Optimum Statistic Analysis about Test Results of Full Scale Wind Turbine and Wind Turbine Model in Wind Tunnel

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Abstract

The purpose of paper is to find the optimum sites for wind turbines by comparing the full scale results with the wind tunnel test results. A wind observation station was established at Colobraro in Italy. The data collected in this observation station every 10 minutes last five years, which is from 2003 to 2007. All of the data were statistically analyzed by MATLAB program. Compared the wind velocity and power of full-scale turbines with that of wind tunnel models, it is validated that the wind tunnel is a perfect reproduction of full scale; A comparison among these three turbines is to find the optimum sites where we can generate more power. Because wind tunnel test will be much more economical than full scale experiment，It is commercial way to set up a wind farm.

Key words: Wind data, Wind turbines, Statistical analysis, Full scale and wind tunnel;

1 Introduction

Limited reserves of fossil fuels and their negative impact on the environment lead institutions, organizations and governments pay more and more attention on the renewable energy.

Wind energy is an abundant, clean, affordable, environmentally preferable, elegant and inexhaustible energy source. Today, the use and the technology of the wind energy have been developing very fast. Generating electricity from the wind makes economic as well as environmental sense. Wind energy is already competitive with coal or nuclear power across most of Europe, especially when the cost of pollution is taken into account.

Three full scale turbines and one anemometric tower are erected on the mountain near the city of Colobraro in Italy, shown as Figure 1

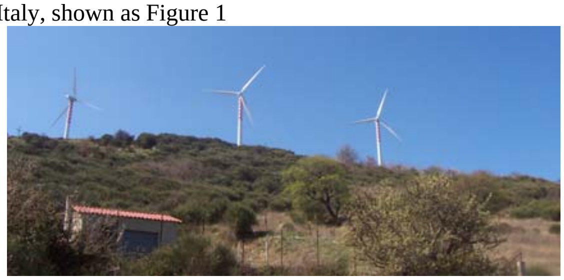


Figure 1: Site of wind turbines and anemometric tower installed.

The detail position of these three turbines and anemometric tower can be seen from Figure 2. The anemometric tower was installed between wind turbine 2 and wind turbine 3. The distance between these three turbines can be seen from table 1.

The three turbines position respect to anemometric tower can be shown as Figure 2.

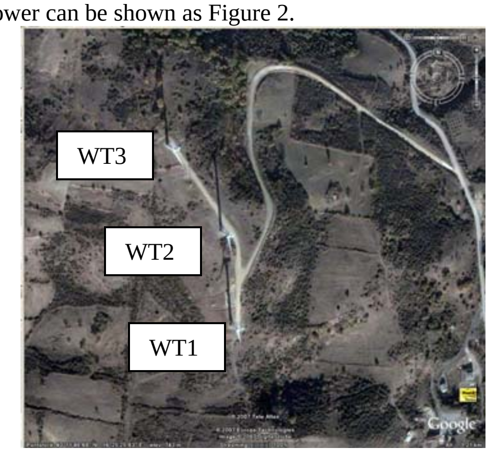


Figure 2: Satellite picture of wind turbines and anemometric tower installed.

Distance from WT1 to WT2	112.6 m
Distance from WT3 to WT2	109.6m

Table 1: Distance of three turbines

It is impossible to set a full scale experiment whenever we want to set up wind farm in different place. Because it is uneconomical. So the best solution is, based on the data we obtained from this full scale experiment, to make a wind tunnel model, and the model should reproduce the prototype as much as possible. Then when the parameters of the wind and the topography of new project are similar to this project, the data we have obtained from the wind tunnel test may be the basis for the new wind tunnel model. And then based on the test results, we can set up wind farm on new place. It is commercial way, because wind tunnel test will be much more economical than full scale experiment.

A Reynolds's model law describes a condition for model testing and for the interpretation of test results with regards to the prototype. The models aerodynamic generators have been made to scale 1 / 50.

Based on the full-scale test results and model laws, the model in wind tunnel was given, see Figure 3.

The wind tunnel test was held in Galleria del Vento del Politecnico di Milano (GVPM). GVPM was designed to provide the highest technological standards for a wide range of applications. GVPM are combined of two parts, see Figure 4. One is lower part, whose dimension is

4x4,while the other part is upper part, whose dimension is 14x4.The detail index of GVPM can be referred to table 2.

Figure 3: Reproduction of full-scale wind farm in the wind tunnel

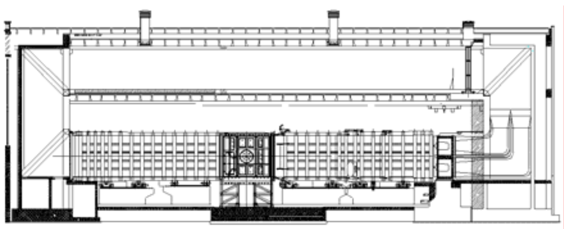


Figure 4: Cross-section of GVPM

Galleria Del Vento of Politecnico di Milano				
Total dimension of wind tunnel	50x15x15[m]			
Maximum power of wind tunnel	1.5[MW]			
Section of test	Dimension [m]	Max wind speed [m]	$\Delta U/U$ %	Intensity Turbulence %
Upper part	14x4	16	$<\pm 3$	<2.0
Lower part	4x4	55	$<\pm 0.2$	<0.15

Table 2: Dimension of GVPM

2 Measurement set-up and data measured

The transducers actually installed on the anemometric tower and behind the turbine are shown as Figure 5. The hub height is 50 m, and the height where transducer installed on the anemometric tower is 50 m.

Figure 5: Measurement instrument installed on anemometric tower and wind turbine

The data gathered from measurement instruments installed on anemometric tower are:

-the mean horizontal wind speed and direction

-the minimum horizontal wind speed and direction

-the maximum horizontal wind speed and direction

The following data are obtained from wind turbine anemometer:

-the mean horizontal wind speed and direction

-the power generated

-the motor rotating speed

-the pitch angle

Ut is the wind speed measured by the anemometer installed on wind turbine while U is the wind speed measured from anemometric tower.

3 Comparison of wind velocity

There are two laws to be used to calculate mean wind speed, logarithmic law and power law. Usually, the mean wind speed can be obtained based on power law， see eq.3.1. The power law has no theoretical basis but is easily integrated over height, a convenient property when wishing to determine bending moments at the base of a tall structure, for example.

To relate the mean wind speed at any height, z, with that at 10 m(adjusted if necessary for rougher terrains, as described in the previous section), the power law can be written:

$$\overline{U}(z) = \overline{U}_{10}\left(\frac{z}{10}\right)^{\alpha} \qquad (3.1)$$

The exponent α will change with the terrain roughness, and also with the height range, when matched to the logarithmic law. A relationship that can be used to relate the exponent to the roughness length, z_0 , is as follows:

$$\alpha = \left(\frac{1}{\log_e(z_{ref}/z_0)}\right) \qquad (3.2)$$

Where z_{ref} is a reference height at which the two 'laws' are matched. z_{ref} may be taken as the average height in the range over which matching is required, or half the maximum height over which the matching is required.

Where z_0 is called roughness length, which is the height above ground where the mean wind velocity is zero, know as the roughness length, see table 3, and it is a measure of the roughness of the ground surface.

Roughness length z_0 (m)	Terrain type
10^{-5}	Plane ice
10^{-4}	Open sea without waves
10^{-3}	Coastal areas, on-shore wind
0.01	Open land with little vegetation and few houses
0.05	Agricultural areas with few houses and wind breaks
0.3	Villages and agriculture areas with lots of wind breaks
1-10	Urban areas

Table 3: Roughness lengths z_0 for different terrain categories

According to what we have discussed, the wind speed is directly proportional to height. This means that we must find the speed at hub height of the turbine. This can be done using equation (3.1) for the three turbines. But you need measurements at a point, so the mean wind speed is measured at the height 25m (measured for wind shear) and 50m on the anemometric tower. And the hub height of the turbine is about 50 m.

Based on the data of full-scale measured from the anemometric tower, the polar diagram of wind velocity was plotted as given Figure 6. It may be noted that the wind directions are most likely contained within 210-270 degrees, 0 degree are defined as the direction of wind coming from north, and therefore the conclusion should be a major of wind blows from southwest.

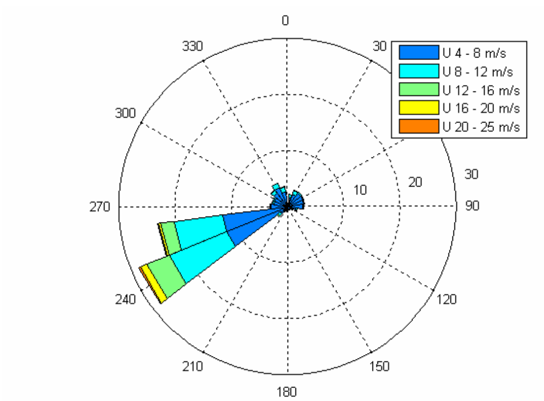


Figure 6: Polar diagram of average velocity distribution in period 2004-2005; Data based on full-scale results

The period to measure the data last for about five years, however, we prefer to use the data measured in 2004 year and 2005 year to analysis. That is because there are no data in 2003 year and 2006 year, even data obtained in 2007, but only several months, and also because the measuring instruments were changed, the several month data can't be add to 2004 year or 2005 year. So all the data can be used are that of 2004 year and 2005 year.

Based on the data we gathered during 2004 to 2005, the average value Ut/U was plotted as Figure 7.

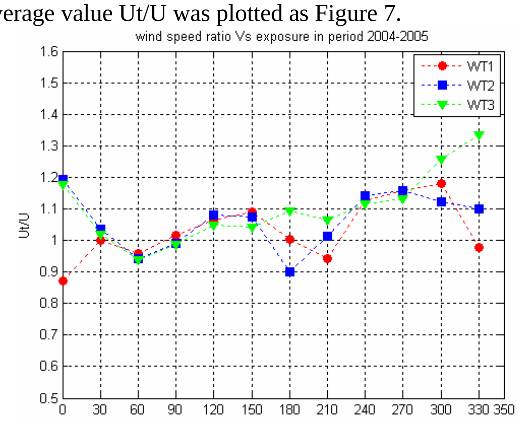


Figure 7: Variation of wind speed with respect to exposure; Based on full-scale results

It is seen that full-scale measurements of the wind speed is mostly satisfied:

(1) The shapes of WT2 and WT3 are similar

(2) And also the average values are higher than WT1

(3) The wake phenomena exist -when the wind directions are to 0 deg and 330 degree, WT1 is in the wake of WT2.

The wind velocity measured in the wind tunnel is shown in Figure 6. The difference between straight line and dot line is obtained by using different measurement instruments. The dot lines represent the wind speed was measured by a cobra probe, which is installed on the anemometric tower; while the solid lines are data by pitot tube, which are installed on turbines. The wind speed measured by cobra probe should be lower that measured by pitot tube. However, the result is opposite, which is because the cobra probe doesn't give a good measurement results.

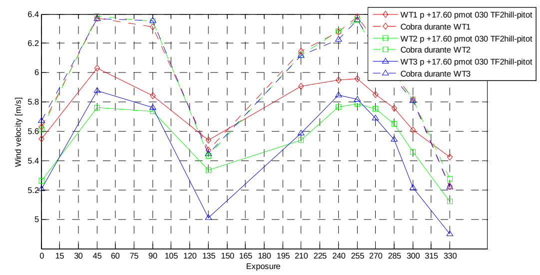


Figure 8: Variation of wind speed with respect to exposure; Data measured in wind tunnel

We are discussing the influence of mountain on the wind speed. When the inlet wind speed is a fixed, we moved the mountain from 0 degree to 330 degree, to find the relationship between wind speed and angle of mountain. It seems the different mountain positions have the different influence on the wind speed. When the angle of mountain is 240 degree or 45 degree, the wind speed has increased much more.

In order to compare with full scale test result, we give the wind speed ratio as Figure 9, which is based on the data from Figure 8.

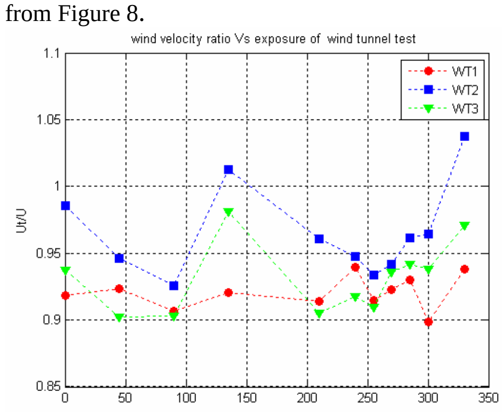


Figure 9: Variation of wind speed with respect to exposure; Based on wind tunnel test results

Anyway, the information we got from the wind tunnel test about wind speed is:
The behavior of WT2 and WT3 is similar; the wind speed of WT1 is lower than the other two; the wake phenomena exist, when the exposure is 0 degree.

The model should reproduce the prototype as much as possible. From above discussion, we know that the model test have reproduced some main features of prototype in some aspects. We got the same information from full-scale experiment and wind tunnel test.

Despite many full-scale measurements reports in literature, the number of dependable comparisons between mode and prototype results remains relatively small. It appears from Figure 7 and Figure 9 that the measurement peaks of the curves differs in wind tunnel from the wind speed on the prototype.

4 Comparison of power generated

The specific power available in a cross-sectional area perpendicular to the wind stream moving at speed U (m/s) is calculated and expressed as following:

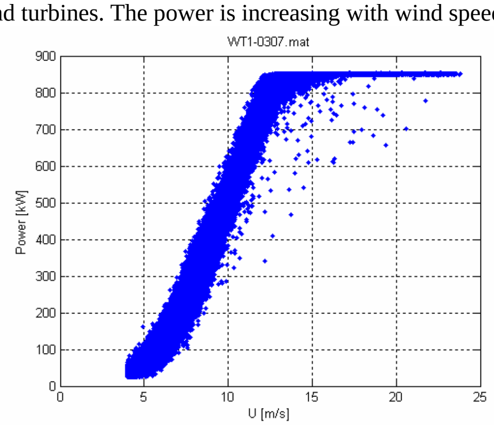
$$P = \frac{1}{2}\rho A U^3 \qquad (4.1)$$

Where $\rho = 1.225 kg/m^3$ is the standard the air density, it depends on the altitude (air pressure) and temperature.

Another important parameter Cp, describing the ratio between the power from wind turbine P_{wt} and the power available from the wind through the rotor area P , is a non-dimensional value, defined as:

$$Cp = P_{wt} / (\frac{1}{2}\rho A U^3) \qquad (4.2)$$

The power data was measured by instruments installed behind the wind turbine. The power is relate to some parameters, such as wind speed, motor rotating speed and pitch angle. Figure 10 is the statistic points, which shows the relationship between power and wind speed for three wind turbines. The power is increasing with wind speed.



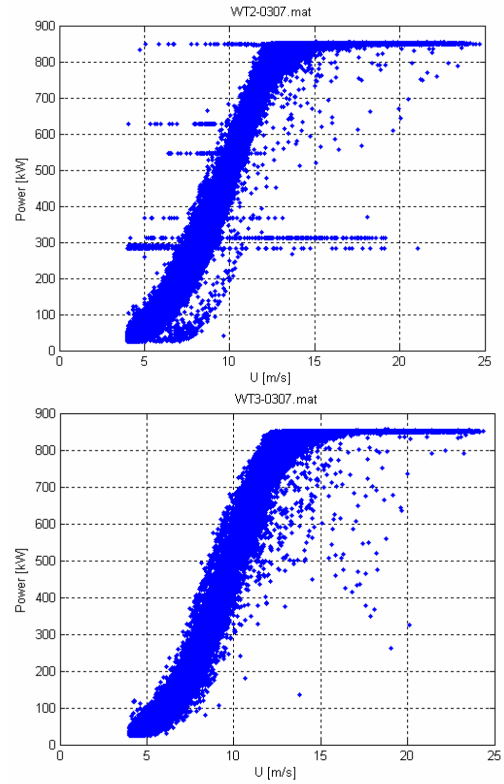


Figure 10: Power generated with respect to wind speed of full scale-WT1-WT2-WT3

Firstly, it is better to filter the wind speed to analyze the data distribution with respect to exposure. Because when the wind speed is lower than 5m/s, the output power of the generator is about 25kW. Because there are a few data can be obtained, it can not give the information about power with respect to exposure. Contrarily, when the wind speed is higher than 15 m/s, the data are concentrated on a certain part, and also it’s no sense to analyze them. Therefore, we chose a typical range and plot the data, shown as Figure 11.

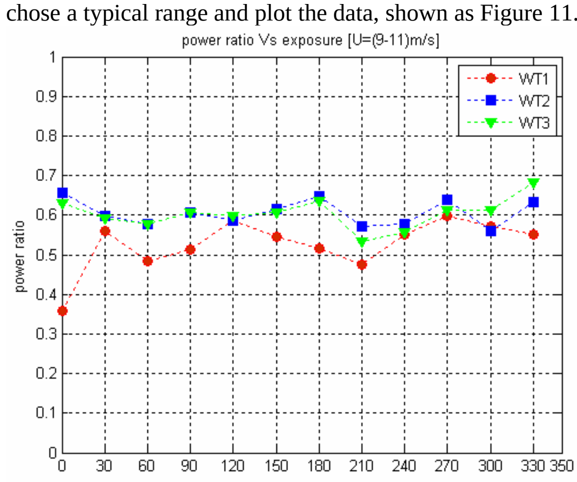


Figure 11: Average power generated with respect to exposure of full scale-WT1-2-3

The statistic points give a clear trend about power to exposure. In order to find the average curve, we try to average these points for each 30 degree, shown as Figure 11.The conclusion should be expressed as:

The tests in the presence of prototype have finally shown the phenomena of wake. The aerogenerator1, particularly, passing from exposure 0 degree or 330 degree is in the wake of aerogenerator 2.

The aerogeneratore1 produces less power than the other two wind aerogenerators

The same conclusion can be obtained from wind tunnel test results, see Figure 12.

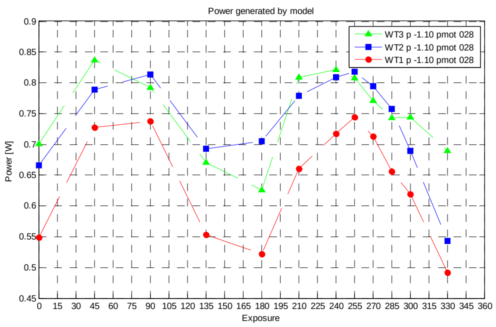


Figure 12: Average power generated with respect to exposure of wind tunnel-WT1-2-3

The power produce by the three generators vary with the exposure. Each of curves obtained from the same wind speed, measured by pitot tube. Because the wind direction can't be changed in wind tunnel, we rotate mountain to find influence of exposure. There are 12 points for each curve in Figure 12.

Theoretically, the energy coefficient Cp should be lower than 0.593. However, Figure 11 shows the power ratio is larger than it. The reason is when we calculate Cp, we use the wind speed measured from the anemometric tower, U, which is lower than the wind speed measured from wind turbine.

Comparison results of Cp calculated by different wind speed can be seen from table 4; we choose 11 instantaneous times to calculate Cp_U (Cp was calculated based on U) and Cp_Ut (Cp was calculated based on Ut).

.No.	Wind turbine	U [m/s]	Ut [m/s]	Power [kW]	Motor rotating speed [rpm]	Exposure [deg]	Pitch Angle [deg]	Cp_U	Cp_Ut	Cp_Ut-Cp_u
1	WT1	6.58	4.81	61.21	17.53	7.51	-0.93	0.17	0.42	0.26
	WT2	6.58	6.59	111.67	20.02	7.51	-1.17	0.30	0.30	0.00
	WT3	6.58	6.85	119.60	20.88	7.51	-2.06	0.32	0.29	-0.04
2	WT1	4.52	5.74	74.41	17.37	253.63	-1.70	0.62	0.30	-0.32
	WT2	4.52	5.86	70.92	17.75	253.63	-1.80	0.59	0.27	-0.32
	WT3	4.52	5.51	65.03	16.90	253.63	-1.40	0.54	0.30	-0.24
3	WT1	3.30	3.73	11.85	16.10	69.99	0.04	0.25	0.18	-0.08
	WT2	3.30	4.08	34.92	17.30	69.99	-0.38	0.75	0.40	-0.35
	WT3	3.30	3.75	31.29	17.62	69.99	0.00	0.67	0.46	-0.21
4	WT1	6.79	8.80	333.82	25.47	21.28	-2.08	0.82	0.38	-0.44
	WT2	6.79	8.69	361.47	24.86	21.28	-1.92	0.89	0.42	-0.46
	WT3	6.79	8.45	352.27	24.41	21.28	-1.92	0.87	0.45	-0.42
5	WT1	9.27	11.84	670.50	25.95	88.47	0.69	0.65	0.31	-0.34
	WT2	9.27	13.11	808.58	26.04	88.47	3.88	0.78	0.28	-0.50
	WT3	9.27	13.19	829.24	26.00	88.47	3.91	0.80	0.28	-0.52
6	WT1	7.33	9.12	333.72	25.30	242.23	-2.07	0.65	0.34	-0.31
	WT2	7.33	9.22	351.55	25.72	242.23	-1.90	0.69	0.34	-0.34
	WT3	7.33	8.82	339.84	25.87	242.23	-2.20	0.66	0.38	-0.28
7	WT1	8.41	10.73	554.22	26.40	251.18	-1.77	0.72	0.35	-0.37
	WT2	8.41	10.77	544.13	26.30	251.18	-1.81	0.70	0.34	-0.37
	WT3	8.41	9.30	460.23	26.06	251.18	-2.02	0.60	0.44	-0.16
8	WT1	5.36	4.73	-0.20	0.00	318.33	86.20	0.00	0.00	0.00
	WT2	5.36	6.51	173.63	20.58	318.33	-1.53	0.87	0.48	-0.38
	WT3	5.36	7.94	258.41	22.95	318.33	-1.73	1.29	0.40	-0.89
9	WT1	6.22	7.14	193.65	21.20	306.16	-1.44	0.62	0.41	-0.21
	WT2	6.22	5.90	128.58	18.45	306.16	-1.30	0.41	0.48	0.07
	WT3	6.22	8.92	407.19	25.07	306.16	-1.90	1.30	0.44	-0.86
10	WT1	13.83	15.17	847.70	26.10	238.40	8.94	0.25	0.19	-0.06
	WT2	13.83	15.26	850.77	26.00	238.40	8.79	0.25	0.18	-0.06
	WT3	13.83	14.70	850.72	26.10	238.40	8.27	0.25	0.21	-0.04
11	WT1	8.30	10.00	427.00	26.10	246.94	-2.20	0.57	0.33	-0.25
	WT2	8.30	10.84	599.67	25.70	246.94	-1.70	0.81	0.36	-0.44
	WT3	8.30	10.63	579.50	26.40	246.94	-1.70	0.78	0.37	-0.41

Table 4: Comparison of Cp_U and Cp-Ut

The last column of Table 4 show the results when we use Cp_U subtract from Cp_Ut, most of which are negative. Because Ut is larger than U, Cp_Ut is lower than Cp_U and also lower than 0.593. So maybe this is the reason why power ratio Cp_U higher than theoretical value.

Conclusion

By comparison between full scale results and wind tunnel test results, as we have expected, the model have reproduce the prototype in some aspects: for example, the characteristic of WT2 and WT3 is similar. And also the wake phenomenon was reproduced clearly in wind tunnel test.

Comparison between three turbines showWT2 and WT3 generate more power than WT1; so the sites of WT2 and WT3 are better choice.

However, due to the limitation of similarity, the model didn't give a completely reproduction of prototype.

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