A Practical Method for Determining Wind Frequency Distributions for the Lowest 200 m from Routine Meteorological Data

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ABSTRACT

A method is described for determining wind speed frequency distributions at any height up to ~200 m above ground for a meteorological station where wind speed and direction is measured at a low reference level (usually 10 m) and which reports routine meteorological data at least once every 3 h. The roughness characteristics of the terrain surrounding the station must be known in detail, because the model calculates the rate of growth of internal boundary layers resulting from discontinuities in roughness as well as the shape of the wind profile in the various layers. The rate of growth of the internal boundary layers has been determined from work by Pasquill (1972). The shape characteristics of the profile are determined as a function of roughness length and of stability by the aid of measurements from three Swedish 100 m masts. The method is successfully tested against an independent set of data from a 100 m mast. Also given are some results from application of the method to Swedish data. The method has been developed for comparatively flat rural terrain and is not valid for urban conditions and mountainous areas.

1. Introduction

The energy crisis has awakened interest in wind energy in Sweden as well as in many other countries. A question of prime importance when the potentials of wind energy are being investigated is the amount of energy actually available in the natural wind field at the height interval of interest for the energy-producing devices. For wind energy systems in the range 50 kW to 5 MW this height interval is roughly 50-150 m above the ground. Direct measurements available from towers extending to this height are not very numerous. For a geographical area like Sweden, with its variations in landscape characteristics, the information available from a few towers is in no way adequate for a realistic appreciation of the national wind energy potential. A nationwide program of representative tower measurements is not realistic—the costs and times required to get reasonably representative data sets are prohibitive. Instead, routinely available meteorological data must be used in combination with some kind of physical model of the atmospheric boundary layer.

The wind speed at some height above the ground depends on a number of physical factors. One of these is the roughness of the underlying ground. But the concept of “the underlying ground” means a lot more than the very spot where the anemometer mast stands. In actual fact the roughness characteristics of a certain upwind path length is the relevant parameter. The length of this characteristic path increases rapidly with increasing height of the measuring point. As will be shown later the characteristic length of the relevant upwind path for a measuring height of, say, 150 m is several kilometers. In practical applications we often encounter the problem that an anemometer installed for, say, aviation purposes at the top of a 10 m mast give values representative of a fairly localized area (an air field in this case), so that the characteristic roughness for the 10 m and the 100 m levels may differ widely (the air field may be surrounded by a forest).

This paper describes a simple model which in a crude way takes into account the effects of change of terrain characteristics and of stability on the wind profile in the lowest 100 or 200 m of the atmosphere. The model is not primarily intended for giving exact individual profiles but rather for producing statistics of wind speeds at levels in the height range below, say, 200 m. This kind of statistic is needed in many applications other than wind energy, e.g., air pollution studies (emission from high chimneys in particular) or building aerodynamics. It must be noted, however, that this study is concerned with rural conditions only. Comprehensive work on urban wind profiles is under way, and preliminary results indicate striking differences between the urban and rural cases.

2. Physical basis of the model

The wind profile in the atmospheric boundary layer at a given site at a given time depends on a number of physical factors, such as speed of the wind above the friction layer, mechanical and other properties of the underlying ground (at the local site as well as upwind), heat flux at the earth interface, presence of clouds in
the boundary layer, and the state of the boundary layer during the previous 6 h or so. This very complex situation can be treated numerically by solving the simultaneous time-dependent equations for the conservation of momentum, mass, entropy and moisture with appropriate boundary conditions. This is a very active area of research today (reference is given to the last few volumes of *Boundary Layer Meteorology*), but an area with many fundamental problems still awaiting satisfactory solutions.

In this study we shall restrict ourselves to the lowest 200 m or so. This is generally far too deep a layer to be considered a constant flux layer, but it is shallow enough to have a characteristic time scale of the order of minutes in most cases. Thus it is reasonable to assume that the wind profiles below 200 m are in approximate equilibrium. Knowing the wind speed at some reference level (usually 10 m) leaves the profile to be determined largely by two external factors: the surface heat flux and the surface roughness over a certain upwind distance. In many cases the terrain characteristics change discontinuously, e.g., at boundaries between grass field, forest, sea, etc. At every such discontinuity an internal boundary layer starts to build up. It grows vertically at a rate which is determined by the degree of turbulence. In this way a 200 m deep vertical profile may consist of two or more layers with distinct physical characteristics.

When air flows over an area of *uniform* terrain characteristics a wind profile develops that is uniquely determined by the local roughness length \( z_0 \) and the fluxes of heat \( H \) and momentum \( \tau \) at the earth interface. When it encounters an area with different characteristics a new boundary layer develops with a profile that is determined by the new values of \( z_0, H \) and \( \tau \). This phenomenon has been studied both theoretically and experimentally. The studies of Rao et al. (1974) and of Peterson (1972) are likely to be the most accurate theoretical studies, as they are based on higher order closure schemes for the solution of the simultaneous partial differential equations. Accurate experimental data that can be used to check the theoretical predictions have been supplied by Bradley (1968) and by Peterson et al. (1976). The general situation is schematically depicted in Fig. 1. The air that flows from Surface 1 to Surface 2 is gradually being modified from below. This influence extends to the top of the internal boundary layer \( \delta(x) \). Local equilibrium with Surface 2 is attained in a relatively shallow layer, the "new equilibrium layer," the depth of which is given as \( h(x) \) in Fig. 1. The layer between \( h(x) \) and \( \delta(x) \) is a transition zone. Figs. 2 and 3 show some computed and measured wind profiles for the smooth-to-rough and rough-to-smooth cases, respectively, taken from Rao et al. (1974). Also given in the two figures are linear extrapolations of two of the new equilibrium profiles (dotted lines). From the figures it can be seen that the deviations between the "actual wind" (computed or measured), on the one hand, and the extrapolated new equilibrium profile is never greater than \( \sim 5\% \) within the internal boundary layer. Figs. 8 and 9 of Peterson et al. (1976)
lead to the same general conclusion. For the purpose of our present model (which will be described in detail in Section 3) this is an acceptable accuracy, so we will make the important simplification that the equilibrium profile of the new layer extends to the upper edge of the internal boundary layer where it connects with the profile of the “old layer.” This means that the wind profile at a certain site during given meteorological conditions can be determined if the following two requirements are met: 1) the rate of growth of the internal boundary layers can be determined and 2) the equilibrium wind profile for each of the corresponding terrain types involved can be determined.

3. Formulation of the model

We assume that a wind profile is made up of \( N \) layers, representing \( N \) internal boundary layers, each one of which can be traced back to a definite terrain discontinuity in the upwind direction. We approximate the wind profile in each of the layers by a power law

\[
\tilde{u}(z) = \tilde{u}(z_i) \left( \frac{z}{z_i} \right)^{\alpha_i}, \quad z_{i-1} < z < z_i,
\]

(1)

where \( z_{i-1} \) and \( z_i \) are respectively the height of the lower and upper boundary of the \( i \)th layer.

At the site the wind speed is measured at a reference level \( z_{\text{ref}} \) (usually 10 m). Since this level is usually within the lowest layer, we have

\[
\tilde{u}(z) = \tilde{u}(z_{\text{ref}}) \left( \frac{z}{z_{\text{ref}}} \right)^{\alpha_1}, \quad z < z_1.
\]

(2)

From (1) and (2) it follows that the wind profile is completely determined if the following parameters are specified: \( \tilde{u}(z_{\text{ref}}), \alpha_1, \ldots, \alpha_N, z_1, \ldots, z_N \). If the terrain upwind of the site is homogeneous for a long enough distance there will be just one \( z_i \) (\( \sim 200 \) m) and one \( \alpha_i \).

According to the discussion in Section 2, we expect the \( \alpha_i \)'s to be a function of the local values of the roughness length \( z_0 \) and of the fluxes of heat \( H \) and momentum \( \tau \) at the earth interface. The parameters \( H \) and \( \tau \) are conveniently combined to form the Monin-Obukhov length

\[
L = \frac{-u^3 T}{k (H/\rho c_p) g},
\]

(3)

where \( u_* = \sqrt{\tau/\rho} \), \( \rho \) is the density of the air, \( T \) the air temperature (K), \( k \) the von Kármán’s constant, \( c_p \) the heat capacity of the air at constant pressure and \( g \) the acceleration of gravity. Then we expect the local wind profile to take on the form

\[
\tilde{u}(z) = u_* \left( \frac{z}{z_0} \right) \left( \frac{z}{L} \right)^{\alpha},
\]

(4)

But \( u_* \) is also determined by (1) and (2), so that \( u_* \) must not be specified explicitly when \( \tilde{u}(z_{\text{ref}}) \) is measured. This means that \( \alpha \) is a function only of \( L \) and \( z_0 \).

In order to evaluate the wind speed at level \( z \) the heights \( z_i \) of the internal boundary layers must also be determined. From similarity arguments it follows that

\[
z_i = z_i(x, L, z_0),
\]

(5)

where \( x \) is the distance between the site and the terrain discontinuity, measured along the wind direction.

In the application of this model to be demonstrated below routine meteorological observation data will be used throughout. Thus \( L \) will not be determined explicitly for the different terrain areas for each case. Instead each case will be characterized by one single stability index, based on the Turner classification scheme (Turner, 1964), but modified somewhat by the Swedish meteorological and hydrological institute. Thus the most unstable Turner category 1 is deleted, because it hardly ever occurs at the latitude of Sweden. The other two unstable categories 2 and 3 are taken together. The neutral class 4 and the stable classes 5–7 are the same as in Turner’s original scheme, although the details of the procedure for the determination of the class differs in certain details. By comparison with measured stability at one mast (the 120 m mast at Ägesta near Stockholm) it was found, for example, that better results were obtained when a stable class was attributed to the hours near sunset and sunrise, because of the prolonged occurrence of low sun elevation angle on a high latitude.

4. Determination of the rate of growth of the internal boundary layers

Pasquill (1972) has calculated the rate of growth of internal boundary layers for two roughness cases \( (z_0 = 3 \text{ cm and } 1 \text{ m}) \), respectively, the values referring to the rougher of the two surfaces at a discontinuity) and three stability classes (neutral, stable and unstable, where the neutral case assumes a geostrophic wind of \( 4 \text{ m s}^{-1} \), and the unstable case is characterized by a heat flux of \( +26 \text{ mW cm}^{-2} \) and a geostrophic wind of \( 4 \text{ m s}^{-1} \) and the stable case by the same geostrophic wind and a heat flux of \( -2 \text{ mW cm}^{-2} \)). The height \( z_i \) of boundary layer as a function of distance \( x \) have been taken from Pasquill’s Table 1 and plotted in log-log representations. Fig. 4 shows the curves for \( z_0 = 1 \text{ m} \). As seen from the figure straight lines of logs against logx are fair representations for the layer of interest here (\( z < 200 \text{ m} \)). Thus we write

\[
z = ax^b,
\]

(6)

where \( a \) and \( b \) are functions of \( z_0 \) and stability. From the diagrammatic representations of Pasquill’s data \( a \) and \( b \) were determined for his six cases. To get values for other \( z_0 \)'s and other stabilities (represented by the index classes described above) values of \( a \) and \( b \) were
interpolated and, in the case of \( \varepsilon_0 \), extrapolated (\( a \) and \( b \) were plotted against \( \log \varepsilon_0 \) and straight lines were drawn). Table 1 gives the result of this analysis.

5. Determination of \( \alpha \) as a function of stability and roughness

The exponent \( \alpha \) of the wind power law (1) has been determined empirically from wind measurements from three 100 m masts in southern Sweden. The masts are all situated at atomic energy power plant sites: Marviken, situated at the Swedish east coast, \( \sim 30 \) km east of Norrköping; Oskarshamn, also at the east coast, \( \sim 20 \) km north of the town with the same name; and Ringhals, situated at the west coast, \( \sim 20 \) km north of Varberg.

The masts, which have been instrumented and run by the Swedish meteorological and hydrological institute, are equipped with anemometers and wind vanes at 12.5, 25, 50 and 100 m and temperature sensors at the same levels and in addition at 2 m.

The mast sites were inspected by one of the authors (A.S.). All the masts were found to be situated in very heterogeneous terrain. In order to get a reasonably clearcut result, certain rather narrow sectors with well-defined terrain characteristics were chosen for the study. The sectors chosen can be described accordingly:

1) Ringhals. Direction 270°–340°. Flat rocks with sparse, low vegetation (\( \varepsilon_0 = 0.02 \) m) up to 1000 m from the mast, beyond that open sea (\( \varepsilon_0 = 0.001 \) m).

2) Oskarshamn. Direction 240°–270°. Level ground with dense forest of \( \sim 15 \) m high spruce and pine trees (\( \varepsilon_0 = 1.0 \) m), extending far beyond 10 km distance from the mast.

3) Marviken. Directions 357°–43° and 85°–120°, which have very similar character: first a \( \sim 75 \) m wide belt of fairly sparse wood (\( \varepsilon_0 = 0.5 \) m) and beyond that open sea (\( \varepsilon_0 = 0.001 \) m).

The values for \( \varepsilon_0 \) given above have been taken from a table in ESDU (1972), which is reproduced here as an Appendix.

Table 1. Calculated values for \( a \) (upper value) and \( b \) (lower value) of the approximate relation for the growth of internal boundary layers, \( \varepsilon = \alpha \varepsilon^b \). The roughness values refer to the rougher of the two surfaces at a discontinuity.

<table>
<thead>
<tr>
<th>Stability class</th>
<th>( \varepsilon_0 &gt; 1.5 )</th>
<th>( 0.5 &lt; \varepsilon_0 \leq 1.5 )</th>
<th>( 0.2 &lt; \varepsilon_0 \leq 0.5 )</th>
<th>( 0.06 &lt; \varepsilon_0 \leq 0.2 )</th>
<th>( \varepsilon_0 &lt; 0.06 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2, 3</td>
<td>0.77</td>
<td>0.64</td>
<td>0.49</td>
<td>0.35</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>0.57</td>
<td>0.49</td>
<td>0.35</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>4</td>
<td>0.83</td>
<td>0.73</td>
<td>0.55</td>
<td>0.38</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>0.73</td>
<td>0.55</td>
<td>0.38</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>5</td>
<td>0.73</td>
<td>0.65</td>
<td>0.50</td>
<td>0.34</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>0.68</td>
<td>0.45</td>
<td>0.32</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>6</td>
<td>0.69</td>
<td>0.65</td>
<td>0.69</td>
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<tr>
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<td>0.32</td>
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</tr>
<tr>
<td>7</td>
<td>0.50</td>
<td>0.44</td>
<td>0.36</td>
<td>0.29</td>
<td>0.20</td>
</tr>
<tr>
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<td>0.59</td>
<td>0.60</td>
<td>0.62</td>
<td>0.63</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Fig. 4. The growth of internal boundary layers as a function of distance from the discontinuity for three stability classes. \( \varepsilon_0 = 1.0 \) m for the rougher surface. After Pasquill (1972).

For each one of the measuring sites data for 200 to 600 h with winds in the selected sectors were used for the analysis. For every hour the following procedure was used:

1) A stability estimate was made. Routine meteorological observations needed for the evaluation of the modified Turner classes (cloudiness, etc.) were not available for the mast sites. Instead, a more direct stability classification was intended to be performed on the basis of the temperature and wind data from the mast. Unfortunately, the quality of the temperature data was far from satisfactory, so often more indirect information had to be used. The unstable class 3 could safely be attributed to clear summer days and the neutral class 4 to overcast and windy winter periods. For the stable cases it was not considered possible from the data available to get a reliable subdivision of the material into the three classes 5, 6 and 7. Instead the cases were classified as either slightly stable (5) or very stable (7).

2) Having identified the stability class, this was used together with \( \varepsilon_0 \) to determine, from Table 1, the relevant values for \( a \) and \( b \) to be used to determine the height of the boundary layer separation with (6). This was, of course, only done for the Ringhals and the Marviken data, because the surface is uniform for the sector selected in Oskarshamn.

3) The exponent \( \alpha \) of the wind power law (1) was determined from the wind speed measurements for each boundary layer separately. For Ringhals this sometimes meant using two values, sometimes only one value, because in the unstable case the boundary layer formed at the shoreline had reached a height greater than 100 m. For Marviken two layers are always found in the profiles because of the short distance between the mast and the shoreline. For Oskarshamn there is always one value as mentioned above. \( \alpha \) was not
calculated for those cases where there was just one wind measurement point within the layer in question. For the lowest layer at Marviken an exception to this rule was made in order to get any $\alpha$ values for that layer for the stable and neutral cases from that mast. For the lowest layer a line is drawn through the lowest measuring point and the intersection between the line obtained for the upper layer and a horizontal line in the diagram

<table>
<thead>
<tr>
<th>Site</th>
<th>Terrain</th>
<th>$z_0$ (m)</th>
<th>Stability</th>
<th>Mean value $\alpha$</th>
<th>Standard deviation $\alpha$</th>
<th>Number of cases</th>
<th>Expected error of the mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marviken</td>
<td>sparse wood</td>
<td>0.5</td>
<td>very stable</td>
<td>1.05</td>
<td>0.31</td>
<td>18</td>
<td>0.08</td>
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<td></td>
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<td>0.5</td>
<td>stable</td>
<td>0.48</td>
<td>0.14</td>
<td>57</td>
<td>0.02</td>
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<tr>
<td></td>
<td>sparse wood</td>
<td>0.5</td>
<td>neutral</td>
<td>0.24</td>
<td>0.07</td>
<td>160</td>
<td>0.006</td>
</tr>
<tr>
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<td>sparse wood</td>
<td>0.5</td>
<td>unstable</td>
<td>0.20</td>
<td>0.08</td>
<td>61</td>
<td>0.01</td>
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<tr>
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<td>0.001</td>
<td>very stable</td>
<td>0.56</td>
<td>0.21</td>
<td>18</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>sea</td>
<td>0.001</td>
<td>stable</td>
<td>0.20</td>
<td>0.13</td>
<td>57</td>
<td>0.02</td>
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<td>sea</td>
<td>0.001</td>
<td>neutral</td>
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<td>160</td>
<td>0.005</td>
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<tr>
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<td>0.001</td>
<td>unstable</td>
<td>0.04</td>
<td>0.03</td>
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<td>Oskarshamn</td>
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<td>1.0</td>
<td>very stable</td>
<td>0.60</td>
<td>0.15</td>
<td>49</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>forest</td>
<td>1.0</td>
<td>stable</td>
<td>0.51</td>
<td>0.13</td>
<td>72</td>
<td>0.02</td>
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<tr>
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<td>1.0</td>
<td>neutral</td>
<td>0.29</td>
<td>0.06</td>
<td>99</td>
<td>0.006</td>
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<tr>
<td></td>
<td>forest</td>
<td>1.0</td>
<td>unstable</td>
<td>0.23</td>
<td>0.06</td>
<td>88</td>
<td>0.006</td>
</tr>
<tr>
<td>Ringhals</td>
<td>level ground</td>
<td>0.02</td>
<td>very stable</td>
<td>0.56</td>
<td>0.12</td>
<td>7</td>
<td>0.05</td>
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<tr>
<td></td>
<td>level ground</td>
<td>0.02</td>
<td>stable</td>
<td>0.25</td>
<td>0.10</td>
<td>47</td>
<td>0.01</td>
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<td>0.02</td>
<td>neutral</td>
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<td>160</td>
<td>0.002</td>
</tr>
<tr>
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<td>0.02</td>
<td>unstable</td>
<td>0.05</td>
<td>0.04</td>
<td>21</td>
<td>0.009</td>
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</table>
Table 3. Values of the constants \( c_0, c_1, \) and \( c_2 \) of the expression (7) for \( \alpha \) as a function of log \( z_0 \).

<table>
<thead>
<tr>
<th>Stability class</th>
<th>( c_0 )</th>
<th>( c_1 )</th>
<th>( c_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2, 3</td>
<td>0.18</td>
<td>0.13</td>
<td>0.03</td>
</tr>
<tr>
<td>4</td>
<td>0.30</td>
<td>0.17</td>
<td>0.03</td>
</tr>
<tr>
<td>5</td>
<td>0.52</td>
<td>0.20</td>
<td>0.03</td>
</tr>
<tr>
<td>6</td>
<td>0.80</td>
<td>0.25</td>
<td>0.03</td>
</tr>
<tr>
<td>7</td>
<td>1.03</td>
<td>0.31</td>
<td>0.03</td>
</tr>
</tbody>
</table>

neutral profiles at Marviken, Oskarshamn and Ringhals. In unstable and stable stratification the profiles are more or less curved in a log-log representation. The curvature is more pronounced in unstable than in stable cases. Fig. 5 shows a typical unstable profile from Oskarshamn. For these cases a mean value of the exponent for the whole layer is evaluated. The stable log-log plots are often not curved at all.

The data obtained for \( \alpha \) in the way described above have been averaged for every combination of \( z_0 \) and stability class and the result is displayed in Fig. 6 and in Table 2.

Fig. 6 gives the variation of \( \alpha \) with \( z_0 \) for each one of the four stability classes. The circles represent mean values from Marviken, the squares from Ringhals and the triangles from Oskarshamn. The crosses, which come very close to the curve drawn through the data points for the neutral case, are average data for neutral stratification from a number of studies (compiled by ESDU, 1972). As a whole the data points from the neutral profiles at Marviken, Oskarshamn and Ringhals.

indicating the calculated intersection between the two layers. A new \( \alpha \) value can thus be calculated for the lowest layer.

As is known from many studies (see, e.g., Davenport, 1967), the neutral wind profile is very well approximated by a power law. This is also found to be true for the neutron profiles at Marviken, Oskarshamn and Ringhals.

Fig. 7. Schematic diagram of the terrain characteristics and corresponding estimated \( z_0 \) values for the various sectors at Ringhals.
three Swedish masts form a very reasonable pattern, and curves can easily be drawn for each stability class, there being only one extreme point—the Oskarshamn very stable point. Table 2 presents the mean values for \( \alpha \) for all the cases and in addition the corresponding standard deviations, the number of cases and the expected error of the mean. As can be seen from this table the variation in the \( \alpha \) values for the neutral case is very small within a given class of \( z_0 \). This contrasts sharply to the very stable case, where the variation is large. This, however, is entirely expected, as that stability regime covers a very wide range, and the variation of \( \alpha \) with stability in that range is rapid.

The curves drawn by eye to fit the observational data points can be expressed analytically with second-order polynomials in \( \log z_0 \), i.e.,

\[
\alpha = c_0 + c_1 \log z_0 + c_2 (\log z_0)^2. \tag{7}
\]

The values obtained for \( c_0, c_1 \) and \( c_2 \) for the four cases displayed in Fig. 6 are given in Table 3, and in addition, by interpolation, the corresponding values for stability class B.

6. Verification of the model

The model, with the numerical data presented in Table 1 (rate of growth of the boundary layers) and Table 3 (determination of \( \alpha \)) has so far been tested only on a data set from Ringhals. The data set covers another period of time than that used for the determination of the \( \alpha \) values described in the previous section. For the \( \alpha \) analysis the period June 1973–May 1974 was used and for the verification study the period June 1974–May 1975. Furthermore, the verification study covers almost the entire 360° sector, whereas in the \( \alpha \) analysis only the sector 270–340° was used. In this verification test, the sector 340–020° has been excluded because the wind passes the huge buildings of the reactor station at a distance of 400 m from the mast before it reaches the anemometers. The reactor station has been built up during the period of wind measurements, so it is impossible to determine one \( z_0 \) value for the whole period for that sector. Fig. 7 shows schematically the terrain characteristics and corresponding estimated \( z_0 \) values for the various sectors at Ringhals.
As mentioned earlier, no routine meteorological observations are being performed at Ringhals. Instead data were taken from Torslanda airport, 50 km north of Ringhals. Weather conditions, in particular cloudiness, may vary considerably over a distance of 50 km, but in this case the two sites are situated right at the coastline and the general terrain characteristics are similar. Thus, the differences in weather between the two is likely to be small in individual cases and negligible statistically.

For each hour of the period June 1974–May 1975 the stability class was evaluated from Torslanda data. The mean wind direction for the lowest 100 m for the hour was evaluated from Ringhals. The height of possible boundary layers below 100 m at Ringhals were determined with the aid of relevant $z_0$ values for the sector (see Fig. 7) and Table 1. $\alpha$ values for the boundary layers were determined with the aid of Eq. (7) and Table 3. The wind speed at the reference (12.5 m) at Ringhals was evaluated and eventually the wind speed at 100 m was calculated with the aid of (1) and (2).

Figs. 8 and 9 show the result of the calculations for Ringhals at heights of 50 and 100 m in the form of cumulative frequency distributions. The circles give the calculated frequency values for the various wind speed classes and the full line curves show the measured distributions. Also shown is the cumulative frequency distribution for the 12.5 m reference level. The calculated values are in good agreement with the measured ones.

7. Applications of the model

The model has been used to determine wind speed frequency distributions for 50, 100 and 150 m for a number of Swedish stations. For each station frequency distributions of simultaneous wind speed values and wind direction values were evaluated for each of the five stability classes. Observations every hour during a 20-year period (1955–75) were used. The terrain characteristics round the stations were investigated in detail, and the corresponding $z_0$ values were estimated with the aid of the ESDU table (see Appendix). What could be termed “roughness sectors” were identified; that is, sectors which can be described by a given sequence of $z_0$ and corresponding $x$ values (e.g., $x=0$–500 m, $z_0=0.3$ m; $x=500$–2000 m, $z_0=0.03$ m; etc).

![Fig. 9. Measured cumulative frequency distributions for 12.5 m (dotted line) and 100 m (full line) at Ringhals. The rings give the calculated frequency distributions for 100 m.](image-url)
For each one of the stations the following computations were performed:

1) For every stability class and roughness sector the heights of possible boundary layers were calculated [Table 1 together with Eq. (6)] as well as the \( \alpha \) value for each boundary layer [Table 3 and Eq. (7)]. Then \( \bar{u}(z) / \bar{u}(z_{ref}) \) could be calculated for \( z = 50, 100 \) and 150 m, with the aid of (1) and (2).

2) The statistics of \( \bar{u}(z_{ref}) \), stability and wind direction were used together with the above result to calculate wind speed frequency distributions for the levels mentioned above.

3) The cases reported as "calm" require special consideration. For the unstable and neutral calm cases \( \bar{u}(z) \) is set equal to zero. For the stable cases profiles from the three masts used in the previous analysis indicate that high wind speeds may occur at upper levels when \( \bar{u}(z_{ref}) \) is in the "calm" range. The following crude procedure has been adopted for these cases: as the observation "calm" means that no wind direction is indicated an average \( \alpha \) value is derived for each one of the stable categories (i.e., an average over all directions and distances involved). Then \( \bar{u}(z_{ref}) \) is set equal to 0.5 m s\(^{-1}\), and the calculations are carried out with the help of Eq. (2).

Fig. 10 displays some of the results of this study. The geographical sites of the various stations are indicated on the map as dots. Beside each such location dot are two figures: the lowest is the median value of the measured wind speed at the reference level (10 m), the upper value is the calculated median value for the 150 m level. Some features are worth noting. Several stations that are located fairly close to each other, like Ronneby and Kalmar or Nyköping and Norrköping, differ to a significant extent in the case of the 10 m wind but have almost identical 150 m winds. The 150 m median wind for Bromma is a remarkable singularity. The calculated value is, however, very likely to be erroneous. The reason is that the Bromma airport is situated in a typical urban environment (Stockholm suburbs), and the model is not valid for such an area.

A map like Fig. 10 gives a crude picture of the wind at, in this case, 150 m above ground level. It should be noted that mesoscale variations in the mean wind field cannot be obtained from a study like this unless the station network is very dense. In order, for example, to evaluate the gradient in the mean wind field across a coast line, an approach based on numerical solution of the basic equations for the flow is called for.

The above results refer to wind speed frequency distributions irrespective of wind directions. In the process of calculation, however, the data are divided into direction sectors. It is then easy to produce frequency distributions of wind speed at the various levels for separate sectors. Figs. 11a and 11b show examples of such distributions from two sectors at Torslanda airport. The figures give the distribution of the calculated wind at 100 m as well as the distribution of the measured wind at 10 m. The difference between the two diagrams is striking. The increase in wind speed from 10 to 100 m is much more pronounced for the combined west and southwest sectors (Fig. 11a) than for the northeast sector. This effect is a combination of the difference as far as the two sectors are concerned in fetch terrain characteristics (see the legend to the Fig. 11) and in stability class statistics (there being significantly higher frequency of stable classes with
Fig. 11a. Measured cumulative frequency distribution for 10 m (full line) and calculated for 100 m (dotted line) at Torslanda for the W+SW sectors. The estimated $z_0$ values for that sector are $z_0=0.02$ (grass) up to 300 m and behind there $z_0=0.4$ (houses).

Fig. 11b. Measured cumulative frequency distribution for 10 m (full line) and calculated for 100 m (dotted line) at Torslanda for the NE sector. The estimated $z_0$ values for that sector are $z_0=0.02$ (grass) up to 200 m, $z_0=0.001$ (sea) between 200 and 500 m, and behind there $z_0=0.4$ (houses).
winds from the west and southwest sectors than with northeast winds).

8. Discussion and conclusions

The present study has shown that it is possible to describe with remarkable accuracy, at least in a statistical sense, wind profiles up to \( \sim 200 \) m above ground in relatively flat terrain with varying surface conditions. The input to the model is routine meteorological data, including wind at standard anemometer level, and in addition detailed information about the roughness characteristics as a function of distance and direction relative to the measuring point. The parameters that go into the model have been determined from extensive data sets from three Swedish 100 m masts. These data sets might all be biased to some extent by land and sea breeze effects. Unfortunately, no inland mast data were available from Sweden to test this possible lack of universal applicability. From comparison with published data (ESDU, 1972) the neutral case, however, is likely to be universal. This result is quite important, because it indicates that the general approach of describing the wind profile in the various internal boundary layers as power laws with exponents characteristic of the origin of the respective boundary layers is basically valid.

An important restriction to the applicability of the model is that the model, with the numerical parameters presented here, cannot be used in urban surroundings.

The procedure described here requires a lot of computations to be carried out and one could ask whether it would be possible to acquire in practice the same information by applying a simple power law to extrapolate the mean wind from standard anemometer level to 100 or 200 m. The crucial point, however, is how to determine the exponent of such a power law in the case of varying surface conditions. To illustrate this we could take almost any of the stations on the map of Fig. 10. Most of the anemometers are placed on 10 m high masts at air fields. This means that the immediate surroundings are characterized by \( z_0 \) values of the order 1 cm. From Fig. 6 we find \( \alpha \approx 0.12 \) for this roughness value for neutral conditions. With an average 10 m wind speed of 3.9 m s\(^{-1}\) for Ronneby this exponent gives the value 5.4 m s\(^{-1}\) at 150 m. Taking the value obtained by the present model (7.8 m s\(^{-1}\)) the relevant “average exponent” for the Ronneby site is found to be 0.26. Apparently there is no short cut to that value. It is made up of individual \( \alpha \) values that vary within a wide range as shown in this paper. The model determines the relevant \( \alpha \) values for the various physical situations and then makes the correct weighting to form not only the relevant mean wind speed for 100 or 150 m but also the corresponding wind speed distributions.

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APPENDIX

$Z_0$ Values for Typical Terrain Types (After ESDU 72026, 1972)

<table>
<thead>
<tr>
<th>$Z_0$ (m)</th>
<th>Terrain Description of Area within Several Kilometres Upwind of Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Centres of cities with very tall buildings, Very hilly or mountainous areas</td>
</tr>
<tr>
<td>1</td>
<td>Centres of large towns, cities, Centres of small towns, Outskirts of towns, Forest</td>
</tr>
<tr>
<td>10^{-1}</td>
<td>Many trees, hedges, few buildings, Many hedges, Few trees, summer time</td>
</tr>
<tr>
<td>10^{-2}</td>
<td>Isolated trees, Uncut grass, Few trees, winter time, Cut grass ($\approx 3\text{ cm}$)</td>
</tr>
<tr>
<td>10^{-3}</td>
<td>Natural snow surface (farmland), Off-sea wind in coastal areas</td>
</tr>
<tr>
<td>10^{-4}</td>
<td>Calm open sea, Snow-covered flat or rolling ground</td>
</tr>
<tr>
<td>10^{-5}</td>
<td>Ice, mud flats</td>
</tr>
</tbody>
</table>

REFERENCES


ESDU 72026, 1972: Characteristics of wind speed in the lowest
layers of the atmosphere near the ground: Strong winds. Eng. Sci. Data Unit, Ltd., 251 Regent St., London W1R7AD.


