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WIND MEASUREMENTS ALONG A HIGH-VOLTAGE OVERHEAD TRANSMISSION LINE IN NORTHERN GERMANY

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ABSTRACT

The paper focuses on a recently launched project of wind measurements along a high voltage overhead transmission line. For reliable information on the actual horizontal distribution of the wind flow, 13 positions along two spans of an overhead electrical line of about 400 m length each are selected for wind measurements. Simultaneously, the structural response is measured at the towers. Preliminary analyses aim at the system identification of long span transmission lines exposed to gusty wind by derivation of a so called joint acceptance function which describes the admittance from wind velocity to the system’s response. It can be shown that measured structural response can accurately be described using a statistical model which accounts for the irregularity of the wind as well as the structure’s behaviour.

Keywords: overhead transmission lines, wind loading, field measurements, monitoring

INTRODUCTION

Big interest lies in determination of fluctuating wind forces transmitted by the cables to the suspension tower of wide span overhead transmission lines. Various attempts have been made to describe this random process but still the behaviour of the cables under strong winds is not yet clarified satisfyingly. Wind tunnel experiments can only help to clarify within the boundaries of model uncertainties (Loredo-Souza, 2001), whereas results of numerical models need to be validated by field measurements (Paluch, 2007).

In the framework of a sponsored research project headed by BAM Federal Institute for Materials Research and Testing, wind measurements are conducted along an approximately 800 m overhead transmission line section close to Rostock, Germany. Those measurements provide a dense grid of the real wind acting on the conductors and are recorded by 13 ultrasonic anemometers being installed directly on the conductor bundles on their spacers (see Fig. 3). The resulting wind forces are measured simultaneously by means of the sway angle of the insulator chains at a suspension pole situated in the middle of the section.

Statistical concepts to evaluate wind loads on transmission lines as suggested by Davenport (Davenport, 1979) are based on the assumption of linear systems and a known probability distribution of the system’s response. Due to high aerodynamic damping of a hanging cable, assuming linear characteristic can be shown true for the analysis of the support reaction (Matheson, 1981). In addition, linear characteristics are forwarded by a spare correlation of gusts along the wide span resulting in a low ratio between fluctuating and mean response of the system. The validity of these aspects is investigated in the presented paper using data from field measurements.

TEST SECTION AND MONITORING CONCEPT

The equipped line section is situated close to Rostock, Northern Germany and runs from south-east to north-west. Wind blowing lateral to the line direction from south-west passes a rather urban terrain, passing Rostock and its suburbs. Wind from the opposite direction, wind from north-east passes over open country and farmland (see Fig. 1).

Fig. 1 Satellite picture of test section and surrounding area

The two dimensional anemometers are fixed on additional spacers and are placed directly on a four conductor bundle and are distributed with different distances along two spans on both sides of a suspension tower (see Fig. 2).

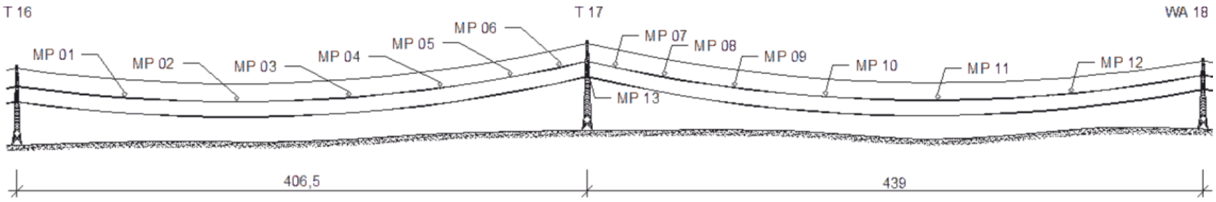

Fig. 2 Sensors' positions in vertical view of the line (true to scale)

The ultrasonic anemometers installed on the line are subjected to the movements of the cable. To overcome that source of erroneous measurements, the anemometers are equipped with inclinometers. Neglecting the error from measuring the vertical component of turbulence, the measured wind velocities u^* are corrected by the instantaneous measured angle of the sensor φ^* as in Eq. (1). It was found in simulations and as well from in situ observations by web cams that lateral movements of the cable are negligible due to the high inertia of masses in movement.

$$u = \frac{u^*}{\cos\varphi^*} \tag{1}$$

For the design of suspension towers the wind load on conductors is crucial. Wind forces are measured by means of sway angle of the insulator strings at the suspension tower in the middle of the test section (see Fig. 3). The measured sway angle represents the response of the cables due to wind action.

Fig. 3 Overview of measurement equipment around suspension tower

STATISTICAL MODEL OF TEST LINE

Generally, the system's response is separated into mean response $\bar{R}$ and standard deviation σ_R describing the fluctuating part. In a subsequent step, in order to determine the peak response a magnified standard deviation has to be considered by multiplication with a statistical peak factor k_p depending on the nature of the dynamic part of response (Davenport, 1979).

$$\max R = \bar{R} + k_p\,\sigma_R \tag{2}$$

The mean response is directly linked to mean wind velocity $\bar{u}$ by considering the general formula for wind force and neglecting higher order parts of fluctuating wind velocities u'.

$$R(t) = F(t) = \frac{1}{2}\,\rho\,c_f\,A\,(\bar{u}+u')^2 \cong \frac{1}{2}\,\rho\,c_f\,A\,\bar{u}^2 + \rho\,c_f\,A\,\bar{u}\,u' = \bar{F} + F' \tag{3}$$

The fluctuating wind velocities are usually analyzed in frequency domain. The theoretical approach by Davenport (Davenport, 1995) can be seen as an effort to generalize the fluctuating part of wind loading of structures. The concept makes use of admittance functions to transmit wind excitation to force spectra in frequency domain. Fig. 4 illustrates this general procedure.

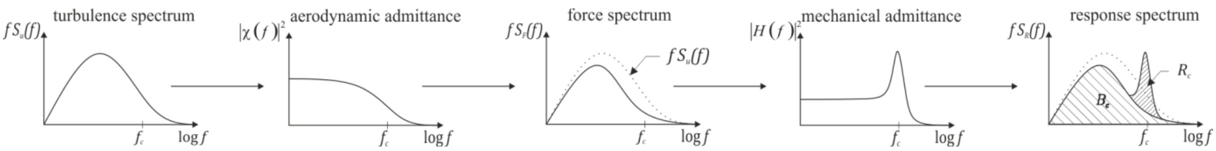

Fig. 4 From wind excitation to force spectrum in frequency domain (Davenport, 1995)

Admittance functions can be expressed by structural assumptions on the system's behaviour such as linearity. That seems not to be applicable on overhead transmission lines but it can be shown by simulation that assuming linearity is justified regarding the support reaction of sagging cables (Matheson, 1981). Accordingly, disregarding any resonant amplification the admittance can be described using a so called joint acceptance function $|\mathrm{JAF}|^2$ expressed by means of coherence $\gamma^2(\Delta y)$ of wind excitation and the influence line $i(y)$ of the structure (Dyrbye, 1997), where y is considered the location on the line with length l.

$$|\mathrm{JAF}|^2 = \frac{\int_0^l \int_0^l \gamma^2(\Delta y)\, i(y_1)\, i(y_2)\, dy_1 dy_2}{\left(\int_0^l i(y)\, dx\right)^2} \tag{4}$$

The coherence function $\gamma^2(\Delta y)$ as assessed in Eq. (5) accounts for the irregularity of wind velocity along the line, characterised by the integral scale of turbulence ${}^{y}L_u$ while the influence line allows for the static impact of the location of the acting wind gusts.

$$\gamma^2(\Delta y) = \exp\left(-\frac{\Delta y}{{}^{y}L_u}\right) \tag{5}$$

Assuming a linear system of a two-span beam representing the strained line for lateral impact, the according influence line can be found in Fig. 5.

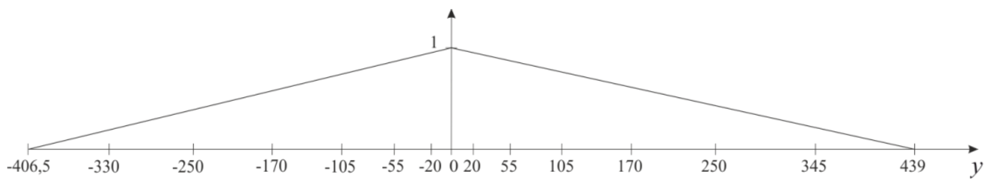

Fig. 5 Influence line of support reaction at suspension tower in the middle of test line (m)

The double integral in Eq. (4) needs to be solved numerically. This can be avoided by approximation of an easier formulation of the joint acceptance function as done in Eq. (6).

$$|\mathrm{JAF}|^2 = \frac{2}{0{,}7\,\lambda} + \frac{2}{(0{,}7\,\lambda)^2}\left(e^{-0{,}7\,\lambda} - 1\right)$$
$$\text{with } \lambda = \frac{L}{{}^{y}L_u} \tag{6}$$

In Fig. 6 both the numerical solution as well as the approximation is displayed. As seen out of the comparison, the approximation shows to be a useful simplification in this case.

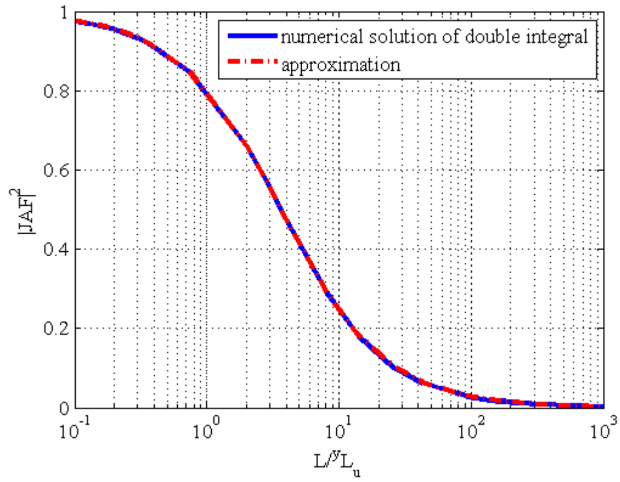

Fig. 6 Joint acceptance function

To describe the resonant amplification in the mechanical admittance of Fig. 4, the system can be linearised and thereby the well known mechanical admittance function can be applied (Bendat, 2000), where k signifies the system's linear stiffness, f_0 the natural frequency and ξ the damping ratio.

$$|H(f)|^2 = \frac{1}{k^2} \frac{1}{\left|1-\left(\frac{f}{f_0}\right)^2\right|^2 + 4\,\xi^2 \left(\frac{f}{f_0}\right)^2} \tag{7}$$

Generally values of damping are determined by standards or other technical guidelines. For the case of sagging cables values of structural damping are low while aerodynamic damping gets very high (Kadaba, 1988) so that the amplification due to resonance is reduced. It is found that for the support reaction of cables of transmission lines the resonant part of the fluctuating response is negligible (Holmes, 2008).

COMPARISON OF EXPERIMENTAL RESULTS WITH THEORETICAL APPROACH

The mean values of measured wind velocity are estimated as the average of means from all 13 sensors. In Fig. 7 the mean values of wind forces derived from measured sway angles are displayed against the respective mean wind velocities. There is a very good agreement with the theoretically determined values according to the corresponding part of Eq. (3) $\bar{F} = 1/2\ \rho\, c_f\, A\, \bar{u}^2$.

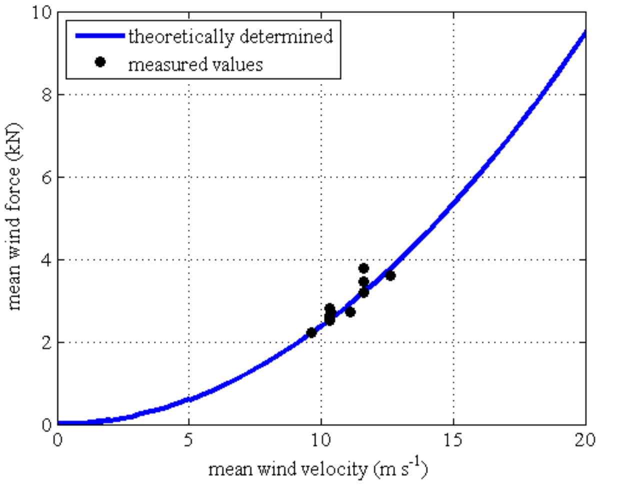

Fig. 7 Mean wind force according Eq. (3) against mean wind velocity

The fluctuating wind velocities are analyzed in frequency domain. The power spectral densities are estimated from the measurements according Welch (Welch, 1967) and are displayed in Fig. 8 together with spectral density suggested by von Kármán. Both spectra show the typically high energy content for low frequencies. The first natural frequency of the pendulum mode of the sagging cables is to be expected around 0.1 Hz.

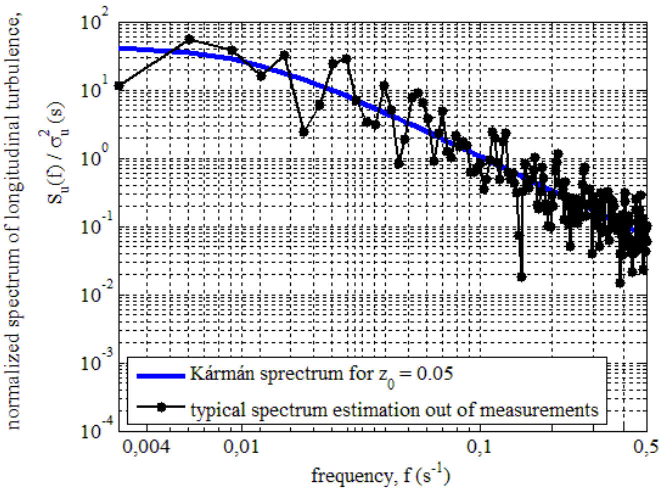

Fig. 8 Example of typical turbulence spectrum

For evaluating the fluctuating part, the assessment of the integral scale of turbulence ${}^{y}L_{u}$ is required in Eq. (5). Therefore the equivalent cross-correlation coefficients $\rho_{1,2}$ are estimated out of two measurements u_1 and u_2 respectively according Eq. (8) (Ruscheweyh, 1982) which is equivalent to the coherence as formulated in Eq. (5). Fig. 9 shows the discrete coherence values between relevant sensors up to 100 m distance. The value for the integral scale lateral to the wind direction is estimated by approximation of an exponential function as given in Eq. (5) using best fit.

$$\rho_{1,2}(\Delta y) = \frac{\frac{1}{n}\sum_{i=1}^{n}(u_1' u_2')_i}{\sqrt{\left(\frac{1}{n}\sum_{i=1}^{n} u'^2_1\right)\left(\frac{1}{n}\sum_{i=1}^{n} u'^2_2\right)}} \tag{8}$$

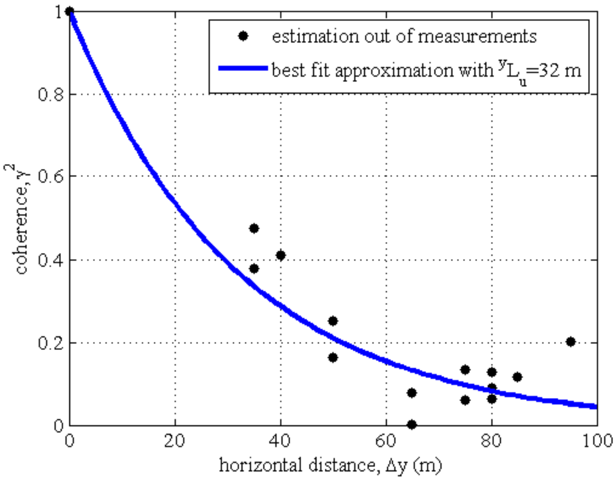

Fig. 9 Integral scale estimation

The estimated integral scale value can be used to approximate the standard deviation of the fluctuating part of the response by means of the joint acceptance function which is called the background response σ_b. The background response is derived by transformation and evaluation of Eq. (3) in frequency domain which results in Eq. (9).

$$\sigma_b^2 = \left(\rho\, c_f\, A\, \bar{u}\right)^2 \sigma_u^2\, |\mathrm{JAF}|^2 = 4\, \bar{R}^2\, I_u^2\, |\mathrm{JAF}|^2 \tag{9}$$

Fig. 10 includes an approximation of the response spectrum using only the presented background response, using the standard deviation of the turbulent wind velocity σ_u or rather the turbulence intensity as the ratio of standard deviation and mean wind velocity $I_u = \sigma_u/\bar{u}$.

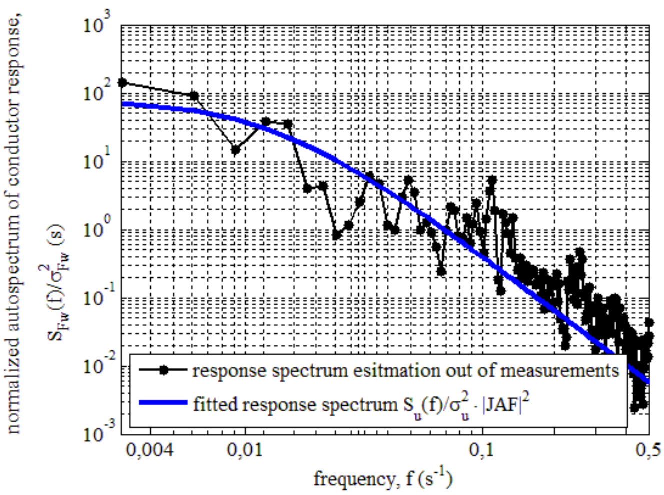

Fig. 10 Example of typical response spectrum estimation

There is a small peak in the response spectrum at the expected natural frequency of 0.1 Hz as it can be seen in Fig. 10. But with assumingly large values of aerodynamic damping, this resonant part of the fluctuating response is always very low.

RESULTS

Table 1 lists some results of analyzed wind events regarding the standard deviation of the structure's response. The measurements show a wide scatter of standard deviations. But the assessment of background response using the presented method shows to be a proper tool to describe the observations.

Table 1 Measurement results for selected observed wind events

Event (10 min)	**Mean response $\bar{R}$ (kN)**	**Turbulence intensity I_u (-)**	**Integral length scale ^yL_u (m)**	**Measured standard deviation σ_R (kN)**	**Background response σ_b (kN) estimated by Eq. (9)**	**Error [%]**
2	3,49	0,18	32	0,37	0,39	7
4	2,84	0,21	35	0,39	0,39	0
7	2,77	0,18	28	0,29	0,31	6
10	2,56	0,16	26	0,21	0,24	15
11	3,24	0,21	46	0,58	0,52	10

CONCLUSION

It could be shown by measurements that mean value and standard deviation of the support reaction of a wide span overhead transmission line due to wind loading can be described accurately taking into account observed wind parameters such as mean wind velocity, turbulence intensity and integral scale and the span. This conclusion is constraint to the rather low wind velocities of the observations as well as the length of the test section. Actually, further investigations are carried out to extrapolate those findings to other spans and to stronger wind events as defined in the standards for wind loading because linearity is not evident.

The sources for nonlinearity are manifold. On the one hand the force coefficient is assumed being constant for all wind velocities herein whereas it is known to be strongly dependent on Reynolds number. On the other hand the estimation of aerodynamic damping is valid for straight motion only. For the swinging cable that assumption can be shown to be erroneous.

Furthermore, the introduced peak factor is a factor from time domain, describing the probability of exceedance of a certain level. Design codes suggest values for the peak factor from 3.0 to 4.0. For those reasons, in order to extrapolate the observations at rather low wind speeds to wind speeds of design and to evaluate the peak factor correctly, time history analyses are indispensable. For enhanced design rules simulations are needed in order to correctly assess the nature of the response under design wind loading.

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