Measurement and simulation of the flow field around a triangular lattice meteorological mast

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Abstract: The international standard IEC 61400-12-1 "Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines" aims to provide a uniform methodology that will ensure consistency, accuracy and reproducibility in the measurement and analysis of power performance by wind turbines. Annex G of this standard provides a methodology for the appropriate arrangement of instruments on the meteorological mast to ensure accurate measurement. For cup anemometers it provides recommendations about their location relative to the mast so that the effect of mast and boom interference on their output may be minimised. These recommendations are given for both tubular masts and lattice masts.This paper compares the flow distortion predicted by the IEC standard and the results of a 3D Computational Fluid Dynamics (CFD) simulation of a triangular lattice mast. Based on the results of wind tunnel and CFD simulation it was found that the flow distortion surrounding the lattice mast was over predicted by the method suggested in appendix G of IEC61400-12-1. Using the CFD data it was possible to determine, for a range of flow directions and mast heights, the distance from the mast that anemometers would need to be in order to be outside the flow distortion field.

Key words: Meteorological mast, interference, lattice tower, flow distortion

1. Introduction

Prior to most wind farm developments a process of resource assessment is required. The usual way for measuring the wind resource is by taking measurements from cup and vane anemometers mounted on the ends of booms attached to a meteorological mast. Figure 1 shows a typical meteorological mast with booms attached. The mast shown in figure 1 is the offshore meteorological mast, Fino 3, located in the north sea [2][3]. The Fino 3 mast is representative of the increasing size of meteorological masts. Due to the increasing hub height of modern wind turbines, which may exceed 100m, there is a requirement for the height of the meteorological mast to be higher than, the hub height of the proposed wind turbine in order to assess the loading across the turbine [4]. For small heights a simple tubular structure might be acceptable but, to reach heights of one hundred meters or more, the mast structures need to be quite extensive and lattice structures made of tubular steel sections are frequently required. This brings into question the accuracy of the measurement of the wind speed by the anemometers [4] and the possible effect of flow distortion, created by the mast structure, on the data measured by cup anemometers mounted on the booms attached to the mast [5][6][7].

The international standard IEC 61400-12-1 "Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines" has been created to provide a uniform methodology to ensure consistency, accuracy and reproducibility in the measurement and analysis of power performance by wind turbines [8].

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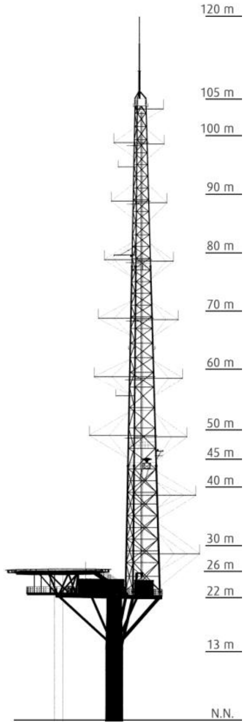

Fig. 1 Lattice type met mast configuration (FINO 3) [2]

Annex G of this standard provides a methodology for determining the appropriate arrangement of instruments on a meteorological mast to ensure accurate measurement of wind speed and direction by cup and vane anemometers mounted on the end of booms attached to the mast. These recommendations are given for both tubular masts and lattice masts.

However, the IEC is based on a simple, disk actuator, momentum sink theory and does not take into account the three dimensional geometry of the actual met mast [9]. This paper compares the results of a CFD simulation of a triangular met mast to predict the minimum boom length required with the results of a similar calculation using the IEC standard.

2. Computational Fluid Dynamics (CFD)

In order to carry out a Computational Fluid Dynamic (CFD) analysis the partial differential equations describing the conservation of mass (continuity) and conservation of momentum (Navier-Stokes equations), given by equations (1) to (4) in three-dimensional form, must be solved:

Conservation of mass

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (1)$$

Conservation of momentum

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+f_x \qquad (2)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+f_y \qquad (3)$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\mu}{\rho}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+f_z \qquad (4)$$

In addition to these equations the effects of any turbulence in the flow may be represented by two additional transport equations which are included within the overall solution for the velocity field [10].

Equations (1) to (4) in their partial differential form cannot be solved analytically and thus such equations must be solved at discrete intervals of space (and time if unsteady). In this way it is possible to convert the insoluble partial differential form into a soluble algebraic one which is suitable for manipulation using high speed computers. This discretisation process is carried out using a technique called the finite volume method and the equations are solved (air speed, temperature, turbulence) at the centres of these discrete volumes or computational cells. Figures 2 and 3 show the computational mesh on the surface of the met mast and in the surrounding fluid respectively.

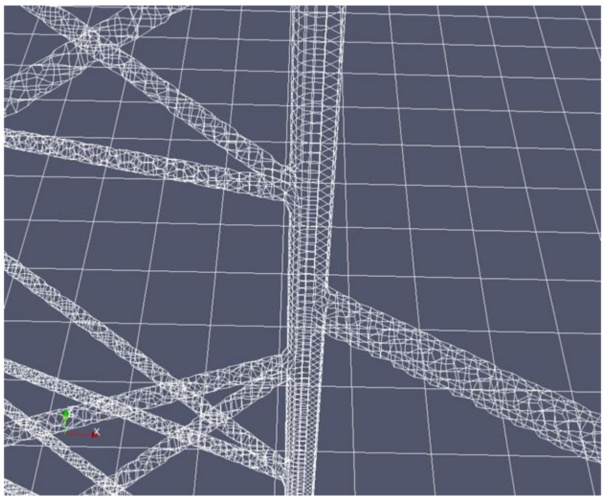

Fig. 2 Computational surface mesh.

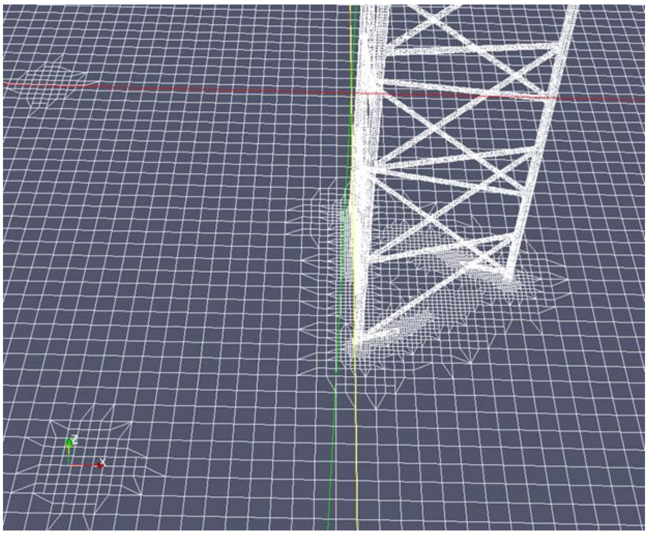

Fig. 3 Computational domain mesh.

The CFD calculations were carried out using the open source CFD code OpenFOΔM® [11]

To assess the effect of the flow approaching the mast at different angles the mast was rotated in the computational domain, relative to the free stream, in $\beta=30^{o}$ steps through a complete rotation of 360^{o}. Figure 4 shows the axis system employed with 0^{o} represented by the dashed line and a positive rotation, β, anticlockwise when viewed from above. The simulation work was carried out with a free stream speed of 10m/s. However, to assess the effect of Reynolds number on the flow distortion, two simulations were also completed at 7m/s and 16 m/s and, to assess the effect of scale, also with different sized mast sections.

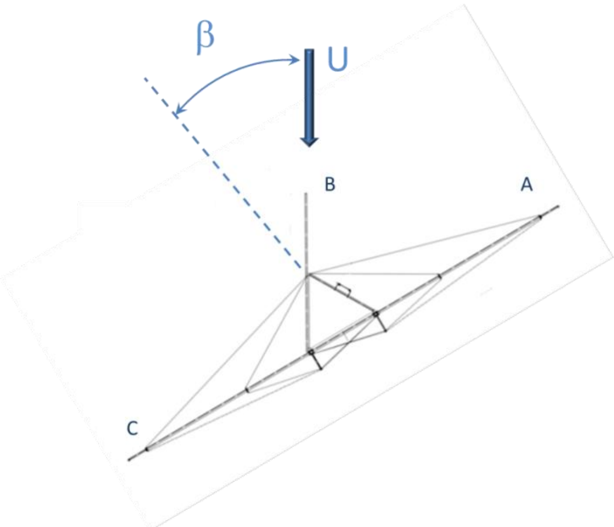

Fig. 4 Definition of CFD axis system.

3. Experimental Verification

To verify that the CFD simulation created a realistic simulation of the flow field surrounding the lattice mast a 1/20th scale model of part of a triangular lattice mast was created and tested in the 1.5m low speed wind tunnel at the University of Strathclyde. Flow velocities around the model were measured using a hot film probe attached at the end of the boom and 3D hot wire probes in the free stream along the boom locations. To simulate the wind coming from 12 different directions the model was rotated around the mast vertical centreline. The velocity data was non-dimensionalised by a single wire probe upstream. A CFD simulation of each flow direction was carried out and the velocity data compared to the wind tunnel results as shown in figure 5. From figure 5 it may be seen that the CFD simulation data produced very good agreement with the wind tunnel data. This verification of the CFD modelling technique gave confidence that CFD could model faithfully the flow field around a triangular lattice mast at full scale. A more complete description of the model validation may be found in references [12] and [13].

4. Results

Figure 6 shows the horizontal non-dimensional velocity magnitude data along the directions of booms A, B and C, figure 4, taken 1m above the booms in the computational domain. One meter above the simulated booms was chosen as it was found to be sufficiently high as to be outside the boom’s effect on the free stream. The dashed lines indicate 99% and 101% free stream speed. Note that for some angles the non-dimensional velocity never

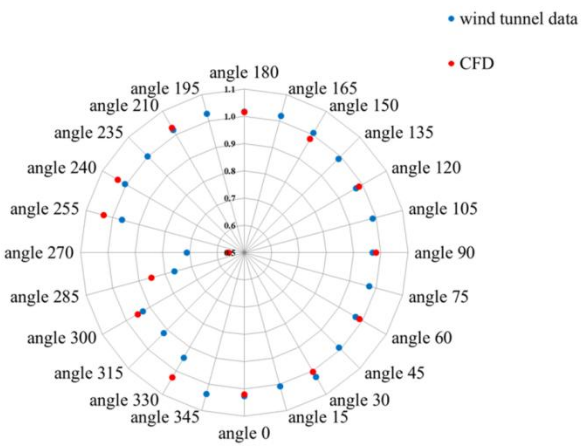

Fig. 5 Comparison of experimental and CFD data

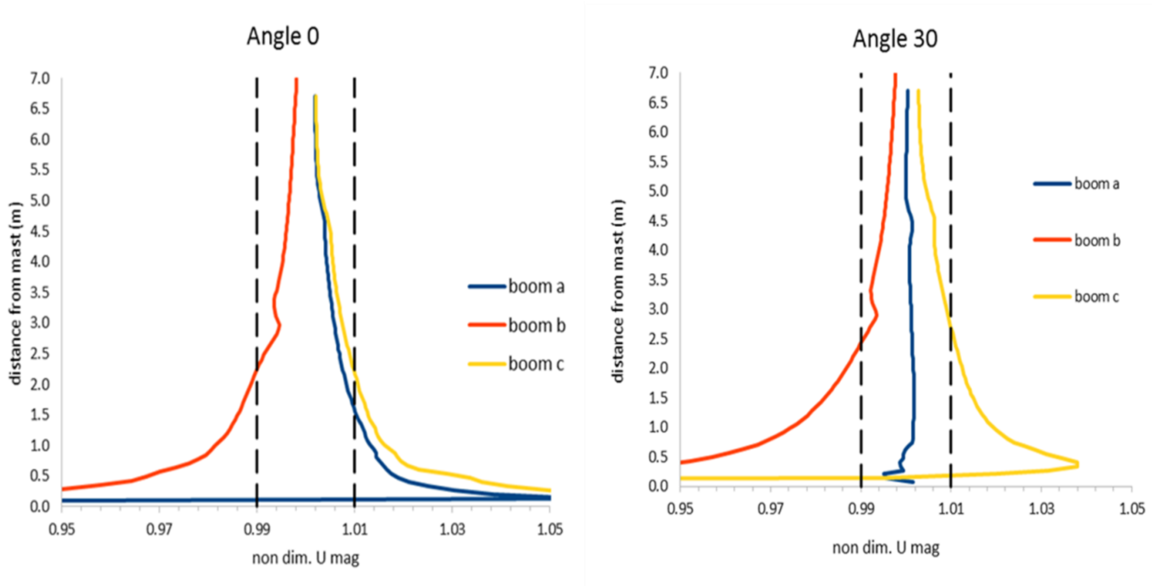

Fig. 6 Non dimensional velocity along lines A, B and C

fell in the range 99% to 101% free stream. This was due to a boom being aligned downstream of the free stream wind vector and therefore totally enclosed in the mast wake. This process and similar plots were created for all flow angles and the limit of the distortion field was therefore determined.

The IEC standard determines the distortion field based on the thrust coefficient, CT, given by equation (5) where t is the mast solidity.

$$C_T = 2.1(1 - t)t \tag{5}$$

Taking the geometry of the mast section simulated it was possible to calculate the solidity. This was found to be t = 0.17. Using this solidity the thrust coefficient was calculated using equation (5) and found to be C_T=0.3. Based on this thrust

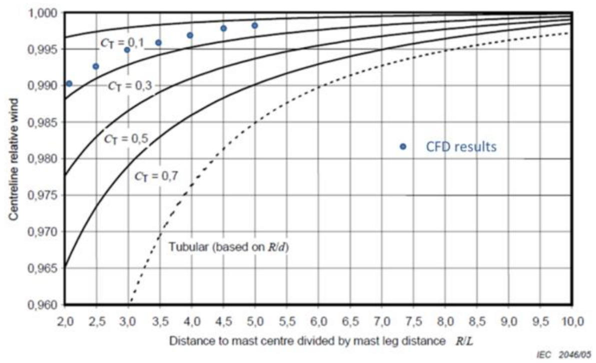

Fig. 7 Comparison between IEC and CFD models

coefficient the IEC standard would predict a distance of 4.7m (R/L =2.35) to 99% free stream velocity. The IEC Figure 7 shows the centreline relative wind from the IEC for a range of thrust coefficients. To compare this data with the results of the CFD simulation the thrust coefficient of the mast section was calculated from the CFD data. The thrust coefficient determined from the CFD data was found to be 0.27. To compare results, from CFD and IEC, the centreline relative wind speed was calculated from the CFD vector field and plotted on figure 7. It may be seen, from figure 7, that the centreline relative wind speed calculated from the CFD model was similar to that presented in the IEC standard for a similar thrust coefficient. It may therefore be concluded that the IEC would produce reasonable results if the boom was mounted perpendicular to each face of the triangular mast. However, for various reasons this is not usually the case and the booms are mounted parallel with each face of the tower as shown in figure 4. Consequently the IEC does not faithfully represent the interference due to the orientation of the actual booms to the flow field.

Taking the data from figure 6 and for all other flow angles it was possible to plot the distance from the mast before the flow was consistently within 1% of the free stream value along the directions of the booms. Figure 8 shows this distance for each individual boom.

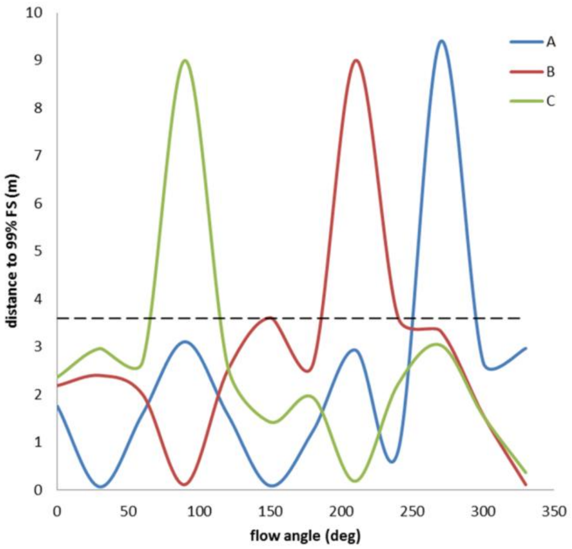

Fig. 8 Distance to within 1% of free stream speed (CFD data)

From figure 8 it may be seen that, apart from a small sector for each boom corresponding to the mast wake, the CFD predicted a boom length of 3.5m (R/L=1.75) outside the mast was sufficient for all data to fall within 1% of the free stream value.

It should be noted that this is less than the 4.7m (R/L=2.35) that would be required from the IEC calculation. However, the IEC calculation assumes that the measurement boom is pointing perpendicular to the face normal to the free stream which, from figure 9, a contour plot of velocity magnitude in the horizontal plane, is directly into the large stagnation region upstream of the mast. However, booms A and C are mounted parallel to each face and, again from figure 9, may be pointed into regions which are relatively unaffected by the flow distortion.

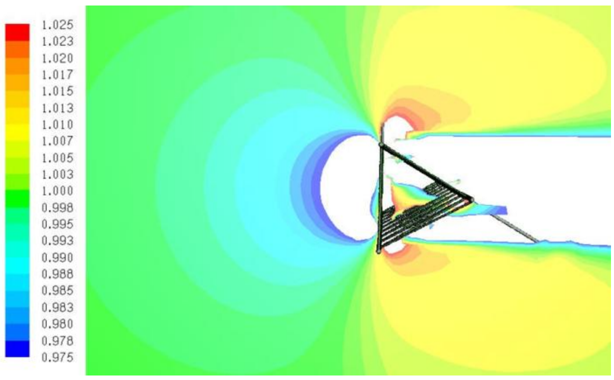

Fig. 9 Non dimensional velocity contours.

5. Conclusions

A CFD simulation of a triangular lattice met mast has been carried out. The simulation was verified by comparison to a 1/20th scale wind tunnel model.

It was found that the data acquired was broadly in agreement with the flow field predicted by the IEC standard.

The CFD analysis of the flow field approaching the mast for 12 difference azimuth angles predicted a minimum boom length to 99% free stream of 3.5m (R/L=1.75) except in the mast wake. The IEC standard predicted a boom length of 4.7m (R/L=2.35) for the same mast configuration.

Based on the results of wind tunnel and CFD simulation it has been shown that the flow distortion surrounding the lattice mast was over predicted by the method suggested in appendix G of IEC61400-12-1. Using the CFD simulation data it was possible to determine for a range of flow directions and mast heights the distance from the mast that anemometers would need to be in order to be outside the flow distortion field. By careful consideration of the simulation data it was possible to use much shorter length booms to place the anemometers outside the flow distortion created by the met mast.

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