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Measurements of downburst wind loading acting on an overhead transmission line in Northern Germany

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Abstract

Along an overhead transmission line in Northern Germany, a unique instrumentation of anemometers and force measurements is installed. Details of this test line with wind measurements along a horizontal axis are given. A recent event of a presumable downburst wind event is analyzed by means of available data and precedent works on thunderstorm analysis. The measured response of the conductors at the suspension tower is investigated and compared with time domain simulation of a finite element model.

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1. Introduction

Overhead transmission lines subjected to synoptic winds are under investigation for a long time now but only recently focus is drawn on the specific behavior under thunderstorm loading [1]. With increasing number of structures as well as an increasing number of heavy thunderstorms occurring in Central Europe, it seems to be appropriate to draw attention to the vulnerability of these wide spanning structures of special public interest. In autumn 2015, a severe downburst developed during a thunderstorm in parts of Germany. In consequence transmission line towers collapsed due to the unexpected overload. In a further distance at a close time, the thunderstorm touched an overhead line equipped with sophisticated measurement systems to capture the horizontal distribution of the wind field acting on the conductors as described in earlier works [2]. From the data, the characteristics of a presumable downburst can be observed with the wind speeds recorded at twelve positions along the line, as well as the dramatic temperature drop, which is inherent to that phenomenon. Comparable recent studies

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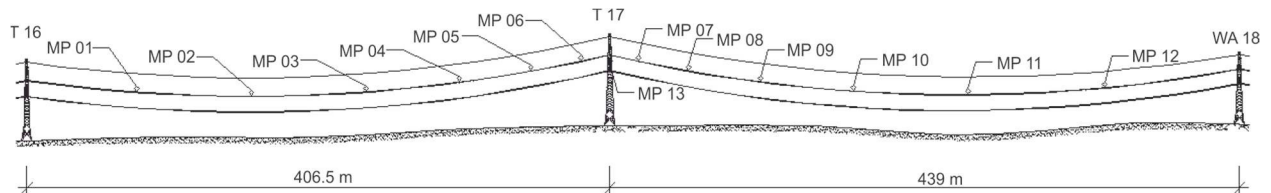


Fig. 2. Elevation of test section with measurement points.

are reviewed and methods are transferred and applied to the observed wind event with results presented in the following work. Finally, the measured response of the conductors of the overhead line is compared with FEM simulation.

2. Measurements along an existing overhead line

2.1. Test section and measuring equipment

To capture the incoming wind field, 13 anemometers are installed along two spans of an existing overhead transmission line of 380 kV, see Fig. 2, situated in Northern Germany. Vertical wind components are considered to be negligible; hence 2D ultrasonic anemometers are used together with inclinometers to measure the vertical misalignment of the sensors. So, wind speed is recorded by its horizontal components normal and parallel to the line direction. In between the two spans the system's response is measured by means of the sway angle of the insulator chain at the suspension tower T17. A more detailed presentation of the section can be found in [3]. Wind measurements are carried out on the upper electrical conductor while the response is measured on the lower one which is considered undisturbed by the sensors. Further measurements of temperature and strain in tower members complement the measurement campaign. Signals are continually recorded with sampling rate of 25 Hz, transmitted and stored in 1 h time histories.

2.2. Observed non-synoptic wind event

On 5 July 2015, a severe thunderstorm was recorded at the above described station. Simultaneous data of wind speed were obtained from 12 sensors (MP 02 was out of order at that time) together with temperature measurement and sway angle of the insulator chains at MP 13. Fig. 1 (left) shows the measured time histories of wind speed recorded along the line with their respective horizontal distance for the time of 30 min. At the beginning, wind speed

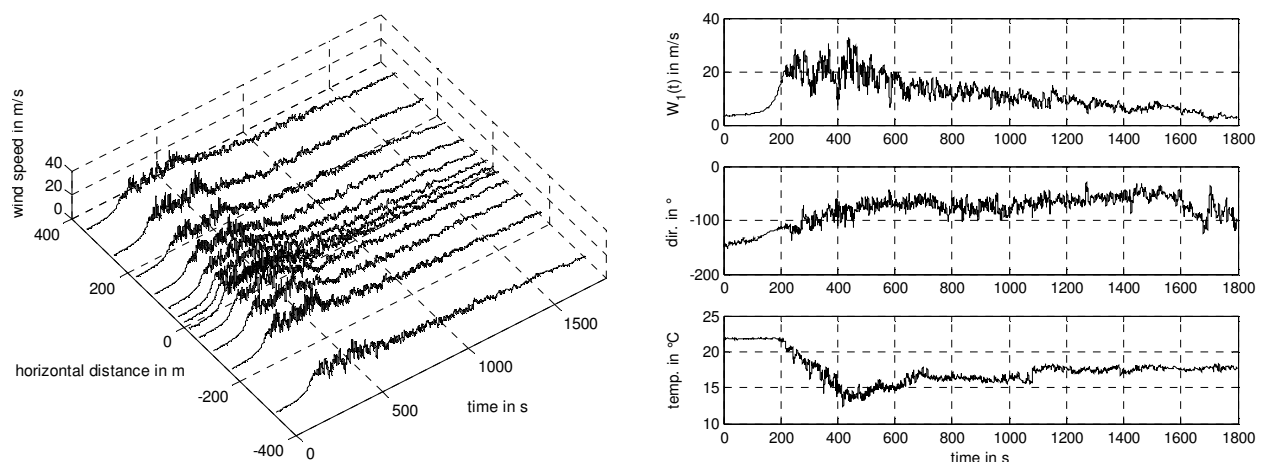


Fig. 1. Wind speed time histories from measurements on 12 positions along the test line (left) and simultaneous time histories of wind speed and wind direction and temperature at location MP 01 (right).

is almost zero, then velocities increase rapidly almost simultaneously up to 20-30 m/s accompanied by an increase in turbulence. That level of wind speed is kept for less than 10 min before the wind speeds decrease slowly.

A closer look into the time history of wind speed at MP 01 together with wind direction and temperature is given in Fig. 1 (right). The vector of wind velocity W_i at point i , $W_i(t) = \sqrt{U_i^2(t) + V_i^2(t)}$ is assumed to be composed by its horizontal components normal and parallel to the line direction, U_i and V_i , which also coincides with the main wind direction which is almost normal to the line (wind direction of 90°) for the largest values of wind velocity. The duration of highest wind speeds of a few minutes together with changing direction of wind and a significant drop of temperature indicates on a downdraft in consequence of a thunderstorm. Whether this is an observation of a downburst, as described in detail in [4] and which was reported at the location of tower failures in a close region of Germany is not yet determined. Further investigation of the records is needed to answer this question with confidence. Since the velocity component lateral to the line direction is negligible for overhead transmission lines and the governing wind direction can be considered orthogonally to the line direction, the following investigations shall focus on the component normal to the line, U . The non-stationary process of wind velocity is therefore decomposed into a time varying mean and fluctuating part, $U(t) = U_m(t) + U'(t)$.

3. Time-varying mean wind and response

3.1. Moving average filter

As a simple method to retrieve the running mean from a nonstationary process, a moving average filter is chosen [5]. Averaging times are adapted to the filtering outcome, resulting in a nearly zero-mean fluctuating part after subtraction and at the same time retaining the random characteristics of turbulence at low frequencies. After a thorough investigation of different time intervals, an averaging time of 30 s is chosen [6], considering fluctuations at frequencies lower than 0.03 Hz to be deterministic describable by the moving average, while fluctuations with higher frequencies are due to the randomness of turbulence which is in accordance with previous studies [7]. Fig. 3 shows the exemplary result for one sensor of time-varying mean wind speed and the resulting turbulent part after subtraction.

3.2. Estimation of mean response

Under quasi-static assumptions, the mean response can be estimated by the well-known equation for aerodynamic pressure over a reference surface with diameter d and length L , as given in Eq. (1). The issue with nonstationary processes is that generally assumed constant parameters, such as temperature and mean values are suddenly dependent on time. Air density ρ is directly linked with temperature, drag coefficients c_d are taken from previous studies [2]. A time varying mean of the all the twelve mean signals is taken as the reference mean wind speed U_m . Since the response is measured by means of the sway angle, the gravity force F_G of the conductors is calculated based on the catenary at the given temperature, giving the mean sway angle as in Eq. (1).

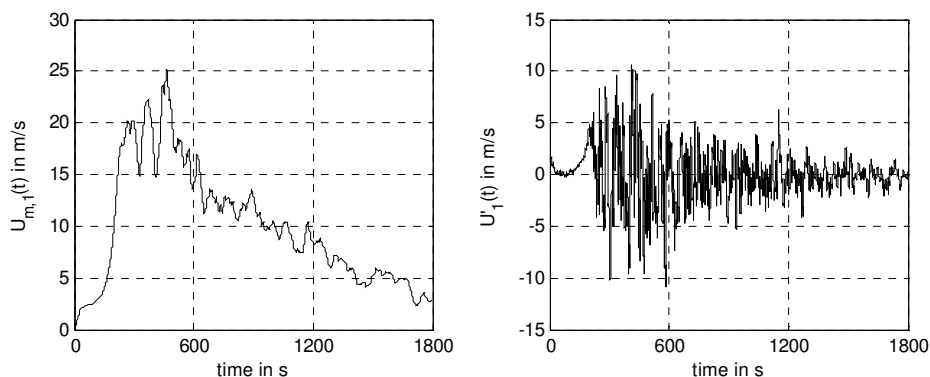


Fig. 3. Time-varying mean wind speed and resulting fluctuating part of MP 01.

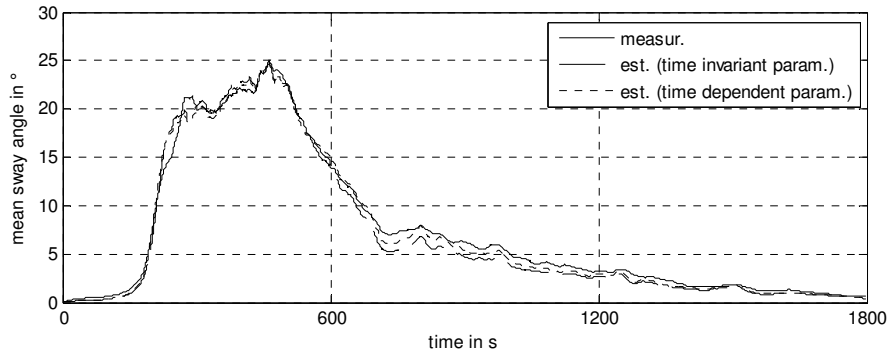


Fig. 4. Time-varying mean response of observations and estimations with time invariant and time dependent parameters.

$$\Phi_m(t) = \arctan \frac{R_m(t)}{F_G(t)} \quad \text{with} \quad R_m(t) = \frac{1}{2} \rho(t) c_d(t) d L U_m^2(z, t) \quad (1)$$

Fig. 4 opposes the mean response from measurements and estimation with assumed constant values $\rho = 1.25 \text{ kg/m}^3$, $c_d = 1.0$ and $F_G = 21.5 \text{ kN}$ and time-varying parameters. It can be shown that difference between the two estimation methods can be attributed mainly to the drag coefficient. All other parameters do not change that much in the range of temperature during that event and presumably any realistic situation. From the quite good agreement between observation and estimation it is concluded that the mean response can accurately be described by quasi-static theory under linear assumptions.

4. Wind turbulence and peak response

4.1. Turbulence intensity and power spectral density

The residual time histories, after subtracting the slowly time-varying mean can be analyzed regarding the turbulence intensity $I_u = \sigma_u/U_m$ as the ratio of standard deviation σ_u and mean wind velocity U_m for stationary processes. Analogically to extracting the mean value by a moving average, the standard deviation is extracted from running windows of 30 s. It was found that both running standard deviation and turbulence intensity are time sensitive. The turbulence intensity is varying between 0.1 and 0.3 for the time of observation which is in accordance with past analyses of that kind [5]. That is why, turbulence intensity is assumed an unsuitable instrument to evaluate turbulence.

Another valid estimate is the power spectral density (PSD) of turbulence. Welch's method [8] for estimation is used for a time window between 100 to 700 s. It is inherent to that method, that estimates are averaged over segments and therefore smoothed over the interval of interest. Fig. 5 is giving the estimation result for one measurement point together with theory of spectral density of random turbulence of a synoptic wind as given by the von Kármán spectrum S_{uu} as in Eq. (2) with variance σ_u^2 and mean wind velocity U_m as the maximum average values estimated before and $L(z) = 100 \text{ m}$. The agreement is quite good, which is in accordance with previous findings [5] although using time varying parameters of a non-ergodic process requires some adaptations and further discussion. It might be concluded that spectral theory, which was developed for boundary-layer winds also be applicable to describe non-synoptic wind events. But still attention is drawn to the fact, that low frequency turbulence is treated as part of the time-varying mean wind speed in this work which is only dependent on the time interval chosen for the moving average filter. Other analyzing methods might lead to different results, see e. g. [9].

$$\frac{f S_{uu}(f)}{\sigma_u^2} = \frac{4 \frac{f L(z)}{U_m}}{\left(1 + 70.8 \left(\frac{f L(z)}{U_m}\right)^2\right)^{5/6}} \quad (2)$$

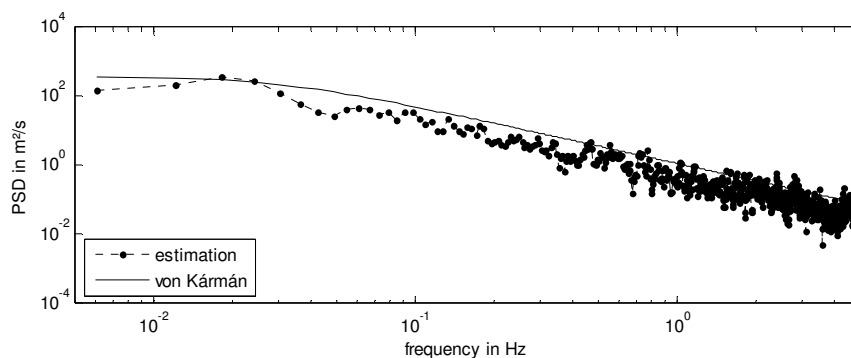


Fig. 5. Power spectral density (PSD) of wind turbulence estimated for MP 03 and *von Kármán* spectrum.

4.2. Lateral cross correlation

One measure to describe the spatial correlation is the cross-correlation coefficient which is defined independent of frequency by using cross and auto-correlation of two signals. Table 1 summarizes the results of correlation coefficients when applying to unfiltered, time-varying mean and turbulent time histories of wind speeds at two measurement points each. Cross correlation of running mean is always larger than the cross correlation of unfiltered signal which is a good indicator that the extracted mean is mainly deterministic without any random part due to boundary layer turbulence. Whereas the small but still relatively large values of cross correlation coefficients compared to previous findings [9] might indicate that a deterministic mean is still present in the turbulent part.

Table 1. Results of estimated and cross correlations coefficients for pairs of measurement points (MP).

Pair of measurement points	Horizontal distance	Cross correlation coeff. for unfiltered signal	Cross correlation coeff. for running mean	Cross correlation coeff. for turbulent signal
MP 06 and MP 13	20 m	0.979	0.993	0.5171
MP 13 and MP 07	20 m	0.977	0.992	0.469
MP 05 and MP 06	35 m	0.987	0.998	0.454
MP 07 and MP 08	35 m	0.990	0.999	0.464
MP 06 and MP 07	40 m	0.987	0.997	0.356
MP 08 and MP 09	50 m	0.987	0.998	0.378

4.3. Peak response

A model of the examined overhead line section was previously built by finite element method and described and calibrated for synoptic winds with stationary characteristics [2]. In that model, aerodynamic damping is incorporated in the equation of motion by the relative velocity of structure and wind. That same model shall be used to investigate the dynamic behavior of conductor cables under non-synoptic wind excitation. For that purpose, the model is built with 24 nodes only to include the measurement points of wind speeds as excitation. The resulting sway angle is compared to the observation in Fig. 6.

From the comparison of measured and simulated time histories of the conductors' response to the investigated wind event, it might be concluded that the response is well reproduced. The maximum response of 31.6° and 33.5° is in good agreement. The parallel progress over time is governed by the well reproduced time-varying mean response as also stated before. Some differences can be observed regarding the characteristics of the random part of the response which should be investigated in future work more thoroughly with regard to the peak response [10].

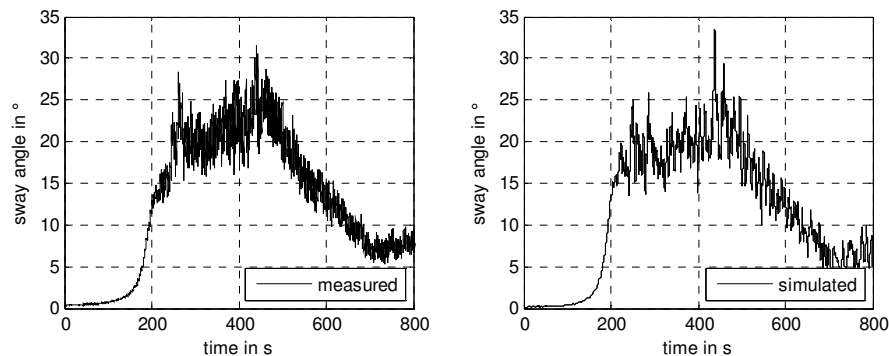


Fig. 6. Time histories of sway angle measured (left) and simulated (right).

5. Conclusion

In this work, preliminary analyses of a nonstationary wind process of a presumable thunderstorm were presented. Investigations suggest that the wind event was a so-called downburst, which was analyzed according to the current state of knowledge. Further research is planned to classify the specific wind event and validate common standard wind assumptions. Focus should lie on the relevance of consideration for horizontally extended structures such as overhead transmission lines. A finite element model of an overhead transmission line was used to compare the measured response with modelling assumptions previously validated for synoptic wind events in time domain. The results are promising and more research is planned to investigate the impact of such wind events on a growing network of overhead transmission lines accompanied with an increasing risk of local wind events like thunderstorms threatening the structures. More knowledge of the relevant characteristics of such local winds is necessary to evaluate the reliability of the supporting structures such as suspension towers.

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