# DISCONNECT BETWEEN TURBINE NOISE GUIDELINES AND HEALTH AUTHORITY RECOMMENDATIONS

John P Harrison
Professor Emeritus, Physics Department, Queen's University
Kingston, ON K7L 3N6
harrisjp@physics.queensu.ca

## INTRODUCTION

There is a disconnect between the setbacks of modern up-wind blade wind turbines from homes as recommended by health authorities and as determined from the noise guidelines of various jurisdictions. Typically, health authorities recommend 1.5 to 2 km while noise guidelines allow setbacks of 400 to 500 metres. The resolution lies in the inadequacy of noise guidelines. There are a number of reasons for the inadequacy: The typical allowance of 10 dBA above background noise; the characteristic periodic or impulsive sound of a turbine; the continuing use, in Ontario and New Zealand, of masking from ground-level wind noise to allow permissible turbine noise to increase with wind speed; the absence of turbulent inflow noise in noise guidelines and assessments; the absence of coherent sound reflection from the ground in the calculation of turbine noise at a receptor.

## HEALTH AUTHORITY RECOMMENDATIONS

Wind turbine noise causes annoyance and health problems. These problems include sleeplessness, anxiety, headaches and migraine, depression, and accentuation of learning disabilities[1-3]. The annoyance also has an impact on concentration and work performance[2, 4-6]. Different people have different reactions to noise and, as expected, the health problems are chronic for those who are noise-sensitive. The annoyance caused by wind turbines is higher than for traffic noise at the same sound pressure level[6] because of the predominance of low frequencies in the sound spectrum and because of the amplitude modulation that results from the blade passage past the tower. Looking at ⅓-octave sound pressure levels, turbulent boundary layer noise, arising from motion of the blades through steady wind, peaks at 1 kHz and falls slowly below that. Turbulent inflow noise, arising from the motion of the blades through turbulent wind, has no peak but instead increases with decrease in frequency. By contrast, traffic noise tends to be white noise. The annoyance from the periodic or impulsive character of turbine noise, associated with the amplitude modulation, is enhanced by the visual annoyance of the rotating blades.

Harry[2], in the UK, followed up on complaints of annoyance from 39 people living between 300 and 2000 metres from one or more wind turbines. The questionnaires showed that 80% experienced health problems with migraine and depression being the main health symptoms. 75% of the 39 respondents had sought help from a doctor. 75% reported sleeplessness. Harry recommended a 1.5 mile (2400 metre) set-back from homes and criticized ETSU-R-97, the basis for setbacks in the UK, as inappropriate for modern turbines 5x the size (power) of those common in 1997.
Frey and Hadden[3], in a remarkably thorough literature survey of the impact of wind turbine noise on people living within 2 km of wind turbines, present over 50 separate items on the impact of the noise. These include statements from residents describing their annoyance and health problems, comments from doctors and from wind energy developers and lists a number of people living up to a kilometre away who just had to

move out. This section of their paper is largely anecdotal but nevertheless it makes for very disturbing reading and should be mandatory reading for all wind energy developers and regulatory authorities. Hadden and Frey also review the nature of turbine noise, emphasize the dominance of low frequency noise with its low attenuation in the atmosphere and by structures, and point to the limitations of ETSU-R-97, the basis for the UK noise regulations. Another section of their report presents a comprehensive summary of the peer reviewed literature on the impact of noise. This includes sociological studies of annoyance and impact on mental performance, the impact on sleep and the effects of sleep disturbance, as well as biological effects such as the hormonal changes associated with annoyance/stress. Frey and Hadden conclude that no wind turbines of up to 2 MW should be sited within 2 km of dwellings and that much more research is needed on understanding why turbine noise does penetrate above ambient noise up to 2 km and more.

Stewart, an acoustician with the UK Noise Association made a study of turbine noise and the annoyance caused by the noise, described in the famous report: Location, Location, Location[7]. He concludes that turbines are causing significant noise problems for some people, that the evidence is persuasive that the noise problems can be exacerbated by the rotating blades and dancing shadows of the turbines and that the main problem is the swish, swish, swish of the blades (amplitude modulation). On behalf of the Noise Association, he recommends that no turbine should be sited closer than 1 mile (1.6 km) from the nearest dwelling.

Pedersen and Perrson Waye made a sociological study of wind turbine annoyance[8]. 351 respondents living in the vicinity of turbines in rural Sweden completed questionnaires. For turbine noise in the range 37.5 – 40 dBA, 51% were annoyed (20% very annoyed); above 40 dBA, 56% were annoyed (36% very annoyed). These numbers compare with earlier measurements, quoted by Pedersen, of 2 – 4% annoyed by transport and industrial noise in the same noise level range[9]. Shepherd et al[10] performed laboratory tests to determine detection threshold and annoyance levels. They found that for noise levels 10 dBA above threshold, they would predict widespread complaints. However, this work cannot compare with the field studies of Pedersen and Persson Waye.

In 2006, the French National Academy of Medicine issued a report[11] on wind turbine noise and health, concluding with a recommendation to halt wind turbine construction closer than 1.5 km from residences. The World Health Organization[12] recommends that the noise level in a bedroom be a maximum of 30 dBA to avoid sleep disturbance. It also uses a rather large and unrealistic 15 dBA sound pressure level drop across a wall, leading to a limit of 45 dBA outside a bedroom. The International Standards Organization (ISO) 1996-1971 Recommendation for Community Noise Limit in Rural Areas is 35 dBA day-time, 30 dBA evening, and 25 dBA night-time (presumably in the bedroom). ISO 9613, the accepted methodology for evaluating sound propagation, suggests 7 dBA sound pressure level drop across a wall. Therefore, using the ISO recommendation, the sound pressure level at night outside a bedroom should be 32 dBA. Finally, the Sierra Club, a responsible proponent of renewable energy, has the following advice on the siting of wind plants: "We suggest that wind developers restrict their impact on involuntary neighbours to near ambient levels at the closest residence[13].

In summary, the consensus is that turbines should be separated from residences by about 1.5 km or that the sound pressure level at a residence should be near ambient which is close to 30 dBA in rural areas at night.

## NOISE GUIDELINES

Regulations for wind turbine siting relative to residences vary world-wide and even vary within countries with local environmental protection jurisdictions. Some regulations specify setback distances and others specify noise limits. The following table shows a selection of international night-time noise limit regulations extracted from a recent review written for the Ontario Ministry of the Environment[14]. The setbacks are estimated from the ISO-9613 procedure for calculating noise at a receptor as a function of distance from a turbine, in this case a typical fixed-speed up-wind turbine with a turbine noise of 105 dBA.

Table 1: Selection of Noise Limits and Estimated Equivalent Setbacks

| Jurisdiction | Noise Limit (dBA) | Setback (m) |
|---|---|---|
| Oregon, Germany, Australia | 35 - 36 | 800 |
| Alberta, British Columbia, Quebec, Denmark and Netherlands | 40 | 450 |
| Ontario, New Zealand | 40 with wind speed adjustment | 450 and below |
| U.K. and Ireland | 43 | 350 metres |
| Various U.S. | 50 and up | 200 metres |

Clearly, the setbacks allowed by these noise limits are far smaller than those recommended by the variety of health experts. There are several reasons for this disconnect; they will be reviewed in the rest of this paper.

## NOISE INTRUSION

In rural areas, background noise levels can be 25 – 30 dBA at night. Therefore, the noise limits in most jurisdictions represent a night-time intrusion of 10 to 20 dBA above background. An intrusion of 3 dBA is noticeable and an intrusion of 10 dBA causes widespread complaints as noted above. The intrusion level is quite arbitrary and is imposed on the rural population; there are no studies that show no problems with the 10 to 20 dBA intrusion. Some jurisdictions specify limits such as background plus 10 dBA or 45 dBA, whichever is the higher, allowing the 10 dBA to be a

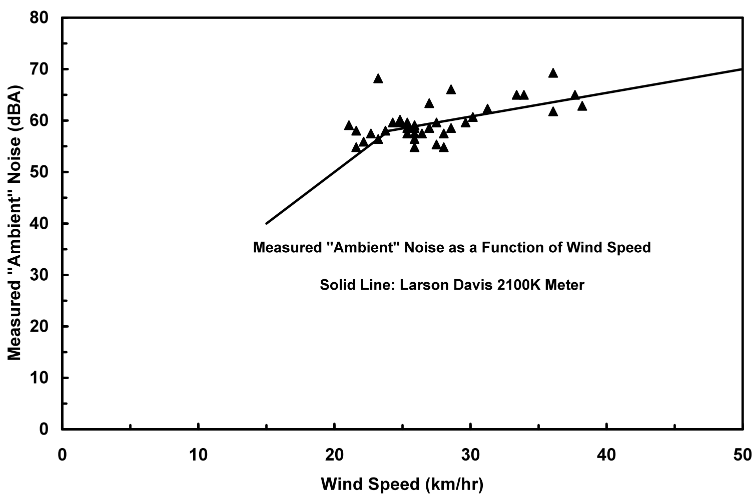


Figure 1. An erroneous measurement of ambient noise.

minimum intrusion. A problem here is that background noise is not easy to measure when there is a wind blowing. The figure shows one consultant's measurement of background noise that I have converted to a plot of background noise as a function of wind speed. Superimposed is the manufacturer's specification for the wind noise in the microphone of a noise meter. For obvious reason, this will remain anonymous.

## AMPLITUDE MODULATION

Wind turbines emit a characteristic sound. There is an abundance of low frequency noise that travels with little attenuation in the atmosphere and it is modulated at the blade passage frequency, about 1 Hz. The amplitude modulation is of the order of 5 dBA[15]. The problem here is that all jurisdictions use $L_{eq.}$ in setting their noise limits and this averages out the modulation. The ear responds on a fast time scale and does not average the noise peak away. It is this periodic noise that causes the widespread annoyance. From above, over 50% of those in the vicinity of turbines were annoyed at noise levels of 40 dBA with about 30% very annoyed. Van den Berg has investigated this annoyance from an acoustic perspective. He showed that at night, the amplitude modulated noise from several nearby wind turbines can drift in and out of synchronization. When synchronized, the modulation is the full 5 dBA of a single turbine but the noise level is higher than for a single turbine and so more audible. When unsynchronized, the amplitude modulation is smaller. Noise limits need to include a 5 dBA penalty for amplitude modulated noise so that the limit reflects the sound perceived by people. Ontario does have such a penalty but it has not been enforced.

## MASKING NOISE

Just two jurisdictions, Ontario in Canada and New Zealand, make an allowance for masking of turbine noise by wind noise at ground level but this is two too many. It was van den Berg[16] who showed that, at night-time, masking noise is largely a myth. He started by investigating noise complaints from residents living near the Rhede wind plant who had been led to believe that they would not be impacted. He showed, particularly for the night-time, that the sound level from the wind plant was indeed very noticeable and, by sound pressure level measurement, in excess of what was expected from concurrent measurements of wind speed. He postulated that the cause was higher wind speed at the height of the turbine hubs (98m) than that expected from the standard neutral atmosphere model. Follow up work with records from the Cabauw meteorological research station and from a literature survey of work elsewhere showed that night-time average values of the ratio of wind speed at 80m to that at 10m, which is used as a proxy for the wind speed at ground level, were invariably higher than supposed for a neutral atmosphere. The most extensive measurements have come from the National Renewable Energy Laboratory in the USA for a variety of sites in the mid-west[17,18]. This laboratory was established by the DOE to support the wind industry in the USA. Masking noise was not one of their interests; they were concerned that unexpected large wind speed gradients could cause turbine failure and intrigued that the large wind speed gradients would lead to enhanced power generation. Table 2 collects together all available measurements of wind speed gradient data that includes both average and night-time averages. This data set includes those referenced in van den Berg's thesis and others that are more recent. The original references give the gradients in terms of a wind shear coefficient α defined by: $v_A/v_B = (h_A/h_B)^\alpha$ where $v_A$ and $v_B$ are the wind speeds at heights $h_A$ and $h_B$ with $h_A$ representing the turbine height and $h_B$ =10 metres representing ground level. A neutral atmosphere, is defined to have α = 0.14; this corresponds to a wind speed ratio $v_{turbine}/v_{ground}$ = 1.35 for an 80m high turbine tower. Noise limits are based upon this number. Table 2 presents the measurements in terms of the more accessible ratio of wind speed at 80m to that at 10m.

Table 2: Average and night average ratios of the wind-speed at 80m to that at 10m.

| Region | Source | Average | Night Average |
|---|---|---|---|
| Neutral Atmosphere | α = 0.14 | 1.35 | 1.35 |
| Netherlands (Cabauw) | Van den Berg[16] | 1.4 | 1.9 |
| Big Spring TX | NREL[17] | 1.55 | 1.85 |
| Algona IA | NREL[17] | 2.0 | 2.45 |
| Springview NE | NREL[17] | 1.6 | 1.85 |
| Glenmore WI | NREL[17] | 1.8 | 2.1 |
| Ft. Davis TX (1860m) | NREL[17] | 1.25 | 1.4 |
| Berlin | Harders[19] | 1.3 | 1.9 |
| Australia 1 (Flat) | Botha[20] | 1.5 | 1.8 |
| Australia 2 (Flat) | Botha[20] | 1.5 | 1.7 |
| N Z (Complex Terrain) | Botha[20] | 1.25 | 1.25 |
| N Z (Complex Terrain) | Botha[20] | 1.25 | 1.25 |
| Kincardine – 30-50m | OMB[21] | 1.85 | 2.55 |
| Sumner KS | NREL[18] | 1.7 | 2.3 |
| Washburn TX | NREL[18] | 1.4 | 1.7 |
| Lamar CO | NREL[18] | 1.35 | 1.6 |
| Crow Lake SD | NREL[18] | 1.55 | 1.8 |
| Kingsbridge ON | Palmer[22] | 1.6 | 1.75 (summer 2.25) |
| Amaranth ON | Palmer[22] | 1.75 | 2.45 (summer 2.75) |
| USA 10 Stations | Archer[23] | | 2.1 ± 0.3 |

Looking at all of the results, we see that the average ratio is 1.4 ± 0.2 and the night-time ratio is 1.9 ± 0.4, higher by 35%.

To see the significance, consider an application to south-western Ontario. Making use of the 3 results from Table 1 and numbers from the Ministry of Natural Resources wind atlas, a daily average ratio of 1.75 is predicted. The wind atlas gives only annual average wind speeds as a function of height above ground level. The higher averages are expected because of the presence of large bodies of water. With the same 35%, the night-time average ratio will be 2.3. Consider the case that the wind speed at 80m is 10 m/s. The assumed neutral atmosphere wind speed ratio of 1.35 gives the wind speed at the ground equal to 7.5 m/s. The Ontario noise limit for this wind speed is 44 dBA, which includes a masking allowance of 4 dBA above the basic 40 dBA. However, with a more accurate night-time ratio of 2.3, the wind speed at the ground is 4.5 m/s. For this ground-level wind speed, there is no masking noise. As another example, for a wind speed at the turbine hub of 14 m/s, the 12 dBA of masking noise is reduced to 1 dBA. Clearly, for night-time operation of wind-turbines, masking noise is a myth. Authorities in the Netherlands have now accepted this and no longer include masking noise in their noise limit.

## TURBULENT INFLOW NOISE

At present, noise generated by the inflow of turbulent air into the turbine (turbulent inflow) is not included in noise guidelines. Turbulent inflow was a particular problem with down-wind rotor turbines because of the turbulence created by the tower. However, with modern up-wind rotors the problem remains because of atmospheric turbulence. Wagner et al[24] did some modeling of turbulent inflow to airfoils but did not apply this to wind turbines. Since then there have been more semi-empirical models of turbulent inflow aerodynamic noise and, from NREL, a comparison of actual turbine measurements with these models[25,26]. The significance here is that turbulent inflow, when present, dominates the aerodynamic noise in the frequency range below 1 kHz, the frequency range where sound propagates with little absorption in the air.

Figure 16 from reference 24, reproduced below, shows a comparison of calculations of various aerodynamic noise sources with measured noise for the National Wind Technology Centre research turbine. It is a 37m tower with a 42m upwind rotor diameter. The wind speed measurement tower is close by. The turbulence intensity, measured over a 1 minute time interval, was a high 46%. The wind speed was 5.7 m/s. The noise measurements were made 58m downwind. The figure is a plot of noise (sound pressure level) in 1/3 octave bands as a function of frequency.

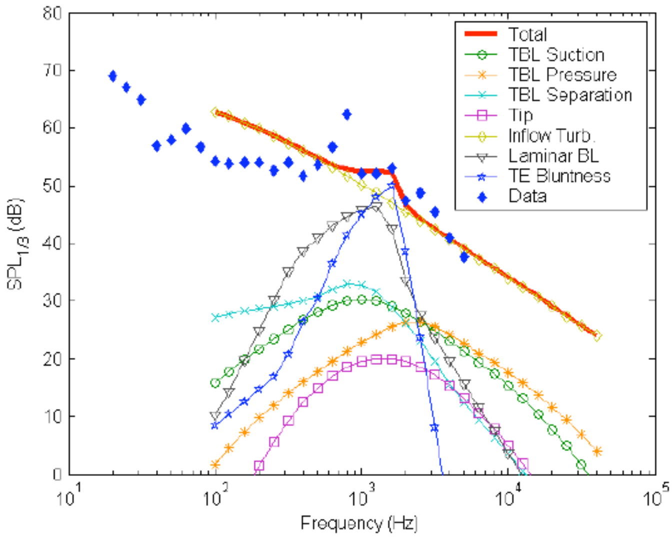


Figure 2: Calculation of aerodynamic contributions to turbine noise level.

TBL is turbulent boundary layer, TE is trailing edge. Note that the character of the measured sound reflects that of turbulent inflow, although the calculation over-estimates the turbulent inflow noise. The authors realized that 1 minute is too long a time for determining the turbulence intensity and that good agreement would have resulted from a 30 sec interval. Turbulent inflow noise can now be estimated on the basis of turbulence intensity measurements, which require wind-speed measurements measured on a fast time scale with the average and standard deviation calculated for 30 second intervals. Before any wind plants are approved, turbulence intensity measurements need to be made and turbulent inflow noise estimated.

**COHERENT REFLECTION**

Wagner et al[24] knew that sound reflects from the ground. Generally the path difference between the direct and reflected sound waves will be much larger than the sound wavelength and it makes sense to add the sound intensities. This is included in ISO-9613[27]. However, when the sound reflects specularly, as it will from a solid surface such as the ground, and the wavelength is comparable to the path difference, the direct and reflected sound waves will add coherently. For frequencies below about 200 Hz and distances of several hundred metres from a turbine this can add an extra 3 dBA to noise at the receptor. Although 200 Hz seems low compared to the spectral peak, low frequencies propagate with less absorption in the atmosphere and through walls. Furthermore, figure 2 shows how low frequencies dominate when the wind is turbulent. Turbine manufacturers know about coherent reflection; they subtract 6 dBA, not 3 dBA, from the measured sound when determining the turbine noise at the hub.

**SUMMARY**

Universally, turbine noise limits at residences allow an intrusion of 5 to 20 dBA above background noise level in rural areas. This can only be justified if there is no alternative. In Europe population density is large and the alternative is to go to off-shore sites. This is now in process. In the USA, Canada, Australia and New Zealand, population densities are low and turbines can be kept away from residences. In general they are not. Even when the annoyance from amplitude modulation is accepted, the 5 dBA penalty is not enforced. Two jurisdictions still allow for masking of the turbine noise by wind noise at ground level. Van den Berg drew attention to the fallacy of the masking at night-time. Extensive measurements from the National Renewable Energy Laboratory in the USA and elsewhere confirm the work of van den Berg and prove unequivocally that masking wind noise at night is a myth. The additional aerodynamic noise arising from the rotation of turbine blades in turbulent wind is not yet included in the noise limits of any jurisdictions. Calculation and measurements from the National Renewable Energy Laboratory demonstrate that this additional noise can add substantial low frequency noise, which is weakly absorbed by the atmosphere and walls. Regulating authorities need to request turbulence intensity measurements and associated noise estimates in the impact assessments required before approval of wind plants. At distances of 500m and more from a turbine, the combination of direct sound and that reflected from the ground can produce an extra 3 dBA of noise at a height of 1m from the ground for frequencies below 200Hz.

In order to see the effect of these deficiencies, consider a typical modern fixed-speed, up-wind rotor 2.3 MW turbine with an 80 m tower and a noise level of 105 dBA: With the 5dBA penalty for amplitude modulation, the standard 0.005 dBA/m for sound absorption in the atmosphere, Figure 6.9 from Wagner et al[24] for ground effect, the following sound levels at a receptor are found:

Table3: Noise Levels Calculated with an Amplitude Modulation Penalty

| | | | |
|---|---|---|---|
| Distance from Turbine (m) | 500 | 1000 | 1500 |
| Noise Level (dBA) | 43 | 40 | 31 |

If the 40 dBA allowance is reduced to below 35 dBA for rural areas in accord, with references 8 and 9, ISO 1996-1971 and the Sierra Club recommendation, then a set-back from a single turbine of 1 to 1.5 km is required. The additional noise from turbulent inflow and coherent reflection for low frequency sound will push this minimum setback to 1.5 km and more. Masking noise is a myth and so this minimum will hold for all wind speeds. Now it is clear why there have been extensive reports of annoyance and health problems suffered by those living within 1.5 km of a modern turbine. The health authorities were quite correct with their recommendations and residents are vindicated in registering their annoyance and health problems.

## REFERENCES


1. N. Pierpont, Wind Turbine Syndrome – Testimony before the New York State Legislature Energy Committee (2006); available at www.ninapierpont.com. This reference, written by a respected physician, has a comprehensive literature review of the health effects of wind turbines. A forthcoming report from Dr. Pierpont will be submitted for publication.
2. A. Harry, Wind Turbine Noise and Health (2007).
3. B. J. Frey and P. J. Hadden, Noise Radiation from Wind Turbines Installed Near Homes: Effects on Health (2007). www.windturbinenoisehealthhumanrights.com
4. K. P. Waye, J. Bengtsson, A. Kjellberg and S. Benton, Noise Health, **4**, 33-49 (2001).
5. K. P. Waye, J. Bengtsson, F. Hucklebridge, P. Evans, and A. Clow, Life Sci. **70**, 745-758 (2002).
6. E. Pedersen and K. Persson Waye, Occupational and Environmental Medicine, **64**, 480-486 (2007);
7. J. Stewart, UK Noise Association Report (2006), available at http://www.countryguardian.net/Location.pdf
8. E. Pedersen and K. Persson Waye, J. Acoustical Soc. America, **116**, 3460 – 3470 (2004); E. Pedersen, Thesis, Göteborg (2007), available at https://gupea.ub.gu.se/dspace/handle/2077/4431
9. H. M. E. Miedema and H Vos, J. Acoustical Society of America, **116**, 334-343 (2004).
10. K.P. Shepherd, W. G. Ferdinand and D. G. Stephens, Noise Control Engineering Journal, **21**, 30 (1983)
11. C-H. Chouard, Repercussions of Wind Turbine Operations on Human Health (in French), Panorama du médecin (2006).
12. W.H.O. Guidelines (1999): http://www.who.int/docstore/peh/noise/Comnoise-4.pdf
13. Sierra Club Wind Siting Advisory Document Version: November 25, 2003, http://www.wind-works.org/articles/scsitingadvisory.html
14. R. Ramakrishnan, Wind Turbine Facilities Noise Issues, Aiolos Report Number 407/1/2080/AR155Rev3, pages 26-29 (2007). Available at: http://www.ene.gov.on.ca/envision/env_reg/er/documents/2008/Noise%20Report.pdf
15. G. P. van den Berg, J. Low Frequency Noise, Vibration and Active Control, **24**, 1-24 (2005); The Sound of High Winds, Thesis, The University of Groningen (2006).
16. G. P. van den Berg, J. Sound and Vibration, **277**, 955-970 (2004); The Sound of High Winds, Thesis, The University of Groningen, (2006).
17. K. Smith, G. Randall, D. Malcolm, N. Kelley and B. Smith, NREL/CP-500-32492, AWEA WindPower Conference (2002).
18. M. Schwartz and D. Elliott, NREL/CP-500-40019, AWEA WindPower Conference (2006).
19. H. Harders and H.J. Albrecht, Proceedings of Wind Turbine Noise, Berlin (2005).

20. P. Botha, Proceedings of Wind Turbine Noise, Berlin (2005).
21. J. W. S. Young, Testimony before the Ontario Municipal Board hearing PL060986 regarding the Kincardine Enbridge Wind Development (2007).
22. W. Palmer, Wind Turbine Noise Conference WTN2007 (2007).
23. C. L. Archer and M. Z. Jacobson, J. Geophysical Research, 108, 1 – 20 (2003). This was an average of data from 10 stations in the USA. The average daytime ratio was $1.4 \pm 0.2$.
24. S. Wagner, R. Bareiss and G. Guidati, Wind Turbine Noise (Springer 1996).
25. P. Moriarty and P. Migliore, NREL Report NREL/TP-500-34478, (2003);
26. P Moriarty, Development and Validation of a Semi-Empirical Wind Turbine Aeroacoustic Code. (NREL Report, 2004);
27. Dr. Alan Lightstone, private communication.