LOCAL WIND FLOW MODIFICATIONS WITHIN THE VICINITY OF A COMMUNICATION TOWER

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ABSTRACT

The boom length obtained from the International Electro technical Commission (IEC 61400-12-1) standard is based on the centreline velocity deficit expression derived on the assumed incident wind that is perpendicular to the tower face, giving rise to a velocity deficit value that is predicted using the upstream contour profile of the modified flow around the tower. The boom length computed thus does not guarantee that wind observation is accomplished within the recommended industry-accepted accuracy of $< 1\%$ errors between 0° and 360° . In this study, the local flow modification around the 3D complex geometry of two communication towers of different construction details located at Amper-bo and Korabib in Namibia were performed using Ansys Fluent flow solver in order to introduce the safe angle range, where boom length computed based on the IEC reference direction ($\theta = 0^\circ$) is long enough to achieve 99 % of the free stream velocity. In this regard, a full 3D CFD flow analysis was performed to obtain the maximum boom length based on the two commonly encountered boom arrangements (perpendicular and parallel to the face of the tower). The boom length obtained based on the IEC standard boom configuration ($\theta = 0^\circ$) is long enough to keep the speed sensors out of the tower wakes if winds arrive at the tower at incident angles $\theta = < \pm 70^\circ$ with respect to each boom configuration reference direction (i.e., $\theta = 0^\circ$), which defines the safe angle range. Winds that arrive at the tower between $\pm 90^\circ \geq x < \pm 150^\circ$ with respect to each boom arrangement reference direction cast their full shadow on the speed sensors. A boom length of approximately $x \geq 7.5\text{ m}$ and $x \geq 6.5\text{ m}$ at Amper-bo and Korabib respectively are needed to keep the speed sensors out of the tower wakes. However, the suitability of a slender boom of this length which is susceptible to vibration and therefore can introduce more errors to the readings of the speed sensors mounted on them is questionable. A shorter boom length of $x \geq 4.5\text{ m}$ to $x \geq 3.5\text{ m}$ or less at Amper-bo and Korabib respectively is needed to keep the sensors out of the tower wakes when the incident wind angles are within the range $\pm 150^\circ \leq x \leq 180^\circ$ from the reference directions. This type of arrangement is not encouraged because any slight shift in the direction of the upstream wind will cast shadows of the tower on the speed sensors. The study further revealed that the boom length computed based on the two popular boom arrangements is independent of the scale and turbulence models used in CFD flow analysis. Also, complex flow interference was reported around the tower structure with no appreciable increase in boom length due to the presence of the secondary support structures. In the second section of the study, a correction method based on the combined field observed wind data is proposed. Based on the accuracy of the correction method, it may no longer be necessary to discard the tower wake affected direction sectors in wind analysis. Finally, the speed sensor to tower separation distance needed to keep the speed sensor away from the tower-induced flow defect was thoroughly investigated using lattice communication towers of different construction details and booms of different arrangements on the towers. A safe angle range ($\theta = < \pm 70^\circ$) was proposed. Winds that arrive at the tower at other angles outside this range will likely induce error readings on the speed sensor mounted on the boom and this explains why most towers instrumented according to the IEC standard still fall short of the 1 % speed deficit recommended.

KEYWORDS: Safe angle Range, Tower Wakes, Speed Deficit, Correction Factor and Boom Length.

Received: Apr 14, 2021; **Accepted:** May 06, 2021; **Published:** May 18, 2021; **Paper Id.:** IJMPERDJUN202135

1. INTRODUCTION

The knowledge and guidelines on tower instrumentation for wind measurement perspective are largely found in research studies and standards, the most prominent of which is the International Electrotechnical Commission (IEC) standard IEC 614200-12-1 Wind turbines–Part 12-1: Power performance measurements of electricity producing wind turbines [1], [2], whose Annex G is of interest [3]. The standard prescribes, among other things, the centreline velocity deficit expression which is based on its standard boom configuration ($\theta = 0^\circ$), derived on the assumed incident wind that is perpendicular to the tower face, giving rise to a velocity deficit value that is predicted using the upstream contour profile of the modified flow around the tower. A user may use this expression to evaluate the tower to speed sensor separation required for the desired maximum flow-induced error reading when the thrust coefficient (C_T) is known. However, the boom length computed using this expression does not guarantee that wind observation is done with the recommended industry accepted accuracy of $< 1\%$ errors between 0° and 360° . This is in agreement with [4], where it was suggested that the choice of boom length based on the IEC recommendations is not a guarantee that measured wind speed between 0° to 360° will always achieve 99% of the free stream velocity. At some incident wind angles, the tower induced error readings on the speed sensor may be $> 1\%$, bringing into question the universal applicability of the speed deficit expressions at incident wind angles other than the IEC reference direction ($\theta = 0^\circ$) and to other towers of different construction details with a solidity ratio (S) that is way off the values specified in the standard. Other limitations of the IEC standard include insufficiency of the numerical model used to draw the iso-speed plots of locally modified wind flow around a meteorological mast to fully and sufficiently describe wind interaction around a complex operational lattice tower, lack of information on how to account for complex flow interferences occasioned by the presence of other secondary support structures, the inadequacy of the prescribed expression to address the wind direction dependence of tower shadowing, and the exact impact of free-stream turbulence on the specified boom length [3]. Previous authors (e.g., [4]–[7]) have made attempts to address some of the identified limitations, but not all. Investigating the impact of atmospheric turbulence on the local flow modifications using CFD flow simulation, [5], [7] reported higher flow distortion than [1], [2], and [5] concluded that the phenomenon is an atmospheric problem and should be treated as such. In a similar study, [6] reported a shorter boom length when compared with [1], [2] and concluded that 3D CFD flow analysis is better suited to study wind interaction with the 3D complex geometry of an operational lattice mast as against the simplified approach used in the IEC614200-12-1 standard. Further computational approach by [8] attempted to investigate the impact of the secondary supporting structures with an oversimplified model and reported that [1], [2] overpredicted the minimum boom length. Efforts by previous authors to address the identified shortfalls of the IEC614200-12-1 standard are evident but the application of such studies to towers of different configurations located at different sites in different atmospheric conditions in the boundary layer may be limited.

In this study, a 3D CFD study of two lattice communication towers of different construction details was performed, to understand the safe angle range $\alpha = \pm \leq \theta^\circ$, i.e., the incident wind angles for which the boom length computed based on the IEC standard configuration ($\theta = 0^\circ$) can effectively keep the speed sensors out of the tower wakes for winds that arrive at the tower within that defined angle range. The exact impact of the secondary support structures on the boom lengths was further investigated. The second section of the study combined wind data obtained from collocated

speed sensors and Light Detection and Ranging (LiDAR) to develop a correction method for correction of the wake affected direction sectors. The detailed approach adopted in this study provides insight on the best approach to instrument lattice communication towers for wind measurement. Finally, successful implementation of the correction method increased the utilization of observed wind data and enhances wind resource assessment because it may no longer be necessary to discard the tower wake affected direction sectors during site wind resource characterisation.

2. SITE AND TOWER CONSTRUCTION DETAILS

The locations are Amper-bo (25.354 °S, 18.313 °E) and Korabib (28.548 °S, 17.820 °E). Amper-bo site is desert-like with almost homogeneous vegetation. It is a class A terrain according to Annex B of (IEC 2005) as reported in [9]. Figure 1a shows the tower construction details. The tower at Amper-bo is 120 m high and L_m (centre-to-centre) of 1.10 m, all through the height. It is guyed and has an equilateral triangular cross-section with three vertical tubular mild steel rods of 100 mm external diameter (OD). The vertical tubular rods from repeating construction units are joined end-to-end by flanged connections. Each construction unit is approximately 3.5 m, and each contains four modules of height 0.89 m. The network of small angular cross bracings made from 45 mm x 45 mm x 5 mm angle bars are bolted to a flat plate (0.045 m x 0.07 m) that is welded to the tubular rods. The boom has an OD of 50 mm and wall thickness of 2 mm and extends approximately 2.56 m away from the tower surface. The cable ladders and the cable bundles which covered almost half of the W to N (clockwise) facing side of the tower are the secondary support structures. At, Korabib the tower is also guyed, 120 m high and L_m (edge-to-edge) of 1.32 m all through the height. It has an equilateral triangular cross-section with three vertical angle bars (70 mm x 70 mm x 6 mm) made from mild steel. The 70 mm x 70 mm x 6 mm angle bars form repeating construction units which are bolted together using flat plate connections (Figure 1b). Each construction unit is 3.024 m, and each contains two modules of height 1.512 m. The network of small angular horizontal and cross bracings made from 60 mm x 60 mm x 5 mm angle bars are bolted to a flat plate (0.144 m x 0.26 m) that is bolted to the vertical angle bar. The detail of the boom construction and the separation distance from the tower is the same as the tower at Amper-bo. The cable bundles and ladder located W to N (clockwise) facing the side of the tower are the secondary support structures.

Figure 1a: A Section of the Communication Tower at Amper-bo Showing the Boom Arrangements and Some Secondary Support Structures. Figure 1b. A Section of the Communication Tower at Korabib Showing the Boom Arrangements and Some Secondary Support Structures.

3. METHODS

Local flow modification around the 3D complex geometry of two communication towers was performed using Ansys

Fluent flow analysis. The holistic approach adopted in this work led to the evaluation of the speed sensor to tower separation distance required for the desired maximum speed deficit.

Figure 2a: Illustration of the IEC Boom Configuration with the Tower Face-on the Wind.

Figure 2b: The Common boom Configurations are used in Operational Towers. Figure 2c. Combination of the Two Boom Configuration Methods.

Two major boom configurations often encountered in lattice tower instrumentation for wind measurement are considered. With the IEC61400-12-1 reference wind direction ($\theta = 0^\circ$), the tower is always face-on to the wind. The velocity deficit is assumed to be on the same axis that passes through the tower centre and perpendicular to the tower face. The incident wind is therefore perpendicular to the same tower face, giving rise to velocity deficit values that are predicted using the upstream contour profiles of modified flow around the tower. Using the IEC standard boom configuration (Figure 2a), CFD flow simulation was conducted over 36 incident wind angles, each at 10° . The boom length was computed with respect to a reference direction ($\theta = 0^\circ$) for each incident wind angle. Similar flow analysis was performed on the second and most common boom arrangement (Figure 2b and Figure 2c), whereby the booms were placed parallel to the face of the tower. For the IEC arrangement, the speed sensors mounted on boom B and boom C are 30° and 90° respectively from the prevailing wind direction (Figure 2b). Based on the IEC standard configuration, a boom length needed to keep the speed sensor A (Figure 2c) out of the tower-induced flow defect was computed and the safe angle range was also defined.

The safe angle range $\alpha = \pm \leq \theta^\circ$ is the incident wind angles for which the boom length computed based on the IEC standard boom configuration can effectively keep the speed sensors out of the tower wakes for winds that arrive at the tower

within that defined angle range. Similar CFD flow analysis was performed to equally establish a safe angle range for booms placed parallel to the face of the tower, i.e., boom B (Figure 2c). The field observed data were combined to establish a correction method for the wake-affected direction sectors.

4. GOVERNING EQUATIONS

The fluid flow is governed by Navier-Stokes's equation and conservation of mass. A steady, incompressible, and isothermal flow was assumed. The flow field is described by the conservation of mass and momentum equations i.e., Eq. (1) and Eq. (2), while the Reynolds Average Navier-Stokes's equations (RANS) take care of the time-average approximations.

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial (\bar{u}_i \bar{u}_j)}{\partial x_i} = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_i} \left\{ \mu_i \left(\frac{\partial \bar{u}_i}{\partial x_i} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \rho \overline{u_i u_j} \right\} \quad (2)$$

where $\bar{u}$ is the Reynolds-averaged velocity, $\bar{P}$ is the averaged pressure, μ is the eddy viscosity and $\overline{u_i u_j}$ is the Reynolds stress tensor which introduces more variables than the number of equations; hence, the closure problem is subsequently resolved using turbulence models. To assess the suitability of each model in the context of this study, common turbulence models often encountered in the aerodynamic of external flow, such as the one-equation Spalart-Almaras turbulence model and the two-equation standard k - ϵ model, the standard k - ω model and k - ω shear stress transport (SST) models, were evaluated and compared.

5. NUMERICAL APPROACH

Ansys Fluent uses finite volume discretization methods to generate a set of linear equations from the partial differential equations, solved by iteration between cell centres in the computational mesh. Velocity and pressure were coupled using the SIMPLE technique in the Ansys fluent solver. Meshing around the tower structure was suitable to properly describe airflow within its vicinity, with velocity inlet and constant pressure outlet boundary conditions applied. Figures 3a, 3b 3c and 3d are the computational domains and surface meshing of the towers at Amper-bo and Korabib, respectively.

Figure 3a and 3c: Computational Domain and Surface Meshing of the Tower at Amper-bo. Figure 3b and 3d: Computational Domain and Surface Meshing of the Tower at Korabib.

6. Comparison of Velocity Profile for Each Turbulence Model

Figures 4a and 4b: Show the non-Dimensional Velocity Profiles Derived from the CFD Flow Simulation along with the IEC Standard Boom Configuration.

Figures 4a and 4b show the non-dimensional velocity profiles derived from the CFD flow simulation around the tower structures using the four turbulence models $k - wSST$, $k - w$ standard equation, $k - e$ and one equation Spalart-Almaras), at Amper-bo and Korabib, respectively.

Using the four turbulence models ($k - wSST$, $k - \omega$ standard equation, $k - \epsilon$ and one equation Spalart-Almaras) often used in external aerodynamics study, it is observed that all the models correctly predicted approximately the same minimum boom length required to achieve 99 % of the free stream velocity. This agrees with the findings in [6] where it

was reported that no individual RANS equation may be considered most suitable for the evaluation of the minimum boom lengths. There was also no significant difference in the drag force computed using each turbulence model though the drag force on the tower at Korabib is larger than that of its counterpart at Amper-bo, as expected, due to the larger surface area presented to the wind by the tower at Korabib.

7. SCALE EFFECT

The scale effect was investigated and illustrated in Figure 5. Figure 5a is the non-dimensional velocity profiles drawn as a function of the boom length for wind speeds 20 m/s, 15 m/s and 6 m/s respectively based on the IEC reference direction ($\theta = 0^\circ$), whereas Figure 5b is the speed profiles for boom C (Figure 2b), that is located 30° with respect to the IEC reference direction. Similar analysis (Figures 5c and 5d) are the non-dimensional velocity profiles for wind speeds 20 m/s, 15 m/s and 5 m/s obtained from the tower at Korabib. Wind speeds 6 m/s and 5 m/s are approximately the observed average speed at Amper-bo and Korabib, respectively at about 60 m height. The results agree with previous literature (i.e., [6] which reported the independence of scale to the CFD derived flow).

Figure 5a: Scaling Effect: Non-Dimensional Velocity Profile versus R_d/L_m along the Boom Length based on the IEC Standard Configuration ($\theta = 0^\circ$) at Amper-Bo. Figure 5b. Non-Dimensional Velocity Profile versus R_d/L_m along the Boom Length for the Boom Located 30° with Respect to the IEC Standard Configuration at Amper-bo.

Figure 5c: Scaling Effect: Non-Dimensional Velocity Profile versus R_d/L_m along the Boom Length based on the IEC Standard Configuration ($\theta = 0^\circ$) at Korabib. Figure 5d. Non-Dimensional Velocity Profile Versus R_d/L_m along the Boom Length for the Boom Located 30° with Respect to the IEC Standard Configuration at Korabib.

8. 3D CFD Flow Simulation

The CFD-derived flows around the towers are illustrated in Figure 6. Figures 6a and 6b are modified flow around the towers when they are face-on to the winds (i.e., when $\theta = 0^\circ$) whereas Figures 6c are 6d illustrate flow modification around the towers when the boom is placed at 30° clockwise from the IEC reference direction.

Figure 6a: CFD Derived Flow Simulation Around the Tower at Amper-bo when the Tower is Face-on the Wind.

Figure 6b: CFD Derived Flow Simulation Around the Tower at Korabib when the Wind is Face-on the Wind.

From the CFD-derived flows, the minimum boom length required to achieve 99% of the free stream speed for speed sensors mounted on the booms A and B for each of the 12 incident wind directions were computed (Figures 7a and 7b). Figure 7a shows the estimated boom lengths for the tower at Amper-bo and Figure 7b are those of the tower at Korabib. As seen in Figure 2c, earlier discussed, boom A is based on the IEC recommendation whereas boom C is the most common boom arrangement in operational tower instrumentation.

Figure 6c: CFD Derived Flow Simulation Around the Tower at Amper-bo when the Winds Arrive at the tower at 30° Incident wind Angle. Figure 6c: CFD Derived Flow Simulation Around the Tower at Korabib when the Winds Arrive at the Tower at 30° Incident Wind Angle.

At Amper-bo, based on the IEC recommendations (Figure 1), a boom length of 2.4 m protruding from the tower face is required to achieve 99 % of the freestream velocity. The boom lengths computed based on the IEC standard configuration are long enough to keep the speed sensors out of the tower wakes provided that the winds arrive at the tower

at incident angles $\theta = < \pm 70^\circ$ with respect to the reference direction (i.e., $\theta = 0^\circ$). Similar analysis reveals that when the direction of boom B is taken as the reference direction (i.e., $\theta = 0^\circ$), the boom length needed to achieve 99 % of the freestream speed is approximately 1.3 m.

Figure 7a: The Estimated Boom Lengths to Achieve 99% of the Free Stream Speed for the Tower at Amper-bo for 12 Different Incident Wind Angles. Figure 7b. The Estimated boom Lengths to Achieve 99 % of the Freestream Speed for the Tower at Korabib for 12 Different Incident Wind Angles.

The shorter boom length reported is expected due to the minimum obstructions encountered because of the alignment of the tower legs when the tower face is parallel to the incident wind direction. Based on the safe or effective angle range (i.e., $\theta = < \pm 70^\circ$), a boom length of approximately 2.2 m computed when the winds arrive at the tower at 60° is appropriate. For both boom arrangements, the study acknowledges that the boom length computed when the tower is face-on to the wind is long enough to keep the speed sensors out of the tower wakes if winds arrive at the tower within the safe angles range (i.e., $\theta = < \pm 70^\circ$). Similar results were obtained from the tower at Korabib (Figure 7b). In (Figure 2c), a boom length of 1.76 m protruding from the tower face is required for boom A to achieve 99% of the free stream velocity. Again, this boom length computed based on the IEC standard configuration is long enough to keep the speed sensors out of the tower wakes provided that the winds arrive at the tower at incident angles $\theta = < \pm 70^\circ$ with respect to the reference direction (i.e., $\theta = 0^\circ$). Again, when the direction of boom B is taken as the reference direction (i.e., $\theta = 0^\circ$), the incident wind is now parallel to the face of the tower, and a boom length of approximately 1.3 m is needed to achieve 99 % of the freestream velocity. As earlier mentioned in respect to the tower at Amper-bo, a shorter boom length is needed due to the alignment of the tower legs. Considering the safe angle range mentioned earlier (i.e., $\theta = < \pm 70^\circ$), this boom length is long enough to keep the speed sensors out of the tower wakes provided that the winds arrive at the tower at incident angles $\theta = < \pm 70^\circ$ with respect to the reference direction. The safe or effective boom placement angle range observed from the towers investigated is $\pm 30^\circ$ less than the range suggested in [2] where it was stated that the speed sensors mounted on a tower based on the IEC standard configuration will only be in the wake of the tower if winds arrive at the mast at angles ($\theta = > \pm 100^\circ$) with respect to the standard incident wind direction ($\theta = 0^\circ$). The proposed safe angle range based on IEC 2017 does not hold on operational towers of the configurations investigated in this work.

For winds that arrive at the tower between $\pm 90^\circ \geq x \geq \pm 150^\circ$ with respect to the reference direction of each boom

arrangement, will cast their full shadow on the speed sensors. A boom length of approximately $x \geq 7.5$ m and $x \geq 6.5$ m respectively at Amper-bo and Korabib are needed to keep the speed sensors out of the tower wakes. Unfortunately, a slender boom of this length might be susceptible to vibration and will introduce more errors to the readings of the speed sensors mounted on them. A shorter boom length of 3.5 m to 4.5 m for each of the towers is needed to keep the sensors out of the tower wakes when the incident wind angles are within the range $\pm 150^\circ \leq x \leq \pm 180^\circ$. Although the boom length within this range of incident wind angles appears shorter, good practice from a wind measurement perspective may be to consider this arrangement as not the most appropriate because any slightest shift in the wind direction will completely cast its shadow on the speed sensors. It is important to note that booms mounted parallel to the face of the tower require shorter boom lengths to keep the speed sensors out of the tower wakes when compared to their counterparts mounted according to IEC61400-12-1 standard configuration and this is directly related to the thrust coefficient of the towers. To achieve 99 % of the freestream speed or a speed deficit of 1% when the tower is instrumented based on the IEC standard configuration, or based on the approach proposed in this study for booms mounted parallel to the face of the tower, a combination of physical and computational modelling of the tower is required to accurately obtain the relevant parameters especially the controlling parameters of the IEC centreline velocity deficit expression and to understand the prevailing wind pattern of the site. The IEC approach has always resulted in a longer boom length, as is the case in this study, yet towers assumed to have been instrumented based on the standard mostly fall short of the recommended 1 % speed deficit because the relevant parameters in the speed deficit expression are not properly characterized and or the site prevailing wind direction is not taken into consideration during the instrumentation stage.

9. Secondary Support Structures

Secondary support structures are critical components of an operational tower. They come in different configurations and their sizes depend on the application of the parent tower. The presence of these substructures produces discrete wakes, which makes flow interference within the vicinity of the tower more complex, contrary to the idealized mast configuration presented in [1] and [2]. In this study, cross and horizontal bracings are considered natural members of an operational tower and are treated as such. However, cable ladders, cable bundles and other substructures provided for safe climbing and proper instrumentation of the tower are the secondary support structures investigated. Based on the CFD study, complex flow interference was reported within the regions very close to the tower due to the presence of secondary support structures. However, their presence does not result in any appreciable increase in the boom length.

10. Identification and Correction of Tower Waked Direction Sectors

In the field observed data, methods utilized to identify tower waked direction sectors are traditional speed ratio and the coefficient of determination (R^2) of the turbulent kinetic energy (TKE) and turbulence intensity (TI) of the collocated sensors [9], [10]. A new and simpler approach that uses time series WSC for wind data that are collected from two intermediate heights with approximately the same azimuth angle from the north, when speed sensors collocated at the same height are not available, was proposed [11]. In the Amper-bo experiment, speed sensors (WS4 and WS4B) are collocated at 16.88 m and placed approximately 120° apart. WS4 and WS4B are located at approximately 159° and 278° azimuth from the north. The instrumentation details of the communication towers at Amper-bo and Korabib are summarised in Tables 1 and 2. Ten different heights plus the default pre-set height (38 m) where the Lidar measured wind speed is reported in Table 3.

Table 1: Instrumentation Details of the Tower at Amper-bo

Sensors	August 2012 Arrangement		March 27, 2014 Arrangement	
	Heights (m)	Angle (ϕ) degree	Height (m)	Angle (ϕ) degree
WS1	3.88	159	-	-
WS2	4.88	159	-	-
WS3	8.68	159	8.68	159
WS4	16.88	159	16.88	159
WS4B	-	-	16.88	278
WS5	32.68	160	32.68	160
WS6	64.92	160	64.92	160
WS6B	-	-	64.92	278
WS7	120.38	159	120.38	159
WD1	4.88	38	4.88	38
WD2	16.88	38	16.88	38
WD3	64.92	38	64.92	38
WD4	120.38	279	120.38	279

Table 2: Instrumentation Details of the Tower at Korabib

Sensors	Heights (m)	Angle (ϕ) Degree
WS1K	19.86	168
WS2K	51.11	164
WDK	51.11	287

Table 3: Instrumentation details of the tower at Korabib

Height (m/s)	10	17	33	38	49	65	75	90	12	150	200
Sensor	LWS1	LWS2	LWS3	LWS4	LWS5	LWS6	LWS7	LWS8	LWS9	LWS10	LWS11
Mean speed (m/s)	3.73	4.26	5.21	5.46	5.81	6.25	6.46	6.73	7.09	7.33	7.54

The speed ratio and coefficient of determination (R^2) computed based on the collocated speed sensors at Amperbo are shown in Figure 8 and Figure 9.

Figure 8: The Ratio of WS4/WS4B Plotted on a Sector-wise Basis Binned in 1° wind Direction Intervals with the Tower Waked Direction Sectors Properly Described.

Figure 9: Coefficient of Determination (R^2) of WS4 and WS4B Binned in 1° Wind Direction Intervals.

Figure 10: Time Series WSC Calculated for the in-situ (8.88 m to 16.88m) and LiDAR (10 m to 17 m), Binned in 1° Wind Direction Intervals and Drawn as a Function of the Wind Direction at the Same Height.

Figure 11 is a summary of the direction sector selection rule that was used to derive the correction factor for both the collocated speed sensor at 16.88 m (WS4 and WS4B) and the LiDAR observed speed at approximately the same height. The ratios of WS4 and WS4B, WS4 and LWS and WS4B and LWS are plotted on a sector-wise basis and binned in 1° bin of wind direction intervals with the wake affected direction sectors clearly illustrated. The ratio of wind speed in the wake-affected direction sectors (target direction sectors) and the corresponding ratio of wind speed at angles directly opposite the wake-affected direction sectors (reference direction sectors) are evaluated. Based on the direction sectors selected, an expression for correcting the wake affected direction sectors have been proposed, as follows in Eq. (5):

$$C_f = \frac{U_{aff}}{U_{opp}} \quad (5)$$

U_{aff} is the ratio of the time series wind speed recorded in the wake affected direction sectors. It is simply the ratio of the target wind speed to the reference wind speed in the wake-affected direction sector. In this case, WS4 is the target wind speed whereas WS4B is the reference wind speed. Therefore, WS4, $U_{aff} = WS4/WS4B$. The WS4 wake affected direction sector is between 80° and 140° (Figure 11a). Again, $U_{aff} = WS4/WS4B$, for time series wind speed measure between 260° and 320° (Figure 11a). The expression for the correction factor (C_f) is shown in Eq. (6).

$$W_c = \frac{U_{orig}}{C_f} \quad (6)$$

where U_{orig} is the original or raw wind speed measured in the wake affected direction sector.

Similarly, the correction factor for WS4B's wake-affected direction sectors was computed (Figure 11b) using the collocated wind speed (WS4). Again, using the LiDAR undisturbed wind data, a correction factor for WS4 (Figure 11c) and WS4B (Figure 11d) were computed.

Figure 11a: Selection Rule for the Direction sectors used to Derive the Correction Factor for WS4 using WS4B as Reference. Figure 11b: Selection Rule for the Direction Sectors used to Derive the Correction factor for WS4B using WS4 as Reference.

Figure 11c: Selection Rule for the Direction Sectors used to Derive the Correction Factor for WS4 using LWS as Reference. Figure 11d: Selection Rule for the Direction Sectors used to Derive the Correction factor for WS4B using LWS as Reference.

Figure 12a: The Graph of the Reference Winds Speed (WS4B) Versus the Corrected wind Speed (WS4). Figure 12b: The Graph of the Reference Winds Speed (WS4) Versus the Corrected Wind Speed (WS4B).

Figure 12 is the graph of the reference wind speed versus the corrected wind speed. In Figure 12a, WS4 was corrected using WS4B. The coefficient of determination R^2 improves from 0.1281 to 0.9901 after correcting WS4 with WS4B (Table 4a). At 106° (worst affected direction sector), the highest speed deficit of 50.38% was recorded but reduces to 8.1% when the correction factor is applied. Similarly, for WS4B, R^2 improved to 0.9817 from 0.0449 after applying the correction factor. Again, based on the same bin interval, WS4B encountered the higher wake effect at 235° with a speed deficit of 35.26 % when the target (WS4B) was compared to the reference (WS4) which reduced to 4.19% after applying the correction factor (Table 4a). Again, the LiDAR observed speed was used as reference wind speed to derive the correction factor for WS4 (Figure 12c) and WS4B (Figure 12d). The R^2 value obtained when the corrected WS4 was compared to the reference LiDAR wind speed was 0.8897 as against 0.0234 when the raw data were compared. The speed deficit of 52.43 % was computed from the pairs of the raw data at the most severely affected direction sector (107°), which reduced to 16.10 % after applying the correction factor. Similar evaluation with LiDAR data shows that R^2 is 0.8646 after the correction factor was applied as against 0.0226 obtained when the pair of data (corrected WS4B and LiDAR) was compared. There is a drop to 1.32 % from the previous error of 41.27% computed using the pair of the raw data (Table 4b).

Figure 12C: The Graph of the Reference Winds Speed (LWS) Versus the Corrected wind Speed (WS4). Figure 12d: The Graph of the Reference Winds Speed (LWS) Versus the Corrected Wind Speed (WS4B).

Table 4a: Summary of the Key Parameters used to Illustrate the Efficacy of the Correction Factor.

Parameters of the Wind Measurement				
WS4 = target data; WS4B = reference data				
	Key Parameters of Raw Data (WS4 and WS4B) at WS4 Wake Affected Direction Sector		Key Parameters (Corrected WS4 and WS4B)	
R^2	0.1281		0.9901	
RMSE	1.333		0.382	
Wind speed (m/s) at 106°	WS4B	WS4	WS4B	Corrected WS4
	4.44	2.20	4.44	4.08
Average wind speed (m/s) between 80° and 140°	WS4B	WS4	WS4B	WS4
	5	3.97	5	4.63
WS4B = target data; WS4 = reference data				
	Key Parameters of Raw Data (WSB and WS4) at WS4B Wake Affected Direction sector		Key Parameters (Corrected WS4B and WS4)	
R^2	0.0449		0.9817	
RMSE	0.756		0.127	
Wind speed (m/s) at 235°	WS4	WS4B	WS4	Corrected WS4B
	3.66	2.44	3.57	3.50
Average wind speed (m/s) between 215° and 265°	WS4	WS4B	WS4	WS4B
	3.87	3.34	3.87	3.76

Table 4b: Summary of the Key Parameters used to Illustrate the Efficacy of the Correction Factor

WS4 = target data; LWS = reference data		
	Key Parameters of Raw Data (WS4 and LWS) at WS4 Wake Affected Direction Sector	Key Parameters (Corrected WS4 and LWS)
R^2	0.0254	0.8896
RMSE	1.4215	0.541

Wind speed (m/s) at 107°	WS4	LWS	Corrected WS4	LWS
	2.31	4.86	4.08	4.86
Average wind speed (m/s) between 80° and 140°	WS4	LWS	WS4	LWS
	3.90	5.02	4.49	5.02
WS4B = target data; LWS = reference data				
	Key Parameters of Raw Data (WS4B and LWS) at WS4B Wake Affected Direction Sector		Key Parameters (Corrected WS4B and LWS)	
R^2	0.0226		0.8646	
RMSE	0.923		0.189	
Wind speed (m/s) at 235°	WS4B	LWS	Corrected WS4B	LWS
	2.17	3.70	3.65	3.70
Average wind speed (m/s) between 210° and 270°	WS4B	LWS	WS4B	LWS
	3.22	3.92	3.75	3.91

The suitability of the correction method was validated by comparing the percentage difference between pairs of raw WSB and WS4 observed between (80° and 140°), corrected WS4 compared to raw WSB between (80° and 140°) and the undisturbed raw WS4B and WS4 measured between 260° and 320° are illustrated (Figure 13a). Again, a similar percentage difference between pairs of raw WS4 and WS4B observed between (215° and 265°), corrected WS4B compared to raw WS4 between (215° and 265°) and undisturbed raw WS4 and WS4B measured between 35° and 85° are shown in figure 13b. There are no significant difference between the corrected wind speed in the target direction sectors (wake affected region) and the reference direction sectors (opposite the wake affected region). This shows that the percentage difference computed after the correction factor had been applied is due to the difference between raw wind speeds that the speed sensor would have captured if it is not exposed to the tower wakes. This correction mechanism can therefore be applied reliably to correct wind speeds in the wake-affected direction sectors instead of discarding them. In Figures 13a and 13b, the wake-affected direction sectors are clearly illustrated.

Figure 13a: Percentage Difference between Pairs of Raw WSB and WS4 Observed between (80° and 140°), Corrected WS4 Compared to raw WSB between (80° and 140°) and Undisturbed raw WS4B and WS4 Measured between 260° and 320°. Figure 13b. Percentage Difference between Pairs of raw WS4 and WS4b Observed between (215° and 265°), corrected WS4B Compared to raw WS4 between (215° and 265°) and Undisturbed Raw WS4 and WS4B Measured between 35° and 85°.

11. CONCLUSIONS

Local flow modification around the 3D complex geometry of two communication towers located at Amper-bo and Korabib in Namibia was performed using Ansys Fluent flow solver. The speed sensor to tower separation distance needed to keep the speed sensor out of the tower-induced flow defect was computed and the safe angle range based on the two major boom configurations often encountered in lattice triangular tower instrumentation from a wind measurement perspective was defined. With the IEC standard boom configuration ($\theta = 0^\circ$), the tower is face-on to the wind and the incident wind is considered perpendicular to the same tower face, giving rise to velocity deficit values that are predicted using the upstream contour profiles of the modified flow. Similar flow analysis was performed on the second and most common boom arrangement, for a boom that is placed parallel to the face of the tower. For each of the boom configurations, a total of 36 incident wind angles were considered. The corresponding boom lengths for each incident wind angle were computed with respect to the reference direction ($\theta = 0^\circ$), and the study concludes thus:

- At Amper-bo and Korabib, a boom length of 2.4 m and 1.76 m respectively, protruding from the tower face, is required to achieve 99 % of the freestream velocity using the IEC standard configuration ($\theta = 0^\circ$). Similarly, when the direction of the booms placed parallel to the tower face is considered as the reference direction, the tower at Amper-bo and Korabib needed approximately 1.3 m boom length to achieve 99% of the free stream velocity. The shorter boom length reported was expected due to the minimum obstructions encountered because of the alignment of the tower legs when the tower face was parallel to the incident wind direction.
- For both boom arrangements on the two towers, boom lengths obtained based on the IEC standard boom configuration ($\theta = 0^\circ$) are long enough to keep the speed sensors out of the tower wakes if winds arrive at the tower at incident angles $\theta = < \pm 70^\circ$ with respect to each boom arrangements reference direction (i.e., $\theta = 0^\circ$). This defines the safe or effective angle range.
- Winds that arrive at the tower between $\pm 90^\circ \geq x < \pm 150^\circ$ with respect to each boom arrangement reference direction will cast their full shadow on the speed sensors. A boom length of approximately $x \geq 7.5$ m and $x \geq 6.5$ m respectively at Amper-bo and Korabib are needed to keep the speed sensors out of the tower wakes. The suitability of a slender boom of this length which might be susceptible to vibration and introduce more errors to the readings of the speed sensors mounted on them is questionable.
- A shorter boom length of $x \geq 4.5$ m to $x \geq 3.5$ m or less for Amper-bo and Korabib towers, respectively, is needed to keep the sensors out of the tower wakes when the incident wind angles are within the range $\pm 150^\circ \leq x \leq \pm 180^\circ$. Although the boom length within this range of incident wind angles appears shorter, a good practice for wind measurement perspective may consider this arrangement, not the most appropriate because any slight shift in the upstream wind direction will completely cast a shadow of the tower on the speed sensors.
- The study further revealed that the boom length computed based on the two popular boom arrangements is independent of the scale and turbulence models used in the CFD flow analysis. Also, complex flow interference was reported within the regions very close to the tower structure with no appreciable increase in boom length due to the presence of the secondary support structures.

In the second section of the study, wind data observed from the collocated speed sensors and the LiDAR captured data were combined to derive a correction factor that accurately predicts the site representative wind speeds when applied

to the wake-affected direction sectors. The following conclusions are drawn from the corrected wake affected direction sector when the direction sector selection rule was applied:

- There is a tremendous improvement in the coefficient of determination R^2 when the corrected wind speed is compared with the reference wind speed. When the correction factor derived using WS4B is applied to WS4, the R^2 value improves from 0.1281 to 0.9901 whereas the Root Means Square Error (RMSE) decreases from 1.338 to 0.386 i.e. when the pair of the raw wind speed is compared with the corrected wind speed. For WS4B, R^2 improved to 0.9817 from 0.0449 after applying the correction factor based on WS4 whereas the RMSE decreases from 0.756 to 0.127.
- The LiDAR observed speed was used as a reference wind speed to derive the correction factor for WS4 and WS4B. The R^2 value obtained when the corrected WS4 is compared to the reference LiDAR wind speed is 0.8897 as against 0.0234 when the raw data were compared, and a corresponding decrease of RMSE from 1.4215 to 0.541. A similar analysis using LiDAR data as reference wind data shows that R^2 is 0.8646 after the correction factor is applied as against 0.0226 obtained when the pair of raw data was compared. The RMSE values also decreased from 0.923 to 0.189.

Finally, the speed sensor to tower separation distance needed to keep the speed sensor away from the tower-induced flow defect was thoroughly investigated using two lattice triangular towers of different construction details and different arrangements. A safe angle range ($\theta = < \pm 70^\circ$) was proposed. Winds that arrive at the tower at other angles outside this range will likely induce error reading on the speed sensor and this explains why towers instrument according to IEC standard still fall short of the 1 % speed deficit recommended. Therefore, accurate instrumentation of the tower from a wind measurement perspective requires a combination of physical modelling and CFD flow simulation at the desired incident wind angle. Thus, based on the accuracy of the correction method proposed, it may no longer be necessary to discard the tower-affected direction sectors in wind analysis.

ACKNOWLEDGMENTS

Initial funding for this project was provided by the Ministry of Foreign Affairs of Denmark, United Kingdom Department for International Development, Ministry of Foreign Affairs of Finland, Austrian Development Agency, and Namibia Power Corporation. Invaluable support is provided by Namibia Energy Institute under Namibia University of Science and Technology. Thanks to Mobile Telecommunication (LTD) Namibia for permitting the instrumentation of their communication towers for the NWRAP project.

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