PREDICTION OF EXTREME WINDSPEEDS AT WIND ENERGY SITES.

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ABSTRACT:The wind loading on a structure is related to the wind speed. Therefore, knowledge of the gust factor is important when determining the wind speed which a structure would be expected to withstand. Such considerations need to be incorporated into the design process, leading to the requirement of an accurate assessment of the gust wind speed at a site. This paper examines the both the temporal and directional behaviour of the gust factor and considers gust factor variations with respect to the mean windspeed and the height at which observations are made. The validity of formulations to calculate the gust factor in conditions where the maximum windspeed is not measured are also considered. The frequency distribution of gust speeds is investigated, in particular with respect to the fit of the distribution to the Weibull probability density function considering both spatial variation of the Weibull parameters and their variation with height.
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1. SITE SELECTION AND DESCRIPTION

Figure 1 Site Locations

Data made available to this study from the databases of National Wind Power, ETSU and the UK Met. Office were examined to determine those sites for which suitable data were available. This lead to the selection of twenty one sites from the western side of the UK mainland for further analysis (Figure 1). Sites were categorized by orography (a measure of the form roughness of the area) and by roughness length (a measure of the smaller scale frictional effects on the flow of a fluid over the orography [1]). This served to ensure that the selected sites were representative of a wide range of topographical variations and not representing extreme site conditions only.

2. GUST FACTOR ANALYSIS

The gust factor is defined [2] as the ratio of the maximum wind speed to the mean wind speed during a given observation period. This should not be confused with the *gustiness factor* which is defined [3] as the "percentage ratio of the difference between the maximum and minimum horizontal wind speeds to the mean wind speed in a given period", neither with the *gust ratio* [4], the ratio of the maximum wind speed to the mean wind speed. In this paper, the term *gust factor* refers to the definition of [2].

2.1 Diurnal Variation

Diurnal variations are strong but the combination of seasonal and diurnal effects may be masking the true variation. Here the data from Site 9 are filtered diurnally and seasonally to separate the effects. Given that the data are ten-minute averages, this produces 144 points to the 'day'. Figure 2 shows the variation (maximum to minimum) is much greater in summer (0.11), although the winter data (0.03) still shows the characteristic mid-day peak. The summer months typically see greater heating effects producing more turbulent flow and hence higher gust factors. The winter period is characterised by more stable conditions (although the mean wind speed may be higher), hence gust factors are less variable.

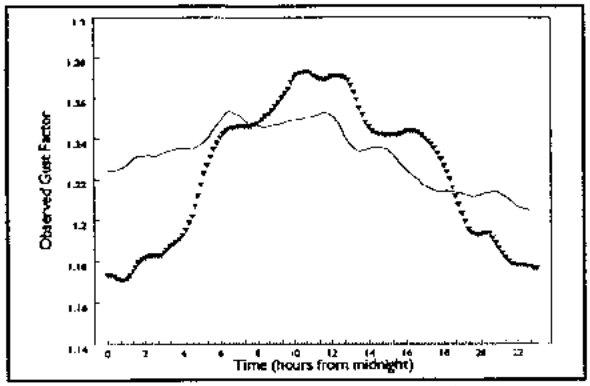

Figure 2. Diurnal Variation in Gust Factor (▼ - Summer, — - Winter).

22 Directional Variation

All sites where wind direction was collected quote a ten minute mean. This value is of little use in extreme value analysis since the direction associated with the gust may be dramatically different from any quoted mean value. Analysis of the variation of gust factor with direction was not specifically performed for this reason, but there was one site where specific characteristics allowed further analysis. Site 13 is sited close to the south west coast of Scotland and hence significant directional differences can be observed in the upwind characteristics. To the west, the fetch is dominated by the open ocean, whilst to the east, the terrain is fairly mountainous. Westerly data was defined as being within the range 270°±90° and easterly data fell within the range 90°±90°. Figure 3 shows that starting from similar minima at 00:00hrs, the westerly data (from a low orography, low roughness region) rise to give a much higher mid-day maximum than the easterly data (from a high orography, high roughness region), possibly due to sea breeze influences.

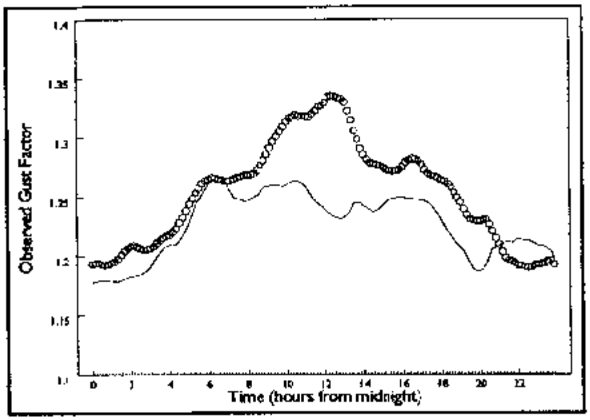

Figure 3. Directional Variation in Gust Factor, presented Diurnally (○ - West, — - East).

2.3 Variation of Gust Factor with Height.

The connection between gust factor and measurement height is important when considering design wind speeds for a structure. Wind speed measurements for the determination of the potential for wind energy sites are sometimes made at a different height from the hub height of the resulting windfarm. The use of a gust factor from a lower height may not be appropriate. Several sites had simultaneous measurements at two heights allowing investigation of the variation in observed gust factors. In all cases, the gust factors at the lower measurement height were found to be higher than those at the upper height. The use of a gust factor derived from 10m data for calculating the gust wind speed at 25m or 30m, say, would appear to be conservative by as much as 7.5%.

2.4 Variation with Mean Wind Speed.

The gust factors for the twenty-one sites were examined to determine whether any variability could be accounted for by fluctuations in the mean wind speed. Figure 4 shows that the variation in the gust factor at Site 1 (25m agl) appears to be largely independent of speed. A linear regression was performed on the data within the typical operational wind speed range for a wind turbine. No statistical relationship between gust factor and mean wind speed is indicated, with $r^2 = 0.0068$. The regression slope and offset were 0.00158 and 1.21 respectively. The mean gust factor is 1.22.

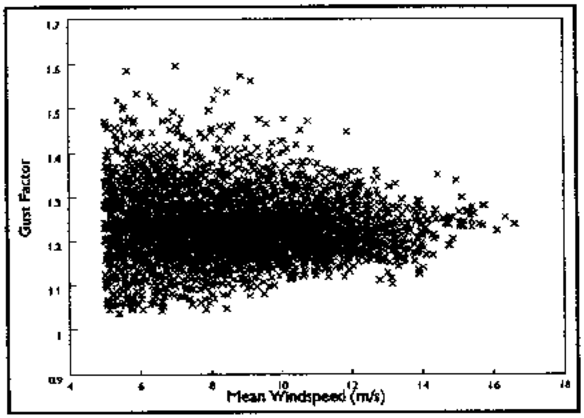

Figure 4. Variation in Gust Factor with Mean wind Speed.

It is clear from Figure 4 that although there is no overall relationship, the maximum observed value of gust factor for a given wind speed does decrease with increasing wind speed, tending towards a value close to the overall mean gust factor. This 'limiting effect' would indicate that the application of a mean gust factor to estimate extreme gust speeds is generally appropriate.

2.5 Calculation of Gust Factor

In cases where only the mean value of wind speed is recorded, a calculated gust factor is required to estimate the extreme maxima. It is possible [4] to calculate a gust factor for a gust of duration equal to the observation period of the raw data. However, as the data available for the twenty-one sites consist of ten minute averaged data, this method will only produce a gust of ten minute duration, which is of little use here. A method for calculation of the gust factor, implying a linear dependance on the inwind turbulence intensity and a logarithmic dependence on the gust duration is proposed in [2] & [5]. This method requires standard deviation data in addition to the mean wind speed for calculation of turbulence intensity and assumes a linear dependence on the inwind turbulence intensity and a logarithmic dependence on the gust duration. The t second duration gust factor, g_t, is given by:

$$g_t = 1 + 0.42\, I_F \ln\left(\frac{3600}{t}\right)$$

where I_F is the inwind turbulence intensity diveded by the mean wind speed. To test the accuracy of this relationship, gust factors were calculated for all 21 test sites.

The calculation method consistently underestimated the observed gust factor by between 2.41% and 15.74% with one exception, Site 19, where the prediction is an overestimate of 1.76%. Interestingly, the two most significant deviations come from sites (18 and 20) which are located in the south west of England. The disturbing conclusion to be drawn from these analyses is that the methodology would almost certainly result in an underestimation of extreme gust loading and as a result this method for gust factor calculation should only be used with extreme care.

3. VARIATION IN WEIBULL PARAMETERS

In this section, the frequency distribution of gust speeds is investigated, in particular with respect to the fit of the distribution to the Weibull probability density function. Besides providing useful guidance on the extent to which the Weibull k and c parameters are accurate descriptors of gust speed frequency distributions, the analyses presented below also demonstrate the extent to which there is spatial, inter-annual, and height-dependent coherence in these parameters.

3.1 Variation in Weibull Parameters with Time

The period of record for most of the 13 Met. Office stations is 1973 to 1979. Examination of the annual shape and scale parameters reveals a fairly high degree of inter-annual variation (Figure 5). The annual shape parameters vary between 1.6 and 2.3 whereas the scale, reflecting the magnitude of the mean (gust) wind speed, $\bar{u}_{gust}$, ranges from 8.0 to 14.8 ms^{-1}. Large shape parameters are noticeable at most sites in 1977, and, to a lesser extent, in 1974 and 1975 (Figure 5b). In 1976, however, there is a marked drop in k. In comparison, the scale parameter also demonstrates a peak in 1977, along with another of equal magnitude in 1974 (Figure 5c). Years of low c are 1973, 1975 and 1976, and 1979. The inter-annual behaviour of $\bar{u}_{gust}$ is nearly identical to the behaviour of c (Figure 5c).

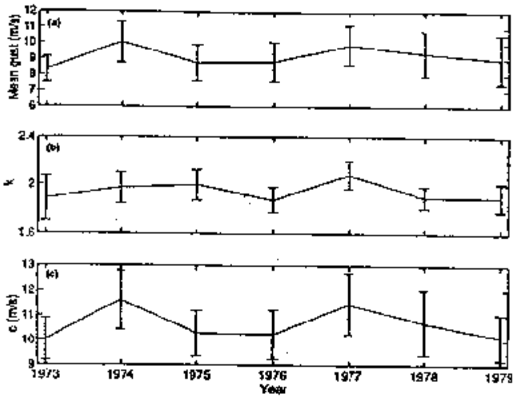

Figure 5 Averaged annual gust speed (a) shape (b) and scale (c) parameters. Errors represent ±1 standard deviation.

Although the cause of this inter-annual behaviour remains unclear, it is present in the parameters of most of the Met. Office stations. To further assess the inter-annual behaviour of k, c, and $\bar{u}_{gust}$, a correlation analysis was conducted. In spite of the shared peaks in 1974 and 1977, the average correlation between annual k and c at each of the 13 stations is 0.38, with Gorleston having the highest (0.90) and Sumburgh the lowest (0.06) correlation. Furthermore, two stations (Lizard and Milford Haven) had weak negative correlations. Correlations between k and $\bar{u}_{gust}$ were not significantly different (at p=0.001) from the correlations between k and c. Correlations between c and mean gust speeds, however, were extremely, and consistently, high. The average c-$\bar{u}_{gust}$ correlation was 0.95 (with a standard deviation of 0.07). The strongest c-$\bar{u}_{gust}$ correlation (0.997) was at Dungeness while the lowest (0.743) was at Lynemouth (this value is, however, suspect, as South Shields (23 km away) has a correlation of 0.96).

3.2 Spatial Variation of Weibull Shape Parameters

Although attempts to build a single Weibull model for a number of stations have proved difficult [6], Met. Office stations in close proximity to one another demonstrated similar inter-annual behaviour of both shape and scale parameters (Figure 6). In some instances, we find that stations separated by several hundred kilometres also exhibited remarkable temporal correspondence. Comparison of time series of neighbouring stations shows that most are in general agreement; however, some distant pairs of stations had near perfect (circa 0.97) correlations for either shape (i.e. Lynemouth-Dungeness, 504.3 km) or scale (i.e. Portland Bill-Milford Haven, 223.9 km) parameters.

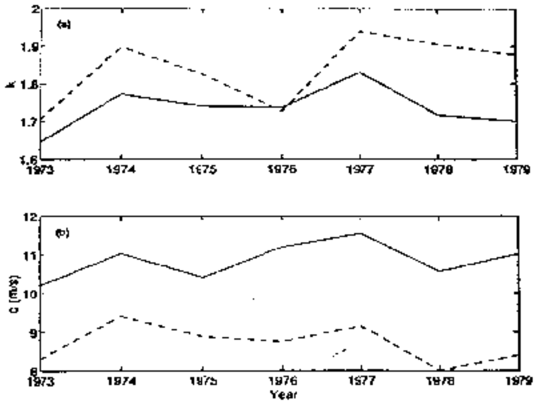

Figure 6 Weibull shape (a) and scale (b) parameters for two stations in close proximity(— Lynemouth; -- South Shields)..

The average interstation distance was 427.5 km, with Lynemouth-South Shields (23.1 km) being the smallest and Sumburgh-Scilly (1150.8 km) the greatest distance. The average nearest neighbour distance was 119.5 km. Analysis of interstation correlations (of shape) versus the distance between stations resulted in a fairly strong distance-decay. Using a linear best-fit line, stations within 100 km of each other are expected to have correlations around 0.75. Beyond 200 km the variation in correlations becomes too great to obtain a meaningful average value.

4.3 Variation of Weibull Parameters with Height

Weibull parameters were estimated for five of the non-Met. Office (NMO) anemometer records with data at two heights. These stations are well distributed down the western coast of the UK, with only NMO-1 and -14 being somewhat inland. The sites are well exposed and, with the exception of NMO-1 (10 m and 25 m), have data recorded at 10 and 30 m above ground level. Only observations where both heights had data available were used in the maximum likelihood estimation of k and c. Examination of the parameters with height shows that there does not appear to be a substantial variation of k with height. In addition to exploring the difference in Weibull parameters at two heights, it may be desirable to estimate these parameters at a proposed wind turbine hub height, using parameter estimates derived from data obtained at a lower level. The wind profile power law ($v_2=v_1(h_2/h_1)^{\alpha}$) is a method that has been widely used in the field of wind energy for the vertical extrapolation of the mean wind speed. We investigate here whether it is applicable to the scale parameter of the Weibull distribution. A common value for α, the power law exponent, is 1/7, or 0.1428 [7];[8]. Given the Weibull scale parameters at two heights, it is possible to empirically derive estimates for α by substituting the known scale parameters for the speeds at the observation heights, and solving the power law for α. In doing so, α is found to range between 0.2005 and 0.2928 for c (and 0.1822 and 0.2709 for $\bar{u}_{gust}$). When applied to heights ranging from 1 to 100 m, these values of a result in a strong similarity in profiles between scale and mean gust speeds. On the basis of the results from this section, it would appear feasible to estimate the scale and shape parameters of the Weibull distribution at the turbine hub height from measurements taken at another height, whilst the k parameter can be assumed to remain constant with height up to 100m above ground level.

5. SUMMARY AND FURTHER WORK

This paper describes the initial work undertaken as part of an investigation into the prediction of extreme winds at typical UK wind energy sites. The work completed to date includes analysis of the variation of gust factors and analysis of the frequency distribution of extreme wind speeds. Further work will consist of an analysis of a number of methods to predict extreme wind events from a short-term data set. The results of this study will be published as a set of guidelines.

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