Effects of Inflow Parameters and Operating Conditions on the Structural Response and Power Production of a Commercial Wind Turbine

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Effects of Inflow Parameters and Operating Conditions on the Structural Response and Power Production of a Commercial Wind Turbine

By

Jamie C. Smith

A Thesis
Submitted to the Faculty of Graduate Studies through the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada

2014

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Effects of Inflow Parameters and Operating Conditions on the Structural Response 
and Power Production of a Commercial Wind Turbine

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DECLARATION OF CO-AUTHORSHIP/PREVIOUS PUBLICATIONS

I hereby declare that this thesis incorporates material that is the result of joint research, as follows:

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ABSTRACT

Onshore wind farms can experience a wide variety of wind conditions, even in simple or flat terrain, as a result of diurnal and seasonal changes in stability in the atmospheric boundary layer. At a farm in Southwestern Ontario, a commercial-sized wind turbine operates in close proximity to a meteorological mast capable of quantifying the inflow parameters of the approaching wind profile. The turbine’s steel supporting tower has been instrumented with an optical strain gauge array measuring longitudinal deformation at multiple elevations. Wind conditions have been classified into two major profile types on the basis of two key inflow parameters: vertical wind shear and horizontal turbulence intensity. The resulting effects of changing profile on turbine power production and tower structural response have been characterized across changing operating conditions and wind speeds.
DEDICATION

To Meghan and my family.
I’d like to extend a sincere thanks to my advisor, Dr. Rupp Carriveau, and co-advisor, Dr. David S-K Ting, for the support they’ve provided these past few years. I have truly enjoyed working with them in the Turbulence & Energy Laboratory, and I have found them to be accommodating and knowledgeable whenever I’ve sought their insight. I also wish to extend thanks to the remaining members of my committee, Dr. Colin Novak and Dr. Rajesh Seth, for offering their comments on my research, and to Dr. El Ragaby for assisting with my defence. Acknowledgement should also be made to two previous graduate students, Jeff Bas and Phil McKay, for the technical assistance and mentoring they’ve provided. This research would not be possible without the generous support from our industrial partner, and I wish to thank Michael Cookson, JJ Davis, Paul Dawson, and Jason Stoner for their efforts. This work has been supported by the Natural Sciences and Engineering Research Council of Canada and the Ontario Ministry of Training, Colleges and Universities.
# TABLE OF CONTENTS

Declaration of Co-authorship/Previous Publications ......................................................... iii

Abstract ......................................................................................................................................... v

Dedication ...................................................................................................................................... vi

Acknowledgements ..................................................................................................................... vii

List of Tables ................................................................................................................................. x

List of Figures ................................................................................................................................. xi

Chapter 1: Introduction ............................................................................................................... 1

References ....................................................................................................................................... 3

Chapter 2: Wind Turbine Power Production Under Changing Wind Profile ....................... 5

2.1 Introduction ............................................................................................................................. 5

2.2 Experimental Setup ............................................................................................................... 8

2.3 Results ..................................................................................................................................... 11

2.4 Concluding Remarks & Future Work ................................................................................... 19

References ....................................................................................................................................... 20

Chapter 3: Effects of Wind Regime and Inflow Parameters on Wind Turbine Tower

Loading ........................................................................................................................................... 22

3.1 Introduction ............................................................................................................................. 22

3.2 Experimental Setup ............................................................................................................... 24

3.3 Results ..................................................................................................................................... 31

3.4 Concluding Remarks & Future Work ................................................................................... 43

References ....................................................................................................................................... 44

Chapter 4: Inflow Parameter Effects on Wind Turbine Tower Cyclic Loading .................... 47

4.1 Introduction ............................................................................................................................. 47

4.2 Experimental Setup ............................................................................................................... 49

4.4 Rainflow Counting .................................................................................................................. 52

4.3 Results ..................................................................................................................................... 54
4.4 Concluding Remarks & Future Work .................................................................63
References ............................................................................................................64
Chapter 5: Conclusions ..........................................................................................68
Appendix A: Meteorological Mast Data Output Sample ......................................71
Vita Auctoris .........................................................................................................72
LIST OF TABLES

Table 2.1: Wind condition classification. ................................................................. 11
Table 2.2: Characteristics of wind condition in Westerly sector over study period. .... 14
Table 3.3: Strain gauge locations and corresponding tower properties. ................. 25
Table 3.4: Wind condition classification ................................................................. 26
Table 3.5: Characteristics of wind conditions in Westerly sector during study period. 37
Table 4.6: Strain gauge locations and corresponding tower properties at Level 3. .... 51
Table 4.7: Wind condition classification. ................................................................. 52
LIST OF FIGURES

Figure 2.1: Aerial view of wind turbine under study and testing site layout. ............... 8
Figure 2.2: Ground view of the testing site layout ............................................ 9
Figure 2.3: Wind rose for direction probability over study period ....................... 10
Figure 2.4: Wind speed distribution for Westerly sector ............................... 12
Figure 2.5: Diurnal variation in wind speed and resulting power production ...... 13
Figure 2.6: Diurnal variation in wind shear and turbulence .......................... 14
Figure 2.7: Wind speed distribution for sheared and turbulent conditions ......... 15
Figure 2.8: Power production of turbine under differing wind condition ........ 16
Figure 2.9: Power production of turbine for selected wind speeds ................. 18
Figure 2.10: Power production of turbine for Southerly wind sector .......... 19
Figure 3.11: Strain signal under turbulent winds ........................................... 28
Figure 3.12: FFT plot under turbulent winds ................................................. 28
Figure 3.13: Strain signal under sheared winds ........................................... 29
Figure 3.14: FFT plot under sheared winds .................................................. 29
Figure 3.15: Average bending moment and vertical strain in the tower .......... 32
Figure 3.16: Mean base bending moment versus wind speed for Westerly winds .... 33
Figure 3.17: Maximum base bending moment versus wind speed for Westerly winds ... 35
Figure 3.18: Gust loading factor versus wind speed for Westerly winds .......... 35
Figure 3.19: Mean base bending moment versus wind speed, by wind condition ...... 38
Figure 3.20: Maximum base bending moment versus wind speed, by wind condition ... 38
Figure 3.21: Base bending moment standard deviation versus wind speed .......... 39
Figure 3.22: Directional & nacelle position standard deviation versus wind speed .. 40
Figure 3.23: GLF versus wind speed and turbulence intensity for constant shear .... 41
Figure 3.24: GLF versus wind speed and wind shear for near constant turbulence ... 42
Figure 4.25: Ten-minute sample of longitudinal stress for West gauge at Level 3 .... 54
Figure 4.26: Mechanically-induced loading cycle spectra for study period ............ 55
Figure 4.27: Total loading cycle amplitude and mean spectra for study period ......... 56
Figure 4.28: Loading cycle amplitude spectra ................................................. 57
Figure 4.29: Loading amplitude spectra for hour of operation below rated speed ...... 59
Figure 4.30: Loading amplitude spectra for hour of operation at and above rated speed. 59
Figure 4.31: Loading amplitude spectra at $U_{80} = 6$ m/s, classified by wind condition ... 61
Figure 4.32: Loading amplitude spectra at $U_{80} = 8$ m/s, classified by wind condition ... 61
Figure 4.33: Loading amplitude spectra at $U_{80} = 13$ m/s, classified by wind condition ... 62
Figure 4.34: Loading amplitude spectra at $U_{80} = 17$ m/s, classified by wind condition ... 62
CHAPTER 1

Introduction

Wind conditions can be subject to significant diurnal and seasonal variation with potential implications for the power collection and structural loading of commercial-sized horizontal-axis wind turbines operating in onshore environments. As modern commercially-available turbine hub heights and rotor diameters continue to increase, blades are projected into higher reaches of the atmospheric boundary layer, causing an increase in the complexity of the approaching wind profile across the rotor. To optimize turbine design and reduce associated uncertainties with prospective wind farm site assessment, a more thorough understanding of the impacts of inflow parameters on all aspects of turbine operation must be developed.

The content of this research is a continuation of the work that has previously been conducted by the University of Windsor through the research partnership maintained with a commercial wind farm operator in Southwestern Ontario, which has granted access to an individual turbine for instrumentation of the tower and to operational data from across the farm. Mourad (2010) [1] constructed a numerical modal model and physical model for a commercial-scale horizontal-axis wind turbine tower, and proposed a potential instrumentation system to monitor structural response. Preliminary modal analysis was also conducted via forced excitation of the full-sized turbine tower by an impact sledgehammer. Through the use of discrete wavelet transform signal processing, Bassett et al. (2010, 2011) [2, 3] analyzed the frequency content of turbine tower vibration during varying operational states in order to assemble the healthy baseline for a structural health monitoring scheme. Bas et al. (2012) [4, 5] characterized the strain response of the tower
to transient turbine operational events, such as rotor re-positioning and manual shutdown. The fiber Bragg grating optical strain gauge array employed by Bas et al. will similarly be used in this research study. McKay et al. (2011, 2013) [6, 7] proposed and investigated potential impacts of the wakes of operating wind turbines and quantified the sensitivity of wind turbine power production to varying operational parameters (2013) [8].

The purpose of this work is to utilize the wealth of data collected over a measurement campaign spanning several months of Fall 2011 and early Winter 2012 at the aforementioned wind farm to investigate impacts of inflow parameters and operating conditions on the structural response and power production of a commercial-scale wind turbine operating onshore. The three primary sources of data used to conduct this research were as follows:

- Longitudinal strain recorded by the fiber Bragg grating optical strain gauge array affixed to the interior of the hollow cylindrical steel tower of a turbine onsite.
- Wind inflow parameters recorded by a meteorological mast, in close proximity to the instrumented turbine, outfitted with an array of wind sensors at multiple elevations.
- Turbine operational parameters recorded by the supervisory control and data acquisition (SCADA) system in place at the farm.

The research in this study is composed of three individual papers. The first of which, intended as a paper to be submitted at the 2014 Offshore Energy & Storage Symposium and potentially expanded to be submitted to a peer-reviewed journal, provides a brief description of the diurnal patterns observed in atmospheric conditions at the studied wind
farm site over the course of the measurement campaign, and the resulting effects of changing wind conditions on turbine power production.

The second paper, to be submitted to the Journal of Wind Engineering & Industrial Aerodynamics, investigates the flexural loading of a full-sized turbine tower during varying modes of operation and under changing inflow parameters.

The third paper, now submitted to Wind Engineering journal, quantifies the cyclic loading spectra to which the tower is subjected. A twelve-week sample of the tower loading history is constructed using data collected over the measurement campaign, and hour-long cyclic loading spectra are shown for varying wind condition.

REFERENCES


CHAPTER 2

Wind Turbine Power Production Under Changing Wind Profile

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Turbulence and Energy Laboratory, Ed Lumley Centre for Engineering Innovation, University of Windsor, Ontario, Canada

2.1 INTRODUCTION

International standards for evaluating commercial wind turbine power performance require only hub height wind speed and air density to be recorded as the primary inflow parameters for the formulation of power curves [1, 2], which makes the inherent assumption that wind speeds vary only linearly across the turbine rotor. This assumption disregards the potential complexities in the approaching wind profile that can arise from nonlinear vertical wind speed gradient and atmospheric turbulence, which can vary seasonally and diurnally even in simple, flat terrain. Wagner et al. [3] observed a wide range in expected energy flux for wind speed profiles with the same speed at hub height and at the same location. They instead recommended that an equivalent wind speed be used that takes the average speed at multiple heights weighted by their corresponding portion of the swept rotor area. Through the use of LiDAR (light detection and ranging) remote sensing technology to construct vertical wind speed profiles and resulting equivalent wind speeds, Wagner et al. [4] demonstrated a reduction in turbine power curve uncertainty when compared with single hub height measurements taken by a conventional anemometer. Antoniou et al. [5] used met masts and LiDAR remote sensing to measure wind profiles in both flat and complex terrain. They similarly noted considerable changes in wind profiles during seasonal and diurnal variation, including
negative shear gradients at some heights leading to otherwise unexpected local maxima. Use of LiDAR remote sensing by Frehlich & Kelley [6] also noted the potential for rapid change in vertical profiles of wind speed and turbulent eddy size. Sumner & Masson [2] observed a near 5% reduction in the expected annual energy production of a given wind farm through consideration of an equivalent wind speed averaged across a rotor disk versus the energy production predicted by hub height wind speeds alone; suggesting the potential for single point measurements to overestimate available resources.

Wind conditions in the atmospheric boundary layer at onshore sites are subject to significant variation driven by atmospheric stability. Atmospheric stability, or the suppression of the vertical motion of air, is typically categorized into unstable, neutral, and stable classes [7]. Further categorization can also be made into very unstable, slightly unstable, very stable, etc. During daytime solar heating of the ground, air rises to produce large-scale turbulent eddies; creating unstable, convective stability conditions characterized by higher turbulence and relatively uniform wind speeds with increasing elevation [8]. Overall wind speeds are also expected to be lower under unstable, convective conditions. At night, the ground acts as a heat sink [2], and turbulent mixing is reduced to create stable conditions characterized by lower turbulence and a highly sheared vertical speed profile [8]. At certain sites, such stable conditions can give rise to a nocturnal low level jet that form at elevations near the upper reaches of modern wind turbine rotors [9]. Stability conditions defined as neutral arise in the transition between atmospheric classes, and are characterized by relatively higher wind speeds with moderate levels of turbulence and shear. Such neutral atmospheric stability can arise during overcast conditions [10]. In recent years, attention has been given to inflow
parameter effects on the power production of full-sized wind turbines operating in commercial wind farms. At a wind farm site in the US Great Plains/Midwest region, Rareshide et al. [11] found that higher shear values coincided with greater power production across nearly all surveyed wind speeds below rated. For a high plains wind farm site East of the Rocky Mountains in North America, Vanderwende & Lundquist [12] found that unstable, convective winds produced greater power production for low-to-moderate hub height wind speeds up to 12 m/s; with stable, sheared conditions producing modest power gains at higher speeds. Wharton & Lundquist [13], however, found that such stable, sheared conditions consistently improved turbine power performance at a near-coastal farm in Western North America. Sumner & Masson [2] observed higher turbine power coefficients for more turbulent conditions at a UK farm in flat, pastoral terrain. The overall lack of consensus on the specific impacts of differing wind profile on expected turbine power extraction suggests that such impacts could be unique to a given site [12]. This study will characterize these impacts at a commercial wind farm in the Great Lakes region of Southwestern Ontario, which has become a major area of growth for large-scale wind energy use. The province of Ontario currently has in excess of 1700 MW of installed capacity, with 3000 MW scheduled to come online by the end of 2014 [14]. A 2.3 MW turbine at the studied wind farm operates near a meteorological mast, outfitted with a vertical array of wind speed anemometers to assess two key inflow parameters: vertical wind shear and horizontal turbulence intensity. Such measurement will provide a more complete description of the approaching wind profile than the single point measurements taken by the small meteorological station positioned at the rear of the turbine nacelle. Diurnal patterns in the onsite atmospheric boundary layer will be
observed over the six-month measurement campaign, and the power production of the turbine will be investigated for comparable speeds under two major wind condition classifications characterized by the wind profile measured by the meteorological mast.

2.2 EXPERIMENTAL SETUP

The turbine under study is a Siemens 2.3 MW MKII variable speed model employing pitch control, and is one of eighty-eight others onsite at an onshore commercial wind farm. With a rotor diameter of 93 m and hub height of 80 m, the swept rotor area of the blades reach a minimum elevation of 34 m and a maximum elevation of 127 m above ground level. A meteorological mast is positioned 150 m West of the wind turbine, as pictured in Figure 2.1 with the closest turbine also shown. The wind farm is sited in a predominantly flat agricultural setting with some surrounding tree hedges. Lake Erie is located 3100 m South of the turbine under study.

![Figure 2.1: Aerial view of wind turbine under study and testing site layout [15].](image)
A North-facing view of the testing site is also shown in Figure 2.2, with the studied turbine indicated in the background and the closest turbine in the foreground. The meteorological mast is also depicted.

![Figure 2.2: Ground view of the testing site layout.](image)

The onsite wind rose over the six-month measurement campaign is shown in Figure 2.3, with the Southwest acting as the predominant wind direction. To assess directly the parameters in the incoming wind profile, this research will study the land-influenced winds from the Westerly direction (270° ± 30°). This wind sector is also clear of other turbines operating in close proximity to the studied turbine, with none located within twenty rotor diameters upwind, thus largely preventing potential wake interaction.
The meteorological mast features five anemometers elevations spanning the bottom of the swept rotor area to the hub height at elevations of 34, 61, 70, 77 and 80 m above ground level. A short data sample has been included in Appendix A, showing the wind speed data output from the mast. A wind vane is also located 77 m above ground level to assess prevailing wind direction. Vertical wind shear is evaluated from using 10-minute averages of the shear exponent given in the power law equation [16]:

$$U(z) = U_R \left( \frac{z}{z_R} \right)^\alpha$$  \hspace{1cm} (1)

where $U$ is the mean horizontal wind speed at a given height $z$, and $U_R$ is the mean speed at a given reference height $z_R$. Turbulence levels are evaluated using the 10-minute hub height horizontal turbulence intensity [17]:

$$I_U = \frac{\sigma_u}{U}$$  \hspace{1cm} (2)

where $\sigma_u$ and $U$ are the horizontal wind speed standard deviation and mean at 80 m. Wind conditions are categorized into two wind profile classes: turbulent and sheared.
Turbulence intensity and wind shear thresholds for wind condition classifications are given in Table 2.1, and have been adapted from thresholds used by Rareshide et al. [11].

<table>
<thead>
<tr>
<th>Wind Condition</th>
<th>Wind Shear</th>
<th>Turbulence Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulent</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>$\alpha &lt; 0.2$</td>
<td>$I_U &gt; 11%$</td>
</tr>
<tr>
<td>Sheared</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>$\alpha &gt; 0.2$</td>
<td>$I_U &lt; 11%$</td>
</tr>
</tbody>
</table>

Data has been provided from the wind farm operator at a ten-minute resolution over the measurement campaign spanning September 2011 to February 2012. The atmospheric boundary layer conditions describing the approaching wind profile, provided by the meteorological mast, are correlated with the turbine power output, provided by the supervisory control and data acquisition (SCADA) system in place at the farm.

2.3 RESULTS

2.3.1 Onsite Atmospheric Conditions

Onsite wind speed frequency distribution for winds from the Westerly sector for September 2011 through February 2012 is shown in Figure 2.4. The preliminary measurement campaign conducted before farm construction had classified the site as an IEC 61400-1 [1] Class IIb site, with moderate annual average wind speeds at hub height near 8 m/s and relatively lower atmospheric turbulence levels.
The diurnal variation in speed measurements taken by the hub height anemometer for winds observed in the Westerly sector is shown in Figure 2.5, averaged over the entire six-month measurement campaign. The resulting power production for the studied turbine is indicated as well, and normalized using turbine rated power similarly to Wharton & Lundquist [13]:

\[ P_{\text{norm}} = \frac{P}{P_{\text{rated}}} \times 100\% \]

where \( P_{\text{norm}} \) is the normalized active power produced by the turbine, \( P \) is the actual active power, and \( P_{\text{rated}} \) is the nameplate or maximum power the turbine will produce.
As expected, turbine power production and onsite wind speed correlate well. Power production reaches a maximum during the mid-to-late afternoon where neutral atmospheric stability can be expected.

In Figure 2.6, the averaged diurnal variation in vertical wind shear and hub height horizontal turbulence intensity are shown, and the two inflow parameters demonstrate a degree of inverse correlation. Wind shear is highest during the early morning hours, and turbulence intensity is shown to peak near noon. Given that the surveyed months of the measurement campaign are among the coldest in the Southern Canadian climate, wind shear values will be higher than site average [18]. As a result, the aforementioned thresholds outlined for defined sheared and turbulent wind profiles will produce a lower percentage of turbulent data points for this study.
2.3.2 Power Production Across Condition

Characteristics for the sheared and turbulent ten-minute data points observed are shown in Table 2.2. Sheared data points greatly outnumber turbulent. Of all sheared data points, 74% occur during nighttime hours from 7:00 PM to 7:00 AM, and 76% of turbulent data points occur during daytime hours from 7:00 AM to 7:00 PM.

Table 2.2: Characteristics of wind condition in Westerly sector over study period.

<table>
<thead>
<tr>
<th>Wind Condition</th>
<th>Number of Data Points</th>
<th>Mean Wind Speed (m/s)</th>
<th>Mean Wind Shear Exponent</th>
<th>Mean Turbulence Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulent</td>
<td>893</td>
<td>7.76</td>
<td>0.08</td>
<td>15.63%</td>
</tr>
<tr>
<td>Sheared</td>
<td>3073</td>
<td>7.91</td>
<td>0.41</td>
<td>7.17%</td>
</tr>
</tbody>
</table>

Though mean wind speeds for turbulent and sheared conditions are close, the wind speed distribution under each condition varies considerably, as depicted in Figure 2.7.
Turbulent conditions are shown to coincide more frequently than sheared with wind speeds both higher and lower than onsite average. Note that the turbulent condition thresholds defined in this study generally align with both convective and neutral atmospheric stability vertical wind shear exponent and horizontal turbulence intensity thresholds defined by Wharton & Lundquist [8] and van den Berg [18], whereas the sheared condition thresholds align with stable atmospheric stability thresholds. As a result, turbulent condition speed distribution includes both the typically low-speed convective and high-speed neutral winds.

The resulting power production for the studied wind turbine is given in Figure 2.8 across varying wind profile, where ten-minute data points have been averaged across 0.5 m/s intervals to construct a power curve. The overall trend of the curve is typical of a variable-speed, pitch-regulated commercial-sized wind turbine [19].
Figure 2.8: Power production of turbine under differing wind condition.

Turbulent conditions are shown to coincide with greater power production for hub height wind speeds ranging from cut-in to more than 9 m/s. After which, sheared conditions are shown to coincide with higher power production for speeds from 10 to 12 m/s, near “Region II” of the power curve where the turbine transitions into its rated speed operational mode. Once rated power is achieved, the turbine controller increases blade pitch to reduce rotor power coefficient and maintain steady power production. Were the aforementioned equivalent wind speed or “rotor disk-averaged” speed to be calculated using hub height speed and wind shear exponent, it would be anticipated that turbulent conditions would coincide with greater available energy flux in the approaching wind profile. This could explain the phenomenon observed for hub height wind speeds up to 9 m/s. However, it is important to note that the shear exponent produced in this study only considers wind speeds in the bottom half of the swept rotor area, and potential exists for shear exponent to vary considerably across the rotor diameter above hub height [8] which
would be undetectable given the currently available anemometry instrumentation at the wind farm site. At winds speeds closer to rated, the more variable incoming wind speed expected under turbulent conditions could adversely affect expected turbine performance within the measured ten-minute periods. For example, for a ten-minute period having an average wind speed near 11 m/s but with a high level of variance: higher winds within this period will produce power no greater than rated, but lower winds within this period will produce power less than rated. As a result, the average power the turbine will produce over this ten-minute period will be less than if the wind speed were more consistently near 11 m/s. A review of current literature does not produce an exact consensus for the anticipated effects of atmospheric turbulence intensity on rotor power coefficient, but the results suggest potential benefits to power production in the low-to-moderate wind speed range and a detrimental effect in the higher wind speed range before rated power is achieved, at least for this study site. The disparity in power production across wind condition is shown in greater detail in Figure 2.9, where power production is shown for wind speeds from 6 to 12 m/s, with a single standard deviation indicated.
Figure 2.9: Power production of turbine under differing wind condition for selected wind speeds.

Turbulent conditions retain a nearly 2% or more power increase over turbulent conditions for speeds from 6 – 9 m/s. Whereas sheared conditions have a 2% increase in power production over turbulent for speeds equal to 10 m/s, which diminishes at higher speeds. The same comparison has been made in Figure 2.10, except the lake-influenced winds from the Southerly wind sector (180° ± 15°) have been used instead. Wind direction thresholds have been tightened to prevent potential wake interaction from the turbine located nearby. Though some minor disparities exist, the same qualitative trend is observed for sheared and turbulent winds from this sector.
2.4 CONCLUDING REMARKS & FUTURE WORK

At an onshore commercial wind farm site, trends in meteorological conditions and their impacts on the power production of an individual turbine have been investigated, with the following conclusions drawn and analyses conducted:

- High-turbulence, low-shear conditions have been observed to coincide with higher power production for low-to-moderate hub height wind speeds at the study site.
- High-shear, low-turbulence conditions have been observed to coincide with higher power production for high hub height wind speeds below rated.
- Trends in wind profile effects on power production for land-influenced winds for the Westerly wind sector on site are qualitatively similar for lake-influenced winds from the Southerly sector.
Diurnal variation in atmospheric conditions were observed over the measurement campaign, with identifiable peaks in turbulence intensity and wind shear observed. Future analyses could look to include data collected from the warmer months at the studied site. Furthermore, collecting wind speed measurements at elevations in excess of hub height could help to better explain the observed disparity in power production for changing wind conditions. Use of remote sensing technology such as LiDAR or SoDAR (sonic detection and ranging) could facilitate such measurements, and could be operated at ground level without the need to construct a meteorological mast.

REFERENCES


CHAPTER 3

Effects of Wind Regime and Inflow Parameters on Wind Turbine Tower Loading

Jamie C. Smith\textsuperscript{1}, Phillip McKay\textsuperscript{2}, Rupp Carriveau\textsuperscript{1}, David S-K Ting\textsuperscript{1}, Tim Newson\textsuperscript{3}

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3.1 INTRODUCTION

Having reached their practical size limit, the conventional rigid steel lattice towers of the previous generation of utility-scale horizontal-axis wind turbines have given way to the flexible steel tubular towers favoured in the modern wind energy industry \cite{1}. The slender nature of their construction \cite{2}, along with the heavy distribution of mass presented by the rotor-nacelle positioned at a maximum elevation, create a turbine tower structure characterized by low natural frequencies and low structural damping. Modern towers are often of “soft” design having first bending modes situated between the first and second multiples of the rotational frequency of the rotor \cite{2} and damping ratios on the order of 1\% \cite{3}. As the rotor size and tower height of commercial turbines continue to increase in order to maximize power production, added importance is placed on assessing the impacts of the aerodynamic instability presented by vertical wind shear and the gust-induced buffeting effects of horizontal turbulence intensity. Wind profile inflow parameters such as shear and turbulence can affect power production \cite{4 - 6}, fatigue damage \cite{7}, and even turbine noise production \cite{8}. 

22
This study will use physical data collected from a full-size operating wind turbine at an onshore commercial farm in Southwestern Ontario to assess the loading impacts of varying onsite wind conditions and their respective inflow parameters. Previous studies conducted on this turbine have characterized the frequency content of the vibration response to form the baseline of a structural health monitoring scheme \[9, 10\] as well as the strain response of the tower to transient events such as rotor re-positioning and manual shutdown \[11, 12\]. Rebelo et al. \[13, 3\] correlated stress magnitudes in the shell and pre-stressed bolts of a steel turbine tower across operational wind speeds, along with the quantification of the resulting fatigue loading spectra and characterization of the dynamic response and modal properties of the turbine tower structure. Muto et al. \[14\] investigated the effects of wind speed and turbulence levels on the tower base bending moment of an operating turbine. Numerical modelling has previously been conducted for the design and optimization of turbine tower structures \[15 - 17\] and the impacts of wind gusts and atmospheric turbulence on tower loading \[18 - 20\]. The purpose of this work is to investigate the impacts of varying wind profiles and inflow parameters on the flexural loading imparted to a conventional steel tubular wind turbine tower; including consideration of load quasi-static mean, maxima, and variance across changing inflow wind speed, shear, and turbulence. Such insight into loading magnitudes can assist in the ultimate limit states design of turbine towers, as well as providing the baseline of healthy or expected response for structural health monitoring employed by the wind farm operator.
3.2 EXPERIMENTAL SETUP

3.2.1 Testing Site & Instrumented Turbine

The wind turbine under study is a Siemens 2.3 MW MKII variable-speed model with blade pitch control. Rotor diameter and hub height measure 93 m and 80 m, respectively. For ease of transportation and construction on-site, the hollow cylindrical steel tower consists of three individual sections terminated by stiff flange sections that have been bolted together. The tower measures 78.54 m in height, with an outer diameter that measures 4220 mm at its base and 2452 mm at maximum elevation and a wall thickness that measures 41 mm at its base and 22 mm at maximum elevation. The mass of the tower accounts for half of the total mass of the turbine, excluding the foundation.

The studied turbine is one of eighty-eight machines at a commercial onshore wind farm off the shores of Lake Erie, which is located more than 3000 m South of the studied turbine. The farm is sited in an agricultural setting having predominantly flat terrain with some surrounding tree hedges. The site has been classified as an IEC 61400-1 [21] Class IIb site; having medium wind speeds (annual average close to 8 m/s) and relatively lower turbulence levels. The 50-year return 3-second gust and 10-minute extreme wind speeds at hub height have been quantified as 48 m/s and 34 m/s, respectively. Prevailing on-site wind direction is from the Southwest, with roughly half of all wind direction measurements falling between the Southerly and Westerly directions. No turbine is located within twenty rotor diameters upwind of the turbine in this wind sector, which suggests that wake interaction from other onsite turbines will be minimal in this sector.

A fiber Bragg grating (FBG) sensor array, as presented by Bas et al. [11, 12], measures longitudinal deformation at 100 Hz on the North, South, East, and West interior faces of
the tower at six different elevations. The array transmits a broadband light source through fiber optic cables to the gauges, and the reflected light wavelength from each individual gauge will be proportional to its strain. The vertical location of each set of strain gauges and corresponding tower outer diameter, wall thickness, and moment of inertia are included in Table 3.3.

Table 3.3: Strain gauge locations and corresponding tower properties.

<table>
<thead>
<tr>
<th>Level</th>
<th>Elevation (m)</th>
<th>Diameter (mm)</th>
<th>Wall Thickness (mm)</th>
<th>Moment of Inertia (m$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>77.3</td>
<td>2452</td>
<td>22</td>
<td>0.1240</td>
</tr>
<tr>
<td>4</td>
<td>65.0</td>
<td>3071</td>
<td>13</td>
<td>0.1460</td>
</tr>
<tr>
<td>3</td>
<td>41.8</td>
<td>4200</td>
<td>14</td>
<td>0.403</td>
</tr>
<tr>
<td>2</td>
<td>14.46</td>
<td>4200</td>
<td>25</td>
<td>0.715</td>
</tr>
<tr>
<td>1</td>
<td>4.46</td>
<td>4200</td>
<td>31</td>
<td>1.123</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>4220</td>
<td>41</td>
<td>1.175</td>
</tr>
</tbody>
</table>

3.2.2 Wind Classification

The turbine is located 150 m East of a meteorological mast outfitted with a vertical array of cup anemometers at five different elevations: 34, 61, 70, 77 and 80 m above ground level. This spans an elevation from the bottom of the turbine rotor to hub height. A wind vane is also located at 77 m above ground level to assess prevailing wind direction. Wind conditions are categorized into two classes using two key inflow parameters: vertical wind shear and horizontal (longitudinal) turbulence, which will frequently demonstrate inverse correlation [5]. These parameters can be used to infer atmospheric stability in the boundary layer, and commercial wind farms are more likely to have the proper instrumentation on-site to quantify such parameters than other measures classically-employed for stability such as vertical change in potential temperature and the Obukhov length [22]. The first classification used is a low-shear, high-turbulence condition
referred to as “turbulent.” This condition describes the expected unstable, convective wind profile produced by solar ground heating during the day which facilitates vertical circulation of air masses in the atmospheric boundary layer. The second class is the “sheared” condition characterized by high-shear and low-turbulence, which describes the expected stable wind profile expected during stratification of airflow as the ground cools at night and vertical motion is suppressed. Thresholds for wind condition classification are given in Table 3.4 and have been adapted from those used by Rareshide et al. [23] to determine the impacts of shear and turbulence on power production. Wind shear is evaluated from 34 m to 80 m using 10-minute averages of the shear exponent given in the power law equation [24]:

$$U(z) = U_R \left( \frac{z}{z_R} \right)^\alpha$$  \hspace{1cm} (1)

where $U$ is the mean horizontal wind speed at a given height $z$, and $U_R$ is the mean speed at a given reference height $z_R$, which for this study will be the hub height of 80 m.

Turbulence levels are evaluated using the 10-minute horizontal turbulence intensity [25]:

$$I_U = \frac{\sigma_u}{U}$$ \hspace{1cm} (2)

where $\sigma_u$ and $U$ are the horizontal wind speed standard deviation and mean at 80 m.

<table>
<thead>
<tr>
<th>Wind Condition</th>
<th>Wind Shear</th>
<th>Turbulence Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulent</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>$\alpha &lt; 0.2$</td>
<td>$I_U &gt; 11%$</td>
</tr>
<tr>
<td>Sheared</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>$\alpha &gt; 0.2$</td>
<td>$I_U &lt; 11%$</td>
</tr>
</tbody>
</table>
3.2.3 Signal Analysis

A half-hour sample of the strain signal produced by the FBG array at 100 Hz for the West interior face near tower mid-height is shown in Figure 3.11. When the sample was recorded, winds were coming from the Westerly sector at hub height speeds having an average near 6.5 m/s and were classified as turbulent according to previously outlined thresholds in Table 3.4. Though mean wind speed rises over the course of the sample study period, the effects of prolonged gusts are also evident in the signal, as seen in the short-term rise and fall of the tower strain. Such gusts acting on the turbine cause an increase in tower quasi-static load, followed by periods of increased vibration. Applying a fast Fourier transform (FFT) highlights a noticeable spectral peak at 0.325 Hz, as shown in Figure 3.12. This frequency corresponds to the expected fundamental bending mode in the fore-aft direction of a turbine structure of this size and capacity [3, 26]. A second, lesser spectral peak is also observed near 2.80 Hz; speculated to be the second bending mode frequency in the fore-aft direction of the turbine. Note that gust-induced vibration is significant for structures with eigenfrequencies less than 2 Hz, given the high spectral energy of boundary layer atmospheric turbulence in this range [27].
The half-hour strain signal from the same gauge is shown in Figure 3.13, under Westerly winds with speeds closer to 7.5 m/s. For this time period, winds were classified as sheared according to previously outlined thresholds. FFT analysis, shown in Figure 3.14, likewise demonstrates spectral peaks at 0.325 and 2.86 Hz. High local spectral energy is
also noted at a frequency near 0.70 Hz, corresponding to near three times the rotational frequency of the rotor (also known as the blade passing frequency for a three-bladed turbine) at the given hub height wind speed.

Figure 3.13: Strain signal under sheared winds.

Figure 3.14: FFT plot under sheared winds.
3.2.4 System Calibration

To study the wind profile directly upstream of the turbine and the windward response of the tower, winds from the Westerly sector (having an average ten-minute wind direction at 77 m equal to $270^\circ \pm 15^\circ$) and readings from the East and West gauges will be considered in the analysis. A smaller wind sector than that outlined in Section 2.2 has been used, given the dependency of tower strain on prevailing wind direction and resulting nacelle orientation. The strain values produced by the FBG array are not absolute, given that the system was installed after turbine construction. As a result, the time independent compressive stress presented by the weight of the rotor-nacelle and the self-weight of the tower are not reflected in measured values. Given that the weights of these components are known, the resulting compressive stress at the tower base is estimated near 5.22 MPa. Measured strain values represent a deviation from a baseline established when hub height wind speeds were low (less than 1.5 m/s), the rotor was idle, and the nacelle was facing the West direction. The resulting strain values will therefore also not include the stress introduced by the eccentricity of the rotor-nacelle bearing onto the tower [11], which has experimentally been shown to be near 3 MPa at the tower base.

Readings taken by the strain gauge array have been converted to stress, assuming linear elastic behaviour, and then converted to flexural load using section properties as the corresponding level of the tower, as per the fundamental equation for a beam element subjected to flexural loading [28]:

$$\varepsilon \cdot E = \frac{M \cdot y}{I}$$  \hspace{1cm} (4)

where $\varepsilon$ is the longitudinal strain value produced, $E$ is the elastic modulus of the tower structural tower (200 GPa), $M$ is the resulting flexural load, $y$ is the distance from the
neutral axis of the tower section to the horizontal position of the gauge at the interior of the tower wall, and the $I$ is the moment of inertia for the tower section. These loading values have been compiled into ten-minute mean, maximum, and standard deviation values, and were correlated with readings taken by the meteorological mast and turbine operational values recorded by the farm’s supervisory control and data acquisition (SCADA) system. Data has been collected over a measurement campaign conducted from September 2011 to October 2011 and from December 2011 to February 2012.

3.3 RESULTS

3.3.1 Loading Across Wind Speed

Mean values for flexural loads and vertical deformation recorded by the installed FBG array are shown in Figure 3.15 for average on-site wind speeds (8.0 m/s ± 0.5 m/s) from the Westerly sector, with a single standard deviation indicated in mean value indicated. Values have been collected from the West interior face of the tower and across its elevation.
As expected in Figure 3.15(a), loading is at a maximum at Level 0 at the tower’s base. Bending moment from Level 5 (77.34 m) to Level 2 (14.46 m) increases linearly with distance away from the rotor, as the moment arm produced by axial rotor thrust increases. An increase in this trend is observed at Level 1 (4.46 m), however, which is speculated to be the result of this gauge’s proximity to the turbine’s maintenance access door at the base of the turbine. The opening and surrounding stiffening elements are expected to impact the stress distribution close to the door [17]. Maximum deformation is shown to occur at Level 3 (41.84 m) near tower mid-height. The disparity in strain levels across the tower result from the distribution of section properties, particularly tower diameter and wall thickness. The major disparity between the strain observed at Level 4 (65.02 m) and Level 5 in Figure 3.15(b) is not only the result of a reduction in the moment arm, but also the increased thickness of the tower section at Level 5 in order to prevent localized damage from the rotor-nacelle bearing force. Note that, though not shown, the standard
deviation values for strain measured within ten-minute averaging periods are observed to be highest for Level 3.

Mean base bending moment values at Level 0 are plotted versus wind speed measured by the meteorological mast at 80 m above ground level in Figure 3.16. A total of 1463 ten-minute data points have been compiled over the twelve-week study period. Note that positive values indicate tension and negative values indicate compression.

Figure 3.16: Mean base bending moment versus wind speed for Westerly winds.

Axial rotor thrust causes Westerly winds to introduce compressive and tensile loading onto the East and West faces of the tower, respectively. Outliers exist from periods where sudden and severe changes in wind direction caused temporary rotor misalignment.

Above cut-in speed, moment magnitudes increase proportionally with wind speeds up to a maximum at 11 m/s, where rated power production is achieved. The average mean bending moment at rated speeds (± 0.5 m/s) is approximately 30 200 kN·m. For speeds in excess of rated, loading gradually reduces with increasing wind speed, while power
production remains essentially constant. Similar phenomenon was demonstrated by Rebelo et al. [3] and Muto et al. [14]. This observed reduction in rotor thrust is typical of pitch-regulated wind turbines [2], and is the result of rotor blades pitching towards a feathered position from the approximately -1° pitch angle they maintain during typical operation, as a means of preventing turbine overload. For a hub height wind speed equal to 20 m/s, blade pitch angle approaches 19° with loading magnitude approximately equal to those encountered at a speed of 6.5 m/s.

Maximum base bending moment values at the West and East interior face of Level 0 are plotted versus wind speed in Figure 3.17. Also shown is the resulting moment-based gust loading factor for the West face in Figure 3.18. Wind speeds below cut-in have been removed. The gust loading factor represents a ratio between the expected extreme and mean load values, and is employed in the design of structures subjected to buffeting by wind gusts. This factor is described using the following equation [28]:

\[
G_M = \frac{\hat{M}}{\bar{M}} = 1 + \frac{g_M \sigma_M}{\bar{M}} \quad (5)
\]

where \(G_M\) is the moment-based gust factor, \(\hat{M}\) is the extreme base bending moment, \(\bar{M}\) is the mean base bending moment, \(g_M\) is the gust peak factor, and \(\sigma_M\) is the standard deviation in base bending moment values.
In Figure 3.17, maximum flexural load values again increase proportionally for speeds between cut-in and rated. The average maximum bending moment observed at rated speeds (± 0.5 m/s) is approximately 37 600 kN∙m. For speeds in excess of rated, maximum load values will also reduce, but more gradually than corresponding mean load.
values in this wind speed region. At a hub height wind speed of 20 m/s, the maximum loading magnitude encountered is near that of a wind speed equal to 7.5 m/s. After manual inclusion of the compressive load introduced by turbine self-weight, as well as the inclusion of the moment produced by the eccentricity of the rotor-nacelle bearing, the maximum absolute stress observed over the measurement campaign from operation in a Westerly wind is equal to a compressive stress of 497 MPa in the East interior face of the tower. The resulting moment-based gust loading factor values are shown in Figure 3.18 to be at a minimum for rated wind speed and then increase for all greater wind speeds. Such phenomenon was likewise demonstrated by Muto et al. [14], and is the result of the pitch excitation type vibration that will occur after blade pitch control is activated. In this operating condition, sudden reductions in wind speed during gusts result in a rise in axial rotor thrust. As a result, the mean base bending moment will decrease rapidly compared with maximum moment, and the gust loading factor will increase [14, 29]. Below rated wind speed, higher gust factor values are observed near cut-in wind speed, which is speculated to be the result of dynamic magnification of the asymmetrical thrust load across the turbine rotor. The rotational speed of the rotor at cut-in wind speed is near 7 rpm, with a resulting blade passing frequency of 0.35 Hz, which is in close proximity to the expected first bending mode frequency. Generator cut-in has also been shown to coincide with sudden increases in strain [12]. Higher gust factor values are also observed for wind speeds near 8 m/s, where maximum rotor rotational speed is reached, and increasing reactive power is used by the generator to limit the rotor speed.
3.3.2 Loading Across Wind Condition

Diurnal ground heating is attenuated during the colder months at the testing site during the measurement campaign, resulting in limited turbulent and frequent sheared conditions, having high shear exponents in the land-influenced Westerly sector. Wind conditions demonstrate diurnal correlation; with 83% of turbulent data points occurring from 7:00 AM - 7:00 PM, and 74% of sheared data points occurring from 7:00 PM – 7:00 AM. Mean values encountered for both wind conditions are shown in Table 3.5.

Table 3.5: Characteristics of wind conditions in Westerly sector during study period.

<table>
<thead>
<tr>
<th>Wind Condition</th>
<th>Number of Data Points</th>
<th>Mean Wind Speed (m/s)</th>
<th>Mean Wind Shear Exponent</th>
<th>Mean Turbulence Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulent</td>
<td>171</td>
<td>8.49</td>
<td>0.07</td>
<td>14.86%</td>
</tr>
<tr>
<td>Sheared</td>
<td>753</td>
<td>7.94</td>
<td>0.39</td>
<td>7.20%</td>
</tr>
</tbody>
</table>

Data points for the West interior face of the tower in Figure 3.16 and Figure 3.17 are classified into their respective wind condition class in Figure 3.19 and Figure 3.20. Mean and maximum bending moment values have been binned and averaged at intervals of 1 m/s. Note that a portion of the original 1463 data points included in Figure 3.16 did not adhere to the inflow parameter thresholds for either wind condition class and were therefore excluded. Aforementioned outliers have also been removed, as well as data points below turbine cut-in speed.
Sheared conditions are shown to coincide with marginally higher mean base bending moment than turbulent conditions across nearly all wind speeds. However, maximum bending moment values for sheared and turbulent conditions remain relatively close. The moment-based gust loading factor will therefore be increased under turbulent conditions.
Variance in base bending moment values for turbulent and sheared conditions are shown in Figure 3.21, along with the variance in wind direction and nacelle position in Figure 3.22. Yaw systems are a critical turbine subassembly with potential for high failure rates in variable speed wind turbines [30]. Re-positioning of the rotor moves the high eccentric load imparted to the tower [11]. High levels of yaw activity indicate the potential for periods of rotor misalignment with prevailing wind direction, which can introduce increased in stresses into the tower and can damage rotor-nacelle components such as the main shaft bearing [31]. Individual turbines at the farm yaw themselves independently based on wind direction measurements taken by the meteorological station located at the back of their nacelle.

Figure 3.21: Base bending moment standard deviation versus wind speed.
Base bending moment standard deviation values generally increase with increasing wind speeds. For comparable speeds, turbulent conditions predominantly exhibit higher loading variance than sheared conditions. Though this trend can partially be attributed to higher variance in wind direction, resulting in increased yawing activity, it suggests the potential for increased forced vibration of the tower from atmospheric turbulence. The higher variation in wind direction under turbulent conditions translating to higher nacelle movement would also contribute to the lower mean loads observed under such conditions, as the West gauge would demonstrate lower loading values when rotor thrust was not acting in line with the West direction. Note that both condition classes demonstrate local maxima near wind speeds of 8 and 12 m/s. The first maxima, as previously mentioned, coincides with the initiation of rotor speed control by the turbine generator. The second maxima coincides with the initiation of pitch control to regulate turbine power production.
\subsection*{3.3.3 Effects of Inflow Parameters}

To identify the de-coupled impacts of turbulence intensity and wind shear inflow parameter, points were taken in which the wind shear exponent was restricted to average on-site values plus or minus half a standard deviation ($\alpha = 0.3 \pm 0.07$) and turbulence intensity values were binned into ranges across wind speeds. In Figure 3.23, gust loading factor for the West interior face of the tower under Westerly winds is shown for changing turbulence intensity and wind speed with near constant wind shear. Also included are gust loading factor values for the South interior face of the tower under Southerly winds coming off Lake Erie. Southerly winds account for 48\% of the data points represented in Figure 3.23.

![Gust Loading Factor vs Wind Speed and Turbulence Intensity](image)

Figure 3.23: Gust loading factor versus wind speed and turbulence intensity for near constant wind shear. Gust loading factor is shown to be higher across all surveyed wind speeds for increased turbulence levels. These results agree with the trend predicted by the empirical formulation of the gust load factor by Ishihara et al. [32] for commercial-sized wind turbines, and experimentally verified by Muto et al. [14]. Though this trend can partially be explained as resulting from higher yawing activity under more turbulent conditions, it
also suggests the potential for higher atmospheric turbulence and wind gusts to generate greater dynamic response. To likewise determine the impacts of wind shear, data points were taken in which turbulence intensity was restricted to average on-site values plus or minus half a standard deviation ($I_U = 10\% \pm 1.5\%$), while wind shear exponent values were binned into ranges across wind speed; as shown in Figure 3.24. Once again, winds from both the West and South direction have been included.

![Gust loading factor versus wind speed and wind shear for near constant turbulence intensity.](image)

No strong trend is observed between gust loading factor and wind shear for sampled wind speeds. While gust loading factor is higher for lower shear among more of the sampled wind speeds, it is speculated that this is the result of generally higher turbulence observed under lower shear. These results would suggest that the effect of buffeting action by atmospheric turbulence has a more significant impact on tower vibration and potential for maximum loading than does the aerodynamic instability presented by the wind shear gradient across the turbine rotor.
3.4 CONCLUDING REMARKS & FUTURE WORK

The flexural loads recorded at the base of a steel wind turbine tower have been correlated with varying wind conditions, with the following conclusions drawn:

- While the turbine is operational, tower base bending moment are at maximum at rated wind speed, decreasing gradually with increasing wind speed after maximum power production has been reached. The same is true for maximum base bending moment, though maximum loads decrease more gradually. The resulting gust load factor is shown to be at a minimum near rated speed.

- High-shear, low-turbulence conditions demonstrate marginally higher mean base bending moment than low-shear, high-turbulence conditions across operational wind speeds. Maximum loads encountered at the outlined wind conditions are largely comparable.

- Low-shear, high-turbulence conditions demonstrate higher levels of loading variance and yaw activity than high-shear, low-turbulence conditions across operational wind speeds.

- Horizontal turbulence intensity is shown to have a more tangible effect on the gust loading factor than vertical wind shear.

The analyses conducted at an onshore farm in an agricultural setting could also be potentially conducted at offshore installations, in complex terrain, or using water-influenced wind profiles.
REFERENCES


CHAPTER 4

Inflow Parameter Effects on Wind Turbine Tower Cyclic Loading

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4.1 INTRODUCTION

Growth in the wind energy sector has coincided with substantial growth in the physical size of utility-scale wind turbines, for the purposes of improving their power capture. Increases in nacelle mass and tower height create a more flexible structure [1] and larger turbines, with rated power in excess of 1 MW, have already demonstrated higher failure rates than their smaller counterparts [2]. Increases in rotor size and tower height also project turbine blades into higher elevations of the atmospheric boundary layer; exposing the turbine to complex and potentially increased aerodynamic loading. Given their widespread deployment at sites with differing wind conditions and the limited availability of operational history data for multi-MW wind turbines, concerns exist over the ability of modern turbines to meet their projected twenty-year life expectancy. Full-scale physical data can help improve the reliability of turbine service life estimates and provide insight on suitable decommissioning and re-powering options when individual turbine components have expired. A more developed understanding of how changing wind regimes influence turbine structural loading also has the potential to extend service life through better-informed control decisions.
Wind turbines are considered fatigue-critical structures with loading spectra characterized by high cycle counts [3]. Fatigue damage imparted to turbines is heavily attributed to atmospheric turbulence [4], which is influenced by surrounding topography and terrain at onshore wind farms [5]. Onshore farms are also subject to substantial diurnal variation in turbulence levels and wind shear driven by atmospheric stability. Solar heating of the ground during the day can generate turbulent boundary layer mixing to produce convective and unstable conditions having a near uniform wind speed profile. At night, turbulent mixing will typically reduce, producing a wind speed profile that is stable and highly sheared [6]. Simulation has demonstrated the ability of turbulence and wind shear inflow parameters to impact the modal properties of a wind turbine’s operational response, with more turbulent winds exciting a greater number of modes of vibration than sheared winds [7]. Simulation has also demonstrated the potential for accumulated rotor blade fatigue damage to be significantly influenced by the wind profiles expected under changing atmospheric stability conditions [8] or at differing wind farm sites [9].

At a commercial wind farm in Southwestern Ontario, the hollow structural steel supporting tower of a 2.3 MW horizontal-axis wind turbine has been instrumented with a fiber Bragg grating strain gauge array. The tower serves as an integral part of the wind turbine structure, and their failure is not unprecedented [10]. In addition to finite element modelling of turbine towers [1, 11-14], tower monitoring systems have also recently been employed to gather in-situ measurements of applied loading and tower response in modern multi-megawatt turbines. Such monitoring systems can be employed for applications beyond consideration of the tower, as the tower represents a barometer of response for rotor and foundation systems as well. Bang et al. [13] utilized a sensor array
to measure tower response during turbine start-up and shutdown. Rebelo et al. [14, 15] correlated stress magnitudes in the shell and pre-stressed bolts of a steel turbine tower with varying wind speed and characterized tower modal response from vibration measurements. They additionally performed a quantification of accumulated fatigue spectra in the tower over their measurement campaign. Ragan & Manuel [16] also estimated fatigue loads at tower base and blade root using data collected from a utility-scale turbine; employing both time-domain and spectral methods. Muto et al. [17] investigated the impacts of wind speed and turbulence intensity on flexural loads at the base of a turbine tower during typical power production. Previous work on the turbine under study has investigated the vibration and strain response of the tower to transient operational states such as start-up, rotor re-positioning, and manual shutdown [18-21]. The purpose of this work is to quantify the tower’s response to turbine operation across varying wind conditions. Particular consideration will be given to upwind inflow parameters such as vertical wind shear and longitudinal turbulence intensity; offering a more complete representation of the incoming flow field than hub-height speeds alone and for which limited data on structural impacts is available. Given that fatigue strength frequently governs wind turbine tower design [22], the chosen measure of response will be cyclic loading. A sample of the turbine tower’s loading history is to be constructed from multiple months of data collected from the installed strain gauge array and cyclic loading spectra will be assembled under specific wind regime classifications.

4.2 EXPERIMENTAL SETUP

The Siemens 2.3 MW MKII Turbine under study is a variable speed turbine with a rotor diameter of 93 m and hub height of 80 m. The tower is of steel plate construction and a
tapered tubular form, where diameter and wall thickness vary non-linearly along its
elevation. Outer diameter measures 4220 mm at the tower’s base and 2452 mm at
maximum elevation. Wall thickness measures 41 mm at the base and 22 mm at maximum
elevation. Composed of three sections bolted together, the tower measures 78.54 m in
height with a mass of approximately 148 tonnes, and is designed to withstand gusts of
59.5 m/s with an 18% turbulence intensity. A meteorological mast is positioned 150 m
West of the wind turbine. The wind farm is sited in an agricultural setting off the shores
of Lake Erie, which is located 3100 m South of the turbine under study.

The tower has been instrumented with a fiber Bragg grating (FBG) sensor array, as
presented by Bas et al. [20, 21], measuring longitudinal (vertical) deformation in the
tower at 100 Hz. Optical strain gauges are affixed to the North, South, East, and West
interior faces of the tower at six different elevations. Temperature compensation sensors
are also located at each elevation, allowing changes in temperature to be measured and
thermally-induced strain to be extracted from the total strain readings taken by the gauges
to produce mechanically-induced strain values. The West gauge positioned near tower
mid-height, termed Level 3, will be used for analysis given that the highest levels of
strain magnitude and variance are exhibited at this elevation for the instrumented turbine
tower model. The vertical location of the gauge under study and corresponding tower
properties at Level 3 are given in Table 4.6. Though prevailing on-site winds are from the
Southwest, the West direction demonstrates the highest probability of occurrence among
the cardinal directions. This indicates that the West and East sides of the tower will more
frequently be subjected to the direct windward action of the turbine’s axial rotor thrust,
which serves as a primary input of loading to the tower.
Table 4.6: Strain gauge locations and corresponding tower properties at Level 3.

<table>
<thead>
<tr>
<th>Level</th>
<th>Elevation (m)</th>
<th>Outer Diameter (mm)</th>
<th>Wall Thickness (mm)</th>
<th>Moment of Inertia (mm$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>41.8</td>
<td>4200</td>
<td>14</td>
<td>3.24 x 10^{12}</td>
</tr>
</tbody>
</table>

The meteorological mast is equipped with a vertical array of cup anemometers at 34, 61, 70, 77 and 80 m above ground level, and a wind vane located 77 m above ground level.

Wind conditions are categorized into two classes: a low-shear, high-turbulence condition hereafter referred to as “turbulent”, and a high-shear, low-turbulence condition referred to as “sheared”. These two classes are intended to describe the two major types of expected wind profiles produced by diurnal patterns in solar ground heating at onshore sites.

Vertical wind shear is evaluated from 34 m to 80 m using 10-minute averages of the shear exponent given in the power law equation [24]:

$$U(z) = U_R \left( \frac{z}{z_R} \right)^\alpha$$  \hspace{1cm} (1)

where $U$ is the mean horizontal wind speed at a given height $z$, and $U_R$ is the mean speed at a given reference height $z_R$. Turbulence levels are evaluated using the 10-minute horizontal turbulence intensity [25]:

$$I_U = \frac{\sigma_u}{U}$$  \hspace{1cm} (2)

where $\sigma_u$ and $U$ are the horizontal wind speed standard deviation and mean at 80 m.

Turbulence intensity and wind shear thresholds for wind condition classifications are given in Table 4.7, and have been adapted from thresholds used by Rareshide et al. [26] to determine the impacts of shear and turbulence levels on turbine power production. The turbulent condition thresholds approximately correspond with those of atmospheric stability conditions ranging from very unstable to near neutral, and sheared condition.
thresholds correspond with stability conditions from very stable to stable; as have been outlined by Wharton & Lundquist [27] and van den Berg [28].

Table 4.7: Wind condition classification.

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<th>Wind Shear</th>
<th>Turbulence Intensity</th>
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<td>Turbulent</td>
<td>Low</td>
<td>High ( I_U &gt; 11% )</td>
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<td></td>
<td>( \alpha &lt; 0.2 )</td>
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<tr>
<td></td>
<td>High</td>
<td>Low ( I_U &lt; 11% )</td>
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<td></td>
<td>( \alpha &gt; 0.2 )</td>
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<tr>
<td>Sheared</td>
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Measured strain values are not absolute, but rather a deviation from a baseline established when the turbine is non-operational and wind speeds are low. Furthermore, due to the significant effects introduced by the eccentric load present at the nacelle-tower interface [20], the baseline is established when the turbine rotor was also facing South. The 100 Hz readings from the strain gauge array have been converted to stress, assuming linear elastic behaviour. Where shown, positive values indicate tensile stresses and negative values indicate compressive stresses. Data has been collected during periods from September 2011 to October 2011 and from December 2011 to February 2012; spanning a portion of the Fall and Winter months in the Southern Canadian climate. Note that at this wind farm installation, Winter serves as the foremost power production season in the year.

### 4.4 RAINFLOW COUNTING

Time series data from the strain gauge array is converted to loading cycle counts using the often-employed rainflow-counting algorithm. Use of the algorithm requires a preprocessor to identify local extrema in the signal, which are then matched to form closed hysteresis loops or loading cycles having both a stress amplitude and mean stress value [29]. Rainflow counting is conducted using MATLAB numerical computing software,
and the RAINFLOW toolbox developed by Nieslony [30], which prepares cycles according to ASTM standards [31]. All loading cycles having an amplitude less than 1 MPa have been excluded from the tabulated cycle counts, being considered sufficiently small to have a negligible effect on any potential fatigue damage imparted to the steel turbine tower.

A ten-minute sample of the longitudinal stress signal from the West gauge at Level 3 is shown in Figure 4.25 during operation in a Westerly wind near average on-site wind speeds. The path indicated by points A-E-F represents a cycle having a stress amplitude of 21 MPa and mean stress of 28 MPa, which includes an intermediate cycle indicated along B-C-D having a stress amplitude of 7 MPa with a mean stress of 25 MPa. The rainflow counting method facilitates counting the intermediate cycle outlined by B-C-D separate from the cycle outlined by A-E-F; whereas conventional range counting characterization of load spectra would instead identify three individual half cycles along points A-B, B-C, and C-E which would be expected to have a smaller contribution to imparted fatigue damage than would the larger cycle A-E-F [32].
4.3 RESULTS

4.3.1 Loading History

A sample of the turbine’s loading history has been compiled using nearly 12 weeks (86 days) of time series data from the strain gauge array. The first 69 days of data were truncated into half-hour segments by the strain array’s interrogation system. To improve ease of data handling, the system was re-configured so that the last 17 days were truncated into hour segments. To prevent “over counting” of unmatched half cycles, successive half-hour and hour segments were stacked to form 5-day segments of time series data which were then processed individually using the rainflow-counting algorithm. Mean cycle stress and cycle stress amplitude were calculated and binned, with the absolute maximum value in the range indicated in Figure 4.26 and Figure 4.27. A logarithmic vertical axis is used to compare cycle counts of differing orders of magnitude. In Figure 4.26, thermally-induced strain has been extracted from the signal
using the temperature compensation sensors to provide solely mechanically-induced strain, which is generated from loads produced by the wind and turbine operation. No temperature compensation was conducted for the signal used in Figure 4.27, which tabulates the total deformation in the tower over the course of the 12-week study period.

Figure 4.26: Mechanically-induced loading cycle spectra for twelve-week study period.
Figure 4.27: Total loading cycle amplitude and mean spectra for twelve-week study period.

Positive mean stress values are shown to be more likely in Figure 4.26, as the greater degree of Westerly winds will introduce tensile stresses into the West face of the tower.

Figure 4.27 demonstrates a wider range in mean stress values, as a result of the temperature deviation experienced in the Southern Canadian climate over the measurement campaign. A temperature change of 10 °C will result in a near 35 MPa deviation in stress for the structural steel tower. The figures produced could be an asset to the future design of wind turbine towers, given that design loading spectra are traditionally simulation-based. Furthermore, the loading spectra produced could potentially be used to assess the existing service life of the tower using fatigue strength curves for structural components. In Figure 4.26, higher cycle counts are noted for mean stress with an absolute value near 50 MPa and stress amplitude values of 15 MPa or more. This phenomenon is the result of windward loading (from either the East or West directions) introducing high cyclic loading into the West interior face of the tower. The
cycle counts at given stress amplitudes across all mean stress values are shown in Figure 4.28, for both mechanically-induced and total loading cycles. Note that the predominant on-site wind direction over the course of the study period was from the Southwest. Therefore, the cycle counts compiled for the West gauge may potentially underestimate the maximum cyclic loading levels experienced at Level 3.

Figure 4.28: Loading cycle amplitude spectra.

Marginal differences are observed between mechanically-induced and total loading cycle amplitude spectra. Most notably, cycles having stress amplitudes from 35 to 40 MPa are more frequent in the total stress-strain signal, which is thought to be the result of synoptic or diurnal thermal effects. Linearly extrapolating cycle counts over an anticipated twenty-year life expectancy yields in excess of 210 million loading cycles having amplitudes more than 1 MPa.
4.3.2 Loading Spectra Across Wind Speed

To study the effects of the wind profile directly upstream of the turbine on the windward mechanically-induced response of the tower, winds from the Westerly sector (average ten-minute wind direction at 77 m of 270° ± 15°) are used for analysis, with ten-minute wind speeds at 80 m correlated with loading cycle counts compiled by employing the rainflow-counting algorithm on ten-minute segments of time series stress data. Though wind speed values are also directly available from the turbine through the farm’s supervisory control and data acquisition system, such measurements are taken at the rear of the nacelle in the wake of the rotating rotor blades, therefore the unobstructed upwind readings taken by the meteorological mast are used instead. The cycle counts are averaged to construct the amplitude spectrum expected over an hour of operation at a given wind speed. Figure 4.29 shows amplitude spectra across hub-height wind speeds less than the turbine’s rated speed of near 11 m/s, where maximum power production is achieved, and Figure 4.30 shows amplitude spectra across hub-height wind speeds at rated speed and above. Error bars indicate a single standard deviation of sample variance in the positive and negative directions.
Figure 4.29: Loading amplitude spectra for hour of operation across wind speeds, below rated speed.

Figure 4.30: Loading amplitude spectra for hour of operation across wind speed, at and above rated speed.

Noting that mean stress in the tower is expected to increase with wind speed up to a maximum at rated speed and then gradually decrease with increasing wind speed due to a reduction in axial rotor thrust [5, 15, 17], cycle counts across all stress amplitudes are largely shown to increase with increasing hub-height wind speeds. While smaller cycles with amplitudes of less than 15 MPa increase fairly proportionally with wind speed, a
significant increase in cycles having amplitudes in excess of 15 MPa is observed as wind speeds transition from below-rated to above-rated speeds. This is speculated to be the result of pitch excitation type vibration [17], where decreases in wind speed cause the turbine to compensate by decreasing blade pitch angle, thereby increasing the axial rotor thrust and resulting tower bending moment. This phenomenon will occur at above-rated wind speeds where the turbine controller actively pitches the rotor blades to prevent turbine overload and maintain steady power production, as opposed to below-rated speeds where blade pitch is held relatively constant after the cut-in speed of approximately 3 m/s has been reached.

4.3.3 Loading Spectra Across Wind Conditions

Likewise, to study the effects of differing wind profiles on the mechanically-induced windward response of the tower, winds from the Westerly sector at four different hub-height wind speeds, two above rated speed and two below, were categorized into turbulent or sheared conditions. Wind speeds were selected on the basis of availability of data. Ten-minute cycle counts are then compiled into an hour, as shown in Figure 4.31 – 4.34, with error bars of a single standard deviation indicated.
Figure 4.31: Loading amplitude spectra for hour of operation at $U_{80} = 6$ m/s, classified by wind condition.

Figure 4.32: Loading amplitude spectra for hour of operation at $U_{80} = 8$ m/s, classified by wind condition.
Figure 4.33: Loading amplitude spectra for hour of operation at \( U_{80} = 13 \text{ m/s} \), classified by wind condition.

Turbulent conditions are shown to coincide with markedly higher cycle counts across stress amplitudes and surveyed wind speeds, with few exceptions. This phenomenon is partially attributed to higher yawing activity resulting from greater horizontal wind direction variability under such conditions, as the turbine controller attempts to better position the rotor into the prevailing horizontal wind direction and moves the
compressive load presented by the rotor-nacelle along the circumference of the tower wall. Higher cyclic loading under turbulent conditions is also attributed to forced vibration buffeting of the tower under wind gusts, as well as changes in the quasi-static load from load-unloading action of the rotor. From the results in Figure 7, it is therefore suggested that fluctuation in the horizontal component of wind velocity has a greater impact on the cyclic loading subjected to the turbine tower than does the velocity gradient across the turbine rotor.

The disparity between turbulent and sheared condition cycle counts is also shown to vary depending on hub-height wind speed in Figure 4.31 – 4.34. Notably this disparity increases between wind speeds of 13 and 17 m/s for cycle amplitudes in excess of 15 MPa. This is speculated to be the result of heightened dynamic action under turbulent conditions, which increases with wind speed, via the aforementioned pitch excitation mechanism. The moment-based gust reaction factor, a ratio of maximum to average tower base moment, has been expressed empirically by Ishihara et al. [32] and is expected to rise with increasing hub-height wind speed and turbulence intensity [17], when blade pitch control is activated after rated speed has been reached.

4.4 CONCLUDING REMARKS & FUTURE WORK

The cyclic loading of a steel wind turbine tower has been compiled and correlated with varying wind conditions, with the following analyses conducted and conclusions drawn:

- High-turbulence, low-shear conditions coincide with increased levels of loading cycles compared with low-turbulence, high-shear conditions across all surveyed wind speeds
• Loading cycle counts are seen to generally increase with increasing hub-height wind speed.

• A sample of the turbine tower’s loading history has been assembled from a twelve-week measurement campaign, with mean and amplitude stress spectra tabulated with and without consideration of thermally-induced deformation effects. Given the highly stochastic nature of the aerodynamic loading under which the turbine structure is subjected, the loading history sample collected from an operational full-sized commercial wind turbine can aid in the further optimization of tower design.

• Linear extrapolation of the loading history sample yields more than 210 million loading cycles in excess of 1 MPa over an anticipated twenty-year turbine service life.

Future work should look to incorporate the material properties of the structural steel turbine tower to find levels of fatigue damage equivalent loads for the measured load spectra. Measured load spectra from the tower wall can be employed to draw inferences on the loading to which other critical points of the tower, such as welds or flanged sections, are subjected. Given the potential impacts of loading sequence on the expected fatigue strength of structural steel [33], future analysis should also look to characterize the cyclic load sequences unique to wind turbine towers in varying operational state.

REFERENCES


CHAPTER 5

Conclusions

Atmospheric conditions have been correlated with wind turbine tower structural loading and power production at an onshore wind farm in Southwestern Ontario over a six-month measurement campaign spanning September 2011 to February 2012. Sensitivity of power extraction to changes in approaching wind profile have been observed; with high-turbulence, low-shear conditions (referred to in this study as turbulent) raising normalized power by upwards of 2% over high-shear, low-turbulence conditions (referred to as sheared) at low-to-moderate wind speeds. Sheared conditions have produced an increase in normalized power of as much as 2% over turbulent for higher wind speeds close to the rated speed of the turbine. The outlined condition classes demonstrated strong diurnal correlation, with sheared conditions more frequently expected at night and turbulent conditions more frequent during the day. The mean and maximum flexural loading in the base of the tower has shown to be at a maximum at rated wind speed of the turbine, and will gradually reduce with increasing speeds. Though turbulent conditions coincide with lower mean flexural loading measured by a single static strain gauge in the tower, expected in large part to be the result of higher directionally variability under such conditions leading to higher yawing activity, these conditions have also been shown to coincide with much higher loading variance resulting in higher cyclic load. A tower loading history sample has been constructed from twelve weeks of turbine operation, and characteristic hourly cyclic loading spectra have been shown for the tower as it operates in varying wind conditions and operational states.
A trade-off is demonstrated between the higher power production turbulent conditions are capable of producing under average onsite wind speeds versus the higher cyclic loading such conditions impart to the structural supporting tower and presumably to the rotor as well. The results of this work could help improve wind farm operators’ assessments of the useful remaining service for wind turbine components. It could also help improve daily forecasting of individual turbine or wind farm performance based on given climate conditions, which would be valuable to both grid operators working to integrate wind power onto the utility grid and to wind farm operators looking to predict revenue. An improved understanding how site-specific and diurnally or seasonally varying wind conditions affect overall turbine performance, including power production and structural degradation, will reduce the uncertainty associated with wind energy projects and help solidify the future of the industry.

Future work should look to incorporate the other half of the year at the studied wind farm site to demonstrate whether observed trends hold during warmer months. Increasing the number of measurement points for the approaching wind field, potentially through the use of remote sensing technology to characterize wind speeds and turbulence at even higher levels of the atmospheric boundary layer, would allow for an improvement in the characterization of wind condition patterns onsite. Also increasing the measurement time resolution of all studied parameters could help to clarify the physical phenomenon affecting turbine rotor dynamics under changing inflow parameters. The results presented in this study have observed the structural and power production data for a single turbine, but future work should consider the inclusion of multiple turbines within a single farm or even multiple farms within a localized region. As the density of commercial wind farms
continues to rise in the Great Lakes region of Southwestern Ontario, the propagation and interaction of single turbine wakes or group farm wakes under changing atmospheric stability could have major implications for wind farm siting and wind energy forecasting.
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