Wind Turbine Noise: Theoretical and Experimental Study

Claudio Guarnaccia*, Nikos E. Mastorakis**, Joseph Quartieri*

***Abstract*—** Wind turbine acoustical noise is a relevant element to be considered and studied because of the growing interest in renewable energies. The environmental impact of these structures in the surrounding areas is deeply investigated, especially on the acoustical and the landscape point of view. This paper is mainly devoted to the integration between analytical, experimental and software analysis on noise production and propagation, in the framework of a single turbine or a wind farm. The results of a measurement campaign in an operating wind farm are reported and used to tune the model and software parameters, in order to validate the theoretical assumptions. In particular, the pointlike source and other assumptions are verified by means of comparison between experimental and simulated data. The noise mapping is also pursued in the framework of a commercial predictive software, exploiting the possibility to monitor the behaviour of noise in a complex area, in terms of number of sources, propagation, absorption, terrain orography, etc., such as a wind farm.

***Keywords*—** Noise control, Wind turbine, Source modelling, Noise propagation.

I. Introduction

THIS century is going to be characterized by the time of energy crisis. The lack of petrol, the still ongoing research on nuclear fission plants and the global warming are the main elements that lead to the development of green and renewable energies. In this framework, wind turbines are a relevant component of the complex scenario of the sustainable development.

Initially used for farm irrigation and millworks, today's modern wind turbines produce electricity in more than 70 countries. As of the end of 2008, there were approximately 120.800 megawatts of wind energy capacity installed around the world (Global Wind Energy Council, 2009) [1].

However, disturbance from wind turbines may be an obstacle for large-scale production [2]-[3]. Besides these very impressive data, in fact, wind turbines have several detractors, mainly because of noise annoyance, visual impacts, landscape and wildlife disturbances. This environmental cost is primarily felt by those living near the wind farm.

In particular, among these environmental 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. 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, a comparison between the presented model and results obtained with a commercial predictive software are sketched, sharing lights to further investigations.

II. Wind turbine noise background

The wind turbine noise has been quite deeply investigated in literature. 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. This hypothesis was supported in a previous experimental study by Persson Waye and Öhrström [6], where five recorded wind turbine noises were compared in terms of reported perception and annoyance, resulting to be different, although the equivalent A-weighted SPL were the same. This result, together to other subsequent studies, 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].

Sound characteristics as described here could be of relevance 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

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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].

Besides these studies on the phenomenology and on the annoyance from wind turbine noise, many works have been pursued on the 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 two categories:

1) Mechanical sounds, 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.

2) Aerodynamic sounds, 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 is included in the text of Wagner, et al. (1996) [11].

III. Model Presentation and Results

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. In general, since the aim of the paper is to highlight the mathematical properties of the noise intensity function, in a first study one can consider these ideal conditions, postponing a more detailed analysis to a further study.

The geometry of our approximated model is shown in Fig. 2, where the source and the receiver position are highlighted, together with the relevant parameter of the model.

The first step of the procedure is to estimate the source sound power level L_{wA} (A weighted) of the turbine. In order to achieve this result, many procedures, both experimental and theoretical, can be used in an already operating wind farm but, in this paper, a deductive approach will be pursued. This will not diminish the value of the approach because the L_{wA} is an additive parameter that only affect the vertical shift of the curve.

The L_{wA}, in fact, is obtained as a fit on noise emission data provided by datasheets of manufacturers, obtained according to IEC 61400-11 [12]. In Fig. 3, for instance, datasheets of two different turbines are reported.

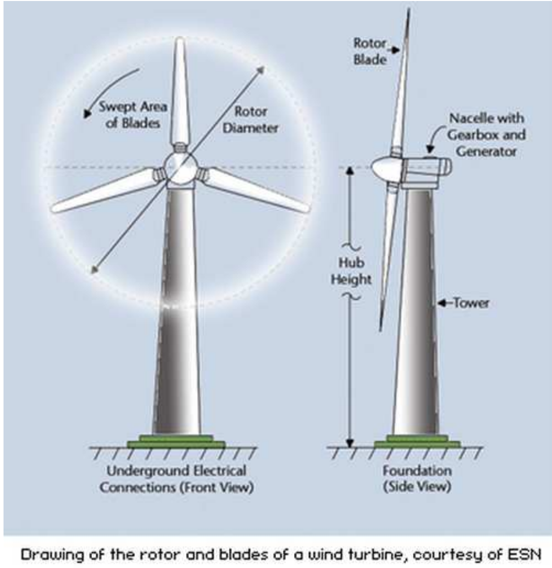


Fig. 1: Sketch draw of a wind turbine taken from the web.

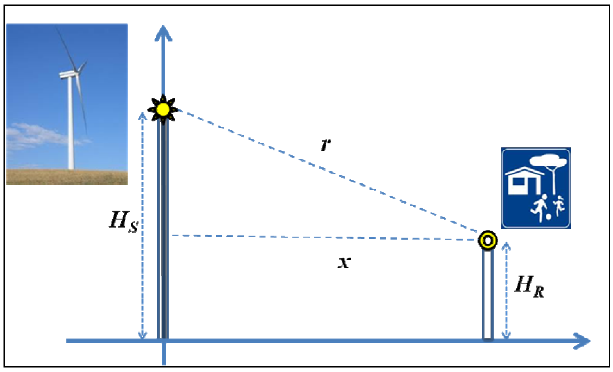


Fig. 2: Geometry of the source and receiver configuration.

These data have been fitted with a polynomial function and the results are reported in Fig. 4.

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. 2) from the source. In the pointlike source and absorbing ground approximations, on can write:

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

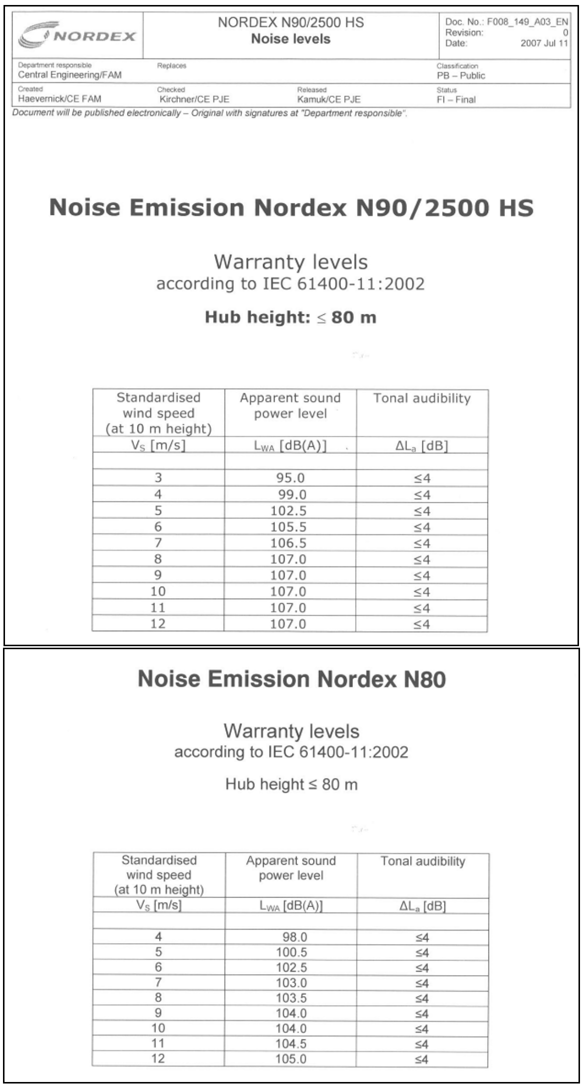
where L_{wA} is the source power level, r_0 is the reference distance, chosen as 1 m and α is the air absorption coefficient. In this study, the N80 fit equation has been used.

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

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Classification: PB – Public
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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

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

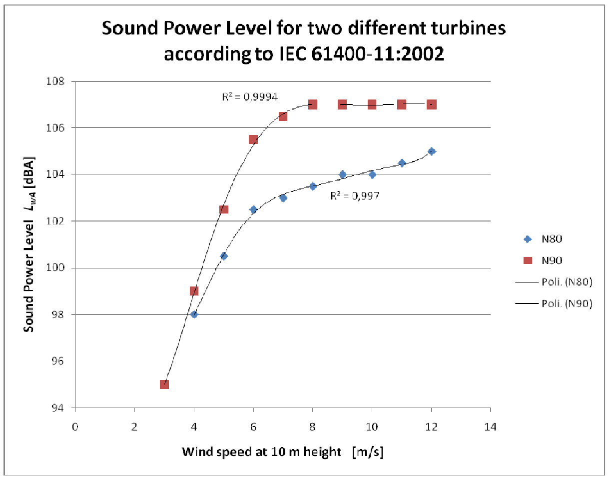

Fig. 4: Sound Power Level data fit for two different turbines. Data have been provided by manufacturer datasheets. The R^2 determination coefficient of the fit is reported in the plot.

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. 2):

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

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. 5.

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. 6).

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.

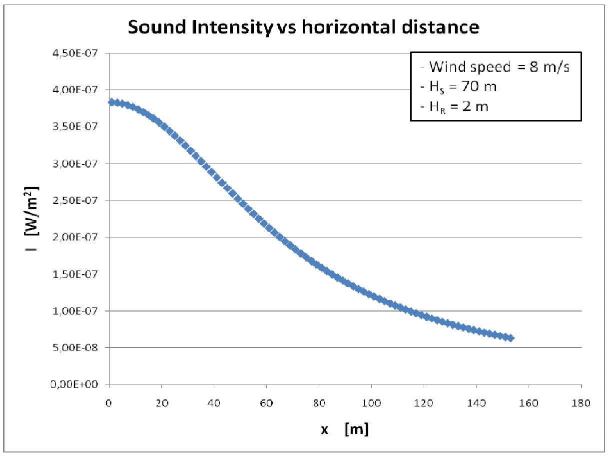

Fig. 5: Sound Intensity vs horizontal distance from the turbine base for a pointlike source with L_W= 103,5 dBA, height of the source = 70 m and height of the receiver = 2 m.

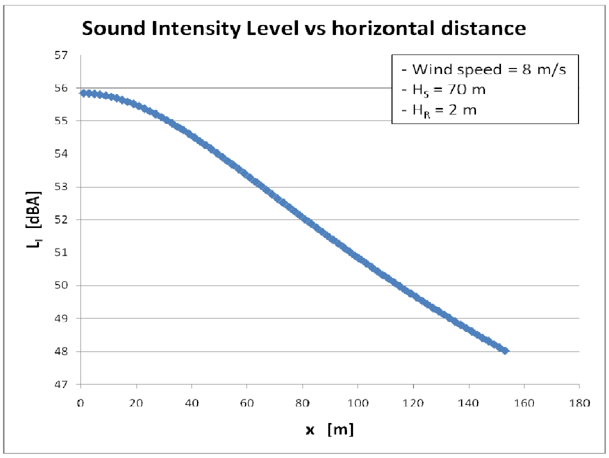

Fig. 6: Sound Intensity Level vs horizontal distance from the turbine base for a pointlike source with L_W= 103,5 dBA, height of the source = 70 m and height of the receiver = 2 m.

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. 7 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.

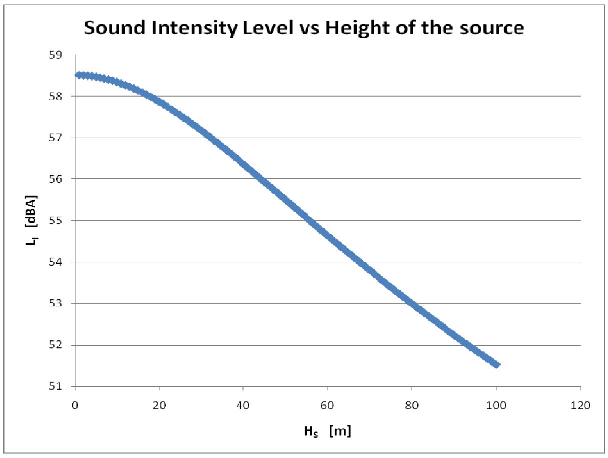

Fig. 7: Sound Intensity Level vs height of the source for a pointlike source with L_W= 103,5 dBA, distance from wind turbine base = 70 m and height of the receiver = 2 m.

IV. Software Results

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

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.

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

Tab. 1: 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. 8 reports the noise level pattern of a single turbine, i.e. a pointlike source without directivity, while in Fig. 9 the noise map of a directive source is presented.

In Fig. 10 the results of the two different simulation, evaluated at the receivers (black and white circles) are plotted, showing the peculiar slope of noise level produced by a directive source.

Fig. 11 and Fig. 12 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 is obtained with the results of the receivers placed in proximity of three turbines.

Finally, in Fig. 13 the comparison between noise level predicted with CadnaA and with the proposed model is presented. The agreement between the two curves is quite good and it implicitly validates the assumption of the presented model.

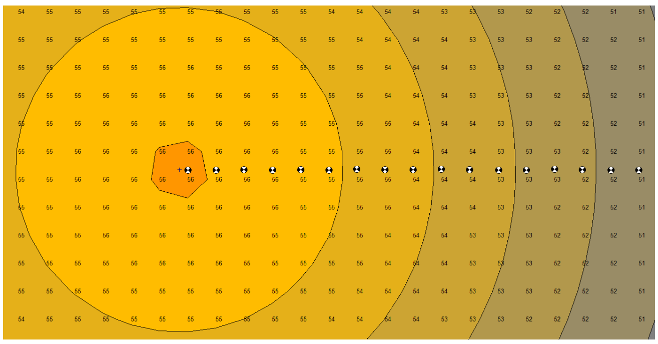

Fig. 8: CadnaA noise map (values are in dBA) for a pointlike source with L_W= 103,5 dBA (wind speed = 8 m/s), height = 70 m, absorbing ground. The grid is evaluated at 2 m from the ground and the distance between two receivers (black and white circles) is 5 m, while their height is 4 m.

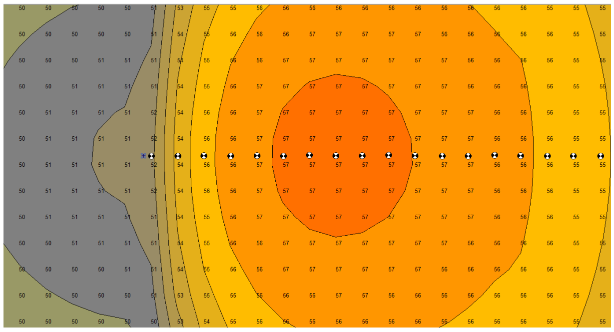

Fig. 9: CadnaA noise map (values are in dBA) for a pointlike source with L_W= 103,5 dBA (wind speed = 8 m/s), height = 70 m, absorbing ground and high directivity. The grid is evaluated at 2 m from the ground and the distance between two receivers (black and white circles) is 5 m, while their height is 4 m.

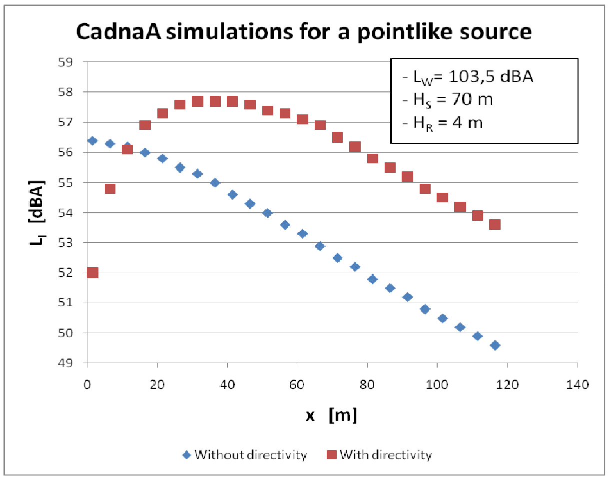

Fig. 10: CadnaA results for a pointlike source with L_W= 103,5 dBA, height = 70 m and absorbing ground. The values are taken at 4 m of height and the plots are with or without directivity.

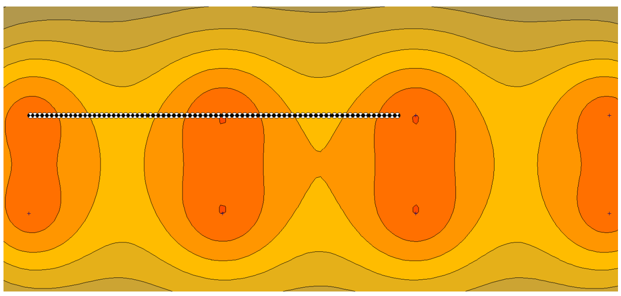

Fig. 11: CadnaA noise map for an array of 8 pointlike sources with L_W= 103,5 dBA, height = 70 m and absorbing ground. The grid is evaluated at 2 m from the ground and the distance between two receivers (black and white circles) is 5 m, while their height is 4 m.

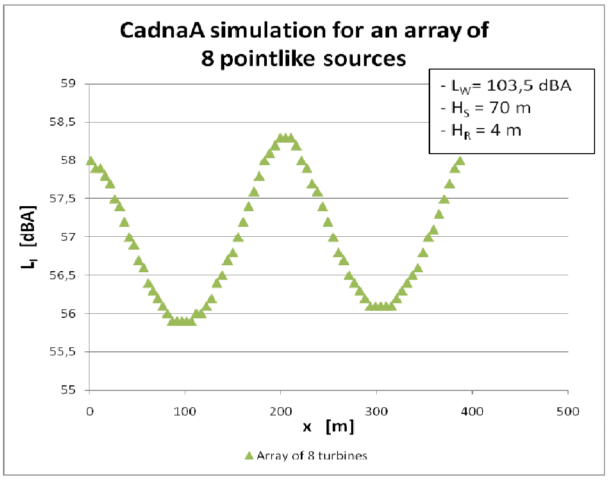

Fig. 12: CadnaA results for an array of 8 pointlike sources, limited to the proximity of three turbines, with L_W= 103,5 dBA, height = 70 m and absorbing ground. Values are taken at 4 m of height and the data points refer to receivers shown in the previous map.

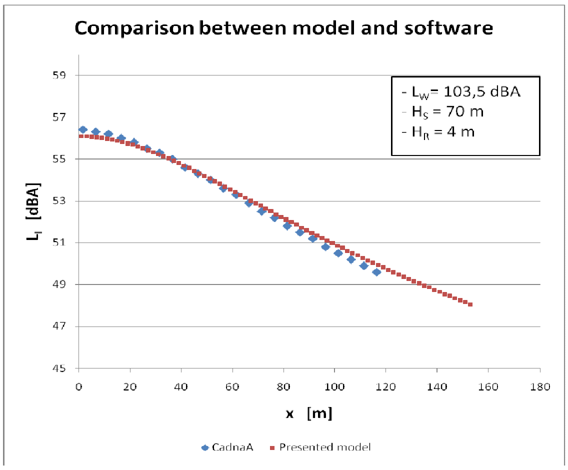

Fig. 13: comparison between noise level predicted with CadnaA (blue diamonds) and with the proposed model (red squares), for a pointlike source with L_W= 103,5 dBA, height = 70 m and absorbing ground. The values are taken at 4 m of height.

V. Experimental Results

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. 14.

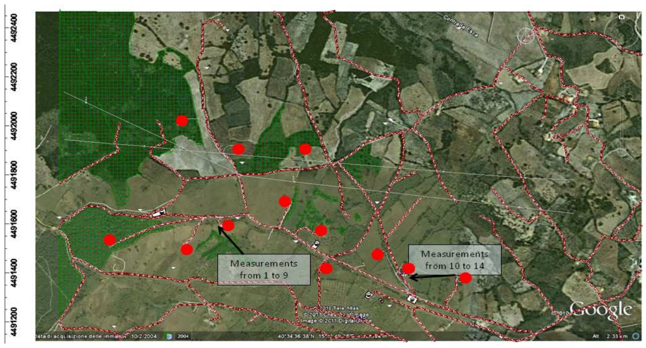

Fig. 14: Map of the area of Taverne Vecchie (SA), Italy, taken from Google map. The map has been implemented in CadnaA framework and the roads have been traced. The turbines are the red circles.

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. 15 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. 6). The results well fit these assumptions and theoretical results. Only one point results to be lower than the expected slope: this is probably due to a relevant lowering in the wind speed during that measurement.

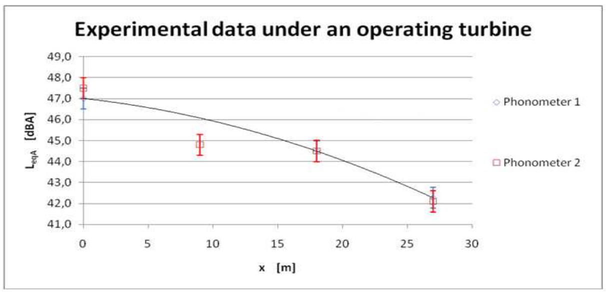

Fig. 15: Experimental data taken in proximity of an operating wind turbine. The receiver is placed at 1,5 m and the phonometers have been placed along two radius pointing to the turbine base.

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. 16.

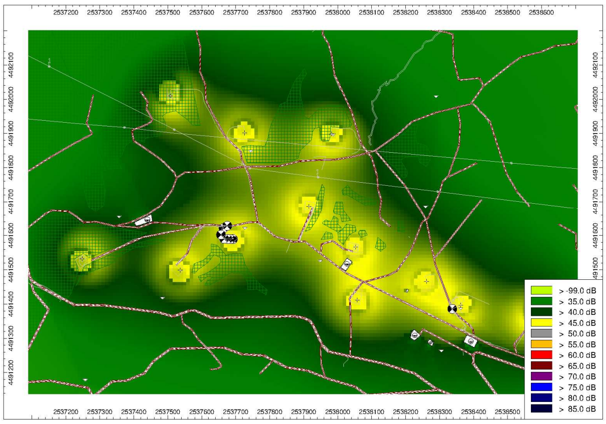

Fig. 16: Noise map of the wind farm area, obtained in predictive software framework. The power of the pointlike sources (turbines) has been set to 93,5 dBA, according to the experimental measurement taken.

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. 17.

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

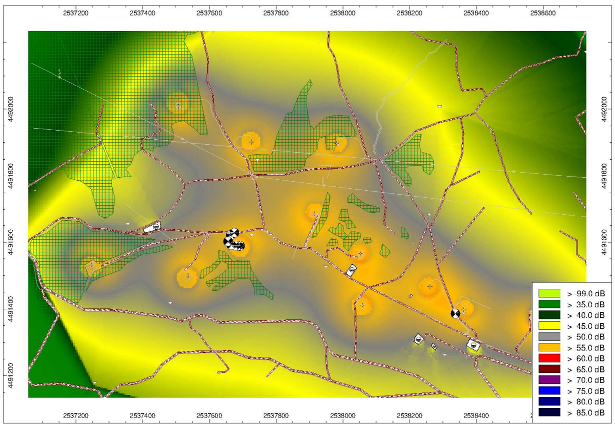

Fig. 17: Noise map simulation in an average wind speed condition, i.e. 8 m/s. The resulting source power is 103,5 dBA.

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. 18 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.

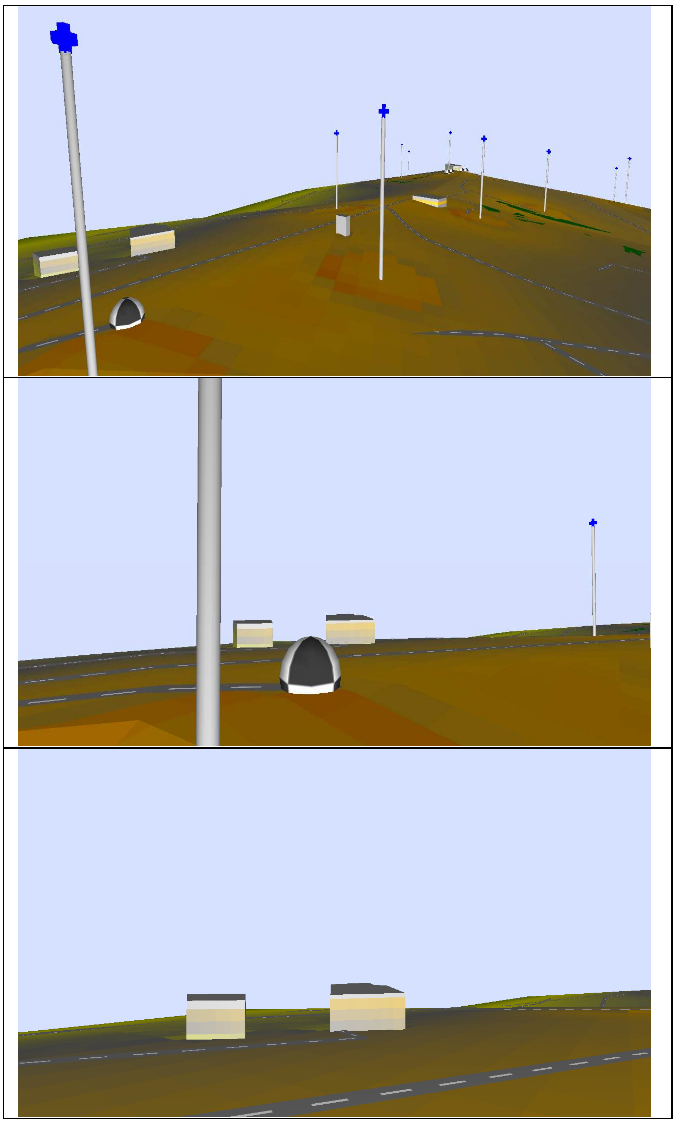

Fig. 18: 3D images of the wind farm area under investigation. The colours on the terrain are according to the noise pattern and the legenda in Fig. 17. The blu crosses are the pointlike sources, mimicking the wind turbines, the white and black circles are the receivers and the parallelepipeds are the buildings. The different colours on the buildings represent the noise level according to the legenda in Fig. 17.

VI. CONCLUSIONS

In this paper, the authors presented a mathematical analysis on the acoustical noise produced by wind turbines. The propagation function in literature usually depends by the distance between source and receiver, resulting in a inverse square dependence, since the acoustical field is a newtonian field. This function can be plotted versus the horizontal distance between the turbine base and the receiver, showing interesting features, such as, for instance, the presence of an inflection point dependant only by the difference between the source and the receiver heights. Since the concavity is negative in the first region (close to the turbine base), one can affirm that in the proximity of the turbine the intensity level decreases slightly slower than further, obeying to a Lorentzian-like function.

This result has been validated with the aid of a predictive software, CadnaA®. The agreement between the analytical curve and the numerical one implicitly validates the assumptions of the presented procedure. In the software framework, more simulations have been performed, introducing the directivity of the source and simulating more turbines in a symmetric array, giving a first description of the results that can be achieved in terms of noise mapping in more complex configurations of wind farms.

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