high or low wind speeds were recorded, even though these periods represent two of the four operating scenarios described as "a pattern of high severity of disturbance". The reason given for excluding the data was that the blade pass frequency and harmonics could not be detected.

Rather than trying to understand the reason why category 5 sensations were recorded when infrasound from the wind farm could not be detected, the Study excludes the contradictory data and proceeds with a hypothesis. No explanation as to why a severity category 5 could be recorded without infrasound from the wind farm being detected has been provided. A scientific approach would explore or, at the very least, identify this prior to establishing a hypothesis.

## Conclusion

The AAAC Wind Farm Subcommittee has conducted a review of The Acoustic Group's Cape Bridgewater report and has concluded that:

- The level of infrasound measured is similar to the level previously measured by others;
- The claimed "pattern" between high severity sensation and modes of operation is not based on a statistical analysis and ignores contradictory occurrences; and
- The hypothesis that there is a link between "sensations" and infrasound is based on excluding data that do not support the hypothesis.

Based on the above, it is considered that the Study does not follow a rigorous scientific method and provides no justification for the AAAC Position Statement to be updated.

Yours faithfully,

**Australian Association of Acoustical Consultants**

Association
of Australian
Acoustical
Consultants

Please address correspondence to:
AAAC Secretary
Level 14, 120 Edward Street
Brisbane QLD 4000
T 07 3120 6800 F 07 3210 3900
E admin@aaac.org.au

# Recent technical references regarding perception of and annoyance from wind turbine noise & infrasound

The following list of recent technical references regarding perception of and annoyance from wind turbine noise and infrasound has been compiled to provide additional information to the Senate Select Committee on Wind Turbines. The list is not exhaustive but seeks to identify recent and relevant information that the Committee may not be otherwise aware of.

**Perception of infrasound**

- Tonin, R. and Brett, J. (2015) *Response to Simulated Wind Farm Infrasound Including Effect of Expectation*, Sixth International Meeting on Wind Turbine Noise Glasgow.

  This study played infrasound from as low as 0.7 Hz, based on that measured at Shirley Wind Farm, to 80 subjects as well as recording symptom reporting. It found no perception amongst subjects and symptom reporting was controlled by people's pre-conceived notions regarding wind turbine infrasound. A copy of the paper is attached and a presentation is available online (http://www.cleanenergycouncil.org.au/dam/cec/events/2015-wif/Presentations-in-PDF/1.14-Renzo-Tonin/1.14%20Renzo%20Tonin.pdf).

- Hansen, K., Walker, B., Zajamsek, B. and Hansen, C. (2015) *Perception and annoyance of low frequency noise versus infrasound in the context of wind turbine noise*, Sixth International Meeting on Wind Turbine Noise Glasgow.

  This study played infrasound and low frequency noise, based on that measured at Waterloo Wind Farm, to test subjects through a large custom built speaker. It found no perception of wind farm infrasound and that low frequency wind farm noise could be perceived at approximately 50 Hz but only when above previously established hearing thresholds. A copy of the paper is attached.

- Walker, B. and Celano, J. (2015) *Progress Report on Synthesis of Wind Turbine Noise and Infrasound*, Sixth International Meeting on Wind Turbine Noise Glasgow.

  Walker and Celano produced infrasound, based on that measured at Waterloo and Cape Bridgewater Wind Farms, using a custom-built speaker designed to reproduce infrasound as low as 0.7 Hz at a level 10 dB greater than measured in the field. They have reported that, to date, no individual "has reported any sensation when exposed to infrasound alone". A copy of the paper is attached.

- Yokoyama, S., Kobayashi, T., Sakamoto, S. and Tachibana, H. (2015) *Subjective experiments on the auditory impression of the amplitude modulation sound contained in wind turbine noise*, Sixth International Meeting on Wind Turbine Noise Glasgow.

  This study is part of a wide-ranging Japanese research program into wind turbine noise. In addition to amplitude modulation, this paper also examined the audible and perceptible components of recorded wind turbine noise by filtering the recordings at different frequencies and playing them to 17 subjects. It found that wind turbine noise below 20 Hz (i.e. infrasound) was not perceived by any test subject as "audible" or "sensible". A copy of the paper is attached.

**Infrasound from other sources**

- Leventhall, G. (2013) *Infrasound and the ear*, Fifth International Meeting on Wind Turbine Noise Denver.

  Geoff Leventhall prepared this paper describing infrasound levels generated in the ear by normal body processes such as heartbeat and breathing. It concludes that internal sources generate significantly higher levels of infrasound than wind turbines do and at equivalent frequencies. A copy of the paper is attached.

- Stead, M., Cooper, J. and Evans, T. (2014) *Comparison of Infrasound Measured at People's Ears When Walking to that Measured Near Wind Farms*, Acoustics Australia, Vol 42, No 3, 197-203.

  This study compared infrasound measured at the ear of someone walking to that measured at residences near wind farms, finding that walking produced markedly higher levels of infrasound at the ear in the region of 2 Hz and lower. A copy of the paper is available at http://www.acoustics.asn.au/journal/2014/Vol42No3-Stead.pdf.

**Wind turbine noise, health and annoyance**

- Michaud, D. (2015) *Wind Turbine Noise and Health Study: Summary of Results*, Sixth International Meeting on Wind Turbine Noise Glasgow.

  A summary of a multi-million dollar large scale epidemiology study undertaken by Health Canada into wind turbine noise. It found no evidence of an association between exposure to WTN and the prevalence of self-reported or measured health effects beyond annoyance. Annoyance was related to A-weighted wind turbine noise but also to other non-acoustic factors. A copy of the paper is attached and a summary of the study is available online at http://www.hc-sc.gc.ca/ewh-semt/noise-bruit/turbine-eoliennes/summary-resume-eng.php.

- Berger, G., Ashtiani, P., Ollson, C., Aslund, M., McCallum, L., Leventhall, G. and Knopper, L. (2015) *Health-based Audible Noise Guidelines Account for Infrasound and Low Frequency Noise Produced by Wind Turbines*, Sixth International Meeting on Wind Turbine Noise Glasgow.

  This study, conducted by a group composed of acoustic consultants and environmental and health scientists, involved measurements of wind turbine noise, infrasound and low frequency noise at distances of 400 – 900 m. It concluded that by controlling overall A-weighted noise levels from wind turbine noise to suitable levels for annoyance, noise levels from infrasound and low frequency noise would also be appropriately controlled. A copy of the paper is attached.

- Council of Canadian Academies. (2015) *Understanding the Evidence: Wind Turbine Noise*, Ottawa, Canada.

  The Council undertook a review to assess the primary question of whether there is evidence to support a causal association between exposure to wind turbine noise and the development of adverse health effects. They concluded that there is evidence to establish a relationship between wind turbine noise and annoyance but inadequate evidence for direct health effects such as fatigue, tinnitus, vertigo, dizziness, cardiovascular diseases, diabetes etc. The report is available online at http://www.scienceadvice.ca/en/assessments/completed/wind-turbine-noise.aspx.

- Tachibana, H. (2014) *Outcome of systematic research on wind turbine noise in Japan*, Proceedings of Internoise 2014, Melbourne.

  Professor Tachibana is leading systematic research into wind turbine noise in Japan looking at human perception and annoyance. This paper summarises key aspects of that study, including perception studies, and concludes that A-weighted noise levels are a suitable metric for wind turbine noise as long as due consideration is given to factors such as amplitude modulation and tonality that may increase annoyance where present. Wind turbine noise in the infrasound frequency region was not found to be important for human perception. A copy of the paper is attached.

### Other

- Bowdler, D. (2015), *Wind Turbine Noise 2015 Post-Conference Report,* Sixth International Meeting on Wind Turbine Noise Glasgow.

  Although not a technical paper, the Post-Conference Report prepared by Conference Chairman Dick Bowdler for the recent Wind Turbine Noise 2015 conference held in Glasgow provides an interesting international perspective on that Conference. With regards to infrasound, it concludes that "there is no evidence that there is any link between infrasound from turbines and any health effects" but does state that annoyance from audible wind turbine noise is an important factor for consideration. A copy of the post-conference report is available online at http://windturbinenoise.eu/wp-content/uploads/2015/05/WTN2015-Post-Conference-Report.docx.

# Sixth International Meeting

# on

# Wind Turbine Noise

# Glasgow, Scotland, 20th – 23rd April 2015

## Title: Response to Simulated Wind Farm Infrasound Including Effect of Expectation

**Authors: Renzo Tonin, Renzo Tonin & Associates (NSW) Pty Ltd and James Brett, Renzo Tonin & Associates (NSW) Pty Ltd**

## Summary

People living near wind farms have reported negative health effects from infrasound and attribute this to their exposure to the sound. Those exposed assert that when removed from the source of infrasound, they experience an almost immediate improvement in health. This, they say, proves the infrasound is the cause. However, there is some scientific evidence that there is no direct link between infrasound and adverse health, rather the explanation can be found in a psychosomatic response (such as a nocebo effect).

An investigation was conducted into the effect on the reported pathological symptoms of simulated infrasound produced by wind turbines. The experimental procedure closely followed that of Crichton (Crichton, F, Dodd, G, Schmid, G, Gamble, G & Petrie, K. J. 2014) except for some important differences in experimental procedure. The infrasound waveform was generated using a custom-made headphone apparatus. Volunteers were manipulated into states of either high or low expectancy of negative effects from infrasound and their reactions to either infrasound or a sham noise were recorded in a double blind experiment. A comparison is made between this study and Crichton.

It was found, at least for the short-term exposure times conducted here-in, that the simulated infrasound has no statistically significant effect on the symptoms reported by volunteers, however the state of prior concern that volunteers had about the effect of infrasound has a statistically significant influence.

## 1. Introduction

From the time Pierpont (Pierpont, N. 2009) coined the term “wind turbine syndrome” to describe the cluster of symptoms people experience around wind turbines (such as sleep disturbance, headache, tinnitus, nausea, vertigo etc.), there has been considerable debate in the professional literature about the topic. The view expressed by Pierpont is that low frequency noise and vibration too weak to be heard and at a level lower than the auditory threshold can still stimulate the human vestibular system potentially leading to the adverse pathological symptoms described by those exposed to the noise. Nissenbaum (Nissenbaum, M. A, Aramini, J. J, & Hanning, C. D. 2012), by means of a social survey, concluded that people living near wind turbines in the study area had impaired mental health and suffered sleep disturbance. This was attributed to high levels of low frequency noise.

Salt (Salt, A. N, & Lichtenhan, J. T. 2014) attributes the stimulation of the ear's sensitive outer hair cells by infrasound to be the cause of symptoms. The reason given for the outer hair cells being sensitive to infrasound (even though they do not contribute to conscious hearing *per se*) is that they are displacement sensitive as a consequence of being mechanically coupled to the tectorial membrane. The long-term stimulation of the outer hair cells, according to Salt, explains the pathological symptoms observed.

Schomer (Schomer, P, Erdreich, J, Boyle, J, & Pamidighantam, P. 2013) proposes that the cause is infrasound pressure reaching the inner ear and exciting the otolith organ which normally responds to acceleration of the head. According to Schomer, the effects of motion sickness can be compared with the pathological symptoms experienced by people living near wind turbines and concludes that wind-turbine acoustic emission triggers motion sickness in those who are susceptible. Rand (Ambrose, S. E, & Rand, R. W. 2011) notes that he suffers from sea-sickness and both he and Ambrose experienced nausea, dizziness and irritability within twenty minutes of starting their noise survey of three wind turbines in Falmouth USA.

Those who disagree with these hypotheses say principally that the evidence for wind turbine noise and infrasound causing health problems is poor (Chapman, S, St George, A, Waller, K, & Cakic, V. 2013). Similarly, the Australian Government's National Health and Medical Research Council found, on review of scientific literature, that wind turbines do not pose a threat to health if planning guidelines are followed (NHMRC, 2010). Jakobsen (Jakobsen, J 2005) concludes that infrasound from modern (upwind) wind turbines can be neglected when evaluating the environmental effects of wind turbines.

Leventhall agrees and asserts there is no evidence that the low levels of infrasound from wind turbines are harmful to humans (Leventhall, G, July 2013). He concludes that the continuous infrasound levels normally produced by the inner ear in everyday situations are in the same frequency range as wind turbine infrasound and are higher in level than that produced by wind turbines (Leventhall, G, August 2013).

Turnbull (Turnbull C & Turner J, 2011) concludes that wind turbines generate infrasound well below the audibility of threshold of 85 dB(G) and at levels that are similar to those produced by other man-made sources as well as natural sources along the coast. According to Turnbull, the level of infrasound measured close to a wind turbine is prevalent in every day urban and coastal environments. The same conclusion was obtained in a study by the Environment Protection Authority in South Australia (Evans T, Cooper J, Lenchine,V. 2013).

So, in the light of such disagreement, what explanation can be provided for the numerous psychosomatic responses reported in the literature? Crichton (Crichton, F, Dodd, G, Schmid, G, Gamble, G, & Petrie, K. J. 2014) in an experiment which manipulated the expectations of volunteers exposed to 10 minutes of infrasound and sham infrasound in a double blind experiment concluded that those volunteers, when given information about the expected physiological effect of infrasound, reported symptoms that aligned with that information. The infrasound exposure itself did not contribute to the symptomatic experience. Symptom expectations were created by viewing information readily available on the Internet, indicating the potential for symptom expectations to be created outside of the laboratory, in real world settings. Crichton concluded that psychological expectations could explain the link between wind turbine exposure and health complaints, that is, a nocebo effect.

Chapman agrees and concludes that the reported spatio-temporal variations in complaints are consistent with psychogenic hypotheses that health problems arising are “communicated diseases” with nocebo effects likely to play an important role in the aetiology of complaints (Chapman, S, St George, A, Waller, K, & Cakic, V. 2013).

There was criticism of the Crichton experiment, most notably that the volunteers were university students, that they were subject to only 10 minutes of infrasound and the sound level of infrasound was not comparable to that measured at actual wind farm sites (Hartman R. S. 2013) (Punch J, 2013).

For this reason, the Crichton experiment was repeated by Tonin but using an experimental procedure designed to avoid those criticisms (Tonin R, Brett J & Colagiuri B, 2015 submitted for publication). The purpose of this paper is to compare the results of the Crichton and Tonin experiments and their conclusions.

## 2. Experimental design

### 2.1 Simulated Infrasound Waveform

A detailed recording and analysis of infrasound generated by wind turbines was first made by Walker at the Shirley Wind Farm in Wisconsin, USA (Walker, B, Hessler G. F, Hessler D. M, Rand R, & Schomer P, 2012). The investigation was conducted at three residences whose occupants reported health problems they attributed to infrasound. The Shirley Wind Farm consists of eight wind turbines located at varying distances from the residences, with the closest turbine being 390 m from the nearest residence.

The infrasound recorded was not random in character but was characterised by a 0.7-0.9 Hz fundamental frequency consisting of multiple harmonics, with a peak sound pressure level of 82-89.5dB with the higher sound levels measured indoors. Walker synthesized the waveform in MATLAB and produced multiple files, one of which is a 0.8 Hz trapezoidal-shaped waveform with 16 harmonics as shown in the figure below.

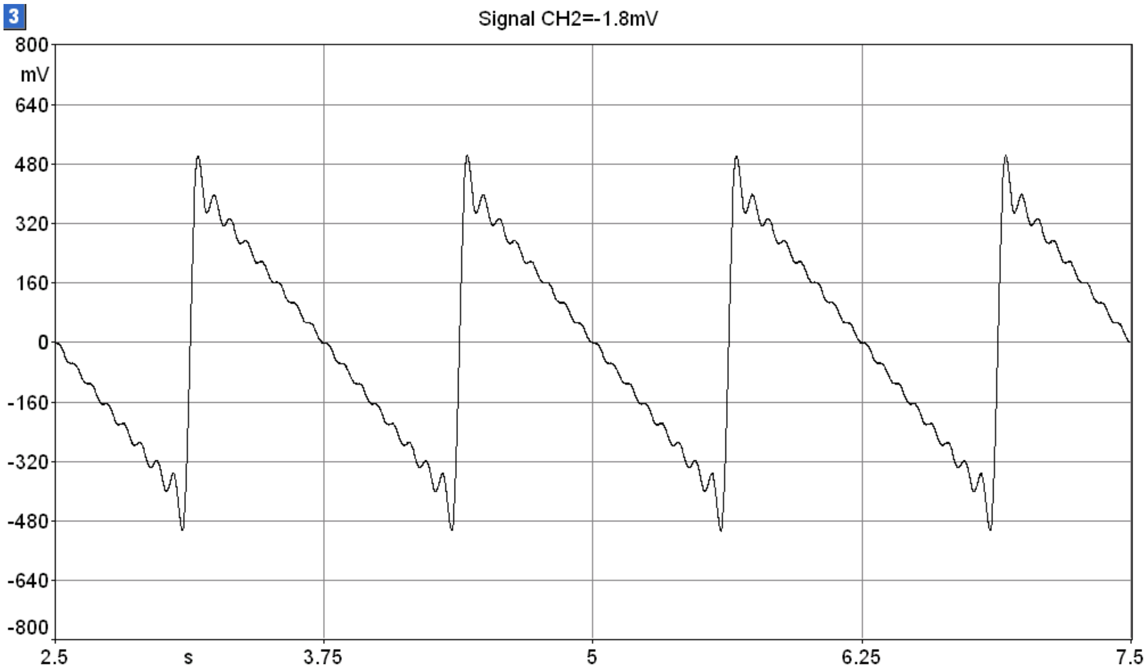


Figure 1 Infrasound signal used in experiment

In the Tonin experiment, this waveform was played at a level of 91dB peak, this being a slightly higher sound level than that recorded at Shirley. It is noted in the Crichton experiment the sound level was played at 40dB at 5Hz (the metric is not published and it is presumed the signal was sinusoidal). This was one of the criticisms by others previously noted.

## 2.2 Apparatus for Generating Infrasound

In the Crichton experiment, the sound level was played using a Mackie HR 150 active studio woofer. However, this speaker is not suitable for generating the low frequencies of interest for this experiment.

There are two approaches for generating sound at 0.8 Hz, one being the use of one or more large speakers to pressurise a receiving room, the other being the transduction of the sound through headphones using a pneumatic driver, each with their own advantages and disadvantages. The first approach has the advantage of being able to subject the whole body to infrasound but is not easily transportable and the experiment would need to be conducted in a quiet receiving room. The second approach has the disadvantage that only the ears are exposed to the signal but the advantage that the equipment is portable and not nearly as susceptible to outside noise. The second generating method is employed in this study and therefore there is an inherent assumption that if infrasound affects the human body, the principal path is via the ears (Møller H & Pedersen C.S, 2004).

The pneumatic generating apparatus consists of a nominal 5” diameter Visaton W 130S loudspeaker screwed airtight to the inside of the lid of Pelican Storm Case iM2075. In the centre of the lid there is fitted a 6 mm air nozzle.

The loudspeaker is driven by a DC amplifier connected to a Sinus Soundbook running SAMURAI 2.0 software which generates the electrical waveform previously described. A 200 Hz low pass filter with DC offset adjustment and a dB attenuator are connected between the Soundbook and the amplifier.

The pressure signal from the speaker is transmitted via a 1.7 m length of 6 mm inner diameter clear vinyl/polyurethane tubing incorporating a brass splitter to connect to each cup of a set of Uvex-X earmuffs as shown in the following figure. One of the cups was modified to house a G.R.A.S. 40AZ ½" Pre-polarised Free-Field Microphone connected to a G.R.A.S. Type 26CG ¼" Low Frequency CCP Preamplifier.  The G.R.A.S. 40AZ microphone has a frequency response of 0.5Hz to 20 kHz (+/- 2dB) which encompasses the range of the study.

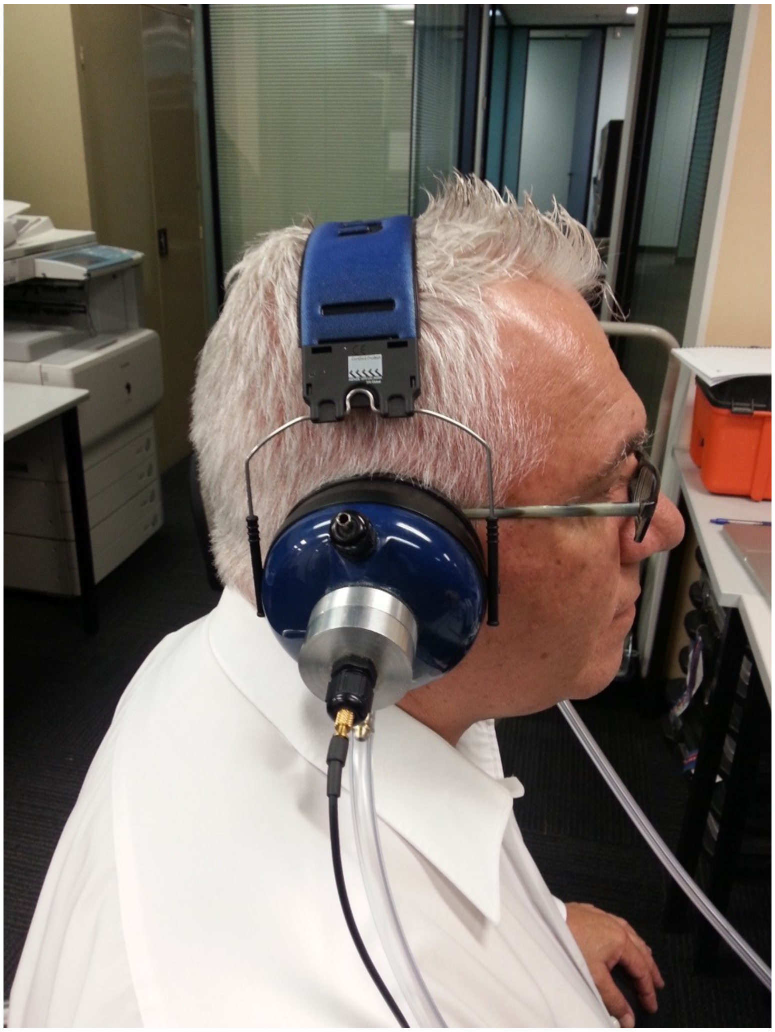


Figure 2 Complete acoustic headphones including 6mm nozzles on both ears with attached tubing, microphone and occlusion port (located just above the silver coloured microphone attachment).

An unexpected complication arose during testing of the headphones. It was found that the measured sound level in the headphones from the heartbeat of the person wearing the headset was in the range 90 dB Peak which confounded the generated infrasound signal. The sound of one's heartbeat is audible to a person wearing earmuffs in a quiet room. The effect was reduced significantly to below 80 dB Peak by incorporating a 3 mm diameter venting port as shown in the figure above.

The source of the occluded heartbeat is thought to be pressure fluctuations from blood vessels near the surface of the skin encapsulated by the headphones, acting like a piston in a cylinder pressurising the entrapped air. Several large blood vessels, such as the external carotid artery and the superficial temporal artery, run close to the ear (Wikipedia, 2014). A detailed examination of this source of sound is beyond the scope of this study, needless to say that the sound level is reduced significantly below the 91dB Peak generated by the loudspeaker and therefore is unlikely to be a confounding factor. This was checked for each volunteer.

The following figure shows the frequency response of the loudspeaker, tubing and microphone combination with the un-occluded vents is linear within about +/-4dB from 0.8Hz to 40Hz which comprises the frequency range of the generated infrasound and harmonics.

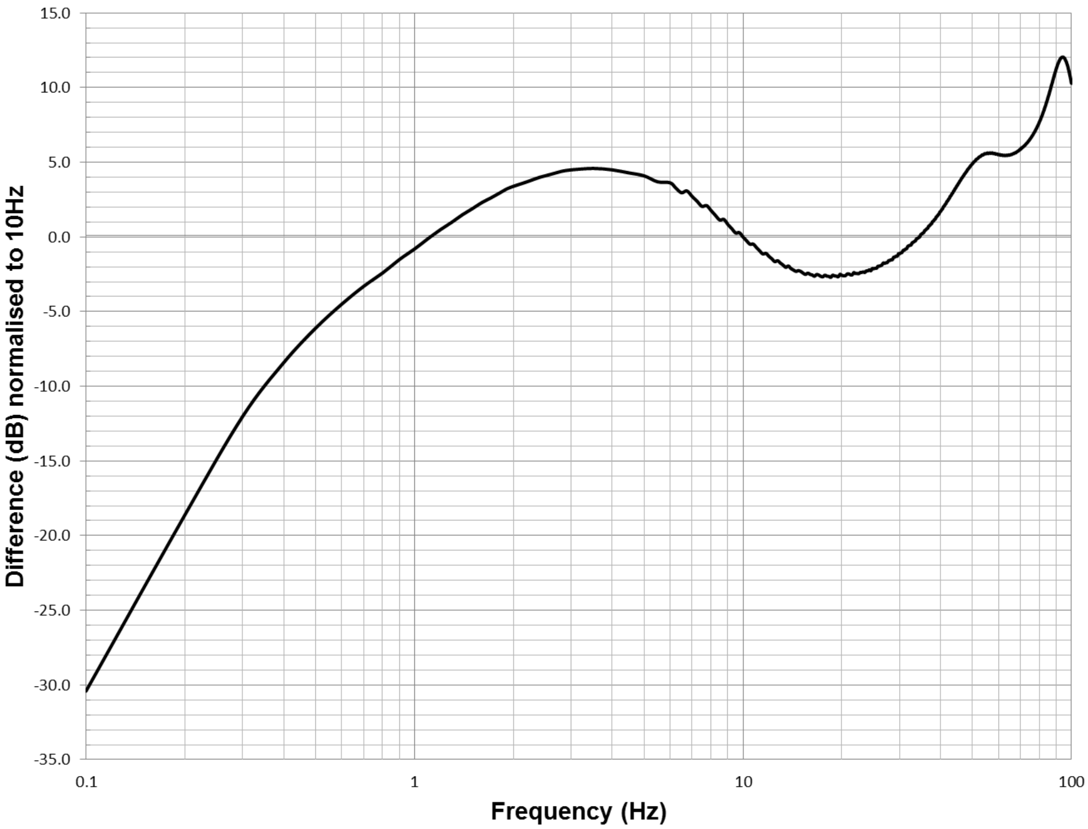


Figure 3 Headphone and Tubing Frequency Response with Attenuator Ports Open

## 2.3 Experimental Design

In the Crichton experiment, there were 54 university students tested, 34 women and 20 men.

In the Tonin experiment 72 volunteers were tested, 27 female and 45 male ranging in age from 17 to 82 years with a median age of 29 years. Volunteers were sourced from professional firms (not associated with wind farms), students, government organisations and family members. This wider mix in age and demographics of volunteers was intended to address one of the concerns of the Crichton experiment previously referred to.

The experiments are a double blind study subjecting the volunteers to either infrasound or no noise (sham noise) after manipulating their expectations into either high or low expectancy by using appropriate videos. Responses were recorded on identical questionnaires filled out by volunteers before and after the experiment according to the following groupings.

Table 1 Experimental Groups

| | Infrasound Applied | Sham Applied |
|---|---|---|
| High Expectancy | Group 1<br>HE/ON | Group 2<br>HE/OFF |
| Low Expectancy | Group 3<br>LE/ON | Group 4<br>LE/OFF |

In the Crichton experiment, the volunteers were exposed to 10 min of infrasound and 10 min of sham infrasound (no sound). In the Tonin experiment, the volunteers were exposed only once to 23 minutes of infrasound or 23 minutes of sham infrasound (but not both). As previously noted, Rand (Ambrose, S. E, & Rand, R. W. 2011) experienced nausea, dizziness and irritability within twenty minutes of starting their noise survey of three wind turbines in Falmouth USA. The selection of 23 minutes of infrasound in the Tonin experiment was intended to address one of the criticisms of the Crichton experiment previously referred to.

Prior to the test, and then again at the conclusion, the volunteers were asked to complete a questionnaire which rated to what extent they were feeling various symptoms on a 7-point Likert scale ranging from 0 (none) to 6 (extreme). There were 24 symptoms listed on the questionnaire, 12 that are typically associated with wind turbine health complaints (headache, ear pressure, ringing in the ears, itchy skin, sinus pressure or irritation, dizziness, pressure in the chest, vibrations within the body, racing heart, nausea, tiredness, feeling faint), and 12 that are not typically associated with wind turbine health complaints (stomach ache, aching legs, aching arms, sore joints, stiff muscles, back pain, numbness or tingling in the body, difficulty swallowing, sore jaw, chills, hot flushes, hand tremble or shake).

Volunteers were also asked to rate how concerned they were about the health effects of wind turbine infrasound on a 7-point scale ranging from 0 (completely unconcerned) to 6 (extremely concerned).

Volunteers then watched one of two introductory videos designed to manipulate their expectations, one to heighten expectations (of an interview of wind farm affected residents explaining their symptoms) and the other to lower expectations (of an academic explaining why infrasound is not a problem). The videos may not have been the same in the Crichton and Tonin experiments however, from the description provided by Crichton, they appear to be similar.

In the Tonin experiment, at the conclusion of the expectation video, the volunteer was fitted with the special headset described previously and was directed to watch a subtitled video documentary of duration 23 minutes with no relevance to the subject matter. The examiner played either the infrasound or the sham infrasound (based on random selection) for the duration of the documentary. The examiner was unaware of which expectation video the volunteer watched nor whether the volunteer would be exposed to the infrasound until it was time to play the infrasound or sham sound. At the conclusion of the video documentary, the volunteer completed the second questionnaire, identical to the first, without referring to the first.

In the Crichton experiment, there is no information about how the volunteers spent their 10 minutes of exposure to infrasound or sham infrasound.

The number of symptoms with a non-zero score was calculated for both the initial and final questionnaires as was the intensity of symptom score calculated as the sum of all the ratings given.

## 3.0 Results

### 3.1 Mean number of symptoms and intensity of symptoms

The results of the mean number of symptoms reported are shown in Figure 4 (total number of symptoms), Figure 5 (number of typical symptoms) and Figure 6 (number of atypical symptoms) for both the Crichton and Tonin experiments.

The results from the means are inconclusive. If the infrasound alone had a direct physiological effect it would be expected that HE/ON and LE/ON would show an increase in the number of symptoms after the experiment, while there would be little to no difference in the other two groups where there was no infrasound present. Conversely, if the infrasound had no direct effect but instead it was the expectation of harm having an effect upon their reactions (i.e. the nocebo effect), it would be expected that HE/ON and HE/OFF would show an increase in the number of symptoms after the experiment whilst there would be little to no difference in the other two groups.

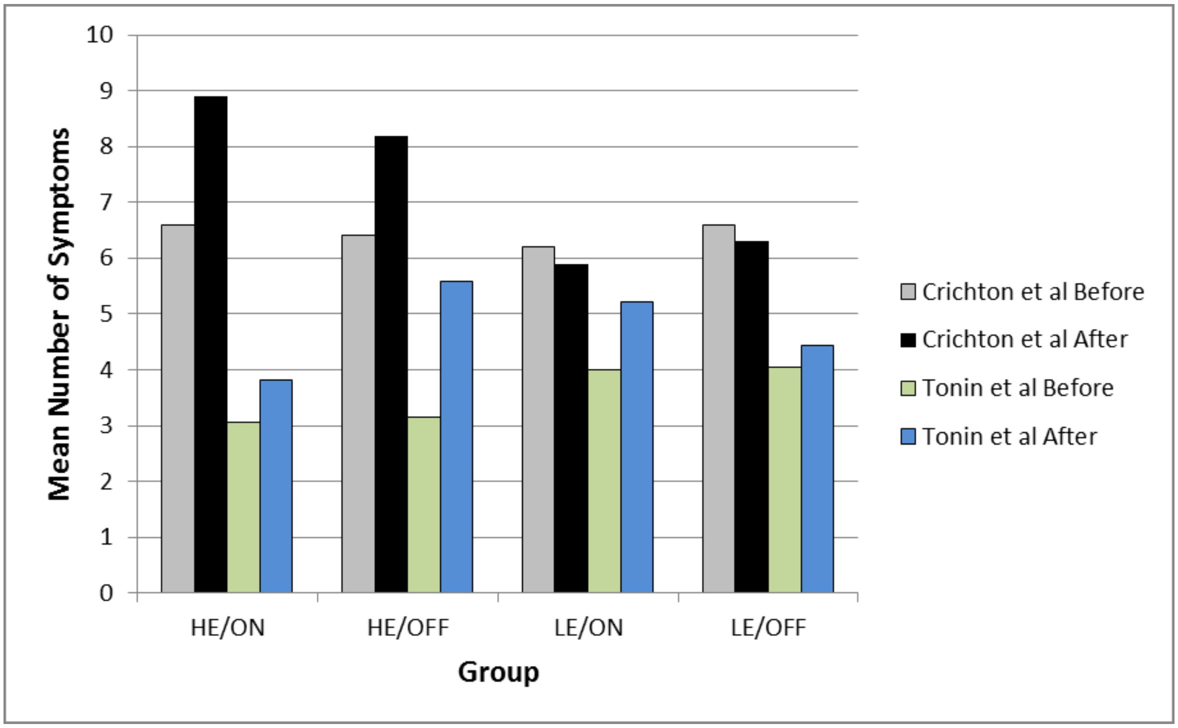


Figure 4 Mean Total Number of Symptoms Before and After per Group

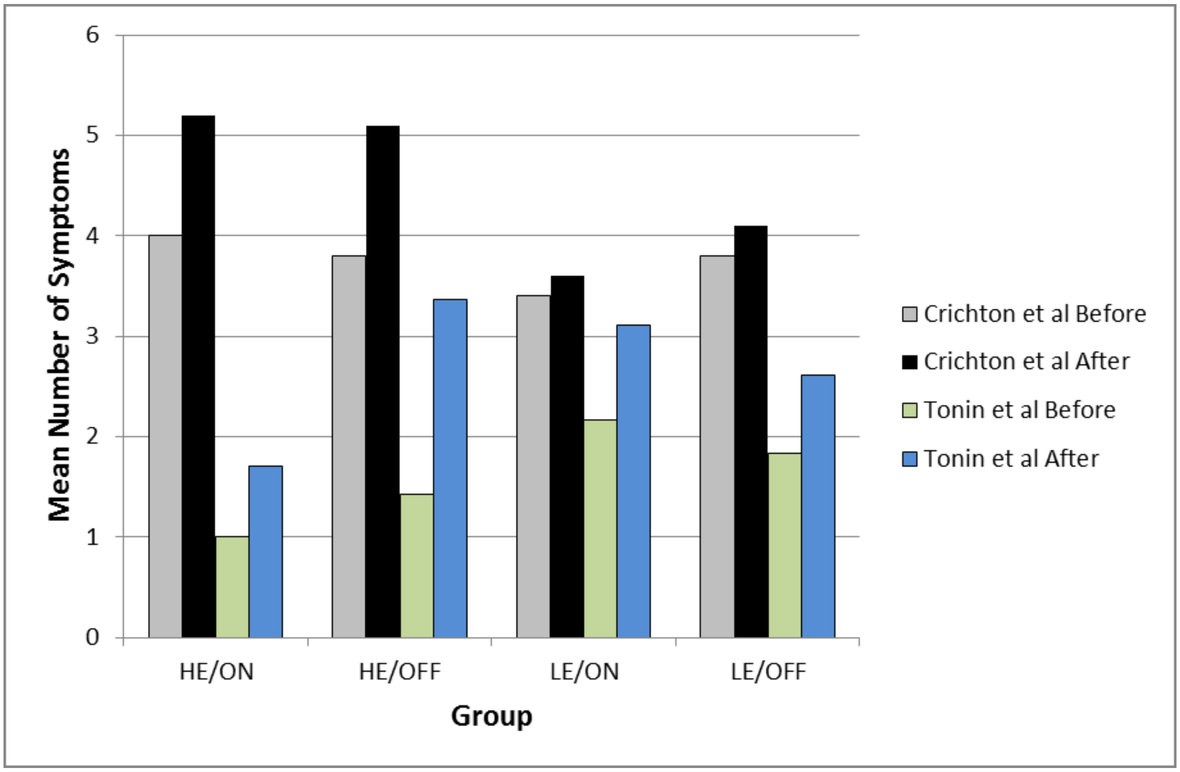


Figure 5 Mean Number of Typical Symptoms Before and After per Group

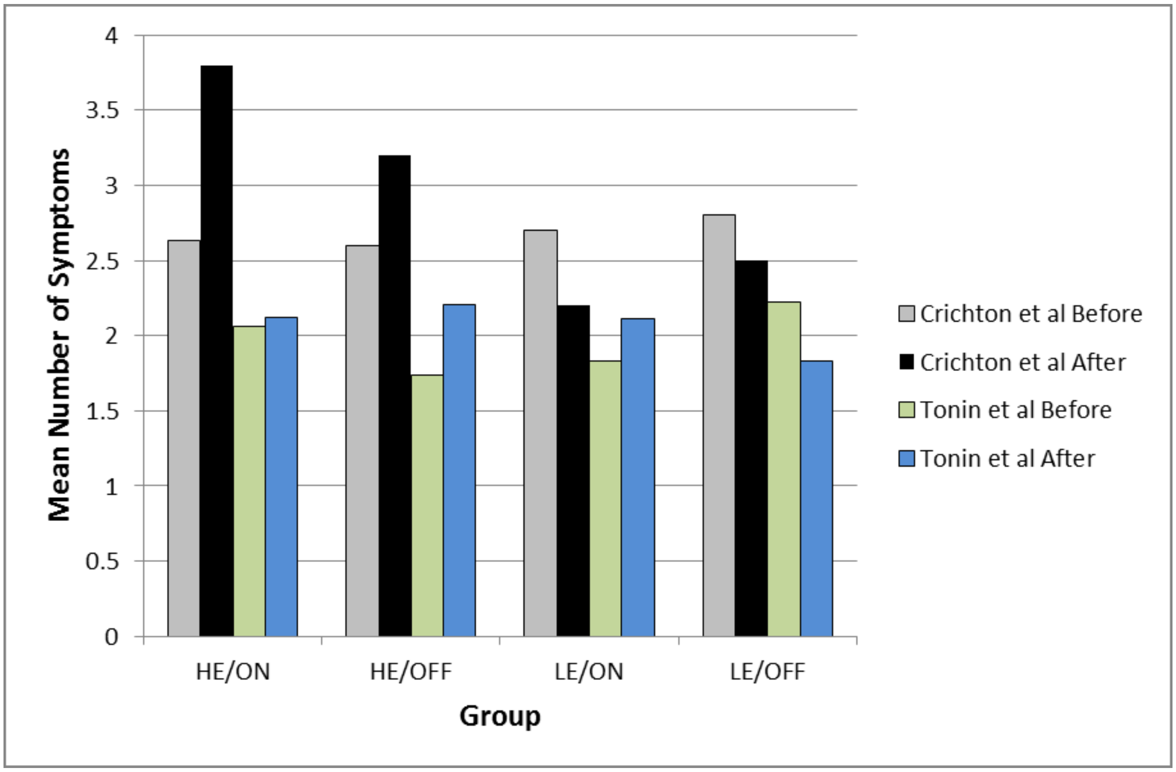


Figure 6 Mean Number of Atypical Symptoms Before and After per Group

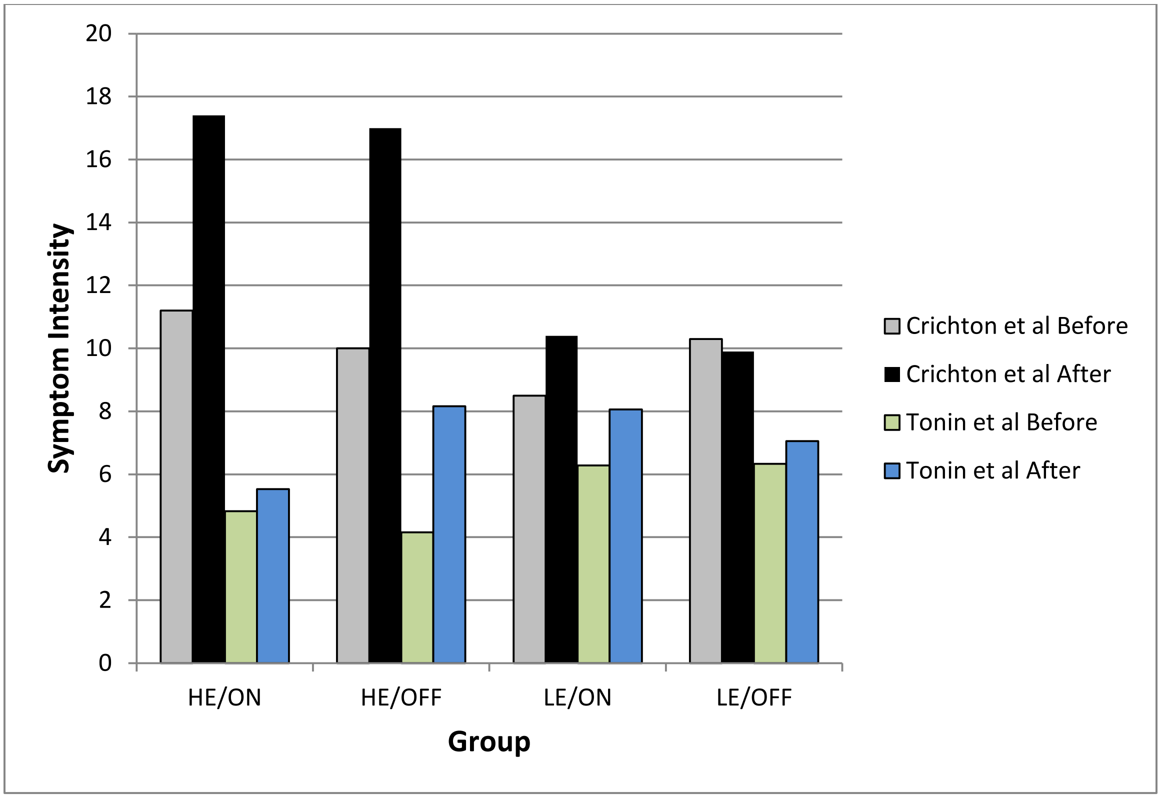


Figure 7 Mean Intensity of Symptoms Before and After per Group

A similar conclusion can be said for the mean intensity of symptoms which is shown in Figure 7. Intensity is the sum total of all the symptom ratings, for instance, if a volunteer rated headache as 2, and tiredness as 1, while all the other symptoms were rated 0, the intensity of symptoms would equal 3.

One point of difference between the two experiments is the higher number of symptoms reported in the Crichton experiment for both HE groups in both the number of symptoms and intensity of symptoms. There is no explanation for this. Nevertheless, the before and after difference in each HE group shows a similar trend.

### 3.1 Effect of infrasound

In the Tonin experiment, a more detailed study of the results presented above was conducted with ANCOVA analysis utilising the statistical program IBM SPSS. According to Figure 5 above, all groups experienced a net increase in the number of typical symptoms. The presence or absence of infrasound had no effect on the number of typical symptoms whereas for the high expectations groups the presence of infrasound had a negative effect F(1, 72) = 4.02, p=.049 which is statistically significant.

The Crichton experiment concluded that the effect of the expectancy group on change scores did not differ whether exposure was to sham or to infrasound. There was a significant increase from the pre-exposure assessment in the number of symptoms reported during exposure to infrasound F(1,26)=8.16, p<.01

and during exposure to sham F(1,26)=12.16, p<.01. Therefore the number of symptoms reported and the intensity of the symptoms experienced during listening sessions were not affected by exposure to infrasound. Importantly, elevated symptom reporting seen in the high-expectancy group was the same during sham and infrasound exposure.

Both experiments conclude that infrasound exposure itself did not contribute to the symptomatic experience.

### 3.2 Base line concern

In the Tonin experiment, the number of typical symptoms showed a statistically significant correlation with the baseline level of concern F(1, 72) = 7.39, p=.008. There is also a statistically significant correlation between the difference in intensity of typical symptoms and the baseline concern F(1, 72) = 7.96, p=.006. There is no significant correlation between the difference in intensity of atypical symptoms and the baseline concern. An ANOVA test was conducted on the baseline concern to confirm that none of the four groups had a disproportionately large mean baseline concern.

In the Crichton experiment, the influence of baseline concern was examined using mixed-model ANCOVA. The high-expectancy group was shown to be significantly more concerned M=72.78, SD=18.99 than the low-expectancy group M=38.00,SD=20.01, about the health effects of sound generated by wind turbines following the expectancy manipulation controlling for baseline scores.

Both experiments conclude the influence of baseline concern as having a significant effect on the reported symptoms.

## 4.0 Conclusions

Despite the differences in their design, both the Crichton and Tonin experiments come to similar conclusions.

Both experiments conclude that the infrasound had no statistically significant effect on the health symptoms reported by the volunteers.

Instead, the level of concern that a volunteer felt prior to the beginning of the experiment had a more statistically significant effect on the reported typical symptoms associated with wind turbine infrasound.

It was found that the volunteers who came into the experiment with pre-conceived notions of infrasound being harmful generally reported more symptoms than volunteers who began the experiment more sceptical about the potential health impacts of infrasound. These results support the hypothesis that a nocebo effect and not a direct physiological effect may be the cause of reported symptoms.

### References

Ambrose, S. E, & Rand, R. W. (2011). The Bruce McPherson Infrasound and Low Frequency Noise Study Adverse Health Effects Produced by Large

Industrial Wind Turbines Confirmed.

Chapman, S, St George, A, Waller, K, & Cakic, V. (2013). Spatio-temporal differences in the history of health and noise complaints about Australian wind farms: evidence for the psychogenic, "communicated disease" hypothesis. Pre-Publication, Sydney School of Public Health, University of Sydney.

Crichton F, Dodd G, Schmid G, Gamble G & Petrie K. J. (2014). Can Expectations Produce Symptoms from Infrasound Associated with Wind Turbines. Health Psychology, 33(4), 360-364.

Crichton F, Dodd, G, Schmid, G, Gamble, G, Cundy, T, & Petrie, K. J. (2013). The Power of Positive and Negative Expectations to Influence Reported Symptoms and Mood During Exposure to Wind Farm Sound. Health Psychology, Advance Online Publication.

Evans, T, Cooper, J, Lenchine,V. (2013). Environment Protection Authority of South Australia in conjunction with Resonate Acoustics. Infrasound levels near windfarms and in other environments.

Hartman, R. S. (2013). The Adverse Health Impacts of Industrial Wind Turbines: A Scientific Response to "It's all in your head". Zoning Board of Charlestown, Rhode Island.

Jakobsen, J (2005). Infrasound emission from wind turbines. Journal of Low Frequency Noise, Vibration and Active Control, Vol 24, No 3.

Leventhall, G (July 2013). Concerns about infrasound from wind turbines. Acoustics Today.

Leventhall, G. (August 2013). Infrasound and the ear. 5th International conference on Wind Turbine Noise. Denver.

Møller, H & Pedersen, C.S, (2004). Hearing at Low and Infrasonic Frequencies. Noise & Health 6(23).

NHMRC (2010). National Health and Medical Research Council of Australia. Wind Turbines and Health. A Rapid Review of the Evidence.

Nissenbaum, M. A, Aramini, J. J, & Hanning, C. D. (2012). Effects of Industrial Wind Turbine Noise on Sleep and Health. Noise & Health, 14(60), 237-243.

Pierpont, N. (2009). Wind Turbine Syndrome A Report on a Natural Experiment. Santa Fe: K-Selected Books.

Punch, J. (2013). Review of Crichton et al (Can expectations produce symptoms from infrasound associated with wind turbines?). Retrieved January 21, 2014, from Waubra Foundation: http://waubrafoundation.org.au/wp-content/uploads/2013/03/Review-of-Crichton-et-al.Jerry-Punch-docx.pdf

Salt, A. N, & Lichtenhan, J. T. (2014). How Does Wind Turbine Noise Affect People? Acoustics Today, 10(1), 20-29.

Schomer, P, Erdreich, J, Boyle, J, & Pamidighantam, P. (2013). A proposed theory to explain some adverse physiological effects of the infrasonic emissions at some wind farm sites. 5th International Conference on Wind Turbine Noise. Denver.

Tonin, R, Brett, J & Colagiuri, B (2015 submitted for publication). The Effect of Infrasound and Negative Expectations to Adverse Pathological Symptoms from Wind Farms. Submitted for publication to Journal of Low Frequency Noise, Vibration and Active Control, January 2015.

Turnbull, C, Turner, J. (2011). Measurement of Infrasound from Wind Turbines and Other Sources. Fourth International Meeting on Wind Turbine Noise, Rome Italy 12-14 April 2011.

Walker, B, Hessler, G. F, Hessler, D. M, Rand, R, & Schomer, P. (2012). A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin. Public Service Commission of Wisconsin.

Wikipedia. (2014). Common Carotid Artery. Retrieved March 7, 2014, from Wikipedia: http://en.wikipedia.org/wiki/Common_carotid_artery

Sixth International Meeting
on
Wind Turbine Noise
Glasgow  20-23 April 2015

# Perception and annoyance of low frequency noise versus infrasound in the context of wind turbine noise

**Kristy L. Hansen - Flinders University, Sturt Rd., Bedford Park 5042, SA, Australia.**

**Bruce Walker - Channel Islands Acoustics, USA.**

**Branko Zajamsek - University of New South Wales, Sydney, 2052, NSW, Australia.**

**Colin H. Hansen - University of Adelaide, North Tce., Adelaide, 5005, SA, Australia.**

## Summary

Limited subjective assessments of synthesized turbine infrasound and low frequency sound comprising frequencies 0.8 to 53 Hz suggest that near-threshold audible cues play a primary role in perception. Infrasound pulses recorded in field environments exhibit peak pressures on the order 0.1 to 0.2 Pa (74 – 80 dB peak SPL) at 400 meters, the approximate minimum setback allowed by any known noise guideline for wind farms. Review of recent field measurements taken at 1,100 meters from a small array of industrial turbines under very steady conditions show peak infrasound amplitudes of approximately 0.04 Pa (66 dB peak SPL) and evidence of blade-pass frequency periodic short bursts of tonal energy just above normal threshold in the frequency range 25 - 53 Hz. Syntheses of infrasound pulses accompanied by these tone bursts produce adverse subjective reaction with or without the infrasound pulses present and no reaction if the tone burst peak pressure is below threshold. The work described here tests the response of two test subjects to synthesized test signals of five-minutes duration. It is possible that longer term exposure could result in some test subjects becoming either more sensitized or acclimated to the noise, resulting in different responses to those described in this paper.

## 1 Introduction

The history of research into human response to low frequency noise and infrasound is long and rich as shown by Leventhall (2009). Nevertheless, the significance of wind farm infrasound is still the subject of considerable controversy. It is widely recognized that the infrasound levels at a typical residential distance from a wind farm do not exceed the audibility threshold for a person with normal hearing.

Early infrasound research regarding sonic booms by Niedzwiecki and Ribner (1978) concluded that increasing the proportion of infrasound in a noise spectrum has no significant influence on the subjective loudness. On the other hand, the results of a listening study carried out by Huang *et al*. (2008) indicated that for an equivalent A-weighted noise level, test samples containing more low frequency components were found to be more annoying. Furthermore, Waye and Ohrström (2002) conducted listening tests using recorded noise from 5 wind farms, adjusted so they had the same values of $L_{Aeq}$. The outcome showed different ratings of annoyance for an equivalent A-weighted sound pressure level but with a different spectral content. In another research study, listening tests were conducted to assess the annoyance of low frequency wind turbine noise (Von Hunerbein *et al*., 2010). Their study used an idealized low-frequency wind turbine noise source containing broadband noise with a specific tone at a single frequency between 32 Hz and 400 Hz. It was concluded that low frequency tones with the same level above the masking noise level as high frequency tones, cause negligible increase in annoyance (Von Hunerbein *et al*., 2010). Therefore, it can be seen that there are conflicting views on the relationship between annoyance and low frequency noise and infrasound, which is the reason for undertaking the experimental work described in this paper.

Other studies have investigated the effect of amplitude modulation on the perceived annoyance. According to listening tests conducted by Lee *et al*. (2010), amplitude modulation of wind turbine noise significantly contributes to noise annoyance. An auditory experiment was also carried out by Yokoyama *et al*. (2013) using recordings of wind turbine noise, in order to examine the effect of amplitude modulation on fluctuation sensation. It was found that the perception of amplitude modulation only occurs at frequencies above 125 Hz (Yokoyama *et al*., 2013). However, the authors only considered amplitude modulation of the entire spectrum with different low-pass filters and did not investigate the effects of amplitude modulation of discrete frequencies, which could be more annoying. In fact, previous research in general has not considered the relationship between amplitude modulated low-frequency tonal noise and annoyance. Also, the effect of tonal infrasound components on the perception of amplitude modulation has not been investigated.

It has been hypothesized by Salt and Hullar (2010) and Kugler et al. (2014) that the ear can respond to much lower levels of infrasound than are required for audibility. The low levels trigger a response in the outer hair cells and thus cause a psychological response (Salt and Hullar, 2010). The possible effect of inner ear excitation on perceived annoyance has not been tested so far.

In multiple informal evaluations of infrasound alone conducted by Walker between 2012 and 2014, periodic signals with fundamental frequency 0.8 Hz and an upper harmonic frequency of 32 Hz or below were perceived by two out of approximately 25 persons who were presented with the signal in three different environments, if the peak pulse amplitude exceeded approximately 0.5 Pa. On the other hand, most evaluators were unaffected at peak pulse amplitudes of 1.5 Pa, the approximate linearity limit of the audio reproduction system.

The aim of this work is therefore to examine the effect of infrasound tonal components on perceived low frequency noise annoyance for short exposure durations. The investigated spectra are synthesized based on measured wind turbine noise, which consists of amplitude modulated tonal components. It is important to understand the effects of infrasound and low frequency noise, since the predicted future increase in wind turbine size will most likely give rise to an increase in noise levels in this frequency range (Møller & Pedersen, 2011).

## 2 Development of a synthesized signal

For the purpose of the listening tests, a synthesized signal was developed based on data measured outside a residence located 1.3 km from the Waterloo wind farm in South Australia. Details of the field measurements are outlined in Hansen *et al*. (2014). Indoor spectral results were considered; however it was observed that upper harmonics were subject to room mode effects and hence the outdoor results were considered to be more representative of the actual wind turbine noise signal. A synthesized signal was used in place of the original signal to allow greater control over the adjustment of various signal attributes. In this way, various components of the signal could be isolated to gauge their relative importance in subjective reaction to the overall signal.

### 2.1 Characteristics of measured wind farm noise

Previous measurements carried out in the vicinity of the Shirley wind farm (Walker *et al*., 2012) have shown that wind farm noise is characterized by discrete peaks at the blade passage frequency (BPF) and harmonics that generally extend to approximately 8-10 Hz. These peaks are followed by broadband noise, often with “haystacks” of acoustic energy in the 20-60 Hz range as indicated in Figure 1. It was originally presumed that the haystacks were broadband noise resulting from blade interaction with incoming medium-scale turbulence. However, data collected in the vicinity of the Waterloo wind farm demonstrates that under conditions that allow very steady turbine operation, these “haystacks” resolve into a series of spectral lines with spacing equal to the BPF. In the case of the Waterloo data, there appear to be three such stacks, centered at approximately 28, 43 and 49 Hz as shown in Figure 2.

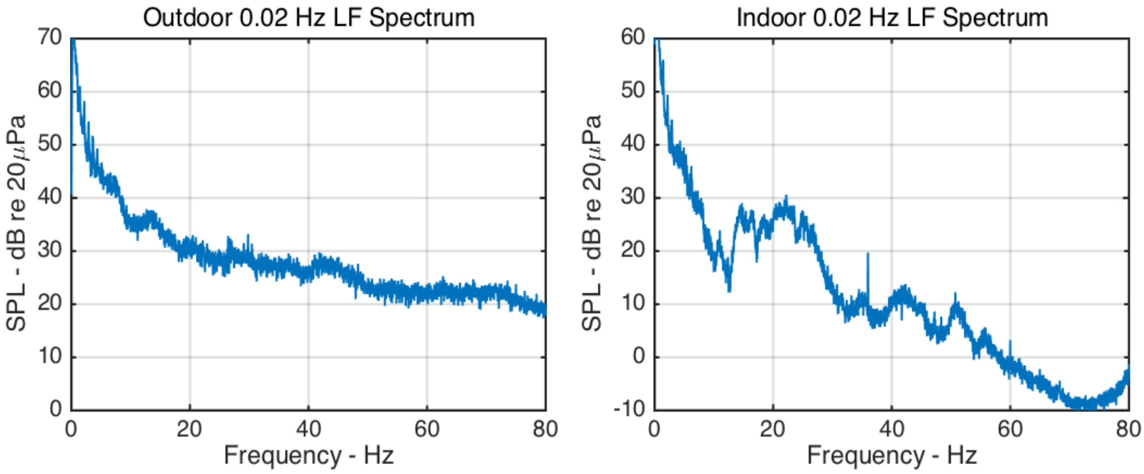


**Figure 1 – Spectra measured in the vicinity of the Shirley wind farm 400 meters from nearest turbine. Resolution is 0.02 Hz.**

By careful analysis of each spectral line and its neighbors, the mean BPF for this measurement was determined to be 0.8033 Hz. The spectra were re-plotted vs. BPF order in Figure 3a-c. It is seen in the expanded spectra that while the spectral peaks up to 16BPF and above 50BPF are closely centered on the actual harmonic number, most of the peaks between 28 BPF and 42 BPF are about 0.15 BPF lower in frequency and therefore BPF-spaced sidebands of some other process. The set of spectral peaks in Figure 3b also shows generally minor peaks that are not BPF harmonics but BPF-spaced sidebands. The presence of sidebands spaced at the BPF suggests that noise at the center frequencies is amplitude modulated at the BPF. Hence, the broadband nature of the low frequency “haystacks” measured near the Shirley wind farm is attributed to changes in the BPF with time caused by variations in the wind turbine operating speed.

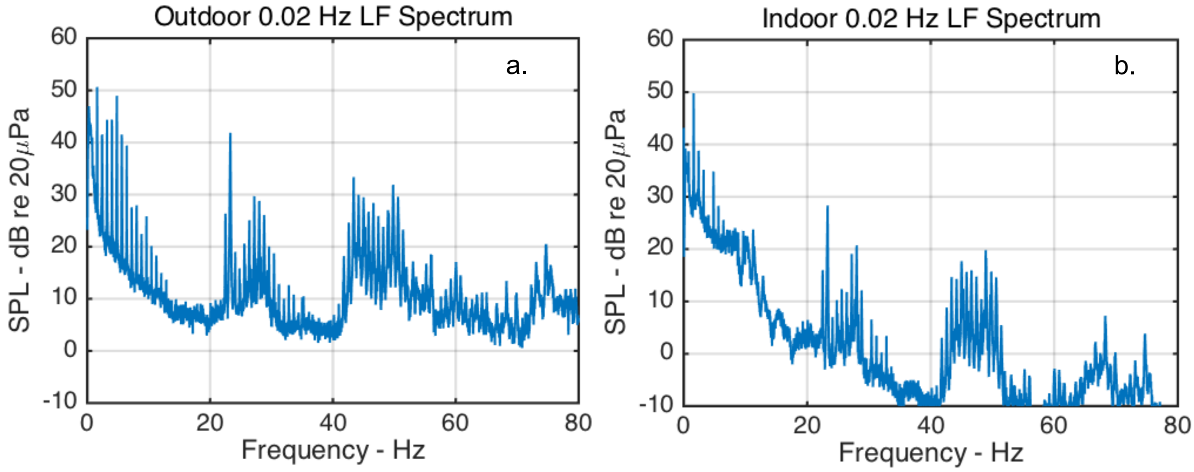


**Figure 2 – Outdoor and indoor spectra measured at a residence located 1300 m from the nearest wind turbine. Resolution is 0.02 Hz.**

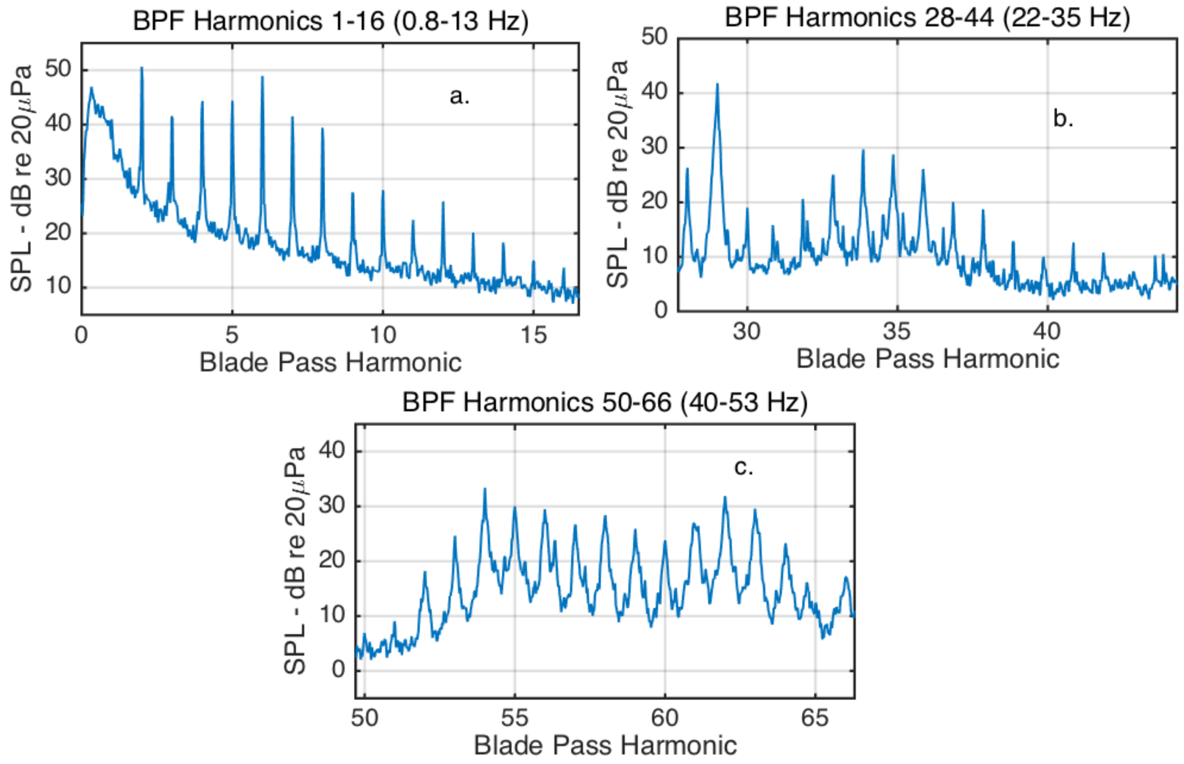


**Figure 3 – Expanded BPF order spectra.**

## 2.2 Waveform analysis

The test data from which the spectrum of Figure 2 was computed is 10 minutes in length, comprising just over 160 rotor revolutions. Ensemble average waveforms were computed in two ways. First, the data were divided into blocks of data of length 38,242 samples. This is the number of samples for one rotor revolution based on the mean blade passage period of 0.8033 Hz and data sampling rate of 10,240 Hz. The resulting blocks of data were averaged to preserve periodic components and suppress spurious noise and atmospheric pressure fluctuations. The result of the ensemble averaging for outdoor test channel 1 and its shaft-order spectrum are shown in Figure 4. This approach matched the infrasound portion of the measured spectrum within about 1 dB but falls significantly short in the upper frequencies, as minor fluctuations in rotor speed and quantization error in the selection of block length affect the higher harmonics disproportionately. The complexity of the mean wave-shape indicates contributions from two or three turbines, which is consistent with the 7-turbine array that forms a row located 1370-3150 meters south of the measurement location.

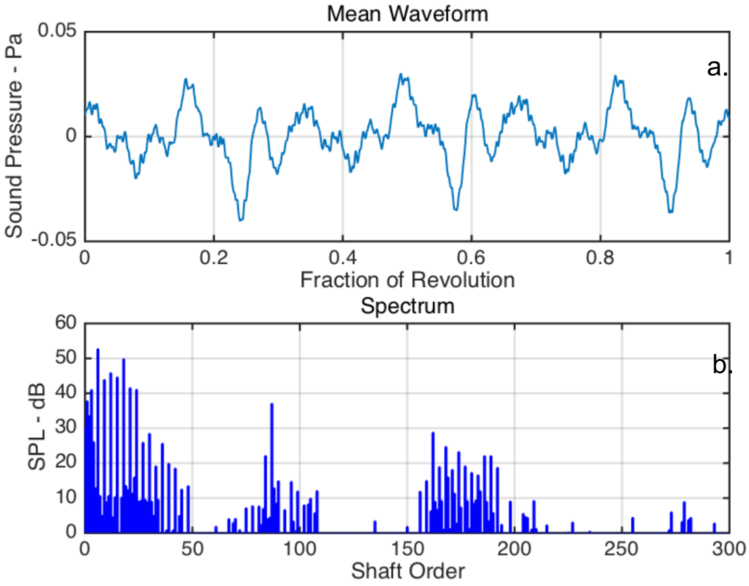


**Figure 4 - Mean Outdoor Waveform Computed from Data Blocks of Length = Sample Rate divided by Mean BPF (0.80331 Hz).**

The second approach assumes the strong peak near 23.3 Hz is a mechanical tone at the 87th shaft order, and uses that as a tachometer to track the relative rotor position and resample the data at a constant 40,000 samples per revolution. The ensemble average and its shaft-order spectrum from this approach are shown in Figure 5. This recovers the level of the 87th shaft order but appears to reduce the level of many of the other measured peaks, suggesting that the 23.3 Hz tone may be a mechanical tone from one of the less dominant turbines in the row.

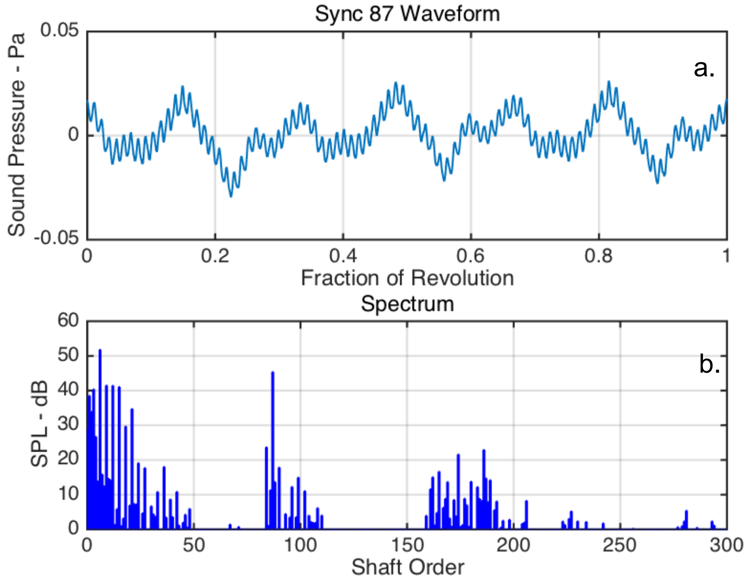


**Figure 5 - Mean Outdoor Waveform from 23 Hz synchronization.**

### 2.3 Modulation analysis

Review of the spectra indicates the possibility of amplitude modulation which results in BPF-spaced sidebands on either side of dominant tones. Two different characters of modulation are indicated. First, at approximately 23.3 Hz, (blade-order 29, shaft-order 87), the indication is of a single tone flanked by relatively weak (-15 and -20 dB) side bands. A modelled example of this is shown in Figure 6. A possible source for this modulated tone could be quasi-sinusoidal gearbox stresses resulting from rotor torque fluctuations in atmospheric wind shear conditions.

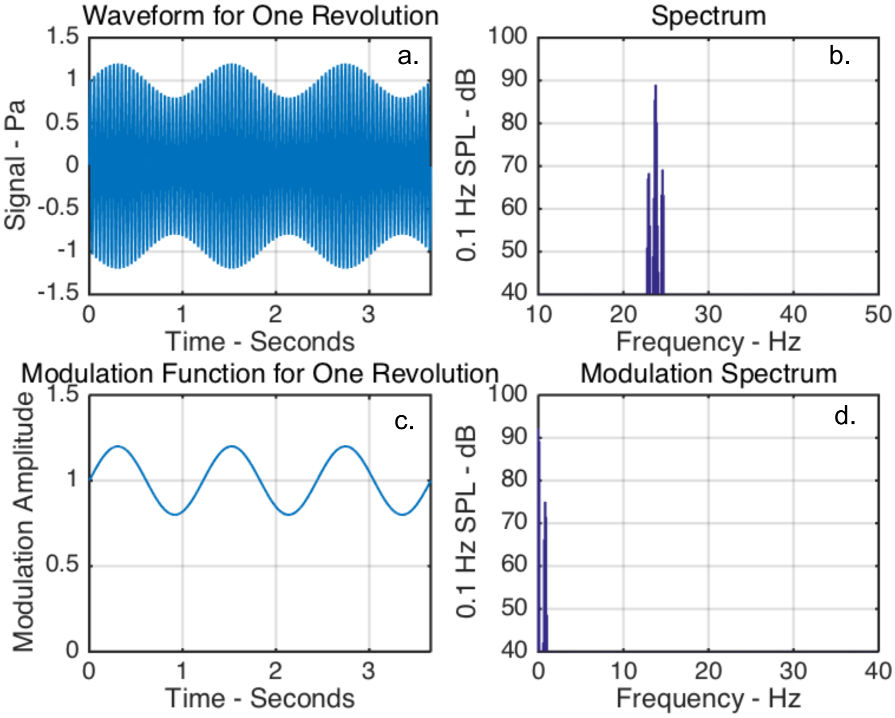


**Figure 6 - Wave and spectrum of 23 Hz tone amplitude modulated by 0.8 Hz.**

The second type of modulation spectrum consists of a “mound” of spectral lines, of which three appear to be present in the data. One possible explanation for the generation of these “mounds” is short duration gating (with a modulating function to modify the amplitude of each sample) of a tone, or BPF harmonic (as in the case of the “mound” between 25 and 34 Hz), not directly related to the BPF. Gating implies that the tone is sampled for a number of short durations during a revolution of the turbine. In practice, this means that the tone only exists for these short durations and during each gating period, the tone has a loudness that gradually increases and then decreases. For a 3-bladed turbine, the number of time periods for which the tone exists is three per revolution (as shown in Figure 7a) and each would correspond to the blade passing the tower. This mechanism can be simulated by sampling a continuous tone using the modulating function illustrated in Figure 7c. The results so obtained are shown in Figure 7, indicating that such modulation does produce a “mound” of spectral lines.

For comparison with the measurement data, Figure 8 shows the modulation spectrum of Channel 1 for a frequency band limited to 40-53 Hz. Although not identical to the modulating spectrum in Figure 7d, the similarity is remarkably clear considering the potential contamination by multiple turbines and propagation distance of over 1 km. For interest, modulation spectrograms were computed for several 1/3-octave bands, with examples in the frequency range of interest shown in Figure 9. Figure 10 illustrates the effect of gating three tones simultaneously.

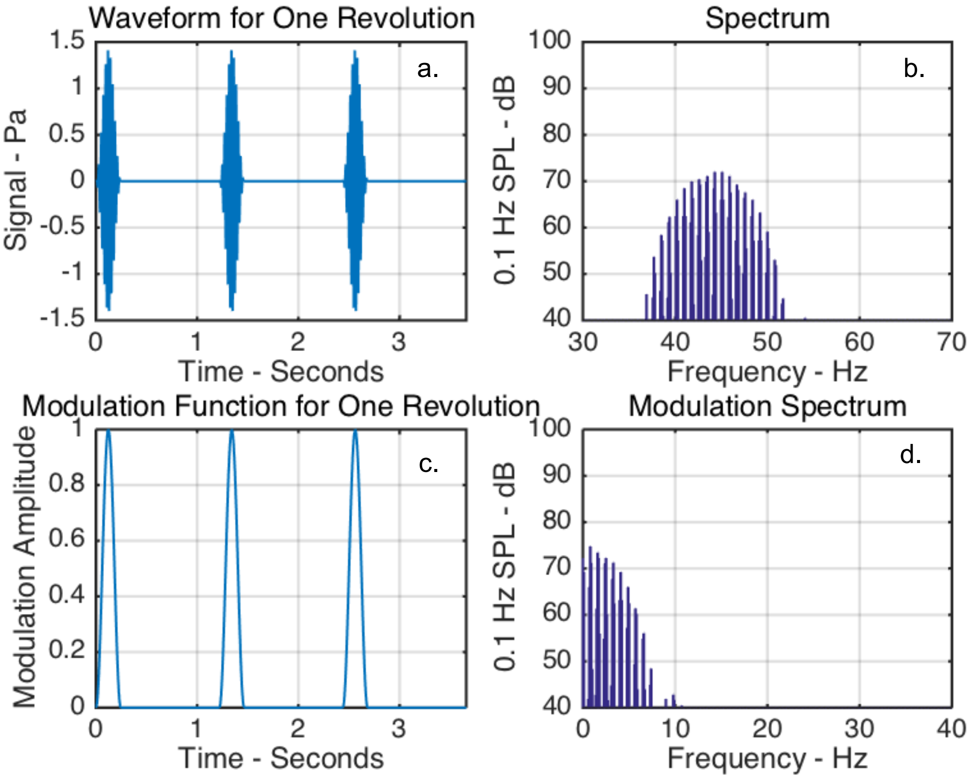


**Figure 7 - Wave and spectrum of 45 Hz tone gated by 0.2 second Hanning windows at 0.8 Hz.**

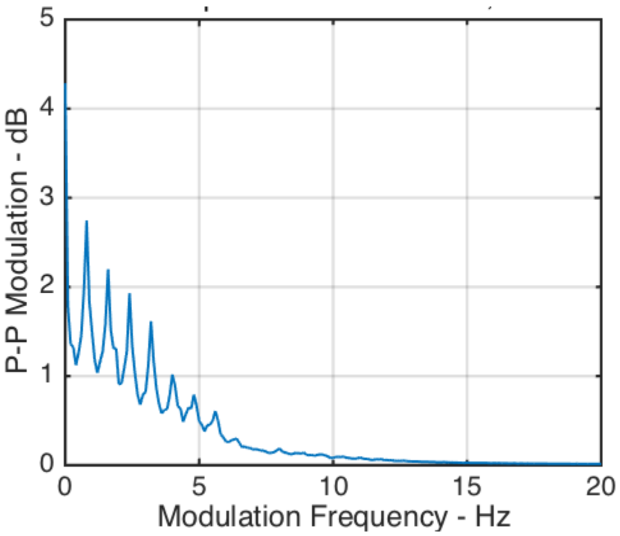


**Figure 8 - Modulation spectrum of 40 - 53 Hz frequency band from Channel 1.**

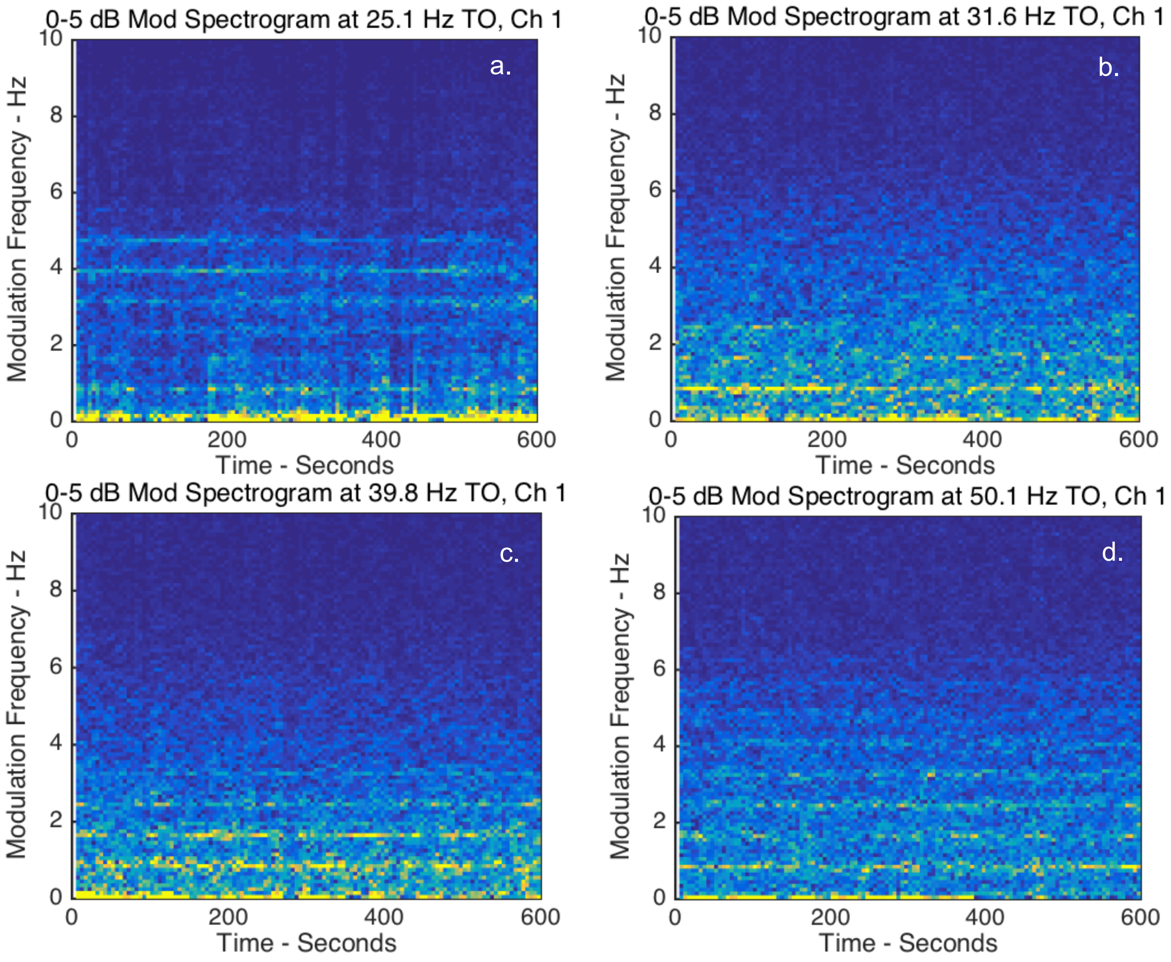


**Figure 9 - Modulation spectrograms for 25 Hz to 50 Hz 1/3-octaves from Channel 1.**

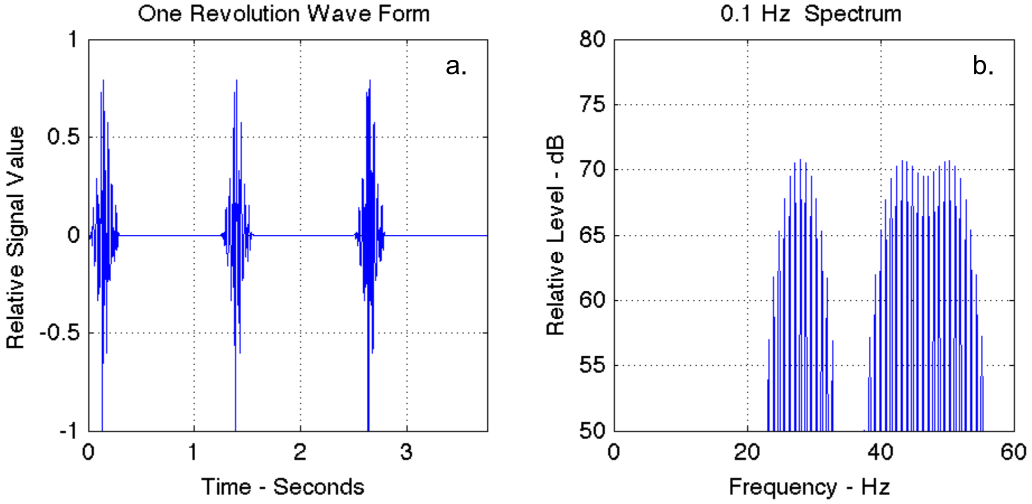


**Figure 10 - Waveform and spectrum for 28, 43 and 50 Hz tones gated simultaneously.**

## 2.4 Signal synthesis

Fourier synthesis can be used to combine the turbine-related elements for subjective evaluation if it is assumed that the signal is periodic at a reasonable repetition period and if the relative phases of all the harmonics are known. Strictly speaking, the frequency shift, away from the exact harmonic frequencies, of spectral peaks in the

25-34 Hz range would make Fourier synthesis difficult, and for purposes of this work, the spectral peaks were forced to the nearest integer BPF harmonic.

To obtain a “best estimate” of phase relationships, measurement signals were filtered in frequency bands encompassing the major “haystack” ranges and then plotted in 100 ms $L_{eq}$ and $L_{max}$ blocks as shown in Figure 11. Periodic peaks with spacing of approximately 1.25 seconds can be seen in Figure 11a and b, and the difference between $L_{max}$ and $L_{eq}$ of the filtered signals is seen to be 10 dB or more. Based on these observations and the results of numerous time-domain analyses of turbine infrasound measurements, synthesized harmonics were taken as sine waves, all with zero phase at time zero, although this phasing does not maximize the signal crest factor (that would require all cosine waves or sine waves with phase 90 degrees at time zero).

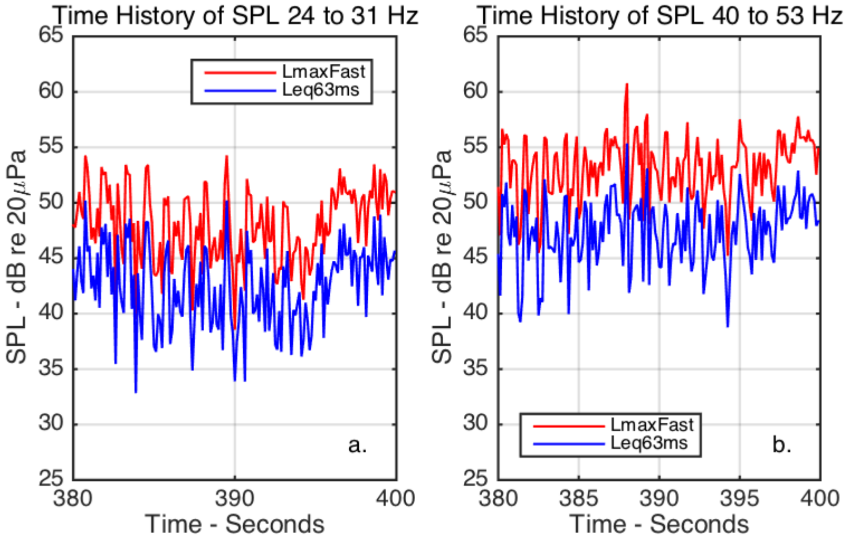


**Figure 11 - Portion of time history of filtered signal from outdoor measurement**

A comparison between harmonic sine waves with zero phase at time zero and sine waves with random phases is shown in Figure 12. It was suspected, and has subsequently been confirmed, that at sound pressure levels near threshold, the peaks in the phase-aligned signal (Figure 12a and b) would give the subjective impression of a sequence of “thumps” while the un-aligned signal (Figure 12c and d) would be inaudible.

In a paper by Palmer (2014), evidence was presented that persons affected by turbine “infrasound” reported that room position had an important effect on severity. At true infrasonic frequencies, the sound pressure is nearly uniform in an enclosed space. This further suggests that exposure to near-threshold periodic bursts of low frequency sound, rather than deeply subliminal levels of infrasound, could be the true perception or annoyance triggers.

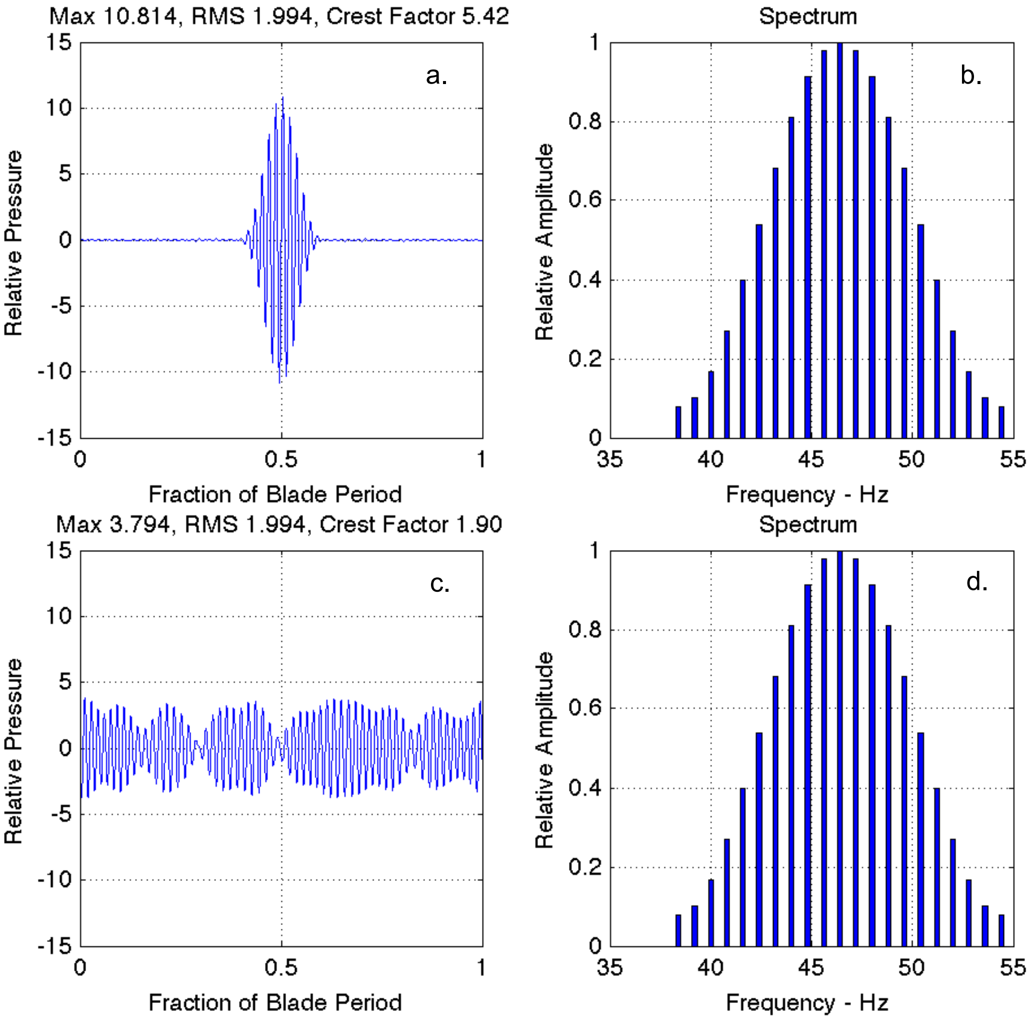


**Figure 12 - Effect of phase alignment on signals with equal spectra and SPL.**

## 2.5 Synthesized Signal Testing

In an approximately 4.4 × 3.8 × 2.7 m residential room, a loudspeaker capable of producing 75 dB or greater sound pressure level from 0.8 to 60 Hz was set in one corner and a sofa-bed was set along an adjacent wall as shown in the schematic plan of Figure 13. The evaluator’s head position was just over 2.5 meters from the center of the loudspeaker, 1.2 meters above the floor. For evaluation relative to the Waterloo data, the full spectrum from 0.8 to 53 Hz (66 harmonics) was synthesized and monitored with a low frequency microphone immediately above the evaluator’s head. System response was equalized so that room effects and loudspeaker response were neutralized as described in Walker and Celano (2015).

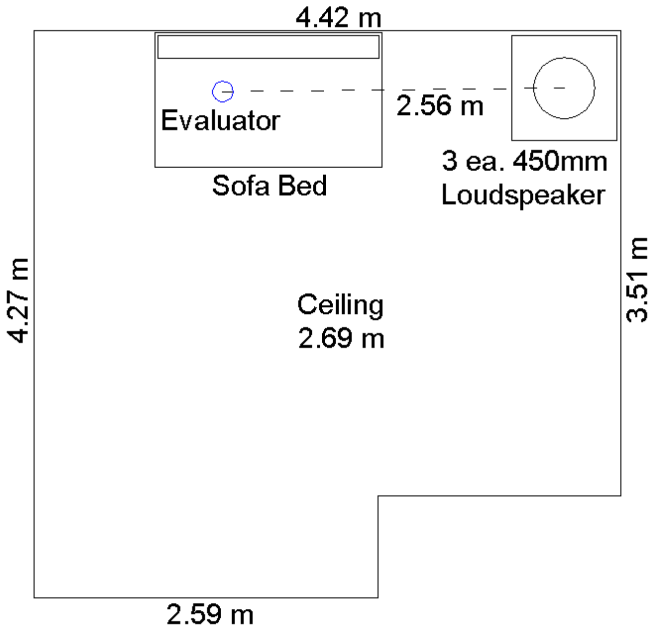


**Figure 13 – Schematic of test room showing source and evaluator positions.**

The synthesis system is equipped with a 5 dB per step attenuator to allow "bracketing" of hearing or other sensitivity thresholds. The test spectrum, as shown in Figure 14a, is equivalent to that shown in Figure 2a, with the exception that upper harmonics are stabilized so that all energy is exactly at the harmonic frequency instead of spreading with slight variations in turbine speed, and the lowest BPF harmonics are adjusted upward by approximately 5 dB to allow for possible multi-turbine interference effects. These effects could, at times of particular synchronicity of the turbines, increase low frequency levels above those captured in the measurements. The pulse waveform associated with the spectrum is shown in Figure 14b. The isolated spectrum line at 23 Hz shows as a quasi-steady oscillation and the "haystack" spectra appear as a burst of 40-50 Hz energy aligned with the pulse produced by the summation of the lowest harmonics (below 20 Hz).

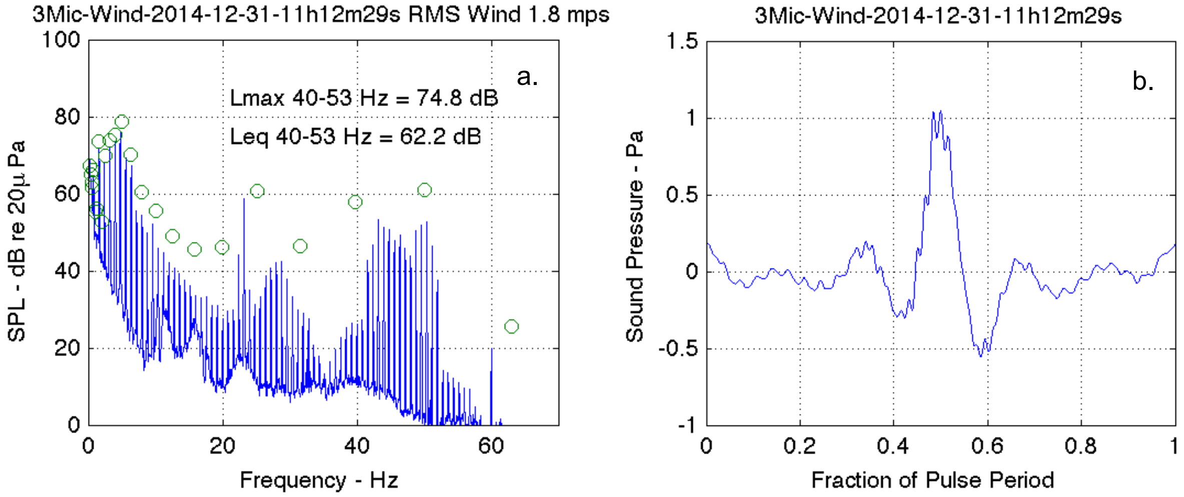


**Figure 14 – a. Synthesized and monitored Waterloo-based all-pass spectrum and b. Pulse waveform from Waterloo all-pass spectrum.**

The evaluators consisted of test person (D) who has normal hearing and an extreme propensity to sea-sickness and test person (J) who has very acute hearing, particularly at low frequencies. In early tests at high amplitude (1.5 Pa peak) with strong harmonics up to 32 Hz, he was made ill and took a while to recover. However, in a subsequent test (months later), synthesized blade “whoosh” with no infrasound started making him queasy. The two evaluators participated as a matter of availability and interest in the overall synthesis project.  Their low frequency hearing and sea-sickness propensities were incidental but judged to be relevant to their evaluations.

Evaluators were presented with the all-pass spectrum (containing energy from 0.8 Hz to 60 Hz) for periods of 5 minutes at each incremental amplitude and they were required to determine which two settings of the 5 dB attenuator bracketed their sensation threshold. The procedure was repeated with three modifications to the spectrum as shown in Figure 15:

- H:  20 Hz high-pass
- K:  30 Hz high-pass
- L:  20 Hz low-pass

All tests were blind in that the evaluators were not aware of which spectrum they were being presented with and the signals were selected randomly.

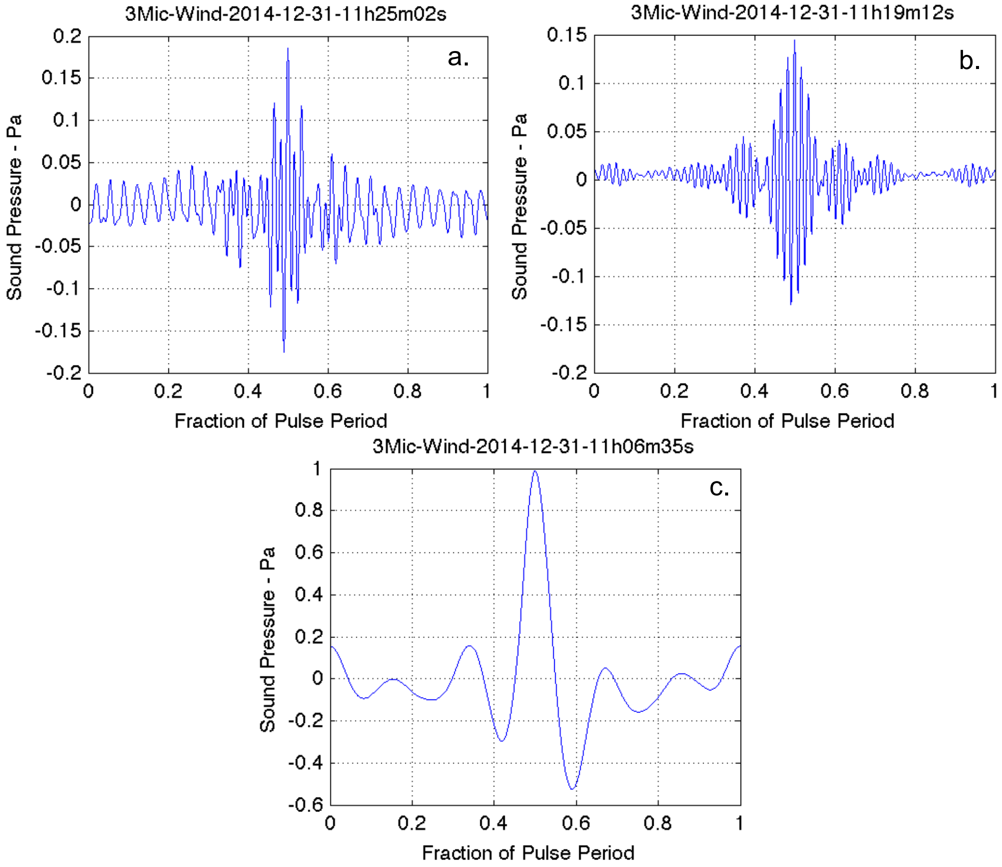


**Figure 15 - Pulse wave forms of filtered signals, a-c: high pass at 20 Hz, high pass at 30 Hz and low-pass at 20 Hz.**

## 3 Results

Results are presented in Table 1 which indicate the opinions of two test subjects on the various noises to which they were subjected. The subjects were asked whether the noise was annoying, and if so, how annoying. They were also asked to comment on the character (rough, smooth, raspy) of the noise and whether it would cause them difficulty in going to sleep. The level of the noise that was presented to the evaluators has been expressed relative to the measured outdoor level in Table 1.

The following analysis discusses the various signal characteristics that resulted in the evaluators reporting “no sensation”, “slight audibility”, “audibility”, “annoyance” and “high annoyance.” In some cases, comments from the two evaluators were expressed differently but appeared to reflect the same perception and therefore some interpretation has been necessary. One of the evaluators provided some insight into the character of the noise and this will also be discussed. Table 1 provides a summary of the evaluators’ comments which are presented in their original format.

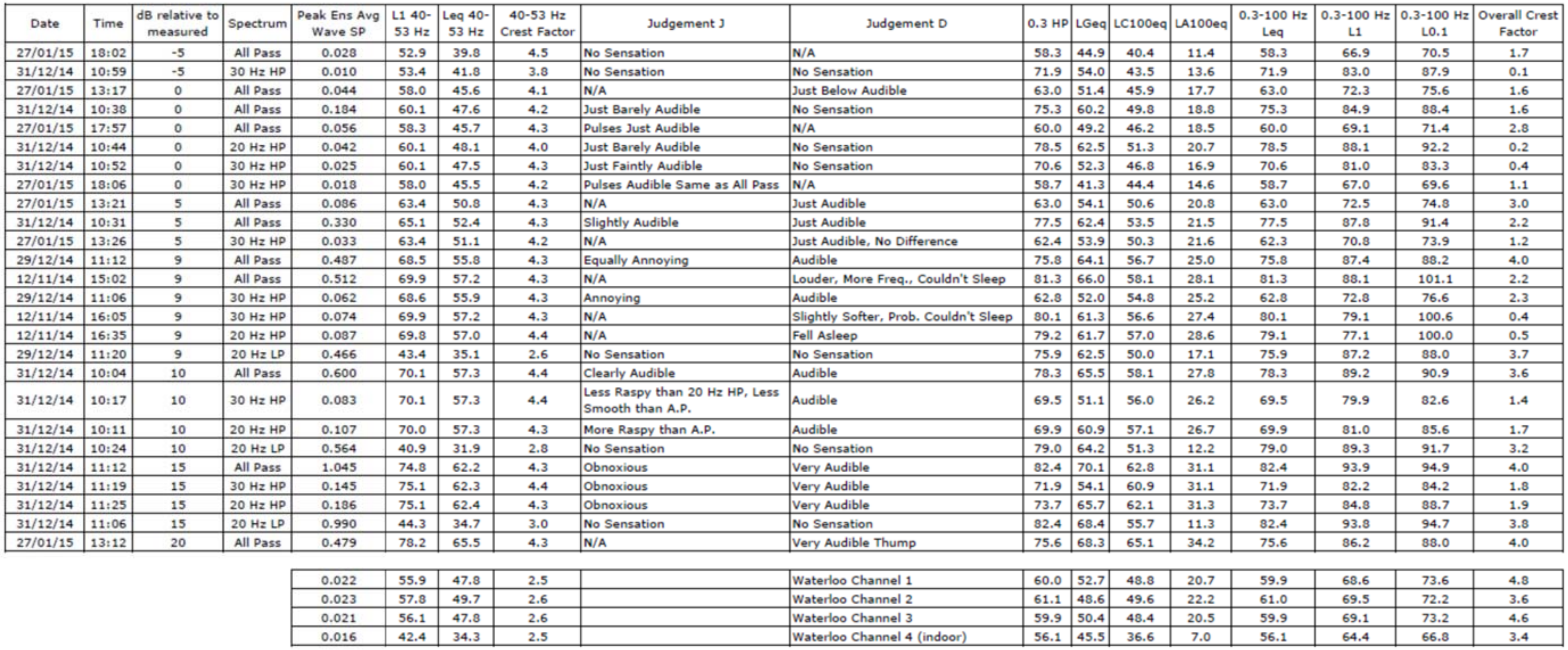
The perception of “no sensation” was expressed when the all-pass filter (0.8 Hz – 53 Hz harmonics summed) was used and the signal amplitude was 5 dB lower than the measured outdoor signal at a residence 1.3 km from the Waterloo wind farm. Not surprisingly, applying a 30 Hz low-pass filter to this signal produced the same result of “no sensation”.

Increasing the signal amplitude to the range encompassing the outdoor measurements resulted in the all-pass signal having “slight audibility” for evaluator “J”, known to have acute hearing, and apparently “no sensation” for evaluator “D”. Applying the 20 Hz and 30 Hz high-pass filters to the signal produced a similar result. It should be noted that the crest factor and $L_{Aeq}$ (low-pass at 100 Hz) of the signal were lower than the measured value outdoors.

The all-pass signal had “slight audibility” for evaluator “D” when the amplitude was increased by 5dB relative to the measured outdoor signal. At this level, evaluator “J” expressed a similar opinion, although differences in wording make comparison difficult. It is also worth noting that evaluator “D” commented that she would be able to sleep if the signal were at this level. At this level, the $L_{Aeq}$ (low-pass at 100 Hz) was in the same range and the crest factor was lower than the measured value. Evaluator “D” found no difference in the signal audibility when the 30 Hz all-pass filter was applied.

A further increase in the signal amplitude by 9 dB relative to the outdoor measured level resulted in “audibility” of the all-pass signal for evaluator “D” and “annoyance” for evaluator “J.” The crest factor was in the same range as the measured signal outdoors for one of the tests and was about half this value for the other but since the latter signal was louder, it was found to be more intrusive to evaluator “D.” This evaluator observed that she couldn’t sleep in the presence of such a noise. With the 30 Hz high-pass filter, this signal was perceived as “slightly softer” but the evaluator commented that she would still not be able to sleep. Despite this assertion, evaluator “D” actually fell asleep when a 20 Hz high-pass filter was applied to the signal, which was in apparent contradiction with her previous comments.

## Table 1 – Signal characteristics of test spectra as well as evaluator comments



| Date | Time | dB relative to measured | Spectrum | Peak Ens Avg Wave SP | L1 40-53 Hz | Leq 40-53 Hz | 40-53 Hz Crest Factor | Judgement J | Judgement D | 0.3 HP | LGeq | LC100eq | LA100eq | 0.3-100 Hz Leq | 0.3-100 Hz L1 | 0.3-100 Hz L0.1 | Overall Crest Factor |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 27/01/15 | 18:02 | -5 | All Pass | 0.028 | 52.9 | 39.8 | 4.5 | No Sensation | N/A | 58.3 | 44.9 | 40.4 | 11.4 | 58.3 | 66.9 | 70.5 | 1.7 |
| 31/12/14 | 10:59 | -5 | 30 Hz HP | 0.010 | 53.4 | 41.8 | 3.8 | No Sensation | No Sensation | 71.9 | 54.0 | 43.5 | 13.6 | 71.9 | 83.0 | 87.9 | 0.1 |
| 27/01/15 | 13:17 | 0 | All Pass | 0.044 | 58.0 | 45.6 | 4.1 | N/A | Just Below Audible | 63.0 | 51.4 | 45.9 | 17.7 | 63.0 | 72.3 | 75.6 | 1.6 |
| 31/12/14 | 10:38 | 0 | All Pass | 0.184 | 60.1 | 47.6 | 4.2 | Just Barely Audible | No Sensation | 75.3 | 60.2 | 49.8 | 18.8 | 75.3 | 84.9 | 88.4 | 1.6 |
| 27/01/15 | 17:57 | 0 | All Pass | 0.056 | 58.3 | 45.7 | 4.3 | Pulses Just Audible | N/A | 60.0 | 49.2 | 46.2 | 18.5 | 60.0 | 69.1 | 71.4 | 2.8 |
| 31/12/14 | 10:44 | 0 | 20 Hz HP | 0.042 | 60.1 | 48.1 | 4.0 | Just Barely Audible | No Sensation | 78.5 | 62.5 | 51.3 | 20.7 | 78.5 | 88.1 | 92.2 | 0.2 |
| 31/12/14 | 10:52 | 0 | 30 Hz HP | 0.025 | 60.1 | 47.5 | 4.3 | Just Faintly Audible | No Sensation | 70.6 | 52.3 | 46.8 | 16.9 | 70.6 | 81.0 | 83.3 | 0.4 |
| 27/01/15 | 18:06 | 0 | 30 Hz HP | 0.018 | 58.0 | 45.5 | 4.2 | Pulses Audible Same as All Pass | N/A | 58.7 | 41.3 | 44.4 | 14.6 | 58.7 | 67.0 | 69.6 | 1.1 |
| 27/01/15 | 13:21 | 5 | All Pass | 0.086 | 63.4 | 50.8 | 4.3 | N/A | Just Audible | 63.0 | 54.1 | 50.6 | 20.8 | 63.0 | 72.5 | 74.8 | 3.0 |
| 31/12/14 | 10:31 | 5 | All Pass | 0.330 | 65.1 | 52.4 | 4.3 | Slightly Audible | Just Audible | 77.5 | 62.4 | 53.5 | 21.5 | 77.5 | 87.8 | 91.4 | 2.2 |
| 27/01/15 | 13:26 | 5 | 30 Hz HP | 0.033 | 63.4 | 51.1 | 4.2 | N/A | Just Audible, No Difference | 62.4 | 53.9 | 50.3 | 21.6 | 62.3 | 70.8 | 73.9 | 1.2 |
| 29/12/14 | 11:12 | 9 | All Pass | 0.487 | 68.5 | 55.8 | 4.3 | Equally Annoying | Audible | 75.8 | 64.1 | 56.7 | 25.0 | 75.8 | 87.4 | 88.2 | 4.0 |
| 12/11/14 | 15:02 | 9 | All Pass | 0.512 | 69.9 | 57.2 | 4.3 | N/A | Louder, More Freq., Couldn't Sleep | 81.3 | 66.0 | 58.1 | 28.1 | 81.3 | 88.1 | 101.1 | 2.2 |
| 29/12/14 | 11:06 | 9 | 30 Hz HP | 0.062 | 68.6 | 55.9 | 4.3 | Annoying | Audible | 62.8 | 52.0 | 54.8 | 25.2 | 62.8 | 72.8 | 76.6 | 2.3 |
| 12/11/14 | 16:05 | 9 | 30 Hz HP | 0.074 | 69.9 | 57.2 | 4.3 | N/A | Slightly Softer, Prob. Couldn't Sleep | 80.1 | 61.3 | 56.6 | 27.4 | 80.1 | 79.1 | 100.6 | 0.4 |
| 12/11/14 | 16:35 | 9 | 20 Hz HP | 0.087 | 69.8 | 57.0 | 4.4 | N/A | Fell Asleep | 79.2 | 61.7 | 57.0 | 28.6 | 79.1 | 77.1 | 100.0 | 0.5 |
| 29/12/14 | 11:20 | 9 | 20 Hz LP | 0.466 | 43.4 | 35.1 | 2.6 | No Sensation | No Sensation | 75.9 | 62.5 | 50.0 | 17.1 | 75.9 | 87.2 | 88.0 | 3.7 |
| 31/12/14 | 10:04 | 10 | All Pass | 0.600 | 70.1 | 57.3 | 4.4 | Clearly Audible | Audible | 78.3 | 65.5 | 58.1 | 27.8 | 78.3 | 89.2 | 90.9 | 3.6 |
| 31/12/14 | 10:17 | 10 | 30 Hz HP | 0.083 | 70.1 | 57.3 | 4.4 | Less Raspy than 20 Hz HP, Less Smooth than A.P. | Audible | 69.5 | 51.1 | 56.0 | 26.2 | 69.5 | 79.9 | 82.6 | 1.4 |
| 31/12/14 | 10:11 | 10 | 20 Hz HP | 0.107 | 70.0 | 57.3 | 4.3 | More Raspy than A.P. | Audible | 69.9 | 60.9 | 57.1 | 26.7 | 69.9 | 81.0 | 85.6 | 1.7 |
| 31/12/14 | 10:24 | 10 | 20 Hz LP | 0.564 | 40.9 | 31.9 | 2.8 | No Sensation | No Sensation | 79.0 | 64.2 | 51.3 | 12.2 | 79.0 | 89.3 | 91.7 | 3.2 |
| 31/12/14 | 11:12 | 15 | All Pass | 1.045 | 74.8 | 62.2 | 4.3 | Obnoxious | Very Audible | 82.4 | 70.1 | 62.8 | 31.1 | 82.4 | 93.9 | 94.9 | 4.0 |
| 31/12/14 | 11:19 | 15 | 30 Hz HP | 0.145 | 75.1 | 62.3 | 4.4 | Obnoxious | Very Audible | 71.9 | 54.1 | 60.9 | 31.1 | 71.9 | 82.2 | 84.2 | 1.8 |
| 31/12/14 | 11:25 | 15 | 20 Hz HP | 0.186 | 75.1 | 62.4 | 4.3 | Obnoxious | Very Audible | 73.7 | 65.7 | 62.1 | 31.3 | 73.7 | 84.8 | 88.7 | 1.9 |
| 31/12/14 | 11:06 | 15 | 20 Hz LP | 0.990 | 44.3 | 34.7 | 3.0 | No Sensation | No Sensation | 82.4 | 68.4 | 55.7 | 11.3 | 82.4 | 93.8 | 94.7 | 3.8 |
| 27/01/15 | 13:12 | 20 | All Pass | 0.479 | 78.2 | 65.5 | 4.3 | N/A | Very Audible Thump | 75.6 | 68.3 | 65.1 | 34.2 | 75.6 | 86.2 | 88.0 | 4.0 |
|  |  |  |  | 0.022 | 55.9 | 47.8 | 2.5 |  | Waterloo Channel 1 | 60.0 | 52.7 | 48.8 | 20.7 | 59.9 | 68.6 | 73.6 | 4.8 |
|  |  |  |  | 0.023 | 57.8 | 49.7 | 2.6 |  | Waterloo Channel 2 | 61.1 | 48.6 | 49.6 | 22.2 | 61.0 | 69.5 | 72.2 | 3.6 |
|  |  |  |  | 0.021 | 56.1 | 47.8 | 2.6 |  | Waterloo Channel 3 | 59.9 | 50.4 | 48.4 | 20.5 | 59.9 | 69.1 | 73.2 | 4.6 |
|  |  |  |  | 0.016 | 42.4 | 34.3 | 2.5 |  | Waterloo Channel 4 (indoor) | 56.1 | 45.5 | 36.6 | 7.0 | 56.1 | 64.4 | 66.8 | 3.4 |

There was little variation in the results when the amplitude of the signal was increased by 10 dB relative to the outdoor measured level. On the other hand, evaluator “J” commented on some aspects of the noise character which varied depending on the filter type applied to the signal. When a 30 Hz high-pass filter was applied, the signal became more “raspy” or less “smooth.” The signal was even more “raspy” with a 20 Hz high-pass filter.

Both evaluators reported that they experienced “no sensation” when they were presented with signals that had been low-pass filtered at 20 Hz at an amplitude of 9 dB above the measured outdoor level. This result did not change as the amplitude was increased by 10 dB and 15 dB. The low frequency content of the corresponding three cases was higher than the measured outdoor signal as shown by the higher relative values of $L_{Geq}$ and $L_{Ceq}$. On the other hand, the overall crest factor of the signal was slightly lower for these cases.

For a signal amplitude corresponding to 15 dB above the measured outdoor noise level, evaluator “J” expressed “high annoyance,” referring to the signal as “obnoxious.” Evaluator “D” found the signal “very audible.” The same judgements were passed when the signal was high-pass filtered at both 20 Hz and 30 Hz. It is interesting to note that the $L_{Aeq}$ (low-pass at 100 Hz) was only slightly greater than 30 dB(A). According to the World Health Organisation night time guidelines (WHO, 2009), there should be no effects on sleep at levels of 30 dB(A) and below, which would not be expected for a “very audible” or “obnoxious” signal. This indicates that in the presence of very low background noise, the loudness of a signal with strong low-frequency components is not well-described by an A-weighted value.

A very audible “thump” was produced according to evaluator “D” when the amplitude of the signal was increased to 20 dB above the outdoor measured level and the all-pass filter was applied. For this test, the $L_{Geq}$ was equal to 68.3 dB(G), which is well below the commonly stated threshold limit of 85 dB(G). This G-weighted threshold was calculated based on unweighted hearing thresholds published by Watanabe and Møller (1990). In considering the 95th percentile of people, two standard deviations should be subtracted from the mean of the original published data, giving approximately 85 dB(G). Nonetheless, it is important to note that the published hearing thresholds (Watanabe & Møller, 1990) were established based on listening tests with pure tones. Therefore the overall G-weighted threshold of audibility could be much lower for complex tones, modulated signals and signals with high crest factors. This is corroborated by the results of this study.

Another point of interest is that despite having an extreme propensity to sea sickness, evaluator “D” did not comment that she felt sick during any of the tests. On the other hand, residents living in the vicinity of wind farms have reported symptoms such as dizziness and nausea and this has been attributed to the cyclic pressure variation caused by wind farm infrasound by Dooley (2013). A possible reason for this discrepancy is that symptoms of dizziness and nausea only occur for longer-term exposures. This is consistent with the phenomena of sea sickness which can take longer than the test period of 5 minutes to manifest in nausea. Thus long-term exposure could result in different perceptions to those reported here. Nonetheless informal tests, not reported in here, indicated that running the full spectrum for periods of up to a couple of hours incidental to sleep did not result in nausea for evaluator “D.”

## 4 Conclusions

At noise levels in the range of those measured outdoors in the vicinity of a wind farm, an evaluator with acute hearing found the noise “slightly audible” whereas another evaluator reported “no sensation” when exposed to 5-minute recordings in a listening test environment. As the signal amplitude was increased, the noise became progressively more audible, eventually reaching the point where it became annoying. At this point the overall A-weighted level (low-pass filtered at 100 Hz) and the G-weighted level were within ranges that are normally considered acceptable.

Applying a high-pass filter to the signal did not affect the audibility, regardless of whether the lower limit of the filter was 20 Hz or 30 Hz. This result was consistent for all signal amplitudes that were presented to the evaluators. The implication of this finding is that the low frequency part of the spectrum between 30 Hz and 53 Hz governed the response of the evaluators. This was further confirmed by the observation that applying a 20 Hz low-pass filter resulted in “no sensation,” even at high signal amplitudes.

There was even some indication at high levels (clearly audible pulses, 0.5 to 1.5 Pa peak SPL if infrasound present), that including the infrasound made the total sound less intrusive. There are a few conjectures about why this might be. One is that the movement of the loudspeaker diaphragms required to generate the infrasound affects the radiation of the audible components. Another is that the infrasound is modulating the evaluator’s hearing sensitivity to periodically reduce sensitivity to some part of the audible signal. This is a corollary to an idea posited by Swinbanks (2012). A further possibility is that this was a coincidence. At all levels, the infrasound presented alone produced “no sensation."

Our sleep subject fell asleep while an audible example (20 Hz high-pass) was being presented. However, she claimed that at this level, the full spectrum and 30 Hz high-pass would prevent sleep. She claimed that the full spectrum 5 dB lower would allow sleep. At this level, the infrasound peak pressure was just under 0.3 Pa (84 dB), which is in the higher range of levels seen in the field. It is possible that this evaluator was more tired at some times than others and she may also have become acclimated to the noise which would lead to a difference between her estimate of its affect on sleep and its actual effect.  In a subsequent test, both all-pass and 30 Hz high pass sounds were initially judged as potentially sleep-interfering but in practice, the evaluator fell asleep within minutes of other sounds being removed while the synthesized turbine sound and/or sound plus infrasound continued.

Hence, for evaluation times of 5 minutes, it has been shown that for the persons tested, the presence of infrasound at realistic levels does not influence audibility, annoyance or ability to fall asleep.

## References

Dooley K. A. (2013). Significant infrasound levels a previously unrecognized contaminant in landmark motion sickness studies. *Journal of the Acoustical Society of America*, **134**(5):4097–4097.

Huang, Y., Di, G., Zhu, Y., Hong, Y., and Zhang, B. (2008). Pair-wise comparison experiment on subjective annoyance rating of noise samples with different frequency spectra but same A-weighted level, *Applied Acoustics*, **69**(12):1205–1211.

Kugler, K., Wiegrebe, L., Grothe, B., Kossl, M., Gurkov, R., Krause, E., and Drexl, M. (2014). Low-frequency sound affects active micromechanics in the human inner ear. *R. Soc. open sci.*, **1**(140166).

Lee S, Kim K, Choi W, Lee S. (2010). Annoyance caused by amplitude modulation of wind turbine noise. *Noise Control Engineering Journal*, **59**(1):38–46.

Leventhall, G. (2009). Review: Low frequency noise: what we know, what we do not know, and what we would like to know. *Journal of Low Frequency Noise, Vibration and Active Control*, **28**(2):79–104.

Møller, H. and Pedersen, C.J. (2011). Low-frequency noise from large wind turbines. *Journal of the Acoustical Society of America*, **129**(6):3727-3744.

Niedzwiecki, A. and Ribner, H. (1978). Subjective loudness of n-wave sonic booms. *Journal of the Acoustical Society of America*, **64**(6):1617–1621.

Palmer, W. (2014). Wind turbine annoyance. A clue from acoustic room modes. *Journal of the Acoustical Society of America*, **136**, 2204.

Salt, A. N. and Hullar, T. E. (2010). Responses of the ear to low frequency sounds, infrasound and wind turbines. *Hearing research*, **268**(1):12–21.

Swinbanks, M.A. (2012). Enhanced Perception of Infrasound in the Presence of Low-Level Uncorrelated Low-Frequency Noise, 15th Conference on Low Frequency Noise, Stratford-upon-Avon, UK, 12-14 May.

Von Hunerbein, S., King, A., Hargreaves, J., Moorhouse, A., and Plack, C. (2010). Perception of noise from large wind turbines (efp-06 project).

Walker, B., Hessler G.F., Hessler, D.M., Rand, R. and Schomer, P. (2012). A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin, Report Number 122412-1.

Walker, B. and Celano. (2015). Progress report on synthesis of wind turbine noise and infrasound, Submitted to Wind Turbine Noise 2015.

Watanabe, T. and Møller, H. (1990). Hearing Thresholds and Equal Loudness Contours in Free Field at Frequencies below 1 kHz, *Journal of Low Frequency Noise Vibration and Active Control*, **9**(3):106-115.

Waye, K. P. and Ohrström, E. (2002). Psycho-acoustic characters of relevance for annoyance of wind turbine noise. *Journal of sound and vibration*, **250**(1):65–73.

Yokoyama, S., Sakamoto, S., and Tachibana, H. (2013). Study on the amplitude modulation of wind turbine noise: part 2 - auditory experiments. In *Proceedings of InterNoise 2013*, Innsbruck.

# Appendices

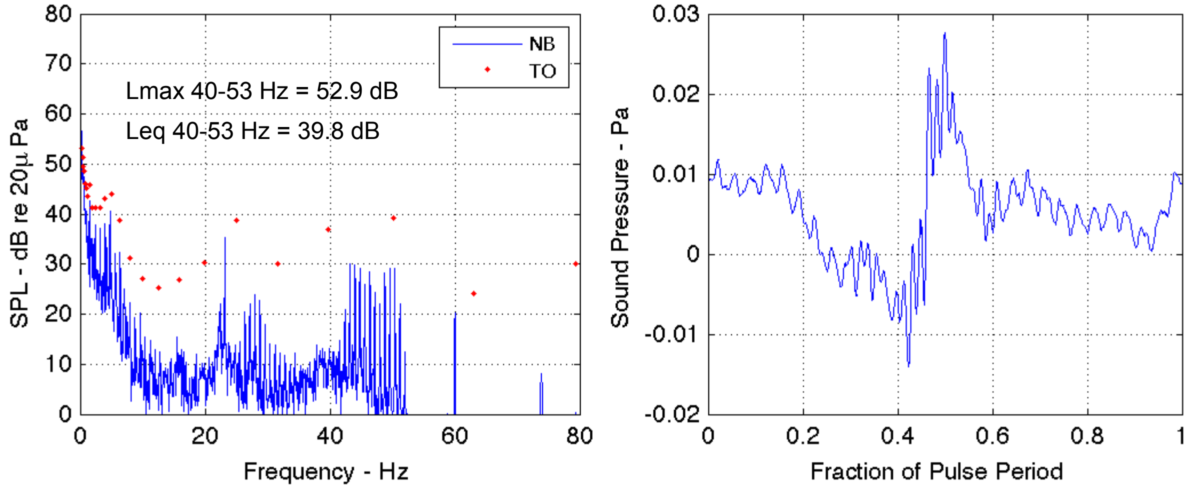


**Figure 16 – All-pass, 5 dB below measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.**

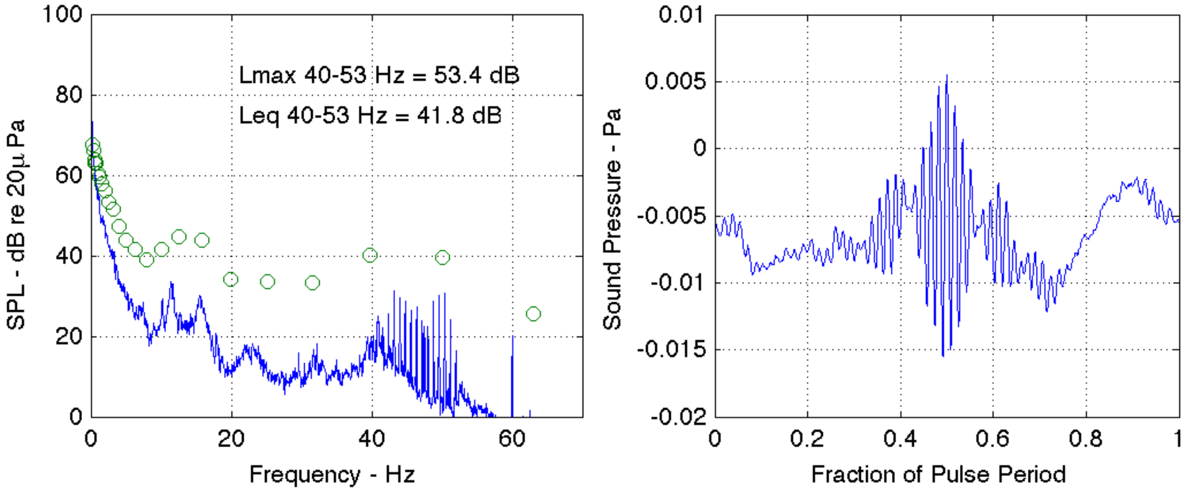


**Figure 17 – 30 Hz HP, 5 dB below measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

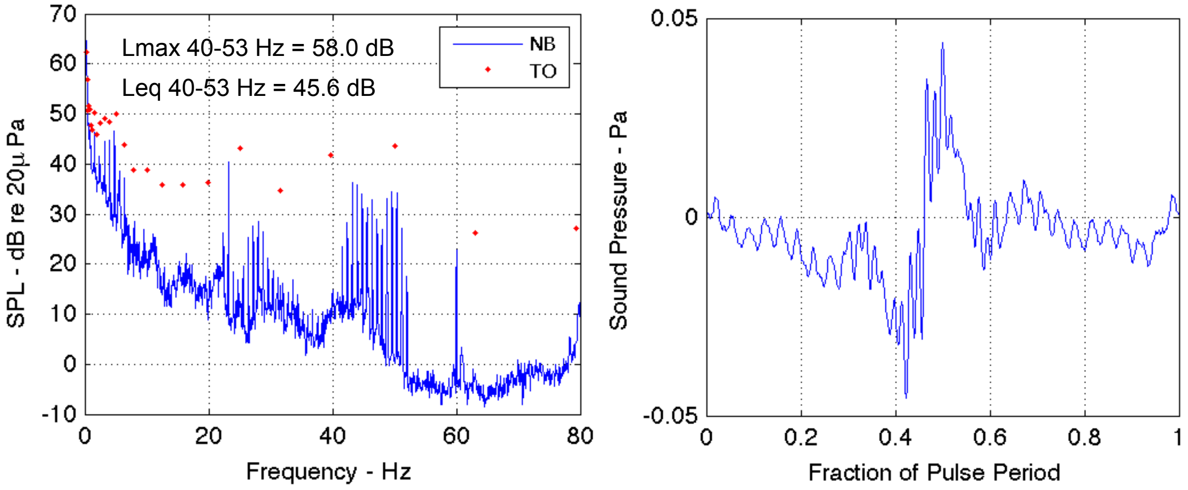


**Figure 18 – All-pass, approximately the same as measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.**

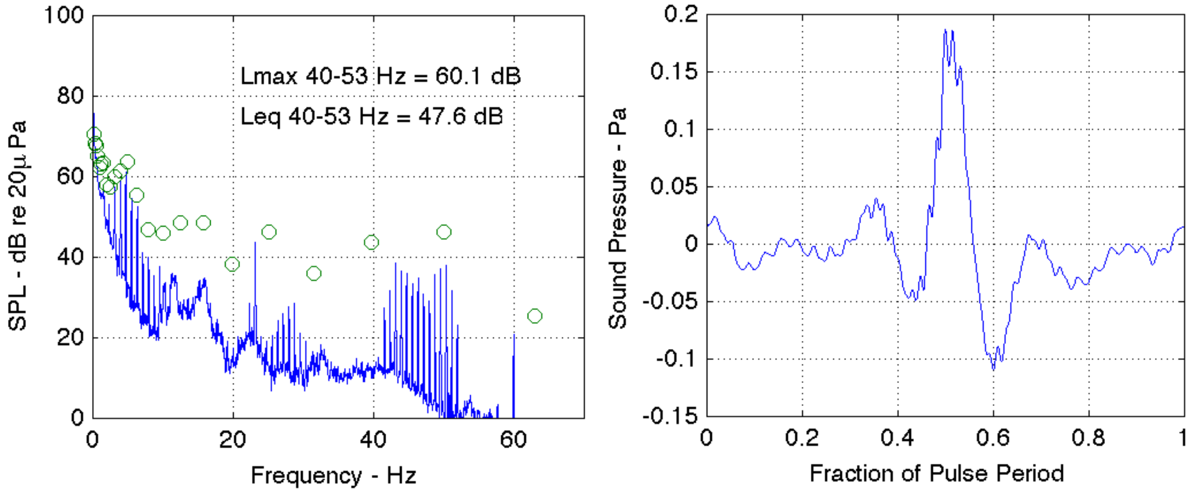


**Figure 19 – All pass, approximately the same as measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

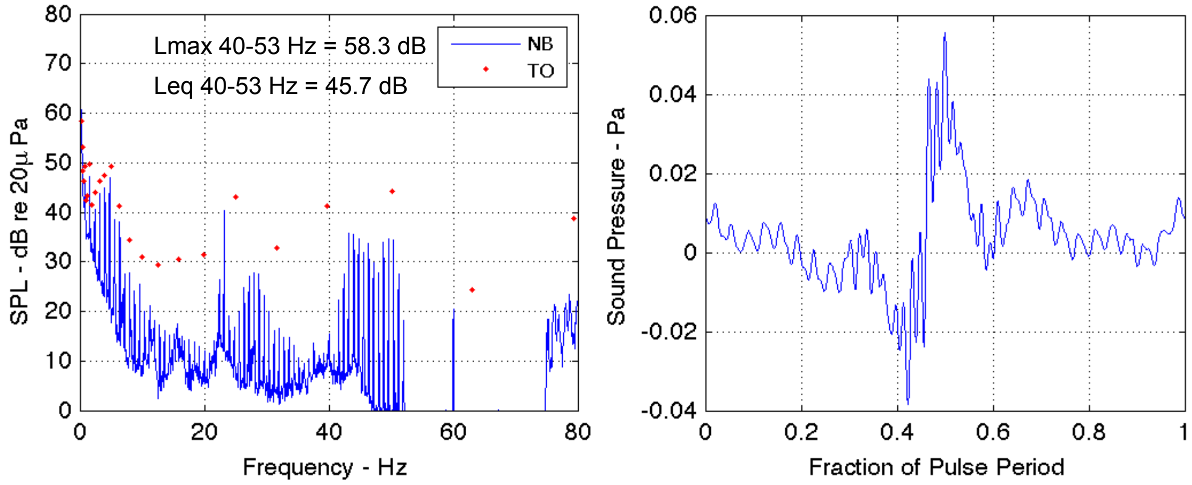


**Figure 20 – All-pass, approximately the same as measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.**

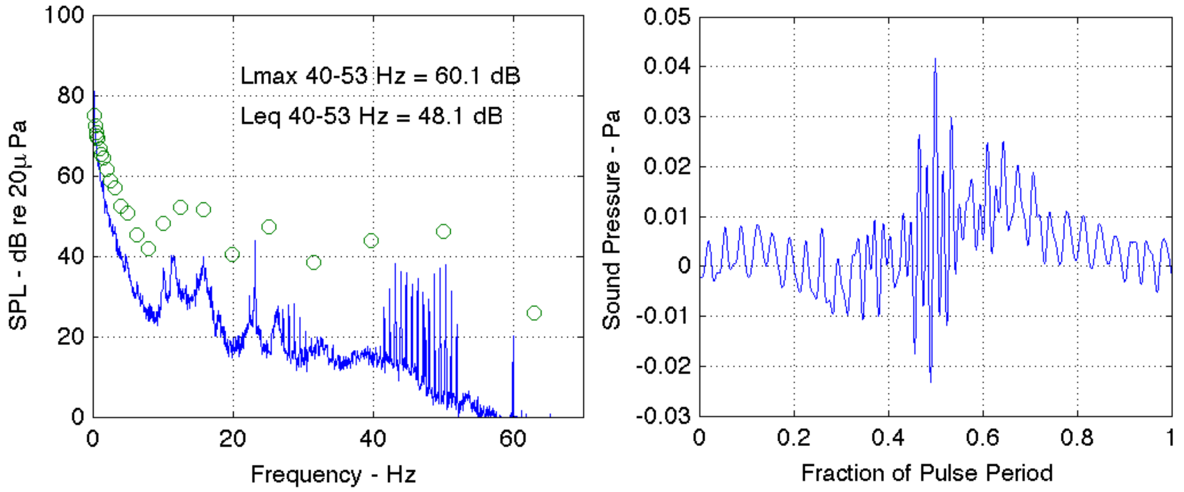


**Figure 21 – 20 Hz HP, approximately the same as measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

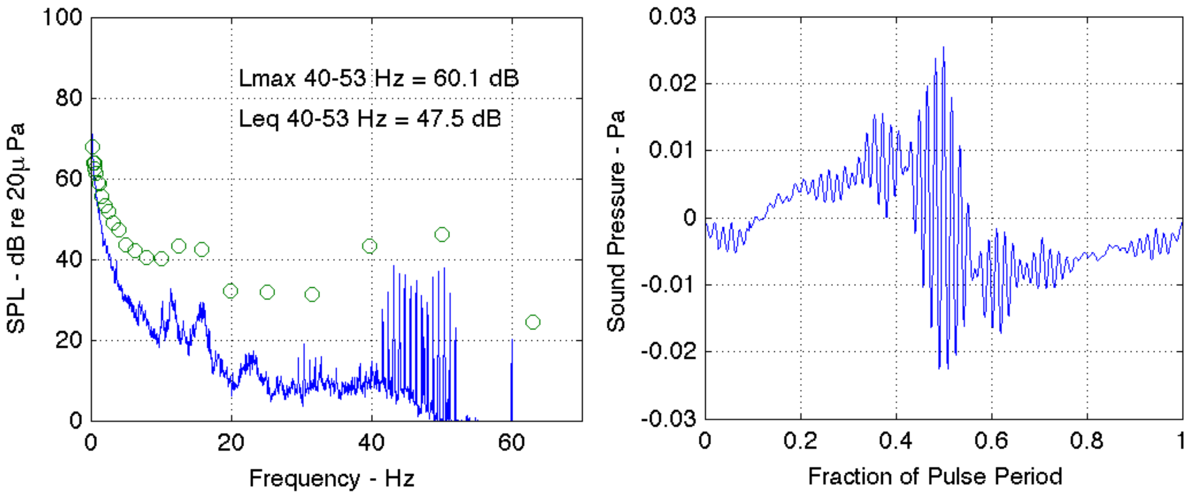


Figure 22 – 30 Hz HP, approximately the same as measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

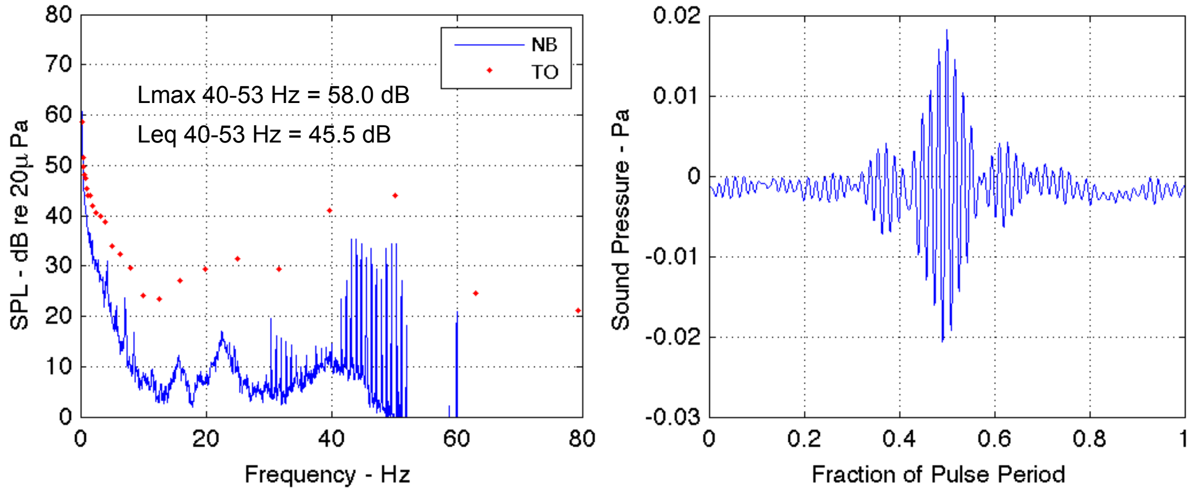


Figure 23 – 30 Hz HP, approximately the same as measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.

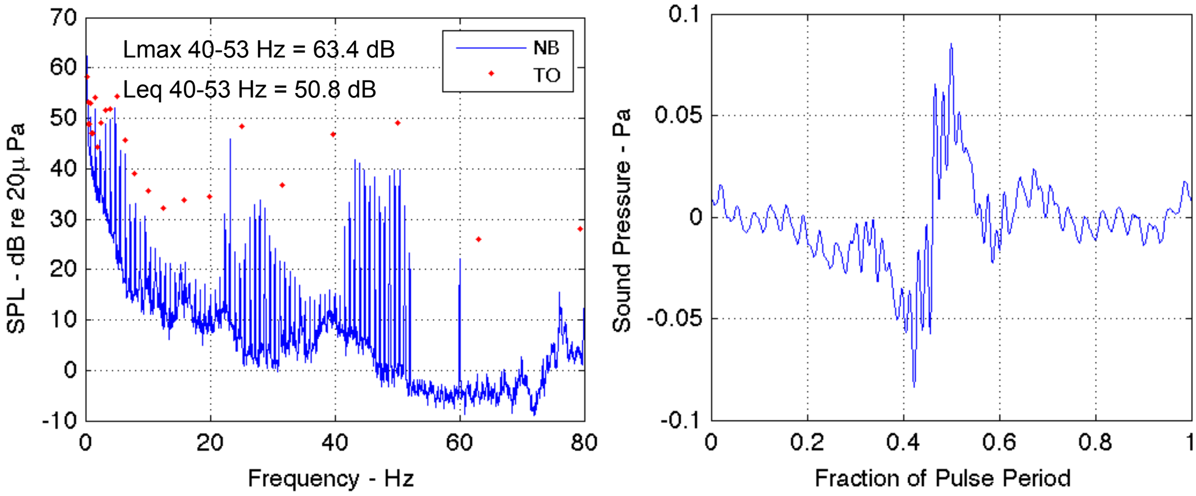


Figure 24 – All-pass, 5 dB above measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.

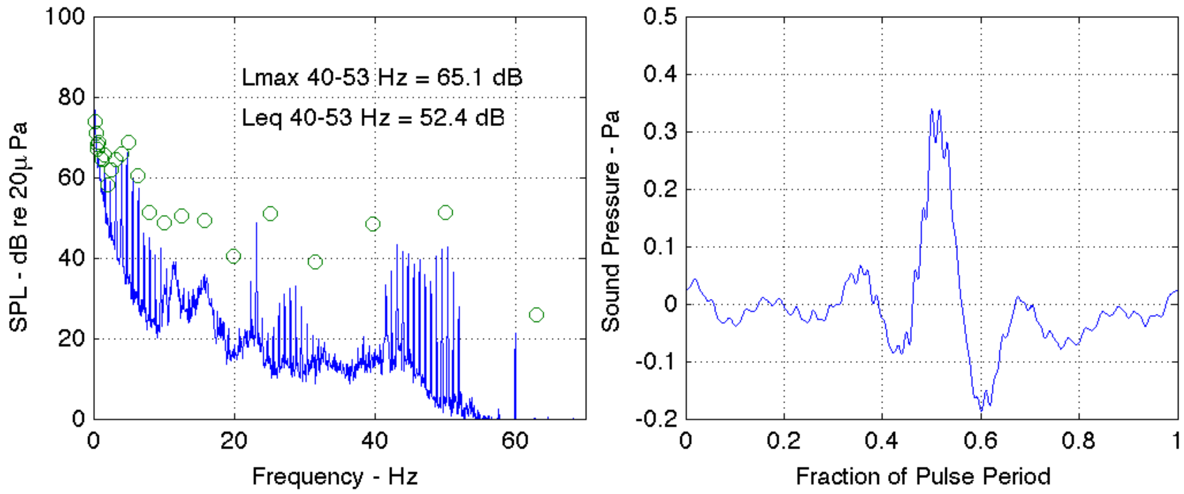


**Figure 25 – All pass, 5 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

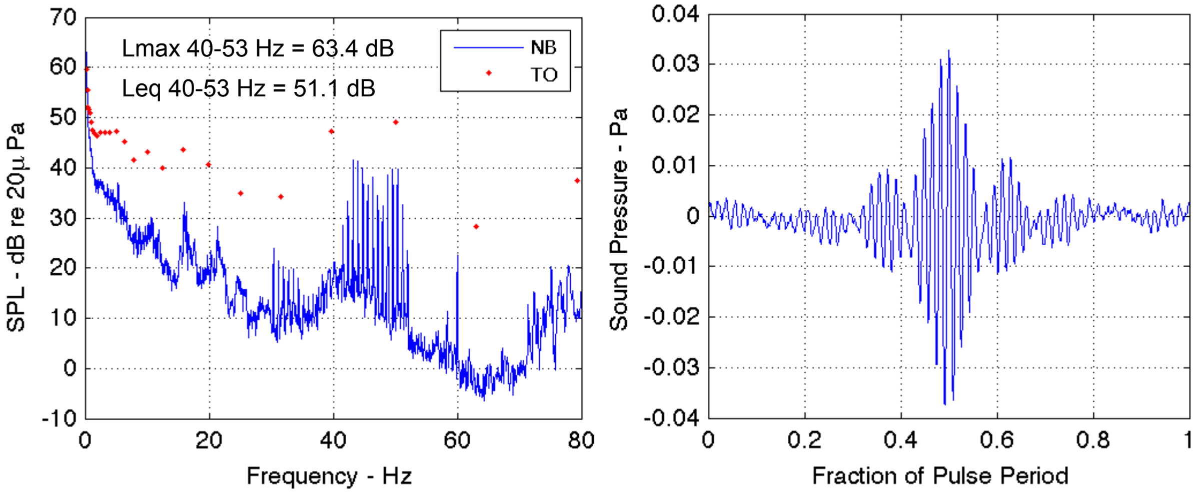


**Figure 26 – 30 Hz HP, 5 dB above measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.**

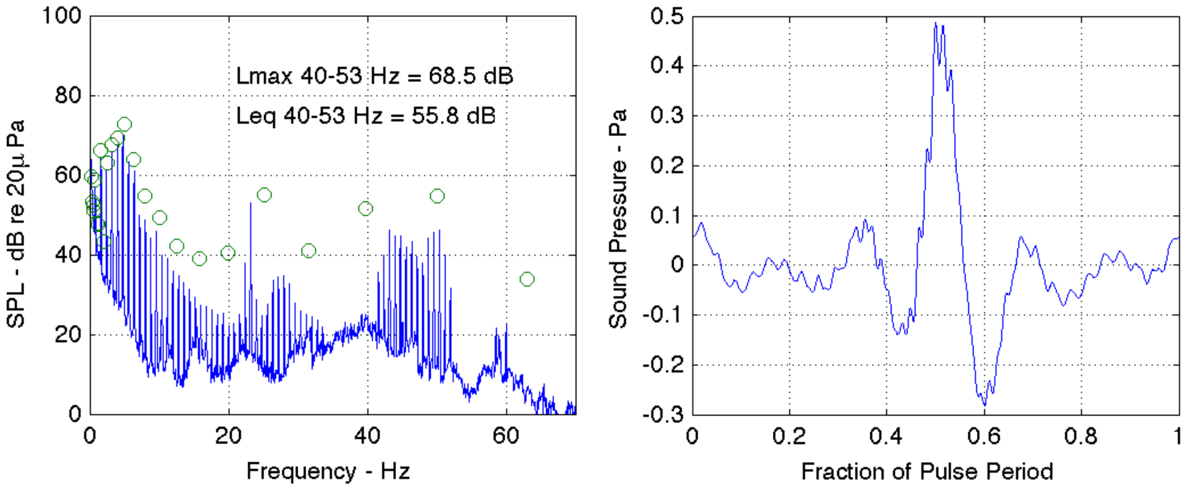


**Figure 27 – All pass, 9 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

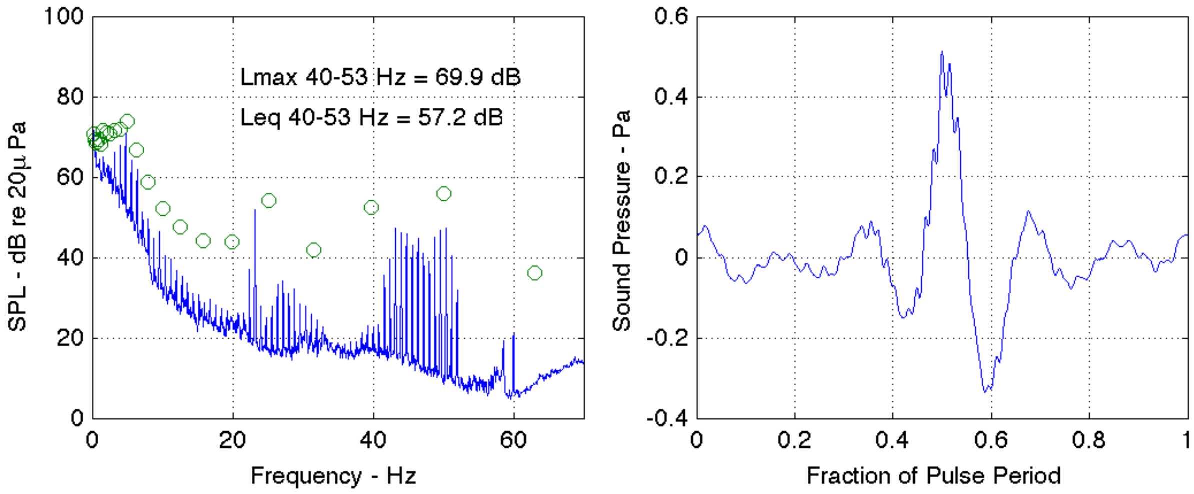


Figure 28. All pass, 9 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

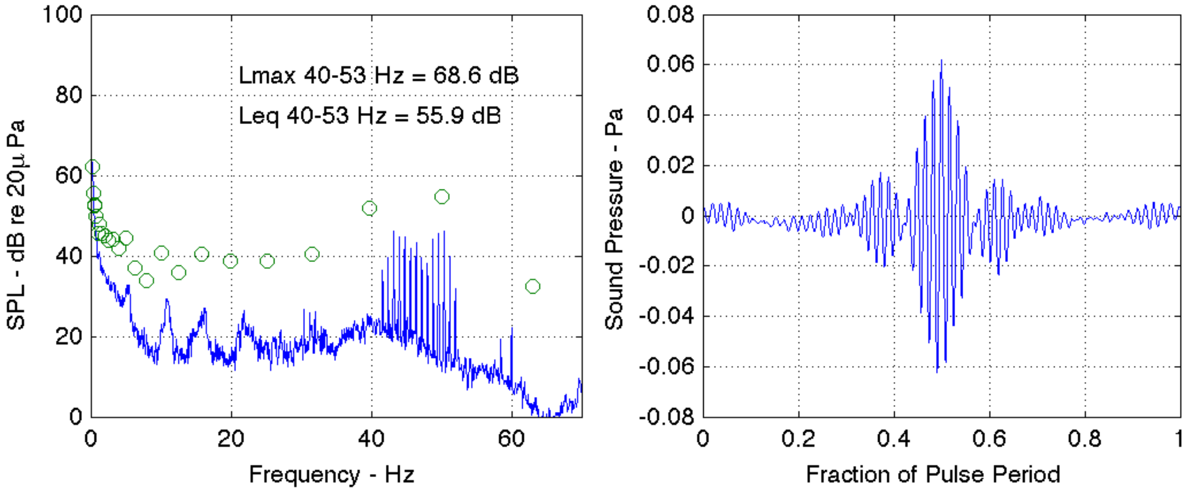


Figure 29 – 30 Hz HP, 9 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

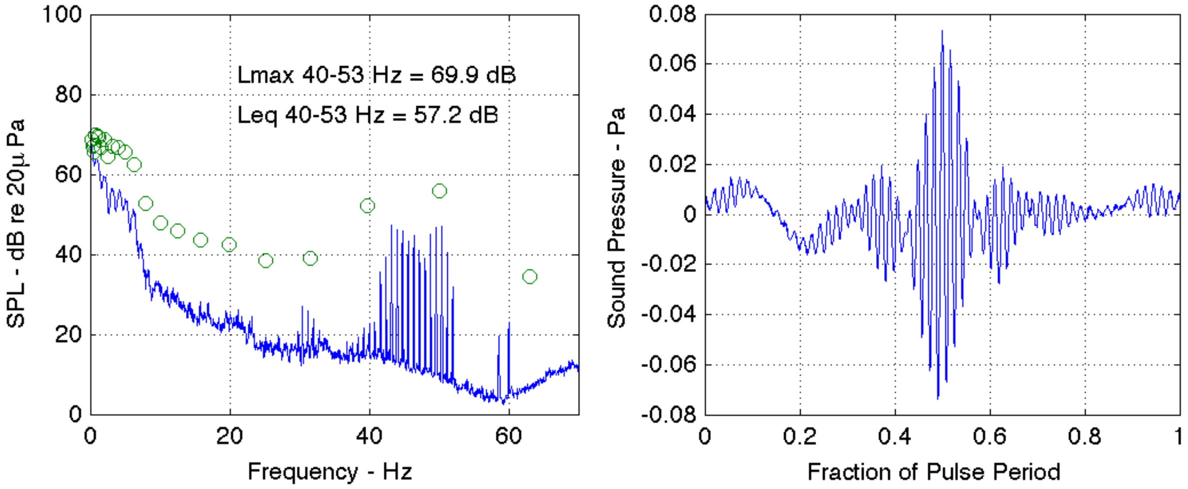


Figure 30. 30 Hz HP, 9 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

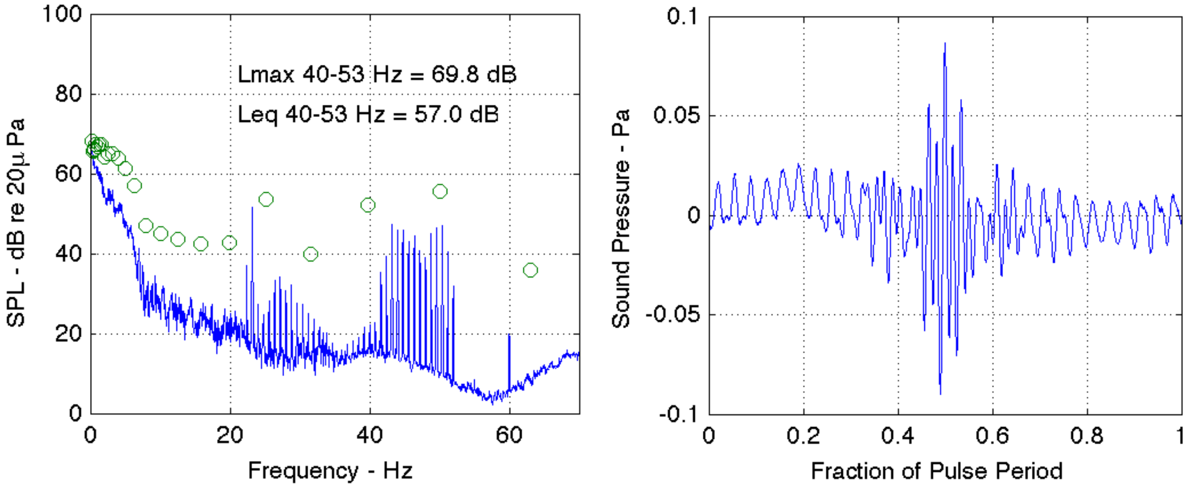


**Figure 31 – 20 Hz HP, 9 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

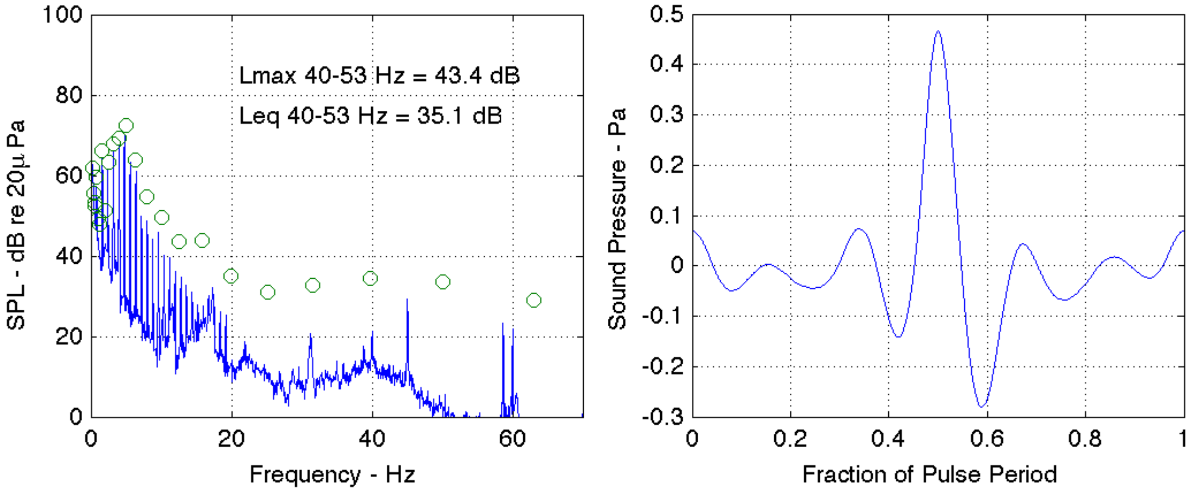


**Figure 32 – 20 Hz LP, 9 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

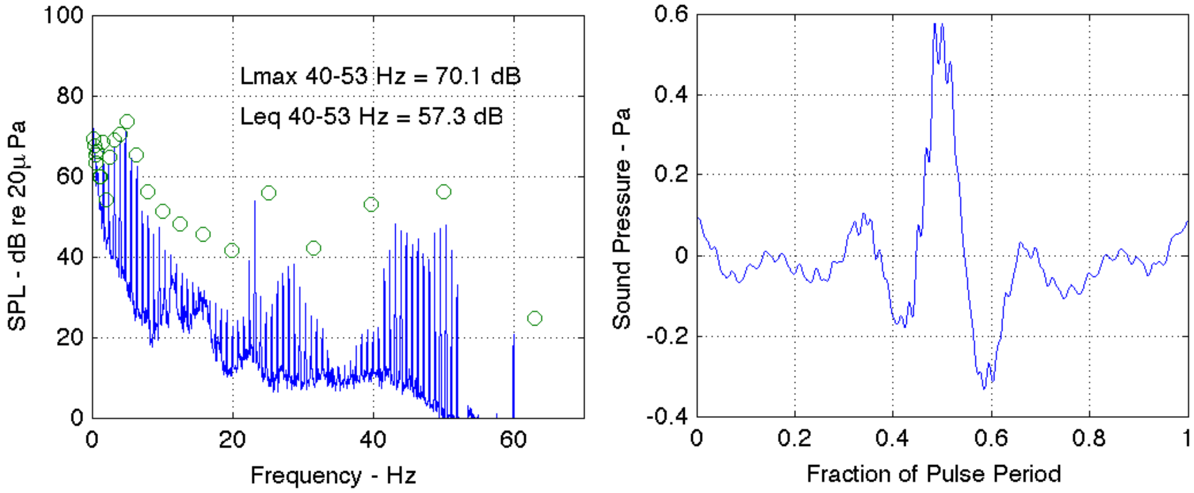


**Figure 33 – All pass, 10 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

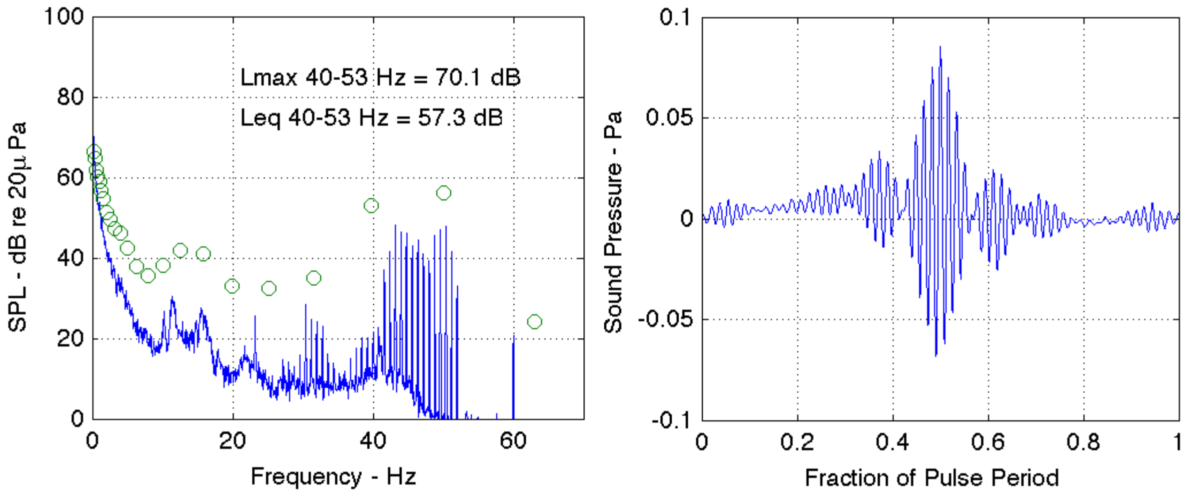


**Figure 34 – 30 Hz HP, 10 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

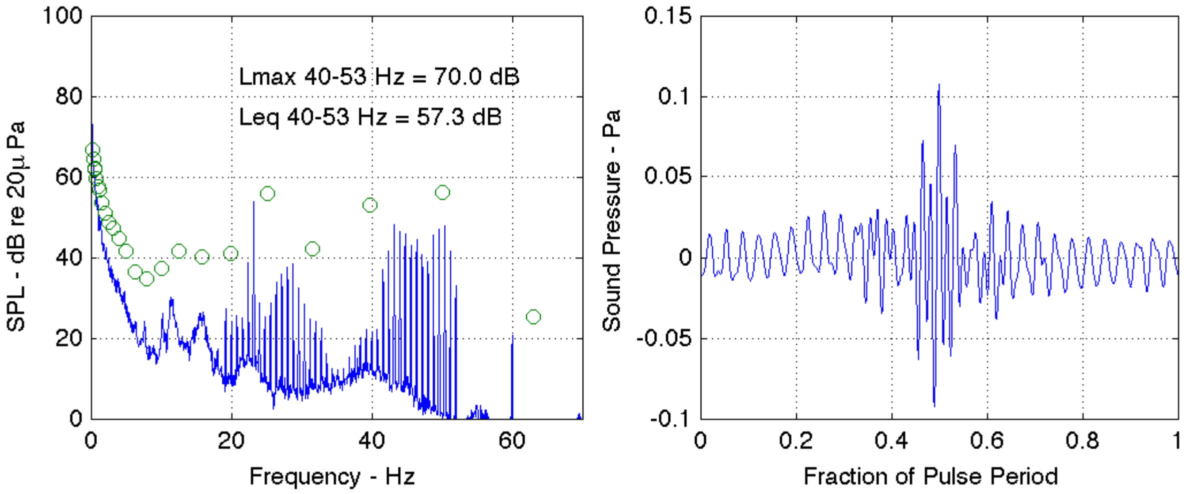


**Figure 35 – 20 Hz HP, 10 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

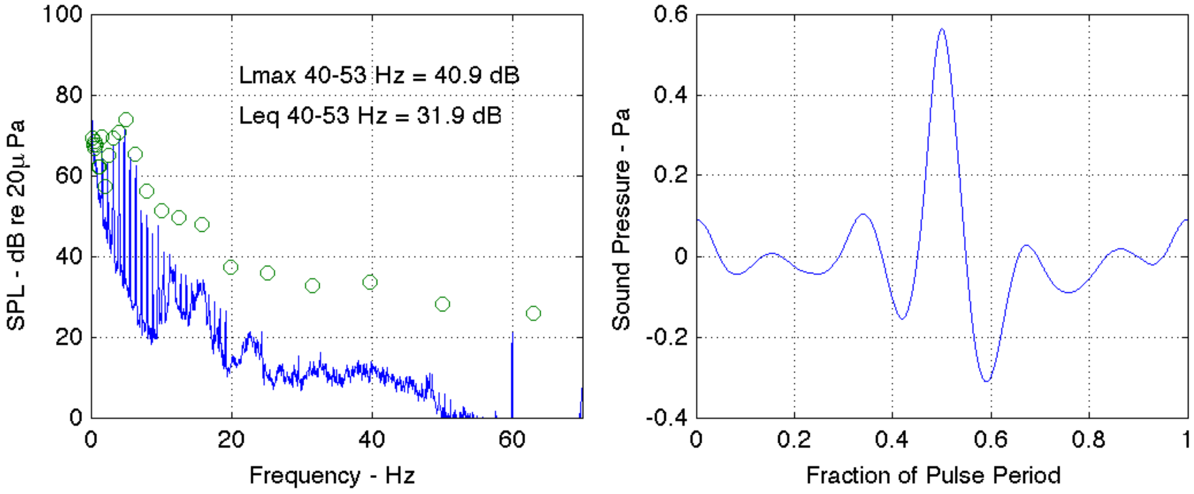


**Figure 36 – 20 Hz LP, 10 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

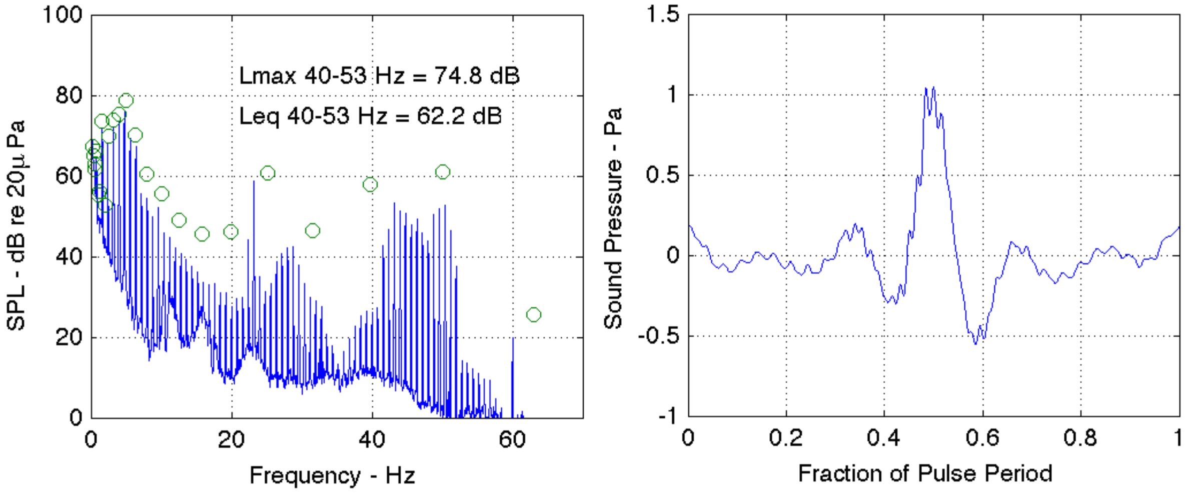


**Figure 37 – All pass, 15 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

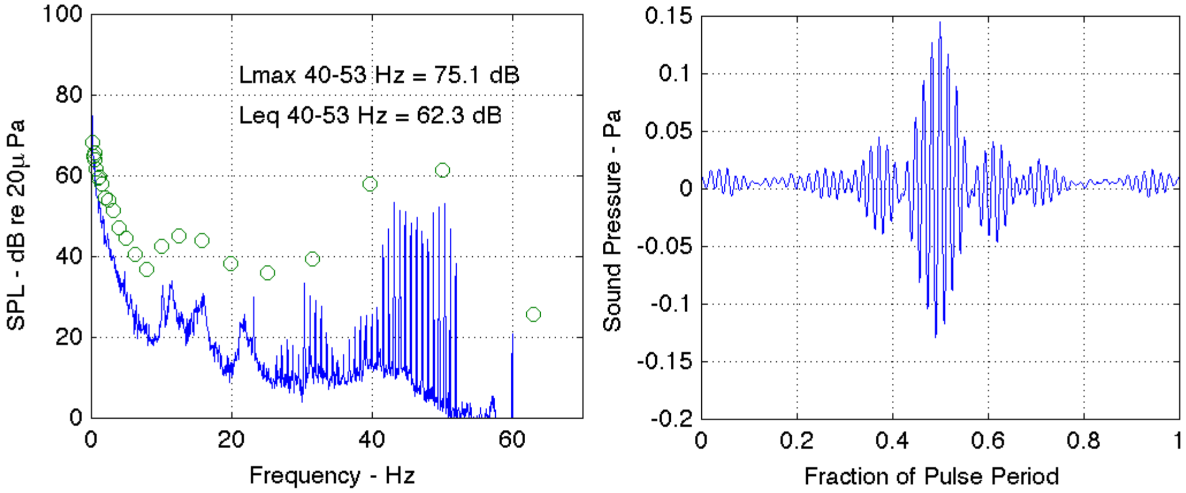


**Figure 38 – 30 Hz HP, 15 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

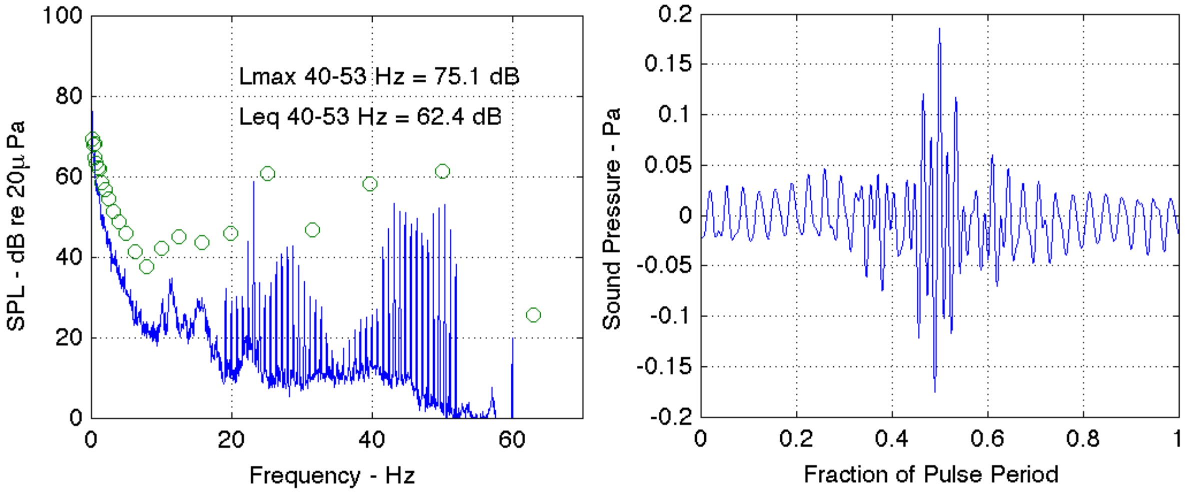


**Figure 39 – 20 Hz HP, 15 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

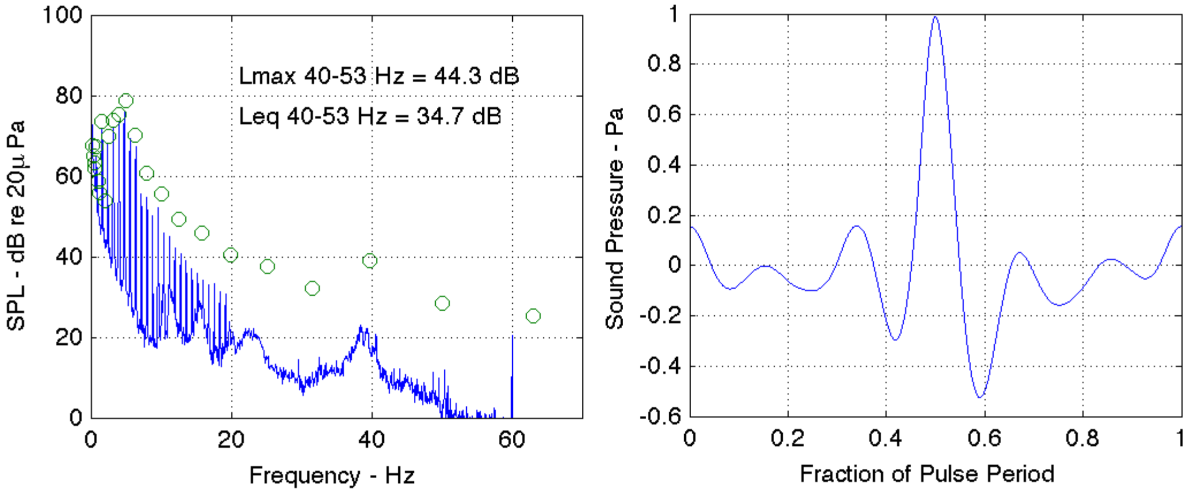


**Figure 40 – 20 Hz LP, 15 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.**

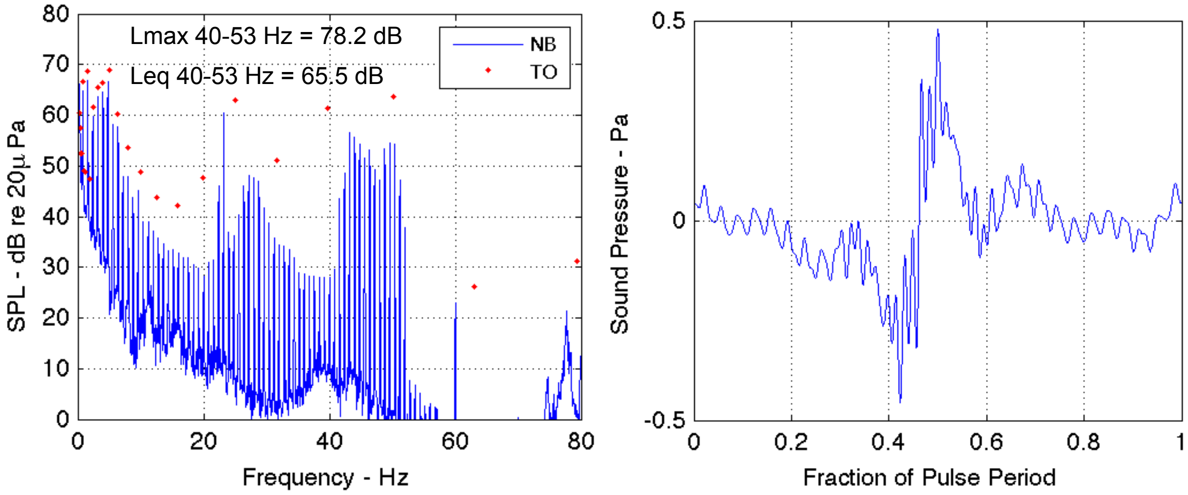


**Figure 41 – All-pass, 20 dB above measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.**

6th International Meeting
on
Wind Turbine Noise
Glasgow  20-13 April 2015

# Progress Report on Synthesis of Wind Turbine Noise and Infrasound

**Bruce Walker   676 W Highland Dr, Camarillo CA 93010 USA.**

**Joseph Celano   Newson-Brown Acoustics Ltd. 2001 Wilshire Boulevard, Suite 301, Santa Monica CA 90403 USA**

## Summary

Study of the subjective effects of wind turbine noise in a controlled environment requires the ability to faithfully generate acoustic signatures produced by actual turbines.  Field measurements indicate that these signatures encompass a wide frequency range, extending from below 1 Hz to several kHz.  Beginning in 2012, the authors have presented conceptual descriptions and preliminary demonstrations of an infrasound synthesizer that is capable of producing turbine-faithful signals at least 10 dB greater than experienced in the field.  The basis of the system is a cubic enclosure housing three 18-inch electro-dynamic loudspeakers, driven by a 300-watt DC-coupled power amplifier.  At 0.8 Hz (a typical blade-pass fundamental in a modern industrial turbine) the system generates 75 dB sound pressure level in a 60 cubic meter residential room environment.  Peak infrasound pulsations up to 97 dB are produced.  The system has been expanded to allow simulation of controlled-spectrum steady broadband noise, amplitude modulated broadband noise and periodically excited bursts of coherent multi-tone noise.  Details of the design and implementation of the system are presented.  In a companion paper, the system is utilized to evaluate the relative subjective effects of audible and inaudible components of acoustic signatures synthesized on the basis of field data.

**1. Introduction** In addition to well-established aero-acoustic and mechanical noises, the acoustical signatures of modern, industrial wind turbines has been shown to include spectral components that extend into the infrasonic range, with potentially significant energy as low as the rotor blade-pass frequency (BPF).  Although the amplitudes of these infrasonic components are substantially lower than hearing thresholds for the components taken individually, it has been postulated (Schomer, 2013) that vestibular system excitation and/or the relatively high crest factor multiple simultaneous BPF harmonics causes the infrasound to be detectable and potentially a health hazard at sub-audible sound pressures.  In one field test, for example (Walker, Hessler, Rand, Schomer, 2012), residents stated unequivocally that they could “sense” the operation of turbines well over 2,000 meters distant from within their homes, while the measured infrasound levels were far below any established thresholds even at a distance of 400 meters.

It became clear that an electro-acoustic simulation of various wind-turbine acoustic components was needed to allow controlled testing and identification of signal properties that contribute to human sensitivity.  Laboratory systems have been proposed and implemented (Tachibana and Yokoyama, 2012; Zosuls et al, 2013) that would perform this function.  The current system is intended for use in a residential environment.

## 2. Synthesis of Turbine Noise Signal Components

Numerous individual components of the wind turbine acoustic signature include:

- Steady broadband noise
- Amplitude modulated broadband noise
- Steady tonal noise
- Amplitude modulated tonal noise
- Infrasonic BPF harmonic series pulsations
- Pulsed short-duration mechanical resonances

Synthesis subsystems in Matlab create each of these separately so they can be mixed and adjusted to simulate field conditions. One-minute long segments of each component are created in software and are repeated for extended exposure testing.

**2.1 Steady broadband noise** covers frequency range 1 to 3000 Hz and spectrum-shaped to an approximate average of a compendium of field data. To preserve continuity of signal and slope for repeated signals, the one-minute of noise is synthesized as a sum of sine waves on 1/60 Hz frequency increments with random phases (i.e., 180,000 separate sine waves with frequency 1/60 Hz to 3000 Hz). Figure 1 shows spectral properties of the synthesized noise as compared to Gaussian noise. Actual spectrum shaping is achieved by appropriate amplitude weighting of the individual sine waves in the synthesis, with final result as shown in Figure 2.

**2.2 Amplitude modulated broadband noise** is a quasi-swept 1/3-octave band of Gaussian noise that is superimposed on the steady noise. The sweep is intended to mimic the Doppler shift of an advancing blade at a location 45 degrees to side upwind of the turbine. However, the intent for listening tests is to provide a BPF-synchronized fluctuation in audible sound that is suggestive of turbine AM rather than a probably-unachievable full representation. **Figure 3** shows the four spectra and modulation envelopes that are sequenced to synthesize a quasi-Doppler shifted noise from a rotating source. The four spectra are created by filtering four statistically independent synthesized noise signals.

**2.3 Tonal noise and infrasound pulsations** are spectrally synthesized based as harmonics of the BPF. The amplitude and phase of harmonics 1 to 65 (0.8 to 52 Hz) can be pre-set individual to simulate a multitude of pulsation, steady tone and amplitude modulated tone signatures. Alternatively, modulation windows can be applied to steady individual tones to generate wave packets or fluctuating tome amplitudes directly.

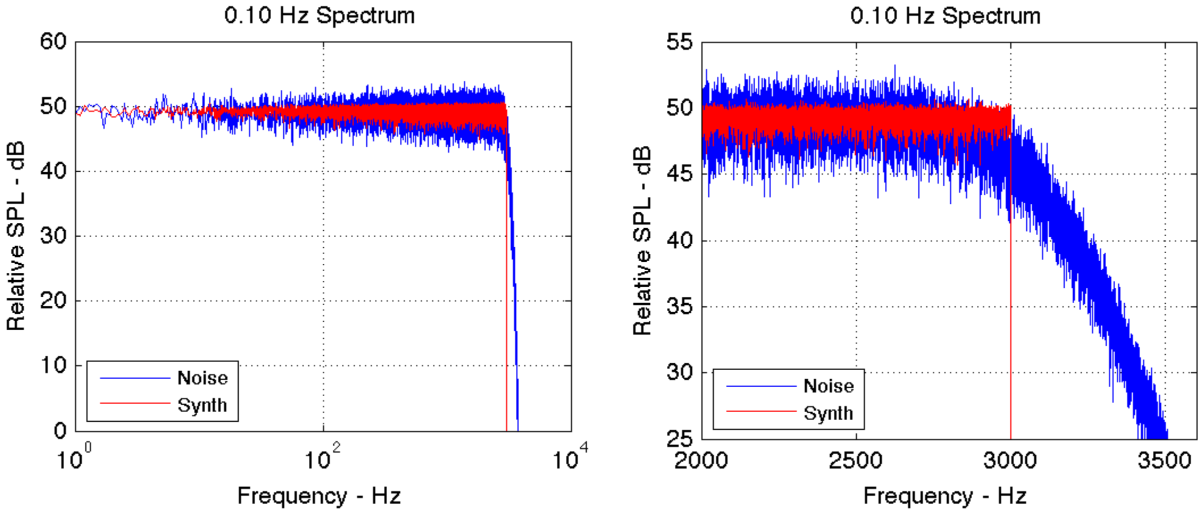


**Figure 1. Narrow band spectra of synthesized and filtered Gaussian noise and expanded response near 3 kHz corner frequency**

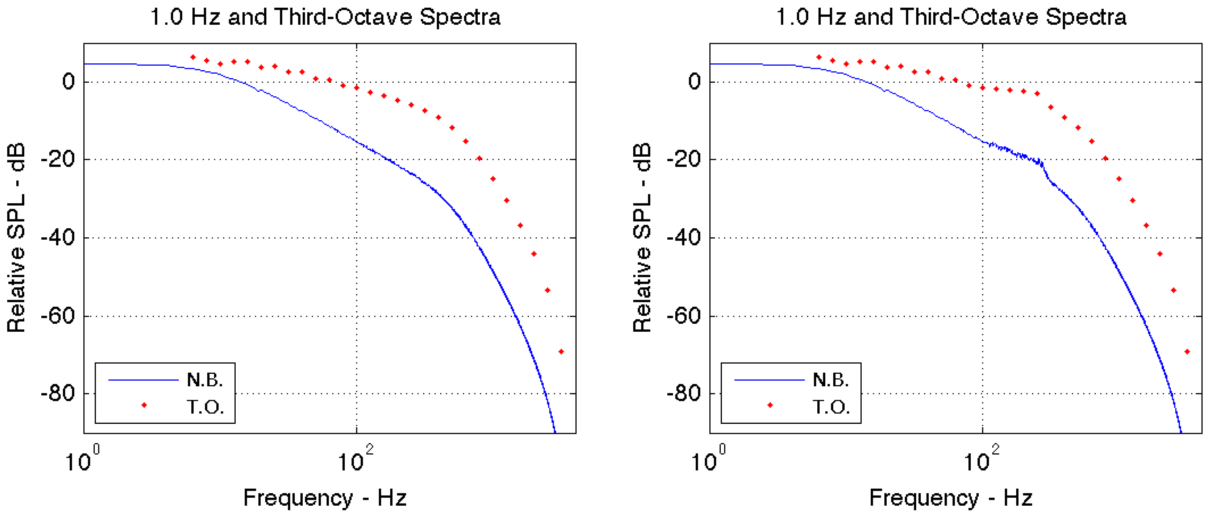


**Figure 2. Baseline spectrum of synthesized random noise with and without "Whoosh"**

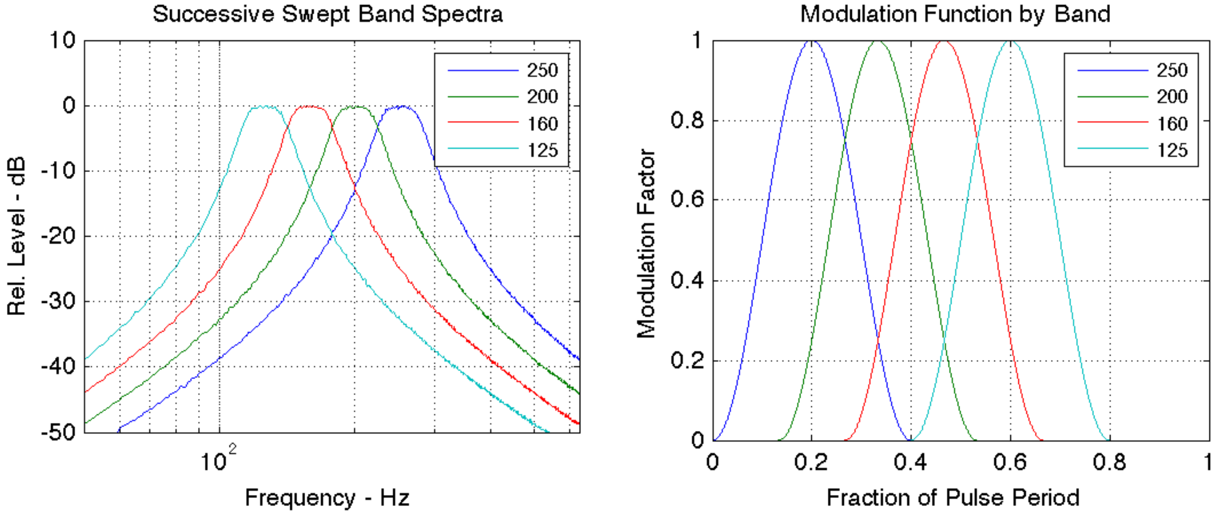


**Figure 3. Spectra and modulation sequence for sequenced Doppler shift "Whoosh" simulation**

## 3.0 Data Collection and Monitoring System

To represent the potential effects of turbine noise in noise sensitive (residential) environment, the synthesis system has been set up in a modest-size guest bedroom, approximately 4x5x3 meters. The gravest resonance mode in this space is 37 Hz. The initial intent was that all test signals would have a maximum frequency of 32 Hz so that a relatively simple transfer function from a sealed-enclosure loudspeaker would obtain. The highest SPL of any turbine BPF harmonic observed in the field is approximately 65 dB at 400 meters. The amplitude goal for the synthesis system is 10 dB above this maximum, or at least 75 dB at any frequency over the range 0.8 to 32 Hz.

**3.1 Loudspeakers.** In a sealed room at frequencies below the gravest resonance, the sound pressure is, per Boyle's law, inversely proportional to the relative variation in room volume. A sealed enclosure loudspeaker modifies the room volume by virtue of diaphragm volume displacement, so a loudspeaker with resonance frequency in the 50 Hz range would operate "stiffness controlled" and ideally provide sound pressure proportional to excitation current.

It was determined that three 18-inch electro-dynamic drivers in a 0.44 $m^3$ cube enclosure would have a resonance frequency just above 50 Hz and provide linear volume-displacement amplitude of .0036 $m^3$. In a 60 m3 sealed room, this translates to SPL 106 dB, with significant correction expected at the lowest frequencies due to room leakage and wall flexing. In practice, with full response equalization as described in Section 4, peak infrasound pressure levels of approximately 97 dB are achieved, nearly 20 dB greater than pressures observed in field measurements.

For audible signal components above 50 Hz, a simple high-quality direct-radiator monitor speaker was set atop the infrasound "cube" as shown in Figure 4.

**Figure 4. In-situ photo of synthesis system loudspeakers**

**3.2 Analog conversion and amplification.** Test signals were generated at 8 kHz data rate, with LFIS signals and audible signals on two separate channels. A 16-bit dual channel D to A converter and reconstruction filter were used to generate analog signals, which were then routed to a 5 dB per step ladder attenuator and a dual channel 300 watt DC-coupled power amplifier.

**3.3 Monitoring.** Four microphones were distributed in the listening room, with the primary position just above the listening seat as shown in Figure 5. The microphones were B&K 4193 with low frequency extensions, having linear response to well below 0.1 Hz. A multichannel simultaneous sampling 24 bit A to D converter was used to capture the microphone signal, the excitation signals and the analog output of an outdoor cup anemometer.

**Figure 5. Photo of listening location with monitoring microphones overhead**

**3.4 System calibration and equalization.** In addition to microphone calibration at the beginning of each test day, the output spectrum of the synthesizer had to be adjusted to compensate for room effects. These are primarily leakage losses at very low frequencies and resonances in the range 30-60 Hz.

The first step in the process was a sine wave frequency response measurement, conducted stepwise from 0.8 to 52 Hz in 0.8 Hz increments. The result is shown in Figure 6, which illustrates that room losses are significant below approximately 3 Hz and that room resonances are significant above about 30 Hz. The 7.5 dB drop between 1.6 and 0.8 Hz suggests that both the room and loudspeaker may have leakages that affect the lowest radiation frequencies.

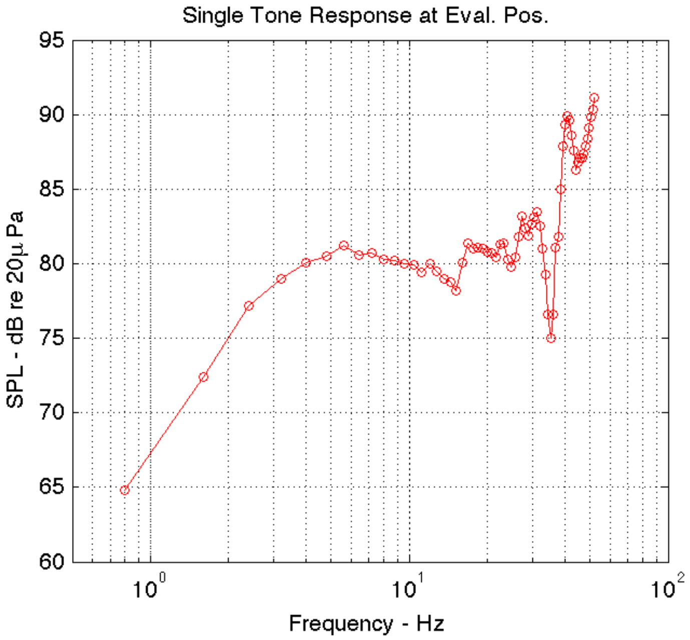


**Figure 6. Results of synthesis system frequency response measurement**

The second step was to curve fit a 35% over-damped second-order high-pass filter function with 1.9 Hz corner frequency to this data, as shown in Eq.1.

$$Loss = 1 + 1.9i\left(\frac{1.9}{f}\right) - \left(\frac{1.9}{f}\right)^2 \qquad \text{Eq.1}$$

The phase of the model loss function and the inverse of the measured response were used to create equalization factors for the excitation signals as shown in Figure 7.

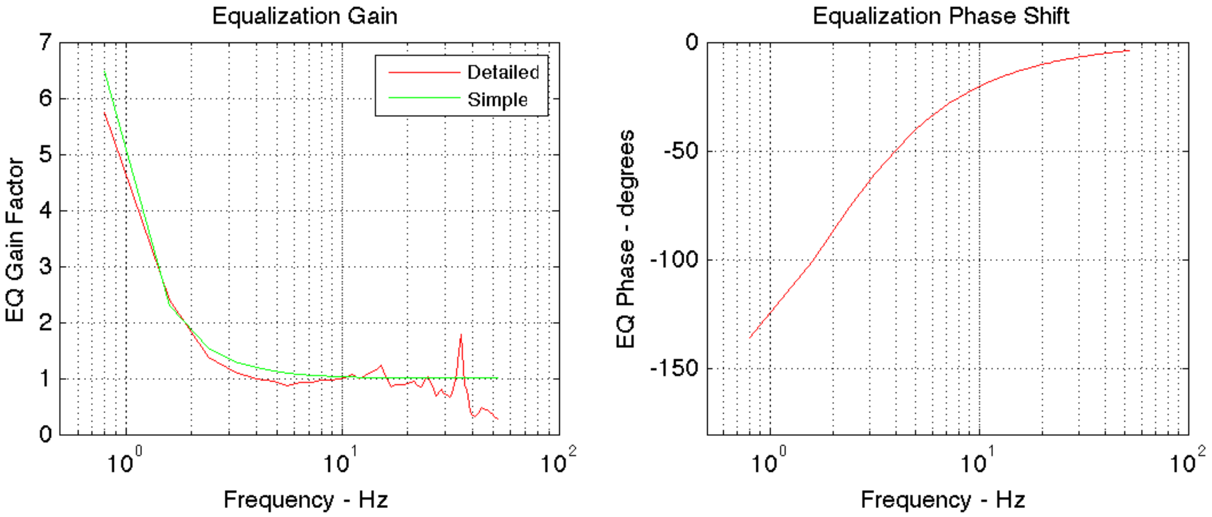


**Figure 7. System equalization gain and phase**

## 4.0 Synthesized Infrasound Spectra and Waves

At the onset of the project, two primary infrasound spectra were of interest. This was expanded to include data mimicking interesting field data as well as including audible components as discussed in Section 2.

**4.1 N-wave.** The first was a classical “N-wave,” consisting of a harmonic series

$$Nwave = \sum_{N=1}^{N_{\max}} \frac{\sin(2\pi N\,BPF\,t)}{N} \qquad \text{Eq. 2}$$

where BPF is the fundamental frequency, which dominates the spectrum, being 6 dB greater than the second harmonic. A useful property of the N-wave is that the maximum slope contribution is the same from each harmonic, so that a slope parameter in the overall wave can be controlled by truncating the spectrum with minimal effect on the total amplitude. An example is shown in Figure 8.

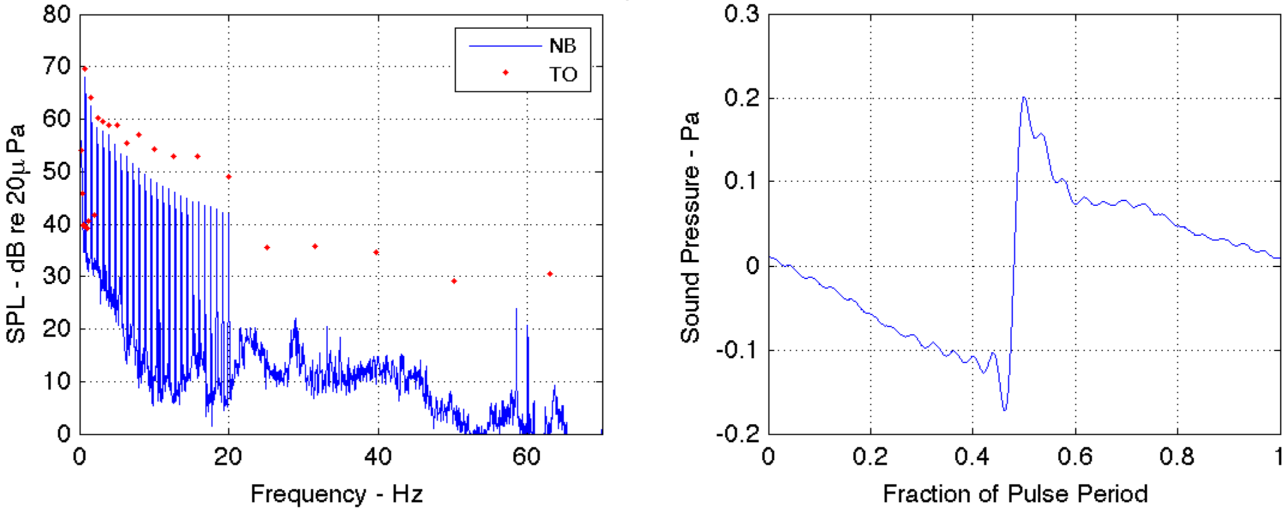


**Figure 8. Spectrum and waveform of synthesized N-wave truncated at 20 Hz**

**4.2 Ch-Wave.** Various field tests conducted by the authors and others have shown that the infrasound signature of wind turbines is not as heavily dominated by the fundamental as the N-wave. A more realistic spectrum is approximately flat up to approximately 7 Hz and then drops more rapidly toward higher harmonics, approximately as $1/N^2$ as shown in Figure 9. The Ch-wave has been used for the infrasound component of the preponderance of listening tests conducted with the system.

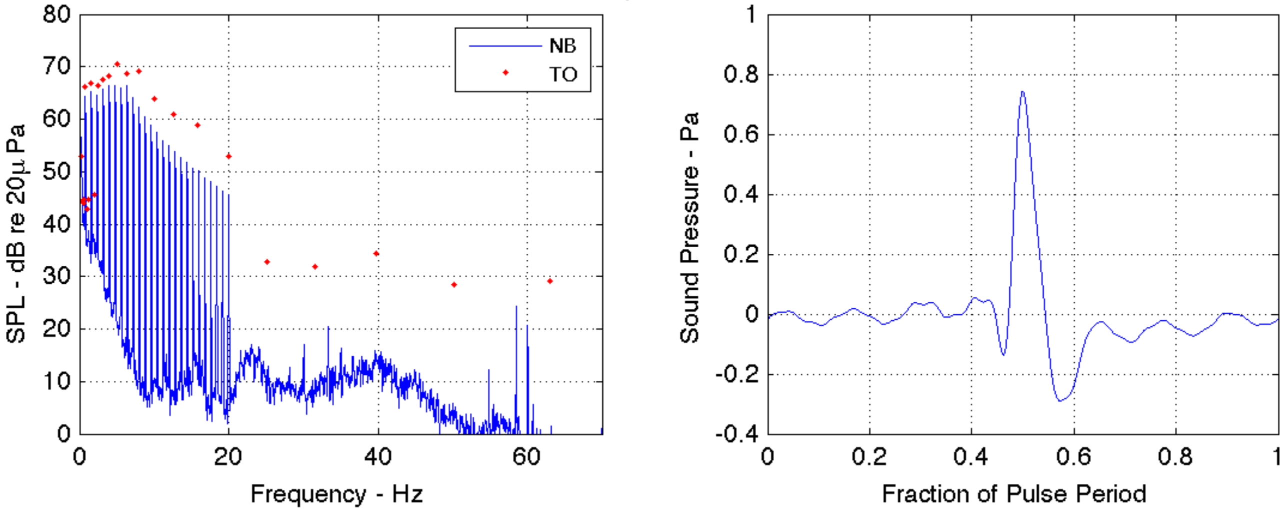


**Figure 9. Spectrum and waveform of synthesized Ch-wave truncated at 20 Hz**

**4.3 Ha(A,H,K,L)-wave.** The spectra described above were used for numerous listening tests with evaluators of normal, sensitive and sub-normal hearing acuity. Even with the upper frequency extended to 32 Hz, no evaluator was able to sense the presence of the pulsations at reproduction levels less than 10 dB above those observed in the field.

Hansen, Zajamsek and Hansen (2014), in a study of turbine noise at Waterloo Wind Farm in Australia, observed that in very steady measurement conditions, clusters of BPF-spaced spectral peaks extend into the frequency range 40-50 Hz and above as illustrated in Figure 10.

Analysis of this data is discussed in a companion paper. However, a simplification for synthesis purposes was to simply extend the BPF harmonic series to 52 Hz (65 harmonics or 0.8 Hz BPF) and assign harmonic amplitudes to approximately match power in the measured spectra.

The narrow band spectrum and waveform of the synthesized pulsation signal is shown in Figure 11. It may be noted that the apparent relative spectral levels of the synthesized signal increase with frequency. This is a result of the relative broadening of the measured spectral peaks, presumably due to minor unsteadiness in turbine rotation speed. In one-third octave bands (red dots), the relative spectra agree within approximately 2 dB. The overall spectrum level of the synthesized signal is adjustable as a testing parameter.

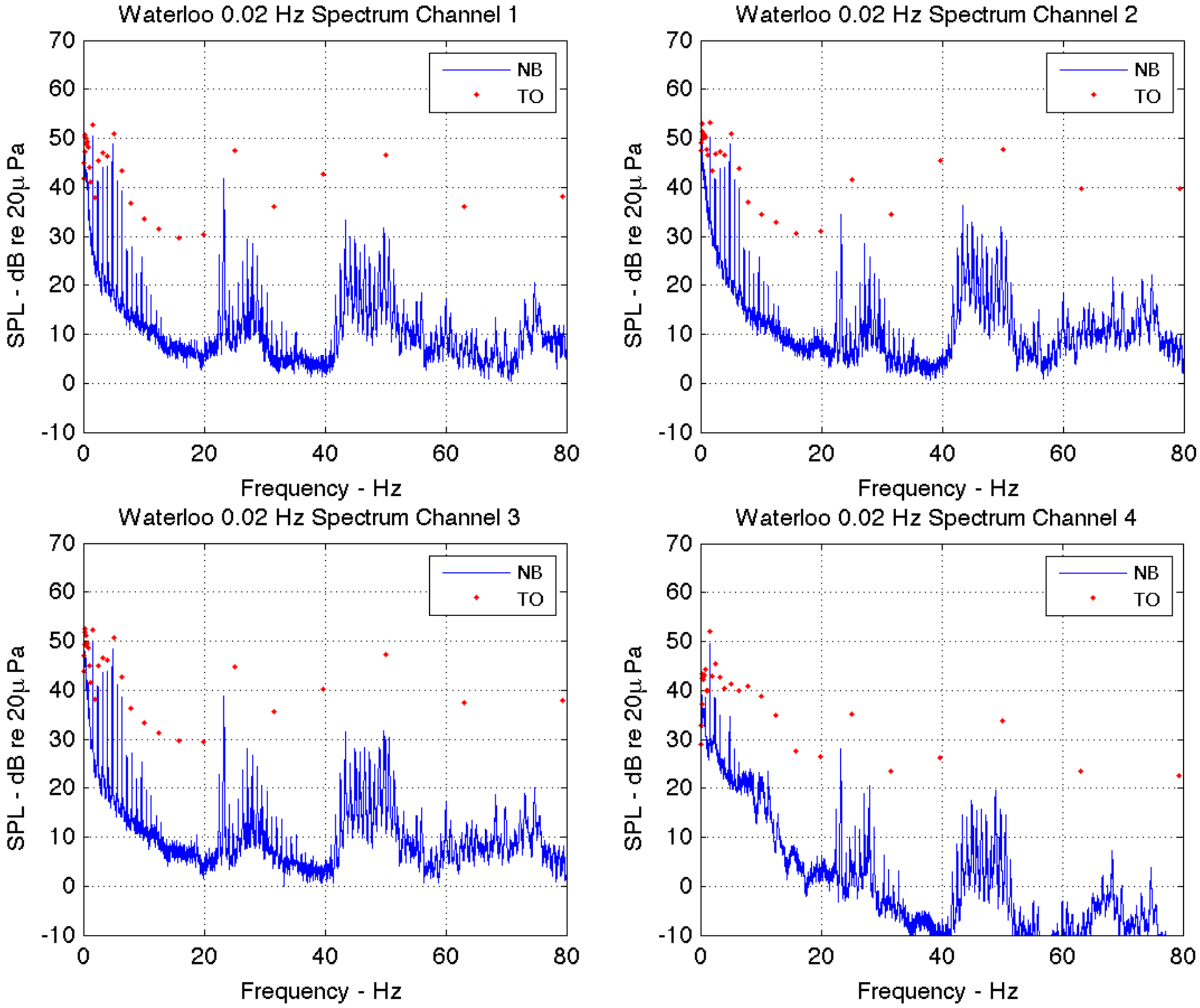


**Figure 10. Narrow band spectra from Waterloo Wind Park in quasi-steady conditions. Channel 4 is Indoors.**

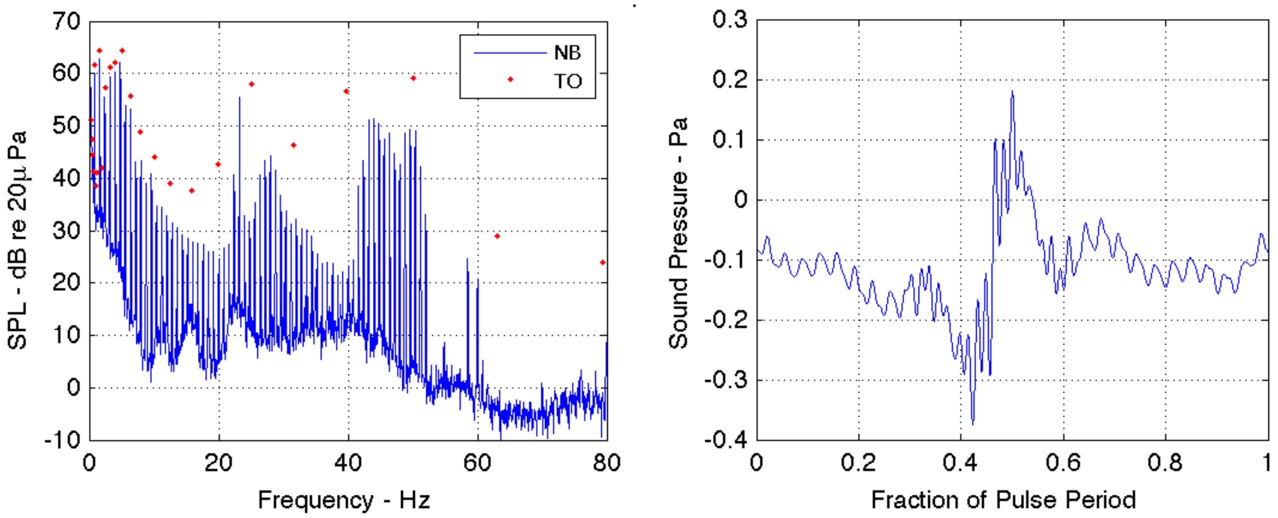


**Figure 11. Spectrum and waveform of synthesized HaA-wave representing outdoor Waterloo data**

The A,H,K,L designations refer to different portions of the spectrum.
A: All Pass
H: 20 Hz High Pass
K: 30 Hz High Pass
L: 20 Hz Low Pass

These spectra could be selected as test parameters to evaluate the relative importance of the infrasonic, low amplitude tone and pulsating audible low frequency elements in the signal.

**4.4 CB-wave.** Data published in Nov. 2014 by The Acoustics Group and measured inside a residence near the Cape Bridgewater Wind Farm in Australia showed a particularly high level of infrasound below 6 Hz, together with apparent strong reaction by residents. The published narrow band spectrum and a waveform computed as the sum of sine waves at the six peak spectral amplitudes is reproduced in Figure 12.

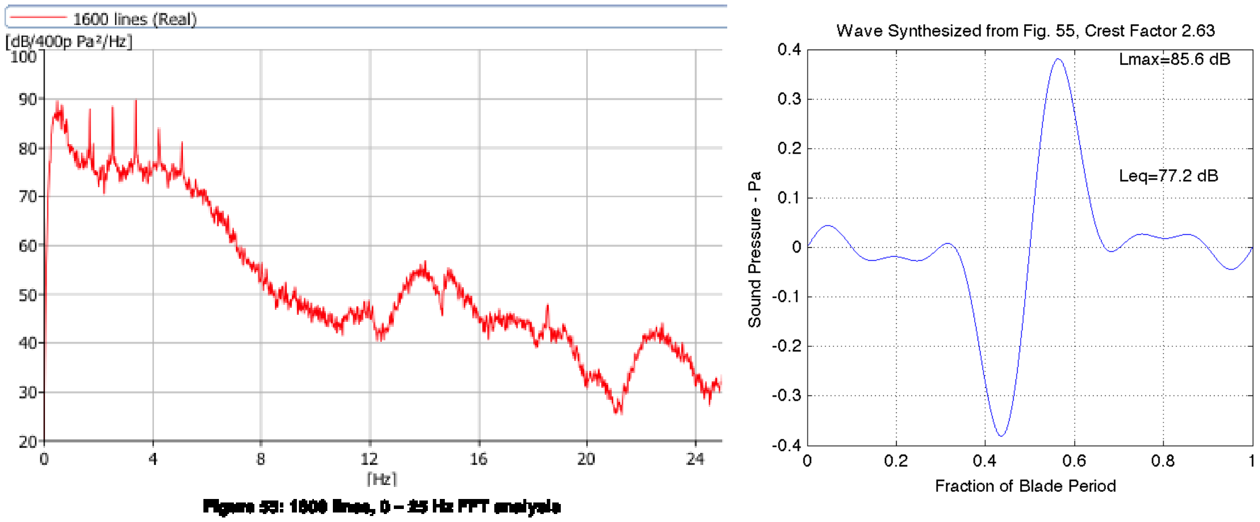


**Figure 12. Measured Spectrum from Cape Bridgewater Wind Farm Acoustic Test Report and Computed Pulse Waveform**

This wave is essentially Ch-Wave truncated at the 6th harmonic, with peak spectrum levels approximately 72 dB. The result of reproducing and monitoring this wave at approximately 5 dB excess amplitude are shown in the ensemble average recorded wave and its narrow-band spectrum of Figure 13. Although the loudspeaker-reproduced wave is not a perfect duplicate of the computed wave in Figure 12, it only differs slightly and the harmonic distortion manifested above 5 Hz are all over 20 dB below the target harmonics.

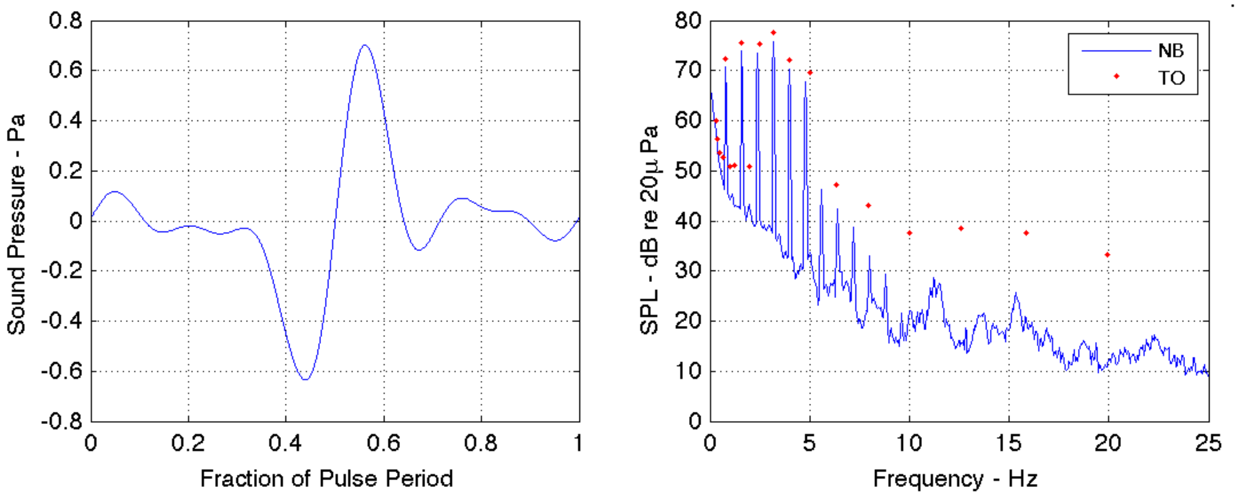


**Figure 13. Mean Waveform and Spectrum of Reproduced and Monitored Representation of The Cape Bridgewater data**

## 5.0 Subjective Responses

Three evaluators have been exposed to a wide range of combinations of infrasound, broadband noise, Doppler shift simulated blade “whoosh,” amplitude modulated tones and window-gated tones. Four additional evaluators have been exposed to spectrum Ch-wave infrasound (truncated 20 Hz) at peak SPL 92-97 dB. Exposure times ranging from two minutes to one hour have been investigated. Some results of interest are:

> Infrasound alone (spectrum Ch, HaL or CB) has not elicited any response at levels up to 97 dB peak.
>
> Steady random noise with 30-35 dB “Whoosh” and no infrasound on one occasion elicited a nausea response from an evaluator with high sensitivity to low frequency noise.
>
> At 88 dB peak SLP, an evaluator with high sensitivity to low frequency noise reported that presence of infrasound reduced the “roughness” of low-frequency pulsation sound (spectra HaA vs HaH) despite the infrasound (HaL) being undetectable alone.

## 6.0 Conclusions

It has been demonstrated that simulation of wind turbine noise and infrasound at levels representative of those observed at distances of 100 meters can be accomplished in a typical residential-sized room with a modest array of electro-acoustic actuators. To date, subjective reactions to the synthesized signals are not conclusive due to the small number of test subjects and constrained exposure times. However, no individual thus far has reported any sensation when exposed to infrasound alone at peak levels up to 97 dB.

### References

Hansen, K; Zajamsek, B and Hansen, C, *Identification of low frequency wind turbine noise using secondary windshields of various geometries*, NCEJ, March-April 2014

*The Results of an Acoustic Testing Program Cape Bridgewater Wind Farm, 44.5100.R7:MSC*, The Acoustics Group, Lilyfield, NSW, November 2014

Walker, B, *Infrasound Measurement, Interpretation, Misinterpretation and Simulation*, Wind Turbine Noise 2013, August 2013

Walker, B and Celano, J, *Measurement and Synthesis of Wind Turbine Infrasound*, Acoustical Society of America Spring Meeting, June, 2013

Walker, B; Hessler, G; Hessler, D; Rand, R and Schomer, P, *A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin*, December, 2012

Zosuls, A; Kelley, R; Mountain D and Grace, S, *Development of experimental facility for testing human response to ILFN from wind turbines,* ICA 2013 Montreal, Canada 2 - 7 June 2013

Schomer, P, *A proposed theory to explain some adverse physiological effects of the infrasonic emissions at some wind farm sites*, 5th International Conference on Wind Turbine Noise, Denver 28-30, August 2013

Tachibana and Yokoyama, *Audibility of low frequency sounds – Part 1: Experiment on hearing threshold for pure tones*, Low Frequency Noise 2012, Stratford, May 2012

Yokoyama and Tachibana, *Audibility of low frequency sounds – Part 2: Audibility of low frequency components in wind turbine noises*, Low Frequency Noise 2012, Stratford, May 2012

6th International Meeting
on
Wind Turbine Noise
Glasgow  20-13 April 2015

# Subjective experiments on the auditory impression of the amplitude modulation sound contained in wind turbine noise

**Sakae Yokoyama,** Kobayasi Institute of Physical Research,
Higashi-Motomachi 3-20-41, Kokubunji, Tokyo, 185-0022, Japan.
E-mail: sakae@kobayasi-riken.or.jp

**Tomohiro Kobayashi,** Kobayasi Institute of Physical Research,
Higashi-Motomachi 3-20-41, Kokubunji, Tokyo, 185-0022, Japan.
E-mail: Kobayashi@kobayasi-riken.or.jp

**Shinichi Sakamoto,** Institute of Industrial Science, The University of Tokyo,
Komaba 4-6-1, Meguro, Tokyo, 153-8505, Japan.
E-mail: sakamo@iis.u-tokyo.ac.jp

**Hideki Tachibana,** Professor Emeritus, The University of Tokyo,
Gumizawa 8-35-49, Totsuka, Yokohama, Kanagawa, 245-0061, Japan.
E-mail: pon-t@iis.u-tokyo.ac.jp

## Summary

Amplitude modulation sound, so called swish sound, is generally contained in wind turbine noise and it can increase psycho-acoustical annoyance in the areas around wind farms. Therefore, the methods to assess the characteristics of this kind of sound should be investigated in both viewpoints, physically and psycho-acoustically. Regarding the latter problem, the authors performed auditory experiments by using a test facility capable of reproducing low frequency sounds including infrasound. As the first experiment, the fluctuation sensation caused by amplitude modulation sounds was examined by using actual wind turbine noises recorded on sites, in which the frequency components were limited in steps by low-pass filtering processing. As a result, it has been found that the fluctuation sensation is apt to be caused by the fluctuation of the frequency components higher than about 100 Hz. As the second experiment, the noisiness sensation due to amplitude modulation sounds were examined by using artificially synthesized sounds by changing their modulation depth in eight steps. As a result, a tendency has been seen that noisiness increases with the increase of AM depth even if the time-averaged sound pressure level is the same.

## 1. Introduction

Regarding wind turbine noise (WTN) problem, a research project entitled “Research on the evaluation of human impact of low frequency noise from wind turbine generators” has been conducted over the three years from fiscal year 2010, funded by a grant from the Ministry of the Environment, Japan. In this research project, nationwide field measurement [1,2], social survey [3], and auditory experiments [4-7] were performed. As an experiment regarding the third topic, the authors have investigated the effect of amplitude modulation (AM) sound and reported the experimental results at inter-noise 2013 [5]. This experiment has been continued by increasing the number of the test subjects to improve the experimental reliability and the results are shown in this paper.

The experiment consisted of two subjects: one was to examine the frequency components in WTN causing fluctuation sensation including the audibility of low frequency components (Experiment-1), and the other was to investigate the effect of AM sounds on noisiness sensation (Experiment-2). In Experiment-1, actual WTNs recorded in the field measurements was used and in Experiment-2 an artificially synthesized noise modelling general WTNs with/without AM components were used.

## 2. Experimental system

In this study, the same experimental facility as used in the former auditory experiments on low frequency noise [4-7] was used again (see Fig. 1 and Picture 1). The facility was constructed in the Institute of Industrial Science, The University of Tokyo. To produce low frequency sounds, sixteen woofers with a diameter of 40 cm (FOSTEX, FW405N, lowest resonance frequency: 27 Hz) were installed on the partition wall between a reverberation room and an anechoic room. For the production of mid/high frequency components up to 8 kHz, a wide-range loudspeaker was set at the centre point of the 16 woofers. The cross-over frequency between the two systems was set at 224 Hz. The listening position was set at a point of 3.5 m from the centre position of the loudspeakers. To correct the frequency characteristic of the total system, the digital inverse-filtering technique was applied.

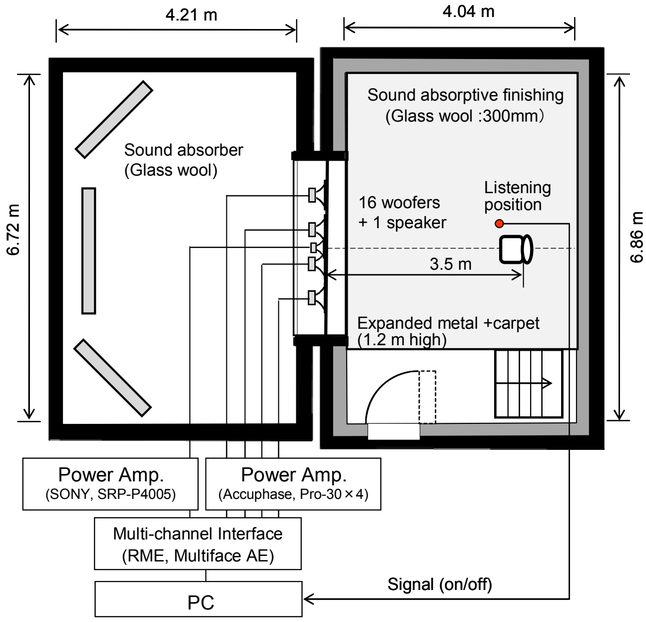


Figure 1 Experimental system.

Picture 1 Loudspeaker system and the listener's position in the receiving room.

## 3.EXPERIMENT-1

To examine the fluctuation sensation caused by AM sounds contained in WTNs, auditory experiment was performed by using actual WTNs recorded on sites.

### 3.1 Experimental conditions

As the test sounds in this experiment, actual WTNs recorded in four immission areas around wind farms in Japan were edited to have a duration time of 15 s (No.1, 2, 3 and 4 in Table 1). In addition, a WTN recorded at a point close to a wind turbine was also included for reference (No.5 in Table 1). The A-weighted time-averaged sound pressure levels (SPLs) for the duration time ($L_{\mathrm{Aeq,15s}}$) of the sounds were from 35.4 dB to 59.5dB. Figure 2 shows the time-traces of the A-weighted SPL by FAST dynamic characteristics ($L_{\mathrm{A,F}}$) of the sounds. The strength of AM of these WTNs were 3.5 dB to 5.2 dB in terms of the Amplitude Modulation Depth $D_{\mathrm{AM}}$ [2] (see Appendix). To avoid click sounds, the signals were gradually risen/fallen with a time of 0.5 s, respectively. Figure 3 shows 1/3-octave-band spectra of the test sounds, which were measured

Table 1  Test sounds used in this study.

| No. | Distance from the nearest wind turbine | $L_{\mathrm{Aeq,15s}}$ [dB] | $D_{\mathrm{AM,15s}}$ [dB] |
|---|---|---|---|
| 1 | 252 m | 46.4 | 4.0 |
| 2 | 416 m | 41.3 | 4.2 |
| 3 | 561 m | 41.9 | 3.5 |
| 4 | 908 m | 35.4 | 5.2 |
| 5 | 36 m | 59.5 | 3.5 |

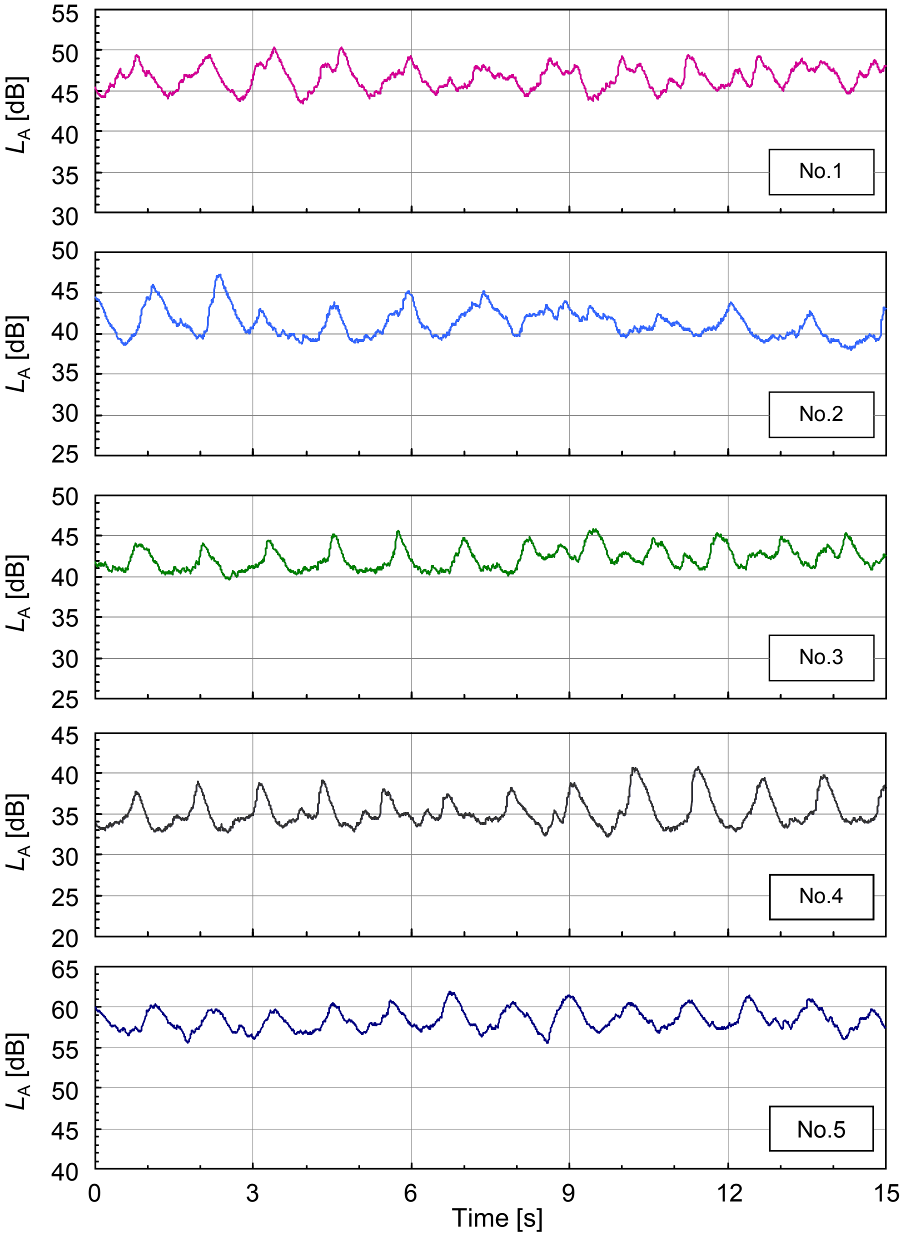


Figure 2  The time pattern of the test signals.

in the absence of the listener at the listening position where the centre of the listener's head would be. To investigate the frequency components causing "fluctuation sensation", the frequency component was limited in steps by using 8$^{\mathrm{th}}$Butterworth low-pass-filter for all of the test sounds. The cut-off frequencies were set at the 1/1 octave series from 1 kHz to 250 Hz and the 1/3 octave series from 125 Hz to 20 Hz, inclusive (12 in total). As an example, Figure 4 shows the original test sound No.1 and its variations made in such a way mentioned above.

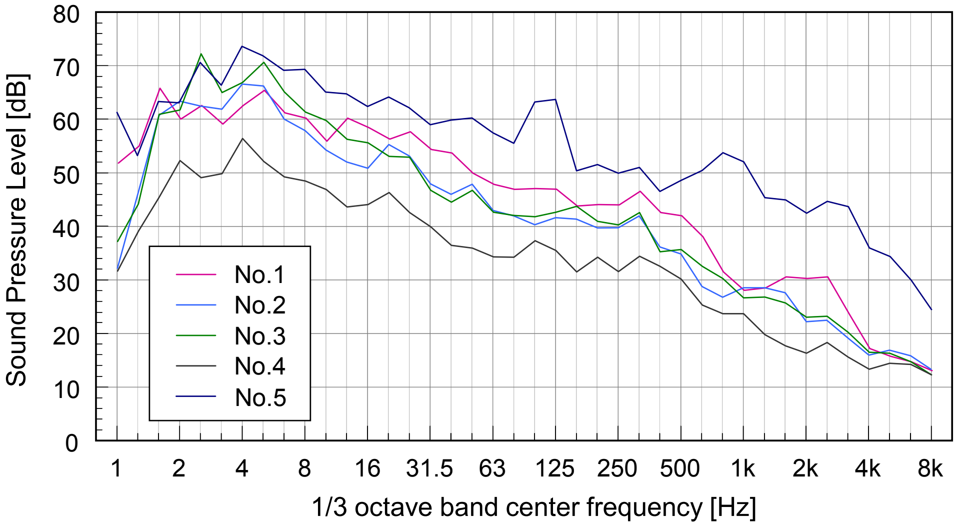


Figure 3 Sound pressure levels in 1/3 octave bands of the test

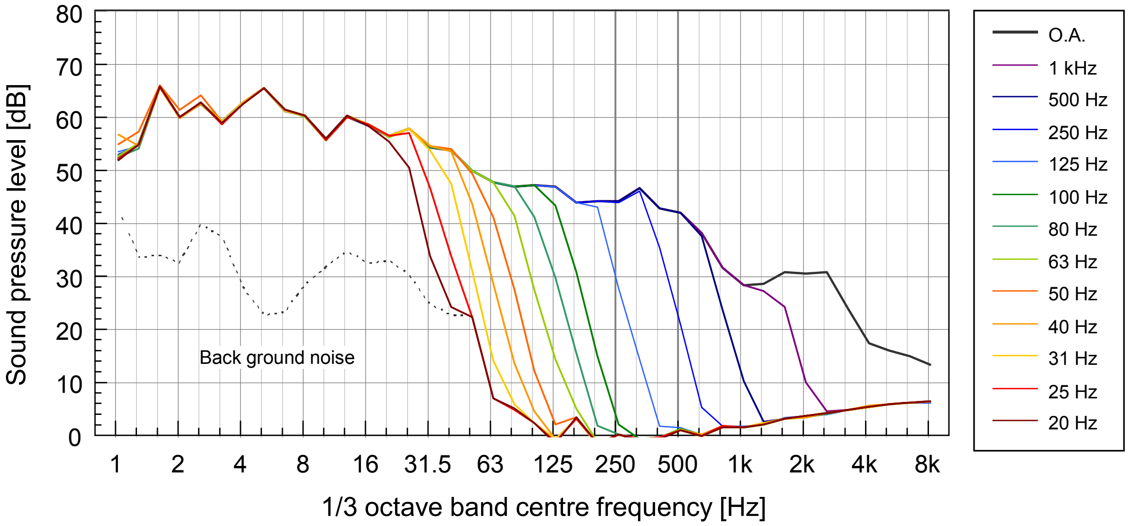


Figure 4 Sound pressure levels in 1/3 octave bands of the original test sound No.1 and its variations made by low-pass filtering.

## 3.2 Experimental procedure

In advance of the auditory experiment, video recording of a rotating wind turbine was presented to each subject and he/she was informed that periodically fluctuating sounds could be heard around a wind turbine due to the rotation of the blades. In the experiment, the subject sat straight on a chair to keep his/her head near the headrest in the test room (see Picture 1). Firstly, the subject was asked to judge the “audibility/sensitivity” of the test sound. In case where the subject judged the test sound “audible/sensible”, he/she was also asked to answer the extent of the “fluctuation sensation” in three-step category as shown in Table 2. The total time needed to complete the test on 65 test sounds (the test sounds No.1 to No.5; 12 modified sounds processed by the low-pass-filtering and original sound) was about 30 minutes including rest times in between. In this experiment, 17 subjects from 21 year-old to 26 year-old (13 males and 4 females) with normal hearing abilities participated. This experiment was performed according to the ethical code of The Kobayasi Institute of Physical Research.

## 3.3 Experimental results

As for the “audibility/sensitivity”, the ratio of the positive response was examined for each test sound. In the result shown in Figure 5, it is seen that the sounds of which cut-off frequency was higher than 80 Hz were 100% judged to be “audible/sensible”, whereas the positive response decreased as the cut-off frequency became lower. A tendency is also seen that the positive response increases as the level of the test sound becomes higher. To see the result for test

Table 2  3-step category.

| | |
|---|---|
| 0 | periodical fluctuation sensation is *not* felt *at all.* |
| 1 | periodical fluctuation sensation is felt *slightly.* |
| 2 | periodical fluctuation sensation is felt *clearly.* |

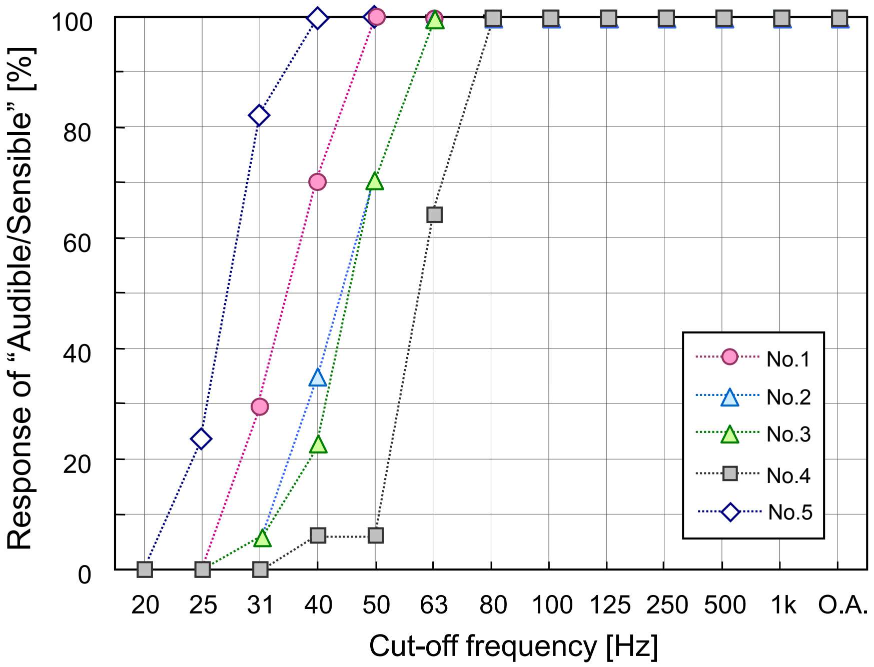


Figure 5  The ratio of the positive response of “audible/sensible” for each test sound.

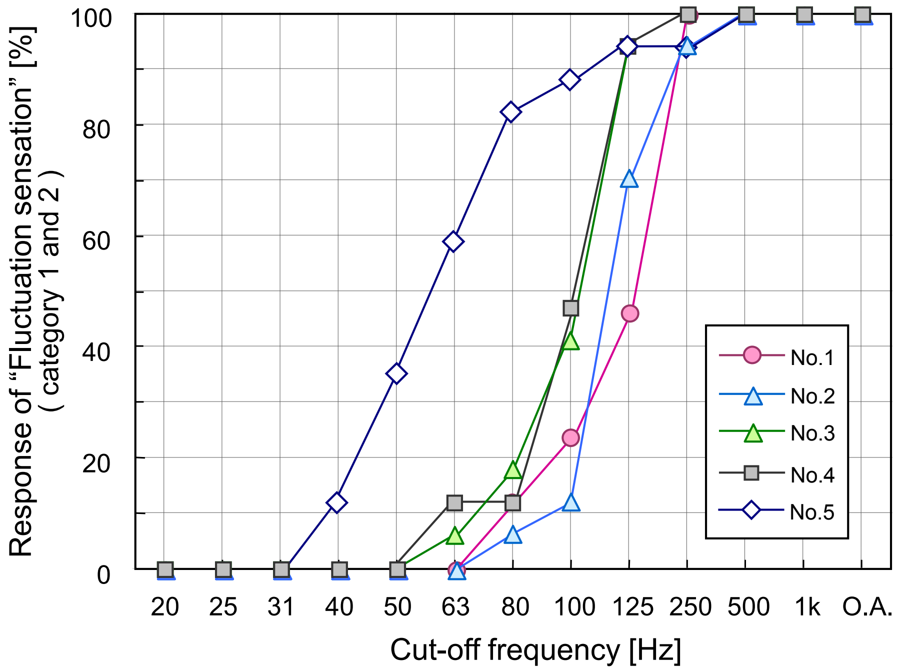


Figure 6  The ratio of the positive response for “fluctuation sensation” for each test sound.

sound No.1 which was the highest level among the test sounds recorded in immission area, the positive response was 0 % under the condition of cut-off frequency of 25 Hz or lower. As for the test sound No.5 recorded at a point close to a wind turbine, the positive response was 0 % under the condition of cut-off frequency of 20 Hz.

To investigate the extent of the "periodical fluctuation sensation", the ratio of the experimental results of "periodically fluctuating" (categories 1 and 2 in the 3-step category shown in Table 2) was examined for each test sound. In the result shown in Fig. 6, it is seen that the sounds with cut-off frequency higher than 500 Hz were 100% judged to be "periodically fluctuating", whereas the ratio of the sensation decreased as the cut-off frequency became lower. For the test sounds recorded in immission areas, the ratio of judgment of "periodically fluctuating" was 0% under the conditions of cut-off frequency of 50 Hz or lower and the fluctuation sensation is apt to cause at frequencies higher than about 100 Hz. Even in the case of the test sound No.5 recorded close to a wind turbine, the ratio of judgment was 0% under the conditions of cut-off frequency of 31.5 Hz or lower and the fluctuation sensation is apt to cause at frequencies higher than about 63 Hz.

## 4. EXPERIMENT-2

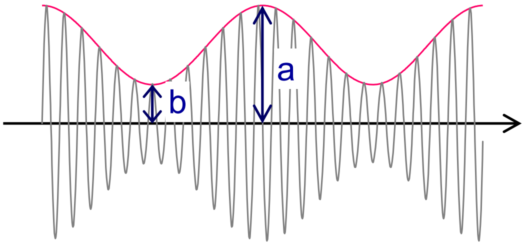
To examine the effect of AM sound in WTN on "noisiness" sensation, another experiment was performed using an artificially synthesized sound by changing its modulation depth.

### 4.1 Experimental conditions

To investigate the relationship between noisiness and the strength of AM, noisiness matching test was performed. As the test sounds, an artificially synthesized sound modelling the frequency characteristics of general WTNs (-4 dB/octave in band spectrum) was edited to have a duration time of 10 s. As for the standard stimulus (Ss), the model noise was set at 2-step; 35 and 45 dB in A-weighted time-averaged SPL ($L_{\mathrm{Aeq,10s}}$). As for the comparison stimulus (Sc), the model noise was modified so that its AM index ($\Delta L$:See Fig. 7) varied in 8-step as shown in Table 3, in which the AM depth ($D_{\mathrm{AM}}$) of the reproduced sounds are also shown. Figure 8 shows the variations of the test signals with 8-step different AM index. To avoid click sounds, the each sound was gradually risen/fallen with a time of 0.5 s.

### 4.2 Experimental procedures

As the test procedure, the method of adjustment was applied using the experimental system shown in Figure 9. In each condition, the standard stimulus (Ss) was firstly presented and secondly the comparison stimulus (Sc) was presented. After that, the subject was asked to adjust the "noisiness" of Sc so as to be equal to that of Ss by using a volume controller (see Picture 2). For the ascending/descending series in the case of Ss was set at 45 dBA, Sc was firstly set at 30/60 dB, respectively. The pair of Ss and Sc was repeated until the subject completed the adjustment. For each experimental condition, four trials (ascending/descending/ ascending/descending) were performed. For each test sound, the subject was also asked to express orally his/her impression on Sc using arbitrary onomatopoeic words. The total time needed to complete the test of 16 test sounds was about 2 hours including rest times in between. In this experiment, the test subjects were the same participated in the former experiment.



$$\begin{cases} a = 1 + m \\ b = 1 - m \end{cases}$$

$$\therefore m = \frac{a - b}{a + b}$$

$$\Delta L = 10 \log_{10} \frac{a^2}{b^2}$$

$$= 10 \log_{10} \left( \frac{1 + m}{1 - m} \right)^2$$

$$\therefore m = \frac{10^{\Delta L / 20} - 1}{10^{\Delta L / 20} + 1}$$

* $m$ : amplitude modulation degree

Figure 7 Definition of the AM index; $\Delta L$.

Table 3 Strength of AM of the comparison stimuli (Sc).

| AM index ($\Delta L$) [dB] | $D_{AM}$ [dB] (Ss: 35 dB) | $D_{AM}$ [dB] (Ss: 45 dB) |
|---|---|---|
| 0 | 0.8 | 0.8 |
| 1 | 1.2 | 1.1 |
| 2 | 1.7 | 1.7 |
| 3 | 2.3 | 2.3 |
| 4 | 3.0 | 3.0 |
| 6 | 4.3 | 4.3 |
| 8 | 5.5 | 5.6 |
| 10 | 6.7 | 6.9 |

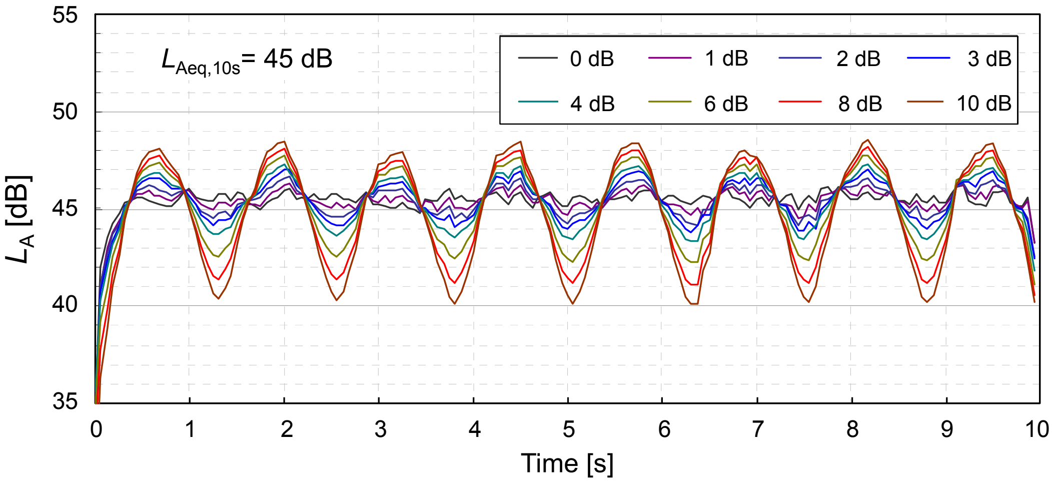


Figure 8 Variations of the test signals modulated in 8 steps ($\Delta L$).

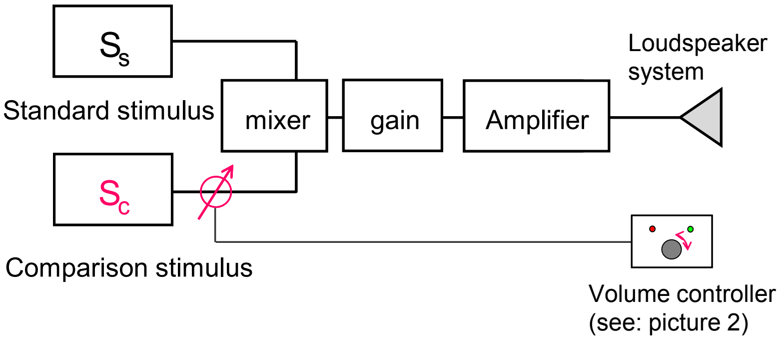
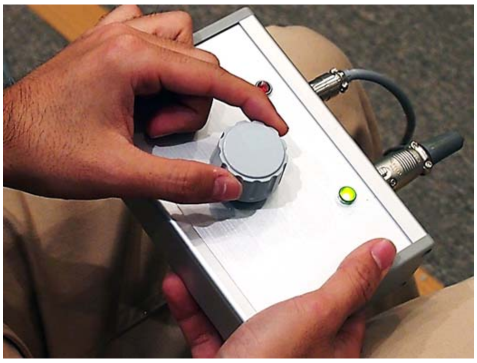


Figure 9 Experimental system for the noisiness matching test.



Picture 2 Volume controller used in the matching test.

### 4.3 Experimental results

Figure 10 show the experimental results of the noisiness matching test. In each figure, X-axis indicates AM index ($\Delta L$) of Sc and Y-axis indicates the adjusted level in $L_{\mathrm{Aeq,10s}}$. In both the figures, 0 dB on Y-axis means the $L_{\mathrm{Aeq,10s}}$ of $\mathrm{S_S}$ and values of $L_{\mathrm{Aeq,10s}}$ of $\mathrm{S_C}$ adjusted by the subjects were plotted in relatively level. The gray plots are the levels of adjusted Sc by each subject, the red ones are the arithmetic average of the levels of adjusted Sc by all subjects and the vertical bars indicate the standard deviations. In these results, it is seen that the averaged level of the adjusted Sc decreased as the AM index became higher. However, it is also seen that the standard deviation increased as the index became higher. This might mean that there are differences among individuals in noisiness sensation for noises with strong amplitude fluctuation.

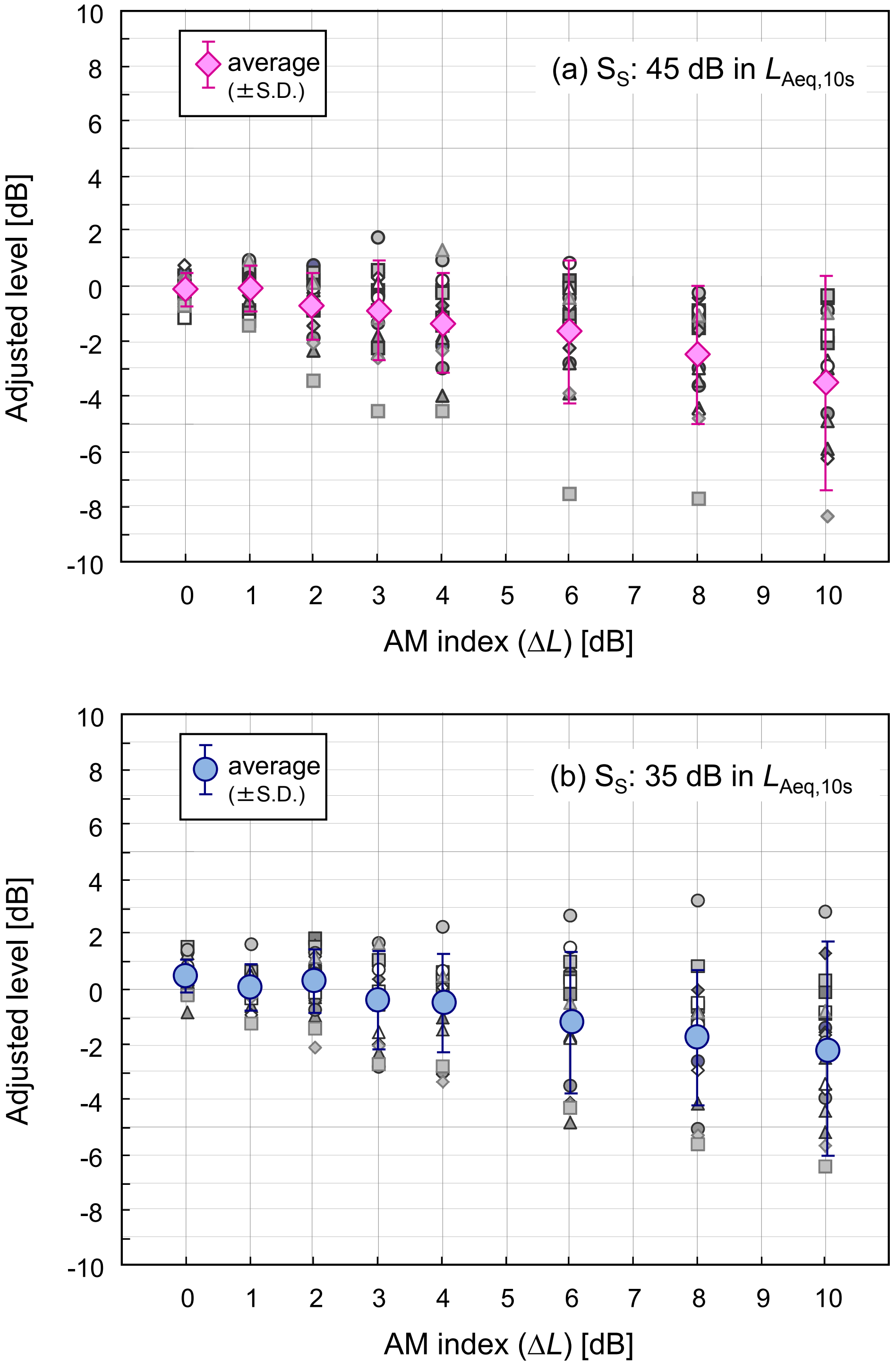


Figure 10 Experimental results of noisiness matching test.

From the results of expression using onomatopoeic words for each test sound, the ratio of "fluctuation sensation" was calculated by applying the logistic regression analysis. In the analysis, such onomatopoeic words as "Zah, Zah", "Zahn, Zahn", "Guon, Guon" were regarded as "fluctuating". Figure 11 shows the relationship between AM index ($\Delta L$) of Sc and the ratio of the results judged as "fluctuating", in which it is seen that the "fluctuating" was caused when AM index was higher than 1.7 dB in the case of Ss was set at 45 dBA (1.5 dB in terms of $D_{AM}$) and 1.9 dB in the case of Ss was set at 35 dBA (1.6 dB in terms of $D_{AM}$), respectively. This tendency is consistent with reference [8].

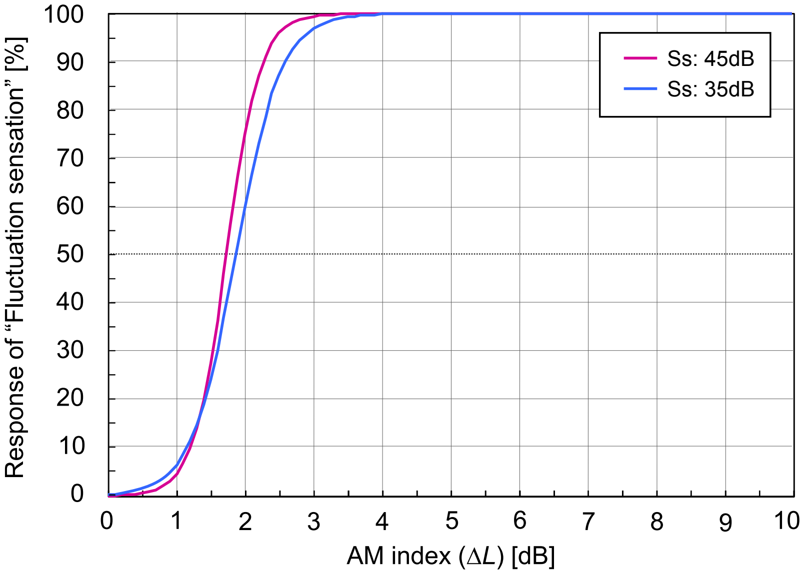


Figure 11 Fluctuation sensation vs. AM index ($\Delta L$) .

## 4. CONCLUSIONS

In this study, the effects of amplitude modulation sounds generally contained in wind turbine noise have been investigated in two kinds of auditory experiments. From the results of the first experiment performed using actual WTNs recorded at wind farm sites, it has been suggested that the frequency components lower than 25 Hz are not "audible/sensible" and "periodical fluctuation sensation" causes due to the frequency components higher than about 100 Hz for WTNs observed in the immission areas.

From the results of the second experiment performed using artificially synthesized test noises with varying strength of AM, the tendency has been found that the noisiness increases as the increase of the strength of AM, whereas there aredifferences among individuals in noisiness sensation for noises with strong amplitude fluctuation. From the results of examination using onomatopoeic words,it has been observed that "fluctuation sensation" causes the AM index was higher than 1.7 dB (1.5 dB in terms of $D_{AM}$) for WTNs of 45 dB in $L_{Aeq}$.

## ACKNOWLEDGEMENTS

The authors would like to express their appreciation to Professor Seiichiro Namba, Professor Sonoko Kuwano and Professor Yôiti Suzuki for their helpful advice. This study was performed as a part of the research project on wind turbine noise sponsored by the Ministry of the Environment, Japan.

## REFERENCES

[1] H. Tachibana, H. Yano, A. Fukushima, S.Sueoka, “Nationwide field measurements of wind turbine noise in Japan,” Noise Control Eng. J., 62(2), 90-101 (Mar-Apr 2014).

[2] A. Fukushima, K. Yamamoto, H. Uchida, S. Sueoka, T. Kobayashi and H. Tachibana, “Study on the amplitude modulation of wind turbine noise: part 1-Physical investigation,” Proc. Inter-noise 2013, (2013).

[3] S. Kuwano,T. Yano, T. Kageyama, S. Sueoka, H. Tachibana, “Social survey on wind turbine noise in Japan,” Noise Control Eng. J., 62(6), 503-520 (Nov-Dec 2014).

[4] S. Sakamoto, S. Yokoyama, H. Yano, H. Tachibana, “Experimental study on hearing thresholds for low frequency pure tones,” Acoust. Sci. & Tech., 35(4), 213-218 (2014).

[5] S. Yokoyama, S. Sakamoto, and H. Tachibana, “Study on the amplitude modulation of wind turbine noise: part 2- Auditory experiments,” Proc. Inter-noise 2013 (2013).

[6] S. Yokoyama, S. Sakamoto, S. Tsujimura, T. Kobayashi, H. Tachibana, “Loudness experiment on general environmental noise considering low-frequency components down to infrasound,” Acoust. Sci. & Tech., 36(1), 24-30 (2015).

[7] S. Yokoyama, S. Sakamoto, and H. Tachibana, “Perception of low frequency components in wind turbine noise,” Noise Control Eng. J., 62(5), 295-305 (Sept-Oct 2014).

[8] D. Bowdler and G. Leventhall, *Wind turbine noise*, Multi-Science Publishing Co., Brentwood, Essex, 2011).

## APPENDIX

The procedure to calculate the AM depth, $D_{\mathrm{AM}}$, is as follows.
The difference of the A-weighted sound pressure levels measured through FAST and SLOW dynamic characteristics of a sound level meter ($L_{\mathrm{A,F}}(t)$ and $L_{\mathrm{A,S}}(t)$, respectively) is calculated as follows:

$$\Delta L_{\mathrm{A}}(t) = L_{\mathrm{A,F}}(t) - L_{\mathrm{A,S}}(t)$$

To evaluate the magnitude of AM statistically, the AM depth is defined as the 90 % range of $\Delta L_{\mathrm{A}}(t)$. That is,

$$D_{\mathrm{AM}} = \Delta L_{\mathrm{A,5}} - \Delta L_{\mathrm{A,95}}$$

where, $D_{\mathrm{AM}}$ is the AM depth and $\Delta L_{\mathrm{A,5}}$ and $\Delta L_{\mathrm{A,95}}$ are the 5 % and 95 % A-weighted sound pressure levels [dB], respectively.

# 5th International Conference
# on
# Wind Turbine Noise
# Denver 28 – 30 August 2013

## Infrasound and the ear

**Geoff Leventhall    Acoustical Consultant    Ashtead  Surrey  UK.**

**geoff@activenoise.co.uk**

### Summary

In an earlier critique of the Wind Turbine Syndrome, the author described how the abdomen was rich in sounds at infrasonic frequencies, originating in the heart beat, muscle contractions, fluid movements etc. (Leventhall 2009). This has now been extended to consider infrasound within the inner ear, infrasound which has also originated in normal body processes. The inner ear is connected through the cochlear aqueduct to the cerebrospinal fluid, which picks up pulsations from the heartbeat and breathing. Typical frequencies are: heartbeat ~I.0Hz and harmonics, breathing ~0.3Hz. Pulsations are transmitted to the inner ear fluid (perilymph) through the cochlear aqueduct at sufficient level to drive the ear in reverse, in a similar manner to otoacoustic emissions. Measurement of the resulting pressure in the occluded ear canal permits estimation of the deflection of the tympanic membrane due to the reverse transmission of internally generated infrasound. Earlier work on this, by others, is described and developed to estimate the external infrasound which would produce similar pressures in the inner ear to that produced by internal infrasound. The result is compared with the levels of infrasound from wind turbines in the same frequency range as the internally generated infrasound.

**1 Hearing at low frequencies.** The pure tone hearing threshold has been measured in a chamber down to 4Hz (Watanabe and Møller 1990) and to lower frequencies using earphones (Yeowart and Evans 1974). The chamber data is shown in Fig 1, where it is compared with the ISO standard threshold (ISO:226 2003). The Watanabe and Møller threshold at 4Hz is 107dB. Yeowart and Evans give higher binaural thresholds: 112dB at 4Hz and 121dB at 2Hz.

The mechanism of hearing down into low frequencies is through normal excitation of the auditory cortex, as shown by fMRI investigations (Dommes, Bauknecht et al. 2009 ). Dommes, Bauknecht et al used functional Magnetic Resonance Imaging (fMRI) to investigate responses of the brain when exposed to infrasound both above and below the hearing threshold. Audible infrasound excited the auditory cortex,

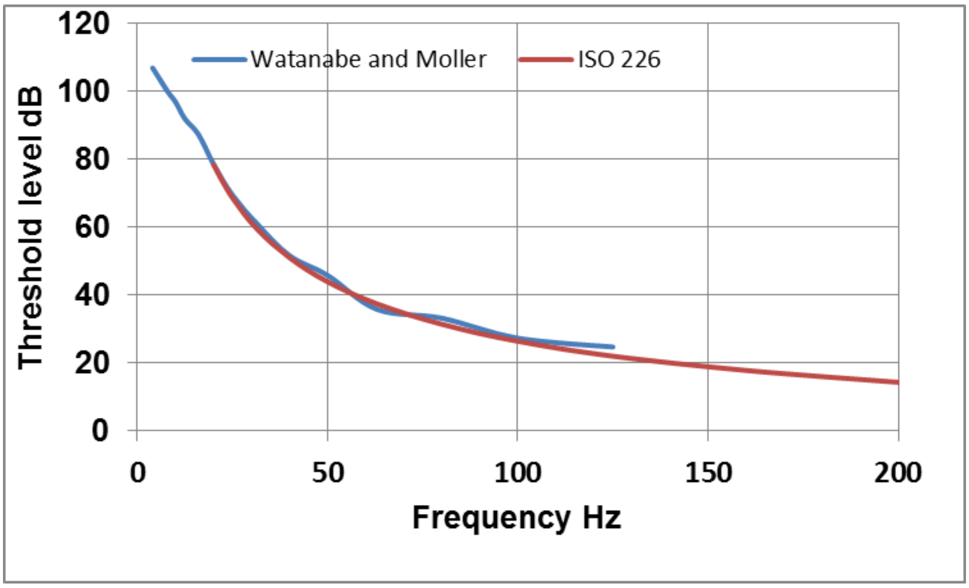


Fig 1 Low frequency hearing thresholds

which is where hearing perception occurs. Inaudible infrasound did not show an excitation. This is to be expected if infrasound enters into the hearing system, and is transmitted to the brain in a similar manner to higher frequency sounds. The following frequencies and levels were used by Dommes, Bauknecht et al.

| Freq Hz | 500 | 48 | 36 | 12 | 12 | 12 |
|---|---|---|---|---|---|---|
| Level dB | 105 | 100 | 70 | 120 | 110 | 90 |

They summarise the results of their work as:

> "In our study, no other cortical regions owed a comparably extensive response to the high-level stimuli as did the auditory cortex, indicating that LFT [low frequency tones] were mainly perceived via acoustic pathways instead of representing a somatosensory phenomenon."
>
> "In our study, cortical activation patterns appeared to be similar for all frequencies applied, suggesting that LFT are processed in a similar way as frequencies of our main hearing range (200 to 5000Hz)."
>
> "We presented the 12Hz stimuli at three different levels. Tone bursts of 120 and 110 dB resulted in cortical activation. The 90dB stimulus did not induce a significant response of the auditory cortex in group analysis which, in agreement with the findings of Møller and Pedersen (2004), indicates that this SPL is below the estimated perception threshold for 12 Hz." (Møller and Pedersen 2004)

This shows that low frequency tones and infrasound are perceived through the normal auditory pathways, the same pathways as for higher frequencies.

Furthermore, sounds, including infrasound, which are below the hearing threshold, do not produce a response in the auditory cortex, as is also the case for higher frequencies at levels below threshold. Whilst the lowest frequency used was 12Hz, the regular slope of the hearing threshold indicates that similar processes are likely to apply at lower frequencies.

## 2. The ear is a two way street

The ear is a mechanical system which operates in both forward and reverse directions. In normal, forward operation, sound waves excite the tympanic membrane (ear drum), which drives the ossicles to impart vibrations to the cochlear fluid (perilymph) via the oval window. (Fig 2) These vibrations propagate up and down the cochlea to the pressure release of the round window, causing waves along the basilar membrane, which excite the hair cells. These then send signals via the auditory nerve to the auditory cortex, where they are interpreted as sound The system is mechanical up to the oval window and hydrodynamic within the cochlea.

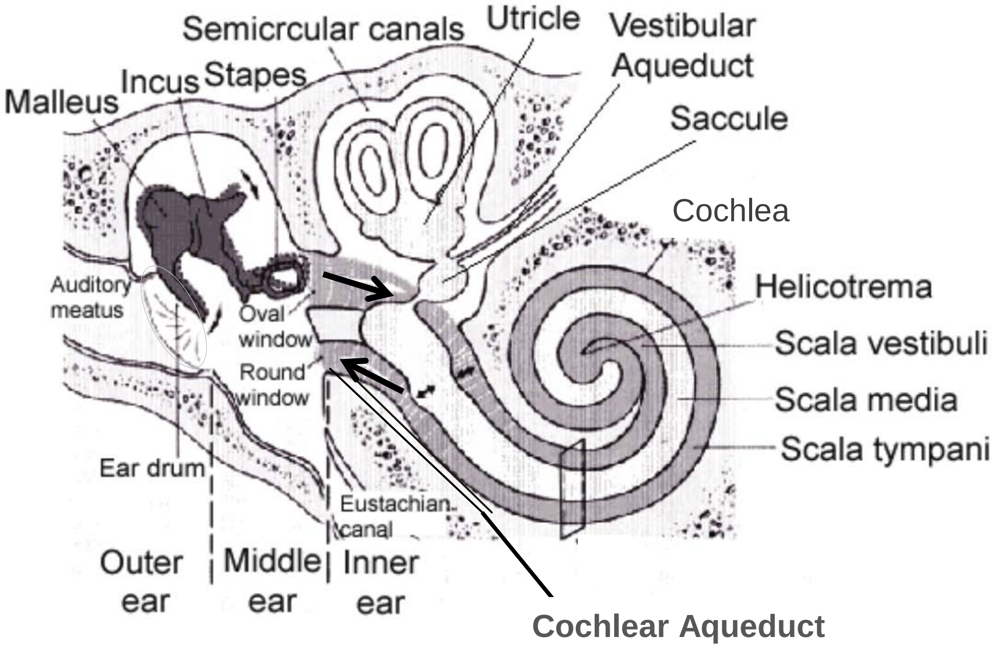


Fig 2 Action of the ear. Adapted From (Maroonroge, Emanuel et al. 2009)

Reverse action of the ear was demonstrated through otoacoustic emissions (OAE) in which “ringing” of the cochlear amplifier, which is based in the outer hair cells, sends vibrations back through the oval window and ossicles to excite the tympanic membrane (TM). Vibrations of the TM can be detected by a microphone in the ear canal (Kemp 2002).

Another example of reverse action of the ear is recent development of a hearing aid which by-passes the ossicles, and is useful for patients with conductive hearing loss. A small vibrator is attached to the round window and is energised from sounds detected externally. The vibrator sends signals in reverse direction through the cochlea, via the round window and, in this way, excites the basilar membrane and produces the correct perception of sounds. (Skarzynski, Olszewski et al. 2013).

In a simple device, for example a lever or a transformer, forward and reverse operation are reciprocal. This assumption will be made, initially, for forward and reverse ear operation of the tympanic membrane-ossicle-oval window system, but modified later.

## 3. Function of the cochlear aqueduct.

The cerebrospinal fluid originates mainly from the choroid plexus in the ventricles of the brain and bathes the brain and the spinal cord in the subarachnoid space, providing protection, lubrication and an egress for metabolic wastes. The fluid can be sampled by lumbar punctures. The cochlear aqueduct is a small duct which connects the subarachnoid space to the perilymphatic space of the inner ear, permitting bidirectional flow of cerebrospinal fluid and allowing pressure equalisation of the cochlea, Fig 3. The cochlear aqueduct offers a high resistance to high frequencies and there has been some discussion about its function, but it appears to pass low frequency fluctuations, originating in the cerebrospinal fluid, into the fluid of the inner ear (Traboulsi and Avon 2007). This effect is strong enough to drive the ear in reverse so that the infrasound generated by heartbeat and breathing, which enters the inner ear via the cochlear aqueduct, can be detected with a microphone in the ear canal.

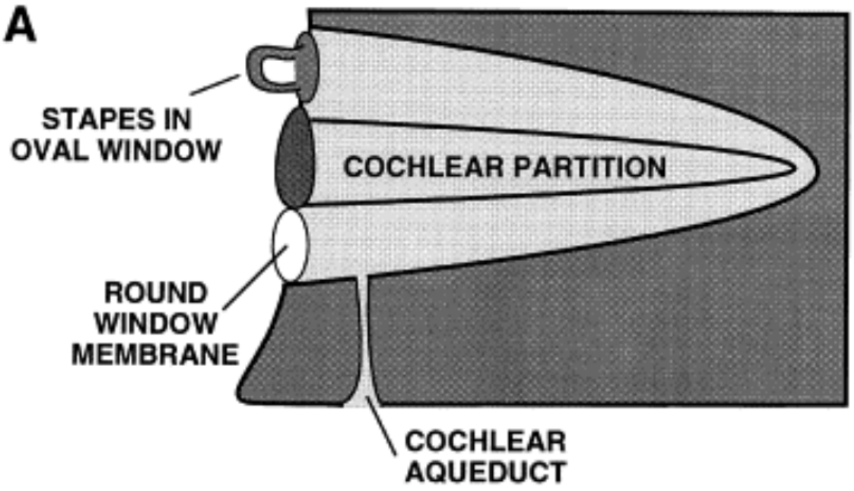


Fig 3 Illustrating the cochlear aqueduct (Gopen, Rosowski et al 1997)
The cochlear partition contains the basilar membrane

Some properties of the cochlear aqueduct have been given by Gopen, Rosowski et al. (Gopen, Rosowski et al. 1997).There are normal biological variations in dimensions, but the following were used as an average for modelling.

Length = 10mm

Radius = 0.1mm

At low frequencies, the acoustical impedance of the cochlear aqueduct ($Z_{CA}$) is resistive with $R_{CA} \approx 2.5 \times 10^{11}$ acoustic ohms ($Pa.s.m^{-3}$).

Additionally:

Cochlear impedance: $Z_C \approx 70 \times 10^9$ acoustic ohms

Stapes impedance: $Z_S \approx -j(3.3 \times 10^{14}/\omega)$ i.e. stiffness controlled

Round window impedance: $Z_{RW} \approx Z_S/10$

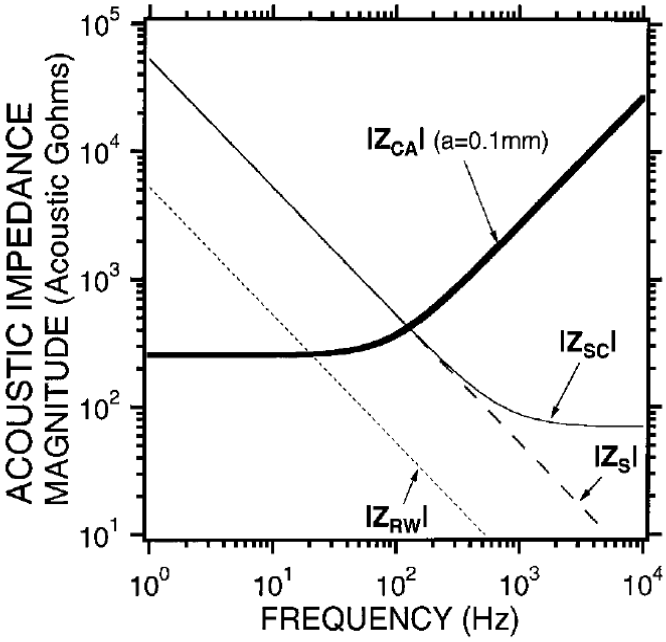


Fig 4 . Impedance magnitudes of cochlear aqueduct $|Z_{CA}|$, round window $|Z_{RW}|$, stapes and cochlear partition $|Z_{SC}|$, stapes alone, $|Z_S|$ from Gopen, Rosowski et al 1997

Fig 4 shows the magnitudes of these ear impedances. The cochlear aqueduct is resistive up to nearly 100Hz, after which the mass component of its contained fluid becomes increasingly significant. The stapes-cochlear partition and the round window are both stiffness controlled, with $|Z_{SC}|$ about 10 times the magnitude of $|Z_{RW}|$. Vibrations at low frequencies, passing through the cochlear aqueduct, see the impedances of the round window and the stapes-cochlear partition in parallel and, since $|Z_{SC}| >> |Z_{RW}|$, most of the flow goes to the round window. However, the remaining energy, which travels through the cochlea to the oval window, is sufficient to vibrate the ossicles and tympanic membrane.

**4 Mechanism** The cochlear aqueduct transmits pressure pulsations, which occur in the cerebrospinal fluid due to heartbeat and breathing, from this fluid to the inner ear fluid. Salt and Hullar suggested that the nearby round window acts as a pressure release to the pulsations into the inner ear from the adjacent aqueduct, so negating any effect of vibrations from the cerebrospinal fluid.(Salt and Hullar 2010). However, from above, Some of the incident energy travels backwards through the cochlea and stapes, exciting the tympanic membrane. Following on from Gopen, Rosowski et al, Traboulsi and Avon considered the cochlear aqueduct to act as a low pass filter, with a corner frequency of about 20Hz, and detected pressure peaks in the inner ear (cochlea) at 0.2Hz from breathing and at 1Hz from heartbeat.(Traboulsi and Avon 2007). Recent work has measured the transfer function between pulsations occurring in the carotid artery in the neck and the consequent pressure detected in the ear canal, when it was occluded by a microphone (Furihata and Yamashiti 2013). The mechanism here is that the low frequency pulsations from heartbeat and breathing transfer to the cerebrospinal fluid, which transmits them to the inner ear via the cochlear aqueduct. The consequent pulsations in the inner ear drive the ossicles in reverse, as in otoacoustic emissions. Furihata and Yamashiti deduce the displacement of the tympanic membrane from the pressure measured in the $700mm^3$ volume of the occluded ear canal.

The infrasonic pulsations which enter the inner ear via the cochlear aqueduct spread throughout the cochlea and activate the hair cells along the basilar membrane, in a similar manner to the operation of the vibratory hearing aid on the round window.

Spontaneous otoacoustic emissions (SOAE), which appear to be at single frequencies, actually show modulation sidebands under detailed analysis, the modulation being closely correlated with heart beat (Long and Talmage 1997). For example, a SOAE of 1658Hz had associated components at about 1657Hz and 1659Hz, both 15dB down on the central component. Long and Talmage suggested that the components may be due to changes in blood flow altering the mass of the basilar membrane, although other causes were also considered. This work illustrates the interaction between the inner ear and the beating heart.

**5. Further Development**. Consider the ossicles and associated membranes (tympanic membrane, oval window) as a bidirectional mechanical system. In normal hearing, the displacement of the tympanic membrane is transmitted through the ossicles to the oval window and into the cochlea. In the reverse process, the oval window is driven by internally generated pulsations of the cochlear fluid, leading to displacements of the ossicular chain and of the tympanic membrane. Initially, assume a simple transformer model in which the forward and reverse processes are balanced. That is, a forward gain of about 25dB and a reverse loss of the same magnitude occur. Then, if the tympanic membrane displacement which results from internally generated vibration of the oval window is known, an external sound, which produces the same displacement of the tympanic membrane, will lead to similar displacement of the oval window.

In order to make an estimate, it is necessary to know:

- The displacement of the tympanic membrane when driven by an internal source.
- The external airborne sound which also produces this displacement.

**6. Magnitudes – Internal source** Furihata and Yamashiti, measured the pressure due to tympanic membrane deflection in the known volume of the occluded ear canal. Levels were 95-98dB, leading to an estimate of tympanic membrane displacement of approximately 0.1µm. Analysis of the waveform, as detected in the ear canal, is shown in Fig **5** over a period of 600 seconds for frequencies below 5Hz.

There is a prominent 1Hz, from heartbeat, with 2Hz and 3Hz harmonics. Below 1Hz there are the frequencies from breathing and other internal sources. This energy has travelled back through the cochlea and ossicles to vibrate the tympanic membrane.

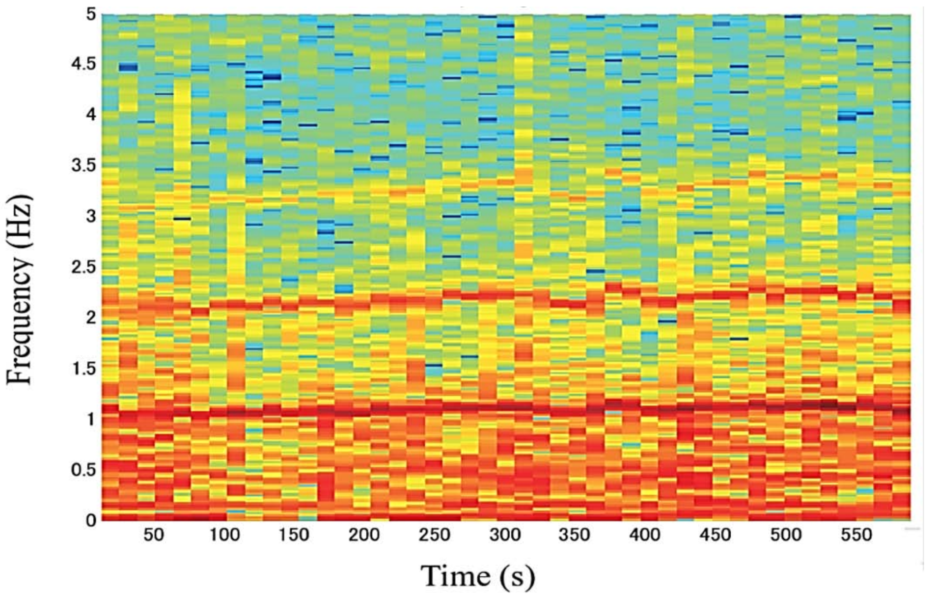


Fig 5 Spectrum of infrasonic pressure in the occluded ear canal

**7. Magnitudes – External source**. The displacement of the tympanic membrane by external sound sources has been measured by a number of authors, normally using optical methods of varying complexity.

- The displacement at low frequencies from an excitation of 60dB was about 1nm (Dalhoff, Turcanu et al. 2007).
- The displacement at low frequencies from an excitation of 80dB was 10-15nm (Huber, Schwab et al. 2001).
- Comparison of several measurements showed that the maximum displacement at low frequencies was from ≈ $2\text{x } 10^{-2}$ to 0.1µm per Pascal, as in Fig 6. (Rosowski, Cheng et al. 2011)

Fig 6, which shows deflections normalised to 1Pa, has an average deflection at low frequencies of approximately $5 \text{ x } 10^{-2}$ µm /Pa, or 0.1µm at 2Pa (100dB).

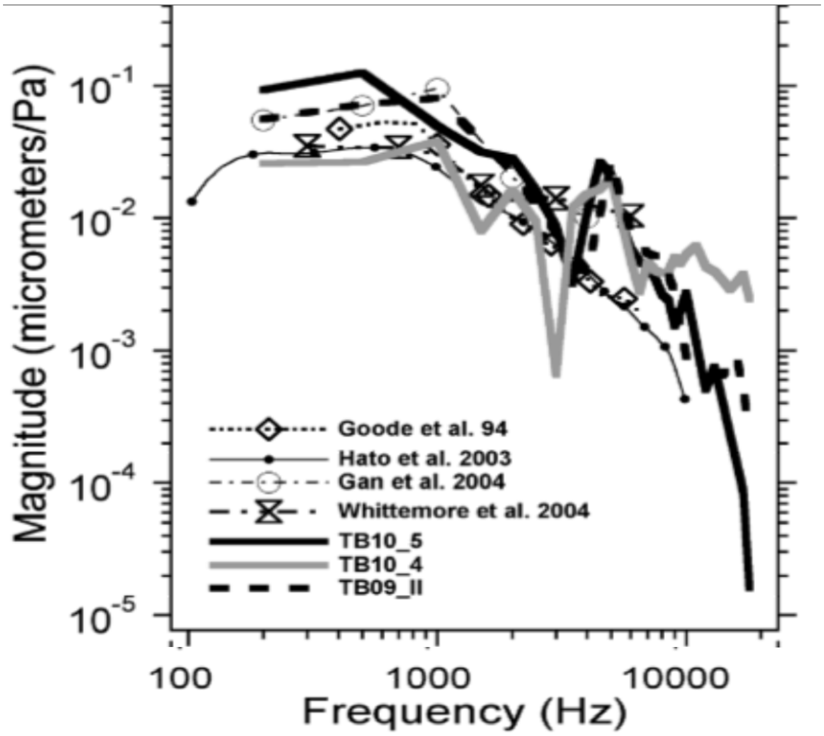


Fig 6 Tympanic membrane displacements. From Rosowski and Cheng

The different measurements described above are consistent, as 1nm = 0.001µm, 10nm = 0.01µm and a 20dB change in pressure level produces a ten times change in displacement. Therefore, 0.1µm displacement of the tympanic membrane can be associated with an external level of about 100dB.

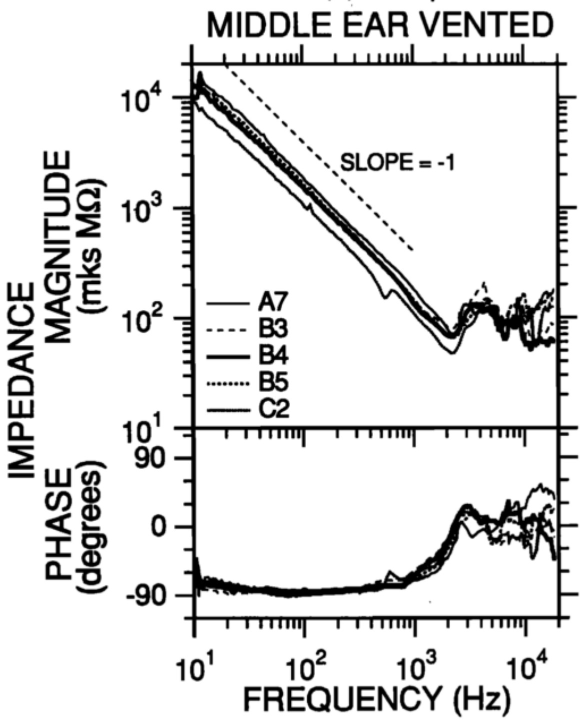


Fig 7 Gerbil middle ear input impedance

Although the tympanic membrane exhibits complex vibration patterns at high frequencies, it moves uniformly at low frequencies(Cheng, Hamade et al. 2013). Fig 6 indicates approximately constant displacement at low frequencies, which is expected from a resonant membrane below its natural frequency.

Human tympanic membrane studies have generally been limited to a low frequency of around 100Hz, but work on animals has used lower frequencies. For example, the gerbil tympanic membrane deflection has been investigated down to 10Hz. (Ravicz, Rosowski et al. 1992). Fig 7 shows frequency dependence of the live gerbil middle ear input impedance.

The impedance is inversely proportional to velocity, which leads to constant displacement for constant force.

Considering the similarities between all mammalian ears, the work on gerbils is a good indication that human ears will continue at constant displacement down to lower frequencies than shown in the measurements of Fig 6.

Therefore it is assumed that external infrasound at a level of 100dB will cause a tympanic membrane displacement of 0.1µm down to very low frequencies. This is similar to the value found for internal infrasound by Furihata and Yamashiti in Section 6 above.

**8 Discussion** The pressure fluctuations in the occluded ear canal, measured by Furihata and Yamashiti, were used to determine the changes of the small volume enclosed between the microphone and tympanic membrane, and hence the average displacement of the tympanic membrane. Factors which might affect the result include:

- Flexible walls of the ear canal
- Heat loss to the walls of the ear canal
- Pressure increase of the enclosed volume opposing the movement of the tympanic membrane
  .

These effects tend to reduce the pressure in the ear canal volume, so underestimating the tympanic membrane displacement from internal infrasonic sources.

Is the assumption of reciprocal forward and reverse action of the ear valid? It is known that the forward gain of the ear is about 25dB. The reverse gain is not as well known. The forward middle ear pressure gain is defined as

$\overrightarrow{M_1 = \frac{P_v}{P_{ec}}}$ and the reverse gain as $\overleftarrow{M_2 = \frac{P_{ec}}{P_v}}$

Where $P_{ec}$ is the ear canal pressure and $P_v$ is the vestibule pressure of the cochlear fluid. (Puria 2003)

Puria measured down to 100Hz on cadaver ears and showed that the gain varied with frequency. Forward gain peaked at 1kHz at about 20dB, but dropped and levelled off at low frequencies (100Hz). Reverse gain at 1kHz was about -30dB, showing an additional 10dB reverse loss. This means that the middle ear is not a reciprocal mechanical system, but has additional losses in the reverse direction, and the simplifying assumption made earlier must be corrected. At the lowest frequency given by Puria(100Hz), forward gain was -5dB and reverse gain -45dB, leading to a 40dB loss.

Cheng et al measured forward transmission in cadaver ears using a loudspeaker source and measured reverse transmission by direct mechanical stimulation of the ossicular chain. (Cheng , Harrington et al. 2011). Results showed that "The ear canal pressure….. produced by TM motions evoked by reverse stimulation is usually 40 dB lower than the forward sound stimulus needed to produce similar stapes motion across most of measurement frequency range". Thus, in the expressions for $M_1$ and $M_2$ above, for equivalent values of $Pv$ (pressure in the vestibule), the forward ear canal pressure $Pec_{(forward)}$ is greater than the ear canal pressure received by reverse transmission $Pec_{(reverse)}$.

Both Puria and Cheng worked with fresh cadaver ears. Live gerbils at higher frequencies showed a 20-25dB forward gain and a 35dB loss for reverse transmission. (Dong and Olson 2006)

Forward transmission ends at the compliant round window and the volume velocities of the oval window and round window are almost the same. In contrast, reverse transmission sees the relatively high impedance of the ossicles. The pressure difference across the scala in the cochlea is lower for reverse transmission than for forward transmission. (Steiger, Rosowski et al. 2013)

The work on forward and reverse transmission indicates that a direct comparison of the tympanic membrane displacements, as suggested in the simple reciprocal model, underestimates the level in the inner ear from internally generated infrasound. The underestimate is not well known, but could be 10- 20dB, or perhaps up to 40dB at low frequencies. Consequently, to allow for the reverse losses, the forward pressure in the ear canal, from external sources, should be increased by, say, 20dB. This requires a forward tympanic membrane displacement of 1.0 µm, which results from the ten times higher pressure, to give similar effect in the vestibule to that which gives a reverse tympanic membrane displacement of 0.1 µm. The forward tympanic membrane displacement will now correspond with an external sound of 120dB.

This is a greater level than the levels from wind farms in the same frequency region as that of the infrasound which is produced internally in the body. For example, the Shirley wind farm gave maximum of about 75dB at 0.3Hz. (Walker, Hessler et al. 2012). A number of other measurements indicate that, at typical nearby residential distances, the one- third octave level at 10Hz is 60~70dB, rising at ~ 5dB/octave into lower frequencies. (O'Neal, Hellweg et al. 2011) (Evans, Cooper et al. 2013) (Hayes 2006). More detailed analysis than one-third octave is required to show the components of the blade passage pulse.

Wind turbine infrasound levels are well below the hearing threshold of Fig1 and, following the work of Dommes, Bauknecht et al described earlier, will not excite the auditory cortex. There is also a large headroom for fluctuations.

The conclusion is that the continuous inner ear infrasound levels due to internal sources, which are in the same frequency range as wind turbine rotational frequencies, are higher than the levels produced in the inner ear by wind turbines, making it unlikely that the wind turbine noise will affect the vestibular systems, contrary to suggestions made following the measurements at Shirley. The masking effect is similar to that in the abdomen (Leventhall 2009). The body, and vestibular systems, appear to be built to avoid disturbance from the high levels of infrasound which are produced internally from the heartbeat and other processes. In fact, the hearing mechanisms and the balance mechanisms, although in close proximity, have developed to minimise interaction. (Carey and Amin 2006)

## Appendix

Professor Peter Seligman, an expert in cochlear implants, stated in his submission to the 2011 Australian Federal Senate inquiry into the 'Social and economic impact of rural wind farms':

> *"Aside from the issue of an adverse response to something which cannot be measured, it is worth noting that apart from external sources, the hearing and vestibular systems are subjected to very high levels of body generated noise. These include, walking, breathing, heartbeat, chewing and head movement. Body noises generated in this way were a problem in the Cochlear Ltd project to develop a fully implantable cochlear implant. In this case the microphone was implanted subcutaneously behind the ear. The level of infrasound picked up from the body by this microphone was a major problem and far exceeded all infrasound from external sources. In fact it was some ten times greater".* (Seligman 2011)

## References

Carey, J. and N. Amin (2006). "Evolutionary Changes in the Cochlea and Labyrinth: Solving the Problem of Sound Transmission to the Balance Organs of the Inner Ear." THE ANATOMICAL RECORD PART A 288A: 482-490.

Cheng , J., et al. (2011). "The Tympanic Membrane Motion in Forward and Reverse Middle-Ear Sound Transmission." What Fire is in Mine Ears: Progress in Auditory Biomechanics AIP Conf. Proc. 1403, doi: 10.1063/1.3658141
521-527.

Cheng, J. T., et al. (2013). "Wave motion on the surface of the human tympanic membrane: Holographic measurement and modeling analysis." J. Acoust Soc Am **133**(2): 918-937.

Dalhoff, E., et al. (2007). "Distortion product otoacoustic emissions measured as vibration on the eardrum of human subjects." Proc Nat Acad Sci (PNAS) **104**(5): 1546-1551.

Dommes, E., et al. (2009 ). "Auditory cortex stimulation by low-frequency tones—An fMRI study." Brain Research: 1 2 9 - 1 3 7.

Dong, W. and S. Olson (2006). "Middle Ear Forward and Reverse Transmission in Gerbil." J Neurophysiol **95**: 2961-3006.

Evans, T., et al. (2013). "Infrasound levels near windfarms and in other environments." Report for South Australia EPA - http://www.epa.sa.gov.au/xstd_files/Noise/Report/infrasound.pdf.

Furihata, K. and M. Yamashiti (2013). "Transfer function for vital infrasound pressures between the carotid artery and the tympanic membrane." J. Acoust. Soc. Am. **133**(2): 1169-1186.

Gopen, Q., et al. (1997). "Anatomy of the normal human cochlear aqueduct with functional implications." Hear Res. **107**: 9-22.

Hayes, M. (2006). "The measurement of low frequency noise at three UK wind farms. DTI Report - 06/1412 "http://webarchive.nationalarchives.gov.uk/+/http:/www.berr.gov.uk/energy/sources/renewables/explained/wind/onshore-offshore/page31267.html.

Huber, A., et al. (2001). "Evaluation of Eardrum Laser Doppler Interferometry as a Diagnostic Tool." The Laryngoscope **111**: 501-507.

ISO:226 (2003). "Acoustics - Normal equal-loudness contours."

Kemp, D. T. (2002). "Otoacoustic emissions, their origin in cochlear function, and use." British Medical Bulletin **63**: 223-241.

Leventhall, G. (2009). "Wind Turbine Syndrome - an appraisal." Evidence for Glacier Hills enquiry . Public Sevice Commission of Wisconsin: document PSC REF#:121877.

Long, G. R. and C. L. Talmage (1997). "Spontaneous otoacoustic emission frequency is modulated by heartbeat." J Acoust Soc Am **102**(5): 2831-.

Maroonroge, S., et al. (2009). "Basic Anatomy of the Human Hearing System." http://www.usaarl.army.mil/publications/hmd_book09/files/Section%2015%20-%20Chapter%208%20Ear%20Anatomy.pdf.

Møller, H. and C. S. Pedersen (2004). "Hearing at low and infrasonic frequencies." Noise and Health **6**: 37 - 57.

O'Neal, R., et al. (2011). "Low frequency noise and infrasound from wind turbines." Noise Control Eng Jnl **59 (2)**: 135-157.

Puria, S. (2003). "Measurements of human middle ear forward and reverse acoustics: Implications for otoacoustic emissions." J. Acoust Soc Am **113**(5): 2773 - 2789.

Ravicz, M. E., et al. (1992). "Sound-power collection by the auditory periphery of the Mongolian gerbil Meriones unguiculatus. I: Middle-ear input impedance." J. Acoust Soc Am **92**(1): 157-177.

Rosowski, J., et al. (2011). "New Data on the Motion of the Normal and Reconstructed Tympanic Membrane." Otol Neurotol **32**(9): 1559-1567.

Salt, A. N. and T. E. Hullar (2010). "Responses of the ear to low frequency sounds, infrasound and wind turbines." Hearing Research **268** 12-21.

Seligman, P. (2011). "Submission to Federal Senate inquiry into the 'Social and economic impact of rural wind farms'.".

Skarzynski, H., et al. (2013). "Direct round window stimulation with the Med-El Vibrant Soundbridge: 5 years of experience using a technique without interposed fascia." Eur Arch Otorhinolaryngol
DOI 10.1007/s00405-00013-02432-00401.

Steiger, C., et al. (2013). "Comparison of forward (ear-canal) and reverse (round-window) sound stimulation of the cochlea." Hearing Research **301**: 105-114.

Traboulsi, R. and P. Avon (2007). "Transmission of infrasonic pressure waves from cerebrospinal to intralabyrinthine fluids through the human cochlear aqueduct: Non-invasive measurements with otoacoustic emissions." Hear Res. **233**: 30-39.

Walker, B., et al. (2012). "A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin." Report 122412-1 Public Service Commission Wisconsin PSC Ref 178200.

Watanabe, T. and H. Møller (1990). "Low frequency hearing thresholds in pressure field and free field." Jnl Low Freq Noise Vibn **9**(3): 106-115.

Yeowart, N. S. and M. J. Evans (1974). "Thresholds of audibility for very low frequency pure tones." J Acoust Soc Am **55**(4): 814-818.

# 6th International Meeting

# on

# Wind Turbine Noise

# Glasgow 20-13 April 2015

## Wind Turbine Noise and Health Study: Summary of Results

**Presented by: David S. Michaud, PhD, Health Canada, Consumer and Clinical Radiation Protection Bureau, Environmental Health and Risk Assessments Division, Ottawa, Ontario, K1A1C1**

### Summary

A cross-sectional epidemiological study was initiated by Health Canada to investigate the prevalence of health effects or health indicators among a sample of Canadians exposed to wind turbine noise (WTN) using both self-reported and objectively measured health outcomes. The sample was drawn from communities in Ontario (ON) and Prince Edward Island (PEI) where there were a sufficient number of dwellings within the vicinity of wind turbine installations. One participant between the ages of 18-79 years was randomly selected from each household. The final sample included 1238 participates (606 males, 632 females) living between 0.250 and 11.22 km from operational wind turbines. The response rate was 78.9% and did not significantly vary across sampling strata or between provinces. Modelled A- and C-weighted WTN levels reached 46 dBA and 63 dBC, respectively, however, dBC analysis yielded limited additional value as results were highly correlated with dBA (r=0.94). Sample characteristics were relatively homogenous, with some minor differences found in age, employment, type and ownership of dwelling. WTN exposure was not found to be related to hair cortisol concentrations, blood pressure, resting heart rate or any of the measured sleep parameters (i.e., sleep latency, sleep time, rate of awakenings, sleep efficiency). Self-reported results obtained through an in-person questionnaire do not provide support for an association between increasing WTN levels and self-reported sleep disturbance, use of sleep medication, or diagnosed sleep disorders. Similarly, no significant association was found between WTN levels and self-reported migraines, tinnitus, dizziness, diabetes, hypertension, perceived stress or any measure of quality of life. Statistically significant exposure-response relationships were observed between increasing WTN levels and an increase in the prevalence of long term high annoyance towards several wind turbine features, including: noise, shadow-flicker, visual impacts, blinking lights and vibrations. The influence of background noise on annoyance and the association between WTN annoyance and other reported and measured outcomes is presented.

## 1. INTRODUCTION

In Canada, jurisdiction for the regulation of noise is shared across many levels of government. Health Canada's mandate with respect to wind power includes providing science-based advice, upon request, to federal departments, provinces, territories and other stakeholders on the potential impacts of WTN on community health and well-being. Provinces and territories, through the legislation they have enacted, make decisions in relation to areas including installation, placement, sound levels and mitigation measures for wind turbines.

Globally, wind energy is relied upon as an alternative source of renewable energy. In Canada wind energy capacity has grown from approximately 137 Megawatts (MW) in 2000 to 9,698 megawatts (MW) in 2015 (CANWEA, 2015). At the same time, there has been concern from some Canadians living within the vicinity of wind turbine installations that their health and well-being are negatively affected from exposure to WTN.

The scientific evidence base in relation to WTN exposure and health is limited, which includes uncertainty as to whether or not low frequency noise (LFN) and infrasound from wind turbines contributes to the observed community response and potential health impacts. Studies that are available differ in many important areas including methodological design, the evaluated health effects, and strength of the conclusions offered (Krogh et al. 2011; Mroczek et al. 2012; Nissenbaum et al. 2012; Pawlaczyk-Luszczyriska et al. 2014; Pedersen and Persson Waye 2004, 2007; Pedersen et al. 2009; Shepherd et al. 2011; Tachibana et al. 2012).

In July 2012, Health Canada announced its intention to undertake a large scale epidemiology study in collaboration with Statistics Canada. The study, entitled the: *Community Noise and Health Study* was launched to support a broader evidence base on which to provide federal advice and in acknowledgement of the community health concerns expressed in relation to wind turbines.

## 2. EXPERIMENTAL DESIGN

The study was undertaken in two Canadian provinces, Ontario (ON) and Prince Edward Island (PEI), where there were a sufficient number of dwellings within the vicinity of wind turbine installations. The study consisted of three primary components: an in-person questionnaire, administered by Statistics Canada to randomly selected participants living at varying distances from wind turbine installations; collection of objectively measured outcomes that assess hair cortisol, blood pressure and sleep quality; and, more than 4000 hours of WTN measurements conducted by Health Canada to support the calculation of WTN levels at residences captured in the study scope.

### 2.1 Calculation of outdoor WTN levels at dwellings

Sound pressure levels were estimated at each receptor using both ISO 9613-1 (ISO, 1993) and 9613-2 (ISO, 1996) as incorporated in the commercial software CadnaA version 4.4 (Datakustik® 2014). The calculations included all wind turbines within a radius of 10 km, and were based on manufacturers' octave band sound power spectra at 10 metre height, 8 metres per second wind speed for favourable propagation conditions. The few dwellings beyond this distance were assigned the same calculated WTN value as dwellings at 10 km. The manufacturers' data was verified for consistency using on-site measurements of wind turbine sound power. To support the assessment and reporting of data, and permit comparisons to other studies, residences were grouped into different categories of calculated outdoor A-weighted WTN levels as follows: <25; 25−<30; 30−<35; 35−<40; and 40−46.

### 2.2 Calculation of outdoor nighttime background sound levels at dwellings

As a result of certain meteorological phenomena (atmospheric stability and wind gradient) coupled with a tendency for background sound levels to drop throughout the day in rural/semi-rural environments, WTN can be more perceptible at the receptor during nighttime (Pedersen et al. 2010 a, b; van den Berg 2011, 2013). It is possible to estimate nighttime sound pressure levels in Canada using the provincial noise regulations for Alberta, Canada (AUC 2013), which estimates ambient noise levels in rural and suburban environments. When modelled in accordance with these regulations, estimated levels can range from 35 dB to 51 dB, based on dwelling density per quarter section, which represents an area with a 451 m radius, and distance to heavily travelled roads or rail lines. In ON, road noise for the six lane concrete #401 Highway was calculated using the US Traffic Noise Model (Federal Highway Administration (FHWA) TNM® 1998) module in the CadnaA software. This value was used when it exceeded the Alberta noise estimate (AUC 2013).

### 2.3 Questionnaire development

During early stages of development, a draft questionnaire in both English and French underwent pilot testing by Statistics Canada in the form of in-home interviews on a sample of 24 adults living near wind turbine installations in ON and Quebec. The location and participants involved in the pilot testing were not part of the final study sample. The final questionnaire reflected feedback following pilot testing and the collective input from subject matter experts and professionals with expertise in the field of community noise, social surveys, and direct physical health measures. The questionnaire underwent additional modifications subsequent to a 60 day public consultation period on the study design. To support the integrity of the study, the consultation did not include the questionnaire itself, but rather identified the themes addressed within the study.

The final questionnaire consisted of modules on demographics, noise annoyance, health effects, medication use, specific illnesses, sleep disturbance, and prevalent chronic disease. In addition to these modules, validated psychometric scales were incorporated, without modification, into the questionnaire. Self-reported stress was assessed using the Perceived Stress Scale (PSS) (Cohen et al. 1983), Quality of Life was assessed with the World Health Organization's (WHO) Quality of Life- BREF (WHOQOL-BREF) (WHOQOL Group 1998; Skevington et al. 2004) and the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al. 1989) was used to measure self-reported sleep quality.

A computer-assisted personal interviewing (CAPI) technique was applied to capture questionnaire responses from participants. CAPI allows for custom interviews for every respondent based upon their individual characteristics and survey responses. Its functionality includes the ability to automatically skip questions not applicable to a respondent, in addition to embedded checks for the identification of inconsistent or out-of-range responses. For the latter, on-screen prompts automatically identified invalid entries allowing for immediate feedback to the participant and correction of inconsistencies. Encryption software was applied to ensure the confidentiality of the data. The final questionnaire is publicly accessible in Canada's two official languages, French and English, through the Statistics Canada website (Statistics Canada 2014).

### 2.4 Data collection

The survey data was collected by 16 Statistics Canada trained interviewers between May and September, 2013. Interviewers introduced the study as the *Community Noise and Health Study*. The purpose of the study, the general content and the time commitment were communicated to potential participants at which time it was also noted that participation was voluntary and that any information provided would be kept confidential under the authority of the Statistics Act (Statistics Act, R.S.C. 1985, c. S-19). Once a roster of all adults (between the ages of 18 and 79 years) living in the dwelling was compiled, one individual from each household was randomly invited to participate in the study. No substitutions were permitted under any circumstances.

Detailed information on the study methodology, including the 60-day public consultation and peer review process is available on the Health Canada website. The detailed methodology for the study was also published by Michaud et al. (2013).

### 2.5 Statistical analysis

The analysis for dichotomous (categorical) endpoints (e.g., proportion of respondents who were highly annoyed to WTN, highly sleep disturbed, etc..), continuous endpoints (e.g., WHOQOL-BREF domains, hair cortisol, PSS, blood pressure and heart rate), and repeated measures endpoints (e.g., sleep actigraphy) all follow very closely to the description as outlined in Michaud et al. (2013), which gives a summary of the pre-data collection study design and objectives, as well as proposed data analysis. All models (for categorical, continuous and repeated measures endpoints) were adjusted for provincial differences. Province was initially assessed as an effect modifier. When the interaction between WTN and province was significant, separate models were reported for each province. When the interaction was not statistically significant, province was treated as a confounder in the model.

For the analysis of dichotomous endpoints, in cases when cell frequencies were small (i.e. <5) in the contingency tables or logistic regression models, exact tests were used as described in Agresti (2002) and Stokes et al. (2000). When the logistic regression model was fit, the Nagelkerke pseudo $R^2$ and Hosmer-Lemeshow (H-L) p-value are reported for all models. The Nagelkerke pseudo $R^2$ is a measure of the explained variance in the model and is referred to as a generalization of the coefficient of determination. When the p-value from the H-L goodness of fit test is >0.05 this indicates there is no statistically significant difference between the modelled and observed data.

In the analysis of repeated measures (longitudinal data) endpoints, data were modelled using linear mixed effects models (LMM), or generalized linear mixed models (GLMM) for counts. The generalized estimating equations (GEE) method, as available in Statistical Analysis System (SAS) procedure PROC GENMOD, was applied to the repeated measures data (Liang and Zeger, 1986; Stokes et al. 2000). PROC GENMOD addresses continuous or discrete responses based on a quasi-likelihood approach when modelling correlated responses. The within-subjects correlations were examined by comparing the quasi-likelihood information criterion (QIC) based on GEE with different working correlation matrix structures (unstructured, compound symmetry and autoregressive of first order), where smaller QIC values are considered to be a better fit of the model. As well, the within-subject correlations were examined graphically for the identification of obvious patterns. The simplest model with the best fit which follows the pattern as observed in the graphs is chosen to model the within-subject variability. The advantage of the GEE method is that they use all available data to estimate individual subject variability, but are not sensitive to the number of missing values.

For all types of endpoints when building the multiple regression models, all potential variables that were significant in the univariate analysis at the 20% level were considered for entry into the models. Variables remained in the final model if they were significant at a 10% level.

Statistical analysis was performed using SAS version 9.2. A 5% statistical significance level is implemented throughout unless otherwise stated. In addition, Bonferroni corrections (for categorical endpoints) and Tukey corrections (for continuous and repeated measures endpoints) are made to account for all pairwise comparisons to ensure that the overall Type I (false positive) error rate is less than 0.05.

The study was approved by the Health Canada and Public Health Agency of Canada Review Ethics Board (Protocol # 2012-0065 and #2012-0072).

## 3. RESULTS

Health Canada has completed its preliminary analysis of the data obtained. Research findings are presented below in accordance with the study component in which they were obtained i.e. in-person, self-report questionnaire findings, objectively measured responses, and noise measurements and calculations. As with other studies of this nature, a number of limitations and considerations apply to the study findings including:

- results may not be generalized to areas beyond the sample as the wind turbine locations in this study were not randomly selected from all possible sites operating in Canada;
- results do not permit any conclusions about causality; and,
- results should be considered in the context of all published peer-reviewed literature on the subject.

## 3.1 Outdoor WTN levels at dwellings

### *3.1.1 A-Weighted*

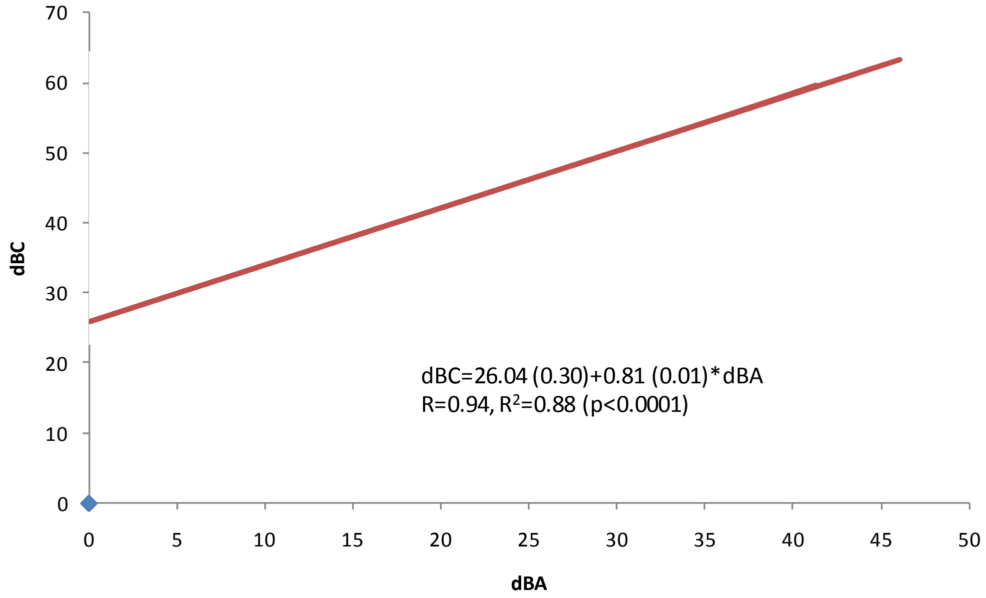
More than 4000 hours of WTN measurements conducted by Health Canada supported the calculations of A-weighted WTN levels at all 1238 dwellings captured in the study sample. Calculated outdoor A-weighted WTN levels for the dwellings in the study reached 46 dBA for wind speeds of 8m/s for favourable propagation conditions. This approach is the most appropriate to quantify the potential adverse effects of WTN. The calculated WTN levels are likely to be representative of yearly averages with an uncertainty of about +/- 5dB.

### *3.1.2 Low frequency noise*

Wind turbines emit LFN, which can enter the dwelling with little or no reduction in energy potentially resulting in rattles in light weight structures and annoyance (ANSI, 1995). Although the boundaries of LFN are not fixed, it generally includes frequencies between 20Hz and 200Hz. C-weighted sound levels can be a better indicator of LFN in comparison to A-weighted levels, and were calculated in order to assess the potential LFN impacts.

Calculated outdoor dBC levels for dwellings ranged from 24 dBC and reached 63 dBC. Three (3)% of the dwellings were found to exceed 60 dBC. No additional benefit was observed in assessing LFN because C- and A-weighted levels were so highly correlated. Depending on how dBC was calculated and what range of data was assessed, the correlation between dBC and dBA ranged from R=0.84 to R=0.97. Figure I illustrates the correlation when the entire dataset is used (R=0.94). It was therefore not surprising that the relationship between annoyance and WTN levels was predicted with equal strength using dBC or dBA and that there was no association found between dBC levels and any of the self-reported illnesses or chronic health conditions assessed (e.g., migraines, tinnitus, high blood pressure, etc.).

**Figure I. Correlation between calculated outdoor A- and C-weighted WTN levels**



Sound pressure levels were found to be below the recommended thresholds for reducing perceptible rattle and the annoyance that rattle may cause (ANSI, 1995). As LFN is generally considered to be an indoor noise problem, it was of interest to better understand how much outdoor LFN makes its way into the dwelling. At a selection of representative dwellings, Health Canada measurements showed an average of 14dB of outdoor WTN was blocked from entering a dwelling at low frequencies (16 Hz - 100 Hz) with closed windows compared to an average reduction of 10dB with windows partially open (data not shown).

### 3.2 Study population and participation

The study locations were drawn from areas in southwestern ON and PEI where there were a sufficient number of dwellings within the vicinity of wind turbine installations. Twelve (12) and 6 wind turbine developments were sampled in ON and PEI, representing 315 and 84 wind turbines respectively. All potential dwellings within approximately 600 m of a wind turbine were selected, as well as a random selection of dwellings between 600 m and 10 km. From these, one person between the ages of 18 and 79 years from each dwelling was randomly selected to participate.

Table I shows the final sample size distributed as a function of distance to the nearest wind turbine. Of the 2004 potential locations identified *a priori* from the address registry, 1570 were found to be valid dwellings during data collection. Of these, a total of 1238 households participated, resulting in an overall participation rate of 78.9%. Participation rate was similar regardless of proximity to wind turbines and equally high in both provinces.

|  | Distance to nearest wind turbine (km) |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  | ≤0.55 | 0.55−<1 | 1−<2 | 2−<5 | >5 | overall | CMH p-value[a] |
| Range of WTN (dB) | 37.4-46.1 | 31.8-43.6 | 26.3-40.4 | 14.6-30.9 | 0-18.2 |  |  |
| Total potential dwellings[e] | 143 | 887 | 781 | 95 | 98 | 2004 |  |
| ON | 76 | 718 | 669 | 60 | 80 | 1603 |  |
| PEI | 67 | 169 | 112 | 35 | 18 | 401 |  |
| Total number of potential dwellings out-of-scope n(%)[f] | 48 (33.6) | 158 (17.8) | 189 (24.2) | 19 (20.0) | 20 (20.4) | 434 (21.7) |  |
| ON | 29 (38.2) | 109 (15.2) | 166 (24.8) | 9 (15.0) | 14 (17.5) | 327 (20.4) | <0.0001[b] |
| PEI | 19 (28.4) | 49 (29.0) | 23 (20.5) | 10 (28.6) | 6 (33.3) | 107 (26.7) | 0.5263[b] |
| Demolished | 26 (18.2) | 25 (2.8) | 18 (2.3) | 5 (5.3) | 8 (8.2) | 82 (4.1) | 0.0142 |
| Vacant | 16 (11.2) | 55 (6.2) | 56 (7.2) | 5 (5.3) | 6 (6.1) | 138 (6.9) | 0.3812 |
| Unoccupied seasonal | 2 (1.4) | 36 (4.1) | 61 (7.8) | 7 (7.4) | 1 (1.0) | 107 (5.3) |  |
| >79 years of age | 4 (2.8) | 35 (3.9) | 50 (6.4) | 2 (2.1) | 5 (5.1) | 96 (4.8) |  |
| Other[c] | 0 (0.0) | 7 (0.8) | 4 (0.5) | 0 (0.0) | 0 (0.0) | 11 (0.6) |  |
| Final number of potential participants[d] | 95 | 729 | 592 | 76 | 78 | 1570 |  |
| Participants n (%) | 71 (74.7) | 583 (80.0) | 463 (78.2) | 58 (76.3) | 63 (80.8) | 1238 (78.9) | 0.9971 |
| ON | 34 (72.3) | 488 (80.1) | 396 (78.7) | 42 (82.4) | 51 (77.3) | 1011 (79.2) |  |
| PEI | 37 (77.1) | 95 (79.2) | 67 (75.3) | 16 (64.0) | 12 (100.0) | 227 (77.2) |  |

[a] The Cochran Mantel-Haenszel chi-square test is used to adjust for province unless otherwise indicated, p-values <0.05 are considered to be statistically significant; [b] Chi-square test of independence; [c] Other out-of-scope locations included dwellings under construction, institution, unavailable to participate and were suppressed here to protect the identify of individual participants; [d] Potential participants from locations established to be valid dwellings (equal to the difference between “Total potential dwellings” and “total number of potential dwellings out of scope”) used in the derivation of participation rates.[e] Total potential dwellings is further broken down by total potential dwellings in each province.[f] Total number of potential dwellings out of scope (given as a percentage of total potential dwellings) is broken down by province, as well it is equal to the sum of Demolished, Vacant, Unoccupied, Seasonal, >79 years of age, and Other. The percentage of dwellings that are Demolished, Vacant, Unoccupied, Seasonal, >79 years of age, and Other are based on the total number of potential dwellings in the area. CMH, Cochran Mantel-Haenszel; dB, decibel; km, kilometer; ON, Ontario, PEI, Prince Edward Island.

### 3.3 Questionnaire results

Results are presented in relation to WTN levels. For findings related to WTN annoyance, results are also provided by proximity to allow for comparisons with other studies. WTN is a more sensitive measure of exposure level and allows for consideration of topography, wind turbine characteristics and the number of wind turbines at any given distance. To illustrate, two similar dwellings may exist in similar environments located at the same distance from the nearest turbine operating in areas with 1 small and 75 large wind turbines respectively. These dwellings would be treated the same if the analysis was conducted using only distance to the nearest wind turbine, however, they would be completely different in terms of their WTN exposure levels.

The following were not found to be associated with WTN exposure:

•self-reported sleep (e.g., general disturbance, use of sleep medication, diagnosed sleep disorders);

•self-reported illnesses (e.g., dizziness, tinnitus, prevalence of frequent migraines and headaches) and chronic health conditions (e.g., heart disease, high blood pressure and diabetes); and

•self-reported perceived stress and quality of life.

While some individuals reported some of the health conditions above, the prevalence was not found to change in relation to WTN levels.

### *3.3.1 Self-reported sleep*

Long-term sleep disturbance can have adverse impacts on health (Knutson et al. 2009; McEwen, 2006; Zaharna and Gulleminault, 2010) and the WHO has proposed limits for protecting against noise-induced sleep disturbance (WHO, 1999, 2009). Self-reported sleep disturbance has been shown in some, but not all, studies to be related to exposure to wind turbines (Knopper and Ollson, 2011; McCunney et al., 2014; Pedersen, 2011).

The Pittsburgh Sleep Quality Index (PSQI) is a frequently used questionnaire for providing a validated measure of reported sleep pathology where scores can range from 0-21 and a global score of greater than 5 is considered to reflect subjective sleep pathology (Buysse et al. 1989). The PSQI was administered as part of the overall questionnaire, which also included questions about the use of sleep medication, prevalence of sleep disorders diagnosed by a healthcare professional and how sleep disturbed people were in general over the last year (i.e. percentage highly sleep disturbed). None of these measures were found to be related to WTN levels (see Table II).

### *3.3.2 Self-reported health effects*

As presented in Table II, results related to the reported diagnosis with a number of health conditions. None of these conditions were found to be associated with WTN levels. These conditions included, but were not limited to chronic pain, high blood pressure, diabetes, heart disease, dizziness, migraines and tinnitus.

### *3.3.3 Self-reported stress*

Exposure to stressors and how people cope with these stressors has long been considered by health professionals to represent a potential risk factor to health, particularly to cardiovascular health and mental well-being (Sapolsky et al. 2000; Stansfeld and Marmot, 2002). The PSS is a validated questionnaire that provides an assessment of the degree to which situations in one's life are appraised as stressful (Cohen et al. 1983). Average PSS scores were not found to be related to WTN levels.

**Table II. Self-reported measures related to sleep and illness as a function of WTN levels**

| Variable | WTN (dBA)<br><25 | <br>25−<30 | <br>30−<35 | <br>35−<40 | <br>40-46 | <br>overall | CMH[b] *p*-value |
|---|---|---|---|---|---|---|---|
| N | 84[a] | 95[a] | 304[a] | 521[a] | 234[a] | 1238[a] | |
| Health compared to one year ago (n, %Worse) [d] | 17 (20.2) | 12 (12.6) | 46 (15.1) | 90 (17.3) | 51 (21.8) | 216 (17.5) | 0.1724 |
| Migraines (n, %) | 18 (21.4) | 24 (25.3) | 56 (18.4) | 134 (25.8) | 57 (24.4) | 289 (23.4) | 0.2308 |
| Dizziness (n, %) | 19 (22.6) | 16 (16.8) | 65 (21.4) | 114 (21.9) | 59 (25.2) | 273 (22.1) | 0.2575 |
| Tinnitus (n, %) | 21 (25.0) | 18 (18.9) | 71 (23.4) | 129 (24.8) | 54 (23.2) | 293 (23.7) | 0.7352 |
| Chronic Pain (n, %) | 20 (23.8) | 23 (24.2) | 75 (24.8) | 118 (22.6) | 57 (24.5) | 293 (23.7) | 0.8999 |
| Asthma (n, %) | 8 (9.5) | 12 (12.6) | 22 (7.2) | 43 (8.3) | 16 (6.8) | 101 (8.2) | 0.2436 |
| Arthritis (n, %) | 23 (27.4) | 38 (40.0) | 98 (32.2) | 175 (33.7) | 68 (29.1) | 402 (32.5) | 0.6397 |
| High Blood Pressure (n, %) | 24 (28.6) | 36 (37.9) | 81 (26.8) | 166 (32.0) | 65 (27.8) | 372 (30.2) | 0.7385 |
| Use of high blood pressure in previous month (n, %) | 26 (31.3) | 34 (35.8) | 84 (27.6) | 163 (31.3) | 63 (27.0) | 370 (29.9) | 0.4250 |
| History of high blood pressure in family (n, %) | 44 (52.4) | 49 (53.8) | 132 (45.5) | 254 (50.6) | 121 (53.8) | 600 (50.3) | 0.6015 |
| Chronic bronchitis, emphysema, COPD (n, %) | 3 (3.6) | 10 (10.8) | 17 (5.6) | 27 (5.2) | 14 (6.0) | 71 (5.7) | 0.7676 |
| Diabetes (n, %) | 7 (8.3) | 8 (8.4) | 33 (10.9) | 46 (8.8) | 19 (8.2) | 113 (9.1) | 0.6890 |
| Heart disease (n, %) | 8 (9.5) | 7 (7.4) | 31 (10.2) | 32 (6.1) | 17 (7.3) | 95 (7.7) | 0.2110 |
| %Reporting high sleep disturbance[e] (n, %) | 13 (15.7) | 11 (11.6) | 41 (13.5) | 75 (14.5) | 24 (10.3) | 164 (13.3) | 0.4300 |
| Diagnosed sleep disorder e.g., sleep apnea or insomnia (n, %) | 13 (15.5) | 10 (10.5) | 27 (8.9) | 44 (8.4) | 25 (10.7) | 119 (9.6) | 0.3102 |
| Weekly use of sleep medication (n, %) | 16 (19.0) | 18 (18.9) | 39 (12.8) | 46 (8.8) | 29 (12.4) | 148 (12.0) | 0.0083 |
| Restless leg syndrome (n, %) | 7 (8.3) | 16 (16.8) | 37 (12.2) | 81 (15.5) | 33 (14.1) | 174 (14.1) | |
| Restless leg syndrome (ON) | 4 (6.7) | 15 (17.4) | 27 (11.0) | 78 (17.3) | 28 (16.5) | 152 (15.0) | 0.0629[f] |
| Restless leg syndrome (PEI) | 3 (12.5) | 1 (11.1) | 10 (16.9) | 3 (4.2) | 5 (7.8) | 22 (9.7) | 0.1628[f] |
| Use of medication for anxiety or depression (n, %) | 11 (13.1) | 14 (14.7) | 35 (11.5) | 59 (11.3) | 23 (9.8) | 142 (11.5) | 0.2470 |
| QoL past month[g] | | | | | | | |
| Poor (n, %) | 9 (10.8) | 3 (3.2) | 21 (6.9) | 29 (5.6) | 20 (8.6) | 82 (6.6) | 0.9814 |
| Good (n, %) | 74 (89.2) | 92 (96.8) | 283 (93.1) | 492 (94.4) | 213 (91.4) | 1154 (93.4) | |
| Health past month [g] | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dissatisfied (n, %) | 13 (15.5) | 13 (13.7) | 49 (16.1) | 66 (12.7) | 36 (15.4) | 177 (14.3) | 0.7262 |
| Satisfied (n, %) | 71 (84.5) | 82 (86.3) | 255 (83.9) | 455 (87.3) | 198 (84.6) | 1061 (85.7) | |
| PSQI mean | 6.22 (5.32, 7.11) | 5.91 (5.05, 6.77) | 6.00 (5.51, 6.50) | 5.74 (5.33, 6.16) | 6.09 (5.55, 6.64) | 5.94 (5.72, 6.17) | 0.7497 (ANOVA) |
| PSQI >5[h] (n, %) | 40 (49.4) | 45 (48.9) | 138 (46.5) | 227 (44.4) | 106 (46.7) | 556 (46.0) | 0.4740[i] |
| PSS mean(95%CI) | 11.68 (10.23, 13.13) | 11.17 (9.77, 12.57) | 11.30 (10.49, 12.11) | 11.40 (10.73, 12.08) | 12.27 (11.39, 13.15) | | 0.6606[i] |

[a]Columns may not add to total due to missing data; [b]The Cochran Mantel-Haenszel chi-square test is used to adjust for provinces unless otherwise indicated, p-values <0.05 are considered to be statistically significant; [c]Highly sensitive includes the two ratings: “very” and “extremely” sensitive; [d]Worse consists of the two ratings: "Somewhat worse now" and "Much worse now"; [e]High sleep disturbance consists of the two ratings: “very” and “extremely” sleep disturbed; [f]Chi-square test of independence; [g]Quality of Life and Satisfaction with Health were assessed with the two stand alone questions on the WHOQOL-BREF. Reporting “poor” overall Quality of Life reflects a response of “poor” or “very poor”, and “good” reflects a response of “neither poor nor good”, “good” or “very good”. Reporting “dissatisfied” overall Satisfaction with Health reflects a response of “very dissatisfied” or “dissatisfied”, and “satisfied” reflects a response of “neither satisfied nor dissatisfied”, “satisfied” or “very satisfied”; [h]an overall score above 5 on the PSQI is considered to represent subjective sleep pathology; [i]analysis performed using logistic regression. CMH, Cochran Mantel-Haenszel; dB, decibel; km, kilometer; ON, Ontario, PEI, Prince Edward Island.

### *3.3.4 Self-reported annoyance*

Annoyance is defined as a long-term response (approximately 12 months) of being "very or extremely annoyed" as determined by means of surveys. Reference to the last year or so is intended to distinguish a long term response from one's annoyance on any given day (ISO, 2003).

Statistically significant exposure-response relationships were found between increasing WTN levels and the prevalence of reporting high annoyance. Figure II illustrates that these associations were found with annoyance due to noise, vibrations, blinking lights, shadow and visual impacts from wind turbines. In general, annoyance (of any type) increased with increasing exposure to WTN levels. A statistically significant increase in annoyance was found when WTN levels exceeded 35 dBA.

## Figure II. Percentage highly annoyed by features associated with wind turbines

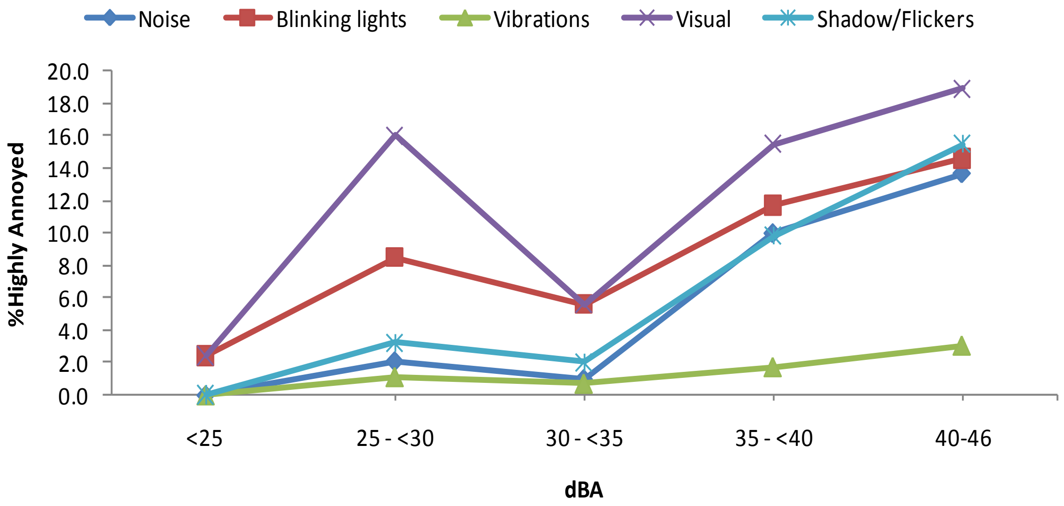


Figure II illustrates the observed prevalence in reported high annoyance to several features associated with wind turbines. There was a tendency for annoyance to increase significantly when WTN levels exceeded 35dBA.

Figure III illustrates the prevalence in high annoyance with WTN in ON and PEI as a function of WTN levels and distance to the nearest wind turbine. At the highest WTN levels (40-46 dBA in both provinces), the following percentages of respondents were highly annoyed by WTN: ON-16.5%; PEI-6.3%. Overall, the pattern of response was similar; however the prevalence of WTN annoyance was 3.29 times higher in ON versus PEI (95% confidence interval, 1.47 - 8.68). Assessed as a function of distance, annoyance was observed to drop at distances between 1-2km in ON, compared to PEI where almost all of the participants who were highly annoyed by WTN lived within 550m of a wind turbine. Investigating the reasons for provincial differences is outside the scope of the current study.

**Figure III. Percentage highly annoyed by WTN in ON and PEI**

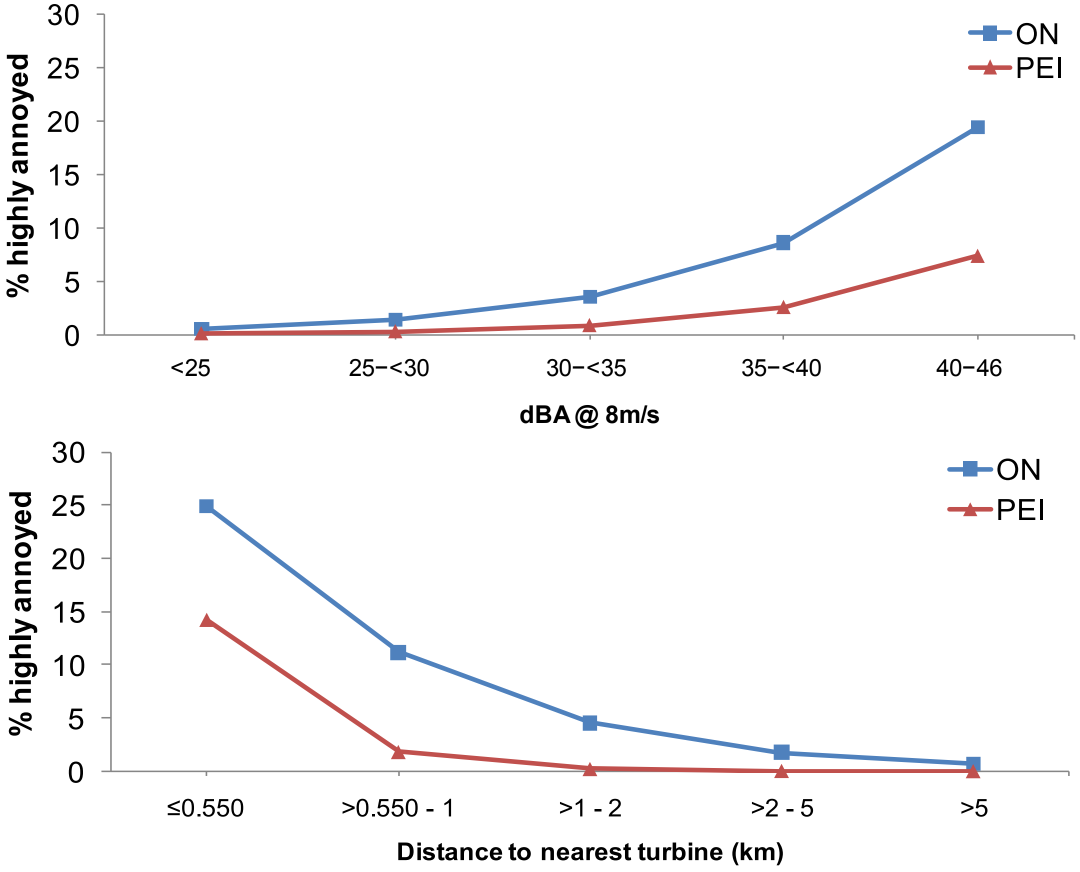


Figure III illustrates the prevalence of high annoyance with WTN in southwestern ON and PEI expressed as a function of WTN levels (top panel) and distance to the nearest wind turbine (lower panel). While the pattern of response was similar in both provinces, the prevalence of WTN annoyance was statistically higher in ON. Fitted results shown.

Additional findings related to reported WTN annoyance included the observation that it was statistically higher in the summer, outdoors and during evening and night time (data not shown).

Considering the difference between background nighttime sound levels and WTN levels, WTN annoyance significantly dropped in areas where calculated nighttime background noise exceeded WTN by 10dB or more (figure IV).

**Figure IV. The influence of background nighttime sound levels on the percentage highly annoyed by WTN**

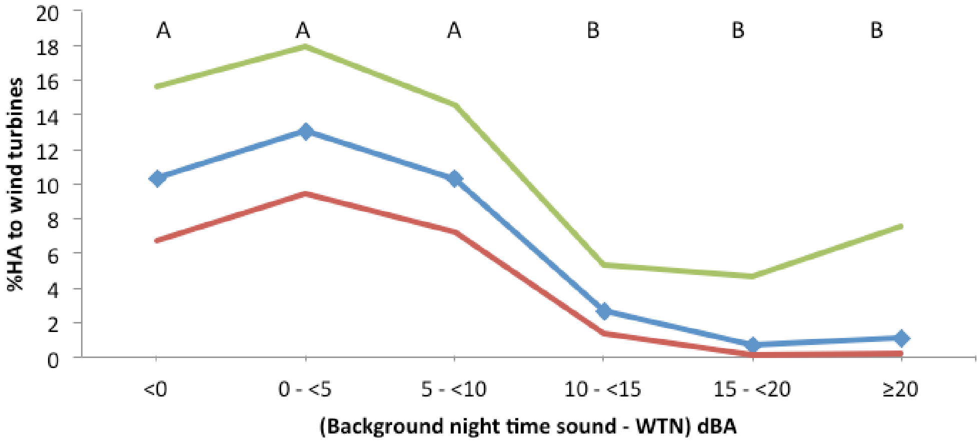


Figure IV illustrates the influence that modelled outdoor background nighttime sound pressure levels was found to have on the WTN annoyance. Background sound levels were calculated following the Alberta noise regulation (AUC, 2013). Results are shown as a function of degree to which background sound levels exceeded WTN levels modelled for wind speeds of 8 meters/second at 10 metre heights, for favourable propagation conditions. There was a significant decrease in the audibility of wind turbines when background levels exceeded WTN levels by at least 5 dB (data not shown), and a decrease in annoyance when the difference exceeded 10 dB. The prevalence of high annoyance between groups with the same letter in the figure are statistically similar (P>0.05), whereas groups with different letters are statistically different (P<0.05). All p-values are Bonferroni adjusted for pairwise comparisons. Green and red lines represent the upper and lower 95% confidence intervals, respectively.

#### *3.3.4.1 Annoyance and health*

Irrespective of WTN levels (or the proximity between the dwelling and the wind turbines) WTN annoyance was found to be statistically related to several self-reported health effects including, but not limited to, blood pressure, migraines, tinnitus, dizziness, scores on the PSQI, and perceived stress. WTN annoyance was also found to be statistically related to measured hair cortisol, systolic and diastolic blood pressure. In many cases, these associations were also observed with road traffic noise annoyance. The associations found between WTN annoyance and other health endpoints were no longer significant in any of the final multiple regression models, which adjust for all variables known to have an effect on the factors being assessed (e.g. BMI, smoking status, age, income, other annoyances, etc…).

### 3.4 Personal benefit and WTN annoyance

Figure V illustrates the audibility of WTN and observed prevalence of WTN annoyance among participants that reported to benefit from having wind turbines in the area. Personal benefit could include rent, payments or other indirect benefits through community improvements. WTN annoyance was significantly lower among the 110 participants who received personal benefit.

**Figure V. Response to WTN among participants that personally benefit from having wind turbines in the area**

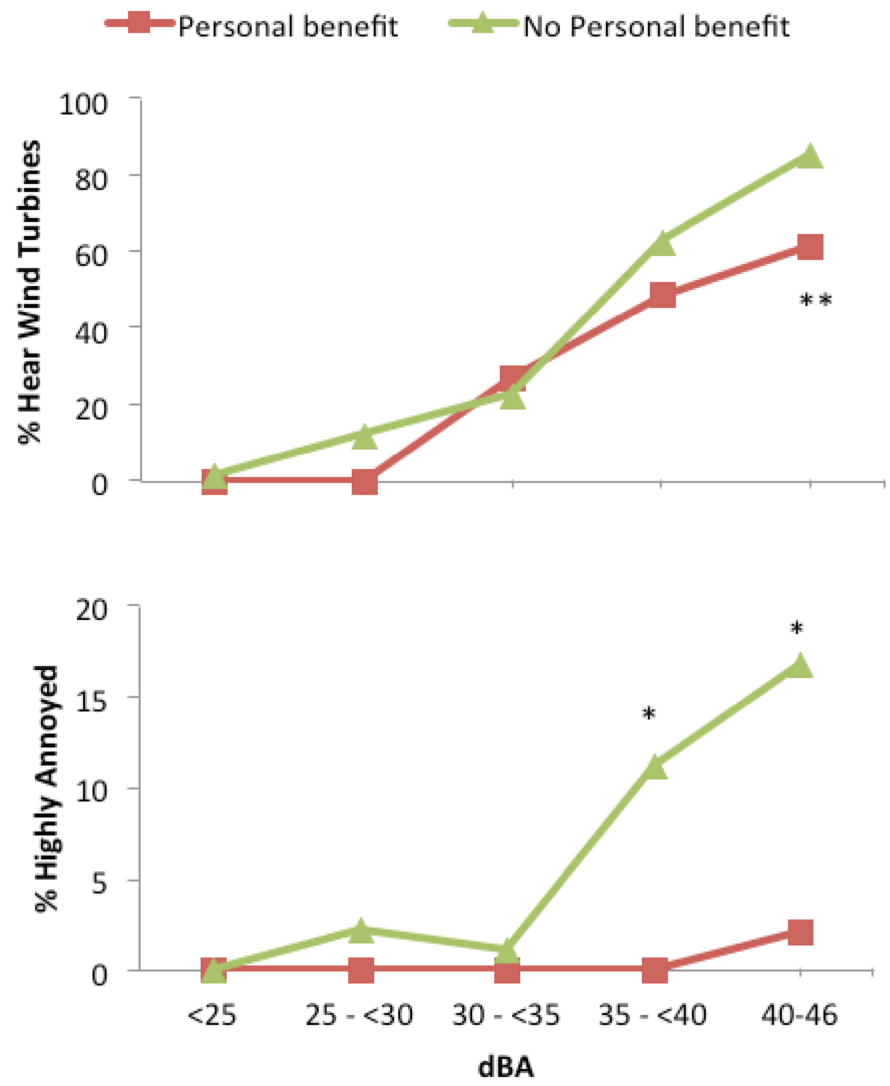


Figure V illustrates the influence that personal benefit was found to have on the reported audibility of wind turbines from inside or outside the dwelling (top panel) and annoyance with WTN (lower panel). Annoyance reflects the percentage of participants reporting to be either very or extremely (i.e. highly) bothered, disturbed or annoyed by WTN while at home. Results are shown as a function of modelled outdoor A-weighted WTN levels for wind speeds of 8 meters/second at 10 metre heights, for favourable propagation conditions. * $0.01 < P \leq 0.05$; ** $0.001 < P \leq 0.01$.

## 3.5 Objectively measured results

### *3.5.1 Measures associated with stress*

Hair cortisol, blood pressure and resting heart rate measures were applied in addition to the PSS to provide a more complete assessment of the possibility that exposure to WTN may be associated with physiological changes that are known to be related to stress (Russell et al. 2012; Stansfeld and Marmot, 2002).

Cortisol is a well-establish biomarker of stress (Sapolsky et al. 2000), which is traditionally measured from blood and/or saliva. However, measures from blood and saliva reflect short term fluctuations in cortisol and are influenced by many variables including time of day, food consumption, body position, brief stress, etc., that are very difficult to control for in an epidemiological study (Broderick et al. 2004; Edwards et al. 2001; Hennig et al. 2000). To a large extent, such concerns are eliminated through measurement of cortisol in hair samples as cortisol incorporates into hair as it grows. With a predictable average growth rate of 1 cm per month (Wennig, 2000), measurement of cortisol in hair makes it possible to retrospectively examine months of stressor exposure. Therefore cortisol is particularly useful in evaluating the potential impact that long term exposure to WTN has on one of the primary biomarkers linked to stress (Russell et al. 2012).

An excerpt from the final multiple linear regression analysis for hair cortisol and scores on the PSS is presented in Table III. Other variables found to be related to PSS scores or cortisol concentrations included age, gender, incomes, BMI, age, smoking status, hair treatment, audibility of other noise sources, migraines, dizziness, chronic pain and diagnosed sleep disorders (data not shown).

**Table III. Multiple linear regression models for perceived stress and hair cortisol (excerpt)**

| | | Perceived Stress Scale | | Hair cortisol (ng/g) | |
|---|---|---|---|---|---|
| Variable | Groups in Variable | LSM (95% CI)[a] | p-value[c] | LSGM (95% CI)[b] | p-value[c] |
| | | ($R^2$=0.21, N=987)* | | ($R^2$=0.14, N=528)* | |
| WTN levels (dBA) | <25 | 13.67 (11.88, 15.46) | 0.8614 | 150.54 (96.94, 233.77) | 0.5416 |
| | 25−<30 | 13.84 (11.92, 15.75) | | 182.20 (118.52, 280.10) | |
| | 30−<35 | 13.18 (11.69, 14.67) | | 191.12 (135.63, 269.33) | |
| | 35−<40 | 13.15 (11.75, 14.55) | | 181.63 (132.24, 249.48) | |
| | 40−46 | 13.48 (12.03, 14.92) | | 160.25 (115.70, 221.96) | |

*Overall $R^2$ values for the full model. For presentation purposes, only results obtained related to WTN levels are shown. [a] LSM, least squares mean and 95% confidence interval (CI) as determined by the multiple linear regression model; [b] LSGM least square geometric mean and 95% CI; [c] p-value for the parameter in the model after adjusting for all other parameters in the multiple linear regression model.

Hair cortisol was positively correlated with the PSS scores (Pearson r=0.13, p=0.0007) regardless of WTN exposure. When examining each of the WTN categories, a positive correlation between PSS and hair cortisol is significant only in the following WTN categories: 25−<30 dB (r=0.35, p=0.0137) and 40−46 dB (r=0.20, p=0.0270). Nevertheless, in fitting a regression line relating hair cortisol to PSS and accounting for WTN exposure and province, the slope is positive and significant (slope=0.02, SE=0.01, p=0.0008). This indicates that higher levels of PSS are correlated with higher levels of hair cortisol. Similarly, while self-reported high blood pressure (hypertension) was associated with higher measured blood pressure, no statistically significant association was observed between measured blood pressure, or resting heart rate, and WTN exposure (Table IV).

**Table IV. Multiple linear regression models for resting blood pressure and heart rate (excerpt)**

| | | Systolic Blood Pressure | | Diastolic Blood Pressure | | Heart Rate | |
|---|---|---|---|---|---|---|---|
| Variable | Groups in Variable | LSGM (95% CI)[a] | p-value[b] | LSGM (95% CI)[a] | p-value[b] | LSGM (95% CI)[a] | p-value[b] |
| | | ($R^2$=0.23, N=810)* | | ($R^2$=0.19, N=815)* | | ($R^2$=0.11, N=990)* | |
| WTN Levels (dB) | <25 | 113.38 (109.17, 117.76) | 0.4990 | 67.98 (64.90, 71.21) | 0.5006 | 68.24 (64.98, 71.66) | 0.5223 |
| | 25−<30 | 116.82 (112.36, 121.45) | | 70.20 (67.01, 73.55) | | 70.59 (67.38, 73.95) | |
| | 30−<35 | 116.53 (113.13, 120.03) | | 69.92 (67.26, 72.70) | | 69.72 (67.17, 72.37) | |
| | 35−<40 | 115.30 (112.17, 118.52) | | 69.66 (67.11, 72.30) | | 69.56 (67.21, 71.99) | |
| | 40−46 | 116.25 (112.83, 119.77) | | 70.34 (67.71, 73.06) | | 70.71 (68.20, 73.32) | |

*Overall $R^2$ values for the full model. For presentation purposes, only results obtained related to WTN levels are shown. [a] LSGM least square geometric mean and 95% CI; [b] p-value for the parameter in the model after adjusting for all other parameters in the multiple linear regression model.

### *3.5.2 Actigraphy measured sleep outcomes*

Sleep was measured using the Actiwatch2™, which is a compact wrist-worn activity monitor that resembles a watch. This device has advanced sensing capabilities to accurately and objectively measure activity and sleep information over a period of several days. This device is considered to be a reliable and valid method of assessing sleep in non-clinical situations (Ancoli-Israel et al. 2003; Sadeh 2011). The following measured sleep impacts were considered: sleep latency (how long it took to fall asleep); wake time after sleep onset (the total duration of awakenings); total sleep time; the rate of awakening bouts (calculates how many awakenings occur as a function of time spent in bed); and sleep efficiency (total sleep time divided by time in bed).

Sleep efficiency is especially important because it provides a good indication of overall sleep quality (Ancoli-Israel et al. 2003). Sleep efficiency was found to be very high at 85% and statistically influenced by gender, body mass index (BMI), education and caffeine consumption.

The rates of awakening bouts, total sleep time or sleep latency were further found in some cases to be related to: age, marital status, closing bedroom windows, caffeine consumption, BMI, physical pain, having a stand-alone air conditioner in the bedroom, self-reports of restless leg syndrome and being highly annoyed by the blinking lights on wind turbines.

While it was found that many variables had a significant impact on measured sleep, calculated outdoor WTN levels near the participants' dwelling was not found to be associated with any of the sleep endpoints measured with actigraphy (data not shown).

## 4. CONCLUSIONS AND DATA AVAILABILITY

Including both self-reported and physically measured health effects together provides a more complete overall assessment of the potential impact that exposure to wind turbines may have on health and well-being. The overall conclusion to emerge from the study findings is that the study found no evidence of an association between exposure to WTN and the prevalence of self-reported or measured health effects beyond annoyance. Collectively, the findings related to annoyance suggest that health and well-being effects may be partially related to activities that influence community annoyance, over and above exposure to WTN. Therefore, efforts that aim to identify and mitigate high levels of annoyance with wind turbines may have benefits that go beyond annoyance.

Detailed descriptions of the above results will be submitted for peer review with open access in scientific journals and should only be considered final following publication. All publications by Health Canada related to the study will be identified on the Health Canada website http://www.hc-sc.gc.ca/ewh-semt/noise-bruit/turbine-eoliennes/scientific-journal-publications-scientifique-eng.php.

Raw data originating from the study is available to Canadians, other jurisdictions and interested parties through a number of sources: Statistics Canada Federal Research Data Centres, the Health Canada website (acoustical data), open access to publications in scientific journals and conference presentations. Plain language abstracts outlining the research and identifying the scientific journals where papers can be found will further be published to the Departmental website.

## 5. SELECTED REFERENCES

Agresti A. (2002). Categorical Data Analysis, 2nd edition. New York: Wiley & Sons, Inc.

Alberta Utilities Commission (AUC). (2013). Rule 012-Noise Control. http://www.auc.ab.ca/acts-regulations-and-auc-rules/rules/Pages/Rule012.aspx (accessed on 11/24/2014).

ANSI (1995). “Criteria for evaluating room noise,” ANSI S12.2-1995 (R1999).

Broderick, J.E., Arnold, D., Kudielka, B.M., Kirschbaum, C., 2004. Salivary cortisol sampling compliance: comparison of patients and healthy volunteers. Psychoneuroendocrin. 29, 636-650.

Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. (1989). The Pittsburgh sleep quality index: a new instrument for psychiatric practice and research. Psych Res., 28:193–213.

Canadian Wind Energy Association. (2015). Installed capacity. http://canwea.ca/wind-energy/installed-capacity/ (accessed on 02/11/2015).

Cohen S, Kamarck T, Mermelstein R. (1983). A global measure of perceived stress. J Health Soc Behav., 24:386-396.

DataKustik GmbH ®. (2014). Software for Immission Protection. Available: www.datakustik.com (accessed on 02/12/2015).

Edwards, S., Evans, P., Hucklebridge, F., Clow, A., (2001). Association between time of awakening and diurnal cortisol secretory activity. Psychoneuroendocrin. 26, 613-622.

FHWA Traffic Noise Model®. (1998). Technical Manual. US Department of Transportation, Federal Highway Administration.

Hennig, J., Friebe, J., Ryl, I., Krämer, B., Böttcher, J., Netter, P., (2000). Upright posture influences salivary cortisol. Psychoneuroendocrin. 25, 69-83.

ISO. 1993. Acoustics. Attenuation of sound during propagation outdoors. Part 1: Calculation of the absorption of sound by the atmosphere. ISO 9613-1. Geneva: International Organization for Standardization.

ISO. 1996. Acoustics. Attenuation of sound during propagation outdoors. Part 2: General method of calculation. ISO 9613-2. Geneva: International Organization for Standardization.

ISO. 2003. Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys. ISO/TS-15666. Geneva: International Organization for Standardization.

Knopper LD and Ollson CA. (2011). Health effects and wind turbines: A review of the literature. Environ Health, 10:78.

Knutson K.L., Van C.E., Rathouz P.J., Yan, L.L., Hulley, S.B., Kiu, K., Lauderdale, D.S., (2009). Association between sleep and blood pressure in midlife: the CARDIA sleep study. Arch Intern Med., 69,1055–61.

Krogh CME, Gillis L, Kouwen N, Aramini J. (2011). WindVOiCe, a self-reporting survey: adverse health effects, industrial wind turbines, and the need for vigilance monitoring. Bull Sci Technol Soc 31:334–345.

Liang KY and Zeger SL. (1986). Longitudinal data analysis using generalized linear models. Biometrika 73:13-22.

McCunney R, Mundt KA, Colby WD, Dobie R, Kaliski K, Blais M. 2014. Wind turbines and health: A critical review of the scientific literature. J Occup Envi Med 56(11): e108-e130.

McEwen, B. (2006). Sleep deprivation as a neurobiologic and physiologic stressor: allostasis and allostatic load. Metabolism: Clinical and Experimental, 55 (supp 2): S20-S23.

Michaud DS, Keith SE, Feder K, Soukhovtsev V, Marro L, Denning A. et al. (2013). Self-reported and objectively measured health indicators among a sample of Canadians living within the vicinity of industrial wind turbines: social survey and sound level modelling methodology. Noise News Int., 21:14-27.

Mroczek B, Kurpas D, Karakiewicz B. (2012). Influence of distances between places of residence and wind farms on the quality of life in nearby areas. Ann Agr Environ Med., 19(4): 692-696.

Nissenbaum MA, Aramini JJ, Hanning CD. (2012). Effects of industrial wind turbine noise on sleep and health. Noise Health 14(60): 237-243.

Pawlaczyk-Łuszczyńska M, Dudarewicz A, Zaborowski K, Zamojska-Daniszewska M, Waszkowska M. (2014). Evaluation of annoyance from the wind turbine noise: a pilot study. Int J Occup Environ Health 27:364-388.

Pedersen E, Persson Waye K. (2004). Perception and annoyance due to wind turbine noise – a dose-response relationship. J Acoust Soc Am 116: 3460-3470.

Pedersen E, Persson Waye K. (2007). Wind turbine noise, annoyance and self-reported health and wellbeing in different living environments. Occup Environ Med 64:480-486.

Pedersen E, van den Berg F, Bakker R, Bouma J. (2009). Response to noise from modern wind farms in The Netherlands. J Acoust Soc Am 126:634-643.

Pedersen E, van den Berg F, Bakker R, Bouma J. (2010a). Can road traffic mask sound from wind turbines? Response to wind turbine sound at different levels of road traffic sound. Energ Policy 38(5):2520-2527.

Pedersen E, van den Berg F, Bakker R, Bouma J. (2010b). Why is wind turbine noise so poorly masked by road traffic noise? In Proceedings of Internoise, Lisbon, Portugal.

Pedersen E. (2011). Health aspects associated with wind turbine noise – Results from 3 field studies. ," Noise Control Eng J 59:47-53.

Russell, E., Koren, G., Rieder, M., Van Uum, S.H., (2012). Hair cortisol as a biological marker of chronic stress: current status, future directions and unanswered questions. Psychoneuroendocrin. 37(5), 589-601.

Sadeh A. The role and validity of actigraphy in sleep medicine: an update. Sleep Med Rev 2011;15:259-67.

Sapolsky, R.M., Romero, L.M. Munck, A.U. (2000). How do glucocorticoids influence stress responses? Integrating permissive, suppressive, stimulatory, and preparative actions. Endocrine Reviews, 21(1): 55-89.

Shepherd D, McBride D, Welch D, Dirks KN, Hill EM. (2011). Evaluating the impact of wind turbine noise on health-related quality of life. Noise Health 13(54): 333-339.

Skevington SM, Lotfy M, O'Connell KA. (2004). The World Health Organization's WHOQOL-BREF quality of life assessment: psychometric properties and results of the international field trial—a report from the WHOQOL group. Qual Life Res., 13:299–310.

Stansfeld, S.A., Marmot, M.G. (eds), (2002). Stress and the heart: psychosocial pathways to coronary heart disease. BMJ Books, BMA House, Tavistock Square, London.

Statistics Act, R.S.C. 1985, c. S-19 http://laws-lois.justice.gc.ca/eng/acts/S-19/FullText.html (accessed on 02/12/2015).

Statistics Canada. (2014). Community noise and health study. http://www.statcan.gc.ca/daily-quotidien/141106/dq141106c-eng.htm (accessed on 02/12/2015).

Stokes ME, Davis CS, Koch GG. (2000). Categorical Data Analysis Using the SAS System, Second Edition. Cary, NC: SAS Institute Inc.

Swedish Environmental Protection Agency (SEPA). (2001). Ljud från vindkraftverk (Noise from wind turbines). Report 6241 (in Swedish). Stockholm.

Tachibana H, Yano H, Sakamoto S, Sueoka S. (2012). Synthetic Research Program on Wind Turbine Noise in Japan. New York, NY: Inter-Noise.

van den Berg, F. (2011). The effects of wind turbine noise on people. In Bowdler R & Leventhall G (ed.) Wind Turbine Noise. Multi-science, Brentwood UK:129-152.

van den Berg, F. 2013.. Wind turbine noise: an overview of acoustical performance and effects on residents. In Proceedings of Acoustics, Victor Harbor, Australia.

Wennig, R. (2000). Potential problems with the interpretation of hair analysis results. Forensic Sci. Int. 107, 5-12.

World Health Organization (WHO). Guidelines for Community Noise. Berglund B, Lindvall T, Schwela DH (Eds). 1999. http://www.who.int/docstore/peh/noise/guidelines2.html (accessed 02/12/2015).

World Health Organization (WHO). Night Noise Guidelines for Europe. Hurtley C. (Ed). 2009. http://www.euro.who.int/__data/assets/pdf_file/0017/43316/E92845.pdf (accessed 02/12/2015).

WHOQOL Group. (1998). Development of the World Health Organization WHOQOL-BREF quality of life assessment. Psych Med., 28:551-558.

Zaharna M, Guilleminault C. (2010). Sleep, noise and health: review. Noise Health,12(47):64-9.

6th International Meeting
on
Wind Turbine Noise
Glasgow  20-13 April 2015

# Health-based Audible Noise Guidelines Account for Infrasound and Low Frequency Noise Produced by Wind Turbines

**Robert G. Berger   Intrinsik Health Sciences Inc., Mississauga, ON, Canada**

**Payam Ashtiani   Aercoustics Engineering Limited, Mississauga, ON, Canada**

**Christopher A. Ollson   Intrinsik Environmental Sciences Inc., Mississauga, ON, Canada**

**Melissa Whitfield Aslund*   Intrinsik Environmental Sciences Inc., Mississauga, ON, Canada**

**Lindsay C. McCallum   Intrinsik Environmental Sciences Inc., Mississauga, ON, Canada**

**Geoff Leventhall  H.G. Leventhall – Consultancy, Ashtead, Surrey, United Kingdom**

**Loren D. Knopper   Intrinsik Environmental Sciences Inc., Mississauga, ON, Canada**

## Summary

Setbacks for wind turbines have been established in many jurisdictions to address potential health concerns associated with audible noise. However, in recent years it has been suggested that infrasound (IS) and low frequency noise (LFN) could be responsible for the onset of adverse health effects self-reported by some individuals living in proximity to wind turbines, even when audible noise limits are met. The purpose of this paper was to investigate whether current audible noise-based guidelines for wind turbines account for the protection of human health, given the levels of IS and LFN typically produced by wind turbines. New field measurements of indoor IS and outdoor LFN at locations between 400 m and 900 m from the nearest turbine, which were previously underrepresented in the scientific literature, are reported and put into context with existing published works. Our analysis showed that indoor IS levels were below auditory threshold levels while LFN levels at distances >500 m were similar to background LFN levels. A clear contribution to LFN due to wind turbine operation (i.e., measured with turbines on in comparison to with turbines off) was noted at a distance of 480 m. However, this corresponded to an increase in overall audible sound measures as reported in dB(A), supporting the hypothesis that controlling audible sound produced by normally operating wind turbines will also control for LFN. Overall, the available data from this and other studies suggest that health-based audible noise wind turbine siting guidelines provide an effective means to evaluate, monitor, and protect potential receptors from audible noise as well as IS and LFN.

# 1. Introduction

Wind power has become the fastest growing source of new electric power generation, with several countries achieving high levels of wind power capacity and overall penetration (Wiser and Bolinger 2013). Public support for the use of wind energy is typically high; however, acceptance of projects at the local level does not always reflect this trend. While support is found in some locations, strong opposition stemming from concerns of visual aesthetics, health risk perception and noise levels can be found in others (Baxter et al. 2013; Jobert et al. 2007; McCallum et al. 2014; Wolsink 2000).

Currently, there exists an ongoing debate surrounding the relationship between wind turbines and human health within both the public and the scientific communities (Knopper and Ollson 2011). This debate is driven by the fact that some people that live near wind turbines have reported adverse health effects such as (but not limited to) ringing in ears, headaches, lack of concentration, vertigo and sleep disruption that they attribute to the wind turbines. Some argue that reported health effects are related to wind turbine operational effects (e.g., electromagnetic fields [EMF], shadow flicker from rotor blades, audible noise, low frequency noise and infrasound); others suggest that when turbines are sited correctly, reported effects are more likely attributable to a number of subjective variables, including nocebo responses, where the etiology of the self-reported effect is in beliefs and expectations rather than a physiologically harmful entity (Chapman and St George 2013; Crichton et al. 2013a; 2013b; Pedersen and Persson Waye 2004; 2007).

It is well known that exposure to excessive levels of audible noise, regardless of the source, can cause annoyance, sleep disturbance, cognitive impairment and other serious health effects. According to the World Health Organization (WHO), nighttime exposure to noise levels above 55 dB(A) outdoors averaged over the year is considered increasingly dangerous for public health and a sizeable proportion of the population will be highly annoyed and sleep-disturbed (WHO 2009). As a result, jurisdictions across the globe have developed noise regulations specific to wind turbine projects to protect the public from potential noise-related health effects. Though some variability exists among jurisdictions, the majority of the guidelines center around an outdoor limit between 35-45 dB(A). This limit coincides with the WHO Europe nighttime noise guideline of 40 dB(A) outdoors, a health-based value derived to “protect the public, including the most vulnerable groups such as children, the chronically ill and the elderly, from the adverse health effects of night noise” (WHO 2009).

Even when these health-based noise limits are met, some people living near wind turbines self-report a variety of adverse health effects that they attribute to living near the wind turbines (Knopper and Ollson 2011; Knopper et al. 2014). As a result, the etiology of these health effects has been hypothesized by some to stem from exposure to low frequency sounds, including infrasound (IS; 0.01-20 Hz) and low frequency noise (LFN; 10-200 Hz) (Møller and Pedersen 2011; Salt and Hullar 2010; Salt and Kaltenbach 2011), both of which are known components of the broadband sound associated with normal wind turbine operation (Leventhall 2006; Pedersen and Persson Waye 2004; Persson Waye and Öhrström 2002). In response to these concerns, a number of investigations have measured IS and LFN associated with modern wind turbine operation at a variety of distances, operating scenarios, and geographic and meteorological conditions. Collectively, these reports suggest that sound associated with well-functioning wind turbines has measurable energy within the IS and LFN spectra. However, IS levels, which are often described in dB(G), are consistently well below auditory perceptual levels (Boczar et al. 2012; Evans et al. 2013a; Evans 2013; O'Neal et al. 2011; Turnbull et al. 2012) and LFN is below available guidelines (O'Neal et al. 2011). Furthermore, IS levels at relatively close distances to wind turbines are equivalent to or less than those produced by a number of natural or engineered sources that individuals are exposed to on a regular basis (Evans et al. 2013a; Evans et al. 2013b; Turnbull et al. 2012). The physical characteristics of sounds emitted from wind turbines have been recognized to influence the perception and annoyance to wind turbine associated sounds; however, this generally refers to sounds that are above the auditory level of perception (Bolin et al. 2011; Pedersen and Persson Waye 2007; van den Berg 2013).

It has been suggested that wind turbine noise limits set in dB(A), which simulates the sensitivity of human hearing and perception, may underestimate the contribution of IS and LFN from wind turbines (Salt and Kaltenbach 2011). Alternative sound weightings, including G-weighting (dB(G)) and C-weighting (dB(C)), have been proposed as more appropriate metrics for noise limits when LFN and IS are present, respectively (Salt and Kaltenbach 2011; Sloven 2005). However, Health Canada recently suggested that there was "no additional benefit in assessing LFN as C- and A-weighted levels were so highly correlated (r=0.94) that they essentially provided the same information" (Health Canada 2014). Accordingly, the purpose of this paper is to examine further IS, LFN and overall sound levels typically produced by wind turbines and provide discussion as to whether concerns regarding wind turbine associated IS and LFN are warranted. Field measurements of outdoor LFN and overall sound levels and indoor IS at locations between 400 m and 900 m from the nearest wind turbine, which were previously underrepresented in the scientific literature, are reported. The results of these measurements are put into context with existing published works and current available guidelines based on dB(A) to provide a weight-of-evidence conclusion.

## 2. Experimental design

### 2.1. Indoor Infrasound Measurements

Sound measurements were conducted in three residences, two at 450 m and one at 900 m from the nearest wind turbine. These turbines were part of an operating wind farm with over 40 turbines, each with a power capacity of 1.5 MW. The measurements were carried out using Class 1 instrumentation with sufficiently low frequency range and noise floor. Measurements were carried out on a ground plane fitted with a double windscreen. The double wind screen consisted of the thin hemispherical wireframe (450mm diameter) covered with a thin layer (approx. 10mm) of open cell foam. This setup is consistent with that defined in IEC 61400-11 with the exception that the measurement location was at a dwelling rather than close to a wind turbine. Although not in a windy environment, a double windscreen helps protect very low frequency and infrasonic measured levels against pressure fluctuations within a dwelling caused by moving air from ventilation and opening/closing doors.

For these measurements, access was not available to turbines in order to conduct on/off tests for quantifying ambient levels. Additionally, turbine power performance was not made available during the study. In order to identify whether the turbines in the facility were operating, an autocorrelation technique was used in the signal analysis in order to detect characteristics in the sound signal attributable to the turbine operation. This autocorrelation technique (Richarz et al. 2011) exploits the periodicity in the signal attributable to the wind turbine operation and uses this feature to detect when the turbines were operating. Infrasound levels measured during wind turbine operation were compared to those when the wind turbines were unlikely to be operational (i.e., at wind speeds below turbine cut-in at 3 m/s). Data were collected from 1 to 1000 Hz and subsequently weighted using dB(G) to focus the analysis on the IS component, and allow for comparison to other studies.

The data presented in this report represent the periods where 1-minute interval recordings showed the existence of the wind turbine noise (i.e., characteristic blade passage frequencies) the clearest out of the entire measurement period which was 3-4 weeks. Because the nature of the signal detection mechanism, and the averaging over a minute, the Type A uncertainty for the measured value is difficult to quantify. The Type B uncertainty of the measurement is that of a Class 1 instrumentation which is typically ± 1 dB.

## 2.2. Outdoor Low Frequency Noise and Overall Sound Measurements

Sound levels were measured near two different wind turbine facilities, both with more than 30 wind turbines each. The turbines had a power capacity between 1.5-2.4 MW. Measurements were carried out outdoors at 4.5 m height, and at a distance between 400-800 m. Meteorological data were also recorded at a height of 10 m at the same location. The sound measurements were carried out using Class 1 instrumentation with sufficiently low noise floor. A large 450 mm diameter spherical secondary windscreen was employed in addition to a commercially available 7 cm primary wind screen to minimize pseudo-noise from wind flowing over the microphone. Field sound measurements of wind turbines are highly susceptible to contamination from extraneous noise such as from human activity, fauna, insects, and wind-induced noise. To control for these sources of contamination, the following methods were used:

- sound measurements were only collected during nighttime, between 10 PM and 5 AM;
- measurements were conducted in one minute intervals;
- measurements were binned by wind speed for each one minute interval;
- intervals within one hour of rainfall or snowfall were not used; and
- intervals with gusty winds (>2 m/s above the mean wind speeds) were not used as these periods are more susceptible to wind-induced pseudo-noise.

Measurements were carried out in the vicinity of the wind facility during wind turbine operation as well as with the turbines off. The same filtering and data quality management methods were applied to both data sets. A minimum of 60 data points in each wind bin were gathered. To isolate only the LFN portion of the spectrum, data between 20-200 Hz were analyzed and summed. Once tallied, the mean spectrum for the 3 and 6 m/s integer wind speeds was calculated. For each of those cases, the calculation was made from spectra where the mean wind speeds were within 0.5 m/s of the stated value and was relatively steady during the entire interval. The gust filtering ensures that no gust was more than 2 m/s above the mean. The mean spectrum was calculated by computing the energy averaged sound level for each 1/3rd octave band between 20-200Hz, and then computing an A-weighted sum of the spectrum.

The self-noise emitted by the system itself was assessed using the measurements conducted during periods when the wind turbines in the vicinity were not operating. The mean spectrum at various wind speeds was compared to those found in other literature comparing measured ambient levels with respect to wind speed. The most applicable study, conducted by the Japanese Ministry of Environment and reported by Tachibana (2013) compared sound levels measured with various windscreens ranging from naked microphone to a specialized dodecahedron double windscreen. Measured low frequency levels were at or below those reported in the double windscreen case in the Japanese study for most wind speeds and locations. It should be noted that although the measured ambient levels are consistent with those measured with high degree of windscreen protection, pseudo-noise contamination of the signal cannot be fully avoided.

Based on the measurements conducted, the typical measured standard deviation for the A-weighted level was ±3 dB for the turbines ON, and ±2dB when the turbines were OFF. The standard deviation was higher at lower wind speeds and decreased with increasing wind speed. This is due to wind induced ambient noise (which is fairly steady) dominating the signal at the higher wind speed. At lower wind speeds, because the ambient levels are lower, individual non-turbine related events such as vehicular traffic, faunal noise, or other intermittent noises increase the variability in background noise. Additionally, during lower wind speeds, the wind turbine noise source would be more susceptible to changes in wind speed at the hub. For example, for two cases where the ground level wind speed is 3 m/s, the hub height wind speed could be 4m/s in one case and 8m/s in another. This would result in a difference in the amount of noise produced by the turbine. It is the authors' view that given the above variability, wind turbine noise measurements at far field distances should carry a nominal uncertainty value of ±3 to ±5dB.

## 3. Results and Discussion

### 3.1. Indoor Infrasound Measurements

Infrasound levels in the homes at 450 m were relatively similar, measuring 59 and 58 dB(G) (Table 1). Infrasound measured at the furthest location of 900 m was comparable to the measurements at 450 m, measuring 60 dB(G). These data indicate that IS levels were relatively constant with increased distance from the nearest wind turbine and were approximately 25 dB below the level of human perception (approximately 95 dB(G) (Watanabe and Møller 1990)), which may be indicative of non-wind turbine associated distant sources of IS. The results reported here are consistent with previous measurements at varying distances (Boczar et al. 2012; Evans et al. 2013a; Evans 2013; O'Neal et al. 2011; Turnbull et al. 2012). For instance, IS measurements from 290-323 m from wind turbines were 20 to 30 dB below the human auditory threshold levels (O'Neal et al. 2011). Additional measurements of IS in the 1-30 Hz range at a distance of 200 m from the wind turbines also remained below the human auditory threshold (Boczar et al. 2012). Other investigations have shown that at further distances (1.5 km) indoor IS levels in two residences were between 49-61 dB(G), with no reported difference between operational and shutdown periods, also suggesting that there are other sources of IS contributing to these results (Evans et al. 2013a). The same group (Evans and Cooper 2012) also showed that indoor IS levels were between 50-70 dB(G) at distances of 1.8 and 2.7 km from the nearest wind farm. In conjunction with these reports, the results from the current field investigation indicate that wind turbines are a source of IS; however, sound levels are well below the human auditory threshold.

**Table 1** Indoor infrasound measured at three homes at two different distances to 1.5 MW turbines.

| WT Rated Power (MW) | Distance (m) | IS Level (dB(G)) |
|---|---|---|
| 1.5 | 450 | 59 |
| 1.5 | 450 | 58 |
| 1.5 | 900 | 60 |

Only two jurisdictions have developed clear guidelines for IS and neither is specific to wind turbine noise. The Queensland Department of Environment and Resource Management's Draft *ECOACCESS Guideline- Assessment of Low Frequency Noise* proposed an interior IS limit of 85 dB(G) (Roberts 2004). This value was derived based on a 10 dB protection level from the average 95 dB(G) hearing threshold (Watanabe and Møller 1990) and previous Danish recommendations for IS limits (Jakobsen 2001). The Japanese Handbook on Low Frequency Noise provides an IS reference value of 92 dB(G) at 10 Hz and 1/3 octave bands up to 80 Hz (Kamigawara et al. 2006). These values were derived from investigations that monitored complaints of mental and physical discomfort from healthy adults exposed to low frequency sounds in a room (Kamigawara et al. 2006). Though the Japanese guidelines were derived through short-term monitoring experiments and are not equivalent to the long term exposure associated with living in proximity of wind turbines, the levels of IS measured as part of this current study (Table 1) are 20-30 dB below these guidelines.

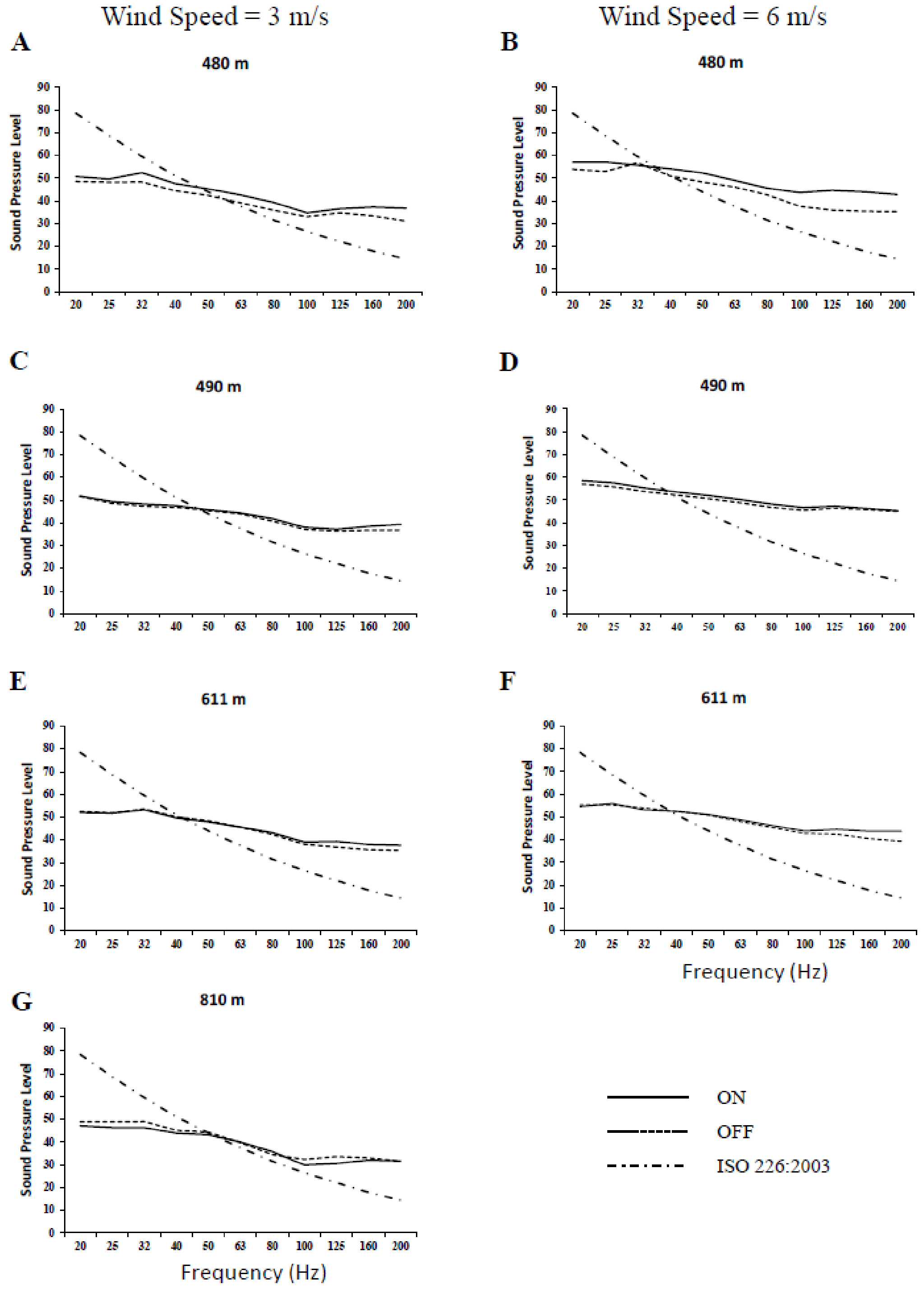
A limited number of reports have suggested that the IS component of wind turbine noise is the cause of self-reported adverse health effects (Ambrose et al. 2012; Rand et al. 2011; Walker et al. 2012). Mechanisms within the inner ear that are sensitive to low levels of IS stimulation have been proposed to be associated with adverse health responses (Pierpont 2009; Salt and Hullar

2010; Salt and Kaltenbach 2011). However, functional magnetic resonance imaging has provided powerful evidence that IS is perceived via similar auditory pathways as audible sounds when above the level of perception with no indication of cortical activation at sub-threshold values (Dommes et al. 2009). Furthermore, exposure to IS is known to originate from other engineered or natural processes, including wind and weather systems (Goerke and Woodward 1966), volcanic (Goerke et al. 1965) and auroral activity (Wilson 1967), and mountain ranges (Bedard Jr 1978); this would arguably also induce stimulation of the inner ear. Recent outdoor measurements have provided an indication of IS levels from a number of natural sources, including sea waves at 25 m from the coast (75 dB(G)), 250 m from a coastal cliff face (69 dB(G)) and 8 km inland from the coast (57 dB(G)) (Turnbull et al. 2012). The authors reported that wind turbine IS levels, that were between 61-72 dB(G) at distances of 85-360 m, were lower than many of the natural sources measured (Turnbull et al. 2012). Infrasound is also generated in urban environments as a result of human activity and engineered sources such as industrial processes, ventilation systems and vehicles (Evans et al. 2013a; Turnbull et al. 2012). Measurements of IS in a typical urban setting have been reported to be up to 70 dB(G) during the daytime and 63 dB(G) at night (Evans et al. 2013a). In comparison, studies reporting biological responses to infrasound exposure were at sound pressure levels that were above the level of auditory perception, much higher than those produced by wind turbines (e.g., 145 dB and 165 dB (Leventhall et al. 2003; Yuan et al. 2009)). Collectively, these reports and the measurements from the current investigation indicate that humans are regularly exposed to IS from several natural and engineered sources at levels that exceed those produced by wind turbines. Although sounds with impulsive characteristics (e.g., wind turbines) generate greater levels of annoyance than non-impulsive sources, annoyance levels have only been associated with noises that are above the threshold of auditory perception (Berglund et al. 1996; Pedersen and Persson Waye 2004). Our measurements of IS, and those from the literature, are all well below the threshold of auditory perception.

### 3.2. Outdoor Low Frequency Noise and Overall Sound Measures

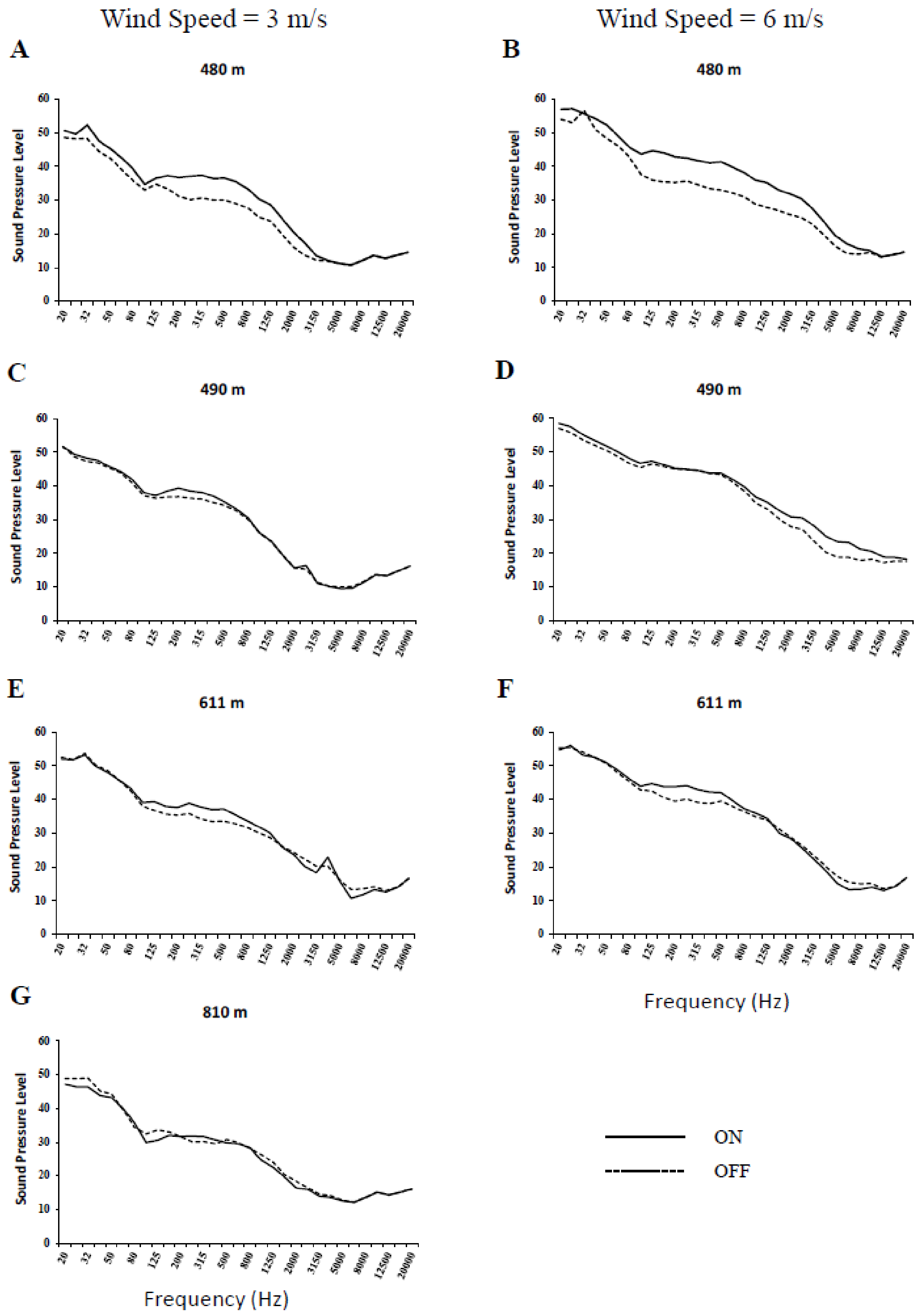
Outdoor LFN levels were assessed through 1/3 octave band measurements with wind turbines operational (on) and during scheduled shutdown periods (off) at distances of 480, 490, 611, and 810 m (Figure 1). At all locations, measured LFN levels with wind turbines on and off (ambient) were similar between 20-100 Hz. At frequencies greater than 100 Hz, a deviation was noted between the ‘on’ and ‘off’ conditions, particularly for measurements taken nearest to the turbines (Figure 1A and 1B). As distance from the turbines increased, the amount by which LFN levels measured with turbines on and off differed decreased in comparison to the measurements reported at 480 m. At all distances and wind speeds, irrespective of wind turbine operation, LFN exceeded the ISO-defined audible threshold at frequencies greater than 40-50 Hz (ISO 2003). These results indicate that the observed increase in LFN during wind turbine operation was found primarily in the frequency range consistent with the audible range of hearing, namely 20-20,000 Hz, and not in the IS range (<20 Hz). It is also noted that the same applies to ambient noise levels, namely that the levels cross the auditory threshold at frequencies between 40-50 Hz and higher.

**Figure 1.** Outdoor low frequency noise measurements at 480 m (A and B), 490 m (C and D), 611 m (E and F), and 810 m (G) from 1.5 MW wind turbines with wind speeds of 3 m/s (A,C, E, G) and 6 m/s (B,D, F) with turbines on and off. Hearing threshold (ISO 226:2003) are also provided.



Through the 1/3 octave band analysis of overall sound levels (20-20,000 Hz; Figure 2) it was apparent that the increase in LFN from wind turbine operation was accompanied by increased sound levels at higher frequencies (i.e., >200 Hz). This was particularly evident at 480 m where wind turbine associated sound levels continued to be above ambient levels until approximately 3150 Hz (Figure 2A and 2B). At further distances, sound levels were above ambient levels at frequencies between 125-1000 Hz, but not easily distinguishable from ambient levels below 125 Hz, or above 1 kHz (Figure 2C-2F). These results indicate that though there was an observed increase in LFN levels during wind turbine operation at the 480 m location this increase was accompanied by an increase in sound levels up to 3 kHz.

**Figure 2.** Outdoor sound measurements at 480 m (A and B), 490 m (C and D), 611 m (E and F), and 810 m (G) from 1.5 MW wind turbines with wind speeds of 3 m/s (A, C, E, G) and 6 m/s (B, D, F) with turbines on and off.



At closer distances where the LFN component can be measured above the ambient conditions, the mid frequency sound levels were also above ambient levels. In those cases, the signal-to-noise ratio of the mid frequency sound levels was higher than that below 125 Hz, indicating that the most audible portion of the frequency spectrum was between 125-3150 Hz. At further distances, it was evident that the signal-to-noise ratio decreased, such that only acoustic energy between 125Hz and about 800-1000 Hz was above background, with the highest signal-to-noise ratio between 200-500 Hz (Figure 2C-2F). The single measurement point at 810 m showed no measurable increase in any of the mean sound levels. This indicates that a presence of LFN in the signal from wind turbines was accompanied by a presence in mid frequency sound levels. For instances where the LFN levels were considerably above ambient levels, the mid frequency sounds levels were also considerably increased. This indicates that, at the distances of interest, it is the mid frequency region that is the most audible portion of the noise from the turbines. Only at closer distances, where the mid frequency components would be clearly audible (6 to 9 dB signal-to-noise ratio), would the low frequency components from the turbines start to be audible above ambient levels. The overall A-weighted sound pressure level was significantly affected by the mid frequency component. As a result, it would be expected that by controlling the overall sound pressure level (dB(A)) from normal functioning wind turbines, that the LFN component would also mitigated.

When the wind turbines were operating, the highest mean LFN level (dB(A)) was observed at 480 m (Table 2). At the other locations >480 m from the wind turbines, the measured difference between wind turbines on and off was between 1-3 dB, at least half of that observed at 480 m. The mean overall sound levels reported in dB(A) showed very similar trends to those reported in the LFN analysis. Critically, the increase in mean sound levels at the closest location (480 m) reported in the LFN spectrum and overall sound in the 1/3 octave band analysis was maintained. In addition, the observed trends at 490, 611, and 810 m, also remained consistent. From these results it is evident that during wind turbine operation, the increased sound levels that began in the LFN spectrum, at approximately 160 Hz and continued to 1000 Hz, were above auditory threshold levels and represented in the mean dB(A) sound measures. The consistency between the mean dB(A) measurements and trends observed in the 1/3 octave band analysis suggest that the contribution of the LFN component and overall sound levels were accounted for in the calculation.

**Table 2** Low frequency noise (LFN) and overall sound levels with turbines on and off (i.e. background) in dB(A).

| Wind Speed (m/s) | Distance (m) | LFN “On” | LFN “Off” | Overall Sound “On” | Overall Sound “Off”[1] |
|---|---|---|---|---|---|
| 3 | 480 | 30 | 26 | 41 | 35 |
| | 490 | 32 | 30 | 40 | 39 |
| | 611 | 31 | 30 | 42 | 40 |
| | 810 | 25 | 26 | 36 | 36 |
| 6 | 480 | 36 | 30 | 47 | 40 |
| | 490 | 39 | 38 | 49 | 48 |
| | 611 | 37 | 34 | 49 | 45 |

[1] Ambient noise at this location, with turbines off, is influenced by wind speed (3 and 6 m/s) and movement of vegetation in the measuring location.

Similar LFN levels in the proximity of wind turbines have been reported elsewhere (Evans et al. 2013b; O'Neal et al. 2011). Furthermore, the results showing LFN levels passing the auditory threshold between 40 and 50 Hz are similar to those that have been previously reported (Botha 2013; O'Neal et al. 2011). For instance O’Neal et al. (O'Neal et al. 2011) measured indoor and outdoor LFN levels from wind turbines at a distance of 300 m and found the levels were below the United Kingdom’s (UK) Department for Environmental and Rural Affairs (DEFRA) and Japanese guidelines and became audible at approximately 50 Hz (O'Neal et al. 2011). Elsewhere, LFN levels were only marginally higher and remained well below guidelines even though measurements were taken as close as 104 m from the nearest wind turbine (Botha 2013). Low frequency noise measured at 1.8 and 2.7 km from the nearest wind farm was comparable during pre-operational and operational periods of development, though small increases at frequencies above 63 Hz were reported (Evans 2013). At a greater distance of 1.5 km from wind turbines, Evans et al. found LFN levels were similar to those measured at distances of 10 and 30 km from the turbines (Evans et al. 2013b). Further, organized shut downs of the two wind farms showed that the contributions of the turbines to LFN measurements were negligible or relatively small contributions at 100 Hz and above (Evans et al. 2013b). As shown with IS, LFN is also produced by natural and common engineered sources: in urban environments, including offices and residences, LFN levels often exceed available guidelines and are greater than those measured 1.5 km from the nearest wind turbine (Evans et al. 2013b).

The sound characteristics and associated fall off with distance have been extensively measured by Tachibana in the range from 0.8 Hz to 5 kHz at 164 locations around 29 wind farms, using one third octave analysis. The average of the measures fell with a slope of 4 dB/octave over the whole range. The average passed through 55 dB at 10 Hz and crossed the hearing threshold at about 50 Hz (Tachibana et al. 2014). Other, less detailed measurements on individual turbines have shown slopes of 5dB/octave to 6 dB/octave (O'Neal et al. 2011). A spectrum which falls at 5dB/octave and passes through, for example, 60 dB at 10 Hz has an A-weighted level of 39 dB(A), which is mainly determined by a broad peak in the A-weighted spectrum in the region of 200 Hz to 630 Hz. Any shift in the level at 10Hz is reflected in the A-weighted level. Similarly this spectrum has a C-weighted level of 58 dB(C). The difference between dB(A) and dB(C) levels depends only on the spectrum shape and is independent of overall level, indicating that for similar spectrum shapes, the dB(A) and dB(C) levels are highly correlated.

There are currently no widely accepted international health-based limits for LFN specifically derived for wind turbines. A number of jurisdictions have developed both indoor and outdoor LFN limits to address potential issues associated with industrial noise emissions. The majority of the limits are for indoors and utilize 1/3 octave sound pressure level measurements between 5-200 Hz. This analysis enables assessors to identify tonal components within the spectrum that may be problematic. The 1/3 octave band limits vary significantly between jurisdictions. In Poland, LFN limits are around 10 dB(A) across 1/3 octave bands between 10-250 Hz (Mirowska 2001). In Denmark, LFN is limited to a total level of 20 dB(A) between 10-160 Hz (Jakobsen 2012), while in the UK, guidelines are generally between 10-25 dB(A) depending on the frequency between 10-100 Hz (Moorhouse et al. 2005). Indoor LFN limits provide a basis to address specific complaints from local residents; however, for wind farm development, regular monitoring of outdoor sound levels presents a more practical option.

Only a small number of jurisdictions, including the province of Alberta, Canada (AUC 2013), Japan (Kamigawara et al. 2006), and the Australian States of South Australia and New South Wales (New South Wales Planning and Infrastructure 2011), have introduced outdoor LFN noise limits. Several of these guidelines determine the difference between C- and A-weighted sound measurements. This calculation can provide an indication of an unbalanced spectrum; a difference greater than 20 dB between two weightings may warrant further investigation based on those regulations (Broner and Leventhall 1983; Leventhall 2004). The ability of this calculation to predict LFN issues is limited, particularly when there are low levels of background noise that result in a large difference between the A- and C-weighted sound levels that are not associated with increased levels of annoyance (Broner 2011). In the current investigation the difference between wind turbine operational scenarios (i.e., on and off) was <5 dB at the 490 and 611 m locations at both wind speeds. Measured background levels at 490 and 611 m were also high, measuring 48 and 45 dB(A) respectively. A number of noise guidelines, including those in the UK (Barclay 2012), New Zealand (NZWEA 2010) and several of the Australian states (Department of Planning and Community Development 2012; New South Wales Planning and Infrastructure 2011; South Australia Environmental Protection Authority 2009; Western Australian Planning Commission 2004), take into account the potential for high levels of background noise by suggesting that the contribution of wind turbines to be limited to <5 dB above background. In the current investigation, the 480 m location was the only one observed to be ≥5 dB above background levels (6 dB at 3 m/s and 7 dB at 6 m/s).

## 4. Conclusion

Data from the current investigation indicate that wind turbines produce noise that is broadband in nature, which includes energy within the IS and LFN spectrums. Based on the data presented here, the indoor IS component of wind turbine noise measured as dB(G) at distances of 450 and 900 m, was well below the levels of human perception (Watanabe and Møller 1990), providing further support to previous reports (Boczar et al. 2012; Evans et al. 2013a; Evans 2013; Leventhall 2006; 2013; O'Neal et al. 2011; Turnbull et al. 2012). Infrasound is produced at levels comparable or greater than those shown here by natural and engineered sources (Leventhall 2013; Turnbull et al. 2012). There is no scientific evidence to indicate that exposure at these G-weighted levels of IS can directly impact human health. Recent studies have indicated that psychological factors (Crichton et al. 2013a; 2013b) and the manner in which information is presented from media reports and non-scientific sources may influence the perception and expectations associated with wind turbine sounds (Deignan et al. 2013). These reports suggest that subjective variables may be a more likely etiology for self-reported effects than from exposure to IS associated with normal wind turbine operation.

The LFN analysis showed that when the turbines were both on and off sounds above 40-50 Hz exceeded the threshold for auditory perception as defined by ISO 226:2003 (ISO 2003). A clear contribution from the operation of the wind turbines was only observed at the closest location of 480 m when compared to background levels. Increases in LFN observed between 100-200 Hz corresponded to increases in overall sound measures reported in dB(A). The use of alternative sound weightings (i.e., dB(C)) may have utility in instances where there are significant increased levels of LFN, particularly when a tonal component is present. However, the results from the current investigation indicate that increases in LFN associated with wind turbine operation are correlated with increases in overall sound levels. These results, in conjunction with those of previous reports, suggest that controlling for overall sound levels produced by normally operating wind turbines will inherently control for LFN (Møller and Pedersen 2011; Parnell 2012; van den Berg 2013). The results reported here are in agreement with a recent report issued by Health Canada, which concluded that following over 4,000 hours of wind turbine noise measurements, there was "*no additional benefit in assessing LFN as C- and A-weighted levels were so highly correlated (r=0.94) that they essentially provided the same information*" (Health Canada 2014). Given the low levels of IS and the correlation between LFN and overall sound levels from wind turbines, the development and enforcement of suitable outdoor guidelines and limits, based on dB(A), provide an effective means to evaluate, monitor, and protect potential receptors.

## References

Alberta Utilities Commission. 2013. Rule 012: Noise control. .

Ambrose S, Rand R, Krogh C. 2012. *Wind turbine acoustic investigation: Infrasound and low-frequency noise - A case study*. B Sci Technol Soc 32(2):128-41.

Barclay C. 2012. Wind farms - distance from housing. House of Commons Library, UK Parliament; London, UK. Report nr SN/SC/5221.

Baxter J, Morzaria R, Hirsch R. 2013. *A case-control study of support/opposition to wind turbines: Perceptions of health risk, economic benefits, and community conflict*. Energ Policy 61:931-43.

Bedard Jr A. 1978. *Infrasound originating near mountainous regions in Colorado*. J Appl Meteorol 17(7):1014-22.

Berglund B, Hassmen P, Job RS. 1996. *Sources and effects of low-frequency noise*. J Acoust Soc Am 99(5):2985-3002.

Boczar T, Malec T, Wotzka D. 2012. *Studies on infrasound noise emitted by wind turbines of large power*. Acta Phys Pol A 122(5):850-3.

Bolin K, Bluhm G, Eriksson G, Nilsson ME. 2011. I*nfrasound and low frequency noise from wind turbines: Exposure and health effects*. Environ Res Lett 6(3):035103.

Botha P. 2013. *Ground vibration, infrasound and low frequency noise measurements from a modern wind turbine*. Acta Acust United Ac 99(4):537-44.

Broner N. 2011. *A simple criterion for low frequency noise emission assessment.* Acoust Aust 39(1):7-14.

Broner N and Leventhall H. 1983. *Low frequency noise annoyance assessment by low frequency noise rating (LFNR) curves*. J Low Freq Noise V A 2(1):20-8.

Chapman S and St George A. 2013. *How the factoid of wind turbines causing 'vibroacoustic disease'came to be 'irrefutably demonstrated'*. Aust N Z J Publ Heal 37(3):244-9.

Crichton F, Dodd G, Schmid G, Gamble G, Cundy T, Petrie K, J. 2013a. *Can expectations produce symptoms from infrasound associated with wind turbines?* Health Psychol 33:360-4.

Crichton F, Dodd G, Schmid G, Gamble G, Cundy T, Petrie KJ. 2013b. *The power of positive and negative expectations to influence reported symptoms and mood during exposure to wind farm sound*. Health Psychol .

Deignan B, Harvey E, Hoffman-Goetz L. 2013. *Fright factors about wind turbines and health in ontario newspapers before and after the Green Energy Act*. Health Risk Soc 15(3):234-50.

Department of Planning and Community Development. 2012. Policy and planning guidelines for development of wind energy facilities in Victoria. Victorian Government Department of Planning and Community Development; Melbourne, Australia.

Dommes E, Bauknecht H, Scholz G, Rothemund Y, Hensel J, Klingebiel R. 2009. *Auditory cortex stimulation by low-frequency tones—An fMRI study*. Brain Res 1304:129-37.

Evans T, Cooper J, Lenchine V. 2013a. *Infrasound levels near wind farms and in other environments*. South Australian EPA and Resonate Acoustics; Adelaide, Australia.

Evans T. 2013. *Macarthur wind farm - infrasound & low frequency noise*. Resonate Acoustics and AGL Energy Limited; Adelaide, Australia. Report nr A12130.

Evans T, Cooper J, Lenchine V. 2013b. *Low frequency noise near windfarms and in other environments*. South Australian Environment Protection Authority, Resonate Acoustics; Adelaide, Australia.

Evans T and Cooper J. 2012. *Comparison of predicted and measured wind farm noise levels and implications for assessments of new wind farms*. Acoust Aust 40(1):28-36.

Goerke V and Woodward M. 1966. *Infrasonic observation of a severe weather system*. Mon Weather Review 94(6):395-8.

Goerke V, Young J, Cook R. 1965. *Infrasonic observations of the May 16, 1963, volcanic explosion on the island of Bali*. J Geophys Res 70(24):6017-22.

Health Canada. 2014. Wind turbine noise and health. The Government of Canada.

ISO (International Organization for Standardization). 2003. ISO 226:2003. Acoustics - normal equal-loudness level contours, 2nd edition. Geneva, Switzerland: ISO.

Jakobsen J. 2012. *Danish regulation of low frequency noise from wind turbines*. J Low Freq Noise V A 31(4):239-46.

Jakobsen J. 2001. *Danish guidelines on environmental low frequency noise, infrasound and vibration*. J Low Freq Noise V A 20(3):141-8.

Jobert A, Laborgne P, Mimler S. 2007. *Local acceptance of wind energy: Factors of success identified in french and german case studies*. Energ Policy 35(5):2751-60.

Kamigawara K, Yue J, Saito T, Hirano T. 2006. *Publication of "Handbook to deal with low frequency noise (2004)"*. J Low Freq Noise V A 25(2):153-6.

Knopper LD and Ollson CA. 2011. *Health effects and wind turbines: A review of the literature.* Environ Health 10(1):1-10.

Knopper L, Ollson C, A., McCallum L, Whitfield Aslund M, Berger R, G., Souweine K, McDaniel M. 2014. *Wind turbines and human health*. Front Public Heath 2:1-20.

Leventhall G. 2013. *Concerns about infrasound from wind turbines*. Acoust Today 9(3):30-8.

Leventhall G. 2006. *Infrasound from wind turbines-fact, fiction or deception*. Can Acoust 34(2):29-36.

Leventhall G. 2004. *Low frequency noise and annoyance*. Noise Health 6(23):59-72.

Leventhall G, Pelmear P, Benton S. 2003. *A review of published research on low frequency noise and its effects*. Department for Environment, Food and Rural Affairs; London, UK. Report nr EPG 1/2/50.

McCallum LC, Aslund ML, Knopper LD, Ferguson GM, Ollson CA. 2014. *Measuring electromagnetic fields (EMF) around wind turbines in Canada*: Is there a human health concern? Environ Health 13(1):9.

Mirowska M. 2001. *Evaluations of low-frequency noise in dwelling. new polish recommendations*. J Low Freq Noise V A 20:67-74.

Møller H and Pedersen CS. 2011. *Low-frequency noise from large wind turbines*. J Acoust Soc Am 129(6):3727-44.

Moorhouse A, Waddington D, Adams M. 2005. Proposed criteria for the assessment of low frequency noise disturbance. Department for Environment, Food and Rural Affairs; London, UK. Report nr NANR45.

New South Wales Planning and Infrastructure. 2011. NSW planning guidelines: Wind farms. draft for consulation. NSW Department of Planning and Infrastructure; Sydney, Australia.

New Zealand Wind Energy Association (NZWEA). 2010. The new zealand wind farm noise standard. The New Zealand Wind Energy Association; Wellington, New Zealand.

O'Neal RD, Hellweg Jr. RD, Lampeter RM. 2011. *Low frequency noise and infrasound from wind turbines*. Noise Control Eng J 59(2):135-57.

Parnell J. 2012. *Development of the draft NSW planning guidelines: Wind farms*. Acoust Aust 40(1):79-83.

Pedersen E and Persson Waye K. 2007. *Wind turbine noise, annoyance and self-reported health and well-being in different living environments*. Occup Environ Med 64(7):480-6.

Pedersen E and Persson Waye K. 2004. *Perception and annoyance due to wind turbine noise--a dose-response relationship*. J Acoust Soc Am 116(6):3460-70.

Persson Waye K and Öhrström E. 2002. *Psycho-acoustic characters of relevance for annoyance of wind turbine noise.* J Sound Vib 250(1):65-73.

Pierpont N. 2009. Wind turbine syndrome: A report on a natural experiment. Santa Fe, NM, USA: K-Selected Books.

Rand RW, Ambrose SE, Krogh CM. 2011. *Occupational health and industrial wind turbines A case study*. B Sci Technol Soc 31(5):359-62.

Richarz W., Richarz H. and Gambino T. 2011. Correlating very low frequency sound pulse to audible wind turbine sound. Fourth international meeting on wind turbine noise; April, 2011; Rome, Italy. .

Roberts Cedric. 2004. EcoAccess guideline for the assessment of low frequency noise. Acoustics 2004; November, 2004; Gold Coast, Australia. .

Salt A, N.. and Kaltenbach J, A. 2011. *Infrasound from wind turbines could affect humans*. B Sci Technol Soc 31(4):296-302.

Salt A, N.. and Hullar T, E. 2010. *Responses of the ear to low frequency sounds, infrasound and wind turbines.* Hearing Res 268:12-21.

Sloven P. 2005. *LFN and the A-weighting.* Journal of Low Frequency Noise, Vibration and Active Control 24(3):157-62.

South Australia Environmental Protection Authority. 2009. Wind farms environmental noise guidelines. Environmental Protection Authority; Adelaide, Australia.

Tachibana H., Yano H. and Fukushima A. 2013. Assessment of wind turbine noise in immission areas. Proc. 5th international conference on wind turbine noise Denver, USA. .

Tachibana H, Yano H, Fukushima A, Sueoka S. 2014. *Nationwide field measurements of wind turbine noise in Japan*. Noise Control Eng J 62(2):90-101.

Turnbull C, Turner J, Walsh D. 2012. *Measurement and level of infrasound from wind farms and other sources*. Acoust Aust 40(1):45-50.

van den Berg Frits. 2013. Wind turbine noise: An overview of acoustical performance and effects on residents. Proceedings of acoustics; November, 2013; Victor Harbor, South Australia. Australian Acoustical Society. 1 p.

Walker BW, Hessler GF, Hessler DM, Rand R, Schomer P. 2012. A cooperative measurement survery and analysis of low frequency and infrasound at the shirley wind farm in brown county, wisconsin. Public Service Commission of Wisconsin. Report nr 122412-1.

Watanabe T and Møller H. 1990. *Low frequency hearing thresholds in pressure field and in free field.* J Low Freq Noise V A 9(3):106-15.

Western Australian Planning Commission. 2004. Guidelines for wind farm development. Department for Planning and Infrastructure; Perth, Australia. Report nr 67.

WHO (World Health Organization). 2009. Night noise guidelines for europe. Copenhagen: The Regional Office for Europe of the World Health Organization; Copenhagen, Denmark.

Wilson CR. 1967. *Infrasonic pressure waves from the aurora: A shock wave model*. Nature 216:131-3.

Wiser R and Bolinger M. 2013. 2012 wind technologies market report. US Department of Energy.

Wolsink M. 2000. *Wind power and the NIMBY-myth: Institutional capacity and the limited significance of public support.* Renew Energ 21(1):49-64.

Yuan H, Long H, Liu J, Qu L, Chen J, Mou X. 2009. *Effects of infrasound on hippocampus-dependent learning and memory in rats and some underlying mechanisms*. Environmental Toxicology and Pharmacology 28(2):243-7.

# Outcome of systematic research on wind turbine noise in Japan

Hideki TACHIBANA[1]

[1] Professor Emeritus, The University of Tokyo

## ABSTRACT

In Japan, serious complaints about wind turbine noise have arisen from nearby residents since the commencement of large-scale construction of wind generation plants in about 2000. Regarding this new type of environmental noise problem, scientific knowledge is insufficient and no standard methods for measuring and assessing the noise have been established in Japan. To improve this situation, a research project entitled “Research on the evaluation of human impact of low frequency noise from wind turbine generators” has been conducted over the three years from fiscal year 2010, funded by a grant from the Ministry of the Environment, Japan. This project consisted of three main subjects: (1) physical research on wind turbine noise by field measurement, (2) a social survey on the response of nearby residents, and (3) auditory experiments on the human response to noises containing low frequency components. In this paper, the outcome of the research project is reviewed and standard methods for measuring and assessing the wind turbine noise are discussed.

Keywords: Wind turbine noise, Low frequency sound, Amplitude modulation sound
I-INCE Classification of Subjects Number(s): 14.5.4 and 63.2

## 1. INTRODUCTION

In Japan, since the commencement of large-scale construction of wind generation plants in about 2000, serious complaints have arisen from nearby residents regarding wind turbine noise (WTN). Regarding this new type of environmental noise problem, scientific knowledge is insufficient and no standard methods for measuring and assessing the noise have been established in Japan. To improve this situation, a research project entitled “Research on the evaluation of human impact of low frequency noise from wind turbine generators” has been conducted over the three years from fiscal year 2010, funded by a grant from the Ministry of the Environment, Japan (1). This project consisted of three main subjects: 1. physical research on WTN by field measurement, 2. a social survey on the response of nearby residents, and 3. auditory experiments on the human response to noises containing low frequency components. Figure 1 shows the organization of the research groups and the main subjects in the project. In this paper, the outcome of the research project is reviewed by putting emphasis on the field measurements and some technical points for the measurement and assessment of WTN are discussed

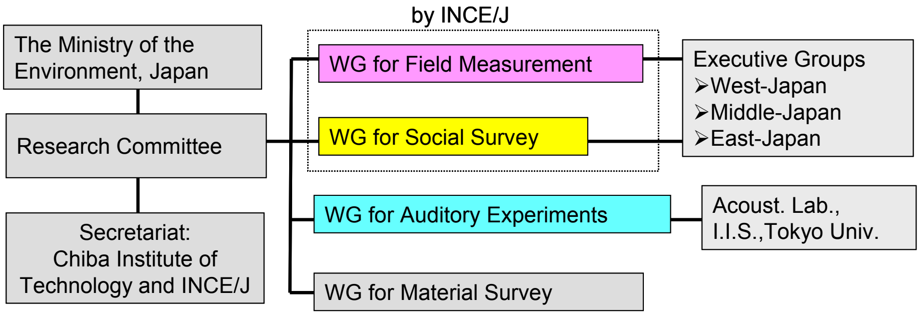


**Figure 1** – Organization of the research groups and the main subjects

---

[1] pon-t@iis.u-tokyo.ac.jp

## 2. FIELD MEASUREMENTS OF WTN

### 2.1 Outline

Regarding WTN problem, no systematic field survey has been conducted in Japan so far except for some case studies on noise complaints about WTN. In this research project, therefore, a systematic investigation was planned and field measurements were conducted for 34 wind farms across Japan. Moreover, to investigate the actual state of residual noise in quiet rural districts, similar measurements were also conducted in 16 control areas with similar local characteristics to the wind farm areas but were not affected by WTN. At the same time as the field measurements, interview-based questionnaires were also conducted both at the wind farm sites and in the control areas to investigate the effect of WTN on nearby residents (2, 3, 4).

From the results of preliminary trials and consideration of the practical conditions at the measurement sites, the following procedures were adopted in the field measurements.

### 2.2 Measurement Methods and Procedures

In the WTN problem, the effect of low frequency components including infrasound is an important matter of controversy, and therefore prototype wide-frequency-range sound level meters with a measurement frequency range from 1 Hz to 20 kHz and a function for recording the sound pressure signal were used.

To prevent wind-induced noise at a microphone particularly at low frequencies, a prototype wind-screen set shown in Figure 2 was devised. This set is of a double-skin type consisting of a globular wind-screen of 20 cm diameter made of urethane foam and a newly designed dodecahedral second screen covered with a thin cloth (nylon 90% and polyurethane 10%; opening ratio: 60%) with high elasticity. The insertion loss of this wind-screen set is below 1 dB up to 4 kHz as a result of measurement in anechoic room. Its wind-shielding effect was checked by a field measurement in a very quiet plain (1).

The field measurement was performed unattended and continuously for 5 days at each measurement site and the sound pressure was recorded on an SD card installed in the sound level meter.

Although WTN can sometime be audible inside residential buildings potentially disturbing residents' sleep at night, acoustic measurements inside buildings are very difficult from a physical viewpoint and can invade residents' privacy. Therefore, it has been decided to perform the measurement facing the nearest wind turbine in the yard of the residence under investigation, and the microphone of the sound level meter covered with the double wind-screen set was placed on the ground so that the center of the microphone was located 20 cm above the ground. The height of the measurement point was decided in order to minimize the effect of wind on the microphone and to avoid various difficulties in keeping the microphone at a high position for a long time (see Figure 2).

In the field measurement around each wind farm, seven measurement positions were uniformly distributed in the residential area within a distance of about 100 m to 1 km from the nearest wind turbine. Moreover, an additional measurement point (reference point) was located near a wind turbine to observe the operation condition of the wind farm.

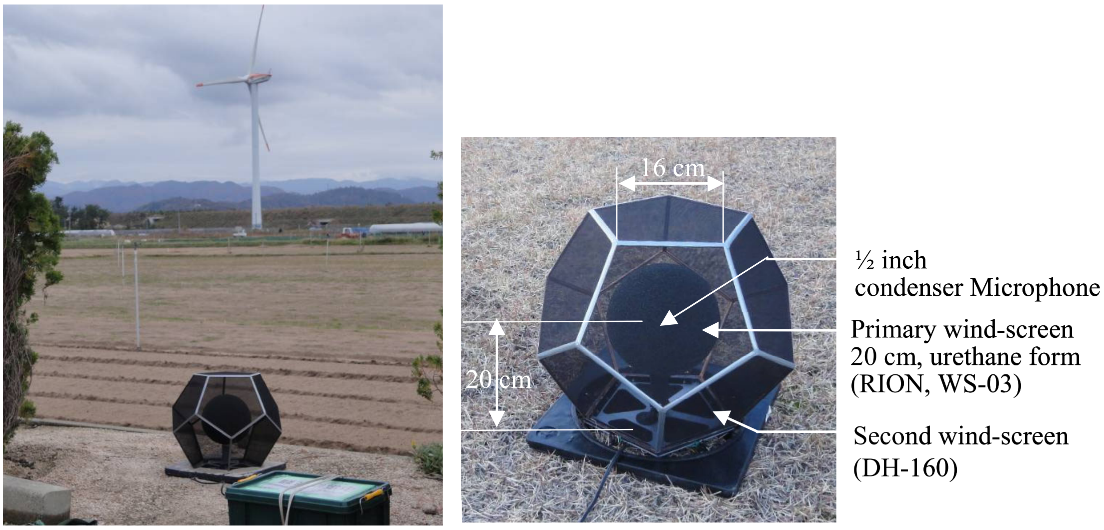


**Figure 2** – An example of field measurement using the double-skin type wind-screen.

## 2.3 Data Analysis

Data were analyzed by putting priority on nighttime as the reference time interval as shown in Figure 3, since the effect of WTN is generally most severe at night (2) and the effect of the background noise is smallest during this time zone.

At the reference time interval, the recordings for 10 min of every hour during which the wind turbines were judged to be under a rated operation condition were reproduced, and 1/3-octave-band sound pressure levels (SPLs) and A-, C-, and G-weighted time-averaged SPLs were obtained.

When carrying out the analysis, the effect of background noises such as road traffic noise, aircraft noise, and the sounds of various creatures were carefully examined through level recordings and a hearing check for the recorded sounds. If the effect of these background noises was severe, the data were not adopted. In cases where the sounds of insects were dominated in summer and autumn, high-cut filtering was applied to eliminate the frequency components higher than 1.25 kHz in 1/3-octave-band, because the A-weighted SPL is apt to be determined by these sounds.

As the representative values of the 1/3-octave-band and frequency-weighted SPLs for the reference time interval ($L_{p\mathrm{eq,night}}$), the energy-mean values of the respective SPLs over every 10 min ($L_{p\mathrm{eq,10min}}$) were calculated.

For the measurements in the control areas, 95 percentile levels of 1/3-octave-band and A-, C-, and G-weighted SPLs over 10 min ($L_{p\mathrm{95,10min}}$) of every hour at night were obtained, and the representative values ($L_{p\mathrm{95,night}}$) were calculated as the energy-means of the respective SPLs over every 10 min.

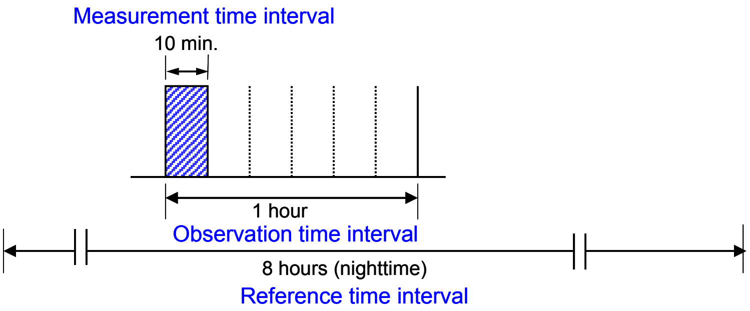


**Figure 3** – Time intervals used for the analysis of WTN.

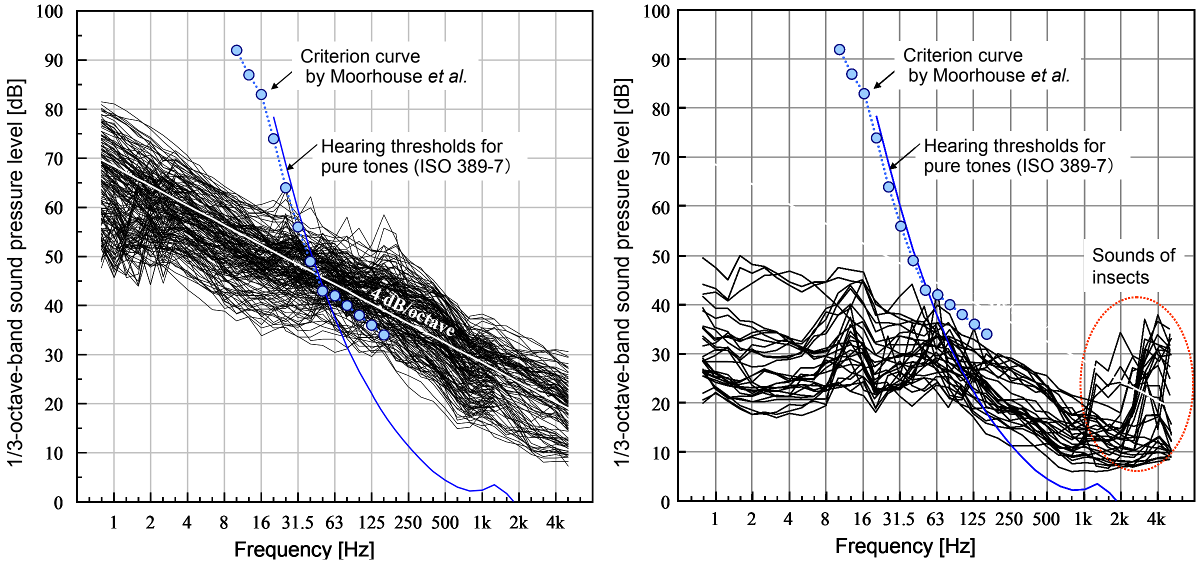
## 2.4 Measurement Results

Among the 34 wind farms, the measurement was unsuccessful in the areas around four coastal wind farms being disturbed by sea waves and windbreak. Another measurement was to investigate the emission characteristics of a wind turbine. Excluding these data, time-averaged 1/3-octave-band SPLs measured at 164 points around 29 wind farms are given in Figure 4(a). Brief description of the 29 wind farms is as shown in Table 1. In Figure 4(a), it can be seen that almost all WTNs have similar spectral characteristics, which can be approximated by a slope of - 4 dB/octave in band spectrum. By comparing these results with the criterion curve for the assessment of low frequency noise proposed by Moorhouse*et al.* (5), it can be seen that the frequency components below 20 Hz for all the WTNs measured in the immission areas were much lower than the curve. The validity of this criterion curve has been confirmed by an auditory experiment on the audibility of low frequency sounds conducted as part of this project (6).

The measurement results of residual noise assessed by 95 percentile level in each 1/3-octave-band at 33 points in 14 control areas are shown in Figure 4(b). Compared to the results for WTNs, the levels were generally much lower and the spectrum characteristics were not uniform.

All of the measurement results for $L_{\mathrm{Aeq}}$, $L_{\mathrm{Ceq}}$, and $L_{\mathrm{Geq}}$ are shown in Figure 5 in the form of histograms. In these figures, the data of the residual noise level in terms of $L_{\mathrm{A95}}$, $L_{\mathrm{C95}}$, and $L_{\mathrm{G95}}$ measured at 33 measurement points in the control areas are also shown for comparison. In Figure 5 (a), it can be seen that $L_{\mathrm{Aeq}}$ for WTN was distributed from 25 dB to 50 dB and the modal class was 41-45 dB. On the other hand, the residual noise level in the control areas was distributed in the ranges from 20 dB to 35 dB. Thus, there was a big difference between the WTN in terms of $L_{\mathrm{Aeq}}$ and the residual noise in terms of $L_{\mathrm{A95}}$ in the control areas.

Regarding the problem of WTN, the difference between $L_{\mathrm{Ceq}}$ and $L_{\mathrm{Aeq}}$ is often discussed. To investigate this point, the relationship between the two indicators was examined using the 164 data. The result is shown in Figure 6, in which it can be seen that $L_{\mathrm{Aeq}}$ and $L_{\mathrm{Ceq}}$ had a fairly high correlation.



(a) WTNs (164 data for 29 wind farms) (b) Residual noise (33 data in 14 control areas)

**Figure 4** – Measurement results of WTN and residual noise in the control areas.

**Table 1** - Wind farms under the field measurements

| ID | Scale of the wind farms and geographical features | Measurement |
|---|---|---|
| W01 | 1 turbine of 1.98 MW on a hill of a peninsula | Dec. 2010 |
| W02 | 7 turbines of 2.5 MW in mountainous area | Jan. 2011 |
| W03 | 10 turbines of 2 MW in mountainous area | Feb. 2011 |
| W04 | 10 turbines of 1.3 MW in mountainous area | Mar. 2011 |
| W05 | 9 turbines of 1.5 MW on a tableland | Feb. 2011 |
| W06 | 6 turbines of 1.5 MW on a tableland | Feb. 2011 |
| W07 | 9 turbines of 2.3 MW along the ridge of a mountain | Aug. 2011 |
| W08 | 21 turbines of 2.4 MW in mountainous area | Oct. 2011 |
| W09 | 9 turbines of 1.5 MW along a coast | Dec. 2011 |
| W10 | 1 turbine of 1.5 MW in the skirts of a mountain | Dec. 2011 |
| W11 | 1 turbine of 1.98 MW on a mountaintop along a coast | Jan. 2012 |
| W12 | 5 turbines of 1.99 MW in a hilly area | Aug. 2011 |
| W13 | 1 turbine of 1 MW in a plain | Nov. 2011 |
| W14 | 17 turbines of 2 MW along the ridge of a mountain | Dec. 2011 |
| W15 | 15 turbines of 2.5 MW along the ridge | Jan. 2012 |
| W16 | 5 turbines of 3 MW along a coast | Jan. 2012 |
| W20 | 2 turbines of 400 kW, 4 turbines of 600 kW and 2 turbines of 1.5 MW in flat farmlands | Oct. 2011 |
| W22 | 1 turbine of 1.95 MW on a mountaintop | Aug. 2012 |
| W23 | 1 turbine of 1.955 MW in a plain along a coast | Aug. 2012 |
| W24 | 10 turbines of 1.3 MW on a mountaintop | Sep.-Oct. 2012 |
| W25 | 8 turbines of 1.3 MW along the ridge of a mountain | Oct. 2012 |
| W27 | 20 turbines of 1 MW, 5 turbines of 1.5 MW and 14 turbines of 1.65 MW in a vast grassland | Sep. 2012 |
| W28 | 5 turbines of 1.5 MW and 1 turbine of 2.5 MW (not operated) on a hill along a coast | Oct. 2012 |
| W29 | 1 turbine of 1.5 MW in gently sloping mountainous area | Oct. 2012 |
| W30 | 10 turbines of 2 MW around a gently sloping mountainous area | Nov. 2012 |
| W31 | 1 turbine of 600 kW on a hill | Jan. 2013 |
| W32 | 1 turbine of 1 MW between harbor facilities and a coastal park | Sep. 2012 |
| W33 | 1 turbine of 400 kW in a hilly park | Sep. 2012 |
| W34 | 10 turbines of 1.95 MW in farmlands | Sep. 2012 |

In Figure 5(c), it is clear that the G-weighted sound pressure levels measured in the areas around wind farms were higher than those measured in the control areas. Even in the areas around wind farms, however, the levels were much lower than the infrasound threshold level described in ISO 7196.

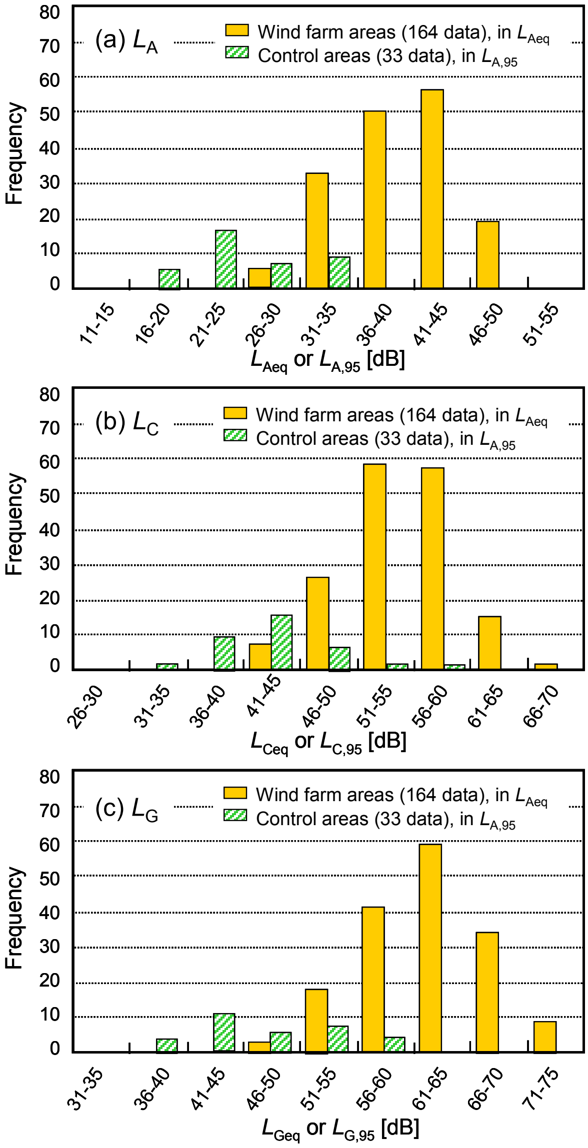


**Figure 5** – WTNs and residual noise in the control areas.

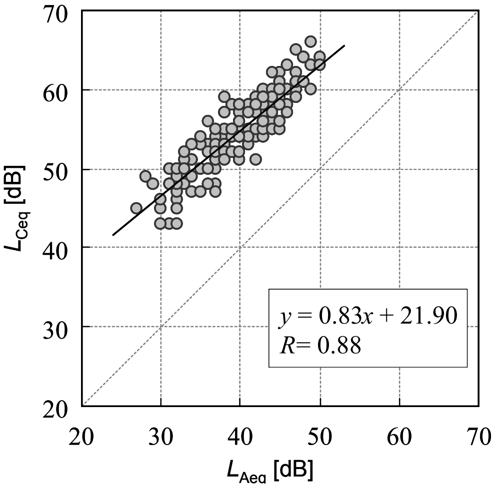


**Figure 6** – Correlation between $L_{Aeq}$ and $L_{Ceq}$ of WTN

To see the SPL distribution in distance, $L_{\mathrm{Aeq,night}}$ was examined as a function of the distance from the wind turbine for all of the measurement data shown in Figure 4(a). The results are shown in Figure 7(a) for single wind turbines (51 points at 10 sites) and in Figure 7(b) for wind farms with more than one wind turbine (113 points at 19 sites). These results show that the sound level tends to gradually decrease with increasing distance, but the plots are scattered. WTN propagation is generally very complicated owing not only to meteorological conditions but also to topographical condition, vegetation condition, *etc*. Especially in Japan, wind power plants are often constructed in hilly areas and the sound propagation is very complicated.

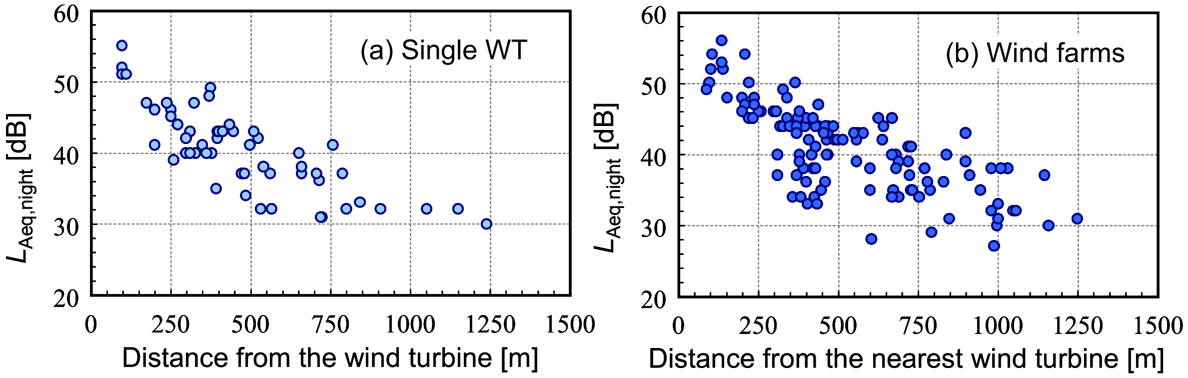


**Figure 7** – Distribution in distance of WTN

## 3. AMPLITUDE MODULATION

When the blades of a wind turbine rotate, they generate a periodic fluctuating sound, the so-called "amplitude modulation (AM) sound" or "swish sound", and such sounds much increase psychological annoyance (7, 8). AM sound is related to the directivity of the aerodynamic trailing edge noise and Doppler amplification, and its main frequency components audible in immission areas are in the mid-frequency range (about 400 to 1000 Hz) (7).

To objectively quantify the level of AM, several methods have been proposed (9-12), in which the frequency and magnitude of the envelope of amplitude modulation are detected by applying sophisticated signal processing techniques. As another method, the authors adopted a very simple and practical method in this study as described below.

Figure 8(a) shows an example of the A-weighted sound pressure levels of WTN recorded with FAST and SLOW time-weightings for 3 min. The data were measured at a point 1,152 m from a 1.95 MW wind turbine. In this case, it is clearly seen that the mean sound pressure level varied with time. Therefore, it is necessary to find a suitable method for quantitatively assessing the strength of AM over a long time. As a simple idea to achieve this, the difference between the A-weighted sound pressure level with FAST time-weighting ($L_{\mathrm{A,F}}(t)$) and that with SLOW time-weighting ($L_{\mathrm{A,S}}(t)$) is calculated as

$$\Delta L_{\mathrm{A}}(t) = L_{\mathrm{A,F}}(t) - L_{\mathrm{A,S}}(t) \qquad (1).$$

Then, the width of the 90% range of the level difference is obtained as a measure indicating the AM depth.

$$D_{\mathrm{AM}} = \Delta L_{\mathrm{A5}} - \Delta L_{\mathrm{A95}} \qquad (2)$$

where, $D_{\mathrm{AM}}$ is the AM depth in dB, and $\Delta L_{\mathrm{A5}}$ and $\Delta L_{\mathrm{A95}}$ are the 5% and 95% levels of $\Delta L_{\mathrm{A}}(t)$, respectively.

Figure 8(b) shows a magnification of the recording in Figure 8(a) over 40 s, and the level difference between the FAST and SLOW time-weightings is shown in Figure 8(c). Figures 9(a) and 9(b) show the auto-correlation coefficient and the auto-power spectrum calculated for the level difference $\Delta L_{\mathrm{A}}(t)$ for 3 min shown in Figure 8(c). In these results, it can be clearly seen that the level difference had a dominant spectrum at 1.03 Hz, which corresponds to the blade passing frequency of the turbine under measurement. Figure 8(d) shows the procedure to determine $D_{\mathrm{AM}}$,. In this case, $D_{\mathrm{AM}}$ is 2.8 dB.

The above procedure was applied to the sound pressure recordings made at 81 points at 18 wind farm sites. As a result, it was found that amplitude modulation depth ($D_{\mathrm{AM}}$) ranged from 1 dB to 5 dB and that the modal group was 2.0 to 2.4 dB as shown in Figure 10. It is known that the sensation of fluctuation begins at an AM depth of approximately 2 dB (7). This was confirmed in a recent auditory experiment performed as part of this research project (13). According to these findings, fluctuation due to AM can be detected at about three-quarters of the measurement points examined in this study.

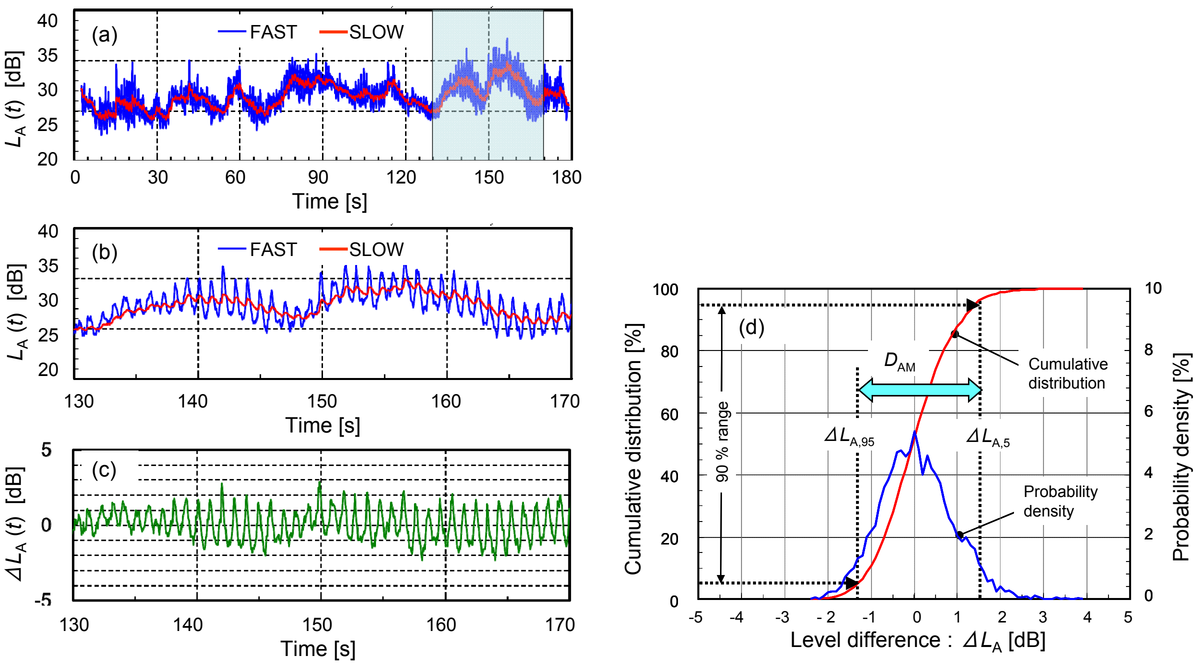
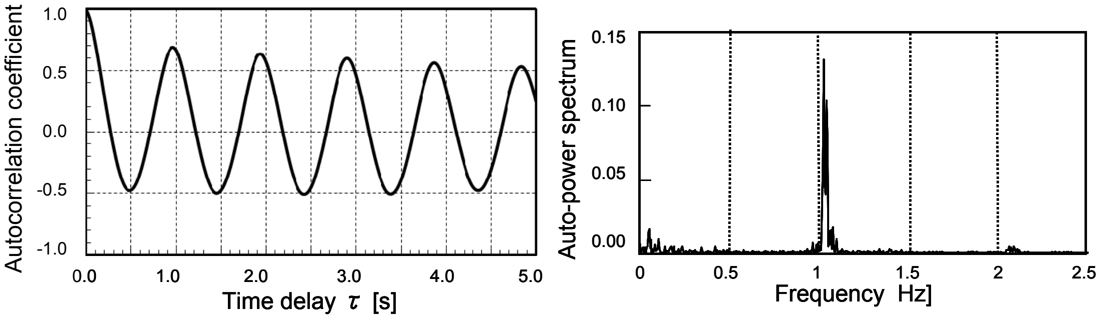


**Figure 8** – An example of objective quantification of the level of Amplitude Modulation. **(a)** A-weighted SPL recorded with FAST and SLOW time-weightings for 3 min, **(b)** magnification of recording shown in **(a)** over 40 s, **(c)** level difference between FAST and SLOW, and **(d)** statistical determination of AM depth ($D_{AM}$) from the level difference shown in (c).



(a) Autocorrelation coefficient (b) Auto-power spectrum

**Figure 9** – Autocorrelation function and auto-power spectrum of the level difference $\Delta L_A(t)$.

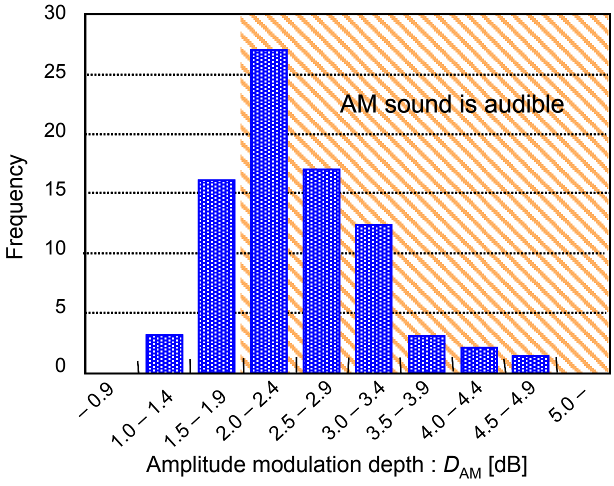


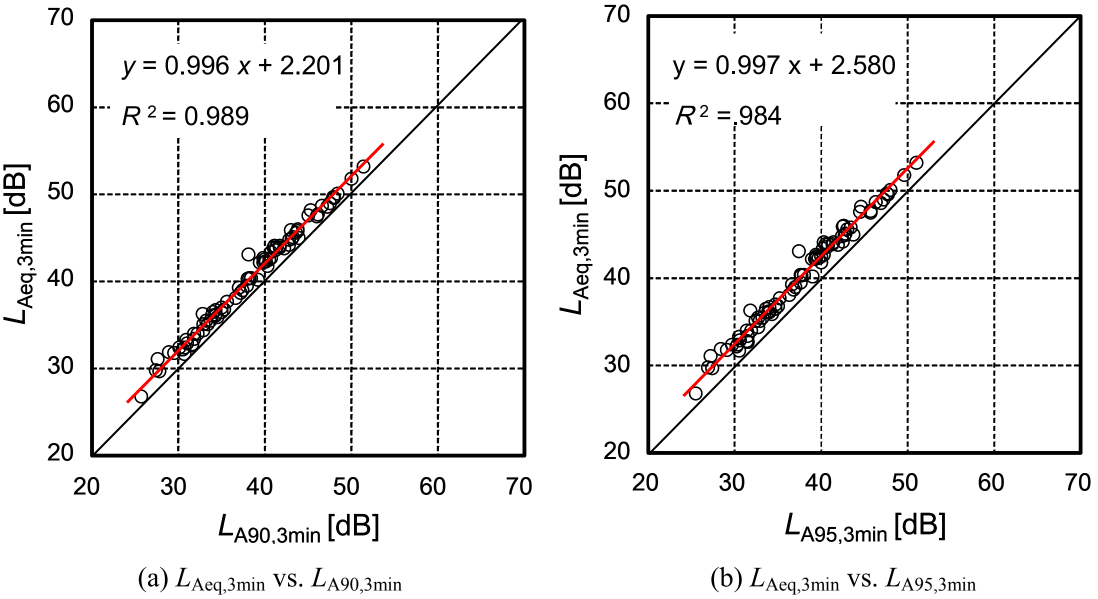
**Figure 10** – Distribution of AM depth, $D_{AM}$, in the data measured at 81 points in the areas around 18 wind farms.

## 4. INDICATOR FOR WTN ASSESSMENT

Noise limits or guidelines for WTN are legislated in many countries, states, and provinces, and almost all legislations are specified in terms of the A-weighted SPL, in common with general environmental noises. Regarding the A-weighted SPL, however, many critical arguments have been made (14-16). In particular, for WTN with relatively dominant low-frequency components, the applicability of the A-weighted SPL needs to be reexamined experimentally. For this aim, we conducted a basic loudness test using various environmental noises including WTN that were recorded so as to include low-frequency components down to infrasound and were reproduced in an experimental facility capable of reproducing low frequency sounds down to 4 Hz (17). The experimental results were evaluated using the A- and C-weighted SPLs, Zwicker loudness level, and Moore-Glasberg loudness level. As a result, it has been found that the A-weighted SPL is a simple and appropriate indicator for the loudness assessment of general environmental noise. In the results of other auditory experiments we conducted in this research project, the applicability of the A-weight SPL to the assessment of perceived loudness of sounds with dominant components at low frequencies has been found (6). These facts might suggest that the A-weight SPL can be used in the assessment of WTN as a primary indicator.

## 5. EFFECTS OF BACKGROUND NOISE

In the field measurements in this study, the time-averaged A-weighted SPL was obtained as mentioned above, but it is a hard job and needs close attention to eliminate the background noise because the level of WTN in immission areas is relatively low. A practical way to avoid such a problem is to obtain the 90% or 95% value of the A-weighted SPL for the measurement time interval. Figure 10 shows the relationship between (a) $L_{\mathrm{Aeq,3min}}$ and $L_{\mathrm{A90,3min}}$ and (b) $L_{\mathrm{Aeq,3min}}$ and $L_{\mathrm{A95,3min}}$ of WTNs measured at 81 points around 18 wind farms. Here, the effect of the background noise was eliminated when measuring $L_{\mathrm{Aeq}}$. In both cases, a considerably high correlation is seen between the respective indicators. This means that $L_{\mathrm{Aeq}}$ can be approximated by adding 2.2 dB to $L_{\mathrm{A90}}$ or 2.6 dB to $L_{\mathrm{A95}}$. Strictly speaking, the difference between $L_{\mathrm{Aeq}}$ and $L_{\mathrm{A90}}$ or $L_{\mathrm{A95}}$ depends on the level of the amplitude modulation, but its effect can practically be neglected when considering general WTNs in immission areas around wind farms.



(a) $L_{\mathrm{Aeq,3min}}$ vs. $L_{\mathrm{A90,3min}}$ (b) $L_{\mathrm{Aeq,3min}}$ vs. $L_{\mathrm{A95,3min}}$

**Figure 10** – Relationship between $L_{\mathrm{Aeq,3min}}$ (the effect of the background noise was eliminated) and $L_{\mathrm{A90,3min}}$ or $L_{\mathrm{A95,3min}}$ of WTNs measured at 81 points at 18 wind farm sites.

## 6. CONCLUSIONS

As a result of the systematic research on WTN in Japan conducted to obtain fundamental material to produce guidelines of noise impact assessment of wind power plants, the following findings have been obtained.

(1) **Acoustical characteristics of WTN**: From the measurement results obtained at 164 points in the residential areas around 29 wind farms, it was found that WTN generally has a spectrum characteristic of about - 4 dB/octave in band spectrum and the components in the infrasound frequency region were much below the hearing thresholds. This fact was examined through a laboratory experiment conducted as part of this research project (6). These indicate that WTN is not a problem in the infrasound frequency region. However, most of the frequency components in audible frequency range are above the hearing thresholds. This means that WTN should be discussed as an "audible" environmental noise.

(2) **Noise effects:** All the measurement results of WTN in the immission areas obtained in this study were between 25 dB to 50 dB at most in terms of $L_{\mathrm{Aeq}}$. Although these levels are not so high compared with other community noises, they are audible, especially at night, and might cause serious annoyance and sleep disturbance in residential areas which are generally very quiet rural districts. Legislative and administrative measures (noise limits or guidelines) should be prepared by considering these points.

(3) **Noise indicator**: WTN can be assessed by the A-weighted SPL as a primary indicator, similarly to general environmental noises. Since WTN is relatively low level in general, it is rather difficult to accurately measure $L_{\mathrm{Aeq}}$ being influenced by various background noises. In this respect, it is preferable to measure the percentile level like $L_{\mathrm{A90}}$ or $L_{\mathrm{A95}}$ from which $L_{\mathrm{Aeq}}$ can be approximated statistically.

(4) **Amplitude modulation**: Amplitude modulation generated by the rotation of the blades of wind turbine is inevitable in WTN, and is apt to increase residents' annoyance. Therefore, the effect of AM sound should be considered when preparing noise limit or guideline for WTN (18). To objectively assess the extent of amplitude modulation, a simple statistical method was proposed in this research project.

(5) **Tonal components**: In the measurement results of this study, tonal components were observed in some cases, especially in the areas near some types of wind turbines. Tonality is also a serious factor to increase annoyance of WTN (19, 20) and the effect should be considered as an additional penalty when any tonal components are included in WTN (18). The method for objectively assessing the tonality is specified in IEC 61400-11: 2012 and is also being discussed at ISO/TC43. The effectiveness of these assessment methods are being investigated also in Japan.

(6) **Measurement points**: For some physical and practical reasons as mentioned in 2.2, the measurement points should be located outside of buildings in principle. In the measurement, the microphone should be covered with wind-screen with a high wind-shielding effect and be placed close to the ground in order to prevent the wind-induced noise as far as possible.

(7) **Residual noise:** In the WTN problem, the audibility of the noise when the environment is quiet is serious. Therefore, the environmental condition without WTN should be assessed by the residual noise which is an ambient noise excluding every specific noise such as road traffic noise, aircraft noise, and the sounds of various creatures. To that end, 90 or 95 percentile level should be measured and used in the assessment of the environmental condition.

## ACKNOWLEDGEMENTS

This research project was financed by a grant from the Ministry of the Environment, Japan. The author gratefully acknowledges the members of the Research Committee of the project for their wholehearted cooperation. The author also thanks Mr. Tatsuya Ohta at NEWS Environmental Design Inc. and Dr. Tomohiro Kobayashi at Kobaysi Institute of Physical Research for their technical assistance in this study.

## REFERENCES

1. H. Tachibana, H. Yano, A. Fukushima and S. Sueoka, "Nationwide field measurements of wind turbine noise in Japan", *Noise Control Eng. J.*, 62(2), 90-101 (2014).
2. S. Kuwano, T. Yano, T. Kageyama, S. Sueoka and H. Tachibana, "Social survey on community response to wind turbine noise in Japan", *Inter-Noise 2013* (2013).
3. T. Yano, S. Kuwano, T. Kageyama, S. Sueoka and H. Tachibana, "Dose-response relationships for wind turbine noise in Japan", *Inter-Noise 2013* (2013).
4. T. Kageyama, T. Yano, S. Kuwano, S. Sueoka and H. Tachibana, "Exposure-response relationship of wind turbine noise with subjective symptoms on sleep and health: a nationwide socio-acoustic survey in Japan", *ICBEN 2014* (2014).

5. A. T. Moorhouse, D. C. Waddington and M. D. Adams, “A procedure for the assessment of low frequency noise complaints”, *J. Acoust. Soc. Am.*, 126(3), 1131-1141 (2009).
6. S. Yokoyama, S. Sakamoto and H. Tachibana, “Perception of low frequency components contained in wind turbine noise”, *Wind Turbine Noise 2013* (2013).
7. D. Bowdler and G. Leventhall, *Wind Turbine Noise*, Chapter 5, Multi-Science Publishing Co. Ltd. (2011).
8. J. Bass, D. Bowdler, M. McCaffery and G. Grimes, “Fundamental research in amplitude modulation – a project by RenewableUK”, *15th International Meeting on Low Frequency Noise and Vibration and its Control* (2012).
9. S. Lee, K. Kim, W. Choi and S. Lee, “Annoyance caused by amplitude modulation of wind turbine noise”, *Noise Control Eng. J.*, **59**(1) (2011).
10. J. N. McCabe, “Detection and quantification of amplitude modulation in wind turbine noise”, *Wind Turbine Noise 2011* (2011).
11. D. McLaughlin, “Measurement of amplitude modulation frequency spectrum”, *Wind Turbine Noise 2011* (2011).
12. G. Lundmark, “Measurement of swish noise, a new method”, *Wind Turbine Noise 2011* (2011).
13. S. Yokoyama, S. Sakamoto, and H. Tachibana, “Study on the amplitude modulation of wind turbine noise: part 2 – Auditory experiments”, *Inter-Noise 2013* (2013).
14. R. Hellman and E. Zwicker, “Why can a decrease in dB(A) produce an increase in loudness?”, *J. Acoust. Soc. Am.*, **82**(5), 1700-1705 (1987).
15. S. Kuwano and S. Namba, “Advantages and Disadvantages of A-weighted SPL in Relation to Subjective Impression of Environmental Noises”, *Noise Control Eng. J.*, **33**(3), 107-115 (1989).
16. R. L. St. Pierre, Jr. and D. J. Maguire, “The impact of A-weighting SPL measurements during the evaluation of noise exposure,” *NOISE-CON 2004* (2004).
17. S. Sakamoto, S. Yokoyama, S. Tsujimura, and H. Tachibana, “Loudness evaluation of general environmental noise containing low frequency components”, *Inter-Noise 2013* (2013).
18. Standards New Zealand NZS 6808 Acoustics – Wind farm noise (2010).
19. J. Cooper, T. Evans and D. Petersen, “Tonality assessment at a residence near a wind farm”, *Wind Turbine Noise 2013* (2013).
20. L. S. Søndergaard and T. H. Pedersen, “Tonality in wind turbine noise. IEC 61400-11 ver. 2.1 and 3.0 and the Danish/Joint Nordic method compared with listening tests”, *Wind Turbine Noise 2013* (2013).

Association
of Australian
Acoustical
Consultants

Please address correspondence to:
AAAC Secretary
Level 14, 120 Edward Street
Brisbane QLD 4000
T 07 3120 6800 F 07 3210 3900
E admin@aaac.org.au

1 June 2015

Select Committee on Wind Turbines
PO Box 6100
Parliament House
Canberra ACT 2600

**Attention: Dr Richard Grant**

Dear Richard,

**Summary of Wind Turbine Noise 2015 Conference**

Several members of the Association of Australian Acoustical Consultants (AAAC) Wind Farm Subcommittee attended the recent Wind Turbine Noise 2015 Conference held in Glasgow from 20 – 23 April 2015. The Wind Turbine Noise series of conferences are international events run by the Institute of Noise Control Engineering (INCE) Europe. The conferences started in 2005 and are held every two years.

The 2015 conference was attended by almost 200 delegates from acoustic consultancies, academic institutions, regulatory authorities, wind turbine manufacturers, energy companies and interest groups. A total of 90 papers were submitted to the conference covering a range of topics including wind turbine noise and health, noise prediction and propagation, regulations, infrasound, aeroacoustics, tonality and amplitude modulation.

This document provides a brief summary on key aspects of the conference that have relevance to current discussions in Australia, in particular as part of the current Senate Select Committee on Wind Turbines. We consider it important that the Committee understands the current state of research into wind turbine noise as presented at this international conference regarding the subject.

**Wind turbine noise and health**

Dr David Michaud from Health Canada gave a plenary presentation of the findings of their recent epidemiological study into the prevalence of health effects in 1238 Canadian residents living between 250 m and 11 km from operational wind turbines. The study included both objective and self-reported health indicators and found no support for any relationship between wind turbine noise and health effects such as sleep disturbance, migraines, tinnitus, dizziness, diabetes, hypertension, perceived stress or any measure of quality of life.

The Health Canada study did find a statistically significant association between wind turbine noise and self-reported annoyance, although annoyance was also affected by other factors such as blinking lights, shadow flicker and visual impacts. It also concluded that there was no difference in the relationship demonstrated between annoyance and A-weighted or C-weighted (low frequency) noise levels.

Brian Howe from HGC Engineering also presented the findings of a recent review by the Council of Canadian Academies into wind turbine noise. In a similar fashion to the Health Canada study, the Council's review was only able to identify a causal relationship between wind turbine noise exposure and annoyance with insufficient evidence to link wind turbine noise to more direct health effects.

Both presenters did not seek to downplay the importance of annoyance and noted it is important to determine wind turbine noise criteria taking into consideration the typical percentage of the population that may be annoyed.

Dr Michaud also identified that annoyance was approximately three times higher in the Ontario province study sites than in the Prince Edward Island province study sites. This suggests factors other than noise level are significant moderators of the above annoyance. If participants received personal benefit (including rent, payments or indirect community benefits) from having wind turbines in the area, annoyance was significantly lower.

It was interesting to note from the Health Canada study that:

- at the typical distances to wind farms in Australia, 1-2 km, the percentage of the overall study population identified to be highly annoyed was approximately 5% in Ontario and 1% in Prince Edward Island

- at noise levels of 35 – 40 dB(A), the percentage of the percentage of the overall study population identified to be highly annoyed was almost 10% in Ontario and approximately 3% in Prince Edward Island.

For comparison, a noise level that results in no more than 10% of the population being highly annoyed is typically selected for the basis of Australian noise regulations regarding sources such as road, rail and aircraft noise.

### Infrasound

A number of studies into the perception of infrasound produced by wind turbines were presented during the conference. Four studies of infrasound perception were presented by:

- Renzo Tonin and James Brett – Australia

- Kristy Hansen, Bruce Walker, Branko Zajamsek and Colin Hansen – Australia

- Bruce Walker and Joseph Celano – USA

- Sakae Yokoyama, Tomohiro Kobayashi, Shinihi Sakamoto and Hideki Tachibana – Japan.

These studies included the reproduction of wind turbine noise, including infrasonic signals, recorded at operational sites. For example, Bruce Walker reproduced infrasound signals measured as part of recent studies at Waterloo Wind Farm and the Cape Bridgewater Wind Farm, and played them to test subjects through a large loudspeaker. The wind turbine noise was played to test subjects in various conditions such that at times only infrasound was played (i.e. only noise below 20 Hz) and at other times only noise at typical audible frequencies was played (i.e. noise above 20 Hz).

In all four studies, it was found that the level of infrasound present at these wind farms was not of sufficient level to be perceptible to the studied subjects either through the ears or through other parts of the body. The studies by Hansen and Yokoyama identified that, in fact, it was only noise above the typical hearing threshold that was perceived by test subjects. These studies identified audible low frequency noise in the range of 40 – 50 Hz as the lowest frequencies at which wind turbine noise could be perceived at typical residential locations.

Tonin's study identified that the reporting of symptoms was related to pre-conceived notions about wind turbine infrasound rather than whether actual infrasound was present in the signal. He concluded that this provided evidence to support the nocebo effect with respect to health concerns related to wind turbine noise and infrasound.

Yours faithfully,

**AAAC Wind Farm Subcommittee**