

University of Groningen

The sound of high winds

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Document Version

Publisher's PDF, also known as Version of record

Publication date:

2006

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

van den Berg, G. P. (2006). *The sound of high winds: The effect of atmospheric stability on wind turbine sound and microphone noise*. s.n.

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I WIND POWER, SOCIETY, THIS BOOK: an introduction

Bobby asks: 'Do you ever hear the windmills?'

'What sound do they make?'

'It's a clanking metal noise, but when the wind is really strong the blades blur and the air starts screaming in pain.' He shudders.

'What are the windmills for?'

'They keep everything running.'

'If you put your ear to the ground you can hear them.'

'What do you mean by everything?'

'The lights, the factories, the railways. Without the windmills it all stops.'¹

This is the story of the discovery of a new phenomenon: why wind turbines sound different at night time. This discovery was related to a problem in society, namely that of perceived noise by residents living close to such turbines..

This introduction sketches the context in which my work proceeded: how the questions came up, why noise is an inseparable part of wind power development, and that being critical does not need to imply a negative attitude towards wind power. Let's start at the beginning.

1.1 A 'new' phenomenon

The discovery was modest: I have not found a new law of nature or a new way to make money. It was rather the idea to apply existing knowledge in a new context: the application of atmospheric physics to solve the mystery why people complained about noise from wind turbines that according to wind developers and acoustic consultants they should not even be able to hear. In principle it was not very difficult to find out why. When Walter Flight (a very Dutch citizen despite his name) told me he could see the wind turbines near his house rotating at high speed while at the same time his garden was completely calm, I thought: oh yes, I know that, that's

¹ 'The suspect', by Michael Robotham, Time Warner Paperbacks, 2003 (p. 151)

because at night, especially on nice summer evenings, the atmosphere becomes stable. I teach this in a course, Environmental Techniques. The phenomenon is treated extensively in this book, but for now it is sufficient to know that, due to strong winds at greater heights coupled with very light winds at ground level, wind turbines can be a lot noisier in a night time atmosphere than they are in daytime. This was why Walter and his neighbours complained. Also the nature of the sound changes: a thumping character can become very pronounced at night.

In this book I will often use the terms 'day' and 'night', though the distinction is more accurately stated as the atmosphere being unstable (which is usually in daytime, that is: sun up) or stable (night time, sun down). The heat coming in from the sun or radiated out at night is the real cause of the difference in stability. In between is another state, namely neutral, where heating or cooling are unimportant because of heavy clouding and/or strong wind and which can occur in day as well as night time, though not very often in a temperate climate and over land. Atmospheric stability means that vertical movements in the air are damped and as a consequence horizontal layers of air can have a greater difference in velocity: close to the ground the wind can be weak while higher up there is a strong wind.

Though in principle the explanation is simple and easily understood, it of course had to be shown from solid theory and with sufficient data that the explanation was correct. The first steps were extensive measurements in Bellingwolde, where severe complaints had arisen about noise from the nearby Rhede wind farm. This I did together with Richard de Graaf, then a physics student.

After this simple discovery, a new mystery (to me) was why this did not play a role in the assessment of wind turbine noise? Every meteorologist knows about atmospheric stability, so why had none of the experts dealing with wind turbine sound ever come across it? Wind turbines have been built for several decades and since the 1980's in ever larger numbers, so there should be a lot of accumulated experience. Had no one (except some

residents) noticed the discrepancy between predicted and real noise exposure?

There are probably several reasons. One of them is that for a long time wind turbines were not big enough for the effects of atmospheric stability to be clearly noticeable. Since wind turbines have grown taller the effect manifests itself more clearly. Secondly, as the more distant locations have become scarce, more and more turbines are being built closer to where people live, so more people now experience the sound of wind turbines. Thirdly, atmospheric stability over flat land is easier to understand and quantify than in a mountainous or coastal area where the atmosphere is more complex so the effect on wind turbines may be less easily recognizable.

Wind turbines as such have not become that much noisier, despite their increase in height and blade span (the sound power depends more on speed than on physical dimensions of the towers). Earlier machines could be quite noisy due to whining or severe thumping, and modern designs are certainly better. The point is they now reach into less familiar parts of the atmosphere.

Finally, an important reason to not recognize the unexpected high sound levels certainly is the fact that it impedes commercial interests and national policy. The positive ring of the term 'sustainability' helps investors in wind energy and local authorities (applying national policy) to counterbalance objections concerning possible disadvantages of new projects. As these objections are sometimes strong enough to torpedo projects, investors and authorities don't welcome more negative news. Though the population widely supports sustainable energy, reactions are less positive when a new project adversely affects their lives. This 'contradictory behaviour' is in fact quite understandable: when a new project is planned in an area, residents for the first time have to balance the positive social consequences to the negative local impact: visual impact, flickering shadows, noise and possibly ice throw from turbine blades.

The first reaction of wind energy proponents, represented by the Windkoepel ('Wind dome'), to our research results was to pay a consultant

to comment on our report [Van den Berg *et al* 2002]. This consultant boasted of having advised a large number of wind farm projects, so he clearly understood the position of the wind power industry. In the resulting ‘second opinion’ [Kerkers 2003] no material critique was presented, only procedural arguments were used to declare our results inaccurate and thus irrelevant. The Windkoepel issued a press statement concluding that we had made a lot of fuss, but had not contributed any new insights.¹ They could get back to business.

1.2 Digging deeper

I too went back to my business, which can be summarized as helping citizen groups to defend their position by objective arguments using known principles of physics. In 2004 an article about my research was published in a scientific journal [Van den Berg 2004a] lending my results the respectability of peer review and triggering an international e-mail influx from interested consultants as well as worried residents, as our first report had done earlier on a national scale.

What still puzzled me at that time was how a single turbine could start thumping at night. I thought I understood how the modest blade swish of a single turbine could evolve into louder thumping: the small sound variations due to blade swish from several turbines could add up to louder pulses. But with a single turbine there is nothing to add! Apart from this, in news media in the UK there were complaints that low frequency wind turbine noise had been underestimated and had been making people sick.²

Some thoughts about this were presented at a conference in Maastricht [Van den Berg 2004b]. I agreed with delegate Jørgen Jakobsen, who presented a paper on low frequency wind turbine noise [Jakobsen 2004],

¹ Press statement February 2, 2003 “Onlangs is opschudding ontstaan,” (“Recently an upheaval was caused...”), De Windkoepel, Arnhem

² Catherine Milner: “Wind farms make people sick who live up to a mile away”, online Telegraph, filed January 25, 2004 (<http://news.telegraph.co.uk/news/main.jhtml?xml=/news/2004/01/25/nwind25.xml>, consulted December 10, 2005)

that even though wind turbines did produce an appreciable amount of infrasound, the level was so far below the average human hearing threshold that it could not be a large scale problem. But it was possible that complaints had been expressed in a way not understood by experts. Perhaps people bothered by the endless thumping of a relatively low pitched sound (such as I had heard myself on several occasions), thought that 'low frequency sound' was a term to use, as official sounding jargon. They might not be aware that the term 'low frequency sound' makes acousticians think of frequencies below 100 to 200 hertz, and in that range the sound level was not considered to be problematic. A classical misunderstanding perhaps, that could be clarified. After the Maastricht conference I wanted to quantify my ideas on the origin of the night time thumping of wind turbines and the relevance of low frequencies. This resulted in a second scientific article [Van den Berg 2005a] in which I tried to put these ideas together.

What had surprised me from early on was that people in the wind power business seemed to know so little about their raw material, the wind. In the Windkoepel press statement (see footnote previous page) a wind turbine manufacturer's spokesman argued that if the hub height wind velocity indeed was structurally higher at night, this must be visible in production statistics. This indeed seems plausible, so why not investigate that? If the wind industry had done so, they might have come up with results I found from measured wind profiles at Cabauw over an entire year [Van den Berg 2005b]. Indeed for an 80 m high turbine the night time yield is significantly higher than expected, whereas the daytime yield is lower. The net result was that in the real atmosphere at Cabauw annual production was 14% to 20% (depending on wind turbine power settings) higher than in an atmosphere extrapolated from 10-m wind velocities with a perpetual neutral wind profile. For wind power production forecasting there is a method that incorporates a correction for atmospheric stability [Troen *et al* 1989], but such knowledge has never been used for sound exposure forecasting.

1.3 Commercial and policy implications

So from an energy point of view a stable atmosphere is very attractive. The challenge is to use that potential, but not put the burden on those living nearby. One solution is to build wind farms offshore where no people are affected if enough distance is kept (and calculation models are used that accurately model long range sound propagation over water). Over large bodies of water seasonal, not diurnal atmospheric stability will boost production in part of the year but lower it when the water has warmed. Another solution is to improve turbine design from two perspectives: decreasing sound power without substantially decreasing electric power, and reducing annoyance by minimizing fluctuations in the sound. Part of any solution is to respect complainants and try to achieve a better balance between national benefits and local costs.

Oblivious of any research, residents had already noticed a discrepancy between predicted and real noise exposure. Opponents of wind farms have organized themselves in recent years in the Netherlands and elsewhere, and word had spread that noise exposure in some cases was worse than predicted. Though atmospheric stability and sometimes a malfunctioning turbine could explain this, most wind farm developers and their consultants relied on the old prediction methods. An energy firm's spokesman complained that each and every new project attracted complaints (from local groups) and called this "a new Dutch disease".¹ This is a very narrow view on the problem, denying the detrimental effects for residents. If their real concerns are denied it is not unreasonable for residents to oppose a new project, because practical experience shows that once the wind farm is there (or any other noise producer) and problems do arise, complaints will very probably not alter the situation for at least several years. Social scientists are familiar with such situations and suggest better strategies such as being honest and respectful, treating residents as equal partners, and not being arrogant: already in 1990 Wolsink mentioned this in a study on acceptance of wind energy and warned that it was wrong to label opposition as NIMBY (Not In My Back Yard) and refuse to recognize

¹ NRC Handelsblad, August 26 2005: "Verzet tegen windmolens succesvol" ("Opposition to wind mills successful")

legitimate problems [Wolsink 1990]. It is sad that most of the proponents still emanate a WARYDU attitude (We Are Right but You Don't Understand).

When real complaints are not addressed seriously, the “new Dutch disease” may well become an Australian, British, Chinese or any nation's disease. In the Netherlands assessment of wind turbine noise still is according to the old standard procedure (with one exception, see chapter VII), assuming a neutral atmosphere at all times, even though this has been admitted to be wrong for more than a year now.¹ Consultants apparently are afraid to be critical, perhaps because they don't want to jeopardize new assignments or because a change in assessment implies they were not correct before (they were not correct, but we were wrong collectively). Though most consultants claim to be impartial, the problem of ‘not biting the hand that feeds’ is more subtle, as I concluded in an earlier desk study on the quality of acoustic reports [Van den Berg 2000]. *E.g.*, it involves authorities who do not question the position of paid experts, and a society hiding political decisions behind the demand for more research.

I hope other countries do not to follow the Dutch way: first denying the consistency and legitimacy of the complaints, then being late in addressing them and in the end finding this has created more opposition. It is evident that also in the UK there are (a few?) serious complaints from honest people that are not dealt with adequately. In at least some cases atmospheric stability again seems to offer an explanation for observations of unpleasant wind turbine noise by residents (see example in box on next page), but the matter has not been investigated correctly.

¹ In March 2004 I showed in an article in ‘Geluid’, a Dutch professional journal, how to deal with non-neutral atmospheric conditions within the existing legal procedures [Van den Berg 2004c]; in July 2004 the Ministry of Housing, Environment and Spatial Planning advised to investigate the ‘wind climate’ at new wind farm locations (letter on “Beoordeling geluidmetingen Natuurkundewinkel RUG bij De Lethe, gem. Bellingwedde” to Parliament by State Secretary van Geel, June 21, 2004); in the 2005 Annual report of BLOW, a union of local, provincial and national authorities to promote wind energy development, it is recognized that the effect of wind shear still should be addressed, but no action is announced (Annual report BLOW 2005, January 2006).

NOISE FROM WINDFARM MAKING LIFE A MISERY

A recent settler in Caithness claimed yesterday his life is being blighted by ghostly noises from his new neighbours, the county's first large-scale windfarm. (.....) Mr Bellamy said: "The problem is particularly bad at night when I try to get to sleep and there's a strong wind coming from the direction of the turbines. "They just keep on droning on. It's a wooh wooh type of sound, a ghostly sort of noise. It's like torture and would drive anyone mad."

Mr Bellamy believes the noise is being transmitted through the ground since it seems to intensify when he lies down. He said he has got nowhere with complaints to the wind company and environmental health officers. "I feel I'm just getting fobbed off and can't get anyone to treat me seriously," he said. Mr Bellamy has been asked to take noise readings every 10 minutes during problem times, something he claims is unrealistic to expect him to do. He said the company's project manager Stuart Quinton-Tulloch said they could not act until it had proof of unacceptable noise levels. Mr Bellamy said: "I'm not the moaning type and I have no problem with the look of the windmills. I'm not anti-windfarm. It's just the noise which is obviously not going to go away." (.....)

Highland Council's principal environment officer Tom Foy who has been dealing with Mr Bellamy's complaint was unavailable for comment. His colleague David Proudfoot said he was aware of noise complaints about the Causewaymire turbines being lodged by two other residents, but said he had gone out several times and found no evidence to support the concerns.



Part of an article in *Press and Journal* of Aberdeen, 25 May 2005

Thinking that this could perhaps be solved by the Sustainable Development Commission (SDC), the UK government's 'independent advisory body on sustainable development'. I wrote to the SDC about remarks on wind turbine noise in their report "Wind power in the UK" [SDC 2005], which was in my opinion too positive and somewhat overly optimistic regarding wind turbine noise. The SDC replied, on authority of its (unknown) consultants, that they had no detailed knowledge of atmospheric conditions in the UK but still thought an impulsive character of the noise 'likely to be very rare'. After I presented some examples the SDC preferred to close the discussion.

The situation in the Netherlands is not very different. In the latest annual report of the body of national, provincial and local authorities responsible for wind energy development it is acknowledged that the problem of underrated noise has justly been brought to the policy agenda.¹ Nevertheless, no activity is undertaken to remedy this.

1.4 Large scale benefits and small scale impact

Though wind turbine noise is the main topic of this book, it is not the main problem in wind power development. Visual impact is usually considered the most important and most discussed local or regional effect. It is often presented as a matter of individual taste, though there are some common factors in 'public taste'. One such factor is the perceived contrast of a wind turbine (farm) and its environment: a higher contrast will have more impact, either in a positive or negative way. A peculiarity of turbines is that the rotational movement makes them more conspicuous and thus enhances visual impact. This common notion suggests that wind turbines in a built up area will have less impact relative to a remote natural area (though this may be overruled by the number of people perceiving the impact).

A second factor is attitude: *e.g.* farmers usually have a different attitude to the countryside than 'city folk' have, and hence they differ in judgments on the appropriateness of a building, construction or activity in the

¹ Jaarverslag BLOW (Bestuursvereenkomst Landelijke Ontwikkeling Windenergie). 2005 (Annual report BLOW 2005; in Dutch), January 2006

countryside. It is predictable that when residents have a positive association with a neighbouring wind farm they will experience less annoyance from the visual impact. For a wind turbine owner the sound of each blade passing means another half kWh is generated¹ and is perhaps associated with the sound of coins falling into his lap, a lullaby. The very same rhythm, like the proverbial leaking faucet tap, might prevent his neighbour from falling asleep.

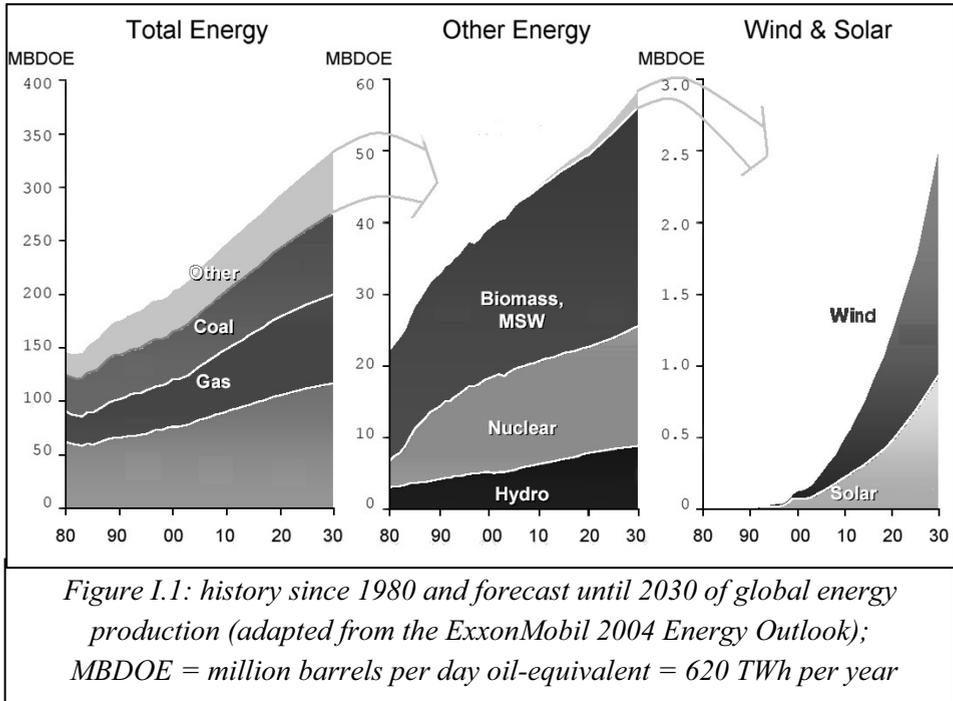
Other issues have gained attention in the public discussion, such as the modest contribution of wind energy to total energy consumption and the problematic variability of wind power. This is not the place to discuss these issues, except that they partially depend on a person's world view and expectations of the future. But I would like to show my personal position here. I find it astounding to realize that *all* wind turbine energy generated in the Netherlands in one year (2004) is equal to two months' *growth* of the total Dutch energy consumption. And even though wind turbine energy now provides about 2% of the total Dutch electricity consumption, this is only 0.2% of our total energy consumption.² This is also true on a global scale as is clear from figure I.1: wind power is now negligible and expected to supply 0.5% in 2030.

Despite the disappointingly low percentages I still think that wind energy need not be insignificant. In my view the problem is rather that we use such vast amounts of energy and keep on using ever more, which is a problem that no source, including wind power, can solve. Society will need to find a stand in the variety of opinions that have been brought forward since the 1970's. In a recent newspaper discussion about the liberalization of the energy market an opinion maker stated: "It is now generally appreciated that the end of the rich era of energy approaches rapidly, and the competition has begun for the last stocks", whilst his opponent the Minister of Economic Affairs wrote: "The lights must be kept burning, the

¹ when the turbine generates 2 MW at 20 rpm

²: the percentages are based on data from Statistics Netherlands (Centraal Bureau voor Statistiek) for the Netherlands for the year 2004: wind energy production: 1.9 TWh; total electricity consumption: 108.5 TWh; total energy consumption: 919 TWh. Growth in total energy consumption in period 1995 – 2004: + 100 TWh or 1.7 TWh per two months. Growth in total electricity consumption 1995 - 2004: +23 TWh or 2.3 TWh per year.

gas must keep flowing”¹. I do not agree with the Minister: I think that a limited resource should require limited consumption, even at the cost of some discomfort to our spoiled society. If we can curb our Joule addiction, wind power may help us to produce part of the sustainable energy we need to satisfy basic needs.



Wind turbine noise is a problem that may grow due to neglect by wind energy proponents and thus it may be another reason for part of the public, with politicians following, to turn away from wind power. This problem can be solved when it is also addressed at the level of local impact: sustainability must also apply at the local level. Some technical possibilities for noise reduction are given in this book and more competent, hardware oriented people may come up with better solutions. In addition to this, the social side of the problems must not be neglected. In a recent study [Van As *et al* 2005] it was concluded that “growing public resistance

¹ NRC Handelsblad 8-11-2005, articles “Bezinning nodig over energiebeleid” (“Energy policy needs reflection” by W. van Dieren) and “Nieuw debat scheidt slechts onzekerheid” (“New debate only creates uncertainty” by Laurens Jan Brinkhorst); my translations

to onshore wind turbines” obstructs wind energy development in the Netherlands. According to the report this opposition is now the main bottle-neck: local communities and residents are faced with the disadvantages whilst others (proponents, society at large) reap the benefits. The report recommends that the former share in the benefits too.

1.5 Microphone wind noise

In contrast to the impact my wind turbine research has had in society, the same knowledge of atmospheric physics helped me solve a non-controversial problem of interest to only a few: what is the nature of the noise that wind creates in a microphone? It occurred to me that if atmospheric turbulence was the cause, then one must be able to calculate the level of this noise. I was delighted when I found out how well theoretical considerations fitted hitherto only vaguely understood measurement results. Eureka!, such is the joy of work in science.

Somewhat unexpectedly this second discovery turns out to be related to wind turbine sound, which is why it is in this book. Originally it was considered difficult to measure wind turbine sound, because the strong winds that were supposed to cause high wind turbine sound levels, also were believed to be responsible for a lot of microphone wind noise. Solutions to this problem were either to put the microphone out of the wind on the ground or use several microphones and decrease microphone noise by averaging over all microphone signals. A new solution offered in this book is to take measurements in a stable atmosphere where near-ground wind velocity is so low that microphone noise is far less of a problem. One can measure sound at distances from a wind farm most researchers would not now believe to be possible.

The relationship is even stronger. In some countries the level of ambient background sound determines (part of) the limit imposed on sound exposure. To measure the level of this background sound the microphone must be put up in a place where residents stay outdoors, also in stronger winds. In this case it is important to discriminate between real ambient

sound and the noise that wind produces in the microphone. With the calculation methods in this book it is now possible to do so.

1.6 Research aims

The issues raised above concerning wind turbine noise and its relationship to altitude dependent wind velocity led to the following issues to be investigated:

- ◆ what is the influence of atmospheric stability on the speed and sound power of a wind turbine?
- ◆ what is the influence of atmospheric stability on the character of wind turbine sound?
- ◆ how widespread is the impact of atmospheric stability on wind turbine performance: is it relevant for new wind turbine projects?; how can noise prediction take this stability into account?
- ◆ what can be done to deal with the resultant higher impact of wind turbine sound?

Apart from these directly wind turbine related issues, a final aim was to address a measurement problem:

- ◆ how does wind on a microphone affect the measurement of the ambient sound level?

1.7 Text outline and original work

This book gives an overview of results of the wind turbine noise research that has been presented in the international arena in the last few years, as well as some opinions on this topic in the Introduction and Epilogue. Most of the text in this book has been published in scientific journals or presented at conferences. However, the texts have been adapted somewhat so as to form a continuous story without too much overlap. Other changes have been listed below.

- ◆ *Chapter II* is a reflection on some problems I encountered in doing research and presenting the results, most of it concerning wind turbine noise, but set against a more general background. It corresponds to a

paper presented at Euronoise 2003 [Van den Berg 2003], but some overlap with later chapters is taken out and some new information concerning the variation of wind turbine sound has been added (last paragraph in II.2). The remaining text has been edited slightly.

- ◆ *Chapter III* gives some numbers on wind energy development in the European Union, as well as an introduction on atmospheric wind gradients and the origins of aerodynamic wind turbine sound. It corresponds to sections of two published papers [Van den Berg 2004a and 2005a] to which remarks on the local wind speed at the turbine blade (section III.3) and on the spectrum of thickness sound (footnote in III.4) has been added. Also a description of sound and effects as given by a residential group with practical experience is added (box at end of chapter) and a remark on constant speed and variable speed wind turbines (in III.4).
- ◆ *Chapter IV* corresponds to my first paper on this topic [Van den Berg 2004a] on measurements at the Rhede wind farm. The section on Impulsive Sound has been taken out here and transferred to the next chapter. A new section (IV.10) has been added describing previously unpublished measurements at the Rhede wind farm as well as a comparison with calculated sound levels. Chapter IV demonstrates the fact that sound levels due to wind turbines have been systematically underestimated because hub height wind velocities were not correctly predicted. This effect is becoming more important for modern, tall wind turbines particularly when the atmosphere is ‘non standard’ (*i.e.* diverging from neutrality).
- ◆ In *chapter V* a second effect of atmospheric stability is investigated. Not only has the sound level been underestimated, but also the effect on the sound character: when the atmosphere turns stable, a more pronounced beating sound evolves. Most of the data are from the Rhede wind farm, complemented by data from a smaller single turbine elsewhere and theoretical calculations. In a section on the perception of fluctuating sound, it is explained how an apparently weak sound level variation can indeed turn into audibly pronounced beating. This chapter corresponds to a published paper [Van den Berg 2005a], but the section on interaction of several turbines (V.2.4) has been

combined with the corresponding section of the first paper [Van den Berg 2004a]. In this chapter the fact that wind velocity in the rotor is not equal to the free wind velocity, which was neglected in the paper, has been taken into account.

- ◆ In *chapter VI* data on atmospheric stability and wind statistics are presented. The raw data are from a location in the mid west of the Netherlands and have been provided by the KNMI. The analysis and application to a reference wind turbine help us to understand the behaviour of wind turbines and, together with research results from other countries, show that the atmospheric conditions found at the Rhede wind farm certainly were no exception. This chapter is the text of a paper presented at the WindTurbineNoise2005 conference [Van den Berg 2005b], with some results from other presentations at that conference added (in section VI.6).
- ◆ In *chapter VII* some possibilities are discussed to cope with the effects of atmospheric stability on wind turbine noise, either by controlling wind turbine performance or by new designs. In part this is derived from a project in the town of Houten where the town council wants to permit a wind farm, taking into account the effect on residents, especially at night. This chapter is a somewhat expanded version (a concluding section has been added) of a second paper presented at the WindTurbineNoise2005 conference [Van den Berg 2005c].
- ◆ In *chapter VIII* a new topic is introduced: how does wind affect sound from a microphone? It shows that atmospheric turbulence, closely related to -again- atmospheric stability, is the main cause of wind induced microphone noise. The chapter corresponds to a published article [Van den Berg 2006].
- ◆ In *Chapter IX* all results are summarized. Based on these general conclusions recommendations are given for a fresh look at wind turbine noise.
- ◆ Finally, in *chapter X*, some thoughts are given to conclude the text. After that the appendices give additional information.

