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## Full scale experimental analysis of extreme coherent gust with wind direction changes (EOD)

K S Hansen<sup>1</sup> and G C Larsen<sup>2</sup>

<sup>1</sup>Department of Mechanical Engineering, Fluid Mechanics, Nils Koppels Allé, DTU-Building 403, Technical University of Denmark, DK-2800 Lyngby; Phone: +45 4525 4318

<sup>2</sup>Wind Energy Department, Risø National Laboratories, Technical University of Denmark, P.O. Box 49, DK-4000 Roskilde; Phone: +45 4677 5056

E-mail: ksh@mek.dtu.dk

**Abstract.** A coherent wind speed and wind direction change (ECD) load case is defined in the wind turbine standard. This load case is an essential extreme load case that e.g. may be design driving for flap defection of active stall controlled wind turbines. The present analysis identifies statistically the magnitudes of a joint gust event defined by a simultaneously wind speed- and direction change in order to obtain an indication of the validity of the magnitudes specified in the IEC code. The analysis relates to pre-specified recurrence periods and is based on full-scale wind field measurements. The wind speed gust amplitude, occurring simultaneously with a wind direction change, corresponds well to the recommended ECD value of 15 m/s, except for the complex terrain case, where estimated extreme wind speed gust amplitudes are seen to exceed the IEC value with approximately 50%. The estimated extreme wind direction gust amplitudes associated with the investigated European sites are low compared to the recommended IEC- values. However, these values, as function of the mean wind speed, are difficult to validate thoroughly due to the limited number of fully correlated measurements.

### 1. Introduction

A coherent wind speed and wind direction change (ECD) load case is defined in the IEC 64100-1 standard [1]. This load case is an essential extreme load case that e.g. may be design driving for flap defection of active stall controlled wind turbines. The purpose of the present analysis is to identify statistically the magnitudes of a joint gust event defined by a simultaneously wind speed- and direction change in order to obtain an indication of the validity of the magnitudes specified in the IEC code. The analysis relates to pre-specified recurrence periods and is based on full-scale wind field measurements.

### 2. Nomenclature

ECD	Extreme Coherent
<i>GDI</i>	Gust Directional Index; defined in equation (1)
<i>U</i> (t)	Horizontal Wind Speed time series; sampled with frequency $\geq 1$ Hz
<i>Dir</i> (t)	Horizontal Wind Direction time series; sampled with frequency $\geq 1$ Hz
PDF	Probability Density Function

$\Delta t$	Gust rise time in (=10) seconds
$V_{cg}$	Wind speed gust amplitude (m/s)
$V_{hub}$	10-minute average wind speed at hub height (m/s)
$Dir_{cg}$	Wind direction gust amplitude (°)
$\alpha, \beta$	Parameters defining the EV1 distribution
$T_a$	Apparent basic return period
$P_{50cg}$	50 year quantile
$N_t$	Total number of populations
$N_c$	Number of fully correlated events

### 3. Definitions

Determination of extreme ECD magnitudes requires a large amount of measured time series due to the limited occurrence of such gust events. A suitable collection of data for this analysis is available from “Database on Wind Characteristics” [2], [3], [4], where a huge amount of simultaneously recorded full-scale wind speed and wind direction measurement time series is stored. These time series are indexed in terms of mean statistics, maximum gust sizes and various kinds of derived statistics, which enables a direct identification of ECD situations in the measured data. The index parameter relevant for the ECD event is the Gust Directional Index (*GDI*) parameter, which is defined in equation (1)

$$GDI = \frac{abs(U(t + dt) - U(t))}{\max(abs(U(t + dt) - U(t)))} + \frac{abs(Dir(t + dt) - Dir(t))}{\max(abs(Dir(t + dt) - Dir(t)))} \quad (1)$$

where, at a *given position*,  $U(t)$  is the measured wind speed, and  $Dir(t)$  is the simultaneous measured wind direction. For a given time series, the maximum value of the *GDI* index is in the range [1;2], where the value 1 indicates no correlation between the maximum wind speed gust and the wind direction gust, and the value 2 indicates full correlation between these.

The maximum *GDI* value relates to the ECD gust duration. In the present investigation four different duration periods defined by  $\Delta t=2, 5, 10,$  and 30 seconds, respectively, has been determined for each 10-minute period using a moving window technique. Figure 1 shows an example of a gust event, recorded in complex terrain. The figure illustrates how a negative wind speed gust (16m/s  $\rightarrow$  8m/s  $\rightarrow$  16m/s) correlates with a wind direction gust (320 deg.  $\rightarrow$  365 deg.  $\rightarrow$  320 deg.) during a gust duration time span of 5 seconds. Values of  $\Delta t \geq 5$  seconds typically represent a gust covering a 100m diameter rotor for high mean wind speeds.

In the present analysis *GDI* values larger than 1.98 are used as representative for fully correlated wind speed- and wind direction gust situations. The *GDI* range limit equal to 1.98 has been selected to obtain a reasonable amount of these compound gust events. A *GDI* value equal to 2.00 turned out to result in very few recordings satisfying this requirement, .

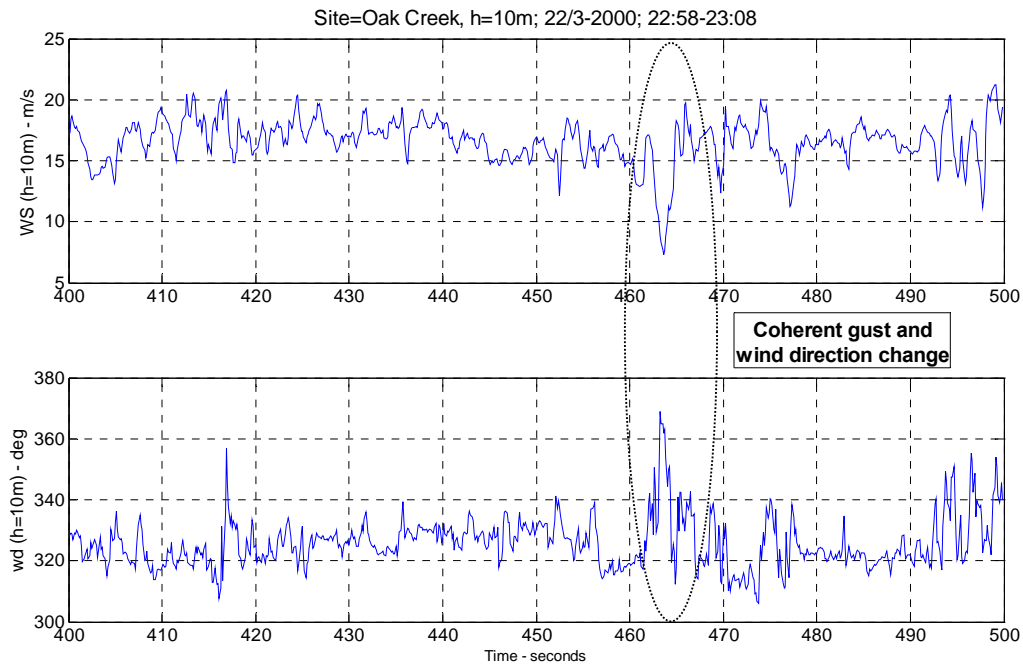


Figure 1: Example of a measured synchronous wind speed gust and wind direction change.

#### 4. Measurements

"Database on Wind Characteristics" [2] contains time series of measurements from more than 60 sites, representing a variety of different terrain types as documented in [4]. Based on huge amounts of 10 minute registrations, the probability of such joint gust observations, referring to different site types, has been shown on Figure 2. The figure indicates a high occurrence probability (PDF-value > 0.001) for a number of sites, but unfortunately not all sites are suitable for this analysis due to the vertical spacing criteria ( $\Delta h \leq 1$  m) for wind speed- and wind direction sensors, respectively, and furthermore some sites includes partly "disturbing" wind turbines, where the associated time series has to be discharged..

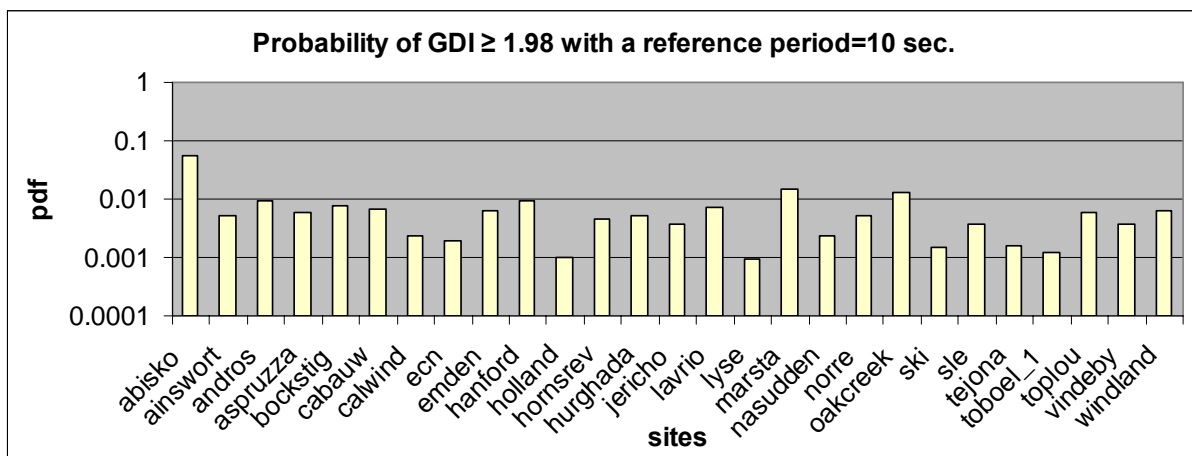


Figure 2: Probability of coherent gust and wind direction changes at different sites, with a gust rise time of 10 seconds, extracted from [2].

The results from initial counts at the different sites, shown on Figure 2, represent different measurement time periods, ranging from 50 to 20.000 hours. *GDI* values from sites with a comparatively large number of observations have been identified, and these are shown on Figure 3 in terms of gust size and wind direction changes - both as function of mean wind speed.

The recommended ECD gust amplitudes, which have to be used for design load calculations according to [3], are as follows:

- i) Wind speed gust amplitude:  $V_{cg}=15$  [m/s];
- ii) Wind direction gust amplitude:  $Dir_{cg}=720/V_{hub}$  [°],

where  $V_{hub}$  denotes the mean wind speed at hub height. Both the wind speed gust amplitude and the wind direction gust amplitude refer to a 10-second rise time, and "cg" indicates a coherent gust.

*GDI* values larger than or equal to 1.98 have been used to identify coherent wind speed and wind direction changes for 4 different sites in Europe and USA, respectively. The results are presented on Figure 3 along with the IEC recommended value for the gust amplitudes in the mean wind speed range [15 m/s; 25 m/s].

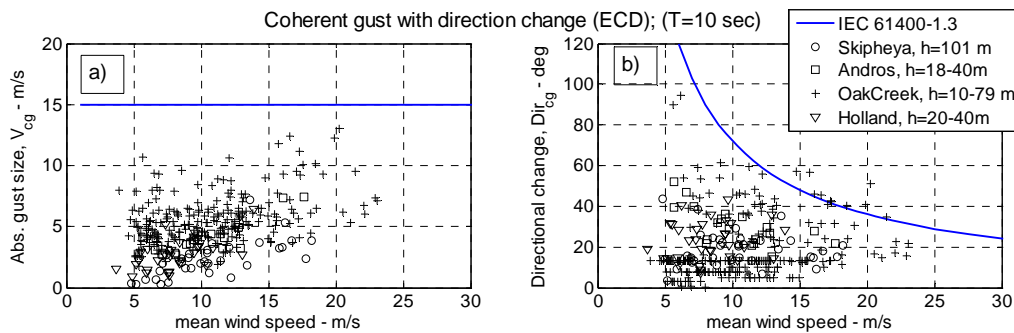


Figure 3: Measured fully correlated gust amplitudes for four different sites and the EDC values from IEC 61400-1.3; a) wind speed gust amplitude as function of mean wind speed; b) wind direction gust amplitudes as function of mean wind speed.

### 5. Data analysis

The gust measurements from the 4 locations, presented in Figure 3, are used to determine the extreme correlated wind speed- and wind direction gust amplitudes. An extreme value distribution can be determined for the positive gust values. The distribution of the largest value among  $N$  time series must asymptotically approach the distribution of the largest value within samples of size  $n$ , provided that an asymptotic distribution exists. An extreme value (Gumbel) distribution, EV1, satisfying these requirements can be derived [5], and initially we will assume that the observed extremes can be described by an EV1 distribution.

The extreme gust amplitudes ( $V_{cg}$ ), conditioned on the hub mean wind speed, will thus be distributed according to a cumulative probability density (CDF) function with two parameters ( $\alpha, \beta$ ) as:

$$F(V_{cg}; \alpha, \beta) = \exp(-\exp(-\alpha \times (V_{cg} - \beta))) \quad (2)$$

The associated probability density function (PDF), is given by:

$$f(V_{cg}; \alpha, \beta) = \alpha \times \exp(-\exp(-\alpha \times (V_{cg} - \beta))) \times \exp(-\alpha \times (V_{cg} - \beta)) \quad (3)$$

Having estimated the EV1 distribution, corresponding to a return period  $T$ , the extrapolation to an (arbitrary) return period  $pT$ , is performed based on an independence assumption in a binomial process. For large  $p$  the determination of the *most likely* extreme event associated with the return period  $pT$  is especially simple as it equals the amplitude value associated with quantile  $(1-1/p)$  in the EV1 distribution associated with the return period  $T$ . This result will be used in the following data analysis based on gust measurements recorded at the Skipheya site, at 101m altitude.

### Skipheya, h=101 m

The fully correlated wind direction gust amplitudes, measured at Skipheya ( $h=101$  m) Norway, are shown on Figure 4 as function of the associated positive wind speed gust amplitudes. Only  $N_c=65$  fully correlated events with  $GDI \geq 1.98$  have been identified out of a total population of  $N_t=43671$  recordings, where each recording represents a 10-minute period. Each gust event is defined with reference to a 10 seconds rise time.

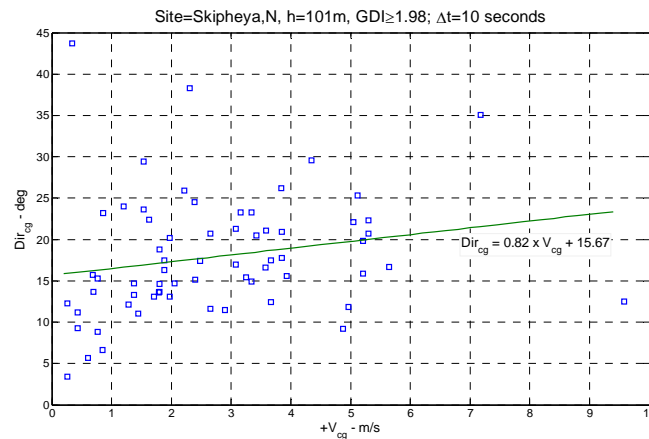


Figure 4: Fully correlated gust amplitudes recorded at Skipheya ( $h=101$ m) associated with a 10 second rise time.

Based on the data presented in Figure 4, a least square linear relationship between the observed wind speed- and wind direction amplitudes can be expressed as

$$Dir_{cg} = 0.8 \times V_{cg} + 15.7 \quad , \quad (4)$$

which indicates a modest correlation between wind speed- and wind direction gust amplitudes, respectively, for the investigated compound gust event.

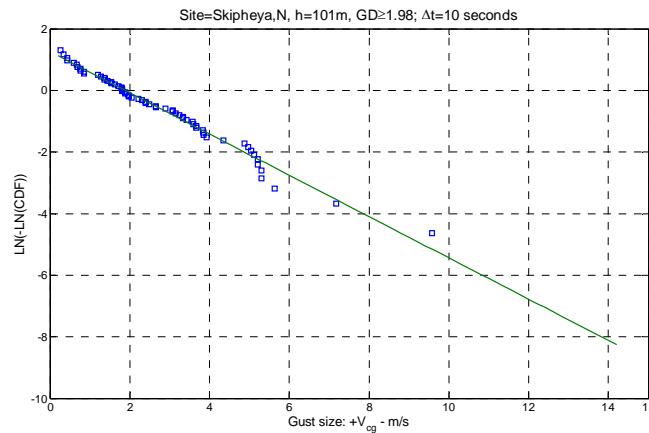


Figure 5: Linear fit of distributions parameters.

Although some scatter is seen around the linear fit in Figure 5, the fit is interpreted as the most likely relationship between fully correlated wind speed gust amplitudes and wind direction gust amplitudes, and subsequently used to reduce the two dimensional PDF of wind speed- and wind direction amplitudes to a one dimensional PDF, on which conventional extreme value estimation techniques can be applied. Ideally, fully 2D extreme value estimates conditioned on the mean wind speed should be conducted, but due to the limited size of the available data population such an investigation has presently not been possible.

The distribution of the wind speed gust values fits well to an EV1-distribution as demonstrated on Figure 5, and the estimated EV1-distribution of the wind speed gusts amplitudes is shown on Figure 6.

The basis time series length of the Skipheya data material is  $T = 10$  minutes. However, as the fully correlated wind speed- and wind direction gust events are rare events, such events are not realized within each of the analyzed 10-minute time series. As a consequence, an *apparent basic return period* equal to  $T_a = (N_t / N_c)T$  must be applied when extrapolating to a 50 year recurrence period. Thus, the relevant quantile, resulting in the 50 year most likely gust amplitudes, is given by  $P_{50cg} = 2.6 \times 10^{-4}$ .

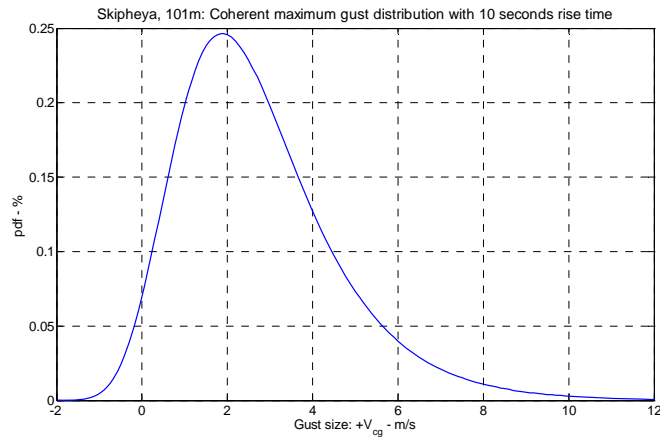


Figure 6: Distribution of extreme coherent gust amplitudes,  $\alpha=0.67$ ;  $\beta=1.88$ .

Based on the estimated PDF shown in Figure 6, corresponding to an apparent ( $N_i/N_c$ ) 10-minute recurrence period, the most likely wind speed gust amplitude ( $V_{cg}$ ), associated with a recurrence period of 50 years, is estimated to 14.2 m/s. Assuming the linear relationship between wind speed- and wind direction amplitudes expressed in (4), the wind direction gust amplitude, associated with a 50 year recurrence period, for the fully correlated event is estimated to  $Dir_{cg} = 27$  deg.. Note, that the above results are conditioned on a rise time equal to 10 seconds. In general, the correlation between wind speed- and wind direction gust amplitudes is weak (cf. Figure 4) – the only exception is the data originating from "Holland".

**Estimated extreme wind speed gust values**

In the present section the extreme gust amplitudes, as resulting from the previous analysis of the fully correlated wind speed- and wind direction events, are compared with a conventional extreme value analysis of isolated wind speed gust events. A priori, the resulting extreme wind speed gust amplitudes are expected to exceed the wind speed gust amplitudes associated with the fully correlated event, as no restrictions are imposed on the selection of the wind speed gust extremes extracted from all available 10-minute series. This is confirmed from the results presented in Table 1, where  $V_{gust}$  denotes the extreme wind speed amplitude associated with wind speed gust events only.

**Table 1:** Estimated 50 year gust amplitudes.

Extremes, with rise time 10 sec.	$V_{gust}$	$V_{cg}$	$Dir_{cg}$
	(isolated)	(correlated)	(correlated)
Skipheya, N; h=101; $N_c=65$ ; $N_i=43671$	18.7 m/s	14.2 m/s	27 deg.
Andros, GR, h=18-40m; $N_c=34$ ; $N_i=3642$	18.7 m/s	13.4 m/s	44 deg
OakCreek, USA, h=10-79 m; $N_c=70$ ; $N_i=12552$	32.5 m/s	22.8 m/s	73 deg
Holland, USA, h=10-40m; $N_c=73$ ; $N_i=28396$	21.2 m/s	12.7 m/s	76 deg

Identification of the extreme correlated events requires a huge amount of suitable measurements, as the combined fully correlated event is rare. The number of observed fully coherent events ( $N_c$ ) is small compared to the total number of investigated time series ( $N_i$ ) as listed in Table 1.

## Discussion

The maximum wind directional change during 10 seconds is 27 - 76 degrees according to Table 1. The load consequences of such short-term yaw values are not likely to be eliminated by the wind turbine yaw control system, because a standard yaw controller uses longer averaging periods (i.e. 20 - 100 seconds).

## 6. Conclusion

The estimated wind speed gust amplitudes  $V_{cg}$ , associated with fully correlated wind speed- and wind direction gust, correspond well to the recommended ECD value of 15 m/s, except for the complex terrain (Oak Creek; USA), where estimated extreme wind speed gust amplitudes are seen to exceed the IEC value with approximately 50%. The respective estimated extreme wind direction gust amplitudes, associated with the investigated European sites, are low compared to the recommended IEC- values. However, it should be noted that these values are believed to be encumbered with a relatively larger uncertainty than the wind speed gust amplitudes due to the approximate approach taken to reduce the 2D extreme value problem to a 1D one. This approach was taken due to limited number of fully correlated measurements in the available data material, which in turn prevented a fully 2D extreme value analysis conditioned on the mean wind speed from being conducted.

As described the present analysis has collapsed a 2D extreme value problem to a 1D extreme value problem formulated in the wind speed variable. However, another, equally logical, choice would be to collapse the 2D problem to a 1D extreme value problem formulated in the wind direction variable. This is a topic for future investigation, as is a consistent full 2D extreme value analysis if a suitable data material becomes available. One obvious possibility to extend the data material is to relax the *GDI* threshold from the present 1.98 to a lower value. This approach would, however, in turn imply supplementing investigations of the sensitivity of the results to the threshold definition.

## 7. Acknowledgement

This analysis has benefited from measurements downloaded from the internet database: "Database of Wind Characteristics" located at DTU, Denmark. Internet: "<http://www.winddata.com/>". Wind field time series from the following sites have been applied: Andros, Greece (CRES, GR); Oak Creek, CA (Risø National Laboratories, Denmark); Holland, MN (NREL, US) and Skipheia (Norwegian University of Science and Technology, Norway). The Database on Wind Characteristics has been initiated by EU and IEA. Operation and maintenance are currently funded by the Technical University of Denmark, DTU and Risø National Laboratories, Denmark.

## 8. References

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