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Tower Wake Distortion Effect: A Comprehensive Review of Methods and Applications

Maduako E. Okorie
PhD Student,
University of KwaZulu-Natal, Durban, South Africa.

Freddie Inambao*
PhD Student, University of KwaZulu-Natal, Durban, South Africa.
ORCID: 0000-0001-9922-5434 (Freddie Inambao)
**Corresponding author.*

Abstract

Literature on the evaluation methods for tower wake distortion effect based on the wind measurement is reviewed, including 50 peer reviewed journal articles, conference papers, standards, thesis and reports published between 1941 and 2019. A review of the literatures published prior to 2005 sets the foundation for a critical review of the International Electrotechnical Commission (IEC) 2005 standard. Thereafter, literature published between 2006 and 2017 is reviewed as the basis for a review of the IEC 2017 standard. A review of literature published post IEC 2017 provides insight into current trends. Considering the current published literature, the shortcomings of IEC 2005 and IEC 2017 standards are identified and discussed and areas for future work noted. The reviewed literature is organised according to the method and tower type used and the purpose and major findings. Prior to 2005, field and wind tunnel experiments were the dominant research approach while field measurement and computational fluid dynamics (CFD) dominated the research methods used between 2006 and 2017. Post-2017 saw an increase in the use of ground profile (LiDAR) for tower shadow evaluation. In field observation there is an unwritten consensus that collocating anemometers at some intermediate height of the tower provides enough information for anemometer consistency checking and tower wake evaluation. Previous studies have agreed that three dimensional (3D) CFD analysis is better suited to characterise flow through the complex nature of an operational lattice tower than the 2D actuator disc approach of IEC 2005 and IEC 2017. It is hoped that this paper can meet the needs of researchers for easy reference to methods of evaluating tower shadowing and hence promote future work on the verification of the remaining shortcomings of IEC 2005 and IEC 2017. While that work is ongoing, these two standards should be regarded a guideline rather than a precise description of flow interference effects through an operational tower.

Keywords: Tower wake distortion; speed deficit; wind direction dependency; secondary support structures; free stream turbulence

I. INTRODUCTION

Wind resource assessment involves the use of various techniques to capture site wind data for analysis to aid informed decision making. Traditionally, wind measurement utilises latticed or tubular towers with boom-mounted sensors attached to the towers. Consideration of other resource parameters that assist in further evaluation of the site's overall suitability necessitates installing speed and direction sensors at some intermediate heights of the tower. Arrangements of this sort inevitably expose the instrumentation to the wake distortion effect of the tower, a phenomenon that is known to introduce a non-negligible error in the wind data observed using anemometers placed on the tower [1]–[8]. Previous works on tower shadow effects have found a 35 % to 50 % wind speed reduction which is known to depend on the tower configurations and boom arrangements [5], [11]–[14]. Such observations have been supported by the computational fluid dynamic (CFD) approach [1], [2], [4], [15]. Furthermore, wind speed error is known to propagate into the power output estimates. Accurate wind speed measurement is therefore a prerequisite for improved wind power prediction and evaluation of a site's techno-economic feasibility [16]. Over the last 74 years the scientific literature has devoted much attention to understand tower wake distortion and in recent times, due to the growing contribution of wind energy to the global energy mix, tower wake effects and their impact on resource parameters has been considered a vital component of research work in wind measurement campaigns. Previous studies have suggested that the phenomenon depends on the tower configuration and the anemometer arrangement on it. However, application of these studies to towers of different structural configurations and different sites' atmospheric conditions in the boundary layers is limited.

To the knowledge of the authors, there is no evidence of published papers on the analytical overview of literature on the tower shadow effect. A study of this kind contributes to reviewing and categorisation of the various methods used to identify, define and correct tower induced flow defects and to reveal some grey areas and knowledge gaps that may require further investigation. In this regard, the authors present a comprehensive literature review of selected literature from scientific papers that have addressed tower distortion effects from the wind measurement perspective. In order to account

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for the past and present trends this review focuses on peer reviewed journal articles, conference papers, standards, theses and reports published between 1941 and 2019. The state of the art and best practice to define and minimise tower wake effects for both lattice (triangular and rectangular) and cylindrical (tubular and rod) towers are fully accounted for in the 50 items of literature reviewed.

II. BRIEF OVERVIEW OF TOWER SHADOW EFFECT

The tower shadow effect describes the uncertainty introduced to wind data captured using boom mounted anemometers placed at some intermediate heights (Fig.2) because of tower induced flow modifications. These modifications are evident in the underprediction of the local wind speeds in the wake and associated speed-ups in the upwind side of the tower. a Tower construction details showing boom arrangement and secondary support structures. b. Ratio WS4/WS4B plotted on a sector-wise basis binned in 5º bins of wind direction intervals

Fig. 1. A section of the tower at Amper-bo showing the boom arrangement and some secondary support structures.

Figure 2 illustrates the tower induced error readings on a pair of collected anemometers represented here as WS4 and WS4B. The speed ratio (WS4/WS4B) binned in 5° wind direction intervals and drawn as a function of the wind direction clearly shows the severity and boundaries of the waked regions (doted oval shaped). At approximately 60° (75° to 135°), WS4 was under tower shading hence the reduction in wind speed captured. Approximately in the (210° to 260°) wind direction sector, tower induced flow perturbation was captured by WS4B. The unsymmetrical pattern of the waked regions may be attributed to the prevalent clockwise wind direction at the site [11].

Tower induced flow perturbations differ through the different planes (Fig. 3a and Fig. 4b) of each module of the lattice triangular tower investigated. Fig. 3a and Fig 3b are computational fluid dynamics (CFD) derived flow showing local wind flow modifications within the vicinity of the tower.

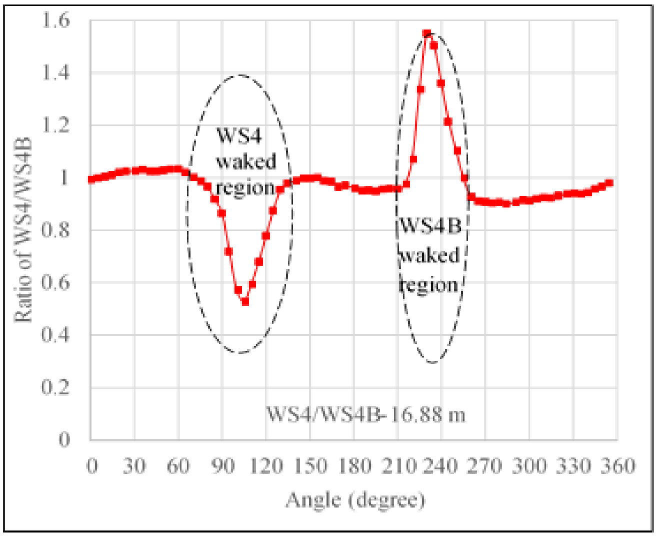

Fig. 2. Ratio of WS4/WS4B plotted on a sector-wise basis binned in 5° wind direction intervals showing waked regions.

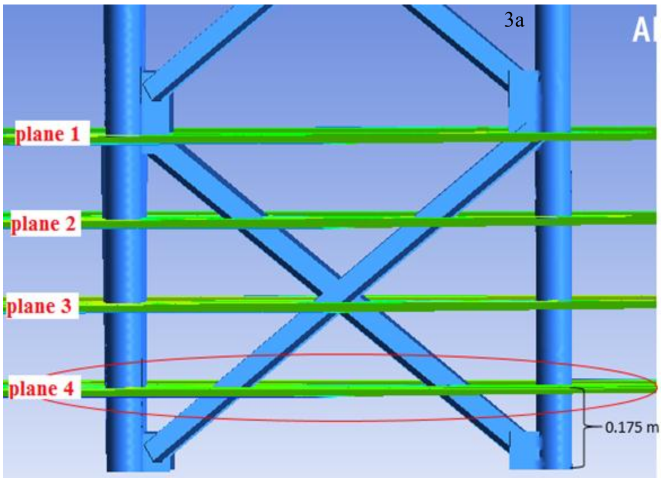

Fig.3a. Convenient plane for positioning the anemometer in the module of the lattice triangular tower at Amper-bo.

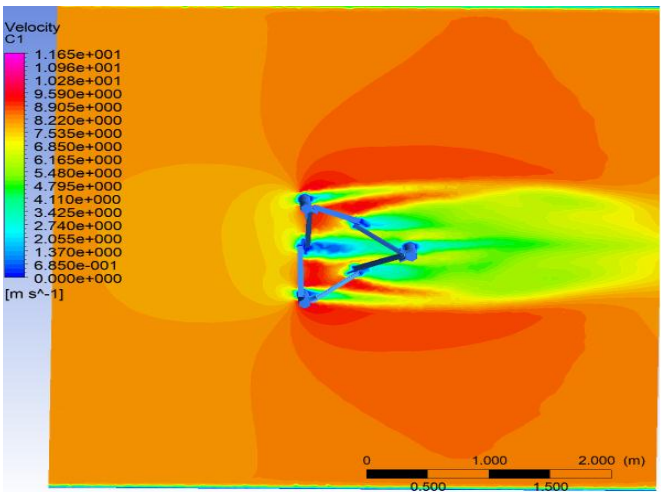

Fig. 3b. 3D CFD flow simulation through a plane of the lattice tower module at Amper-bo (Fig. 3a).

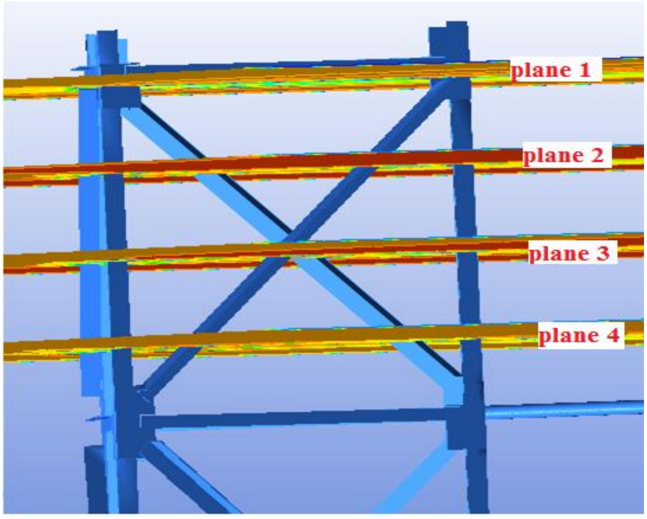

Fig.4a. Convenient plane for positioning the anemometer in the module of the lattice triangular tower at Korabib.

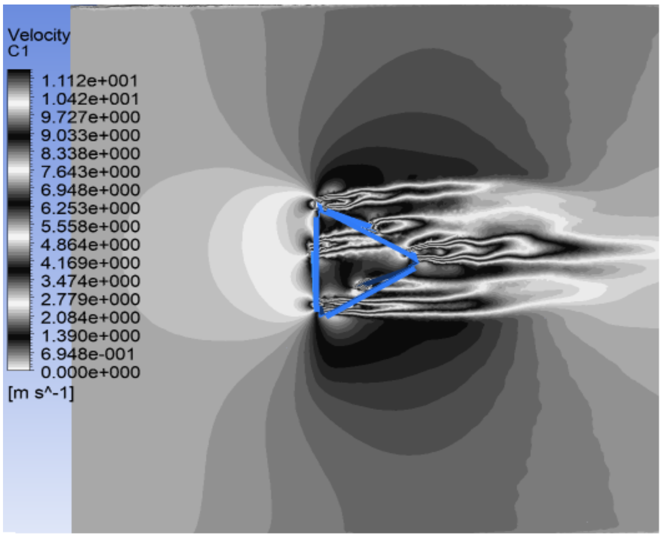

Fig. 4b. 3D CFD flow simulation through a plane of the lattice tower module at Korabib (Fig. 4a).

The flow characteristics differ in each of the planes, an indication that the most convenient plane is the plane with least flow distortion. The optimum boom location for minimum flow distortion is shown in Fig. 3b and 4b with the boom in Fig. 4b directly pointing at the zone of least distortion.

III. METHODS

This study involves an extensive literature review based on the relevant international standards, peer reviewed journal articles, conference papers, reports and theses that have addressed tower induced flow defects in relation to wind measurement. Various methods and approaches used to identify, define and correct tower induced error readings on anemometers have been reviewed. 1941 was chosen as a starting data because it was the year the first article was published that provided a descriptive account of the flow mechanics in the wakes, with emphasis on important parameters such drag, turbulent mixing and vortex shading [17]. The present study, therefore, is based on the review of most relevant literature published from 1941 to 2019, organised systematically to reveal methods used, tower types investigated, purpose of each study and the major findings. The length of period covered in this study is also a testament to the fact that literature on this subject is relatively sparse, so the current study is meant to provide deeper insight into the methods so far used.

For clarity of purposes, the literature is grouped in four major sections around the International Electrotechnical Commission (ICE) standards [3] and [4]. Literature published prior to 2005 is discussed first, setting the foundation for critical review of the (IEC 2005) standard [3]. Thereafter, literature published between 2006 and 2017 is reviewed leading to a review of the (IEC 2017) standard [4]. Articles published post [4] are reviewed to gain insight into the trends, current status and future prospects of this work, which is the core objective of this study.

IV. REVIEW OF LITERATURE

A. Prior to IEC2005 - Tower Wake Effects

Wind energy conversion using windmill technology is centuries old. Due to environmental and sustainability concerns regarding fossil dominant global energy, attention has gradually shifted towards sourcing and using energy in a sustainable manner, but only in the 1980s and 1990s did large-scale utility wind farms start being constructed. Thereafter, wind energy took off and has grown into a multibillion-dollar industry. By 1997, the total global installed capacity of wind power was 7.6 GW, and this grew to a total capacity of 59.2 GW in 2005 i.e. almost 8 times the 1997 global capacity [18]. However, the global consumption of wind energy prior to 2005, evidenced by the global installed capacity, was low when compared to the present time, as was the research on wind energy. The huge investment in the industry necessitated a stringent approach to ensure that quality and accurate data can be measured at a site of interest. Top among the concerns is the placement of instruments on the meteorological (met) mast to minimise the size of the errors associated with the tower induced flow defects.

Research activities in this regard prior to 2005 was dominated by field and wind tunnel experimentation. The oldest scholarly article was published in 1941. Isolated scaled down stack and station models were tested in a wind tunnel experiment and the results provided a good descriptive account of the flow mechanics in the wake, with important parameters such drag, turbulent mixing and vortex shading discussed [17]. A pragmatic and more practical approach to the problem was adopted, by conducting field measurements on lattice towers using test and redundant anemometers [8], [19]. Reference [8] reported speed deficit in the range of 25 % to 50 % and wind direction deviations of about 11 %. Reference [19] reported 30 % deficit upwind and 70 % deficit downwind due to tower wake distortion and both studies suggested a minimum boom length to minimise the effect of tower shadow. Using

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anemometers located 120° and placed at some intermediate height of a lattice triangular met mast at Brookhaven National Laboratory, USA, [14] reported a 35 % speed deficit and 19 % speed-ups and a waked region covering an arc of approximately 60°. In [20], a combined double theodolite pilot balloon and instrumented television tower were used in Oklahoma City to evaluate tower shading effect. The study reported a 7 % underestimation of mean wind speed for an anemometer located 3 m upwind of the tower. Further experimental work revealed the influence of tower secondary support structures on the wind speed captured using a Kansas meteorological mast [21], [22]. In [23], a 232 m lattice tower of the Sicily-Calabria power line in Italy was instrumented for measurement. Findings show a speed deficit of 15 % and 80 % on the upwind side and lee side of the tower respectively due to tower shading. Again, several field experiments using tilt-up tubular tower have been conducted, including [24]. The study concluded that side mounted booms that are sufficiently long enough to remove the anemometer away from the tower shadowing are preferred to a top mounted boom. A 20 % maximum speed deficit and a wake boundary covering about 50° in the waked region of the tower were reported. In an attempt to predict the minimum boom length, it was reported in [25] that significant errors occurred on the lee-side of a cylindrical obstruction for which wind tunnel experiment was performed on its scaled down model. Similarly [24] approached the problem experimentally using a 1:4 scale model of a lattice tower in a wind tunnel to ascertain how increase in turbulence level of the oncoming air stream affects the tower induced perturbations. The study reported that the increase in turbulence level resulted in a 2 % speed defect and stressed that perturbations of the wind-field are chiefly caused by tower configuration and sensor arrangements. Reference [26] used a two-pronged approach (field and wind tunnel experiment) to evaluate tower shading. Reference [27] studied a cylindrical tower and observed a suppressed speed on the lee-side of flow and 3 % discrepancies between the up- and down-stream wind speeds. References [28] and [13] each investigated 1:4 scale models of a 150 m lattice equilateral triangular tower in a wind tunnel experiment. When the result from the two experiments were compared, a 10 % speed deficit occurred in the waked zone of the [28] study, and a speed deficit range of 10 % to 40 % confined to the 30° sector was reported by [13]. Work by [29] showed that a tunnel flow simulation performed on a 1:8 scale model of a 150 m NASA lattice tower predicted shadowing effects reasonably when compared with field observation. In [30], wind tunnel and field measurements found that the boom and its actual placement disturbed the flow seen by the anemometer. In their work as reported in [14] Borovenko et al. explored the use of potential flow solution validated with field experiments. The study showed that 75 % of the readings of the anemometer located upstream of the tower fell within ± 5 % of the potential value and least wake distortion was evidenced at ± 45°, providing useful insight on the possible boom orientation in a cylindrical tower. Using a similar approach, [31] concluded that observed upwind pattern around a cylindrical obstacle (oil drums) is well represented by the potential solution around it, whereas the waked region was asymmetrical. Isopleth diagrams of the speed ratios showed a 6 % and 40 % speed reduction in the upwind and downwind side of the cylinder respectively and a 5 % speed-up at the side of the tower. Further potential flow approaches to the problem revealed a maximum speed deficit of 27 % when compared with field experiments performed on a 150 m NASA tower Computing stream function about the same tower with and without catwalk revealed a speed-up of 3.5 % and 4.5 % respectively, providing insight on the influence of tower secondary support structures. Reference [32] reported that potential flow around a tilt-up cylindrical mast with tapered cross-section predicated disturbed flow due to tower structure reasonably well when compared to observed flow around the same mast at different angles of attack. Rather controversially though, the study opined that the magnitude of the disturbances around the tower exhibits no obvious relation to the geometry of the tower, rather such disturbance is Reynolds number dependent. The study concludes that symmetrical mounting of the booms at both sides of the tower may help to identify the tower induced flow distortion. As reported in [33], a lattice tower was modelled as an actuator disc to estimate its shadowing effect on the readings of the speed sensors mounted on it. The CFD result agreed with field observation performed using the mast at Tjcereborg after both tower and boom induced errors were removed. In a similar approach, [34] assessed the wake distortion effect of a lattice tower of square cross section. The study reported a 19 % mean speed reduction and an increase in turbulence spectra in the waked region of the tower. Reference [35] used a computational approach and experimentation to verify the wake impact of the ship's structure on the shipborne instruments [35]. The CFD result agreed with the observed speed except when the anemometer was in the wake of an upstream obstacle Table I and Table II summarise the above studies in tabular form.

TABLE I. SUMMARY OF THE METHODS AND TOWER TYPES FOR WIND ASSESSMENT BEFORE IEC 2005

Methods and Tower types						
	Field measurement	***Wind tunnel experiment***	***Potential flow solution***	***Computational fluid dynamics***	***Tower types***	
					Lattice tower	***Cylindrical tower***
Sherlock & Stalker (1941)		✓				
Sanuki et al. (1955)		✓				✓
Rider (1960)	✓	✓				✓
Moses & Daubek	✓				✓	

(1960)						
Thornthwaite et al. (1962)	✓					
Borovenko et al. (1963)	✓		✓			✓
His & Cermak (1966)		✓			✓	
Hathorn (1968)	✓	✓			✓	
Gill et al. (1967)		✓			✓	
Cermark & Horn (1968)	✓	✓			✓	
Dabberth (1968a)	✓				✓	
Dabberth (1968b)	✓		✓			✓
Camp & Kaufman (1970)	✓	✓			✓	
Angell & Bernstein (1976)	✓				✓	
Wucknitz (1977)	✓		✓			✓
Lavagnin et al. (1988)	✓				✓	
Pedersen et al.1992	✓	✓			✓	
Hansen & Pedersen (1999)	✓			✓	✓	
Barthlott & Fiedler (2003)	✓		✓		✓	
Yelland et al. (2002)	✓				✓	
Klein (2002)	✓			✓		✓

TABLE II. SUMMARY OF THE PURPOSE AND FINDINGS FROM LITERATURES PUBLISHED BEFORE IEC 2005

Author(s) and Year	Purpose of the study	Major Findings
Sherlock & Stalker (1941)	Causes and remedies to downwash	Causes of downwash of stack gases and remedies
Sanuki et al. (1955)	Evaluation of errors due to cylindrical obstruction	Minimum boom length to keep sensors in the lee and windward sides out of tower wake distortion
Rider (1960)	Evaluate flow distortion of 2.5 cm diameter cylindrical mast	3 % difference in the up and downstream speeds. Speed deficit on the lee side of the tower were evident
Moses & Daubek (1960)	Investigate shadow effect of lattice rectangular tilt-up mast	Speed deficit range (25 % to 50 %), speed-ups and flow deviations and angular dependency of wake effects
Thornthwaite et al. (1962)	Investigate the disturbance of the platform to wind flow.	Minimum boom length, 30 % and 70 % speed deficits for up and downstream directions respectively
Borovenko et al. (1963)	Investigate-wake effect of 300 m long tower of 2.4 m diam.	The study provides insight on the possible location of the boom on a cylindrical tower (±

		45°)
His & Cermak (1966)	TI influence on tower produced perturbations	TI increases tower induced perturbation by only 2 %. Shadow effect depends on tower configuration
Hathorn (1968)	Influence of NASA 150 m lattice tower on wind measurement	Speed deficit of 27 % due to tower shadow. Secondary support structure influence noted
Gill et al. (1967)	Investigate shadowing effects of triangular lattice tower	The study suggests possible boom lengths to keep the sensors away from the wake effect of the tower
Cermak & Horn (1968)	Investigate tower shadow effect of a met tower	Speed deficit range 10 % to 40 % for a boom length of 3.6 m and confined to 30° sector in the tower wake
Dabberth (1968a)	Investigate tower wake effects of a lattice triangular tower	The study defines wake boundaries. Speed deficit of 35 % and speed-up of 19 % are evident
Dabberth (1968b)	Investigate shadowing effects of a cylindrical drum	Speed deficit in the upwind and downwind side of 6 % and 40 % respectively. 5 % speed-up evident
Camp & Kaufman (1970)	Investigate the shadowing effect of 150m NASA tower	Result from both experiments correctly defines the boundary of the tower wakes
Angell & Bernstein (1976)	Investigate flow modification around a television tower	7 % speed deficit as a result of tower wake is evident
Wucknitz (1977)	Investigate flow disturbance of a cylindrical tower	Placement of booms symmetrically at both sides of the tower may help to identify wake boundaries
Lavagnin et al. (1988)	Investigation of tower wake of a disused powerline in Italy	Upwind speed deficit of 15 % and lee side speed deficit of 80 % are recorded
Pedersen et al. (1992)	Investigate anemometer arrangement to reduce error	Suitable position for anemometer location to minimise errors due to tower induced disturbances
Hansen & Pedersen (1999)	CFD approach to investigate tower shadow effect	Minimum boom length and suitable boom orientation for lattice and tubular specified
Barthlott & Fiedler (2003)	Investigate the turbulence structure in the waked region	Speed deficit of 19 % and increase in turbulence spectra in the waked region of a lattice tower
Yelland et al. (2002)	Investigate air flow distortion over a research ship	Modelled errors agreed with anemometer reading except in the upstream of the ship
Klein (2002)	Investigate air tower shadowing effect of a tubular tower	A 20 % maximum speed deficit and a wake boundary covering about 50° in the waked region of the tower

B. The Provisions of IEC 2005 and the Shortcomings

Globally, knowledge and guidelines on tower instrumentation are found in standards and research studies, 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 [3], whose Annex G is the portion of interest. Before the 2017 amended edition [4], the 2005 edition was the internationally accepted guideline for both tubular and lattice tower instrumentation. From the literature (i.e. [4], [11], [12], [36], [37]) it is evident that towers used for wind measurement have a variety of other applications which the standards and available studies did not address in terms of their physical nature and the related effect on wind energy observation. In the context of this study, towers belonging to the mobile telecommunication company MTC of Namibia was instrumented according to [3] for wind measurement. In this regard, [3] was critically reviewed to ascertain its wider applicability to operational towers.

Annex G of [3] specifies three mounting strategies including: a top mounted anemometer, a side-by-side top-mounted anemometer and a side-mounted anemometer. In the top mounted position, the anemometer is placed on the top of the met mast using a vertical tubular rod of specified cross section and length. It is a preferred option contrary to [24]. Top mounted arrangement may eliminate tower shadowing effect but lack enough information for robust anemometer consistency checking with another similar or lower elevation anemometer which enables the evaluation of the site wind shear trend. Better consistency checking may be achieved with side-by-side top-mounted anemometers provided the sectors affected by tower and boom wake effects are identified and eliminated. Consistency checking for lower level anemometers and shear trend evaluation requires that booms be placed at some intermediate height. Anemometers placed at such intermediate heights are exposed to the shadowing effect of the tower. Reference [3] provides recommendations on the minimum boom length to reduce speed deficit to 0.5 %, but wind flow at any site is not constrained to a specified direction; as result, anemometers might be in the tower's wake at some point. The standard further stated that shadowing effects of the tower depends on its solidity, the drag of individual members, direction of the wind and separation of the measurement point from the mast. Plan views of iso-speed lines of normalised flow within the vicinity of both tubular and lattice meteorological towers are presented. The standard further provides a mathematical expression for estimating centreline velocity deficit upstream of the mast given as a function of the thrust coefficient which depends upon the solidity of the meteorological mast and the normalised leg distance. Based on the Annex G of [3], a user may easily estimate the velocity deficit if the tower dimensions are provided.

Based on detailed analysis, it may appear as if [3] has addressed all the problems regarding tower instrumentation for wind observation. However, the standard has limitations resulting from either the factors considered or not considered, or the method of obtaining the information presented. Some of the shortcomings are briefly discussed here and they agree with the findings in [15].

1) Assumed incident wind direction: The mathematical expression that captures the velocity deficit is assumed to be on the axes that pass through the mast centre and perpendicular to the mast face. The implication is that the incident wind is considered perpendicular to the same mast face, giving rise to velocity deficit values that are predicted using the upstream contour profiles of modified flow within the vicinity of the mast. In most cases, this arrangement does not correspond to the anemometer placements in many wind campaign sites, more especially where communication towers are instrumented for wind assessment. For one reason or the other the most prevalent practical mounting arrangements have been to place the boom parallel to the faces of the mast which then becomes perpendicular to [3] reference direction and this is the boom and anemometer arrangement used in Amperbo, Schlip and Korabib, three southern inland locations in Hardap and Kharas regions of Namibia, where wind observations are currently taking place.

2) Universal applicability: In [3], the range of solidity ratio and by extension the thrust coefficients for lattice meteorological masts of different configurations to be used in the mathematical expression of the velocity deficit are specified. For the communication towers investigated in this study and many other operational towers, the values of the solidity ratio and thrust coefficients are outside the specified range in [3] and vary greatly when different incident wind angles are considered. Having thoroughly investigated this concept accurately in this work, one may question how universally applicable the velocity deficit expression is.

3) Numerical method: Two-dimensional Navier-Stokes numerical computation were used to draw the iso-speed plots of local wind flow modification within the vicinity of the met mast. The numerical computation was based upon a combination of actuator disc and Navier-Stokes theory and analysis [3], as in [33]. This approach oversimplifies the problem in terms of the geometry and flow field and may constitute a major source of uncertainty in its application. As opined in [15], this approach may reasonably describe flow around a cylindrical tower but not for a more complex lattice type of tower.

4) Influence of the secondary support structure: As earlier mentioned, lattice towers used in wind data observation are deployed for other uses as well. As a result, the majority of them have discrete members such as cross and horizontal bracings, cable ladders, cable bundles and attachment brackets etc., which produce discrete wakes which result in a more complex flow interference contrary to the idealised mast configuration as presented in [3]. Tthe guideline presented in [3] neither acknowledges the obvious presence of secondary support structures nor suggests an approach to estimate errors due to their presence.

5) Impact of free-stream turbulence: The maximum height of atmospheric boundary layers which occur at late afternoon are around 1500 m [38]. Experimental results show that wind speed varies with height and so does the free-stream turbulence. Instruments located at different heights of the mast may be exposed to different atmospheric conditions [15]. The standard [3] does not consider the impact of free-stream turbulence on flow distortion within the vicinity of the tower.

6) Wind direction dependency: In [3] incident wind angle was considered to be perpendicular to a face of the lattice met mast, along the same line to the speed sensor and all information available in the standard is based on that assumption. The standard justifies this choice of boom and anemometer arrangement on the premise that local flow distortion within the vicinity of the tower is least within the 90° measurement sector.

V. REVIEW OF LITERATURE PUBLISHED BETWEEN 2005 AND 2017

Rapid evolution of CFD techniques and decreasing computer hardware costs accompanied by faster processing times [39] have increased the versatility of application of CFD in various fields of learning. CFD study combined with field observation have been used for predicting flow around and through towers deployed for wind measurement. While [40] gave an account of the minimum boom length and how a tower's surface irregularities contribute to flow perturbations, [41] found that an increase in the vertical separation distance of the top mounted anemometer results in less error readings and concluded that free-stream turbulence has negligible impact on tower induced flow distortion, agreeing with [26]. Reference [42] approached the problem as per [3] where a lattice triangular tower was modelled as an actuator disc. Using the CFD model and varying the solidity and Rd/Lm ratios, a correction factor which provides a qualitative good fit between simulated and observed was derived. In a further computational approach [43] performed CFD analysis of tubular and lattice masts modelled as actuator discs, similar to the approach adopted in literature such as [3], [4], [42] and [44]. Using the k-ω SST two equation RANS model for flow analysis and validating the flow simulation with the field observed data, a correction mechanism for detecting incorrectly mounted booms was suggested. The study by [43] predicted higher flow distortion than [3] and [4] and attributed such to free-stream turbulence that was factored in during the CFD flow simulation. Using the CFD approach, [37] studied the shadowing effect of a lattice triangular communication tower and its secondary support structures and reported that [3] overpredicted the minimum boom length required to place the anemometer away from the tower wakes. Similarly, [1] and [2] performed 3D CFD simulation verified by comparison with 1:20 scale models of FINO 3 lattice towers. While both studies predicted shorter boom lengths at various incident wind directions, [1] reported that one-equation Spalart-Almaras performs surprisingly well compared with its more sophisticated two-equation counterparts k-ε and k-ω SST, based on the sensitivity analysis of the three turbulence models often used in external aerodynamic study. Using CFD flow simulation and wind tunnel measurement, an improved methodology of evaluating shadowing effect of a lattice tower was suggested by [15]. Listing some of the shortcomings of Annex G of [3], as discussed in this present work, the study concluded that tower shadow study is an atmospheric flow problem that requires realistic free-stream boundary conditions corresponding to ABL profiles during computational analysis. Reference [6] proposed a numerical model that combines a potential flow solution in the region outside the tower wake, and a two-dimensional Gaussian turbulent wake within the wake, for the purpose of correcting anemometer readings to remove error due to the shadowing effect of the tower. The study acknowledged the limitation of the model's application due to oversimplification involved in its derivation. As a result of field experimentation, a formula and an in-field calibration for wind speeds and directions measured using booms collocated at 80 m AGL and placed 60° apart in a lattice triangular tower was proposed by [45]. The proposed method extracted direction dependent errors and shadowing effect of the tower to an uncertainty of less than 0.5 %. Similarly [46] clearly shows the severity and boundaries of tower wakes when the speed ratio of collected anemometers placed on an 80 m tilt-up tubular tower was computed. References [47] and [48] approached the problem experimentally using field measurements. Applying different data filtering methodologies, [47] identified and treated the shadowing effect of the tubular tower and proposed two additional methods and correction factors. Using the Levenberg-Marquardt algorithm, measurement from one anemometer was used to recreate data from an anemometer placed at the same intermediate height on the opposite side of a rectangular lattice tower that had failed [48]. Speed ratios plotted as a function of the wind direction clearly revealed the direction sectors and the severity of the tower wake effects. Wind speed deficit in different incident wind directions around a tubular tower was evaluated experimentally by [7], using full-scale wind tunnel testing. A speed deficit of 18 % and 35 % for higher and lower wind speeds was reported in the waked region of the tower and the study concluded that tower wake intensity was speed dependent. Flow induced perturbations of a BT tower building and lattice mast placed on the top of it were investigated [49]. When the results from both experiments were compared, an upward flow deflection due to tower building was evident and uncertainties in speed and direction and speed-ups are all associated with the mast shadowing effect. In [11] and [50], it was reported that higher and lower values of tower distortion factor (TDF) and scatter factor (SCF) are associated with tower waked regions. Table III and Table IV summarise the above studies in tabular form

TABLE III. SUMMARY OF THE METHODS AND TOWER TYPES FOR WIND ASSESSMENT BETWEEN 2005 AND 2017

Methods and Tower types						
Author(s) and Year	***Field measurement***	***Wind tunnel experiment***	***Potential flow solution***	***Computational fluid dynamics***	***Tower types***	
					Lattice tower	***Cylindrical tower***
Filippelli & Mackiewicz (2005)	✓			✓		✓
Perrin et al. (2007)	✓			✓		
Sadoud (2012)	✓			✓	✓	
Tusch et al. (2011)	✓			✓	✓	✓
Bezrukovs et al. (2017)				✓	✓	
Stickland et al. (2013)		✓		✓	✓	
Fabre et., al (2014)		✓		✓	✓	

Lofti et al. (2015)		✓		✓	✓	
Lubitz (2009)	✓		✓			✓
Lindelöw et al. (2010)	✓				✓	
Lang & McKeogh (2011)	✓					✓
Farrugia & Saint (2014)	✓					✓
Farrugia & Sant, (2013)	✓				✓	
Orlando et al. (2011)		✓				✓
Barlow et al. (2011)	✓	✓			✓	
Rehman (2014)	✓					✓

TABLE IV. SUMMARY OF THE PURPOSE AND FINDINGS FROM LITERATURES PUBLISHED BETWEEN 2005 AND 2017

Author(s) and Year	Purpose of the study	Major Findings
Filippelli & Mackiewicz (2005)	Investigate shadowing effect of a tubular tower	Minimum boom length was recommended. Flow perturbation caused by surface irregularities
Perrin et al. (2007)	Investigate flow defect of speed sensor on top of a tubular tower	5 tower diameter vertical distance results in error of less than 1 %. Free-stream turbulence has negligible impact
Sadoud (2012)	Using CFD to investigate the shadowing effect of 134 m lattice tower	A correction factor which provides a qualitative good fit between simulated and observed was derived
Tusch et al. (2011)	CFD to investigate wake effects of tubular and lattice towers	Correction mechanism for detecting incorrectly mounted booms. Free-stream turbulence impact was investigated
Bezrukovs et al. (2017)	CFD to investigate the shadowing effect of lattice triangular communication tower	An attempt to investigate the impact of some secondary support structures
Stickland et al. (2013)	Using CFD to investigate shadowing effect of FINO3 lattice tower	Shorter boom lengths predicted at all incident wind directions
Fabre et al. (2014)	Using CFD to investigate shadowing effect of FINO3 lattice tower	Shorter boom lengths predicted at all incident wind directions. k-ω SST the most suitable turbulence model
Lofti et al. (2015)	Impact of freestream turbulence on tower shadowing effect. A CFD study	Tower shadowing effect is an atmospheric flow problem
Lubitz 2009	Using numerical model and field observation to evaluate tower shadow	Correction factor with limited application due to oversimplification involved was proposed
Lindelöw et al. (2010)	Investigate a methodology to extract tower shadow effect of a lattice tower	Proposed formula for extracting direction dependent errors and tower shadowing effects was proposed
Lang & McKeogh (2011)	Investigating the tower shadow of a tubular tower	Tower wake boundary and intensity are identified

Farrugia & Saint (2014)	Investigating the tower shadow effect of a tubular tower	Proposed two methods for data filtering and correction factors
Farrugia & Sant, (2013)	Investigate tower shadow and method of correction of failed anemometer	Method of recreating lost data from failed anemometer given the data from the opposite anemometer
Orlando et al. (2011)	Using tunnel testing to study tower showing effect of a tubular tower	High wind speeds lead to less speed deficit (18 %) and low wind speeds lead to high speed deficit (35 %)
Barlow et al. (2011)	Investigate flow perturbation of a BT tower and lattice mast on top of it	Speed and direction correction measures were proposed. Flow induced defects from building and mast were evident
Rehman (2014)	Investigate wake effect of a tubular tower by computing the TDF and SCF	Higher values of TDF and SCF in the wake affected regions. Lower values of TDF and SCF in the regions without wake

VI. REVIEW OF IEC 2017

The 2017 edition [4] of the standard acknowledged some of the limitations of the earlier edition discussed above and found in [15]. For instance, on the assumed incident wind direction, the standard (IEC 2017), still uses the same expression for the centre line velocity deficit and its associated uncertainties, as discussed earlier. On the universal applicability, the range of solidity ratio remains as prescribed in [3]. The errors inherent in the use of this expression for operational towers whose solidity ratios are outside the range specified [3] still exist in [4]. Again, the numerical model (combination of actuator disc and two-dimensional Naiver-Stokes theory) used to draw the iso-speed plots of tower induced flow perturbation was carried forward to the newest edition [4]. The standard indicates zones of high accuracy upstream of the mast based on the iso-speed plots on both cylindrical and lattice towers. Furthermore, [4] acknowledges that secondary support structures (cross and horizontal bracings, cable ladders, cable bundles and attachment brackets etc.) produce discrete wakes which make flow interference significantly more complex within the vicinity of the tower, however the standard does not suggest any practical approach to evaluate their contribution to tower induced flow defects. Further comparison of [3] and [4] shows that the 2017 edition of the standard did not also consider whether the free-stream turbulence would affect tower induced perturbations. Finally, on the wind direction dependency, the 2017 edition justifies the choice of boom and anemometer arrangements on the premise that local flow distortion is least within 90° measurement sector and provided that the anemometer is placed a distance Rd > 2 times the met mast leg distance. The 2017 edition further suggests that that flow induced perturbations, having met the stated requirements, are negligibly affected by the met mat orientation (whether the corner or face is oriented into the wind), and as such can be assumed to be the same [4]. The 2017 edition [4] of the standard went a step further and performed a CFD derived flow showing the relative position and hence influence of a secondary support structure on the flow distortion changes with height. Two sets of CFD flow simulation were performed using incident wind at 90° and another at angle less than 90°, both on the same mast face resulting in a distortion that is asymmetric but shows that the optimum location for minimum flow distortion is still within the 90° sector to the flow direction, thereby further reinforcing Annex G of [4]. The standard however acknowledged that winds approaching at an incident angle greater than 100° from the anemometer boom orientation would result in higher flow distortion, though no further explanation was given in that regard.

VII. REVIEW OF LITERATURE PUBLISHED AFTER IEC 2017

Recent advances in the wind energy industry have seen the deployment of light detecting and ranging (LiDAR) and sound detecting and ranging (SODAR) for ground profiling of wind. The shadowing effect of a lattice tower was evaluated through combination of experimental data captured with sonic anemometers, staring and profiling LiDAR [5]. The study reported a maximum speed deficit of up to 50 %, an order of increase in turbulent kinetic energy (TKE), a decrease in wind speed correlation in wake affected direction sectors, and flow deflection due to tower physical structure. Adopting a similar approach, the wake distortion effect of a lattice communication tower was evaluated by analysing and comparing data measured using collocated anemometers and LiDAR [11], [12]. The study reported a maximum speed deficit of 49 %, a decrease in speed and TI correlation in the waked sectors, and an order of increase in turbulence intensity (TI) in the waked zones. The study concluded that TI analysis may be a better predictor of tower wake distortion when compared with the traditional speed ratio approach [11]. Reference [51] in a CFD study developed a correction method that reduced tower induced error readings from 4.1 % to 0.8 % in a field experiment, where four anemometers installed on booms mounted parallel to the four sides of a rectangular lattice tower was proposed. In [52], a study that paralleled [6] was conducted. A preliminary model to remove tower shading and to correct data from pairs of anemometers in which one fails was proposed, though the author acknowledged the limitation of the model's application due to the oversimplification involved in its derivation. Table VI and Table VII summarise the above studies in tabular form.

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TABLE V. SUMMARY OF THE METHODS AND TOWER TYPES FOR WIND ASSESSMENT BETWEEN 2017 AND 2019

Methods and Tower types							
Author(s) and Year	***Field measurement***	***Wind tunnel experiment***	***LIDAR measurement***	***Potential flow solution***	***Computational fluid dynamics***	***Tower types***	
						Lattice tower	***Cylindrical tower***
McCaffrey et al. (2017)	✓		✓			✓	
Lubitz & Michalak (2018)	✓			✓			✓
Nishio (2018)	✓				✓	✓	
Okorie & Inambao (2019)	✓		✓			✓	
Okorie & Inambao (2019)	✓		✓			✓	

TABLE VI. SUMMARY OF THE PURPOSE AND FINDINGS FROM LITERATURES PUBLISHED BETWEEN 2017 AND 2019

Author(s) and Year	Purpose of the study	Major Findings
McCaffrey et al. (2017)	Investigate shadowing effect of a BAO lattice tower	Accurate definition of wake boundaries, speed deficits and speed-ups. Decrease in correlation and tower flow deflection
Lubitz & Michalak (2018)	Investigate speed averaging in the measured magnitude in the wake	A preliminary model to remove wake effects from sensor data and to correct data from a pair of sensors if one fails
Nishio (2018)	Using CFD to investigate and correct the shadowing effect of a rect. lattice tower	Proposed a correction method that reduces tower induced error readings from 4.1 % to 0.8 % using CFD analysis
Okorie & Inambao (2019)	Field and LiDAR observation to investigate wake effects of a lattice communication tower	Wake boundaries defined, speed deficits, decrease in correlation. TI analysis a better tower wake predictor
Okorie & Inambao (2019)	Field and LiDAR observation to investigate wake effects of a lattice communication tower	Wake boundaries accurately defined using collocated anemometers. Speed up of up to 49 % reported.

VIII. RESULTS AND DISCUSSION

A. Distribution of Method of Investigation and Tower Type used

As earlier stated, the length of time covered in this review is a testament that research publications on the theme is very sparse. Between 1941 to 2004, 21 studies that provided insight into tower shadowing effect were reviewed. While Table I provides the summary of the methods and tower configurations used, Table II summarises the purpose and major findings of each study. Field and wind tunnel experiments were the dominant approaches to the problem, accounting for 51.13 % and 28.12 % respectively of the methods used. Numerical approach (potential flow solution) accounts for 12.5 % and CFD for 6.25 % of the methods used. For validation purposes, two or three of the methods are combined (Table I). Moreover, 17 (68.42 %) lattice tower (triangular and square) were examined while 6 (31.58 %) cylindrical (tubular and rod) were studied. Between 2005 to 2017, 16 studies were reviewed. Table III is a summary of the methods and tower configurations used and Table IV summarizes the purpose and major findings of each study. Rapid evolution of CFD techniques and decreasing computer hardware costs accompanied by faster processing times have increased the versatility of the application of CFD in various fields of learning [35]. CFD study and field observation were the dominant research approach, and accounts for 32 % and 44 % respectively of the methods used. Wind tunnel experiments accounted for 20 % while the potential solution approach accounted for 4 % of the methods used. Lattice towers (triangular and square) investigated accounts for 56.75 % while cylindrical towers (tubular and rod) accounted for 43.75 %. Five papers were reviewed that we written between 2017 and 2019. In Table VI, we find a summary of the method and the tower configurations used while Table VII summarises the purpose and the major findings. The experimental methods used were field measurements (50 %) and LiDAR (30 %). Potential solution and CFD simulation accounted for 10 % each. Lattice towers (triangular and square) accounted for 80 % while cylindrical towers (tubular and rod) accounted for 20 %.

The three mounting strategies specified by Annex G of [3] and [4] included top mounted anemometer, side-by-side top-mounted anemometer and side-mounted anemometer. The standards considered top mounted as the preferred option contrary to [24]. Previous literature such as [5], [8], [11], [12], [45]–[47] and [51]–[53]) used collocated anemometers where one serves as the test and the other the redundant. This arrangement provided enough information for better sensor consistency check [4] and site shear trend evaluation. However, there was no consensus on the angle of separation between the booms. On the computational model, literatures such as [1], [2], [15], [37], [43] and [51] agreed that the 3D CFD approach was better suited for modelling flow around and through an operational lattice tower structure than the numerical approach prescribed in [3] and [4].

The identified limitations were further discussed considering the current literature regarding identified areas that needed improvement. The issues of secondary support structures, free-stream turbulence, wind direction dependency and tower shadow impacts on other resource parameters were discussed.

B. Secondary Support Structures

Concerns about stability coupled with the variety of other applications on the towers has made secondary support structure a critical component of today's operational towers. In [36] it was reported that a 1 % increase in speed-ups in a150 m NASA lattice tower was due to the presence of a catwalk. The IEC (2017) standard acknowledged that secondary support structures could produce discrete wakes which would make flow interference significantly more complex within the vicinity of the tower. However, the standard did not suggest any practical approach to evaluate their contribution to the overall wake distortion effect. The only literature that considers wake influences of secondary support structures as a research component in modelling flow through an operational tower is [37]. However, the inconsistencies in determining the solidity ratio of the tower, the contribution of the secondary support structures and the thrust coefficient are sources of concern. Models used in the literature to study the secondary support structures are oversimplified and the centreline velocity deficit expression proposed by the IEC standard has still been used to compute the value of R, meaning that the inherent uncertainties mentioned earlier in [3] and [4], on how the expression was derived and used, are also applicable to [37]. Further investigation is therefore required to improve the method of assessment and to estimate the magnitude of perturbations due to secondary support structures.

C. Free-Stream Turbulence

Both editions of the standards are silent on the impact of free-stream turbulence on tower induced flow perturbations. In the earlier literature (i.e. [26], [41]) it was suggested that free-stream turbulence and turbulence level increase do not have any significant impact on the tower induced flow defect. On the contrary, [15] did a comparative study on the choice of boundary conditions used in literatures for free-stream turbulence analysis and found that tower shadowing effect should be treated as an atmospheric flow problem by setting the free-stream boundary conditions that corresponds to atmospheric boundary conditions (ABL) during the flow analysis rather than treating it as an arbitrary external flow problem as previous studies have done. The result of this study by [15] was in agreement with [43] which reported higher flow distortion than [3] and attributed this to free stream turbulence that was considered during the CFD flow simulation. However, there is a limitation in the application of previous studies on towers of different configurations and different site atmospheric conditions in the boundary layer. In the context of the present work, further investigation is needed to estimate possible speed-ups upstream of the tower due to free-stream turbulence using LiDAR captured wind speed that is considered to be undisturbed.

D. Wind Direction Dependency

The idealised tower and boom arrangement whereby predominant wind speed is always perpendicular to the face of the lattice tower is rare in a typical field measurement. Incident wind may arrive at the tower at an angle less or more than 90°. In the context of the present study, the lattice towers investigated were not originally designed and erected for wind measurement purposes. The prevailing wind pattern in terms of predominant direction at the host sites were not known before they were erected. More so, the booms holding the anemometers were placed parallel to the face of the tower while the incident wind angle was not perpendicular to the tower face. Thus, the incident winds arrive at the tower at angles that are not 90°. As the incident wind angle varies, the assumed tower leg length, solidity ratio and in extension thrust coefficient changes as shown in Fig. 5a-5c and Fig. 6a-6c. If the centreline velocity deficit expression derived from the standard mast configuration ($Ø = 0°$) is the only criterion for quantifying tower flow distortion, the concern about its universal applicability arises again. For this reason, the velocity deficit expression may not precisely predict flow distortion at different incident wind angles. Previous literature (i.e. [1], [2], [15], [37], [40]) that adopted the computational approach to the problem agreed that tower induced flow distortion is angle dependent. However, none of the previous studies had attempted or suggested an approach to modify the velocity deficit expression to truly capture flow distortion at different incident wind angles other than 90° as prescribed in [3] and [4].

Fig. 5 and Fig. 6 are the relationship between parameters of interest derived from the analysis of tower modules (Fig. 3a and Fig. 5b). The variation of incident wind angle with the tower leg length (module face width) for a module 0.890 m and 1.052 m high respectively are clearly illustrated (Fig. 4a and

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Fig 5a). The information available in [3] and [4] assume constant leg length but this is not true. Wind incident angle of less or more than 90° on the same tower face will be exposed to a different tower projected area, hence different leg lengths (face width). At each incident wind angle the projected area differs, hence the solidity ratio (Fig. 5b and Fig. 6b). Least flow distortion would occur at angles (30°, 90°, 150°, 210°, 270° and 330°) corresponding to higher solidity ratio and vice versa. Similar results are found in [15]. Figures 5c and Fig. 6c are the solidity ratios. drawn as a function of the tower leg lengths.

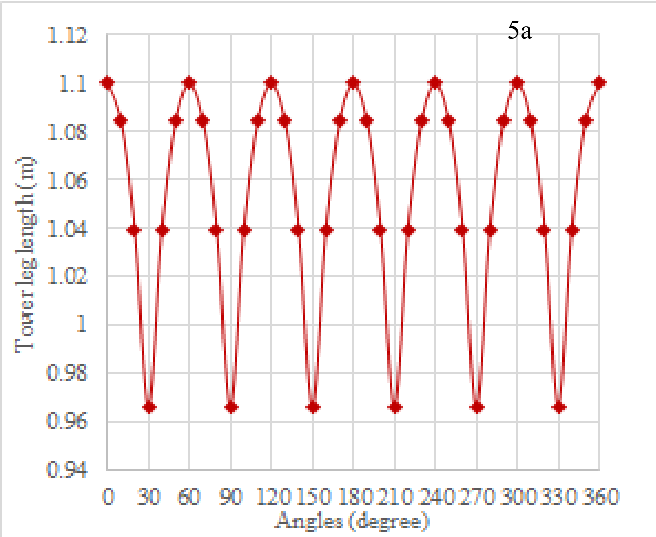

Fig. 5a. Tower leg length (face width) variation with incident wind angle for the module of the tower at Amper-bo (Fig. 3a and Fig.3b).

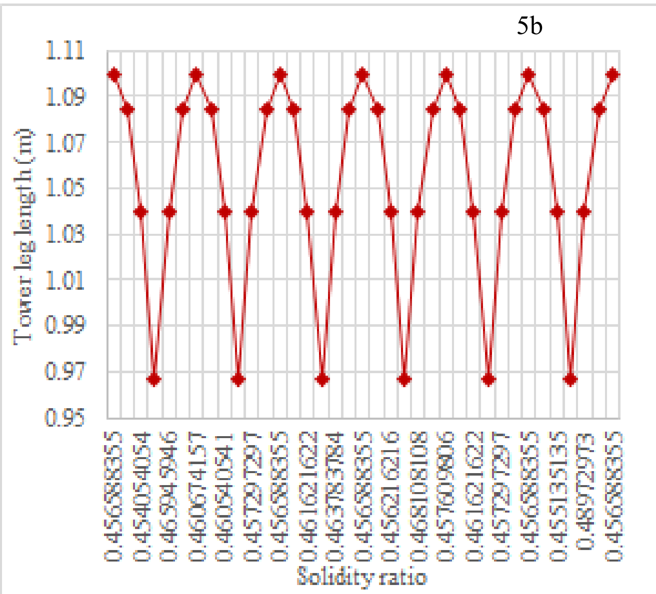

Fig. 5b. Tower leg length (face width) variation with solidity for the tower module of the tower at Amper-bo (Fig. 3a and Fig. 3b).

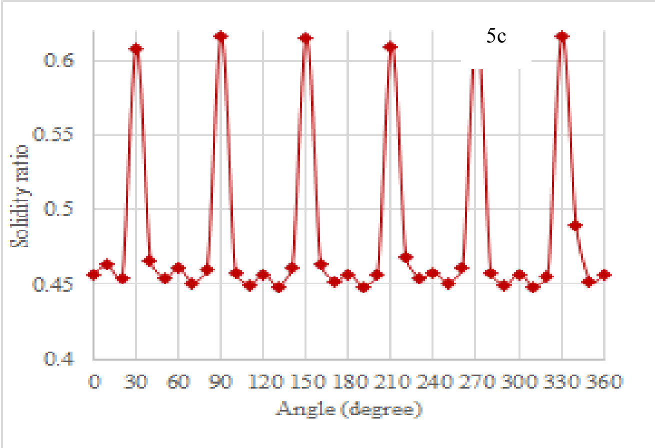

Fig. 5c. Solidity ratio variation with incident wind angle for the tower module of the tower at Amper-bo (Fig. 3a and Fig. 3b).

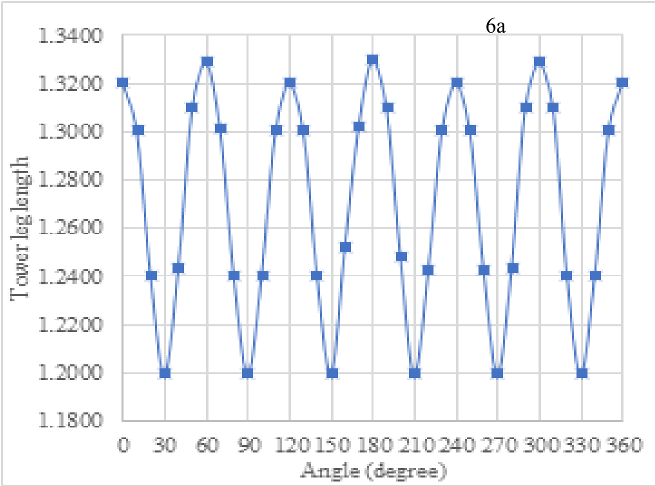

Fig. 6a. Tower leg length (face width) variation with incident wind angle for the module of the tower at Korabib (Fig. 4a and Fig. 4b).

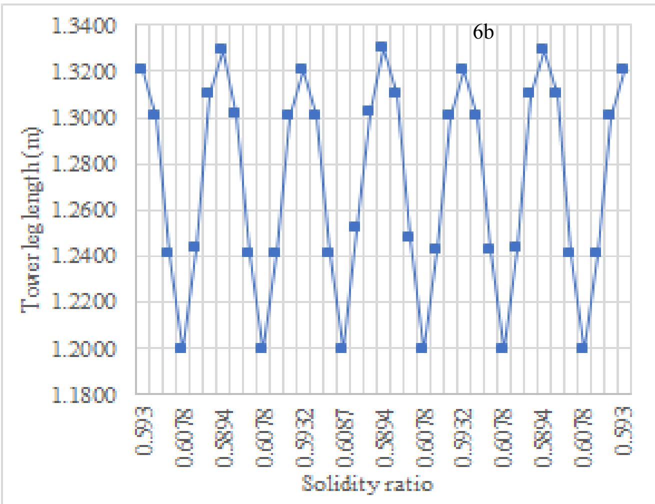

Fig. 6b. Tower leg length (face width) variation with incident wind angle for the module of the tower at Korabib (Fig. 4a and Fig.4b).

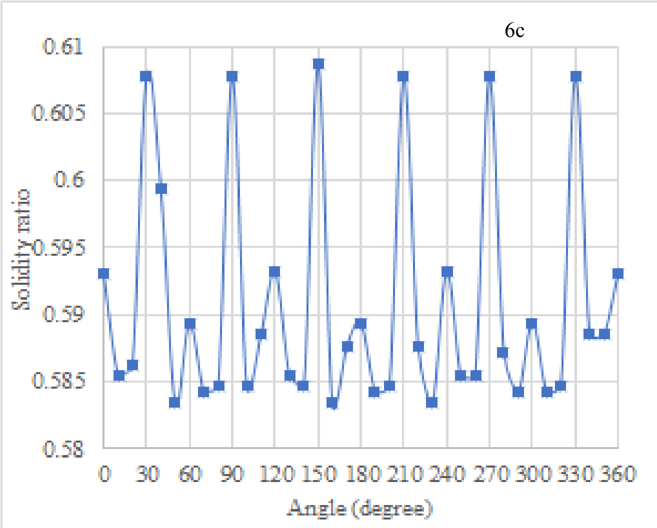

Fig. 6c. Solidity ratio variation with incident wind angle for the tower module of the tower at Korabib (Fig. 4a and Fig. 4b).

The graphs of leg length versus solidity ratio have the same pattern with the graphs of incident wind angles versus leg length. This is well understood because the solidity ratio and the leg length (tower face width) are all computed based on the incident wind angle.

The two lattice triangular towers exhibit rotational symmetry at 120°. Further details of this analysis will be available in future work. Since the two key parameters in the velocity deficit expression (thrust coefficient which depends on the solidity ratio and the tower leg length) are angle dependent, therefore, tower induced flow perturbations are also angle dependent. The universality of application and the assumed incident wind direction based on the recommendations of the standards [3] and [4] are not necessarily true. Again, towers instrumented according to the IEC standards do not guarantee the required 1 % accuracy in waked regions [37]. Based on the critical review of the IEC standards, it is safe therefore, to treat the (IEC 2005 and 2017) as a guideline rather than a document that precisely describes the instrumentation of a typical operational tower. There is a need for a centreline velocity deficit expression that captures variations in solidity ratio and the tower leg lengths to precisely define flow distortions at various incident wind angles around an actual operational tower. There is also a need to improve the method of calculating the solidity ratio, the leg length, and the thrust coefficients, the reduction in porosity due to secondary support structures at any given angle and planes (Fig. 3a and Fig. 4a), and, ultimately, to incorporate wind incident angles into the velocity deficit expression to account for tower wake distortion at such an angle. This may require a parametric approach to the study.

E. Tower Shadow Impact on Resource Parameters

Tower wake distortion is majorly associated with speed deficits and speed-ups. This is evident in all the literature reviewed. Validating field observation with LiDAR captured data, an order of increase in TKE and TI due to tower shading was reported in [5] and [11]. The precise impact of tower shadowing on other resource parameters of interest such as wind shear coefficient, Weibull parameters etc. are not known. For cases where there are no collocated speed sensors, two or three speed sensors are placed at different heights (AGL) but on the same azimuth from the north, but no literature has addressed a method of detecting tower induced flow perturbations to the reading of the sensors. The need to use the undisturbed LiDAR data to quantify the impact of the phenomenon on other resource parameters of interest therefore exists.

IX. CONCLUSION

The current study is a presentation of an extensive review of literature on tower wake distortions and evaluation of methodologies for wind measurement. The best practices to identify, define and minimise tower wake effects for both lattice (triangular and rectangular) and cylindrical (tubular and rod) towers were fully accounted for in 48 of the studies reviewed. The literature was reviewed and organised according to the method and tower type used and the purpose and major findings of each study. Between 1941 and 2004, field and wind tunnel experiments were the dominant approaches to the problem, but from 2005 to 2017 field observation and CFD flow analysis dominated the research approach used. Beyond 2017, field experiments (anemometer and LiDAR) were combined to evaluate tower induced flow defects. Literatures published prior to 2005 was discussed setting the foundation for critical review of the IEC (2005) standard. Thereafter, literature published between 2006 and 2017 was reviewed setting the foundation for further review of the IEC (2017) standard. Finally, literature published post IEC (2017) was reviewed. Arising from this extensive literature, the following grey areas exist for future academic research work:

- (IEC 2017) acknowledged that secondary support structures could produce discrete wakes which would make flow interference significantly more complex within the vicinity of an operational tower. In [37], an attempt was made but there exist inconsistences on how the solidity ratio was evaluated. The model that described the secondary support structures was also over-simplified. Further investigation, especially of towers of different configurations, is therefore required to improve the method of assessment and to estimate the impact of these discrete structures on porosity.
- (IEC 2005) and (IEC 2017) did not assess the impact of free-stream turbulence on tower induced flow perturbations. There exists no consensus on the impact of this phenomenon on tower wake distortion. Some studies opined that free-stream turbulence impact is negligible, while others acknowledged it to be an atmospheric flow problem. Towers of different configurations located at different sites in different atmospheric conditions in the boundary layer requires further verification.
- On the wind direction dependency, relevant literatures

published after IEC 2005 have consistently questioned the universality of the application of the centreline velocity deficit expression derived from a standard incident wind angle (Ø = 0°) as prescribed by the standard. The two key parameters in the expression (thrust coefficient which depends on the solidity ratio and the tower leg length) are all angle dependent. Tower wake distortion is therefore angle dependent. Expression that precisely captures tower induced flow perturbations at various incident wind angles is needed.

- Beside speed deficit, speed-ups and order of increase in TI and TKE reported in the literature, there exists a need to use undisturbed LiDAR observed data to further evaluate the exact impact of tower shadowing on other resource parameters of interest such as wind shear coefficient, Weibull parameters etc. A combination of the knowledge of the resource parameters and the two observation techniques, coupled with the knowledge of CFD, will assist greatly in arriving at the most accurate correction factor for each tower configuration.

The identified limitations suggest that further and continuous studies are needed. Application of previous studies to towers of different configurations located at different sites in different atmospheric conditions in the boundary layer are limited. IEC (2005 and 2017) therefore serve as a guideline rather than a precise description of local flow modification around and through an operational tower instrumented for wind measurement.

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