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On the Propagation Model of Wind Farm Noise

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Abstract

In the last years, the wind turbine became one of the most relevant renewable energy source, in particular in some areas with peculiar wind and orography conditions. Moreover, the presence of residential buildings in proximity of the wind farm can be a relevant issue in the site choice, because of the environmental impact of the turbines. Among the most important elements that annoy people living close to a wind farm, one can find, most of all, the landscape worsening and the acoustical noise problem.

This work is focused on the characterization of the noise coming from wind farms, already operating or still under construction, the latter from a predictive point of view.

Starting from the geometrical and technical data of the farm, the sound power level of the turbine can be analyzed. From the wind data (direction and speed) on a given area, according to the dependence of source power level from wind speed given in literature, the characterization of the source can be performed. Thus, the crucial point is the propagation model choice, that can heavily influence the noise impact. The results of this procedure can be used in the prediction of noise in a farm under construction.

In this work the authors consider a case study and analyze the noise impact due to the operation of turbines, by means of different propagation models compared with a commercial software noise map and experimental measurements.

1. Introduction

The need for new and efficient renewable energy sources is going to become a very relevant research issue. One of the most important solution is represented by the wind turbines. This system is particularly useful in some peculiar areas, where the wind exposition and speed are suitable. In this framework, new technologies need to

be developed in order to reduce the environmental impact of the wind turbines. In particular, besides the various physical polluting agents, acoustical noise must be considered. The turbines generate unwanted sound, both mechanical and aerodynamic. In the last years, with the advancement of technology, wind turbines became much quieter, but their noise is still an important source, to be considered in the site choice phase.

The evolution of wind turbines started with the farm irrigation and millworks. Today's modern wind turbines have been adopted in many countries to produce electricity from a "green" source, i.e. wind. Data presented at Global Wind Energy Council, 2009, refers of approximately 120.800 megawatts of wind energy capacity installed around the world at the end of 2008 [1].

Besides these very impressive data, wind turbines have several detractors, mainly because of noise annoyance, visual impacts, landscape and wildlife disturbances [2]-[3]. This environmental cost is primarily felt by those living near the wind farm.

In particular, acoustical noise must be deeply investigated among these environmental polluting agents, both on a predictive point of view (before installation) and on an experimental basis (for operating turbines). The turbines, in fact, generate unwanted sound, both mechanical and aerodynamic. Recently, thanks to the advancement of technology, wind turbines became much quieter, but their noise is still an important source, to be taken in account. In this framework, new technologies need to be developed in order to reduce the environmental impact of the wind turbines.

Together with the technologies, a source and propagation modelling improvement could be helpful in order to understand the correct behaviour of the noise produced by the wind turbine.

In this paper, the authors analyze the properties of noise intensity function, from an analytical point of view, focusing on its slope when considering different dependences. In addition, in the last section, results obtained with a commercial predictive software are reported; the simulation are performed after a parameters tuning on experimental measurements.

2. Background on wind turbine noise

Noise produced by wind turbine has been deeply investigated. In literature one can find many papers regarding this issue. A relevant result is that annoyance from wind turbines is generally weakly related to the equivalent A-weighted SPL [2]-[4]-[5]. Different sound properties, not fully described by the equivalent A-weighted level, can be related to the perception and annoyance for wind turbine noise, also depending on the operating conditions of the wind farm. Persson Waye and Öhrström [6] pursued an experimental study in order to support this hypothesis, recording noise produced by five wind turbines and comparing them in terms of reported perception and annoyance. A relevant result was that the five different noises gave different annoyance perceptions, although the equivalent A-weighted SPL were the same. More subsequent studies enforced this result and suggested that the presence of sound characteristics subjectively described as lapping,

swishing, and whistling was responsible for the differences in perception and annoyance between the sounds [7].

These subjective sound characteristics could be very relevant for perception and annoyance, especially at low background noise levels. The perception of wind turbine noise, in fact, could be covered by wind generated noise. However, usually the wind turbines have a stable rotor speed, that results in a quite steady noise emission, even if the wind speed and the background level is low. In addition, noise from wind turbines comprises modulations with a frequency that corresponds to the blade passage frequency [8] and it is usually poorly masked by ambient noise in rural areas [9].

Together with these phenomenological studies on the intensity and annoyance from wind turbine noise, a very important effort has been spent in physical modelling of the source and of the noise propagation. Regarding the source, in [10] a summary is reported.

The sources of sounds emitted from operating wind turbines can be divided into mechanical and aerodynamic sources. In particular, mechanical sounds come from the interaction of turbine components such as meshing gears, non-aerodynamic instabilities interacting with a rotor blade surface, or unstable flows over holes or slits or a blunt trailing edge, etc.. Aerodynamic sounds, instead, are produced by the flow of air over the blades, especially interaction of wind turbine blades with atmospheric turbulence (also described as the characteristic "swishing" or "whooshing" sound), localized deficiencies on the blade or disturbed air due to the flow around the tower, etc..

A more detailed review of each of these sound generation mechanisms can be found in the paper of Wagner et al. (1996) [11].

3. A simple theoretical model

In this section, the wind turbine noise analysis is presented, starting from the construction of a simple model, based on the following assumptions:

1. The turbine can be, in a first approximation, considered as a point like source, with a subsequent spherical spreading of the noise.
2. Ground is considered completely absorbing.
3. Air absorption can be neglected over a short range.
4. The source sound power is assumed to be broad band.

Assumption 2 is supported from the fact that usually wind farms are designed and built in countryside environments. Even if these ideal conditions can appear far from reality, the authors will show that this description is enough adequate to the aims of the paper. A more detailed analysis, especially in the frequency domain, is postponed to further studies.

The geometry of the approximated model is shown in Fig. 1, where the source and the receiver positions are highlighted, together with the relevant parameters to be considered.

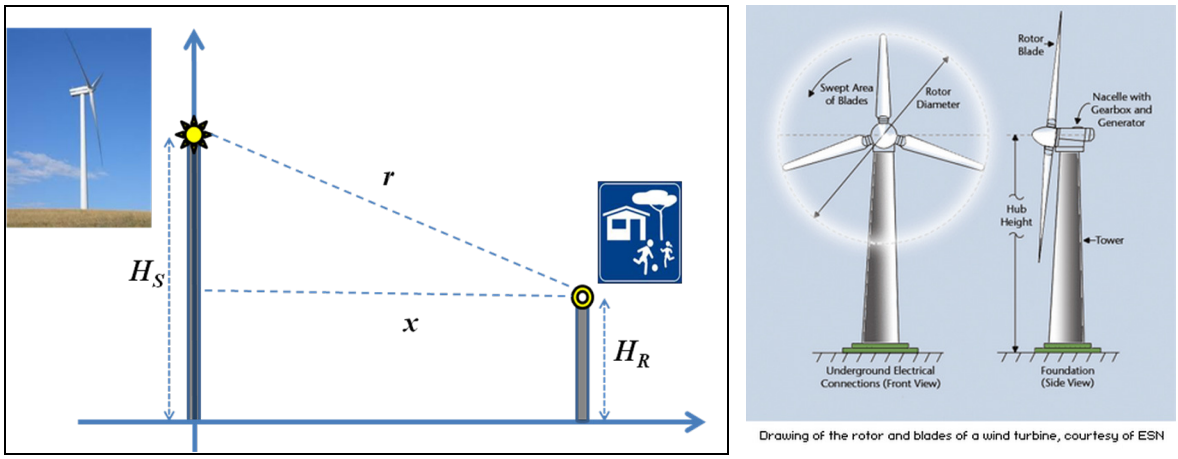

Fig. 1: Geometry of the source/receiver configuration of the presented model and sketch draw of a wind turbine taken from the web.

At the beginning one has to evaluate the source sound power level L_{wA} (A weighted) of the turbine. This result can be achieved, for instance, by fitting noise emission data provided by datasheet of manufacturers, obtained according to IEC 61400-11 [12].

In this paper, the fit on data of two different turbines (Fig. 2) is reported. A polynomial function has been used and results are reported in Fig. 3.

Once the fit equation is obtained, it is easy to relate the source power level global emission to any wind speed value (in the range of the fit). These data can be used to evaluate the sound intensity level L_I at a certain distance r (see Fig. 1) from the source. In the pointlike source and absorbing ground approximations, one can write:

$$L_I = L_{WA} - 20\log_{10}\frac{r}{r_0} - 11 - \alpha\, r \qquad (1)$$

where L_{wA} is the source power level, r_0 is the reference distance, chosen as 1 m and α is the air absorption coefficient. In this study, the N80 fit equation has been used.

The absorption of sound by the atmosphere can be obtained according to the calculation method described in "Acoustics - *Attenuation of sound during propagation outdoors* - ISO 9613-1:1993" [13] and depends on the frequency, temperature, and humidity of the air. In a simple approach, a constant value can be assumed as follow:

$$\alpha = 0{,}005\ dBA/m \qquad (2)$$

Obviously, within 100 m from the source, this attenuation can be neglected since it follows in the experimental uncertainty of any measurement.

With respect to the general propagation formula presented in ISO 9613, in this work some contributions, due for instance to ground reflection, screens, etc., are neglected since they are not relevant in this framework and can be easily implemented in a further study as simply additive terms.

NORDEX

NORDEX N90/2500 HS
Noise levels

Doc. No.: F008_149_A03_EN
Revision: 0
Date: 2007 Jul 11

Department responsible: Central Engineering/FAM
Replaces:
Classification: PB – Public
Created: Haevernick/CE FAM
Checked: Kirchner/CE PJE
Released: Kamuk/CE PJE
Status: FI – Final

Document will be published electronically – Original with signatures at "Department responsible".

Noise Emission Nordex N90/2500 HS

Warranty levels
according to IEC 61400-11:2002

Hub height: ≤ 80 m

Standardised wind speed (at 10 m height)	Apparent sound power level	Tonal audibility
V_S [m/s]	L_{WA} [dB(A)]	ΔL_a [dB]
3	95.0	≤4
4	99.0	≤4
5	102.5	≤4
6	105.5	≤4
7	106.5	≤4
8	107.0	≤4
9	107.0	≤4
10	107.0	≤4
11	107.0	≤4
12	107.0	≤4

NORDEX

NORDEX N80
Noise levels

Doc. No.: F008_158_EN
Revision: 2
Date: 2005 Oct 18

Department responsible: Central Engineering/PDE
Replaces:
Classification: PB – Public
Created: G. Potzka/Sales
Checked: H. Resing-Wörmer/CE FAM
Released: G. Steininger/CE PDE
Status: FI – Final

Document will be published electronically – Original with signatures at "Department responsible".

Noise Emission Nordex N80

Warranty levels
according to IEC 61400-11:2002

Hub height ≤ 80 m

Standardised wind speed (at 10 m height)	Apparent sound power level	Tonal audibility
V_S [m/s]	L_{WA} [dB(A)]	ΔL_a [dB]
4	98.0	≤4
5	100.5	≤4
6	102.5	≤4
7	103.0	≤4
8	103.5	≤4
9	104.0	≤4
10	104.0	≤4
11	104.5	≤4
12	105.0	≤4

Fig. 2: Noise emission levels for two different turbines versus standardised wind speed (at 10 m height) [taken from the web].

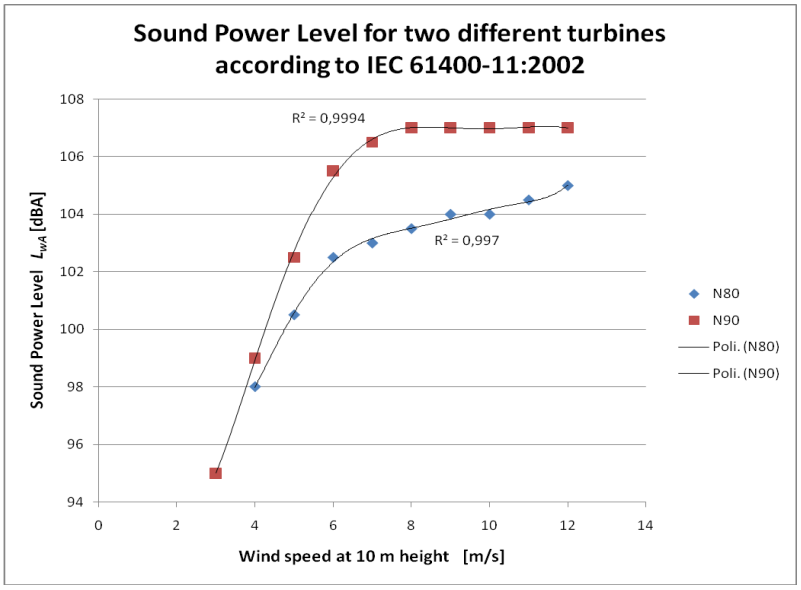

Fig. 3: Sound Power Level data fit for two different turbines. Data have been provided by manufacturer datasheets. The R^2 determination coefficient of the fit is reported in the plot.

Formula (1) is derived from the usual expression of a newtonian field (see for instance [19]) which gives the sound intensity *I* produced by a pointlike source in terms of source power *W* and distance source-receiver *r* :

$$\frac{I}{I_0} = \frac{W/W_0}{4\pi\left(r/r_0\right)^2} \qquad (3)$$

W_0, I_0, r_0 are reference values, used to make the logarithm argument dimensionless.

If one includes all the constant values and the source power *W* in a parameter *K* as follow:

$$K = \frac{I_0\, r_0^2\, W}{4\pi\, W_0} \qquad (4)$$

the sound intensity is:

$$I = K\frac{1}{r^2} \qquad (5)$$

Let us underline that, in this model, the parameter *K* is ruled only by the wind speed value which is related to the power of the source by the fit procedure described above.

Considering that (see Fig. 1):

$$r^2 = x^2 + (H_R - H_S)^2 = x^2 + H^2 \qquad (6)$$

with $H = H_R - H_S$, the sound intensity can be finally written as:

$$I = K\frac{1}{\left(x^2 + H^2\right)} \qquad (7)$$

This Lorentzian-like function is plotted vs *x* in Fig. 4.

Studying function (7), one can easily find that it has a maximum in $x = 0$, with value $I_{max} = K/H^2$, and an inflection point in:

$$x = \frac{H}{\sqrt{3}} \qquad (8)$$

where the second derivative is null.

Of course the 10 Log operator does not affect the properties on *x* axis, thus also the sound intensity level L_I has an inflection point (see Fig. 5).

By this result, one can affirm that there is a first region of proximity to the turbine in which the intensity level decreases slightly slower than the second region. The concavity, in fact, influences the slope of the sound intensity function.

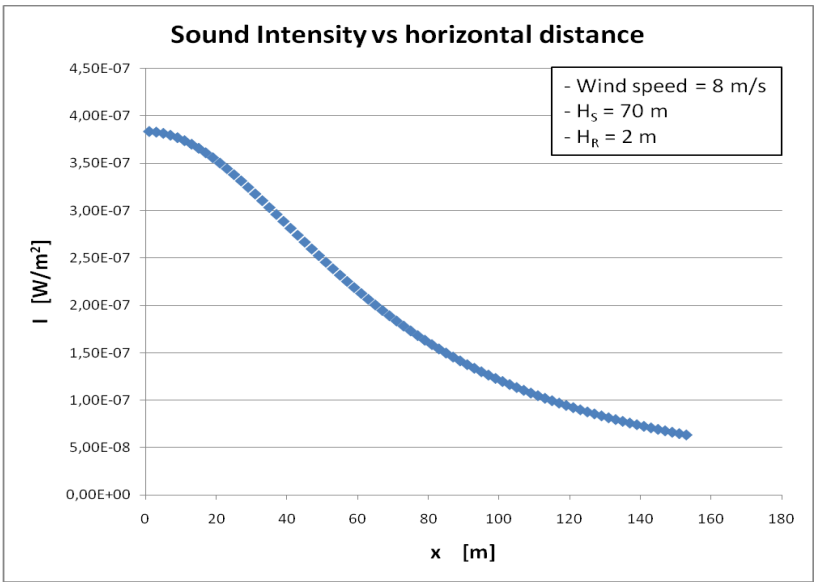

Fig. 4: Sound Intensity vs horizontal distance from the turbine base for a pointlike source with L_W= 103,5 dBA, height of the source = 70 m and height of the receiver = 2 m.

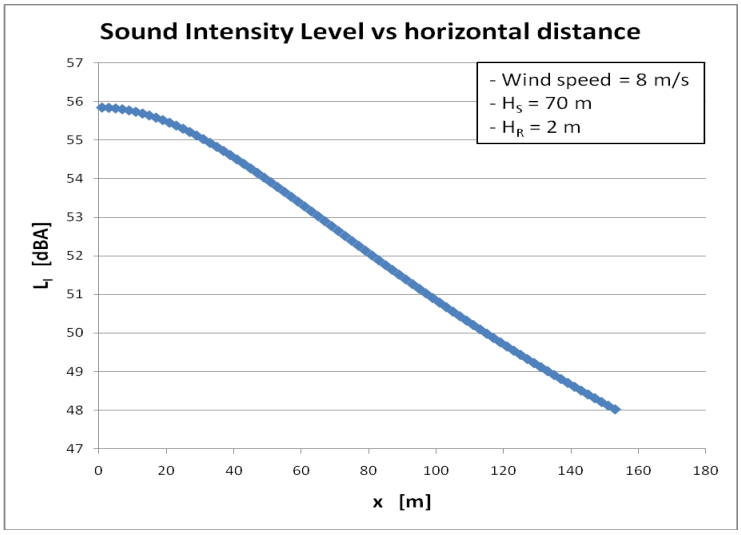

Fig. 5: Sound Intensity Level vs horizontal distance from the turbine base for a pointlike source with L_W= 103,5 dBA, height of the source = 70 m and height of the receiver = 2 m.

It is valuable to underline that the only parameter that influences the delimitation of the regions of different concavity is the difference between the source and the receiver heights.

An additional study that can be easily performed is the dependence of the sound intensity and of the intensity level from the height of the source in a fixed point. Looking at formula (7), one can easily notice that the function has the same dependence from the *x* and *H* variables, that means that it has the same slope with respect to each of them. The result of the plot is shown in Fig. 6 and, as discussed above, it is again a Lorentzian-like function with the same properties. It is easy to understand that the higher is the source, the lower is the noise impact on the receiver.

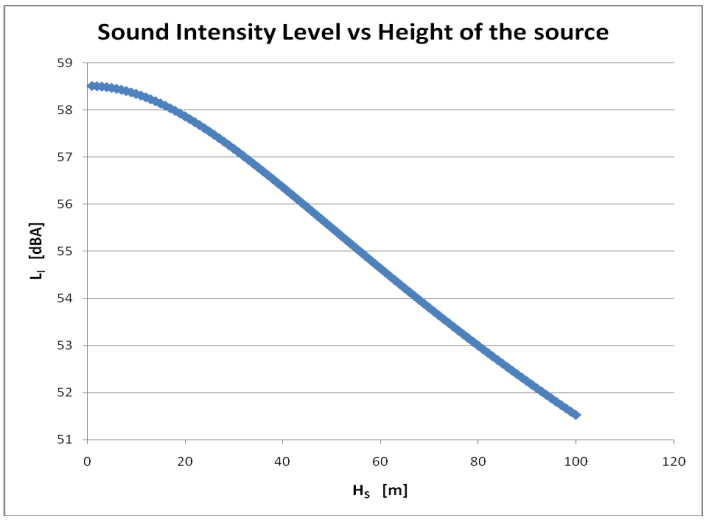

Fig. 6: Sound Intensity Level vs height of the source for a pointlike source with L_W= 103,5 dBA, distance from wind turbine base = 70 m and height of the receiver = 2 m.

4. Predictive software simulation and experimental results

In this section, results obtained with a different model, embedded in a predictive software, i.e. CadnaA®, are presented for different situations and compared with the model presented above and with experimental measurements.

The “Angle Scanning” and the inverse “ray-tracing” principles are at the basis of the software algorithm. The calculation grid is obtained dividing area under analysis in many small surfaces in which a receiver is placed at a variable height (in our case is 2 m). Each grid element releases many rays with a full angle coverage (omni directive) and these rays, eventually after many reflections, intercept the noise source. The path length of the single ray describes the attenuation of the sound wave coming from a certain noise emitter. In addition, specific receivers can be inserted in the map, with the possibility to export the results in a worksheet. In this study, these receivers have been placed 5 m from each other and at 4 m height, in order to compare the results with the model presented in previous section.

A first study has been pursued to validate results of the previous section. For this purpose, a pointlike source has been placed in a certain point and the propagation of noise has been studied both by means of noise mapping and of fixed receivers.

The parameters of the first simulation are resumed in Tab. 1.

Tab. 1: Single wind turbine simulation parameters

Pointlike source approximation	
L_W	103,5 dBA
Wind speed	8 m/s
Height of the source	70 m
Evaluation grid height	2 m
Receivers height	4 m
Distance between receivers	5 m

Fig. 7 reports the noise level pattern of a single turbine, i.e. a pointlike source, while in Fig. 8 the comparison between this simulation and the results from the theoretical model presented in previous section, is shown. The agreement between the two curves is quite good and it implicitly validates the assumption of the presented model.

Fig. 9 and Fig. 10 show the results of the simulation of an array of 8 wind turbines, approximated again as a pointlike source with the same parameters as above. The plot in Fig. 10 is obtained with the results of the receivers placed in proximity of three turbines. The Lorentzian slope is clearly evidenced.

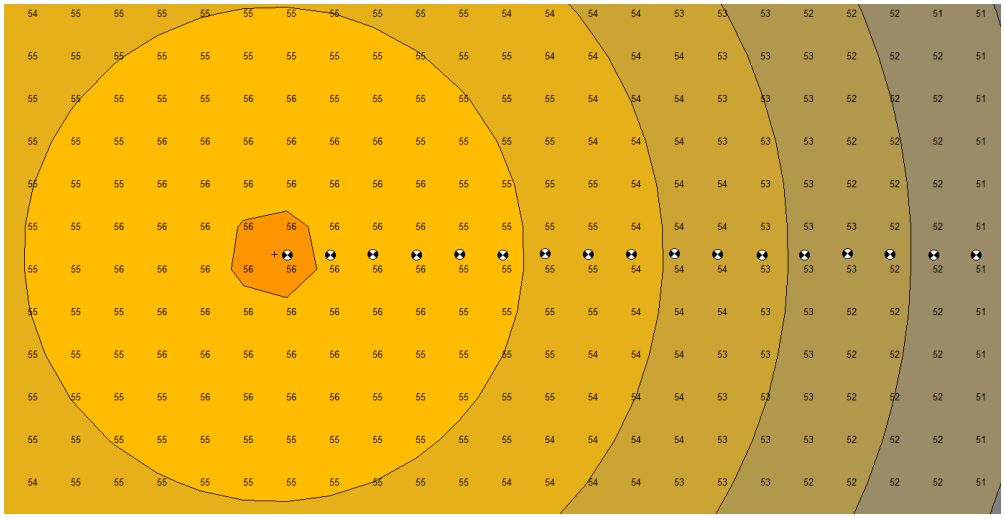

Fig. 7: CadnaA noise map (values are in dBA) for a pointlike source with L_W= 103,5 dBA (wind speed = 8 m/s), height = 70 m, absorbing ground. The grid is evaluated at 2 m from the ground and the distance between two receivers (black and white circles) is 5 m, while their height is 4 m.

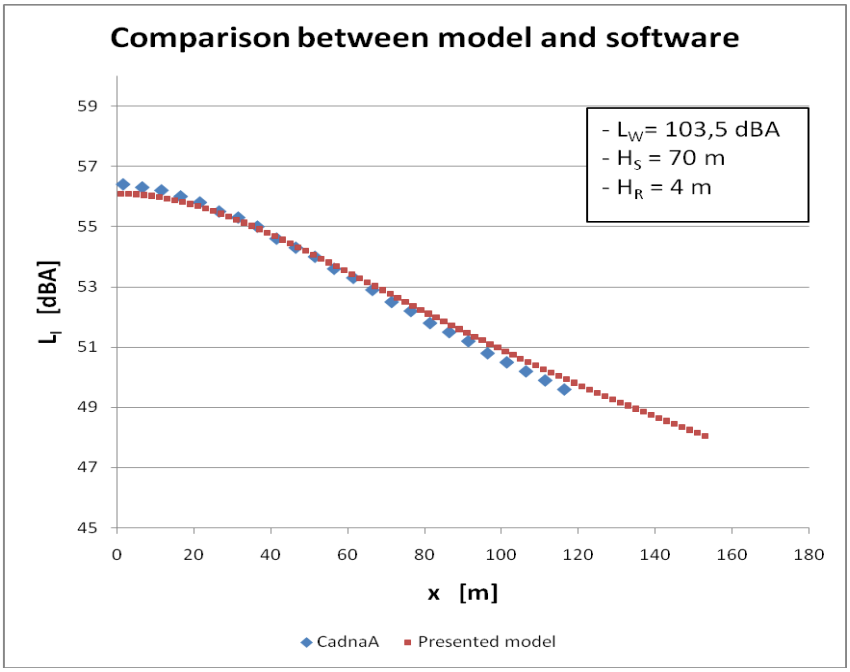

Fig. 8: comparison between noise level predicted with CadnaA (blue diamonds) and with the proposed model (red squares), for a pointlike source with L_W= 103,5 dBA, height = 70 m and absorbing ground. The values are taken at 4 m of height.

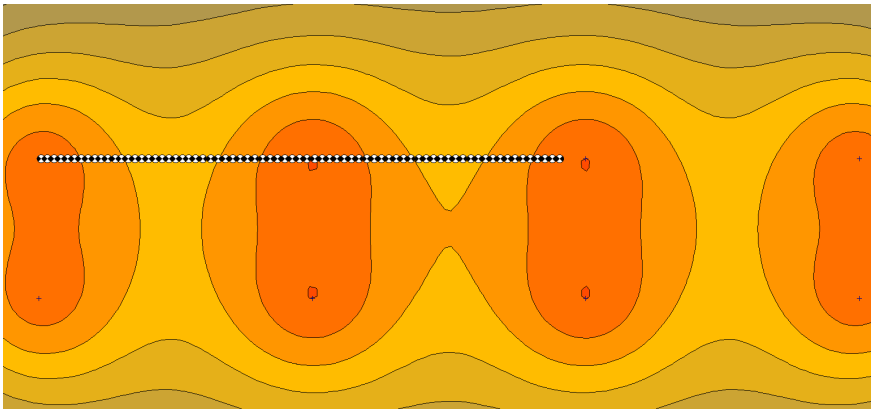

Fig. 9: CadnaA noise map for an array of 8 pointlike sources with L_W= 103,5 dBA, height = 70 m and absorbing ground. The grid is evaluated at 2 m from the ground and the distance between two receivers (black and white circles) is 5 m, while their height is 4 m.

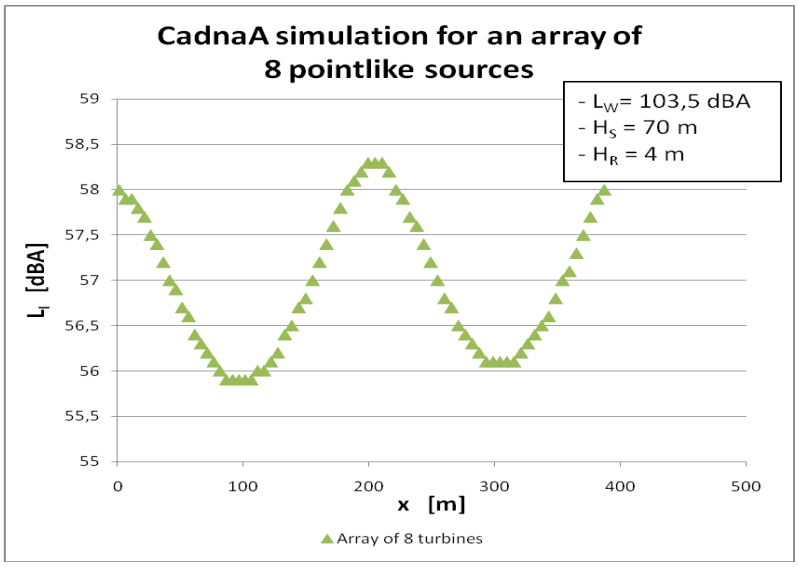

Fig. 10: CadnaA results for an array of 8 pointlike sources, limited to the proximity of three turbines, with L_W= 103,5 dBA, height = 70 m and absorbing ground. Values are taken at 4 m of height and the data points refer to receivers shown in the previous map.

In order to validate the model and to better tune the parameters of software simulation, an experimental session has been pursued in an operating wind farm, located in Taverne Vecchie (Salerno), Italy.

The map of the area, taken from Google map © and implemented in the software CadnaA, is shown in Fig. 11.

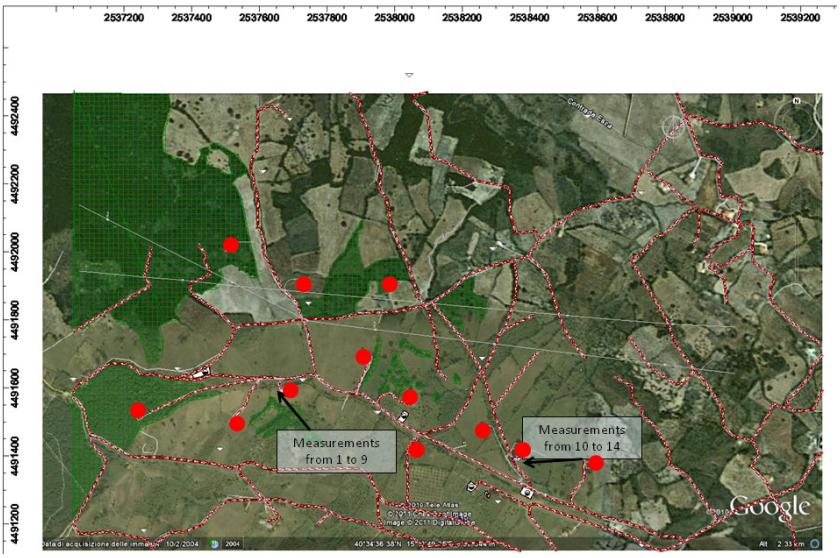

Fig. 11: Map of the area of Taverne Vecchie (SA), Italy, taken from Google map. The map has been implemented in CadnaA framework and the roads have been traced. The turbines are the red circles.

The experimental measurements have been taken according to ISO standard, with Class 1 devices and in weather conditions fulfilling regulation requirements. Let us remind that even if the turbines were operating with a wind speed of about 5-6 m/s, at the ground level, where the receivers were placed, the wind was below the threshold fixed by regulation.

In Fig. 12 the data taken in proximity of an operating wind turbine have been plotted. The receivers have been moved along two radius pointing to the turbine base, in order to both validate the spherical propagation (pointlike source) assumption and the lorentzian shape of the intensity plotted versus the horizontal distance (see Fig. 5). The results well fit these assumptions and theoretical results. Only one point results to be lower than the expected slope, but during that measurement a strong lowering in the wind speed has been registered, making reasonable the lowering of the measured level.

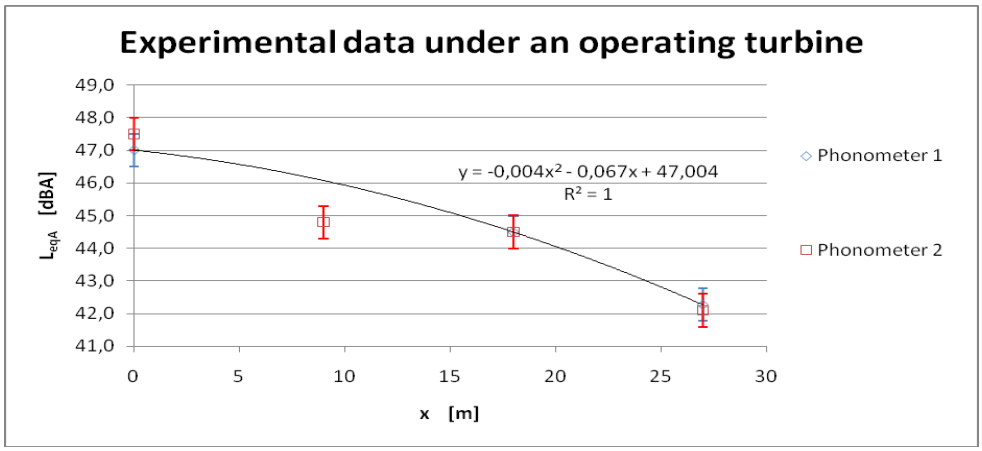

Fig. 12: Experimental data taken in proximity of an operating wind turbine. The receiver is placed at 1,5 m and the phonometers have been placed along two radius pointing to the turbine base.

Once this measurements have been performed, it resulted interesting to model the entire wind farm in the predictive software, in order to achieve a complete mapping of the noise in the area. Starting from the experimental data and back propagating to the source, the source power level has been chosen to 93,5 dBA and a simulation was performed. Resulting noise map is shown in Fig. 13.

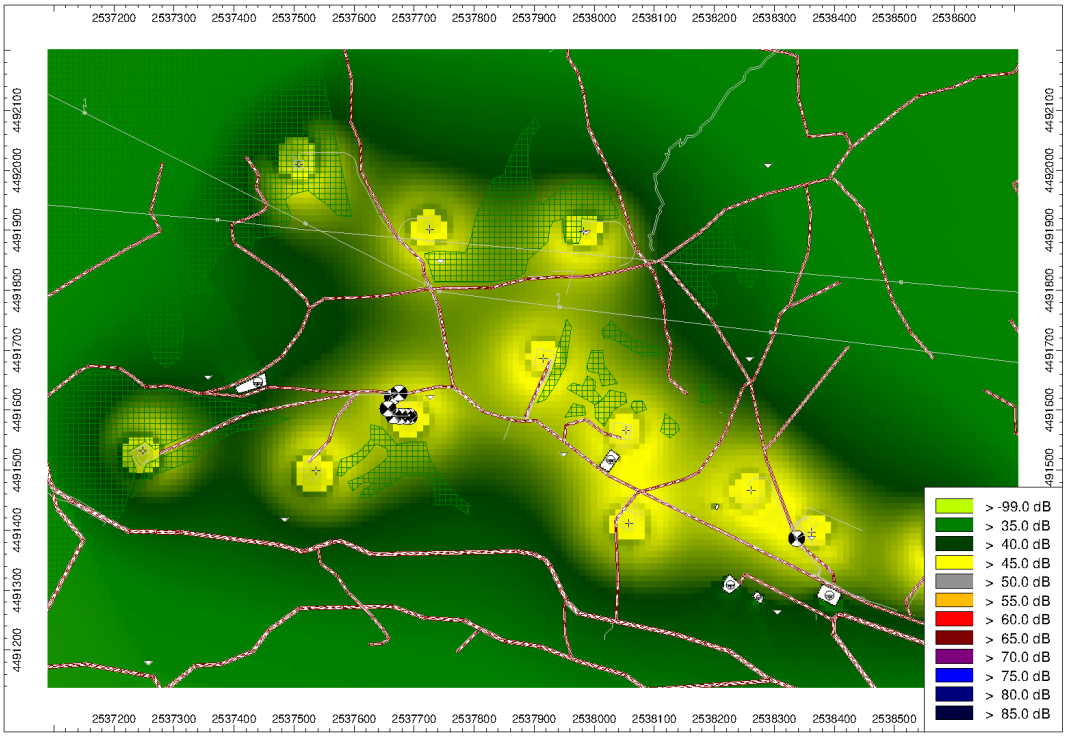

Fig. 13: Noise map of the wind farm area, obtained in predictive software framework. The power of the pointlike sources (turbines) has been set to 93,5 dBA, according to the experimental measurement taken.

This noise is evidently not very significant, as experienced also by the operators during the measurement session. In any case, the main aim of tune the software parameters on experimental data has been achieved and now this propagation model can be used in order to predict the noise impact in different wind conditions. The following figures, thus, have been obtained for a wind speed of 8 m/s, with a resulting source power of 103,5 dBA. Simulation parameters are resumed in Tab. 2 while the noise map is shown in Fig. 14.

Tab. 2: Wind farm simulation parameters

Pointlike source approximation	
L_W	103,5 dBA
Wind speed	8 m/s
Height of the source	65 m
Evaluation grid height	4 m
Receivers height	1,5 m

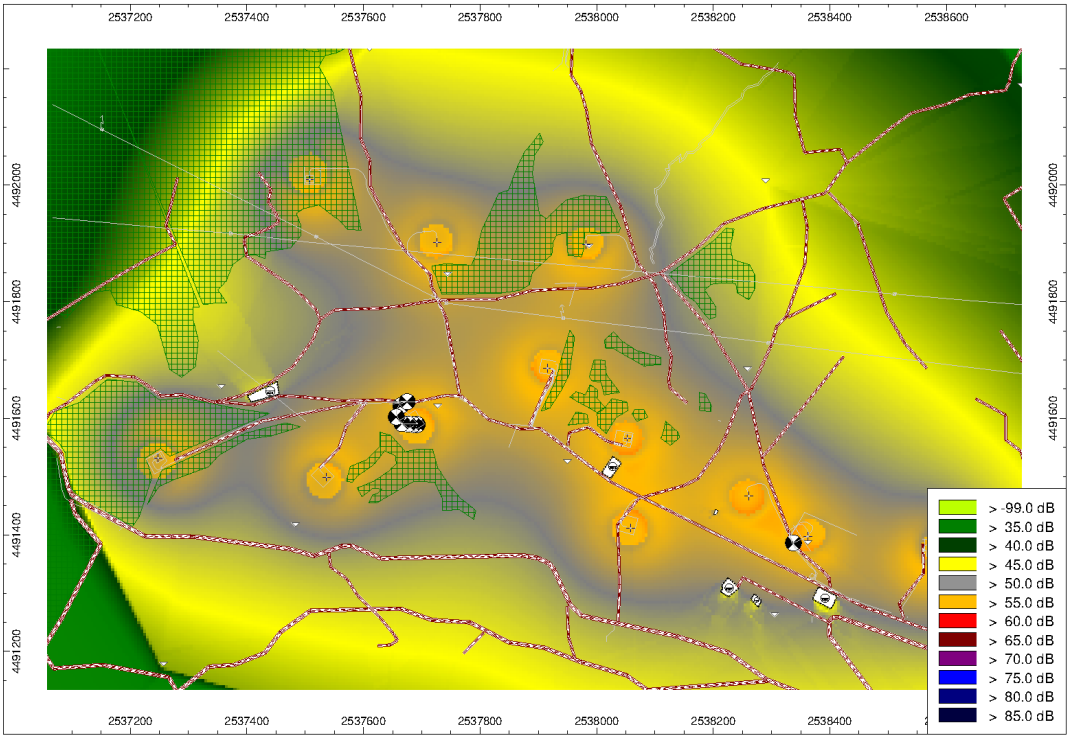

Fig. 14: Noise map simulation in an average wind speed condition, i.e. 8 m/s. The resulting source power is 103,5 dBA.

The pattern clearly shows the peaks in correspondence of the wind turbines, and it can be deduced that the orography of the terrain has a certain influence in the noise propagation. The latter consideration can be also exploited thanks to the 3D image engine of the software. In Fig. 15 a collection of 3D images is shown. The images are correspondent to the region in the bottom-right area of the map in Fig. 14, where the receiver is placed. It is evident how the orography and the position of the sources and of the receivers/buildings influence the resulting noise level.

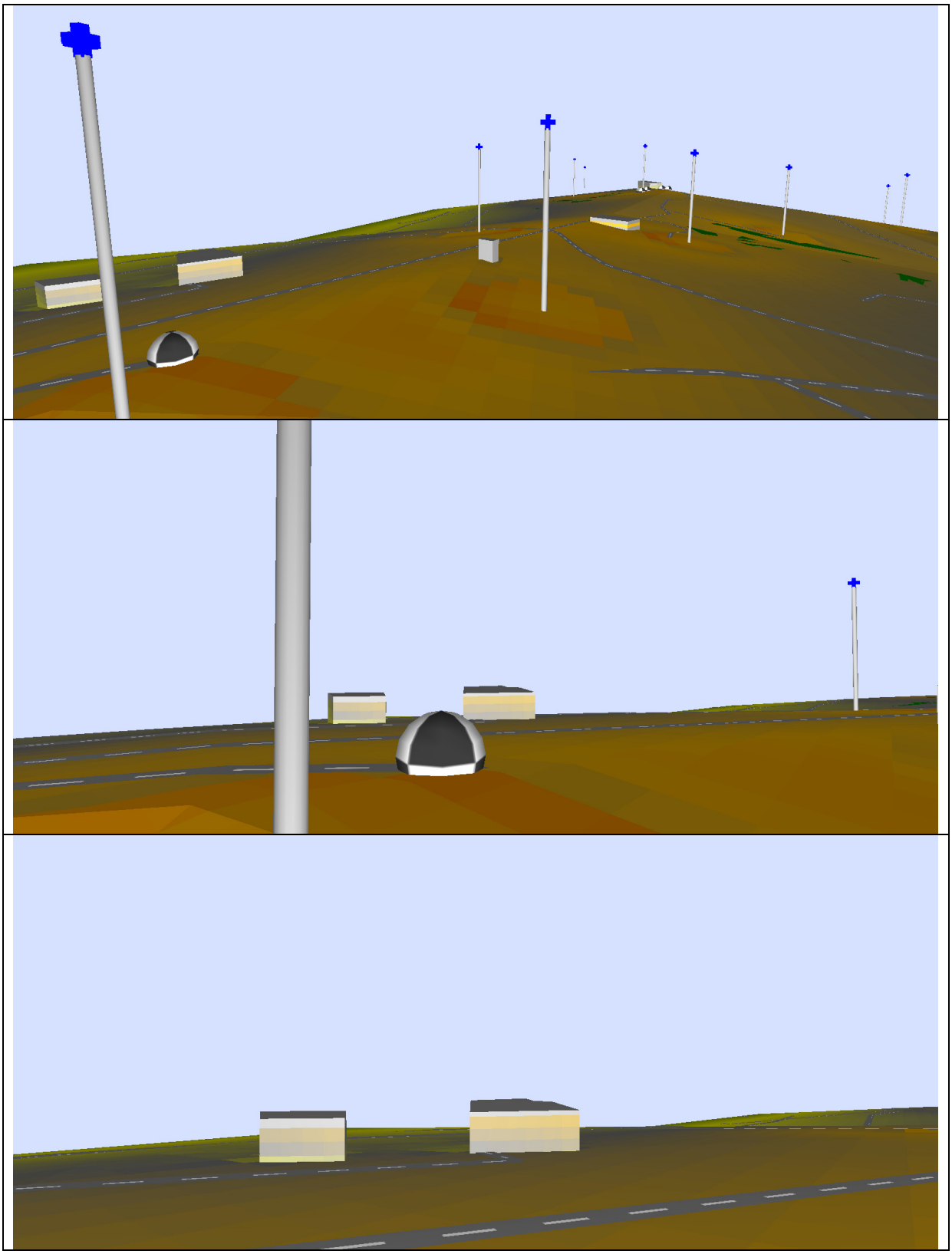

Fig. 15: 3D images of the wind farm area under investigation. The colours on the terrain are according to the noise pattern and the legenda in Fig. 14. The blu crosses are the pointlike sources, mimicking the wind turbines, the white and black circles are the receivers and the parallelepipeds are the buildings. The different colours on the buildings represent the noise level according to the legenda in Fig. 14.

5. Conclusions

In this paper, the authors analyzed the propagation of noise produced by a single wind turbine and an operating wind farm. This study has been performed in terms of a theoretical approach, an experimental analysis and predictive software simulations.

The turbine has been characterized and approximated to a pointlike source. This assumption led to a specific noise propagation theoretical model studied in section 3. The function is lorentzian-like and can be analytically studied in terms of slope, maximum and inflection point.

The theoretical model has been then tested in the CadnaA predictive software framework and compared to experimental measurements.

These measurements have been used to tune the parameters of the simulations, leading the authors to obtain a full noise map of the area under investigation. Once the source power level has been tuned, the prediction of different situations can be easily performed and an example has been reported.

Moreover, the software 3D imaging has been performed in the last part of section 4, showing the influence in the noise map of orography of the terrain and turbines site choice. In addition, the 3D plots are very useful to understand what happens to building with a not negligible height, as well as in the phase of presentation of the results.

Finally, this paper shares lights to further investigations on the noise propagation modelling, being a relevant integration of theoretical, experimental and software issues. Very often, in fact, these elements are not considered together.

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