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Across-wind vibration on free-standing wind turbine towers based on field measurements

Ika Kurniawati [1], Francesca Lupi [1,2], Marc Seidel [3],
Rüdiger Höffer [1,2], Hans-Jürgen Niemann [1,2]

[1]Ruhr-Universität Bochum, Bochum, Germany, ika.kurniawati@ruhr-uni-bochum.de
[2]Niemann Ingenieure GbR, Bochum, Germany
[3]Siemens Gamesa Renewable Energy GmbH & Co. KG, Hamburg, Germany

SUMMARY

Further application of vortex-induced vibrations (VIV) prediction models to estimate across-wind vibration to a full-scale structure requires validation with field measurements. The natural characteristics of the wind profile and sectional vortex shedding load have not yet been fully explored with field measurements. A full-scale measurement campaign is being conducted in Østerild, Denmark, where both response and wind pressure are collected. One of the measurements is performed over a long period of time in a free-standing wind turbine (tower without nacelle) configuration with varying diameter, and many VIV events were recorded. This work focuses on experimental evidence for lock-in curve characteristics and the influence of the atmospheric boundary layer profile and turbulence intensity. Different lock-in curves in a data set can be addressed by different wind profile exponents and incoming wind directions that occur. Furthermore, sectional vortex shedding is investigated with ongoing analysis of pressure measurements at two different levels along the tower.

Keywords: Field measurement, Vortex Induced Vibration, Lock-in, Wind profile, Vortex shedding load

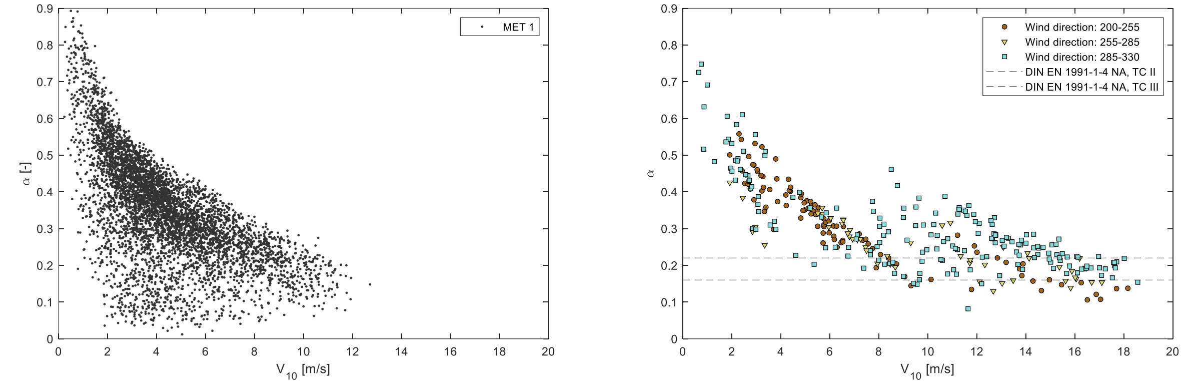
1. INTRODUCTION

Prediction methods for vortex-induced vibration (VIV) on slender structures such as industrial chimneys and wind turbine towers are continuously being developed. It is important to address not only the maximum response but also the shape of the lock-in curve, taking into account the vibrations characteristic found in nature. For example, the influence of the atmospheric boundary layer profile is important if the tower has varying diameter. Iterative development of the prediction method using full-scale measurement data and the natural wind load can provide more realistic insights. Some previous field tests on chimneys focusing on the study of across-wind vibration are referred to: (Christensen and Askegaard, 1978) investigated a 130 m long concrete chimney through pressure and response field measurements, presenting the measured resonance response in comparison with the mean wind speed. (Galemann and Ruscheweyh, 1992) investigated the VIV with evaluation of the measured lift coefficient on a 28 m long steel chimney. The measured maximum resonance amplitude was compared with the prediction method of (Ruscheweyh, 1986) and presented in comparison with the Scruton number. (Sanada et al., 1992) investigated pressure and tower response measurements out on a 200 m long concrete chimney and the wind force in across-wind and along-wind directions were studied in detail, and the tower response in resonance as a function of wind speed was briefly discussed. (Ellingsen et al., 2022) investigated the across-wind vibration due to VIV on a 35 m high steel chimney as a function of the mean wind speed and the occurrence was evaluated considering the incident wind direction. The wind profile is briefly discussed. Although full-scale measurements have been carried out since the last century, the data are still scarce. The evaluation of measured across-wind vibration in natural atmospheric boundary layer has yet to be fully exploited, and the evaluation of distributed oscillation over the height of the tower is novel. The consideration of the wind profile directly in the prediction and calculation can be further validated by a comprehensive full-scale measurement campaign, including sectional measurement of wind pressure. This work is part of a field measurement campaign that includes pressure and response measurements on wind turbine towers in a test centre in Østerild. Measuring masts and lidar are available to obtain as much information as possible about the wind condition and the atmospheric wind profile. The towers have a very smooth surface and a high Reynolds number range that gives a transcritical regime with the lowest drag. Measurements are performed on two different configurations: a free-standing wind turbine tower and including the RNA (rotor-nacelle-assembly) of the wind turbine. The aim of this paper is to present the recorded across-wind vibrations taking into account the wind profile, the Strouhal number determined from the pressure measurement and the measured lift coefficient. The sectional vortex shedding load is addressed based on the ongoing field pressure measurement. The observation in this work related to the nature of field measurement data should provide further insight into the development of predictive models.

2. FIELD MEASUREMENTS AND MEASURED ACROSS-WIND VIBRATION

Two wind turbine towers of Siemens Gamesa Renewable Energy are being measured, being D8 and SG 14-222 DD towers. Both towers have very smooth surface. The across-wind vibration measurement is carried out mainly on D8 being the tower with long period of free-standing configuration. The vibration is measured through strain gauges at the bottom and accelerometers at the top of the tower. Free-standing D8 tower is measured from July 2021 to April 2022, allowing many VIV events being recorded in various mean wind speeds that range up until 35 m/s.

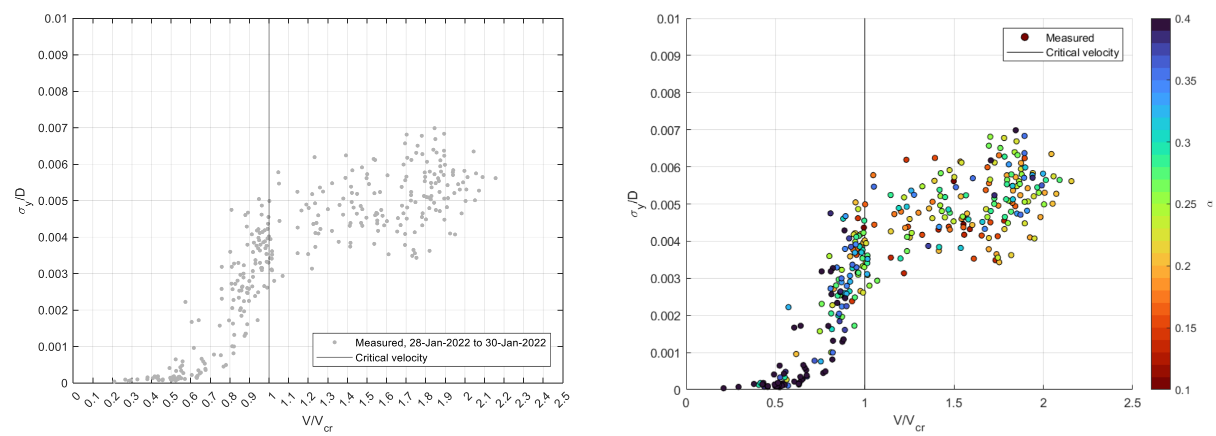
For the determination of terrain roughness, terrain categories II or III were expected. Figure 1a shows a distribution of estimated wind profile exponent α based on Hellmann profile (power-law) from each measured 10-minute mean wind speed. The distribution is obtained by evaluating 10-minute data points from 01-Feb-2022 to 14-Mar-2022. To simplify the evaluation, all the wind profile are assumed to follow a Hellmann profile, where in fact many different wind profile types had been identified in nature (Willecke, 2012). In the higher wind speed, the distribution is within a range of α=0.16-0.22. In the lower wind speed variations of wind profile exponent are expected and observed in Figure 1, making an evaluation to consider the wind profile to be necessary. Figure 1b shows the distribution of wind profile exponent from data set 28-Jan-2022 to 30-Jan-2022, where vibrations are also distinguished based on the incoming wind direction. For example, the vibrations with wind direction in range 285°-330° have larger α distribution in wind speed at 10 m height larger than 8 m/s, when compared to when the wind coming from 200°-255. It is known that the surrounding terrain in the 285°-330° sector are filled with more forests.



(a) (b)

Figure 1 Distribution of wind profile exponent estimated for Hellmann profile in respect to wind speed at 10-m height (V_{10})

On 28-Jan-2022 to 30-Jan-2022, wind speed ranges from $0.2 \cdot V_{cr}$ to $2.1 \cdot V_{cr}$. Each 10-minute normalized standard deviation of the recorded across-wind vibration σ_y/D at tower top are shown in Figure 2a in respect to the ratio of wind speed at tower top to the critical wind speed of the tower V/V_{cr}, with $V_{cr} = 14.3$ m/s. Figure 2b shows the information of wind profile exponent α distribution (color bar) in the lock-in. The lock-in characteristics by means of distribution of scatters in Figure 2 is currently being studied by making further evaluation on other measurement dates. The authors had noticed the high across-wind response in higher wind speed $V \geq 1.7 \cdot V_{cr}$, where effects such as intermittency of the vibration, across-wind turbulence and effect of velocity pressure are currently being explored. It should be mentioned that the tower does not have a uniform diameter over the height, where different values of critical velocity occur. Under these conditions, it is considerable to include the effects of the wind profile in the analysis.



(a) (b)

Figure 2 Lock-in on D8 Tower on 28-Jan-2022 to 30-Jan-2022: (a) all measured points of 10-minute normalized standard deviation of across-wind vibration; (b) with the display of wind profile exponent α distribution

3. SECTIONAL PROPERTIES OF WIND AND VORTEX SHEDDING LOAD BASED ON FIELD PRESSURE MEASUREMENT

The measurement conducted on SG 14-222 DD (SG14) is substantial as not only tower vibrations were measured but differential pressure sensors were installed around the circumference of the tower at two levels (z/H=0.63 and z/H=0.82) to measure the incoming wind pressure. Field experimental investigation of vortex shedding load can be made possible with this technique. In October 2021, the SG14 is in free-standing configuration and from December 2021 onwards, the SG14 had been fully installed. Some notable challenges in the pressure measurement are the missing knowledge of appropriate dynamic pressure value and the offset of the pressure sensors. Throughout the project, the process to gain the knowledge of dynamic pressure is developed. The dynamic pressure can be estimated by using the information of the initial base pressure coefficient distribution, where the initial average of five measured base pressure is assumed to be $c_{p,b}(i)=-0.5$. The difference of base pressure and stagnation pressure can indicate the appropriate value of dynamic pressure. The process involves iteration until the assumption of dynamic pressure value is stable. More details of the determination of dynamic pressure and aerodynamics of transcritical regime trend around the tower can be referred to (Höffer et al., 2022). The assessment of vortex loading and wake flow at two different levels on tower height are the contributing element used for comparison with the measured across-wind vibrations.

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