Engineering Structures 168 (2018) 462–472

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Porous and geometry-resolved CFD modelling of a lattice transmission tower validated by drag force and flow field measurements

Jonas Allegrini[a,b,*], Jan Maesschalck[c], Giacomo Alessi[d], Gertjan Glabeke[d], Julien Christophe[d], Jeroen van Beeck[d]

[a] Laboratory for Multiscale Studies in Building Physics, Swiss Federal Laboratories for Materials Science and Technology (Empa), Überlandstrasse 129, 8600 Dübendorf, Switzerland

[b] Chair of Building Physics, Swiss Federal Institute of Technology Zurich (ETHZ), Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland

[c] Elia Engineering, Leon Monnoyerkaai – Quai Léon Monnoyer, 3, 1000 Brussels, Belgium

[d] von Karman Institute for Fluid Dynamics, Environmental and Applied Fluid Dynamics Department, Waterloosesteenweg 72, 1640 Sint-Genesius-Rode, Belgium

ARTICLE INFO

Keywords:
Transmission tower
Lattice structure
Wind tunnel
Drag force
Particle image velocimetry
Computational fluid dynamics
Porous media
Validation

ABSTRACT

The assessment of the aerodynamic forces acting on transmission towers is of crucial importance for their design. These predictions are mainly based on an extrapolation of wind tunnel measurements done on simple structures which are the base of the present design codes. This extrapolation results in an uncertainty which often leads to insufficiently accurate drag force predictions, because of a lack of agreement between the basis of the design codes and their use for tall and complex tower geometries. Therefore, in the present study drag forces are measured in a wind tunnel on a scaled transmission tower and three representative sections of it. Results show similar drag coefficients for the entire tower and the different sections it is composed of. Additionally, the flow fields in the wake of these structures are measured with PIV (Particle Image Velocimetry). With low lattice densities the effect of each lattice element can be seen in the wake, while the lattice structures act as a porous media for higher densities. Based on these results a CFD (Computational Fluid Dynamics) approach, in which the transmission tower is modelled as a porous media, is proposed in this paper. The CFD simulations are performed substituting the tower geometry with a representative porous model, decreasing considerably the computational time and cost of the simulations. A validation against the experiments and classical CFD simulations, where the detailed geometries are resolved, is performed and shows the applicability of the developed approach. The drag forces as well as the velocity deficit in the wake of the transmission tower are well predicted with the porous CFD simulations. For regions with low lattice densities the porous CFD simulations cannot predict the effect of individual lattice elements on the flow field, because the individual lattice elements are not explicitly resolved.

1. Introduction

The installed renewable energy sources in non-industrial environments are increasing [1], leading to a need of new power lines. Since electricity storage is not feasible on large scale the potential usage of this renewable energy is expanded by enlarging the number of potential consumers. For this, the electricity has to be redistributed across Europe with an interconnected grid and new power lines. Such new power lines have to cross big natural obstacles or existing industrial areas resulting in the need of special crossing transmission towers. The tallest transmission towers are as tall as 370 m [2]. Design codes are used to determine aerodynamic forces on lattice tower structures. These codes (e.g. [3]) are mostly developed for slimmer and more condensed lattice geometries, what often leads to insufficiently accurate drag force predictions. In most design codes the drag coefficients are determined as a function the solidity ratio. Tall transmission towers have large empty spaces between the legs of the towers and the determination of the solidity ratio is not straight forward. The question arises: should these empty spaces be included in the calculations of the solidity ratio or not? And if they are not included, which are the critical dimensions from which on they have to be excluded? Maesschalck et al. 2018 [4] discuss these questions and the impact of the different approaches on the predicted aerodynamic forces. Accurate drag force predictions are essential to be able to minimize the weight and price of the transmission towers without increasing the risk of failure. Even for common transmission tower geometries failures are reported for extreme wind

* Corresponding author at: Laboratory for Multiscale Studies in Building Physics, Swiss Federal Laboratories for Materials Science and Technology (Empa), Überlandstrasse 129, 8600 Dübendorf, Switzerland.
E-mail address: jonas.allegrini@empa.ch (J. Allegrini).

https://doi.org/10.1016/j.engstruct.2018.05.007
Received 3 January 2018; Received in revised form 12 March 2018; Accepted 2 May 2018

conditions [5]. Expensive full-scale tests are conducted to study transmission tower failures for towers, which have been carefully designed [6,7].

For lattice structures, aerodynamic forces are historically mainly evaluated with wind tunnel measurements. In the 1970's Lindley and Willis [8] conducted wind tunnel measurements and found that for certain conditions the wind loads might be underestimated by the design criteria of the New Zealand Electricity Department. Eden et al. 1983 [9] and 1985 [10] improved the empirical methods for calculating wind forces on lattice structures for tower-like structures with rather low complexity using wind tunnel measurements. Bayar 1986 [11] additionally studied the impact of different wind directions and geometrical details on the drag forces for lattice towers. Reynolds number effects on the drag coefficients of lattice structures were found by Holdo 1993 [12] with wind tunnel measurements using low Reynolds numbers.

Wind loads on guyed masts, which can be divided into elements with low complexity, are studied experimentally as well as numerically in literature (e.g. [13,14]). For guyed masts also the flow close to the lattice elements is studied to determine the optimal location for anemometers mounted on weather masts [15,16]. Less information can be found on transmission towers. Yang et al. 2016 studied the wind loads acting on an angled steel triangular transmission tower, but they simplified the tower geometry for their wind tunnel tests and CFD simulations [17]. Deng et al. 2016 investigated the response of a transmission tower to skew incident winds [18] and Calotescu and Solari 2016 studied the alongwind load effects on lattice towers [19]. Xie et al. 2017 [20] conducted a study on wind-induced vibration of transmission tower systems. Finally, Prud'homme et al. 2014 determined the drag forces of individual lattice elements [21]. These drag forces can be used to determine the drag forces of lattice structures (see also below).

The fact that most studies on lattice structures reported in literature are conducted in wind tunnels shows that it is not feasible to use CFD to determine the wind loads on an entire transmission tower with the currently available computational power. Accurate predictions of the wind loads are needed to construct strong enough towers without being too conservative and therefore expensive. The aim of this study is to predict the wind loads on a new tall transmission tower with complex lattice geometries. Based on the literature study above, it was decided to measure the wind loads on a scaled model in a wind tunnel. Additionally to the aerodynamic forces, we also measure the flow fields in the wake of the transmission tower models. To our best knowledge, the flow field in the wake of lattice structures have neither been studied experimentally nor numerically (CFD). Information on the flow fields in the wake of lattice structures could lead to a better understanding of the flow dynamics around these structures, what could help improving the design of lattice structures. The flow fields in the wake of the transmission tower show that in regions with medium to high lattice densities a transmission tower acts as a porous media, while only in regions with low lattice densities the influence of individual lattice elements can be seen. Based on these results a second goal of this study is to determine the aerodynamic forces acting on the transmission tower with CFD using a computationally efficient porous media approach. For tall complex towers, the top part mostly has higher lattice densities compared to the lower parts. Therefore also a combined approach using porous media modelling and classical CFD (resolving the lattice elements) could be used.

Using a porous media approach is an efficient way to simulate the flows through porous-like structures, because the flow can be simulated with a much lower number of cells compared to simulations where the detailed geometry is resolved. This approach is commonly used in wind engineering to evaluate the effect of vegetation on the wind flows, without having to simulate the detailed flow fields around individual branches and leafs (e.g. [22–25]). It is also used to model the effect of windbreaks, fences (e.g. [26,27]), vertical panels (e.g. [28]) or to study the flow through woven screens [29].

The porous media approach proposed in this paper is validated for a section of the transmission tower with the wind tunnel measurements presented in this paper. The results are also compared with results of classical CFD simulations resolving all the lattice elements of the same section of the tower and the wind tunnel measurements of this section. The aerodynamic forces predicted with the design codes are not included in the comparison, due to the challenges in the determination of the solidity ratio for tall transmission towers (see discussion above). The porous media approach is not only computationally more efficient than geometry-resolved CFD simulations, but is also less time consuming and less expensive than wind tunnel tests, where scaled transmission tower models with detailed complex geometries have to be constructed.

The structure of the paper is as follows. The transmission tower geometry studied in this paper is given in Section 2. In Section 3 details of the experimental facility and the measurement systems are presented. In Section 4 the numerical models are explained. The results of the study are given in Sections 5 and 6. Section 5 presents measurement results and in Section 6 the validation of the porous media approach is given. In Section 7 the results are discussed and in Section 8 the conclusions are drawn.

2. Transmission tower geometry and studied cases

A scaled (1:100) model of a transmission tower is used for this study (Fig. 1). This transmission tower (tension level: 380 000 V AV; permanent ampacity: 2.766A) is designed to be installed in Antwerp (Belgium) to cross the River Scheldt. Wind conditions according to EN1991 1-4 [3] with the terrain category "0" and a base wind speed of 26 m/s are used for the design. In this study the terrain is not modelled to get more general results and conclusions, which can also be used for other locations. The total height of the entire tower is 192 m (full-scale). The transmission tower consist of L-shaped lattice elements with different dimensions. All main elements of the tower have square cross sections as can be seen in the 3D view in Fig. 1. The different sections of the tower are 3D printed with Polyamide 12. To avoid an influence of the surface roughness of the wind tunnel model on the measured aerodynamic forces, a very high quality 3D printer is used, which is able to print the wind tunnel model with smooth surfaces. In the CFD simulations the surfaces are modelled as smooth surfaces and the simulated drag forces compare very well with the measured drag forces (see below), proofing that there is no influence of the surface roughness on the measured forces. The resistance of Polyamide 12 is about seven times smaller compared to the resistance of steel. Attention has to be given that resulting model is reinforced enough, since the Polyamide model does not have the same strength as the full scale steel structure due to a reduction of the buckling strength of the individual elements. The lattice elements of the wind tunnel model are then printed seven times thicker compared to the scaled dimensions of the transmission tower to ensure its printing and stiffness. The increased thickness of the L-shaped lattice elements does not lead to an increased wind exposed area and therefore does not have an impact on the measured drag forces.

First measurements are conducted for three different sections of the tower individually, which are representative for the tower geometry (Fig. 1). Section 1 and Section 2 have very similar geometries. They are representative for the lower part of the tower, which consists of five sections with similar geometries. The footprint of Section 2 is smaller compared to Section 1 and therefore the lattice elements at the front and the back of Section 2 are closer to each other, what might lead to stronger interactions between the different lattice elements. Section 3 is the top part of the transmission tower, which is the only part with a significantly different geometry compared to the lower sections. After the measurements with the individual sections, the tower is glued together, and force measurements are conducted for the entire tower. The flow fields in the wakes of the three tower sections are measured with