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Derivation and Application of an Empirical Equation to Estimate Hub-height Wind Speed from Sea Surface Wind Speed

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Summary: In this paper, a simple empirical equation to estimate hub-height (60 m) wind speed from sea surface (10 m) wind speed is derived, using data from a meteorological mast at the Danish offshore wind farm Horns Rev. The accuracy is verified in comparison with the Monin-Obukhov similarity theory and numerical simulation using a mesoscale model. Finally, this paper shows a map of annual mean 60m-height wind speed around Japan, made by applying the obtained empirical equation to the Japan Meteorological Agency Meso-Analysis data.

I. Introduction

These days, various kinds of sea surface wind data are getting available from satellite observation and objective analysis, as well as in-situ measurements. Thus, it would be convenient if the sea surface wind data can be easily converted into hub-height wind speed using a simple equation, without complicated software and iterative calculation. Over land, the power or logarithmic laws are representative as such a simple equation. But, usefulness of these laws is somewhat doubtful for the case over the sea, because mechanical turbulence is weaker there due to smaller roughness and consequently the surface layer becomes thinner compared to over land. This means that, in case of a large offshore wind turbine, the hub height might be much higher than the top of the surface layer.

In this study, not a theoretical but an empirical approach is attempted in the derivation of the equation to estimate hub-height wind speed from surface wind speed. A simple empirical equation will be finally derived, using data from a meteorological mast at the Danish offshore wind farm Horns Rev. The height of the met mast used is 62 m, and consequently a target hub height of the empirical equation is defined as 60 m in this study. Moreover, the vertical wind profile over the sea is known to be greatly affected by atmospheric stability [1]. Taking its effects into consideration, the empirical equation is designed to be a function of the bulk Richardson number, which can be calculated using only three surface parameters; wind speed, air temperature and sea surface temperature. The concept of the empirical equation is shown in Fig.1.

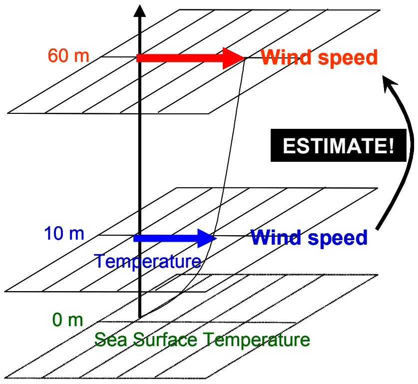

Fig.1 Concept of this study

2. Measurements at Horns Rev

The derivation of the empirical equation is based on data from Horns Rev, spreading in the North Sea about 14 km west from the Jutland coast. The data used in this study is from a meteorological mast called Mast 2, located in the northwest part of the wind farm. It is noted that the 10-minutely dataset of October 2001 through April 2002 used here include no effects of the wake by wind turbines because the measurement was before the construction of wind turbines.

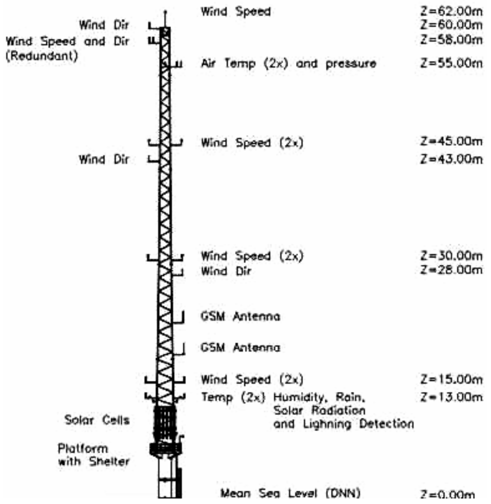

Fig.2 Mast 2 at Horns Rev (http://www.winddata.com)

On Mast 2 with a 62 m height, shown in Fig.2, wind speed is measured with cap anemometers installed at heights of 15 m, 30 m, 45 m and 62 m, and wind direction with wind vanes at 28 m, 43 m and 60 m. Air temperature is measured at 13 m and 50 m, and water temperature at a depth of 4 m under mean sea level. Using these wind speeds measured at four heights, 10m- and 60m-height wind speeds are firstly calculated, since they are regarded as typical surface and hub-height wind speeds, respectively. The 10m-height wind speed is obtained by extrapolating measurements at 15 m and 30 m, assuming wind speed is in proportion to log z, while the 60m-height wind speed by interpolation of measurements at 45 m and 62 m.

The empirical equation is designed to be a function of the bulk Richardson number R_{iB}, which is calculated from surface wind speed, air temperature and sea surface temperature with the following equation.

$$R_{iB} = \frac{g}{\overline{T}} \frac{(dT/dz + g/C_p)}{(dU/dz)^2} \approx \frac{g}{(T_{10} + T_{sea})/2} \frac{\left[(T_{10} - T_{sea})/10 + g/C_p\right]}{(U_{10}/10)^2} \tag{1}$$

where, g is gravitational acceleration, C_p is specific heat for constant pressure, U_{10} is the 10m-height wind speed, T_{10} is calculated using T_{13} and the dry adiabatic lapse rate, and T_{sea} is assumed to be the same as water temperature measured at depth of 4 m.

3. Derivation of the empirical equation

First, relation between the ratio of 60m-height wind speed to 10m-height wind speed and the bulk Richardson number R_{iB} is examined. Fig. 3 shows scatter plots of the ratio U_{60}/U_{10} versus R_{iB} for 2135 data with 60m-height wind direction in the sea sector between 135 to 360 deg. It seems that the ratio can be mostly expressed as a function of R_{iB}, although a large variance is seen especially in strong stable conditions. Thus, we here attempt to derive a simple empirical equation for the ratio, which is assumed to take the following form;

$$\frac{U_{60}}{U_{10}} = \begin{cases} (\alpha - \gamma)\left[1 - \dfrac{\beta}{(\alpha - \gamma)} R_{iB}\right]^{-1} + \gamma & (R_{iB} < 0) \\ \alpha + \beta \cdot R_{iB} & (0 \le R_{iB} \le R_{iC}) \\ \alpha + \beta \cdot R_{iC} & (R_{iC} < R_{iB}) \end{cases} \cdot \tag{2}$$

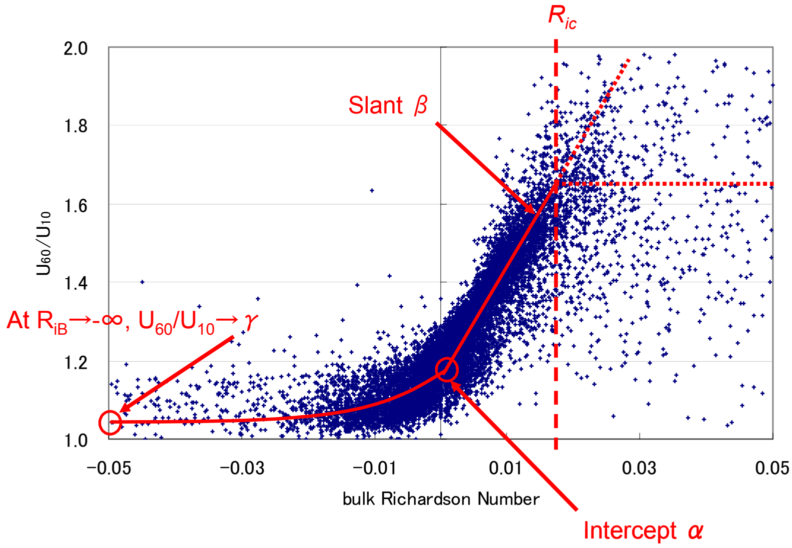

Fig.3 Scatter plots of U_{60}/U_{10} versus R_{iB} and outline of Eq. (2).

This form of the equation (Fig.3) is determined with the following four hypotheses.

① In an unstable condition ($R_{iB}<0$), the ratio decreases in inverse proportion to R_{iB} from α at $R_{iB}\to0$ to γ at $R_{iB}\to-\infty$.

② At $R_{iB}=0$, intercept α and slant β are continuous.

③ In a stable condition ($0\le R_{iB}\le R_{iC}$), the ratio is in proportional to R_{iB} with a slant of β.

④ In a strong stable condition ($R_{iC}\le R_{iB}$), the ratio is set to constant because the ratio seems to be no longer a function of R_{iB}.

With the least-square method, the coefficients in the above equation are determined as

$$\alpha = 1.17, \beta = 25.5, \gamma = 1.08, R_{iC} = 0.017\,. \qquad (3)$$

Regarding the anemometer at 62 m of Mast 2, it has been known that the measured wind speed deviates from a logarithmic shape expected from measurements at 15 m, 30 m and 45 m, with higher values (e.g., [2]). Recently, in comparison with LiDAR measurements, it is shown that the anemometer- measured wind speed ($U_{62,A}$) is somewhat higher than the LiDAR-measured one ($U_{62,L}$), and roughly there is the following relation between them [3];

$$U_{62,L} = 0.96 \cdot U_{62,A} + 0.15\,. \qquad (4)$$

Actually, this relation is just a preliminary result in their comparison between SODAR and LiDAR measurements, but it is worthwhile to test it for obtaining an alternative set of coefficients of Eq. (2). In case using $U_{62,L}$ in place of $U_{62,A}$, the coefficients are changed to

$$\alpha = 1.14, \beta = 24.9, \gamma = 1.07, R_{iC} = 0.018\,. \qquad (5)$$

At the moment, since it is difficult to say which set of coefficients is better, Eqs. (3) or (5), both will be examined in the following sections.

4. Estimation with Monin-Obukhov similarity theory

In order to examine a vertical wind profile, the Monin-Obukhov (M-O) similarity theory is usually used in most cases. Thus, we use not only the empirical equation obtained in the previous section but also the M-O similarity theory to estimate 60m-height wind speed, and compare their accuracy. According to the M-O similarity theory, the vertical wind speed profile in the surface layer is written as

$$u(z) = \frac{u_*}{\kappa}\left(\ln\frac{z}{z_0} - \psi_m\left(\frac{z}{L}\right)\right), \tag{6}$$

where z_0 is the aerodynamic roughness length, L the Obukhov length scale and ψ_m the integrated universal stability function. Over the sea, z_0 is related to the friction velocity u_* through the Charnock relation;

$$z_0 = z_{ch}\frac{u_*^{\,2}}{g} \quad (z_{ch} = 0.0185)\,. \tag{7}$$

As for ψ_m, the conventional formulation

$$\psi_m\left(\frac{z}{L}\right) = \begin{cases} \ln\left[\left(\frac{1+x^2}{2}\right)\left(\frac{1+x}{2}\right)^2\right] - 2\tan^{-1}x + \frac{\pi}{2} \quad with \;\; x = \left(1-16\cdot\frac{z}{L}\right)^{1/4} & for \;\; \frac{z}{L} < 0 \\ -5\cdot\frac{z}{L} \qquad for \;\; \frac{z}{L} \geq 0 & \end{cases}, \tag{8}$$

is used. The non-dimensional stability parameter z/L is calculated as a function of the bulk Richardson number R_{iB}, using the following formulation [4];

$$\frac{z}{L} = \begin{cases} 10\cdot R_{iB}\left(1+\frac{R_{iB}}{-4.5}\right)^{-1} & (R_{iB} < 0) \\ \frac{10\cdot R_{iB}}{1-5\cdot R_{iB}} & (R_{iB} \geq 0) \end{cases}. \tag{9}$$

R_{iB} is calculated in the same way as the case with the empirical equation. If L is given by Eq. (9), two unknown parameters u_* and z_0 can be solved simultaneously from Eqs. (6) and (7), Finally, substituting the obtained L and z_0 for the equation,

$$\frac{U_{60}}{U_{10}} = \frac{\ln\left(\frac{60}{z_0} - \psi_m\left(\frac{60}{L}\right)\right)}{\ln\left(\frac{10}{z_0} - \psi_m\left(\frac{10}{L}\right)\right)}, \tag{10}$$

the ratio U_{60}/U_{10} can be calculated. This Eq. (10) based on the M-O similarity theory will be compared with the empirical equation (Eq. (2)) in the following sections.

5. Verification of the empirical equation

Accuracy of the derived empirical equation is verified in comparison with the M-O similarity theory, firstly using in-situ surface measurements at Horns Rev. In the same way as in deriving the empirical equation, U_{10}, T_{13} and T_{sea} are used again as inputs for the equation. Fig. 4 shows the ratios of U_{60}/U_{10} calculated with the empirical equation (Eq. (2)) and the M-O similarity theory (Eq. (10)). As for Eq. (2), two cases using the coefficients Eqs. (3) and (5) are depicted separately. It is also noted that Fig.4 shows only the cases with wind from the sea sector.

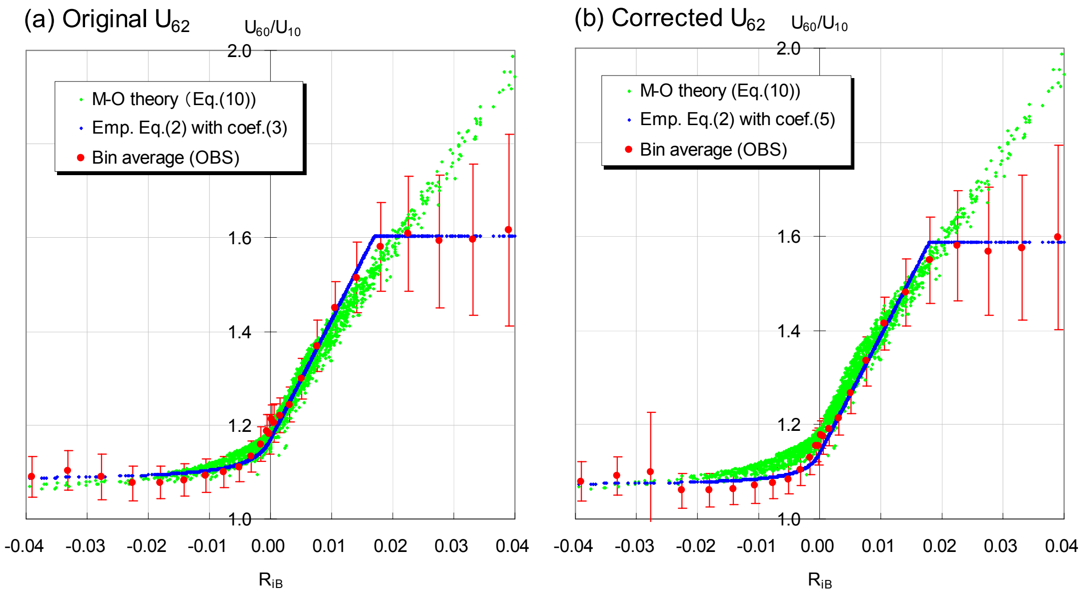

Fig.4 Ratios U_{60}/U_{10} calculated using the empirical equation (Eq. (2)) and the Monin-Obukhov similarity theory (Eq. (10)) for each case with (a) original and (b) corrected 62m-height wind speeds.

A remarkable difference between the two methods is the slant in the stable region. The slant of the empirical equation as well as the bin average of measurements is obviously steeper than the M-O similarity theory. Consequently, the M-O similarity theory yields higher values near neutral to weak unstable regions and lower values in a moderate stable region at R_{iB}=0.01~0.02. In the strong stable region beyond R_{iC}, the M-O similarity theory overestimates the ratio, while the empirical equation is designed so that it matches to the bin average. In case with corrected U_{62} (Fig.4(b)), the line of the empirical equation and bin averages shift downward, leaving the plots from the M-O similarity theory unchanged. In this case, the M-O similarity theory is found to overestimate the ratio in a wide range from weak unstable to weak stable via neutral conditions.

Statistics on the accuracy of the two methods are shown in Table.1. For both cases with original and corrected U_{62}, the accuracy of the empirical equation is mostly higher than that of the M-O similarity theory, although this is reasonable since the empirical equation is derived based on the same data as this verification. In case with original U_{62}, the bias, RMSE and correlation coefficient are -0.05 m/s, 0.58 m/s and 0.992, respectively. The accuracy of the empirical equation becomes better with the correction of U_{62}, and in the case the bias and RMSE decrease down to 0.00 m/s and 0.55 m/s, respectively. This better result with the correction for the empirical equation is in contrast to the result for the M-O similarity theory, which becomes worse with the correction, exhibiting a larger bias as already expected in Fig.4.

Table 1 Accuracy of the 60m-height winds based on the empirical equation (Eq. (2)) and M-O similarity theory (Eq.(10))

	For original 62m-winds		For corrected 62m-winds	
	Eq.(2) with (3)	M-O Theory	Eq.(2) with (5)	M-O Theory
Bias (m/s)	-0.05	0.01	0.00	0.32
RMS error (m/s)	0.58	0.65	0.55	0.71
Correlation	0.992	0.989	0.992	0.989

As a next step, in order to verify the empirical equation without surface measurements at Horns Rev, surface data of NCEP FNL Analysis, thoroughly independent of Horns Rev, is used to estimate the 60m-height wind speed at Horns Rev. The NCEP FNL is the global objective analysis data with a spatial resolution of 1 x 1 degrees and a temporal resolution of 6 hours. In this study, one month data of January 2002 is used, and three surface parameters (wind speed, air temperature and sea surface temperature) are inputted into Eqs. (2) and (10). The NCEP FNL data is also used as input for the mesoscale model MM5 to simulate the 62m-height wind speed at Horns Rev. An in-depth description of the numerical simulation with MM5, the reader can refer to our previous paper [5].

Table 2 shows the accuracy of the 60m-height (62m-height only for MM5) wind speeds estimated with three methods; the empirical equation (Eq.(2)), the M-O similarity theory (Eq.(10)), and the numerical simulation with MM5. In case with original U_{62}, the bias, RMSE and correlation coefficient for the empirical equation are -0.44 m/s, 1.29 m/s and 0.960 respectively. When U_{62} is corrected, the accuracy slightly increases, with a bias of -0.39 m/s, RMSE of 1.22 m/s and correlation coefficient of 0.961. It seems that the bias tends to be negative regardless of method or correction. This is most likely due to the inputted NCEP data rather than the estimation methods themselves. The sea surface temperature of NCEP FNL is always 1 to 2 degrees higher than measured water temperature at Horns Rev, and consequently the surface layer tends to be more unstable, leading to the underestimation of U_{62} with any methods.

The most important here is the fact that the accuracy of the empirical equation is comparable to or better than those of the M-O similarity theory and MM5, in spite of its quite simple form. Up to now, the verification has not been done for other sites except Horns Rev, but it is thought that the empirical equation is valid, to some extent, anywhere if it is an open ocean.

Table 2 Comparison of accuracy among the empirical equation, M-O similarity theory and mesoscale model MM5 for NCEP FNL data as input.

	For original 62m-winds			For corrected 62m-winds		
	Emperical	M-O Theory	MM5	Emperical	M-O Theory	MM5
Bias (m/s)	-0.44	-0.50	-0.25	-0.39	-0.20	0.06
RMS error (m/s)	1.29	1.31	1.43	1.22	1.20	1.33
Correlation	0.960	0.962	0.950	0.961	0.962	0.950

6. Application to making of offshore wind resource map

In this section, the derived empirical equation is applied to making of an offshore wind resource map. In Japan, since 2001, the Japan Meteorological Agency (JMA) provides Meso-Analaysis (MANAL) data with 6-hourly temporal and 10km x 10km spatial resolutions. This data is useful for understanding the general distribution of offshore wind resource around Japan. Then, we attempt to make a map of annual mean 60m-height wind speed by using the empirical equation (Eq.(2) with Eq.(3)) to estimate 60m-height wind speed from the surface wind speed of JMA MANAL. As input for the empirical equation, the surface wind speed and temperature in MANAL is used, but sea surface temperature is not contained in MANAL. Thus, the sea surface temperature data is obtained from the Japan Coastal Ocean Predictability Experiment (J-COPE) .

Thus, a map of annual mean 60m-height wind speed is made as an average for 2003 to 2005. But, it is known that annual mean wind speed usually varies year to year, typically with a

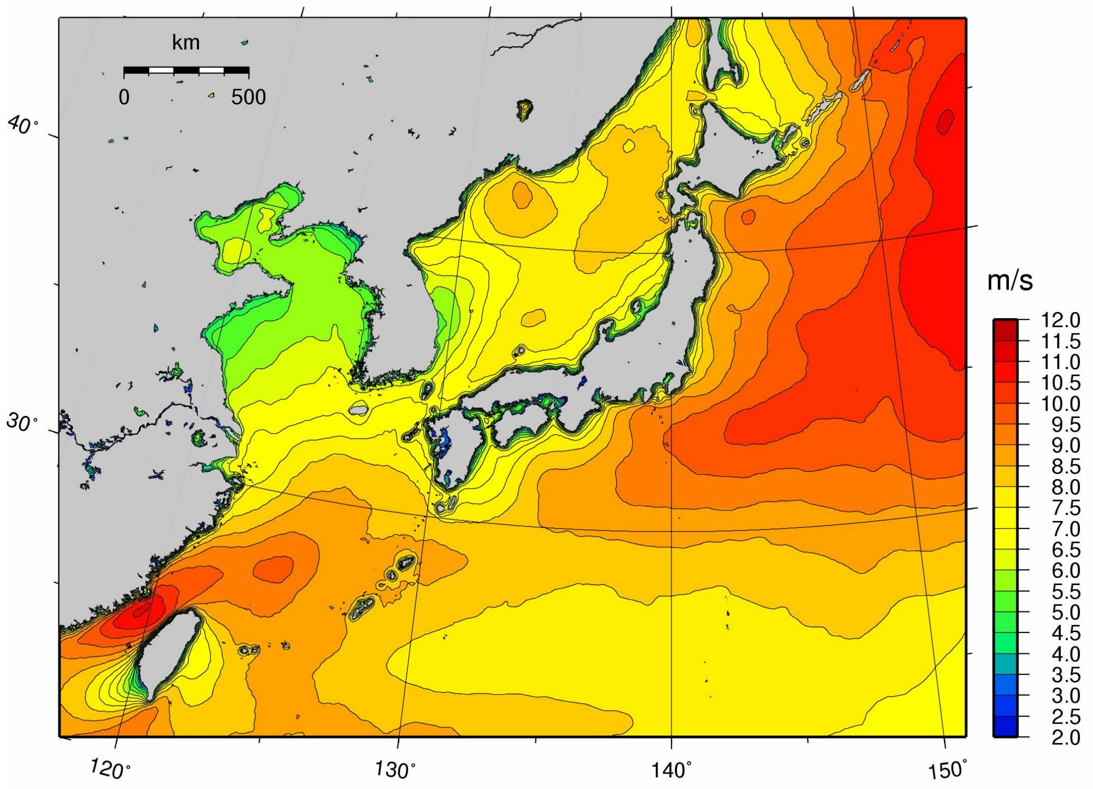

Fig.5 Map of annual mean 60m-height wind speed around Japan, based on JMA MANAL.

standard deviation of about 10 % of mean wind speed. Therefore, the obtained 3-year averaged annual mean wind speed is corrected using NCEP Re-analysis for 30 years of 1976 through 2005. The completed map of the annual mean 60m-height wind speed around Japan is shown in Fig.5. Actually, in the processing of making this map, a huge amount of data is dealt with. Like this, when a lot of calculations are needed to estimate hub-height wind speed from surface wind speed, the empirical equation exhibits its ability with simplicity and adequate accuracy.

7. Conclusions

This study is concluded as follows.

1) Based on data from a met mast (62m) at Horns Rev, we derived a simple empirical equation which can be used to easily estimate 60m-height wind speed from 10m-height wind speed through the bulk Richardson number.
2) The obtained empirical equation is Eq.(2) with coefficients Eq.(3). In case that measured U_{62} is corrected with Eq.(4), the coefficients are changed to ones in Eq.(5).
3) As a result from verification with in-situ measurements or NCEP FNL analysis data, it is found that the accuracy of the 60m-height wind speed estimated from the empirical equation is comparable to or better than those from the Monin-Obukhov similarity theory and numerical simulation with the mesoscale model MM5, in spite of its simple form.
4) With an adequate accuracy verified above, a map of annual mean 60m-height wind speed around Japan (Fig. 5) is made by applying the empirical equation to the 10km x 10km meshed JMA Meso-Analaysis data.

Acknowledgment

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