Vertical wind profile measurement using a pulsed LIDAR system

A. Honrubia*, A. Vigueras-Rodríguez†, E. Gómez Lázaro*,
*Wind Energy Department. Renewable Energy Research Institute.
Department of Electrical Engineering. School of Industrial Engineering. University of Castilla-La Mancha.
02071 Albacete, Spain. Email: andres.honrubia@uclm.es
†Wind Energy Department. Renewable Energy Research Institute.
Albacete Science & Technology Park. Albacete, Spain.

***Abstract*—To achieve reliable wind resource assessments as well as for an accurate short-term wind power forecast, the vertical wind profile from 40 m to 200 m heigth above the ground has been measured. Measurements have been performed on a real wind farm with a very complex terrain using a remote sensing equipment, specifically a LIDAR one. The importance of taking into account all the wind profile over the swept rotor area of a wind turbine has been analysed. It is proposed to rely more on vertical remote sensing than on the theoretical extrapolation when assessing the vertical profile over a complex terrain.**

I. Introduction

In wind energy systems, wind speed plays the most important role when the energy produced by a wind energy conversion system is assessed. Due to the cubic relationship between velocity and power, it is expected that a small variation in the wind speed will result in a large change in power. Therefore one of the most important phenomena related to the wind energy scope is the knowledge how does wind speed varies according to the altitude.

Unlike it could be thought, the analysis of the changes of wind speed with height is not a recent issue. In [1], a relevant approach based on studying the suitability of using a power law equation to depict the wind speed at several heights is found. It is stated that during nighttime the wind profiles measured were far from the ones derived from power law profile equations.

In the latest edition of the international standard for power performance, [2], the wind speed at hub height is the primary input parameter for power curve measurements, therefore wind speed at hub height is the only reference of wind speed over the whole turbine swept rotor area. This method has no major relevance for smaller wind turbines, but the large multi-MW turbines currently used could be exposed to highly varying wind conditions. Hence, the measurement of the wind speed at more heights within the swept rotor area provides a better knowledge of the wind profile, just like a better estimation of the energy produced, than the measurement based only on the hub height speed.

Nowadays, there are lots of authors showing the advantages of measuring wind speed in the whole rotor swept area instead of using hub heigh only, for example, in [3] are listed some of them. Most of the works developed in this scope use remote sensing technolgies to measure wind speed at several heights. Basically, remote sensing technologies are based on two principles, sound detection and ranging (Sodar) and light detection and ranging (Lidar). In the present paper, a Lidar instrument, specifically a WindCube one, has been used for performing all the measurements. In [4], a deep explanation about lidar instruments is found.

The aim of the present study is to analyse the characteristics of the wind profiles measured over a very complex terrain. Furthermore, the suitability of using theoretical approximations is investigated. Thus, in section II a brief description of the test site features is shown. Next, section III depicts in depth concepts about wind shear and shows the different wind profiles measured. Finally, section IV summarizes all the ideas found in the work.

II. Test site features

A WindCube LIDAR equipment has been used in an experimental test covering a period of three months, from june to august, 2009. WindCube equipment has been set to measure wind speed at 9 heights once a second. Then, the 10 min. average value is chosen for all the calculations because the energy contained between the 10 min. and 5 hours period is quite small, [5]. Table I shows the measurement heights selected.

40m	64m	67m	87m	107m	117m	127m	137m	200m

TABLE I
Measurement heights

Since WindCube recorded nine wind speeds each 10 min., the amounts of data expected during the test period would be 13224 points at each height. Really, due to communications troubles, approximately 13 measurement days were lost. Hence, 11298 have been the final amounts of measurements performed by the WindCube.

Though, like the measurement method is based on the spread of light, the higher the measurement high, the more difficult is to perform a measurement for the WindCube. Thus,

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according to the measurement heights chosen in the present work, until the fourth measurement height no data were lost, whereas from the fifth to the ninth measurement height, 3, 6, 14, 21 and 878 amounts of data, respectively, were not measured by this reason.

The test was performed in a wind farm located in the south of Spain (due to confidentiality issues it is not allowed to clarify the location more exactly). In order to perform a consistent work, it becomes necessary to study the characteristics of the terrain. According to [6], when the differences in elevation exceeded 60 m within a radius of 11.5 km in the surroundings of a wind turbine, that terrain must be considered as complex terrain. Thus, in figure 1, the changes in elevation versus the distance covered in the surroundings of the wind farm are shown. It is concluded that the terrain over all the measurements were performed is a complex one. Moreover, it must be pointed out that the topography is a very uncommon one due to its complexity.

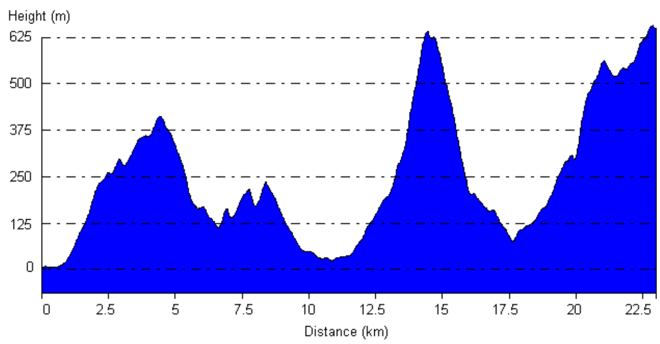

Fig. 1. Terrain in the surroundings of the wind farm.

III. Theoretical Wind Profile

The friction of the moving air masses against the earth's surface slows down the wind speed from an undisturbed value at great altitude (geostrophic wind) to zero directly at ground level, [7]. The flow of air above the ground is retarded by frictional resistance offered by the earth surface (Boundary Layer Effect), [8].

The instantaneous increase in wind speed with elevation depends on several meteorological factors, which determine the atmospheric stability. However, the mean value to be expected statistically over a long term at a particular height is largely determined by the roughness of the earth's surface. The surface roughness of a terrain is usually represented by the roughness class or roughness height, z_0, and its values vary between 0 and 5, [5], [7]–[9], according to the smoothness or roughness of the terrain, respectively.

A conventional approach to depict the increase in wind speed with height is the logarithmic height formula:

$$\bar{v}_H = \bar{v}_{ref} \cdot \frac{ln\frac{H}{z_0}}{ln\frac{H_{ref}}{z_0}} \tag{1}$$

where:

- $\bar{v}_H$ = mean wind speed at elevation H, (m/s)
- $\bar{v}_{ref}$ = mean wind speed at reference elevation H_{ref}, (m/s)
- H = height (m)
- H_{ref} = reference height (m)

Eq. (1) could be more complicated to use in some cases than the so-called *Power Law* aproximation, according to Hellman, which is sufficient for many engineering tasks:

$$\bar{v}_H = \bar{v}_{ref} \cdot \left(\frac{H}{H_{ref}}\right)^{\alpha} \tag{2}$$

where, $\bar{v}_H$, $\bar{v}_{ref}$, H and H_{ref} were defined in equation (1), and α is Hellman's exponent or shear exponent. Both equations have the same technical concept: at wind speeds below reference height, the obstacles in the terrain (equal to say "greater roughness height") will produce a decrease in wind speed. Whereas at wind speed over reference height, the larger the roughness height, the greater wind speed. In [10] it is formulated that equation (2) offers a nearly perfect fit to equation (1) under atmospheric stable conditions for certain surface roughness conditions and a good approximation under neutral and unstable conditions in the limit of very smooth surfaces.

A. Measured wind profile

The wind speed recorded during the test period at the measurement heights depicted in table I is shown in figure 2. Within the three measurement months, high wind speeds were recorded in mid of each month. In order to appreciate more exactly the hourly changes of wind speed with height, figure 3 shows the wind profile during the 5th of June 2009. In can clearly be seen that in the daytime, when the temperature near the ground is greater than at upper heights due to solar irradiation, the difference between the wind speed is small. Though, during nighttime, the temperature distribution changes sign because of the cooling of the ground, thus producing large changes in wind speed with height. This effect is called *Thermal Stratification*, [9].

Apart from showing the instantaneous wind profile during one day, figure 3, it becomes important to analyse the hourly mean wind profile. Thus figure 4 shows the mean wind profiles appearing at each hour a day. Two ideas must be pointed out from that graphic. On the one hand, higher wind speeds have been measured during sunny hours than during nighttime. And, on the other hand, very different shapes are found for the wind profiles. Roughly, from 10 pm to 10 am, the wind profiles could fit a power law approximation, whereas during the rest of the day, depicted by sunny time, a maximum wind speed is located between 110 m and 130 m above the ground and for greater heigths, a decrease in wind speed with height is observed. Furthermore, the different shapes of the wind profiles will affect the energy produced by each wind turbine, [3].

Another similar approach is the calculation of the diurnal variation of the shear exponent for different couples of heights.

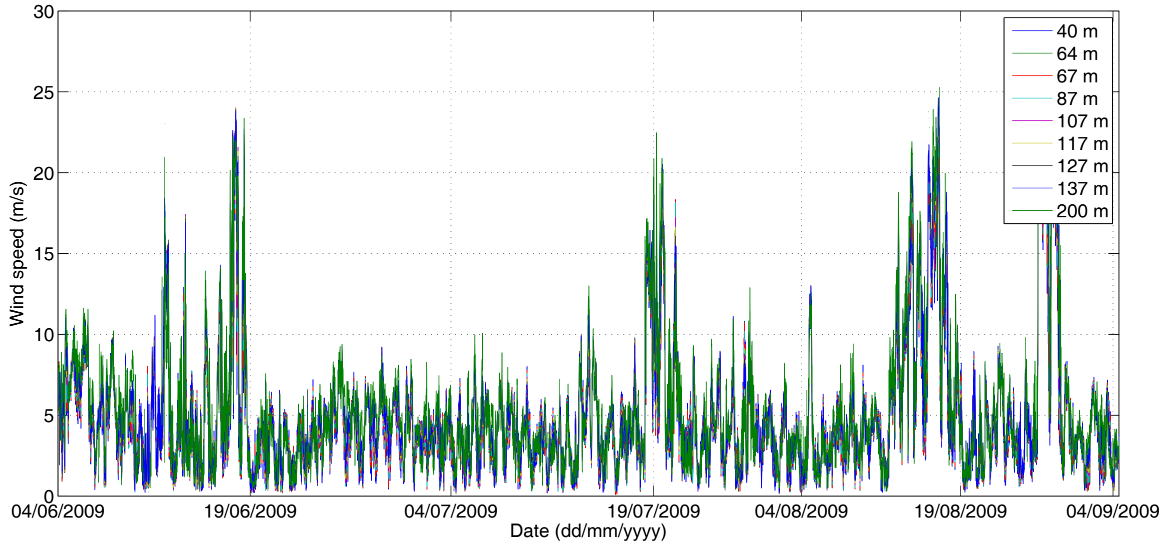

Fig. 2. Wind Speed at WindCube Measurement Heights

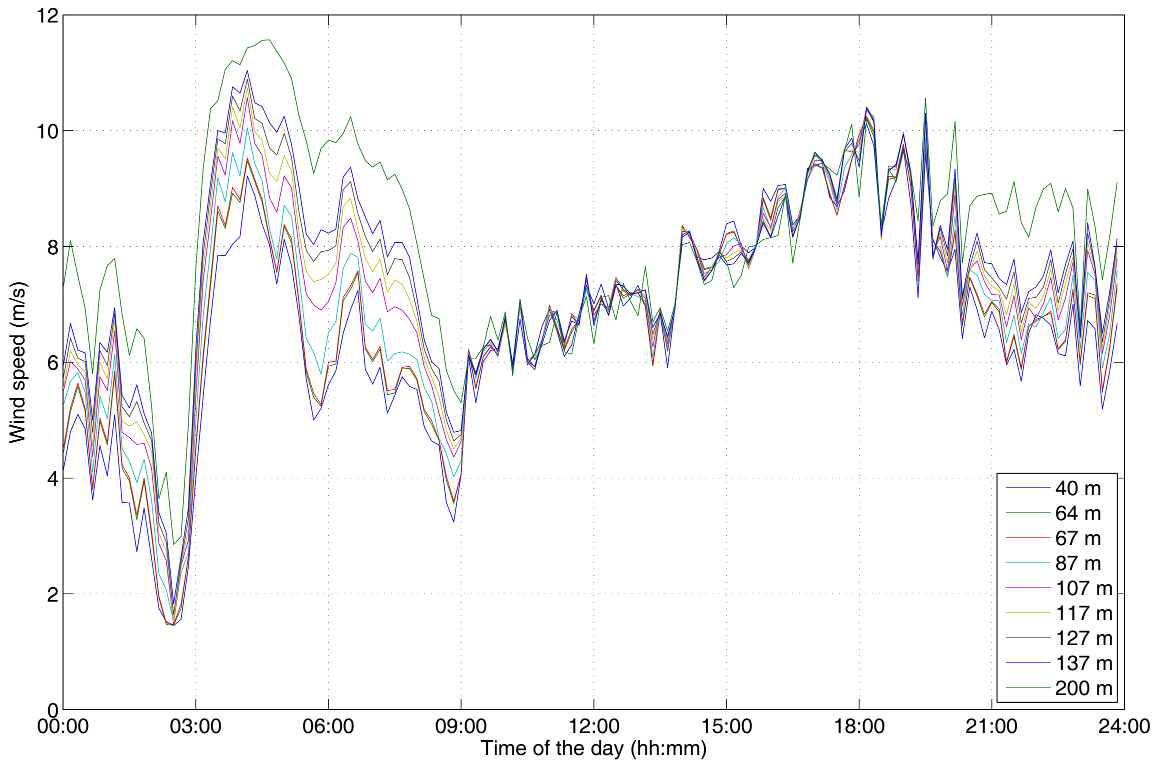

Fig. 3. Wind Profile During the 5th of June 2009

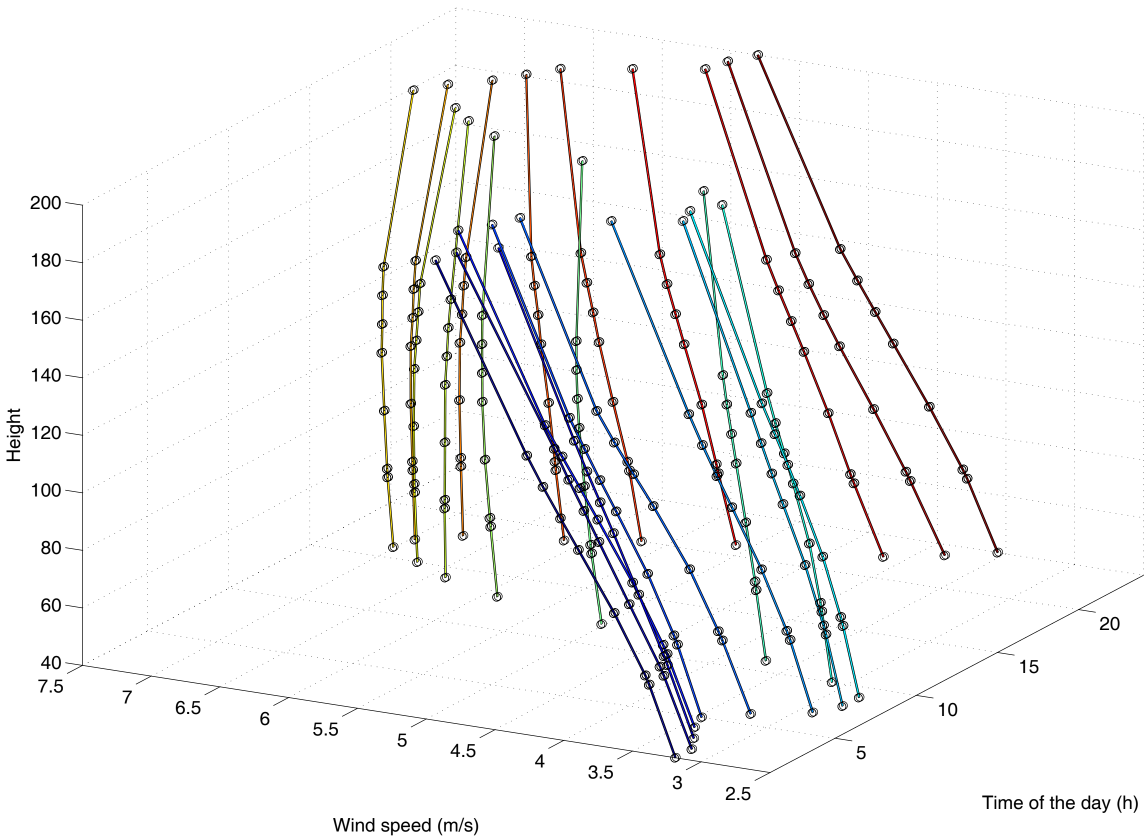

Fig. 4. Mean Daily Wind Profiles

The results are shown in figure 5, which are in line with the ones presented by [11] and [12] about the wind shear characteristics. It is interesting to notice that during the daytime, lower shear exponents are achieved than during nighttime. Anyway, the shear exponents obtained become quite large because the measurement campaign was performed during summer time.

IV. Conclusions

The wind shear over a complex terrain was investigated with the help of a remote sensing equipment. Wind speed was measured at 9 heights at the same time. The wind profiles were found to vary considerably each hour, and to deviate both from the logarithmic and the power law profile. On some occasions, wind profiles with a lower wind speed at higher heights were observed.

Besides, a simple power law can not accurately depict a complete wind profile. Furthermore, the shear exponent is found to vary continuously according to the hour of the day.

In wind energy terms, the large wind shears recorded by the Lidar instrument will present a potential hazard to the current large wind turbines. They will experience severe stresses during strongly stable conditions where the differences in wind speed with height are relevant. Therefore, the need to take into account the whole wind profile in front of the wind turbine, not only for wind energy resource assessments, but also for the evaluation of the loads supported by the blades, has been proven.

In conclusion, the evolution of remote sensing equipment, has made the wind shear measurements a manageable task. In the near future these instruments could be used to measure the wind shear in front of a wind turbine, and they will probably be used to filter the data for power curve characterization, above all in complex terrain where high shear exponents normally happen.

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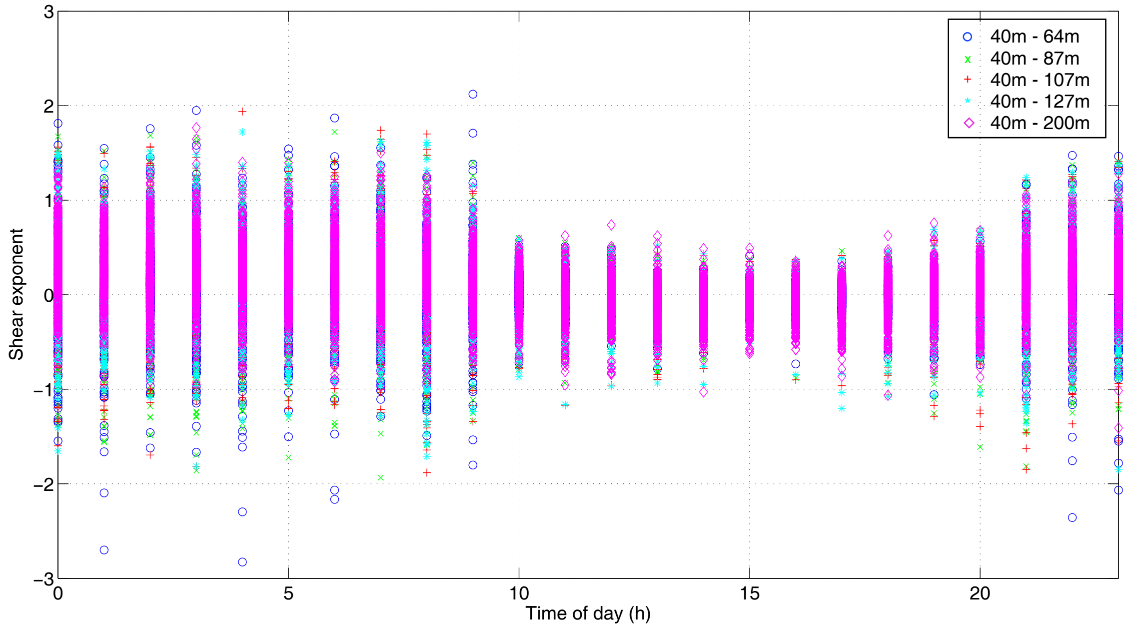

Fig. 5. Shear exponents according to time of day

14th International Symposium for the Advancement of Boundary Layer Remote Sensing, 2008.

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