Stochastic thunderstorm model for dynamic response assessment

Sien, Michael Hay Wah

2007

Sien, M. H. W. (2007). Stochastic thunderstorm model for dynamic response assessment. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/12003>

<https://doi.org/10.32657/10356/12003>

Nanyang Technological University

Downloaded on 26 Apr 2023 22:19:49 SGT

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**STOCHASTIC THUNDERSTORM MODEL FOR
DYNAMIC RESPONSE ASSESSMENT**

MICHAEL SIEN HAY WAH

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

2007

Stochastic Thunderstorm Model for Dynamic Response Assessment

Michael Sien Hay Wah

School of Civil and Environmental Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of Master of
Engineering

2007

Abstract:

Thunderstorm winds have been known to be highly non-stationary as compared to other large scale winds like monsoons. The highly localized nature of these winds generates ferocious winds at low to mid-height, deviating from the boundary layer wind profile that most building codes recognized. The thunderstorm downdraught rushes down vertically and spreads out radially like a wall-jet. Highest wind speeds are registered at locations which are nearest to the storm cell centre.

The collection of thunderstorm data by an existing facility in the Nanyang Technological University campus provides the means by which a stochastic thunderstorm model may be constructed. The random nature of natural wind allows computation of stochastic response by using the random vibration theory. The thunderstorm time-history can be modelled by two separate parts: the non-stationary mean and the stochastic part. The non-stationary part is a deterministic function which can be predicted based on the time-history profile. This project attempts to extract the stochastic part based on assumption of the Holmes and Oliver's model instead of the conventional moving average technique which was reported to have shortcomings. The quality of the resulting stochastic thunderstorm spectrum is compared with that generated by the moving average technique. The Davenport spectrum is shown to be sufficient for wind load design.

Acknowledgements:

I wish to express my gratitude to Assistant Professors Au Siu Kui and Gho Wie Min for their invaluable advice, guidance and understanding throughout the course of the study. Their insightful advices are immensely beneficial to me as a Graduate student, and expose me to various roles of an engineer that encompasses planning, communication and team work when I undertake the various tasks of responsibility. I have enjoyed the challenges that I have come across at every point in the process of research, especially when a particularly difficult problem is solved by an equally ingenious solution. I also wish to express my gratitude to Professor Choi Cheong Chuen Edmund for his insightful advice whenever a particularly difficult problem arises. This allowed me to tap into his wealth of experience and I have learnt much from it. Special thanks to Mr. Tay Lye Chuan for the handling of matters pertaining to data collection and the wind data collection facility in the campus.

Of course, I would not have completed such a gruelling research programme without the support of my family and my friends. I wish to thank my parents for their encouragement and support throughout the duration of this course. I also wish to thank my fellow graduate students from the research office N1-B4-04 for all the joyous moments you have given me. Special thanks to Mr. Lim Yee Yan and Mr. Hey Chunn Kiat Farrand whom I had the chance to share with them the joyous experience of being an undergraduate and postgraduate student together. Last but not least, our senior Mr. Ng Leng Ping Jeffrey who has shared with us valuable experiences on and off-campus during lunch breaks. I also wish to express my gratitude to the Meteorological Services of Singapore for providing the radar imaging pictures. The research scholarship provided by Centre for Advanced Construction Studies of Nanyang Technological University is gratefully acknowledged.

Table of contents:

ABSTRACT	i
ACKNOWLEDGEMENTS	ii
TABLE OF CONTENTS	iii
LIST OF FIGURES	v
LIST OF TABLES	vi
LIST OF SYMBOLS	vii
CHAPTER 1: INTRODUCTION	1
1.1 Background	1
1.2 Scope and Objective	3
CHAPTER 2: THUNDERSTORM MODELS	6
2.1 Climatology of Singapore	6
2.1.1 Monsoon	7
2.1.2 Thunderstorm	8
2.2 Atmospheric Turbulence	9
2.3 Physics of Thunderstorm downbursts	9
2.4 Mathematical models	11
2.5 Vertical Profile	12
2.6 Wind Speed variation with time	15
2.7 Combined wind speed in a thunderstorm	18
CHAPTER 3: FIELD MEASUREMENT AND DATA ANALYSIS	20
3.1 Monsoon wind	21
3.2 Thunderstorms	25
CHAPTER 4: THE DYNAMICS OF STRUCTURES	31
4.1 Single degree of freedom (SDOF) system	32
4.2 The Duhamel Integral	35
4.3 Random process of wind	37
4.4 Along-wind response	39
4.5 Across-wind response	43
CHAPTER 5: ANALYSIS BY MOVING AVERAGE TECHNIQUE	44
5.1 Selection of time period of thunderstorms	45
5.2 Selection of a suitable averaging period	53
5.3 Analysis of thunderstorm data	56
5.4 Regression Analysis	74
5.5 Summary of the chapter	74
CHAPTER 6: ANALYSIS BY THUNDERSTORM MODEL	79
6.1 Thunderstorm models	81
6.2 Application of model on time-history data	86
6.3 Summary of the chapter	86

CHAPTER 7: APPLICATION OF WIND LOADING CODE	103
7.1 Governing parameters	104
7.2 Wind loading design based on monsoon wind	108
7.3 Deterministic monsoon wind load	110
7.4 Stochastic component of monsoon wind	111
7.4.1 Gust Response Factor	112
7.4.2 Application of GRF method	114
7.5 Wind load design against thunderstorms	115
7.5.1 Quasi-static component	116
7.5.2 Dynamic component	118
7.6 Implementation of design framework	119
CHAPTER 8: CONCLUSION AND RECOMMENDATIONS	124
8.1 Conclusion	124
8.2 Recommendations	125
APPENDIX A	127
APPENDIX B	129
REFERENCES	131

List of figures:

2.1	Location of the site at NTU	7
2.2	Time history of Andrews AFB downburst	11
2.3	The comparison of the three models used for the vertical profile	14
2.4	Plot of horizontal wind speed with distance r	16
3.1	20m wind mast and schematic diagram	20
4.1	A SDOF system and its common representation	32
4.2	The Davenport spectrum	42
5.1	Time history of wind speed in the 18 thunderstorms	49
5.2	Variation of wind speed spectrum with varying window length	55
5.3a	Wind data from normal speed data logger	57
5.3b	Wind data from high speed data logger	58
5.4a	Radar picture on 25 th Mar 05, 1602 hrs	60
5.4b	Radar picture on 25 th Mar 05, 1615 hrs	60
5.4c	Radar picture on 25 th Mar 05, 1705 hrs	61
5.5a	Wind data from normal speed data logger	62
5.5b	Wind data from high speed data logger	64
5.6a	Radar picture on 26 th Mar 05, 1332 hrs	65
5.6b	Radar picture on 26 th Mar 05, 1353 hrs	65
5.6c	Radar picture on 26 th Mar 05, 1414 hrs	65
5.7a	Wind data from normal speed data logger	66
5.7b	Wind data from high speed data logger	67
5.8a	Radar picture taken at 1021 hours	70
5.8b	Radar picture taken at 1023 hours	70
5.8c	Radar picture taken at 1033 hours	70
5.9	Wind speed time-histories and their respective stochastic components	72
5.10	Fourier transform of the stochastic components plotted together with the Davenport spectrum	73
5.11	3D Plot of the function E with respect to parameters a and b	75
6.1	Horizontal profile of wind speed (Holmes and Oliver's model)	82
6.2	Horizontal profile of wind speed with $e=500m$	84
6.3a	Horizontal profile of wind speed with $e=1000m$	85
6.3b	Horizontal profile of wind speed with $e=1500m$	85
6.4	Time history of wind speed in selected ensemble of data	88
6.5a	First plot: wind speed and direction data on 26 th Mar 05	92
6.5b	Second plot: Comparison of properties on 26 th Mar 05	93
6.5c	Third plot: Comparison of stationarity of data on 26 th Mar 05	94
6.6	Histograms of stochastic components obtained from 25 th Mar to 21 st Apr 05	96
6.7	Log-log plot of stochastic spectrum obtained from 25 th Mar to 21 st Apr 05	98
7.1	SDOF test structure	120
7.2	Dynamic and quasi-static response of SDOF structure	121

List of tables:

2.1	Values used for parameters in different models	13
3.1	Storing format of hourly statistics in data logger (partial)	22
3.2	Storing format of treated data (normal wind conditions) (partial)	23
3.3	Mean wind statistics from Dec 2000 to Feb 2003	24
3.4	Storing format of rain data in data logger (partial)	26
3.5	Storing format of rain data in treated data (partial)	27
3.6	Storing format of thunderstorm data in high speed data logger (partial)	28
5.1	Best fit regression coefficients for the 18 data sets	77
6.1	Regression coefficients of a,b,c for using Holmes' model	99
6.2	Regression coefficients of a,b,c for moving average	100
7.1	Dynamic amplification factors of SDOF subjected to time-histories	122

List of Symbols:

A	=	projected surface area
C_{dyn}	=	dynamic response factor
C_{exp}	=	exposure factor
C_{fig}	=	aerodynamic shape factor
c	=	damping coefficient of a Single Degree of Freedom system
χ	=	aerodynamic admittance function
d_0	=	x-component distance of the observing point from the storm centre
δ	=	the height where the velocity is equal to half its maximum value
e	=	characteristic height in the boundary layer
e	=	offset distance of downburst track from the point of observation
F_D	=	drag force
g, g_v	=	peak factor
H	=	mechanical admittance function
I_h	=	turbulence intensity
k	=	stiffness coefficient of a Single Degree of Freedom system
m	=	mass coefficient of a Single Degree of Freedom system
n	=	frequency in Hertz
n_0	=	natural frequency in Hertz
v	=	upcross rate
R	=	characteristic radius of the downburst “shaft”

R_r	=	radial length scale
r	=	radial coordinate from the centre of downburst
$r_{\max}$	=	radial distance from the stagnation point
ρ_{air}	=	air density
S_u	=	spectrum of wind speed
S_x	=	spectrum of displacement response
u	=	wind speed
$\bar{u}$	=	mean wind speed
u'	=	fluctuating wind speed or stochastic component of wind speed
u_*	=	frictional wind velocity
V	=	basic wind speed
$V(z)$	=	maximum mean wind speed at elevation z
V_c	=	combined velocity
$V_{r,\max}$	=	maximum velocity in profile
ω	=	natural frequency in radians per second
ω_D	=	damped natural frequency in radians per second
z	=	elevation height
z^*	=	characteristic height out of boundary layer
ζ, ζ_s	=	structural damping, as a ratio of critical damping

Chapter 1: Introduction

Thunderstorms have been studied by researchers intensively in the past two decades. They are found to be highly localized and display higher mean wind speed and turbulence intensity than the monsoon winds despite having a shorter duration. The formation of gusty winds causes it to deviate significantly from the conventional power law profile (Choi, 2004) when the storm cell is very near. Thunderstorms are known to be capable of causing considerable damage to structures. There have been reports of structural failures induced by thunderstorm downbursts in Australia, US and Japan. Structures that are vulnerable to such failures include transmission towers and wind sensitive structures. The behaviour of thunderstorm winds is not well understood and their effect on structural response of buildings needs to be investigated. This study will lead to the development of a stochastic thunderstorm model that can be used in the prediction of dynamic response of structures to thunderstorms.

1.1 Background

The radar observations and the NIMROD and JAWS programs (Fujita, 1985) initiated in the United States have provided most of the information about the wind structure of thunderstorms. The downburst simulations have revealed that thunderstorms have unique characteristics that are very different from monsoon winds. In addition to having higher mean wind speed and turbulence intensity, they also induce a low level maximum wind speed as well as a highly non-stationary wind field. The vortex ring model (Caracena et al, 1989) and the impinging wall jet model (Hjelmfelt, 1988) are most often referred to when describing the structure of

downburst winds in thunderstorms.

Researchers have come up with a number of mathematical models for thunderstorms. There are models which describe the deterministic time-history profile of a thunderstorm, as well as those which describe the vertical profile of wind speeds along a vertically cantilevered structure. These models are based empirically on the observations made during thunderstorm downburst simulations. The deterministic dynamic response of the structure due to thunderstorm can be calculated based on the above models.

However, little is said about the modelling of the stochastic component of the downburst winds. It is of paramount importance for the construction of a stochastic thunderstorm model to be implemented as well if the actual dynamic response of the structure is to be predicted accurately. The highly non-stationary nature of the downburst winds makes extraction of a stationary stochastic wind component difficult. It is required of the stochastic component to be a stationary random process before the random vibration theory can be applied. The application of the random vibration theory allows the stochastic component to be interpreted in statistical terms, from which its contribution to additional response can be readily understood.

1.2 Scope and Objective:

The objective of this study is to devise a system identification methodology and to construct a stochastic thunderstorm model based on the wind data collected. The thunderstorm data collected from a wind mast in the Nanyang Technological University (NTU) campus is analyzed using the moving average technique and the Fast Fourier Transform (FFT). The extraction of the stochastic component is performed through a numerical technique known as the moving average. A suitable averaging period is required for the moving average technique to extract a stationary stochastic component successfully. Trial values for different averaging periods may be tested for stationarity of stochastic component in a systematic manner. Choi and Hidayat (2002) did a comparative study amongst a range of 30s to 120s, and a value of 60s is recommended for the averaging period. Alternatively, the stochastic component may be extracted based on a new technique proposed in this project. This new technique utilizes the empirical model proposed by Holmes and Oliver (2000).

The collection, sorting and analysis of the respective thunderstorm data is carried out. The data collected during the period of late-March to May corresponds to the pre-southwest monsoon period which is part of the inter-monsoon season, where thunderstorms govern the weather system. Extra care is exercised when extracting the thunderstorm data from the normal monsoon wind data, as their engineering characteristics differ greatly. The thunderstorm data are captured by a separate data logger which dynamic range has been upgraded from 4Hz to 20Hz. This data logger triggers into high speed mode and captures wind data at 20 samples per second continuously for one hour when the cup-type anemometer registers a preset triggering wind speed of 8m/s.

The analysis of the thunderstorm data would be done with the help of MATLAB®. The one-hour data files containing the thunderstorm parameters describing wind speed and wind direction for the five levels of anemometers on the wind mast are stored as CSV (comma-separated values) format in the data logger. The data logger is collected on a weekly basis and the data files are downloaded into a computer. They are to be converted to readable formats before being analyzed using MATLAB®. Two MATLAB® programs are written. One is written for the purpose of extracting the data from the data logger responsible for continuous monitoring of the monsoon wind, while the other is for the analysis of the thunderstorm wind data by extracting the stochastic component of the wind. It is hoped that these would facilitate the construction of a stochastic thunderstorm model that will allow the computation of structural response due to thunderstorms.

Two methods are be used to extract the thunderstorm stochastic component. The moving average technique is utilized in the extraction of a stationary stochastic component from the downburst winds. This technique calculates the average of a number of sampling points within a specified time period along the entire time-history. This specified time period is known as the averaging period. The moving average requires a suitable averaging time period as input in order for the stochastic component to be completely free of non-stationarity. The stationary stochastic component may then be extracted by subtraction of the moving average from the downburst time-history. The Davenport spectrum (Davenport, 1961) is commonly used in predicting dynamic response due to stationary stochastic wind components.

The second method is proposed in this study based on the application of the Holmes and Oliver's model. The extraction is based on the locality of the storm to the site as well as the relatively movement known as storm path. The Holmes and Oliver's

model may be utilized in the extraction of the stochastic component when the relevant thunderstorm information is known.

This study includes the collection and analysis of both monsoon and thunderstorm data. A facility responsible for collection of wind speed data is installed in the vicinity of the university campus. The continuous collection of monsoon wind and thunderstorm wind data (triggers when wind speed $> 8\text{m/s}$) allows for continuous monitoring of wind speeds in the campus. The construction of a database of thunderstorm data serves to enhance understanding into the behaviour of these highly localized winds and also to spearhead future research efforts.

It is hoped that by performing a series of analysis, a system identification methodology for identifying the parameters in the stochastic thunderstorm model may be developed. The stochastic thunderstorm model will consist of the various parameters that are known to influence thunderstorm characteristics and behaviour.

Chapter 2: Thunderstorm models

The characteristics of thunderstorms have been of interest to the wind engineering community, due to its difference from that of the conventional wind systems like the monsoons and hurricanes. There has been much research carried out on the formation of thunderstorms, thunderstorm wind characteristics, and its effects on engineering structures like buildings and bridges in particular. It has been shown that in addition to influencing the extreme wind characteristics of a region, it can produce strong winds close to the ground. This may be of concern to buildings that are of low to medium height, which may not be designed to resist such wind loads as compared to code requirements which are based heavily on boundary layer profile wind type. Researchers have developed a series of mathematical models that describes the variation of horizontal and vertical wind speed profile from experimental data. This chapter discusses the climatology of Singapore, and the general characteristics of thunderstorm winds. It also introduces the various findings by researchers and their corresponding mathematical models based on empirical results from experimental observations.

2.1 Climatology of Singapore

Singapore lies slightly north of the Equator near latitude 1.5 degrees North and longitude 104 degrees East. Due to the geographical location and maritime exposure, its climate is characterized by uniform temperature and pressure, high humidity and abundant rainfall. The climate of Singapore can be divided into two main seasons, the Northeast Monsoon and the Southwest Monsoon season. These two monsoons are separated by short inter-monsoon periods. This is the period of time where the climate is characterized by abundant rainfall and frequent thunderstorms. According

to Choi and Tanurdjaja (2002), Singapore is also often subjected to squall lines mainly due to the geographical feature of the Malacca Straits between Singapore and Sumatra Island. The climate in Singapore that of a mixed climate system, governed by monsoons and thunderstorms. The fact that Singapore is of a mixed climate system suggests that wind speed data may not be analyzed in a straightforward manner. The data need to be sorted for occurrence of different events (e.g. a thunderstorm event vs a non-thunderstorm event).

Figure 2.1 Location of the site at NTU

2.1.1 Monsoon

Monsoons are circulations generated as a result of the thermal effect due to the differential heating of the land and sea masses. As the land masses of the continents are very large, these weather systems are large and last for days and weeks. The inclination of the earth's axis to the ecliptic causes seasonal oscillations of these systems. In Singapore, the Northeast monsoon dominates during the months of December to March, and the Southwest monsoon during the months of June to September. Choi (2004) reported that Northeast monsoon winds are found to be slightly stronger than that of the Southwest monsoon winds. The inter-monsoon

period refers to the months in between where neither the Northeast or Southwest monsoon dominates. This period is often the time when occurrences of thunderstorms are frequent.

2.1.2 Thunderstorm

There are usually more than 200 occurrences of thunderstorms recorded in Singapore annually (Choi and Hidayat, 2002). The inter-monsoon season is usually the time when occurrences of thunderstorms are frequent. Every thunderstorm is produced by a cumulonimbus cloud and is always accompanied by thunder and lightning. Thunderstorms usually begin when a parcel of air, either warmer than the surroundings or being pushed up by colder encroaching air such as a cold front, begins to rise. This unstable updraught forms the ‘eye’ of the thunderstorm. Condensation takes place when it is sufficiently moist; the latent heat released adds buoyancy to the vapour. The rising air stream form an updraft which keeps the water droplets and ice crystals suspended. As more droplets are formed and precipitation starts, the frictional drag induces downdraught.

During the mature stage of the thunderstorm, downdraught intensifies. This is the most active period of a thunderstorm, characterized by gusty winds and heavy precipitation. The leading edge of the cold air resulting from the downdraft is called the gust front, or the first gust. The gust front is characterized by an abrupt change in temperature, wind speed, and an increase in pressure. In severe thunderstorms, the strong downdraft develops into a downburst, which diverges horizontally as an outburst of destructive winds upon reaching the grounds. The gust front usually moves ahead of the thunderstorm. Unlike the monsoon wind or even the typhoon wind where the wind moves in horizontal direction over the ground, winds from thunderstorms rush vertically down and spread outwards like a wall jet, with the

strongest winds close to the thunderstorm cell centre. The magnitude of such winds depends largely on the size of the cell, rain intensity, and the proximity of the site. In the case when the cell is of a considerable distance away, terrain roughness is a governing factor in the magnitude of achievable wind speed.

2.2 Atmospheric Turbulence

The atmospheric boundary layer is a zone of turbulent mixing in the Earth's atmosphere. The Earth's surface exerts a retarding force on the moving air within this zone. The depth of this zone ranges from a few hundred meters to several kilometers, depending upon wind intensity, terrain roughness, and angle of latitude. The wind speed increases with elevation, to a maximum at the top of the boundary layer often referred to as the gradient speed. Beyond the boundary layer, the wind flows approximately with the gradient speed along the isobars.

2.3 Physics of Thunderstorm Downbursts

The motion of the atmosphere is governed by the fundamental equations of continuum mechanics. This includes the equation of continuity and the Navier-Stokes equation. The boundary layer wind is known to be heavily dependent on the terrain roughness and elevation, giving rise to the well-known logarithmic and the power law profile. Therefore, terrain roughness has a pronounced effect on large scale winds like the monsoon wind. The downburst wind, on the other hand, is less affected due to its site locality. The thunderstorm downdraft, which follows the gust front, rushes down vertically at the site local to the cell. The site that is of closest proximity to the thunderstorm cell registers the highest wind speed from the downdraft.

As described earlier, the downdraft rushes down like a wall jet, which spreads out horizontally as it reaches the ground. Therefore, thunderstorms are able to unleash strong winds despite their localized nature. Extreme wind studies had shown that thunderstorm events account for a substantial amount of peak wind speeds collected from samples in a region. In the 1960s, Whittingham (1964) recognized the importance of thunderstorms in the Australian extreme wind climate. Gomes and Vickery (1976) specifically analyzed Sydney thunderstorms for extreme wind speeds in 1975. Re-analysis of extreme wind speeds in Australia by Holmes (1999) has indicated that, outside of cyclone regions, almost half occur in thunderstorm events, and in some instances the peak wind speed resulted from severe cases of downbursts. Analysis of gust wind speeds in the United States also indicated that about one-third occur in thunderstorms, while Twisdale and Vickery (1992) demonstrated that thunderstorm winds dominate the high return period end for several US stations. In short, there is ample evidence that thunderstorms do have significant impact on the extreme wind characteristics of any non-cyclonic region.

A downburst occurs when the downdraft from a thunderstorm cell intensifies. Should a downdraft develop into a downburst, as described by Fujita (1985) as “a strong downdraft”, it can induce damaging winds on or near the ground. He further sub-divided downbursts into microbursts and macrobursts, the earlier with damaging winds extending only 4km or less and the latter with outburst winds extending in excess of 4km.

Figure 2.2 Time history of Andrews AFB downburst

Fujita's NIMROD and the JAWS experiments have enabled a better understanding of the flow structure near the ground during such an event. It was based on the time-history of a very severe microburst which struck Andrews Air-Force Base near Washington DC in 1983, with a recorded peak gust wind speed of 67m/s at a height of 5 metres. It has been observed that the strongest winds occur at about one downdraft diameter from the "eye". The strong winds, which are near to the ground, may induce higher amount of response in low to mid-rise buildings, as opposed to the boundary layer wind assumption of increasing wind speed with elevation. Highly non-stationary wind field was observed as well. The lateral movement of the downdraft causes a downburst velocity increase in front of the storm, and a decrease in velocity on the trailing side.

2.4 Mathematical models

The formulation of mathematical models is crucial in the investigation of thunderstorm wind characteristics because it permits a physical process to be approximately described by a mathematical expression. Though it is known that

thunderstorm wind may be modelled as a random process its deterministic component is approximately describable by an equivalent mathematical model. Models that describe vertical profile and variation of wind speed with time are both immensely useful in coming up with a model that accurately describe stochastic response. Intensive research has generated several noteworthy models that are listed here. Osguera and Bowles (1988), Vicroy (1992), and Wood and Kwok (1998) developed models that describes the vertical profile of a simulated downburst, while Poreh and Cermak (1959) came up with a model that describes the downburst time-history. These models will give a complete picture of the deterministic wind velocity field of a simulated downburst when combined together.

2.5 Vertical Profile

There are two models developed by researchers for describing downburst winds. They are the vortex ring model by Caracena et al (1989) and the impinging wall jet model by Hjelmfelt (1988). The development of these two physical models has been motivated by field observations. The descending column of air from a downburst has been described by observers to be similar to that of a formation of a vortex ring. The impinging wall jet, on the other hand, arises from the steady state flow of a continuously impinging column of air on the ground. Three empirical models were also developed for the vertical profile.

The Oseguera and Bowles (1988) model satisfies the mass continuity but does not provide information concerning storm movement. The vertical profile is shown as:

$$V(z) = \left(\frac{\lambda R^2}{2r} \right) \left[1 - e^{-(r/R)^2} \right] \left(e^{-z/z^*} - e^{-z/\varepsilon} \right), \quad (2.1)$$

where $V(z)$ is the maximum mean wind speed at elevation z ; r is the radial coordinate from the center of the downburst; R is the characteristic radius of the downburst “shaft”; z^* is a characteristic height out of the boundary layer; e is a characteristic height in the boundary layer; λ is a scaling factor.

The Vicroy (1992) model is expressed as:

$$V(z) = 1.22 \times \left[e^{-0.15 z / z_{\max}} - e^{-3.2175 z / z_{\max}} \right] \times V_{\max} \quad (2.2)$$

where $V_{\max}$ is the maximum speed in the profile; $z_{\max}$ is the height at which the maximum speed occurs.

The Wood and Kwok (1998) model is expressed as:

$$V(z) = 1.55 \left(\frac{z}{\delta} \right)^{1/6} \left[1 - \operatorname{erf} \left(0.7 \frac{z}{\delta} \right) \right] \times V_{\max} \quad (2.3)$$

where δ is the height where the velocity is equal to half its maximum value; erf is the error function. Wind tunnel experiments have shown that Wood’s profile only applies once the wall jet stabilized beyond around 1.5 jet diameters.

Table 2.1 values used for parameters in different models

	Oseguera & Bowles	Vicroy	Wood
$r(m)$	1121		
$R(m)$	1000		
$Z^*(m)$	200		
$\varepsilon(m)$	30		
$\lambda(1/s)$	0.414		
$V_{\max}$	80*	80	80
$z_{\max}$	65*	67	73*
$\delta(m)$			400

* These values are calculated from other independent parameters

Figure 2.3 is constructed from parametric values given in Table 2.1. The three models in Figure 2.3 shows varying shapes of vertical profile, but all have maximum wind speed at a low to mid-height. This shows that the vertical wind profile of a thunderstorm may be very different from that of a logarithmic/power law profile.

Figure 2.3 Comparison of the three models used for the vertical profile

It can be seen that the three models describing vertical wind profile uses different parameters in defining their respective models. The model by Bowles and Oseguera (1988) does not require the input of the maximum but requires a scaling factor λ as an additional parameter. Woods and Kwok (1998) present the model in terms of an error function and terms like z/δ which is defined as a ratio between the elevation z to that of the elevation where the wind velocity is half of the maximum velocity,

compared to the Vicroy (1992) model which is defined as an expression containing terms that are exponentials of $z/z_{\max}$.

The Oseguera and Bowles (1988) and Vicroy (1992) models are very similar in profile up to a height of around 60m in the example. Their profiles deviate substantially beyond that, with the Vicroy model registering a higher wind speed. The Wood model overestimates the wind velocity at all elevations as compared to the other two models. But all three models show that thunderstorm downbursts induce a very different profile to that of the conventional boundary layer profile. It induces a maximum wind velocity at a low elevation level.

2.6 Wind Speed variation with time

The time function $f(t)$ describes the time-history of the downburst wind. The time-history will capture the wind speed variation with time when the storm passes over the site. Therefore, it is expected that the wind speed reaches a maxima when the thunderstorm cell is at a distance $r_{\max}$, such that the downdraft rushes vertically down. Holmes and Oliver (2000) hypothesized that the downburst wind speed consists of vector contributions from the radial impinging jet velocity and the storm translation speed.

The velocity distributions in an axisymmetric impinging jet have been investigated by Poreh and Cermak (1959). Holmes and Oliver (2000) came up with a mathematical expression describing the profile of horizontal radial wind speed with time. At an arbitrarily determined height, the model radial profile of horizontal radial downburst wind speed is expressed as:

$$V_r(r) = \begin{cases} V_{r,\max} \times (r / r_{\max}) & (0 \leq r \leq r_{\max}) \\ V_{r,\max} \times \exp\left(-[(r - r_{\max}) / R_r]^2\right) & (r \geq r_{\max}) \end{cases} \quad (2.4)$$

where $V_{r,\max}$ is the maximum velocity in the profile; R_r is a radial length scale; $r_{\max}$ is the radial distance, from the stagnation point (or the storm center); r is the radial distance from the observation point.

The graphical representation of equation (2.4) is shown by Figure 2.4. The linear portion of $V_r(r)$ with r is the part when the storm centre is approaching the observation point. This is also known as the stagnation region. The maximum velocity is reached when $r=r_{\max}$, which implies that the storm centre is directly above the observation point and that is the point where the wind velocity is highest according to the physics of thunderstorm downbursts.

Figure 2.4 Plot of horizontal wind speed with distance r

When $r > 1000$, the storm centre is moving away from the observation point. This will induce a decreasing relation between $V_r(r)$ and r , as shown by the second

equation in equation (2.4). The graph shows an exponential decay profile for $r > 1000$, which decays slowly initially but decays at an increasing rate after $r > 1700$ as shown.

The horizontal model has not considered the effects of environmental wind so far. Environmental wind has been shown to have significant influence over the strength of horizontal wind field during thunderstorms by many researchers. It is commonly referred to as storm translation speed. The actual wind field during a thunderstorm can be shown to be a vectorial addition between the radial impinging jet velocity and the storm translation velocity.

The storm is assumed to be moving forward with a storm translation speed V_t . Let the offset distance of the downburst track from the point of observation be e . At reference time $t=0$, the coordinate of the observing point is (d_0, e) . The initial distance d_0 is the X-component distance of the observing point away from the storm center when the reference time $t=0$. Therefore, the coordinate of the observing point is $r=(d_0-V_t t, e)$, where r may be viewed as a vector. The distance between the observing point and the storm centre at any time t may be denoted as $|r|$. The radial jet velocity vector is obtained by:

$$V_r(t) = \frac{r}{|r|} V_r(|r|) \quad (2.5)$$

where $V_r(.)$ is the function of the radial velocity profile in equation (2.4). The observed wind velocity vector is obviously the combination of the radial jet velocity vector and the storm translation speed:

$$V_c(t) = V_r(t) + V_t \quad (2.6)$$

Ignoring direction of wind speed in the derivation, the time function is then defined by normalizing $V_c(t)$ against the maximum wind velocity:

$$f(t) = \frac{|V_c(t)|}{\max |V_c(t)|} \quad (2.7)$$

The experimental and simulations on the flow structure in a thunderstorm downburst agree to a large extent that the intensity of the flow is indeed radial. This means that the terrain roughness of the site can have some significance in limiting the ferocity of the high winds to a certain distance; an attenuation distance where the high winds resulted from a downburst would have slowed down sufficiently. Such attenuations can also result from the passing of a storm, where the cell moves away from the site.

2.7 Combined wind speed in a thunderstorm

The total combined deterministic wind speed at a particular point is the wind speed that is registered on an anemometer if it is placed at that point. This is important because it gives valuable information on the distribution of wind speed with both time and space. This means that given the time t and location z , the deterministic wind speed $\bar{u}(z, t)$ can be found. Expressing in terms of the vertical profile $V(z)$ and time function $f(t)$ which was derived earlier:

$$\bar{u}(z, t) = V(z) \cdot f(t) \quad (2.8)$$

where z is the elevation, t is the time. It can be seen that a correct choice of both the

vertical profile and the time function will give the most accurate deterministic model for the downburst wind speed. The time function $f(t)$ is a function with a maximum value of 1. The deterministic model may be generated by simply combining the vertical profile and the time function which we have obtained earlier.

The models described contribute to the construction of a thunderstorm deterministic model. This means that the deterministic downburst wind speeds from a thunderstorm may be accurately predicted based on the use of these empirical models. However, it must be noted that the maximum dynamic response of a structure is dependent on the total rather than the deterministic response only. The total response is equal to the superposition of the deterministic and the stochastic response.

Chapter 3: Field measurement and data analysis

Field measurement plays an important part in the development of a stochastic thunderstorm model. Data is being collected from the existing facility on the Nanyang Technological University (NTU) campus. Five cup-type anemometers are installed on different heights (2m, 6.5m, 10m, 15m and 20m) with directional sensors installed on the top three levels of the 20m tall mast near the sports field. A rain gauge tower that is used for wind-driven rain studies is installed next to the mast.

A data logger installed at the foot of the mast is responsible for the continuous collection of the hourly wind statistics that include the mean, root-mean-square (r.m.s), and the maximum wind speed, together with the relevant statistics from the directional sensors. It is housed within an enclosed facility so as to protect the electronics from any exposure to the environment. The data logger is triggered into high speed mode when the anemometer detects wind speed exceeding a preset value of 8m/s. It then collects high wind speed data at a rate of 4Hz continuously for one hour. The rain gauge tower, on the other hand, records the amount of rain and the direction from which the rain is collected. The two facilities provide continuous monitoring of any thunderstorm occurrence.

Fig. 3.1 20m wind mast and schematic diagram

The dynamic range of the data logger is upgraded from 4Hz to 20Hz so as to enable better quality of data when performing dynamic analysis. The data collected will give useful insights into the dynamic characteristics of thunderstorm wind. Data from the rain gauge tower will be valuable, when a correlation study between rain intensity and wind speed is attempted. The data may also suggest the proximity of the site to the thunderstorm cell, in addition to evidence provided by radar pictures. The data obtained are checked regularly against any suspected faults. Faulty channels are recorded so as to prevent usage of these data in the analysis.

3.1 Monsoon wind

The monsoon wind characteristics in Singapore have been documented by Choi (1999). The wind environment in Singapore is of a mixed weather system, comprising of the monsoon wind and the thunderstorm. The monsoon wind is equally important in the analysis of thunderstorms, as the environmental wind is shown to contribute significantly in the form of storm translation speed (Chen and Letchford, 2004). Considering that the monsoon wind is a stationary random process, its characteristics may be directly inferred from its statistical properties. These statistical properties will also give us the idea of the order of magnitude of the most likely wind speed value. This will enable us to have the background information of the wind environment in Singapore.

41	-2.596	209.5	250.2				
41	-2.404	230.4	234.8				
41	-2.5	208.4	208.8				
10	2005	111	1400	0	12.21		
11	0.4	2.753	2.428	1.933	1.692	0	0.947
12	-2.497	194.4	194.6	0.067	32.81	34.72	-2.404
41	-2.5	194.5	208.4				
41	-2.5	203.4	159				
41	-2.596	198	272.6				
41	-2.404	212.6	197.5				
41	-2.404	220.1	220.9				
41	-2.404	227.9	205.6				
41	-2.5	222.3	229.4				
41	-2.5	235.9	249.4				
41	-2.596	255.5	265.2				
41	-2.5	219.8	195.1				

Table 3.1 Storing format of hourly statistics in data logger (partial)

Table 3.1 shows the format of the data stored in the normal speed data logger. The hourly statistics are shown by the numbers in bold print. The row denoted by prefix '10' shows the year, day and time of the recorded data. The row of entries denoted by prefix '11' and '12' contain the relevant wind hourly statistics data.

A MATLAB© program is written to extract relevant entries in the data files stored in the data logger. The values in these entries are converted into readable table format from which the mean wind speed, root-mean-square wind speed, wind direction as well as readings from the rain gauge tower are displayed. The normal wind data is being monitored continuously. The data that contains the raining wind speed (when rain trigger is activated) and rain gauge readings are kept in different files for easy reference.

111	1100	0.4	2.052	1.745	1.569	1.54	0
111	1200	0.4	2.344	2.096	1.833	1.793	0
111	1300	0.4	2.387	2.144	1.864	1.715	0
111	1400	0.4	2.753	2.428	1.933	1.692	0
111	1500	0.4	3.289	2.578	2.121	2.102	0
111	1600	0.4	0.906	0.842	0.547	0.53	0
111	1700	0.4	0.452	0.491	0.341	0.4	0
111	1800	0.4	0.761	0.755	0.551	0.595	0
111	1900	0.4	1.685	1.239	0.789	0.724	0
111	2000	0.4	1.281	1.071	0.722	0.692	0
111	2100	0.4	1.625	1.299	1.068	0.952	0
111	2200	0.4	1.509	1.328	1.15	1.016	0
111	2300	0.4	1.319	1.164	0.896	0.79	0
112	0	0.4	1.141	1.023	0.711	0.706	0
112	100	0.4	0.917	0.736	0.402	0.438	0
112	200	0.4	0.909	0.624	0.338	0.407	0

Table 3.2 Storing format of treated data (normal wind conditions) (partial)

Table 3.2 shows the storing format of files generated from the MATLAB program. These are the hourly wind statistics data compiled as a result of the program, with each row corresponding to one set of data as described by the numbers in bold print shown in Table 3.1. The storing of data in this format enables easy access to any entry corresponding to a particular date and time. The storing of same quantities in different columns also allows speedy computation from their known positions in the file system (e.g. mean wind speed for channel V1 stored in third column from left). This will enable us to compute the statistics of the monsoon wind for long period of time (e.g. months).

Dec 2000- Feb 2003					
	<i>V1 mean</i>	<i>V2 mean</i>	<i>V3 mean</i>	<i>V4 spoil</i>	<i>V5 mean</i>
Mean	1.830372	1.618332	1.459957	-	0.859822
Standard Error	0.007782	0.007571	0.006582	-	0.006013
Standard Deviation	1.08817	1.058594	0.920349	-	0.840721
Sample Variance	1.184115	1.120622	0.847043	-	0.706812
Kurtosis	-0.19261	-0.35721	-0.2353	-	-0.35986
Skewness	0.497728	0.484248	0.615556	-	0.771619
Maximum	5.941	5.534	4.997	-	4.057
Sum	35785.6	31640.01	28543.62	-	16810.38
Count	19551	19551	19551	-	19551
Confidence Level(95.0%)	0.015254	0.01484	0.012902	-	0.011785
	<i>V1 max</i>	<i>V2 max</i>	<i>V3 max</i>	<i>V4 spoil</i>	<i>V5 max</i>
Mean	4.445712	4.192268	3.926691	-	3.21354
Standard Error	0.01686	0.016743	0.016085	-	0.016159
Standard Deviation	2.35746	2.341131	2.249074	-	2.254679
Sample Variance	5.557619	5.480894	5.058334	-	5.083579
Kurtosis	1.114646	1.05456	0.943402	-	1.071353
Skewness	0.870902	0.768095	0.813452	-	0.636646
Maximum	23.13	24.44	21.31	-	27.91
Sum	86918.12	81963.03	76766.8	-	62561.2
Count	19551	19551	19550	-	19468
Confidence Level(95.0%)	0.033047	0.032818	0.031529	-	0.031674

Table 3.3 Mean wind statistics from Dec 2000 to Feb 2003

Table 3.3 shows the statistics of the mean of mean and peak wind speed from Dec 2000 to Feb 2003. It can be seen from the values of the mean of mean wind speed that it is in the region of 2m/s, which is classified as a light breeze with a Beaufort number of 2. However, it does not describe the variations of wind speed due to seasonal oscillations. The standard deviation of maximum wind speed is markedly

more than that of the mean wind speed, indicating the increased turbulence effect of thunderstorms.

3.2 Thunderstorms

The separation of thunderstorm data from the usual monsoon rain data is by no means trivial. This is necessary because Singapore is of a mixed weather system as mentioned by Choi and Tanurdjaja (2002). The thunderstorm events are noted by comparing with the thunderstorm warnings issued by the Meteorological services of Singapore at the website www.nea.gov.sg. Furthermore, a thunderstorm is usually accompanied by lightning and loud thunder. The thunderstorm data are sorted according to their respective date and time of origin. The thunderstorm data also forms part of the thunderstorm database which is one of the main objectives of this project. The thunderstorm database will be used in deploying future research efforts.

The identification of thunderstorm data from a database that consists of both thunderstorms and monsoons must be performed carefully. Thunderstorms come in different sizes and shapes, and each thunderstorm data has a unique shape depending on these parameters. It is very difficult to identify a thunderstorm data even with a trained eye, because of the different intensity of the thunderstorm and the different wind direction from which it comes from. The time-history of the same event can be markedly different depending on the radial distance as well as the storm path relative to the wind collection site.

Therefore, extreme care is taken in identifying thunderstorm data. In addition to monitoring the thunderstorm events personally, data from both data loggers are checked against each other for the record of every thunderstorm event. Due to the way that they are triggered for each event, there may be time lag while recording for

the same thunderstorm event.

41	-2.596	198	272.6				
41	-2.404	212.6	197.5				
41	-2.404	220.1	220.9				
41	-2.404	227.9	205.6				
41	-2.5	222.3	229.4				
41	-2.5	235.9	249.4				
41	-2.596	255.5	265.2				
41	-2.5	219.8	195.1				
41	-2.5	248.6	289				
41	-2.596	13.13	35				
30	2005	111	1412	0			
31	0.4	2.575	2.59	2.206	2.014	0.4	1057
32	-2.493	87.8	137.1				
33	5	0	0	0	0		
41	-2.596	18.22	36.44				
31	0.4	3.374	3.128	2.822	2.588	0.4	1412
32	-2.501	25.86	30.97				
33	8	0	0	0	0		

Table 3.4 Storing format of rain data in data logger (partial)

The format for storing of the rain data by the normal speed data logger is displayed in Table 3.4. The numbers in bold print are the required data for a rain event. The prefix '30' indicates that there is a rain event, followed by the year, date and time of this event. The prefix also indicates that the program has been triggered into 'rain' mode and the relevant wind data is recorded continuously for 60 minutes.

The rows corresponding to prefixes '31', '32' and '33' are the recorded data of wind speed, wind direction and amount of rain, together with their statistics within one minute at a sampling rate of 4Hz.

111	1412	0.4	2.575	2.59	2.206	2.014	0.4
0	0	0.4	3.374	3.128	2.822	2.588	0.4
0	0	0.4	4.571	4.701	4.148	4.006	0.4
0	0	0.4	5.597	5.398	4.565	4.316	0.4
0	0	0.4	6.127	5.46	4.689	4.323	0.4
0	0	0.4	5.588	5.054	4.138	3.69	0.4
0	0	0.4	4.84	4.27	3.702	3.415	0.4
0	0	0.4	5.328	2.69	3.488	3.821	0.4
0	0	0.4	5.339	2.487	3.419	4.165	0.4
0	0	0.4	3.985	2.549	2.185	2.333	0.4
0	0	0.4	5.221	4.17	3.442	3.351	0.4
0	0	0.4	6.213	5.308	4.439	4.285	0.4
0	0	0.4	6.363	5.445	4.205	4.072	0.4
0	0	0.4	6.543	5.547	4.775	4.451	0.4
0	0	0.4	5.095	3.991	2.947	2.934	0.4
0	0	0.4	5.271	4.056	3.339	3.359	0.4
0	0	0.4	4.006	2.894	2.172	2.161	0.4
0	0	0.4	4.968	4.119	3.225	3.126	0.4
0	0	0.4	3.227	2.262	1.9	2.182	0.4

Table 3.5 Storing format of rain data in treated data (partial)

The same MATLAB program that is written for extraction of monsoon wind data has an output that generates wind and rain data during rainstorms as in Table 3.5. Every record of such an event has 60 rows with each row corresponding to one minute wind statistics. The mean wind speeds for channels V1, V2, V3, V4 and V5 are recorded starting from the third column onwards.

Acquisition started 21-Apr-2005 14:23:09							
V1	V2	V3	V4	V5	D1	D2	D3
0	7.68	5.53	4.49	4.62	714.82	34.74	27.93
0	7.67	5.52	4.49	4.63	714.82	35.26	27.76
0	7.67	5.52	4.48	4.64	714.82	34.74	29.85
0	7.67	5.56	4.49	4.66	714.82	33.52	31.42
0	7.66	5.61	4.49	4.67	714.82	32.47	31.6
0	7.63	5.68	4.5	4.67	714.82	32.12	29.85
0	7.59	5.75	4.5	4.67	714.82	32.47	27.23
0	7.58	5.82	4.5	4.66	714.82	32.99	24.26
0	7.57	5.92	4.5	4.66	714.82	33.52	21.47
0	7.56	6.03	4.5	4.65	714.82	33.69	19.55
0	7.53	6.14	4.5	4.65	714.82	35.26	20.25
0	7.52	6.25	4.5	4.65	714.82	37.01	25.14
0	7.5	6.36	4.51	4.65	714.82	36.66	31.42
0	7.46	6.45	4.52	4.65	714.82	33.17	37.53
0	7.4	6.51	4.51	4.66	714.82	29.5	41.89
0	7.38	6.54	4.48	4.68	714.82	29.33	42.59
0	7.38	6.55	4.46	4.7	714.82	31.6	40.85
0	7.38	6.55	4.42	4.71	714.82	34.39	38.75
0	7.36	6.53	4.41	4.72	714.82	36.48	36.83

Table 3.6 Storing format of thunderstorm data in high speed data logger (partial)

The high speed data logger stores thunderstorm data at a sampling rate of 20Hz when triggered by a preset wind speed value of 8m/s. It then records for a continuous duration of 60 minutes. It records the quantities as shown in Table 3.6. V1, V2, V3, V4, V5 are the wind speeds at the elevation levels 20m, 15m, 10m, 6.5m and 2m. D1, D2, D3 are the directions recorded by the directional sensors mounted onto elevation levels 20m, 15m and 10m. Channels V1 and D2 are faulty and their values are disregarded in the analysis.

The starting times for both sequences from normal and high wind speed data logger are seen to be different. The normal wind speed data logger was triggered at 14:12 hours whereas its high speed counterpart triggered at 14:23 hours. This is the phenomenon of time-lag which was mentioned earlier on. In fact, it is observed that

in most cases the normal wind speed data logger has an earlier trigger time. This may be due to the different trigger mechanisms by the two different data loggers. This means that the wind speed when the time the rain commences the wind speed is below the preset value of 8m/s. When taking a closer look, it is found that the magnitude of wind speed when the normal wind speed data logger is close to that of the environmental wind speed.

The data obtained from both normal and high speed data logger combine to give us a wide database on thunderstorm occurrences. Each has its own advantage over the other counterpart. For example, the high speed data logger has the advantage over the normal speed data logger due to its superior sampling rate when conducting dynamic analysis. However, the high speed data logger is limited by its triggering mechanism such that it may not record more than one hour of data should it be a long duration heavy rainstorm. The normal speed data logger can record a second hour should there still be rain, as its triggering mechanism is dependent on the availability of rain. Moreover, the normal speed data logger is the only data logger that records the rainfall intensity. Its data is valuable should a correlation study between storm wind speed and rain intensity be made.

The database of one-hour thunderstorm wind data files provides the samples from which we may derive our understanding for each thunderstorm. From the inspection of each data sample, we can see that each event is unique in its shape of plot between wind speed and time. This may be explained by increased turbulence observed during thunderstorms, which affects the randomness of both the wind speed and the wind direction. The randomness of wind direction also means the variation in terrain effects on wind speed when the cell is not sufficiently near to the wind mast.

The initial wind speed and direction of thunderstorms tends to coincide with those of the monsoon wind. Therefore the suggestion rose by Chen and Letchford (2004) that thunderstorm wind speed is a superposition between storm translational speed (monsoon wind) and speed resulting from wall-jet wind speed profile of a cell may be valid. The initial wind speeds observed during thunderstorms are mainly northeasterly winds, i.e. blowing from the direction of the sports field which is expected to have relatively low terrain roughness.

Chapter 4: The Dynamics of Structures

Structural dynamics is the discipline concerned with the study of structural response to time-varying loads. It is appropriate for this chapter to review certain elements of structural dynamics theory that leads to the derivation of the dynamic response to wind load. Wind loading is generally accepted to be a random process, and therefore random vibration theory may be used in the derivation of the dynamic response. The dynamic response of a structure depends on the number of degrees of freedom in a structure. A continuous structure, by definition, has infinite degrees of freedom and can only be described by a continuous mathematical expression. However, we may formulate an approximate equivalent multiple degree of freedom (MDOF) system that depends on a certain finite number of degrees of freedom which response may be solved to certain accuracy by a finite element code on a computer. In some cases where the masses are concentrated locally in a structure, the degrees of freedom may be further reduced to a single degree of freedom (SDOF) system.

The structural response of a system may be evaluated in the time domain or in the frequency domain. Structural response in the time domain is the time-history of the structural response concerned, with the variations of displacement with time shown. Solving in the frequency domain involves the Fourier transformation of the wind signal itself. An algorithm that allows speedy computation named Fast Fourier Transform (FFT) is widely used in computers. The attractiveness of this technique makes solving structural response in the frequency domain very popular. The Gust Response Factor method which was developed by Davenport (1961) calculates structural response from the frequency domain which takes advantage of the high numerical efficiency of the algorithm.

4.1 Single degree of freedom (SDOF) system

It is very important to understand the response of a single degree of freedom (SDOF) system. It allows us to understand the key concepts concerning the interdependence of the properties of a structure idealized as a SDOF system. There are a number of structures which actual behaviour may be approximated by a SDOF model, due to their geometrical arrangements. The advantage of a SDOF system is that it can be readily computed, as compared to a MDOF system which may involve millions of degrees of freedom. Although technological advancement introduces faster computers, the computation component may still be very time-consuming.

As shown in Figure 4.1, a SDOF system may be represented as a single lumped point mass m connected to the ground by means of a column of stiffness k , and a damper of damping c . It may also be represented as a mass-spring-damper as shown on the right side of the figure.

Figure 4.1 A SDOF system and its common representation

Consider the assemblage shown in Figure 4.1. Four types of forces are acting on the mass. These forces include the following:

Stiffness Force: This force acts on the mass when there is a non-zero displacement of the mass. For a linear system, the force is directly proportional to the relative

displacement of the mass, and this constant of proportionality is the stiffness k itself. A positive displacement implies that the stiffness force “resists” this motion and attempts to “pull back” the mass to its original position. Therefore, this force always acts opposite to the direction of displacement.

Damping Force: This force acts on the mass when there is a non-zero relative velocity between the mass and the ground. For a system with viscous damping, the damping force is directly proportional to the velocity. The constant of proportionality is the damping coefficient c itself. Similar to the stiffness force, the damping force carries the same sign convention, acting opposite to the direction of velocity. Damping is difficult to measure, and is normally represented in critical damping ratio rather than the damping coefficient itself. In civil engineering structures, structural damping is considered to be of about 3-5%.

External Force: This is the force that is applied to the system. As illustrated in Fig. 4.1, the force is $F(t)$. In general it is of a time-varying nature. For wind loads, this can be modeled as a random Gaussian process. This will be discussed further in the later chapters.

Inertial Force: This force arises as a direct consequence of the Newton’s second law. In static analysis it is idealized to be zero. The inertial force is defined as the acceleration of the floor due to imbalance of the abovementioned forces.

In equation form it may be expressed as:

$$\sum F = ma \quad (4.1)$$

where m is the mass and a is the acceleration of the mass. Summation of F is the balance of all the forces in the SDOF system.

Rearranging the terms, the equation may be written in the following form:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \quad (4.2)$$

This is also commonly referred to as the equation of motion. It ensures a dynamic equilibrium amongst the four forces, as opposed to a static equilibrium in a static analysis. The equation (4.2) is a second order differential equation, solving which yields the dynamic response of the structure: the relative displacement $x(t)$, the relative velocity $\dot{x}(t)$ and the absolute acceleration $\ddot{x}(t)$. These three quantities are related to one another by means of differentiation and integration.

When $F(t)$ is zero, the solution of equation (4.2) leads to the response of the SDOF structure to free vibration. The natural frequency of the system may be obtained by

$\sqrt{\frac{k}{m}}$. When divided throughout by mass m , the equation (4.2) becomes:

$$\ddot{x}(t) + 2\zeta\omega\dot{x}(t) + \omega^2x(t) = \frac{F(t)}{m} \quad (4.3)$$

where ζ is the critical damping ratio, ω is the natural frequency of the system.

In the case of free vibrations, $F(t)=0$:

$$\ddot{x}(t) + 2\zeta\omega\dot{x}(t) + \omega^2x(t) = 0 \quad (4.4)$$

By means of solving the equation using the classical method for solving differential equations, we obtain:

$$x(t) = e^{-\zeta\omega_D t} (A \cos \omega_D t + B \sin \omega_D t) \quad (4.5)$$

where A and B are constants to be determined, by substituting the initial conditions into the equation (4.5). ω_D is the damped natural frequency of vibration and t is the time. The negative exponential term represents the damping effect, which reduces the amplitude of free vibration phase with increasing time.

In general, a complete dynamic response of a SDOF system to a dynamic excitation is the superposition of the free vibration and the forced vibration components. In the event of a sinusoidal excitation, we may be interested in the forced vibration component only or commonly referred to as the steady state response. The free vibration component, or the transient response in this context, damps out due to the presence of structural damping in the system. The dynamic response to wind excitation can be treated in a manner similar to that of a sinusoidal response, as we are interested in the steady state dynamic response only. Random wind excitations are in essence a collection of sinusoids with different harmonic components in the frequency domain, therefore their behaviour will be approximate to that of the sinusoidal excitations.

4.2 The Duhamel Integral

The dynamic response of a SDOF system may be evaluated by means of the convolution integral known as the Duhamel integral. This is commonly used when the load is not in a closed form, e.g. random excitation. The derivation of the Duhamel integral is based on the summation of each response that is due to a unit impulse from an arbitrary load. Hence, the integral can only be used for linear systems, since the principle of superposition is involved. The equation may be

expressed in a convolution integral form:

$$x(t) = \int p(\tau)h(t - \tau)d\tau \quad (4.6)$$

$$h(t - \tau) = \frac{e^{-\zeta\omega t}}{m\omega_D} \sin(t - \tau) \quad (4.7)$$

It can be seen that equation (4.6) consists of two parts. The first part is from the load imposed upon the SDOF system, and is a function of τ . The second part $h(t-\tau)$ is the unit impulse response function, which is characteristic of the system's dynamic response to a single unit impulse imparted to the system.

Every strip of infinitesimal $p(\tau)d\tau$ represents the impulse imparted to the system. This will in turn generate a dynamic response from the system, $dx(t)$, that is similar to the free vibration response to that infinitesimal strip. The superposition of all these responses which are separated by a varying phase lag of τ , is equivalent to the response yielded from the conventional solution by classical method of solving differential equations.

Therefore, computation of dynamic response of a SDOF system due to random wind excitation may be further simplified. The computer may be instructed to compute all the separate responses due to different infinitesimal loading strips of length $d\tau$. They can then be superposed by a phase lag of τ to yield the actual response. A time window of suitable length may be chosen so that all values are captured just before it damps out. This will cut down the computation time needed for each SDOF system.

4.3 Random Process of Wind

A stochastic or random process is one which cannot be predicted exactly, either due to the uncertainties associated with the input parameters or the complexity of the physical process it attempts to describe. In such a case the physical process will have to be modelled by statistical methods. Monsoon wind is known to be a stationary random process. It is found that monsoon wind is more or less stationary in a one hour window and hence the popular use of the term hourly mean wind. Within this window, the wind field $u(z,t)$ is decomposed into a mean wind component $\bar{u}(z,t)$ and a stochastic component $u'(z,t)$. The mean wind component $\bar{u}(z,t)$ may be represented as a fixed value throughout the duration of the window. The stochastic component, on the other hand, may be assumed to be a stationary random process as well since the monsoon wind is stationary within the window.

$$u(z,t) = \bar{u}(z,t) + u'(z,t) \quad (4.8a)$$

$$u'(z,t) = u(z,t) - \bar{u}(z,t) \quad (4.8b)$$

Equation (4.8b) illustrates the procedure by which the stochastic component $u'(z,t)$ is extracted. By this definition it can be seen that any stochastic component should have a zero mean and unit variance.

A stochastic thunderstorm model will be constructed based on examination of existing analytical models and qualitative investigation of the data provided by the existing data base. It will model the time-history of wind speed variation at a fixed location during a thunderstorm event. Unlike its large-scale counterparts like the monsoon wind, thunderstorm wind has been shown to possess a non-stationary

mean wind and a fluctuating component. The proposed model will consider the implications of the fluctuating component, and its contribution to the gusty nature that is characteristic of thunderstorm wind. The randomness nature of the fluctuating component indicates that it is best modelled by a stochastic process.

The fluctuating component may be obtained by various methods. The popular method used is the moving average technique, which involves taking an average of the data from each specified averaging period. It is used in removing the non-stationary mean wind component from the wind time-history. The mean wind component is replaced by the moving average term. The fluctuating component can then be conveniently obtained by simply subtracting the non-stationary mean from the wind time-history. A suitable averaging window will be chosen for this purpose. The suitability of the averaging period will have a direct bearing on the analysis results, as the required frequency content in thunderstorm wind may be filtered out unknowingly by using a lengthy averaging window.

The stochastic components from monsoon and thunderstorm wind can be compared based on their respective spectral density functions. The basis of comparison will be that of the proximity of their frequency content to that of actual building structures as well as the shape of the spectra. The occurrence of resonance may induce additional vibrations to a building, which may be of concern to the serviceability and human comfort level criteria. If resonance is not of a major concern, a quasi-static approach may be used instead. In this case, the structure may only need to be designed against an expected maximum probabilistic wind speed in a thunderstorm event.

4.4 Along-wind response

The along-wind response has been traditionally treated using the Gust Response Factor (GRF) method which was introduced by Davenport (1961). This method assumes that the wind speed time-history is stationary.

Wind speeds that are known to be stationary may be easily separated into a mean wind and a stochastic component. The stochastic component is obtained by subtracting the mean wind component from the wind speed time-history.

The structural response to buffeting effects of wind is through resistance against the drag effect of wind, or drag force. The moving wind exerts a drag force on a bluff body like a building, and this drag force is resisted by the structural system like an applied force on the building. As wind loading is dependent upon time, it is prudent to treat it as a dynamic loading.

The equation of motion of SDOF system under a drag force F_D is given by:

$$m\ddot{x} + c\dot{x} + kx = F_D(t) \quad (4.9)$$

where m is the mass of system, c is the damping coefficient, k is the structural stiffness, and x is the relative displacement of the system.

Total drag force $F_D(t)$ is given by:

$$F_D(t) = \frac{1}{2} \rho C_D A u^2(t) \quad (4.10)$$

where ρ is the specific density of air, C_D is the drag coefficient and u is the wind

speed. Expanding u into the mean $\bar{u}$ and the fluctuating component u' , $F_D(t)$ may be expressed as:

$$F_D(t) = \bar{F}_D + F'_D \quad (4.11)$$

$$= \frac{1}{2} \rho C_D A \bar{u}^2 + \rho C_D A \bar{u} u' + \frac{1}{2} \rho C_D A u'^2 \quad (4.12a)$$

the third term may be considered negligible:

$$\approx \frac{1}{2} \rho C_D A \bar{u}^2 + \rho C_D A \bar{u} u' \quad (4.12b)$$

where $\bar{F}_D$ and F'_D are the mean and fluctuating drag forces experienced by the structure.

The total response is equivalent to the addition of deterministic response shown by the first term in (4.12a) and a constant $\rho C_D A \bar{u}$ multiplied by u' . Therefore, the stochastic response is characterized by the second term in the equation.

This means that the response due to the stochastic part of wind speed must also be calculated in order for the total response to be computed accurately. The product between the constant $\rho C_D A \bar{u}$ and the stochastic wind speed is not negligible and thus has to be included in the calculations. The spectral density of the stochastic component of the drag force can be expressed as the spectral density of the wind speed:

$$S_{F(D)} = (\rho C_D A \bar{u})^2 S_u(n) \quad (4.13a)$$

or

$$S_{F(D)} = 4 \frac{\bar{F}_D^2}{\bar{u}^2} S_u(n) \quad (4.13b)$$

The mechanical admittance function $|H(n)|^2$ is given by:

$$|H(n)|^2 = \frac{1}{\left[1 - \left(\frac{n}{n_0}\right)^2\right]^2 + 4\zeta_s^2 \left(\frac{n}{n_0}\right)^2} \quad (4.14)$$

where n_0 is the natural frequency of the structure.

The aerodynamic admittance function may be given by the following expression:

$$\chi(n) = \frac{1}{1 + \left(\frac{2n\sqrt{A}}{\bar{u}}\right)^{4/3}} \quad (4.15)$$

For point-like structures, the function χ may be taken as unity.

By means of random vibration theory, the spectrum of displacement response can be expressed as:

$$S_x(n) = 4 \frac{\bar{F}_D^2}{\bar{u}^2} \frac{1}{k^2} \chi^2(n) |H(n)|^2 S_u(n) \quad (4.16)$$

The variance of deflection is found by integrating (4.16), which yields:

$$\frac{\sigma_x^2}{\bar{x}^2} = 4 \frac{\sigma_u^2}{\bar{u}^2} \int_0^\infty \chi^2(n) |H(n)|^2 \frac{S_u(n)}{\sigma_u^2} dn \quad (4.17)$$

The expression may also be separated into two components, a component response B to background turbulence and a resonant component R:

$$\frac{\sigma_x^2}{\bar{x}^2} = 4 \frac{\sigma_u^2}{\bar{u}^2} (B + R) \quad (4.18a)$$

with

$$B = \int_0^{n_0} \chi^2(n) \frac{S_u(n)}{\sigma_u^2} dn \quad (4.18b)$$

and

$$R \cong \chi^2(n_0) \frac{S_u(n_0)}{\sigma_u^2} \frac{\pi n_0}{4\zeta_s} \quad (4.18c)$$

The spectral density of stochastic component of monsoon wind $S_u(n)$ within a stationary period is known to have the shape modelled by the Davenport spectrum (1961).

The derivation of equation (4.13a) has not included the effects of mechanical and aerodynamic admittance functions, but it shows the important contribution of the stochastic part of the wind speed to total response of a structure.

Fig. 4.2 The Davenport spectrum

From equation (4.13a), we can assume that in the absence of mechanical and aerodynamic admittance functions, the spectral shape of the response is the same as that of the stochastic wind speed. This means that the structure is likely to have its maximum response when its natural frequency matches the driving frequency of the stochastic part of the wind speed. As its natural frequency deviates away from the driving frequency of the fluctuating wind, the response decreases according rapidly as described by the shape of the Davenport spectrum in Figure 3.2. In equation form it is shown as:

$$\frac{nS_u(n)}{u_*^2} = 4.0 \frac{x^2}{(1 + x^2)^{4/3}} \quad (4.19)$$

where n is the frequency in Hz, u_* is the frictional velocity, $x=1200n/\bar{u}_z$.

4.5 Across-wind Response

Most models are based on the along wind response of buildings. Across wind excitations are due to the dynamic loads coming from varying direction with time. In this case the dynamic equations of motion will be based on the deflection angle θ of the building structure instead of relative displacement. Complicated issues that include vortex shedding and galloping may result from across wind excitations. These may lead to excessive vibrations which may induce structural collapse, which is the case in the collapse of the Tacoma Narrows Bridge in 1940. Due to the gusty nature of thunderstorm winds this may be a concern to wind sensitive buildings and bridges. However, this study will be restricted to along wind excitation only.

Chapter 5: Analysis by Moving Average Technique

This chapter discusses the results obtained from the analysis of thunderstorm wind data based on the moving average technique. It highlights the difficulties of correctly identifying the thunderstorm data from that of the monsoon wind, as a result of a mixed weather system in Singapore. It also discusses briefly the environmental wind conditions in Singapore.

The data used in this section are the data stored in two separate data loggers housed under the wind mast tower. The maximum dynamic range of this data logger is 4Hz. The first data logger deals with the daily continuously monitored wind speed, regardless of whether there is rain. This data logger only records the hourly statistics of the continuously monitored wind speed and direction. It is responsible for the recording of the monsoon wind. However when rain occurs, the data logger switches into 'rain' mode and records the wind speed, wind direction as well as the amount of rain in tips from the rain gauge tower for every minute. This 'rain' mode will only last for one hour and will be back to normal after continuously recording for 60 minutes. However, if rain is still detected from the rain gauge tower the 'rain' mode is triggered for the second time. This feature allows the capture of wind characteristics of long duration heavy rain.

The second data logger has a longer dynamic range of 20Hz. Because of the added dynamic range it is used in the calculation of stochastic component for thunderstorm wind. It does not record wind speed continuously like its counterpart. It starts recording only when it is being triggered by some event. This data logger recognizes the recorded wind speed instead. When the wind speed recorded in any channel exceeds a preset value of 8m/s it triggers the data logger. The data logger then records the relevant quantities (wind speed, wind direction, etc) at 20 samples

per second. The recording stops after one hour duration. Unlike the first data logger, it rarely records for a second time if the raining duration exceeds one hour. Therefore, wind characteristics for long duration thunderstorms can only be obtained from the first data logger. The first data logger is hereby referred to as the normal speed data logger while the second one the high speed data logger.

Due to the difference in the record mechanism, there are cases when the record times are different for thunderstorm events between the normal and high speed data logger. A discrepancy in the record times usually suggests that raining commences even before the preset wind speed is being exceeded.

The selection and classification of thunderstorm data plays an important role in this study. The thunderstorm data is chosen from the period of pre-Southwest monsoon where there are abundant thunderstorm occurrences. The analysis of each thunderstorm data and its relevant results are carried out and discussed. The Davenport spectrum is used in comparing against the stochastic wind component of the thunderstorm wind, and different averaging windows is used to verify the suitability of the chosen averaging window.

5.1 Selection of time period of thunderstorms

The thunderstorms during time period of late March to late May 2005 are used for this study. The reason is that during this time period being an inter-monsoon period the number of thunderstorm occurrence should be much higher than any other chosen period. The brief timeline of the thunderstorm written records are as follows:-

Year, date and time of thunderstorm occurrence	remarks
2005,25MAR,1545,1620,1655	
2005,26MAR,1325	
2005,27MAR,1448,1505	(End of NE monsoon)

2005,01APR,1600	(Start of inter-monsoon)
2005,02APR,0715	
2005,03APR,1535	
2005,04APR,0854,1021	(Heavy rain warning)
2005,05APR,UNKNOWN	
2005,06APR,1637	(day 95 on data record)
2005,08APR, UNKNOWN	
2005,11APR, UNKNOWN	(Heavy rain warning)
2005,12APR,1920	
2005,15APR,1411	
2005,16APR,1311,1325,1630	
2005,17APR, UNKNOWN	
2005,18APR,1358	
2005,21APR,1410	
2005,22APR,1753	
2005,24APR,1600	
2005,28APR,1732	

2005,02MAY,1640	
2005,03MAY,1850	
2005,05MAY, UNKNOWN	
2005,06MAY,1246	

2005,08MAY,0745	(Heavy rain warning)
2005,10MAY,1445	
2005,14MAY,0830,2130,2230	
2005,15MAY,0700	
2005,16MAY,0730	
2005,17MAY,0945	
2005,19MAY,1000	
2005,21MAY,1330	
2005,24MAY,1320	
2005,25MAY,0700	
2005,27MAY,1000	
2005,29MAY,1240	(End of inter-monsoon)

2005,01JUN,0920	(Start of SW monsoon)

Wind mast down since 27th May

This written record serves as a valuable source of information to double check on the records by the two data loggers. There is a count of about 37 thunderstorms observed by the author. However, only 18 of them are confirmed thunderstorm data. There are a variety of reasons why the remaining ones are not being recorded. Probable reasons include wind speeds being lower than the programmed triggering wind speed of 8 m/s. There were several occasions when the high speed data logger was detached for downloading purposes while the storm hits the site. Faulty data logger is the main cause for the loss of data. The data logger was faulty on 7th April to 14th April and there be no available data for that week, after which it has been faulty since 27th May 2005 and so the three potential data sets on 27th, 29th May and 1st June had gone unrecorded. Some channels are also found to be faulty

intermittently throughout the months and these have been noted down.

The finalized list of thunderstorm data is decided based on meeting the stringent criteria set out. There are six data sets in which the duration of the thunderstorm is more than one hour. There are two data sets from these samples on the days which the Meteorological services of Singapore issued a heavy rain warning. These cases of long duration and heavy rainstorms will be treated separately from the others in the analysis.

The finalized list of 18 thunderstorm data sets that are confirmed is as follows:-

- 1) 25 Mar 05, 1556
- 2) 26 Mar 05, 1330
- 3) 27 Mar 05, 1441
- 4) 02 Apr 05, 0637
- 5) 03 Apr 05, 1528
- 6) 04 Apr 05, 0941
- 7) 15 Apr 05, 1410
- 8) 16 Apr 05, 1614
- 9) 21 Apr 05, 1423
- 10) 28 Apr 05, 1705
- 11) 06 May 05, 1313
- 12) 08 May 05, 0736
- 13) 12 May 05, 0159
- 14) 14 May 05, 0739
- 15) 16 May 05, 0548
- 16) 19 May 05, 0932
- 17) 21 May 05, 1320
- 18) 24 May 05, 1357

Figure 5.1 Time history of wind speed in the 18 thunderstorms

Figure 5.1 Time history of wind speed in the 18 thunderstorms (continued)

Figure 5.1 Time history of wind speed in the 18 thunderstorms (continued)

Figure 5.1 Time history of wind speed in the 18 thunderstorms (continued)

The 18 thunderstorm time-histories are displayed in Figure 5.1. The shapes and the maximum attained wind speed of the time-histories are seen to vary greatly. The maximum wind speed rarely exceeds 10m/s on average. However, the wind speeds can reach a high value within a very short time period. There is one similarity amongst all the time-histories and that is they are all combinations of time-histories between the downburst horizontal velocity profile and the environmental wind speed profile.

Thunderstorms may not occur accurately at the times indicated by the trigger times of the high wind speed data logger. The high wind speed registered by the data logger may well be the wind speed from the first gust, rather than during the storm. The commencement time of the thunderstorm needs to be confirmed by comparing with the wind/rain data from the normal wind speed data logger.

The direction of the wind is very important in this study because it contributes to the complete information on the wind environment at that particular instant. Wind direction can be changing very frequently during thunderstorms. It induces a 180° change in the readings of the direction sensor when the storm passes directly over the site. In the presentation of the wind directions the wind direction histogram will be used instead so as to give the reader a physical understanding of the directional changes with respect to the directional North.

Given the vast amount of data it is prudent to only analyze data sets of different properties, e.g different profile, different storm duration, etc. The moving average technique requires the input of a suitable averaging time period. Therefore a suitable averaging time period must be decided prior to analysis.

5.2 Selection of a suitable averaging period

MATLAB© is used in the analysis of the wind speed data in this study. The one hour thunderstorm wind data is separated from that of the monsoon wind data. After separating the thunderstorm data, they are each analyzed by separating the fluctuating part using the moving average technique, as mentioned in the earlier chapters. Until this stage, a suitable averaging period has yet to be chosen. The suitable averaging window should be able to fit the stochastic wind speed spectrum

envelope as near as possible to the Davenport spectrum. Once this is achieved, all the non-stationarity of the thunderstorm wind may be completely accounted for by the moving average component, leaving the stochastic component a stationary process.

The Davenport Spectrum is given by:

$$\frac{nS(n)}{u_*^2} = 4.0 \frac{x^2}{(1 + x^2)^{4/3}} \quad (5.1)$$

The frictional wind velocity u_* is calculated based on the logarithmic law profile. A roughness length of $z=0.07\text{m}$ is used for the computation of the frictional wind velocity, which yields a value of 0.177m/s . The value of $z=0.07\text{m}$ is chosen based on the location of the site which is an in-between of airfield and sub-urban area. In the definition of the Davenport Spectrum, the parameter x is equal to $1200/\bar{u}_z$. The Davenport Spectrum is plotted on a log-log plot.

Fast Fourier Transform (FFT) is performed on each of these stochastic components to obtain the wind speed spectrum from the fluctuating component for each case of different averaging window. The different averaging window lengths are chosen to be 60s, 120s and 300s. They are then scaled and plotted on the same plot together with the Davenport spectrum. These plots are then compared for the fit between the two curves as the selection criteria of the averaging period.

The different averaging window lengths are proposed with reference to the values used in Choi and Hidayat (2002). The averaging window length of 60s is reported to give good results when compared with the Davenport spectrum. The purpose of including the cases for averaging lengths of 120s and 300s is to investigate the

behaviour of the wind speed spectrum subjected to increment and decrement of averaging window length.

Figure 5.2 Variation of wind speed spectrum with varying window length

The thunderstorm data chosen is the data on 4th April 2005, 0941-1041 hours. Figure 5.2 shows the moving average of thunderstorm data on the left side, and the log-log plot of the spectrum of the stochastic component plotted together with the Davenport spectrum on the right side. The three plots on each side show the effects of varying averaging window length to the stochastic wind speed spectrum. It can be seen that an averaging window of 60s gives a reasonable envelope approximating that of the upper part of the Davenport spectrum. The lower part of the spectrum which corresponds to lower frequency range generally displays a poor fit for all three cases of different averaging window lengths. As the averaging

window length increases, the envelope distorts sufficiently such that it deviates from the Davenport spectrum. It suggests that an increasing length of averaging period is not suitable for the purpose of this study.

5.3 Analysis of thunderstorm data

The analysis of the thunderstorm data may commence after the selection of a suitable averaging time period for the moving average. The analysis of the thunderstorm data sets are done according to their chronological order. Those with long durations of more than one hour are marked with an asterisk. The graphical form of data from both data loggers is presented. However, the detailed analysis is only done for the data from the high speed data logger, due to its superior sampling rate. Only channel V2 at an elevation of 15m is used because channel V1 has been faulty since February 2005. Three data sets are chosen to give the reader a good idea of the characteristics of these storms.

The Month of March, 2005

Date of selected Data: 25 MAR 05*, 26 MAR 05

1) Data: 25 MAR 05, 1605 hrs Record duration: 2 hrs

Figure 5.3a Wind data from normal speed data logger

The two figures 5.3a and 5.3b show the data stored in the normal and high wind speed data logger. Figure 5.3a shows the complete record of the two hour duration storm. Comparing the trigger times of the two sets of data it is found that the high wind speed data logger was triggered first. The time lag was about 10 minutes. It could happen that the wind speed reaches the triggering speed of 8 m/s even before it rains. In this case the high wind speed data logger may have captured the wind speed due to the first gust of the thunderstorm in the first 10 minutes of data.

Figure 5.3b Wind data from high speed data logger

Due to a difference in triggering mechanisms, these two data loggers capture data of different durations. The high wind speed data logger generally captures only one hour duration of data. However, the normal wind speed data logger has shown that it can capture durations of more than one hour if it continues to rain. This is because its triggering mechanism relies on the availability of rain. In this case the normal wind speed data logger captured the full duration of two hours, whereas the high speed counterpart can only manage to capture one hour of data due to the limitation imposed by the triggering mechanism.

The plots of average and maximum wind speed against time and total rainfall against time are compared in Figure 5.3a. The solid lines represent maximum wind speed in one minute while the circles represent average wind speed in one minute. The wind speeds are not very much higher than the magnitude of the monsoon winds. It can be seen that the peaks in the two graphs occurs simultaneously in most instants, though an increase in rainfall does not seem to induce a proportionate increase in wind speed. The number of cells passing through the site may be best viewed by the plot of total rainfall against time. From the plot, it is seen that two small cells (0th and 20th min) passes followed by two huge cells near the one hour mark. The two huge cells can be deemed to be the storm centre in this storm, as the plot of directional rain against time shows that there is no particular strong rainfall in any direction during that time period.

After passage of the storm, the wind speed decays with time in a manner similar to the time-history model in chapter 2. With the absence of any further heavy rainfall the magnitude of wind speed decays sufficiently to the level of environmental winds with the passage of time.

The focus is now switched to Figure 5.3b, where the duration of data is shorter but

contains more information that can be utilized in further analysis. The directional charts shown are describing the histograms of direction in the durations 0 – 20 min, 21 - 40 min and 41 – 60 min. It is separated in this way to show the change in wind direction with time. The charts show that there is a predominant Southeasterly wind blowing, and it changes to Southwesterly direction before passing through the data collection site.

The radar pictures provided from the Meteorological Service of Singapore may assist in the assumption made about the wind direction by providing a graphical form in which the reader may see the transition of the storm centre.

Figure 5.4a
Radar picture on
25th Mar 05, 1602 hrs

Figure 5.4b
Radar picture on
25th Mar 05, 1615 hrs

Figures 5.4a and 5.4b shows the translation of the storm centre towards to wind data collection site marked with an 'X'. The direction inferred from the storm translation confirms that the direction of the storm centre from the site is indeed southeast. Figure 5.4b shows the dissipation of the cell centre over 'X', which means passage of the storm centre. The timing of this radar coverage coincides with the timing where increment in both wind speed and rain intensity is observed.

Figure 5.4c Radar picture on 25th Mar 05, 1705 hrs

Figure 5.4c shows the radar picture taken at 1705 hours, about one hour after the storm had commenced. It shows that the cell is still hovering above the site and that it had not finished dissipating. This is the time when the data shows the passage of the storm centre, which caused a sharp increase in both wind speed and amount of rainfall.

The graphs shown on the right hand side are the moving average of the thunderstorm time-history using a one-minute averaging time period. The stochastic part shown results from the subtraction of the moving average from the time-history. The scaled Fourier Transform of the stochastic part is then taken and compared with

the Davenport spectrum which is shown as a solid line curve. From the figure it is seen that the stochastic component is relatively stationary when compared to the Davenport spectrum for reduced frequency of above 1 Hz.

2) Data: 26 Mar 05

Duration: 1 hour

Figure 5.5a Wind data from normal speed data logger

The commencement time of this thunderstorm event is only less than 24 hours away from the previous one, but the maximum total amount of rain is almost three times the previous one. Figure 5.5a shows the time-history of the wind speed in this thunderstorm event. The normal wind speed data logger started recording before the high speed counterpart at 1319 hrs. This is about 10 minutes earlier than the trigger time of the high wind speed data logger. This means that when rain commences the wind speed is less than the triggering speed of 8 m/s. This event is the opposite of the event on 25th Mar 05, when the high speed data logger triggers first.

The time-history profile of the wind speed bears resemblance to the time-history downburst profile, with the characteristic decay with the passage of time. It is noticed that the maximum value of both wind speed and total amount of rain occurs simultaneously just like in the previous storm. From the magnitude of the amount of rainfall it is speculated that the storm cell is larger than the previous storm. It is observed that the distinctive peak in the rainfall plot that results from the passage of a storm cell lasts longer than in the previous storm, which generally consisted of contributions from smaller cells as observed from the height of the peaks. The translation time of approximately 30 minutes also gives an idea of the size of the storm cell.

Figure 5.5b shows the analyzed data from the high wind speed data logger. The data is recorded at a later time of 1330 hrs. This means that it can record additional 10 minutes data towards the end of the one hour sequence. The time-history in Figure 5.5b shows a similar profile to that of the profile in Figure 5.5a. The wind speed direction chart shows an initial direction of Southwest. The three charts show the gradual change in direction of wind from Southwest to that of Northwest, which means that the storm centre did not pass exactly through the site. However, the cell may have covered a sufficiently large area such that the time-history profile of the wind speed shows the same effect as that of direct passage by the storm centre.

The sequence of radar pictures shows the progress of the storm over the wind data collection site marked with an “X”. Figure 5.6a shows the relative position of the perceived storm center, which is shown to be very near to the site. The time at which this radar picture is taken coincides with the trigger time of the high speed data logger, which implies that the wind speed was in the region of 8 m/s. It also means that raining had commenced for approximately 10 minutes when this picture is taken.

Figure 5.5b Wind data from high speed data logger

Figure 5.6a Radar picture on 26th Mar 05, 1332 hrs

Figure 5.6b Radar picture on 26th Mar 05, 1353 hrs

Figure 5.6c Radar picture on 26th Mar 05, 1414 hrs

Figures 5.6b and 5.6c show the sequence of the event as well as the movement of the storm centre as it dissipates its energy. The movement of the storm cell is in the South to North direction, which confirms the direction given by the three directional charts in Figure 5.5b.

The moving average technique is then applied to the wind speed time-history in Figure 5.5b. The scaled Fourier transform of the stochastic component of wind speed is then compared with the Davenport spectrum indicated by the solid line. The result is similar to that of the previous storm as it is observed to be of the same profile as that of the Davenport spectrum up to the reduced frequency of 1Hz. The lower frequency spectrum differs significantly as in the previous case.

The Month of April, 2005

Date of selected data: 04 April 05

3) 04 April 05, 0851hrs

Record duration: 3 hour

This data is taken on the day where the Meteorological Service of Singapore issued

Figure 5.7a Wind data from normal speed data logger

a heavy rain warning, also the one of the heaviest and longest duration storm in the whole period of late March to late May. As shown in Figure 5.7a, the wind speed and amount of rain are being recorded by the normal wind speed data logger continuously for 3 hours. The first gust is speculated to have arrived at about 40th to 60th minute when there is still no obvious peak in the rainfall time-history. Oddly, this happened to achieve the highest instantaneous wind speed throughout the duration of the storm.

Figure 5.7b Wind data from high speed data logger

Figure 5.7b Wind data from high speed data logger (continued)

The passage of storm cells can be observed by the number of peaks in the rainfall time-history plot. The peaks show the passage of four cells across the site. The time of passage of these four cells is approximately 100 minutes. The presence of all directional components of rain in these time periods is good evidence of the passage of storm cells.

Figure 5.7b shows the data obtained from the high wind speed data logger. The trigger time is 0941 hrs, which is about 50 minutes away from the triggering time of the normal wind speed data logger. The 50th minute in the normal wind speed data log is approximately the time when the first gust arrives. Therefore, the high wind speed data logger is triggered by the first gust. Due to the limitation of the high speed data logger it can only manage to record one hour of data.

The wind speed time history resembles that of the environmental wind rather than a thunderstorm downburst. It can be due to the weaker strength of the downburst winds relative to the environmental wind in this storm, despite the fact that this storm is a heavy and long duration storm.

The wind direction charts indicate that the initial wind direction is from the west. The main wind direction did not change much and all three charts show prevailing westerly winds.

Figure 5.8a, 5.8b and 5.8c show the progress of the heavy storm over the wind data collection site marked with an “X”. The area that the storm covers is very wide, and the whole island of Singapore is reported to be affected by it. The pictures are not very useful in this storm analysis because the area covered by the storm cell is too wide and that the direction of wind movement cannot be deduced. This is a typical storm that is caused by squalls, which consist of a line of thunderstorm cells.

The moving average technique is applied to the wind speed time-history as shown in Figure 5.8b. The Fourier transform of the stochastic component is then compared with the Davenport spectrum. The result is the same with the previous two storms. The profile of the Fourier transform of the stochastic part agrees well with the Davenport spectrum over the higher frequency range. The lower range of reduced frequency still deviates significantly from the Davenport spectrum.

Figure 5.8a Radar picture taken at 1021 hours

Figure 5.8b Radar picture taken at 1023 hours

Figure 5.8c Radar picture taken at 1033 hours

The detailed analysis into the characteristics of the three storms presented serves to highlight certain aspects of these storms. The storm on 4th April shows that there are thunderstorms with duration as long as three hours as opposed to the view that thunderstorms last usually for one hour. Thunderstorms differ from one another in such a way that each of their wind speed and rainfall time-histories are unique. The magnitude of wind speeds and rainfall in each storm also varies and the proximity of their occurrence to one another does not make them predictable in any of the quantities mentioned above. The normal wind speed data logger provides us with the extended time period where the high speed counterpart fails to capture. The magnitude of wind speed in a storm is also found to be independent of the amount of rainfall in the data, though there is always an increase in wind speed when there is a peak in the rainfall time-history.

The stochastic components generated from all three storms are created from a moving average of one minute duration averaging period. They are shown in Figure 5.9 together with their respective wind speed time-histories.

From figure 5.9 it is seen that these stochastic components are in each case unique. There is no one stochastic component shown here that is similar to the others. This is because the wind speed time-history is unique itself and therefore no stochastic component can be exactly the same. Each stochastic component can be treated as a random sequence of numbers, or a stochastic process.

Figure 5.9 wind speed time-histories and their respective stochastic components

The profile of the dimensionless spectra of the stochastic components is shown to agree well with the Davenport spectrum for the relevant frequency range. This means that the stochastic components in all three storms are considered to be stationary with respect to the Davenport spectrum. However, the result from the lower frequency range does not agree well, this may be due to partial removal of low frequency components in the process of applying the moving average technique.

Figure 5.10 Fourier transform of the stochastic components plotted together with the Davenport spectrum

Figure 5.10 shows the three plots of scaled Fourier Transform of stochastic

component together with the Davenport spectrum. It shows a reasonably good fit for the region of frequencies that is of concern to civil engineering structures, which lies in the upper tail above the reduced frequency of 1Hz. However, the two curves deviate from each other for frequencies at the lower tail of below 1Hz. Additionally, the spectra seem to suffer from aliasing.

The similarity of fit in the profile at region of frequencies that are of structural concern indicates that with a one-minute averaging period, the moving average technique is able to restrict most of the non-stationarity of the downburst wind speed to the moving average component. Therefore the stochastic component is shown to be free of non-stationary components. Another explanation is that the downburst wind speed contains a large component of environmental wind which is responsible for the storm translation. This is largely dependent upon the terrain roughness and this may be responsible for the similarity between the profiles of Fourier Transform of the stochastic component to the Davenport spectrum.

5.4 Regression Analysis

The best fit to the wind speed spectrum from the stochastic component of the thunderstorm wind may be obtained by minimizing the sum-of-square of errors. Regression techniques may be required in the extraction of the parameters to be used for construction of a stochastic model. The coefficients from the regression estimates may offer new insights into the behaviour of the wind spectrum, and perhaps suggest a more suitable spectrum other than the Davenport spectrum. The spread of the coefficients across different samples of thunderstorm data may also suggest the stability of these coefficients with respect to a large sample of thunderstorm data.

The expected value of the best fit for wind spectrum may be as follows:

$$\hat{S} = 4.0 \hat{a} u_*^2 \frac{(x / \hat{b})^2}{\left[1 + (x / \hat{b})^2 \right]^{\hat{c}}} \quad (5.2)$$

where the parameters $\hat{a}, \hat{b}, \hat{c}$ are regression coefficients of best fit to be evaluated from the regression. The parameters x and u_* are used as in Davenport spectrum.

The sum of squared error function, E , is then evaluated by the following equation:

$$E = \sum_{k=1}^N (S_k - \hat{S}_k)^2 \quad (5.3)$$

where S_k is the value of the wind spectrum from the thunderstorm data at successive values of k . $\hat{S}_k$ is the value of the expected value of the wind spectrum when the values of regression coefficients are substituted.

Fig 5.11 3D Plot of the function E with respect to parameters a and b

A

typical three dimensional plot of the sum-of-squared errors function E against parameters a and b is shown in Fig. 5.11. It is shown that there is a minimum point at coordinates (a_0, b_0) , where a_0 and b_0 are the values of parameters a and b corresponding to a minimum of the function E .

The coordinates corresponding to the minimum points may be evaluated by using the `fminsearch` function in MATLAB. It searches for a local minimum point when an input of starting coordinate is given. Moreover, it is able to perform multidimensional minimization and thus problems with more than two regression parameters may also be solved with ease.

The value of $\hat{c}$ is 1.33 in the Davenport spectrum. This coefficient will be involved in the regression as well to find a minimum point. The regression coefficients would be evaluated from the MATLAB function of `fminsearch`. The function allows for multi-dimensional nonlinear regression. The `fminsearch` function requires the input of a function containing the initial guess values of the three regression coefficients. The initial guess values are [1.0, 1.0, 1.33] for the regression coefficients respectively. All of the 18 thunderstorm data sets are used in the regression.

date	a	b	c
25-Mar-05	0.259	1.013	1.059
26-Mar-05	0.420	2.222	1.100
27-Mar-05	0.900	3.106	1.152
02-Apr-05	1.276	4.892	1.191
03-Apr-05	0.606	2.680	1.130
04-Apr-05	1.146	7.813	1.237
15-Apr-05	0.811	4.274	1.187
16-Apr-05	0.750	4.530	1.162
21-Apr-05	0.171	0.623	1.004
28-Apr-05	1.059	4.623	1.190
06-May-05	0.056	0.0429	0.937
08-May-05	0.792	3.218	1.152
12-May-05	1.617	7.382	1.278
14-May-05	0.631	0.0004	1.040
16-May-05	1.079	4.791	1.182
19-May-05	0.096	0.0490	0.970
21-May-05	0.311	1.141	1.041
24-May-05	0.527	3.126	1.120

Table 5.1 best fit regression coefficients for the 18 data sets

Table 5.1 shows the best fit regression coefficients for all 18 thunderstorm data sets. The coefficient values for 6th, 14th and 19th May 05 should be disregarded because of the occurrence of numerical error when zero instantaneous wind speed appeared in their time-histories. It can be seen that the power coefficient which is expressed by the regression coefficient $\hat{c}$ has values in the range of 1.0 to 1.3. Therefore it would seem that the initial assumption of a Davenport spectrum profile may not be valid in this case for thunderstorms. Additionally, the results seem to be badly affected by the effects of aliasing and therefore only the less affected portions of the spectrum is recommended for use.

The rest of the parameters $\hat{a}, \hat{b}$ have values as displayed by table 5.1. The lack of fit at the lower tail section of the wind spectrum is something to be expected since the

Davenport spectrum has encountered a similar problem when the formula does not include variation of the spectrum with height from the ground. The fitted spectrum has this same property since it is modelled upon the format of the Davenport spectrum.

The wind speed data obtained from the thunderstorm database provides the opportunity for a deeper understanding into thunderstorms. Both the wind speed and wind direction time-histories indicate the behaviour of thunderstorms over a period of time. It is shown that thunderstorms can last more than one hour though such cases are infrequent. The stochastic component of the thunderstorm wind speed time-histories is extracted by means of the moving average technique using a one-minute averaging period. The analysis of the wind speed data of the thunderstorms concluded with the evaluation of the best fit regression parameters. Based on these results it is seen that a more appropriate model may be used to describe the stochastic component of the thunderstorm wind speed.

5.5 Summary of the chapter

This chapter discusses the thunderstorm data and highlights difficulties in obtaining an ideal thunderstorm time-history profile. The thunderstorm data is presented together with their corresponding radar picture which enables a better understanding of the time and space where the storm cell is. The moving average technique is used for extracting the stochastic component. Regression technique is then used in the analysis and extraction of the regression coefficients.

Chapter 6: Analysis using Thunderstorm model

The use of the moving average technique has been an attractive tool in extracting a stationary stochastic thunderstorm component from downburst time-history. This ease of use allows for the speedy computation of the stochastic thunderstorm component for each thunderstorm, regardless of the magnitude of the maximum wind speed and its other physical quantities which has been shown to be unique for each storm. However, it ignores other parameters like the size of the storm cell and the direction of approach or departure by storm cell, which dictates the maximum downburst wind velocity as well as the dynamic amplification on a structure.

Therefore, the development of a thunderstorm model is crucial when the response of a structure to thunderstorm downburst needs to be determined. It allows researchers to have a better insight into the structural response when the thunderstorm parameters are varied, e.g. size of storm cell, storm duration and direction of approach, etc. These insights cannot be obtained by applying a numerical method like the moving average technique.

The range of thunderstorm models to be chosen has been considered in chapter 2. They are the deterministic models covered for both vertical and horizontal profile of the thunderstorm downburst time-history. The role of the deterministic models is to simulate the slow-varying component of the downburst time-history. This is previously simulated by the moving average. These deterministic models are used because they are derived based on the physics of the thunderstorm downburst with a set of parameters and may be reproduced when the parameters are changed. A numerical technique like the moving average will not be able to provide.

The stochastic component is obtained in a similar fashion as in the previous chapter,

by subtracting the deterministic component from the downburst time-history. The deterministic component in this case is the one computed by the deterministic model. The stochastic component generated may give us a closer estimate to the fluctuating component in a thunderstorm downburst, since the deterministic component is based on a physical model. However, this also means that the extraction process may be more difficult. This is because the physical parameters, e.g. the dynamic direction of the storm cell, must be known for each storm data before the stochastic component may be extracted. This may result in the redundancy of some data sets due to absence of essential information on the storm parameters. All these factors combine to make the analysis using thunderstorm model an uphill task.

The use of the deterministic model requires the understanding of the dynamic direction of the storm cell in the data. This means that the variation of the wind direction with time will give essential information on the dynamic direction of the storm cell. The wind direction is recorded by directional sensors at the level of V1, V2 and V3 respectively. The passage of the storm centre directly over the wind mast is indicated by a sharp change in the wind direction. However, a storm cell rarely passes over a site directly. Therefore there is always an offset distance e to the line of approach by the storm. If the offset distance is far, this means that the effect of the storm on the site may be small and thus the data will record wind speed time-history of mainly environmental nature.

In the case where multiple cells are present, great care must be taken when the dynamic direction of the storm cell is to be decided. It has been noted that the wind direction recorded does not reflect the true path taken by the storm in the case of multiple cells and it could be due to the turbulence interference amongst the cells. A more accurate estimate could be made based on the rainfall intensity recorded by

the rain gauge. A peak in the rainfall intensity means that the storm cell is nearest at that instance.

6.1 Thunderstorm models

Chapter 2 discussed a wide range of mathematical models that have been based upon intensive research. Osguera and Bowles (1988), Vicroy (1992), and Wood and Kwok (1998) developed models that describes the vertical profile of a simulated downburst, while Poreh and Cermak (1959) derived a model that describes the downburst time-history at a chosen height z . These models will give a complete picture of the deterministic wind velocity field of a simulated downburst when combined together.

Due to the fact that some channels are faulty at different times throughout the year, it is difficult to construct a vertical profile based on the measured data from the wind mast. It is decided that the data sets collected will only utilize channel data from channel V2 at 15m height. The horizontal profile is modeled by the mathematical model proposed by Holmes and Oliver (2000):

$$V_r(r) = \begin{cases} V_{r,\max} \times (r / r_{\max}) & (0 \leq r \leq r_{\max}) \\ V_{r,\max} \times \exp\left(-[(r - r_{\max}) / R_r]^2\right) & (r \geq r_{\max}) \end{cases} \quad (6.1)$$

The model allows for a decay of the downburst with a defined time constant and an exponential decay function:

$$V_r(r) = \begin{cases} V_{r,\max} \cdot (r/r_{\max}) \cdot \exp(-t/T) & (0 \leq r \leq r_{\max}) \\ V_{r,\max} \cdot \exp(-[(r-r_{\max})/R_r]^2) \cdot \exp(-t/T) & (r \geq r_{\max}) \end{cases} \quad (6.2)$$

Figure 6.1 Horizontal profile of wind speed (Holmes and Oliver's model)

Figure 6.1 shows the horizontal profile of wind speed with distance r . This is also referred to as Holmes's model. The profile is based on results obtained from experiments with impinging jets on surfaces. It can be viewed as two separate parts: the linear part of the profile is for distance from zero to $r_{\max}$, and the exponential decay part from $r_{\max}$ to infinity. Since distance is finite the wind speed may be taken as zero at great distance. $r_{\max}$ may be taken as the distance from cell center to the end of the stagnation region.

The deterministic wind force time-history exerted on a point will follow a similar shape to the horizontal wind speed profile described by Holmes and Oliver's model. The shape of the forcing function may defer depending on the approach storm path. It may be a triangular shape or an exponential function as shown by the horizontal

profile in Figure 6.1. The deterministic structural response experienced at that point may then be calculated based on structural dynamics assuming the abovementioned forcing functions.

Thunderstorms rarely pass directly over the data collection site. Storm cells usually pass the site at an offset distance e . This distance can be smaller or greater than the distance $r_{\max}$, depending on the path taken by the storm cell. In extreme cases, the offset distance can be so far that the effects of the storm on the wind speed time-history at the site are negligible. The site will then be recording only the environmental wind speed.

The horizontal profile of wind speed will be different if the storm passes over the site at an offset distance e . This is because the minimum distance between the site and the storm cell centre will be e instead of zero as in the case of a direct pass. As mentioned earlier, the offset distance is dependent on each storm and will vary greatly when a number of storm data are compared against one another. Therefore it is necessary that the variation of the horizontal profile with offset distance must be known.

Different offset distances may give rise to different horizontal profiles. If the offset distance is less than $r_{\max}$, the linear portion of the horizontal profile may be reduced in length but still be found in the time-history of the storm data. When the offset distance is equal to $r_{\max}$, the linear portion will not be shown in the time-history. The exponential decay portion will form the entire time-history of the storm data if the offset distance is more than $r_{\max}$.

Figure 6.2 shows the horizontal wind speed profile similar to that shown in Figure 6.1, except that in this case the storm passes through the site with an offset distance

of $e=500\text{m}$. Since the magnitude of this offset distance is less than $r_{\max}$, the linear portion of the horizontal profile is preserved. It can be seen that the rest of the profile is not affected by the change in offset distance.

Figure 6.2 Horizontal profile of wind speed with $e=500\text{m}$

The choice of e is then increased to 1000m and 1500m . The corresponding horizontal profiles will consist of the exponential decay part only. This is because a choice of 1000m as e implies that $e = r_{\max}$, which effectively eliminated the linear portion.

Figure 6.3a Horizontal profile of wind speed with $e=1000\text{m}$ Figure 6.3b Horizontal profile of wind speed with $e=1500\text{m}$

Figure 6.3a shows the plot of horizontal profile when $e=1000\text{m}$. It is shown that the time-history profile can be represented entirely by the exponential decay function. The linear portion of the horizontal profile that appeared in Figures 6.1 and 6.2 no longer represent the time-history in this case.

Figure 6.3b shows the horizontal profile when $e=1500\text{m}$. Only the horizontal profile of $r>1500\text{m}$ is being shown in the plot. The plot is represented entirely by the exponential decay portion again. It is now clear that the original horizontal profile content that is described by Holmes's model decreases as the offset distance increases. It can be explained physically that the influence of the thunderstorm downburst weakens as it is further away from the site.

6.2 Application of model on time-history data

The application of this knowledge on wind speed time-history data collected may not be straight forward. This is because most of the thunderstorms which are recorded by the data logger will have time-histories that will behave rather differently from the shape described by the model. Moreover, the horizontal profile may not be readily converted to a time-history profile given the unknown nature of the storm translation speed. Comparison of time-history data with the horizontal profile may be based on the general shape as well as the data given by the directional sensors and the rain gauge sensor. The dynamic direction of the storm cell is important and a direct pass over a site may be recorded by either the directional sensor or the rain gauge sensor (or both). This ensures that the storm did pass over the site and that the horizontal profile shown in the time-history can be justified. The data on the directional sensors will give sudden change of direction in when the cell passes them. However, it is found that in multiple cell events the data shown by the directional sensors may not be reliable. This may be due to the physics of multiple wall-jets being placed next to one another. The rain gauge, on the other hand, seems to give a clearer picture of such events when the rain intensity reaches a maximum as the cell centre is overhead.

Based on these comparisons, a best fit linear and exponential decay profile is calculated for each chosen data set using the minimization of least squared errors. The stochastic component is then obtained by taking the difference between the time-history data and the best fit profile. However, in cases where the transition from linear to exponential decay profile is not clear only the linear profile is used in the calculation.

There are 12 data sets chosen from the original ensemble for further analysis using the abovementioned methodology. These chosen sets have portions of time-histories that correspond to the horizontal profile described by Holmes and Oliver's model. Some of the data sets were not chosen because of insufficient information or the complexity of the time-histories.

Figure 6.4 shows the 12 data sets chosen based on the criteria described earlier. The time-histories should show the storm cell to be in the recordable vicinity of radial distance less than or more than $r_{\max}$. Preferably, it should also show the transition of the storm cell from more than $r_{\max}$ or vice-versa. This gives the horizontal profile of the time-history which was hypothesized to be that of an exponential decay function. If the recorded time-history shows the transition of the storm cell from $r_{\max}$ to zero (directly over the site) it then gives the horizontal profile of the time-history which Holmes and Oliver (2000) established it to be a linear line profile. Therefore, the entire duration of the time-histories shall not be used in the analysis. Rather, segments from the time-histories are selected to give the best results that can be obtained from the linear/exponential best fit. The procedure for producing the best fit is based on the regression techniques discussed in the previous chapter.

Figure 6.4 Time history of wind speed in selected ensemble of data

Figure 6.4 Time history of wind speed in selected ensemble of data (continued)

Figure 6.4 Time history of wind speed in selected ensemble of data (continued)

The stochastic components are next extracted by means of subtraction of the best fit from the time-history. This method of extraction may overcome problems of filtering some lower frequency components when the moving average technique is used instead. However, this method depends very much on the correctness of the assumed horizontal profile and therefore extreme care must be taken when the horizontal profile of the time-history is compared against the theoretical profile by Holmes and Oliver (2000).

The stochastic component is then put through a series of tests. The regression estimators $\hat{a}, \hat{b}, \hat{c}$ of the Fast Fourier Transform (FFT) of the samples will be compared against those obtained by the moving average technique. The statistical properties of the stochastic components, namely Gaussianity and stationarity of the ensembles, will be examined as well. These findings will together contribute to the construction of a suitable stochastic thunderstorm model that will allow future forecasting of dynamic response of structures.

The analysis results performed on the thunderstorm dated 26th May 2005 are shown in Figure 6.5a, 6.5b and 6.5c:

a)

Figure 6.5a First plot: wind speed and direction data from data of 26th Mar 05

Figure 6.5b Second plot: Comparison of properties of data from 26th Mar 05

Figure 6.5c Third plot: Comparison of stationarity of data from 26th Mar 05

Figure 6.5a shows the time-history of the thunderstorm's wind speed as well as wind direction. A chronological histogram of the thunderstorm's direction is also shown amongst the plots to give an indication of the dynamic direction of the storm cell throughout the various stages of the storm.

Figure 6.5b shows the comparison of stochastic components obtained by the two different methods: the assumed Holmes' profile and the moving average technique. A 1-min moving average is used in extracting the stochastic component for comparison against one that is obtained by subtracting the assumed Holmes' profile from the time-history itself. They are extracted from parts of the time-history that are considered to be following the theoretical profile of the Holmes' model. There are both similarities and differences between the two components generated in terms of the properties. They are compared against each other for the condition of stationarity and Gaussianity. These are the two assumptions used in the Gust Response Factor (GRF) method.

The `histfit` command generates a histogram plot that fits the stochastic component to a Gaussian distribution. It can be seen that most of the ensemble adheres to the Gaussian profile for the range of -2 to 2 for the reduced variate. Beyond this range, most of the ensemble has heavier tails at the ends of the distribution.

The analysis results of the ensemble of thunderstorm data from Figures 6.5a and 6.5b indicate that the stochastic component of the thunderstorm downbursts is usually higher than that of predicted by the Davenport spectrum. The Davenport spectrum is represented by a dotted line whereas the best fit of Fast Fourier Transform of the stochastic thunderstorm component is represented by a solid line on the same log-log plot. In data where relatively long period of data can be used in the analysis (e.g. more than 10 minutes of data of a linearised profile) difference can

be seen for the method using assumed Holmes' model profile and the moving average technique. The disadvantage of the moving average technique is that it tends to remove some of the lower frequency components as well, which can be seen in samples that possess a long linearized profile.

Figure 6.6 Histograms of stochastic components obtained from 25th Mar to 21st Apr 05

Figure 6.6 shows the histograms of stochastic components obtained from 6 data sets collected during the inter-monsoon period. Most of the samples showed wide sense Gaussian distribution, though some of the histograms show that the shape seems to be skewed. There is a need for more tests to be carried out in order to have an explanation for the deviation from a perfect Gaussian profile.

Figure 6.7 shows that the entire dimensionless frequency spectrum from thunderstorms lies below the Davenport spectrum denoted by the dotted line. This suggests that the Davenport spectrum may be sufficient when it comes to wind design of structures in thunderstorms. However, the number of data is insufficient to support that this is true for all cases of thunderstorms with varying intensities.

Figure 6.7 Log-log plot of stochastic spectrum obtained from 25th Mar to 21st Apr 05

However, the difference is not obvious in samples that have a short duration available for analysis, e.g. 21-Apr-05. Therefore the method making use of the Holmes' model has the shortcoming of not able to give good results for short durations. This may make analysis of events with high storm translation speed difficult using this method.

The best fit estimators $\hat{a}, \hat{b}, \hat{c}$ of the ensemble are shown in the table below:

	a	b	c
25-Mar-05	0.528	16.38	1.327
26-Mar-05	2.407	32.89	1.340
02-Apr-05	2.817	12.99	1.390
03-Apr-05	0.914	13.00	1.350
04-Apr-05	1.584	18.85	1.448
16-Apr-05	3.607	19.40	1.501
21-Apr-05	3.020	14.51	1.443
06-May-05	1.264	15.08	1.384
14-May-05	1.796	19.99	1.459
19-May-05	1.490	8.737	1.216
21-May-05	2.400	11.90	1.367
24-May-05	1.188	37.78	1.467

Table 6.1 Regression coefficients of a,b,c for using Holmes and Oliver's model

Table 6.1 shows the magnitude of the values for the regression coefficients obtained from the thunderstorm events by the utilization of Holmes and Oliver's model. The parameter $\hat{a}$ is dependent upon the severity of the storm and can vary according to each individual event. $\hat{b}$ is the mode and $\hat{c}$ gives the curvature across the frequency spectrum.

	a	b	c
25-Mar-05	0.531	12.42	1.330
26-Mar-05	2.303	27.13	1.299
02-Apr-05	2.767	14.71	1.363
03-Apr-05	0.911	11.67	1.331
04-Apr-05	1.635	19.18	1.461
16-Apr-05	3.559	22.76	1.493
21-Apr-05	2.965	13.60	1.429
06-May-05	1.311	12.54	1.393
14-May-05	1.672	12.76	1.404
19-May-05	1.378	5.018	1.171
21-May-05	2.230	12.34	1.320
24-May-05	1.101	25.41	1.410

Table 6.2 Regression coefficients of a,b,c for moving average

Table 6.2 shows values produced by the moving average technique. It can be seen that the values are slightly different from those produced in Table 6.1. Generally this could be due to the correct representation of the lower frequency components in the ensemble by the method relying upon the Holmes' model. Moving average techniques are known to remove some of the lower frequencies unnecessarily from the stochastic component.

Figure 6.5c compares the stationarity of the stochastic components generated by the two different methods. An average scheme is imposed upon both components generated for each averaging window of duration 2-mins, after which it is normalized by the mean of the ensemble. The difficulty of the next step is the proof of stationarity. It is generally accepted that the moving average technique of averaging window of 1-min produces fairly stationary stochastic component. Therefore, the performance of the stochastic component produced by the assumed Holmes' profile is judged by benchmarking it against that of one produced by moving average of 1-min window length. If the performance of the stochastic component deviates significantly from that produced by a 1-min moving average

then it may be considered as non-stationary.

From the analysis results displayed in the third plot in Figure 6.5c, it can be seen that the magnitude of the normalized moving mean as well as the standard deviations of the stochastic component generated from the assumed Holmes' profile represented by a solid line is comparable to that of the one produced by a moving average of a 1-min averaging period represented by a dotted line for most of the data. This goes to show that the stochastic component generated by this new method may have the same stationarity properties as compared to its predecessors. In some sets of data there may be some cases of wide sense stationarity as compared to the ones generated by moving average. Most of the data follows a normal distribution profile for the range between -2 and 2 for the reduced variate and for those which do not they display wide sense Gaussian properties.

Though in the presence of wide sense stationary and Gaussian properties the process may be classified as stationary and Gaussian, more data should be obtained before such a conclusion is made. The varying lengths of thunderstorm events as well as the linearized profile depend entirely on the randomness of the movement of the storm as well as the point of reference at which the thunderstorm event started. This greatly reduces the usefulness of some data where the time-history does not reflect the horizontal profile hypothesized by Holmes and Oliver's model. In most of the time physical processes that are stationary may only be shown to be wide sense stationary because of discretization. One of the serious limitations is that the amount of usable time-history based on Holmes' model method of extraction is governed by the characteristics of the thunderstorm, e.g. proximity of thunderstorm and the path taken. The length of occurrence of the passage of the storm that possesses a linear wind speed profile varies between 5 to 10 mins. Storms which have a high translation speed will give a short linearized profile and storms which

move slowly will result in a long portion of linear profile.

6.3 Summary of the chapter

This chapter discusses the stochastic model and its applications. The advantages of such a model over the moving average technique is discussed and presented. Thunderstorm data are analysed using the stochastic model. Regression analysis is performed on the stochastic component and the results are compared with that of the moving average. The results are generally affected by the characteristics of different events and there is a large scatter in the regression coefficients. However, most regression coefficients display subtle difference in the samples generated by the two different methods. More data is needed to confirm the gaussianity and stationarity of the process.

Chapter 7: Application of wind loading code

The characteristics of monsoon or boundary layer winds have been well documented in past year research. Most design codes based on these characteristics adopt a deterministic approach to the design of buildings with respect to wind. The effect of stochastic component of monsoon winds has recently been included in some design recommendations such as Eurocode 1 (2005). It should be noted that the stochastic component in wind had first been highlighted by Davenport (1961) and was commented an important element to be included for wind load design regardless of wind types.

The stochastic component of thunderstorm downbursts is difficult to obtain in analysis, mainly due to the highly non-stationary nature of winds in thunderstorms. There is a lack of recommendation on the wind load design with respect to thunderstorms, which is considered to have both a higher magnitude of wind speed and turbulence intensity as compared to the monsoon wind. The wind speeds encountered in a thunderstorm is dependent on meteorological and geographical factors. The dynamic effect that a thunderstorm may have on a structure merits investigation.

In Singapore, several researches have been conducted on the characteristics of monsoon wind as well as the thunderstorms (Choi, 1999, 2000, 2004, Choi & Hidayat, 2002, Choi and Tanurdjaja, 2002). These two wind systems represent the governing events for wind environment of Singapore in different periods of the year. The monsoon wind dominates in the Northeast monsoon and the Southwest monsoon seasons, whereas the thunderstorm dominates in the inter-monsoon seasons. Singapore is also frequently subjected to squall lines from the Straits of Malacca with significant thunderstorms. For this reason, the west and the northwest

regions have a higher occurrence of thunderstorms.

This chapter attempts to provide recommendations with consideration wind loading due to thunderstorms along the wind direction. A comparison of design procedures amongst various design codes with thunderstorms is conducted. Based on the analytical study of wind speed data and the comparison of results, it is recommended that the existing codes should be modified to accommodate a framework for design against thunderstorms for wind loads design.

7.1 Governing parameters

Thunderstorms produce ferocious winds that are highly turbulent and are non-stationary. The vertical profile of such winds also deviates significantly from the traditional boundary layer wind profile. Furthermore, the formation of thunderstorms is a random process. These differences have posed a great difficulty in proposing an ideal scheme with thunderstorms for wind load design.

There are several factors affecting the magnitude of wind speeds in thunderstorms. The wind load design based on probabilistic approach also requires wind speed database for analysis. The averaging period of the wind speeds in these records become so important when winds due to thunderstorms are considered. The duration of thunderstorms is usually last less than an hour. The first gust responsible for inducing high wind speeds usually last from 2 to 20 minutes (Stull, 2000). Thus, the implementation of a one-hour averaging scheme will not be able to show accurately the wind speeds during the event of a thunderstorm.

In the current study, the presence of squall lines is another factor that may subject a region to higher occurrence of thunderstorms. The geographic feature of the Straits

of Malacca has resulted in Singapore, particularly at the west and northwest regions, susceptible to Sumatran squalls with abundance of thunderstorms. Generally speaking, the factors affecting design for wind loading due to thunderstorms can be classified as follows:

a. Frequency of thunderstorm occurrence

There is need to determine the frequent thunderstorms in the region for accurate assessment of wind loading. If the frequency is low, it is difficult to justify the impact of thunderstorms in wind load design. In this circumstance, the meteorological records of that particular region may be necessary for wind load assessment. It should be noted that in some regions thunderstorms may occur once every two or three months. The frequency of occurrence of thunderstorms can be closely monitored through the meteorological or geographical conditions of that region.

b. Magnitude of wind speed in thunderstorm

The magnitude of thunderstorm downbursts varies from region to region in a country. A thunderstorm in the US can be more violent than that in Singapore due to meteorological factors (Stull, 2000). This can be seen from the peak wind speed of 67m/s in the Andrews AFB downburst compared to the average of 10m/s in Singapore. It is important to include thunderstorms in wind load design calculation as the magnitude of wind pressure acting on a structure is dependent upon the wind speed. Furthermore, the dynamic effect due to a sudden increase in wind speed can be captured. The frequency of thunderstorm occurrence may be considered with this factor when design the effect of thunderstorm downburst is significant.

c. The averaging scheme used

Most meteorological stations employ an averaging scheme for continuous recording of wind speeds. The averaging scheme is actually designed based on monsoon winds which are stationary in nature within averaging wind periods. For monsoon winds, high averaging periods will not affect the accuracy of extreme wind analysis as the wind speeds are fairly consistent for several hours or even several days. However, if the high averaging period of one-hour is used in the ensemble of wind speed time-histories due to thunderstorms then the accuracy of wind speeds for design wind load will be an issue. The reason is that thunderstorms usually last for not more than an hour and the duration that high wind speeds occur is probably much lesser. A lower wind speed that results from such an averaging scheme yields a much lower wind speed value for a 50 year return period in extreme wind analysis. The recommended averaging periods for storm design include 3-s gust and 10 minutes average.

d. Turbulence

The stochastic component of wind for wind load design has been largely ignored in the past. One of the earlier codes for wind load design like the CP3 (1972) adopts a deterministic quasi-static approach for simplicity. Many researchers have realized the significance of turbulence to dynamic response. The recent codes require the inclusion of stochastic component of winds such as the Gust Response Factor (GRF) method for wind load design of dynamically sensitive buildings.

Some researchers have explored the possibility of using the GRF method on the stochastic thunderstorm component (Choi and Hidayat, 2002). The problem of non-stationary downburst time-histories is solved using the moving average

technique with a suitably chosen averaging period. This method allows the extraction of a relatively stationary stochastic component for use in the computation of the building response to wind. However, the moving average technique is a numerical technique that allows speedy computation regardless of wind profile and magnitude in the time history. The shortcoming in this method is that some lower frequency components are filtered during the averaging process. Therefore, there is need to develop a suitable method to determine the stochastic component of thunderstorm.

e. Occurrence pattern of thunderstorms

In general, thunderstorms are perceived to occur in a random pattern. The supporting evidence from the meteorological stations showed that the occurrence of thunderstorms in Singapore is more frequent during the inter-monsoon months. The presence of some geographical features which trigger instability conditions may also favour thunderstorms. Additionally, the squall lines from the Straits of Malacca consistently cause a group of thunderstorms to travel in a particular direction to the west and northwest of Singapore. Based on statistical data, more thunderstorms travelling in a particular direction can be determined. Thus, directional method is highly recommended to determine the wind speed due to thunderstorms for wind load design.

f. Design considerations of mid-height structures

Thunderstorms produce winds that are usually of higher magnitude than monsoon winds. The maximum wind speed in thunderstorms is found to occur at a much lower height as opposed to that in boundary layer winds. The occurrence of lower height maxima is due to the propagation of the gust front with wind speed of 5m/s

to 15m/s at depth of 100m to 1,000m respectively (Stull, 2000). Owing to the wind speed variation in vertical profile, the dynamic effect of tall structures can be less than that of a medium height structures. However, structures with medium height require additional attention as they are minimally designed against monsoon wind instead of severe thunderstorms. As a result, structural damage or even failure of these structures could have occurred under severe thunderstorm conditions.

All the abovementioned factors should be simultaneously considered in a framework for the design of wind loading with thunderstorms. Thunderstorms are basically a localized phenomenon dependent upon a number of factors which are more complicated to be analysed than monsoon winds. Besides, the event of each thunderstorm is unique and generates very different wind speed time-histories.

7.2 Wind loading design based on monsoon wind

Most building codes consider wind load due to monsoon winds. In cyclonic regions, the wind speeds can be very much higher but the extreme wind analysis is similar to that based on monsoon winds. The main reason is that the boundary layer profile is still applicable in the cyclonic wind systems.

The extreme wind analysis can be conducted based on the value of basic wind speed for a particular region. The database of wind records can be referenced from the meteorological station. The value of basic wind speed may be decided based on the probabilistic approach of wind load with 50 years return period or 2% of wind speed exceedance per year. However, designers may be considered designing structures with 100 years return period of wind loading under extreme condition.

The codes and recommendations for design of building structures under wind

loading such as AS/NZS1170 (2002), CP3-V (1972), BS6399-2 (1997), Eurocode 1 (2005) and the ISO4354 (1997) are most commonly used in practice. AS/NZS 1170 is the wind load design code jointly developed by Australian and New Zealand authorities. CP3 (1972) and BS6399-2 (1997) are widely used in the United Kingdom (UK) as well as in Singapore. Eurocode 1 (2005) is used in member countries which are under the European Charter and has been structured to replace the existing guidelines in British Standards. However, the basic wind speed extracted from the National Annex for UK document served as a supplementary to the specification in Eurocode 1. ISO4354 is an International Standard widely referenced by code drafting committees for wind load design. The abovementioned codes and recommendations represent the philosophy of wind load design for different eras. These codes and recommendations give chronological account of the advances in the increasing complexity of building designs under wind loading. Furthermore, the specifications in the codes also provide the increasing detail in the procedures for designing building structures in terms of reliability. This can be seen in the change of guidelines for wind load design during the transition from BS6399 to Eurocode 1.

It should be noted that the wind load design in the abovementioned codes of practice usually considers the approach of deterministic quasi-static wind pressure. Eurocode 1 provides a procedure for calculation of contribution from the stochastic component based on GRF method. Whereas, BS6399 referenced the data sheets published by the Engineering Science Data Unit (ESDU). The dynamic analysis of buildings due to wind loading is only performed if the designed building has aspect ratio greater than 1:4 or a height of above 100m. Buildings with a natural frequency of less than 1Hz are generally classified as dynamically sensitive.

The resulting design of buildings using the ISO4354 (1997), AS/NZS 1170 (2002)

and Eurocode 1 (2005) will be very similar to one another. The reason is that the abovementioned codes uses the GRF method in determination of wind load which takes into account the distribution of the fluctuating wind pressure resulting from turbulence. The added response due to turbulence is determined based on the number of standard deviations that the peak will exceed the mean value. With the same set of exposure conditions and aerodynamic shapes the resulting designs are expected to be the same.

7.3 Deterministic monsoon wind load

The dynamic pressure q that results from the treatment of deterministic quasi-static wind loading of the codes can be expressed as follow:

$$q = 0.5 \rho_{air} V^2 (C_{exp} C_{fig} C_{dyn}) \quad (7.1)$$

where ρ_{air} is the air density usually taken as 1.2 or 1.25kg/m³ depending on the code used for wind load calculation. V is the basic wind speed and it varies depending on the wind speed distribution in the country concerned. However, CP3 and AS/NZS 1170 uses 3-second gust, BS6399 and Eurocode 1 uses one hour and 10-min average wind velocity respectively. Generally speaking, the wind speed is based on the return period of 50 years or an average annual occurrence probability of 2%.

$C_{exp} C_{fig} C_{dyn}$ in the above equation are the product of factors taking into account the effects of exposure, aerodynamic shape and dynamic response respectively. These factors vary with the types used in the wind load design such as AS/NZS 1170 adopted M factors to replace the term C_{exp} .

The total force due to wind load acting on the building can be determined as a

summation of forces acting on the individual structural members with surface area A_i :

$$F = \sum_{i=1}^N p_i A_i \quad (7.2)$$

where p_i is the design wind pressure for each point corresponding to subscript i determined from $p = C_p q$, and C_p is the pressure coefficient. A_i is the surface area for each point corresponding to subscript i .

7.4 Stochastic component of monsoon wind

The turbulence of the monsoon wind has been observed and investigated to a large extent by researchers. However, most codes of practice deal with the deterministic response to wind loading as the complex calculations for the stochastic component of wind cannot be directly determined. Davenport (1961) proposed a simple procedure for computing the peak response due to stochastic component in the form of GRF method based on the theory of random vibrations. This allows the information to be used for design purposes and can be codified in the form of data sheets in Engineering Science Data Unit (ESDU) and BS EN 1991-1-4 Eurocode 1 (2005).

7.4.1 Gust Response Factor (GRF)

The GRF method estimates the peak value of the response from the mean and the root mean square value of fluctuating component. The expected peak value of x within a certain time period can be expressed as:

$$\hat{x} = \bar{x} + g\sigma_x \quad (7.3)$$

where g is the peak factor, given by:

$$g = \sqrt{2\ln(\nu T)} + \frac{0.577}{\sqrt{2\ln(\nu T)}} \quad (7.4)$$

with ν being the number of times that the mean value is crossed per unit time and given as:

$$\nu = \sqrt{\frac{\int_0^\infty n^2 S_x(n) dn}{\int_0^\infty S_x(n) dn}} \quad (7.5)$$

The r.m.s of the response can be expressed in terms of the r.m.s of the wind speed fluctuation. Thus the expected peak response can be expressed as:

$$\hat{x} = \bar{x} + 2g\bar{x} \frac{\sigma_u}{\bar{u}} \sqrt{(B + R)} \quad (7.6)$$

and the GRF may be obtained by dividing (7.6) by $\bar{x}$:

$$GRF = \frac{\hat{x}}{\bar{x}} = 1 + 2g \frac{\sigma_u}{\bar{u}} \sqrt{(B + R)} \quad (7.7a)$$

with

$$B = \int_0^{n_0} \chi^2(n) \frac{S_u(n)}{\sigma_u^2} dn \quad (7.7b)$$

and

$$R \cong \chi^2(n_0) \frac{S_u(n_0)}{\sigma_u^2} \frac{\pi n_0}{4\zeta_s} \quad (7.7c)$$

χ is the aerodynamic admittance function and takes a value of unity for point-like structures. S_u is the wind spectral density function and ζ_s is the structural damping ratio.

Many forms of the equation for the spectrum of wind speed ($S_u(n)$) have been proposed by many researchers. There is general agreement that the spectrum is mainly a function of terrain roughness. Davenport (1961) proposed the following equation to be used in the evaluation of the monsoon wind spectrum:

$$\frac{nS_u(n)}{u_*^2} = 4.0 \frac{x^2}{(1+x^2)^{4/3}} \quad (7.7d)$$

where $x=1200n/\bar{u}_z$. The frictional wind speed (u_*) can be calculated from the logarithmic law suggested for boundary layer profile. The original derivation of the GRF equations are based on certain assumptions and one of these is that the process being studied is stationary. The derivation of the GRF equations allows for the evaluation of wind speed spectrum of stationary processes like monsoon winds.

7.4.2 Application of GRF method

Singapore's wind environment is dominated by monsoons and thunderstorms. It is therefore recommended that the 3-sec gust approach be adopted (Draft Singapore Standard, 2003) for design purposes. The following expression has been proposed by AS/NZS 1170 (2002) and Draft Singapore Standard (2003):

$$C_{dyn} = \frac{1 + 2I_h \left[g_v^2 B_s + \frac{H_s g_R^2 S E_t}{\zeta} \right]^{0.5}}{(1 + 2g_v I_h)} \quad (7.8)$$

where,

I_h = turbulence intensity

g_v = peak factor for the upwind velocity fluctuations

B_s = background factor, which is a measure of the slowly varying background component of the fluctuating response, caused by low frequency wind speed variations

H_s = height factor for resonant response

g_R = peak factor for resonant response (10-min period)

S = size reduction factor

E_t = $(\pi/4)$ times the spectrum of turbulence in the approaching wind stream

ζ = ratio of structural damping to critical damping of a structure

The factor C_{dyn} acts as a multiplier to the quasi-static response to account for any dynamic effects arising from the turbulence in monsoon wind. The result is that of a peak response calculated based on the probability of the random variables concerned and can be expressed in terms of the number of standard deviations by

which the peak value exceeds the mean value. This is a convenient and practical method by which the GRF method may be incorporated into code provisions for dynamic effects due to turbulence.

7.5 Wind load design against thunderstorms

This chapter proposes a framework considering the along wind response of buildings subjected to winds arising from thunderstorms. This is based on comparison of procedures developed for the along wind response of buildings subjected to monsoon wind in the codes of practice. The thunderstorm downburst possesses wind speed time-histories that can be highly non-stationary as opposed to a stationary time-history in monsoon winds. This also suggests that the non-stationary winds may have added dynamic effects on structures that are not defined to be dynamically sensitive. These differences are considered in the formulation of the proposed framework for wind load design due to thunderstorms.

The maximum buildings response is generated by the direct overhead pass of a thunderstorm. The wind speed time-history is described by Holmes and Oliver's model (Holmes and Oliver, 2000). Usually the linear profile of the wind time-history in Singapore is observed to translate for an average of 5 to 10 mins. Therefore, the dynamic response due to the deterministic model is expected to be insignificant since the period of load is long compared with the building's natural period of vibration.

Similar to designing against monsoon wind, the wind load of 50 year return period (or higher, depending on usage of building) should be considered in design stage. This load level is calculated based on the Gumbel distribution of the collected data from meteorological stations. In Singapore, works on extreme wind data by Choi

(1999, 2000, 2004), Choi and Tanurdjaja (2002) provided valuable data on the extreme wind climate of Singapore.

The concept of quasi-static response of monsoon wind is referenced in the current formulation of wind load design due to thunderstorms. The approach considers overall structural response as a combination of quasi-static and dynamic component. The quasi-static component considers only the effect due to mean wind pressure on the building structures. On the other hand, the dynamic component takes into account the effects of the non-stationary time-histories and turbulence in thunderstorms.

7.5.1 Quasi-static component

The quasi-static component determines the building response due to the quasi-static wind load. In the case of thunderstorm downbursts, it is taken as the load due to maximum instantaneous wind speed of the entire time-history. Thunderstorms usually last less for than an hour and the period where the maximum wind speed occurs are about 10 to 20 mins. Therefore, the use of the appropriate averaging scheme of wind speed is crucial. The schemes used to determine the wind speed in CP3 (1972), BS6399 (1997) and Eurocode 1 (2005) are 3-second gust, hourly and 10-min average respectively. It is recommended that Singapore uses a 3-sec gust basic wind speed as in the Australian/New Zealand wind loading code AS/NZS1170 (2002). This is due to the frequent visits by thunderstorms which give rise to high gust factor values in the measured wind speed data (Choi and Tanurdjaja, 2002).

The 50 year return period wind speed is determined based on the Gumbel distribution. The data analysis on extreme winds by Choi and Tanurdjaja (2002) gave valuable information for the calculating the quasi-static wind loads with various return periods. This allows the wind speeds to be designed based on specific locations in a country rather than those used in the UK as specified in British Standards. Thus, the basic wind speed should be obtained from the required design reliability of the building such as an annual average probability exceedance of 2%.

Choi and Tanurdjaja (2002) reported a wind gust record of as high as 40.1m/s as recorded at Tengah station, Northwestern of Singapore, April 1984. This area was observed to have a higher average number of thunderstorm occurrences compared to other areas due to Sumatran squalls from the northwest direction. This explains the difference of wind speeds obtained from stations located at Seletar and Changi, which the maximum of 9.3 and 7.9m/s respectively were recorded.

An extreme value analysis was subsequently performed on previous wind records to derive the values for wind load design with 50 years return period (Choi and Tanurdjaja, 2002). The recommended values were 32.0, 15.8 and 11.0 m/s for 3-s gust, 10-min mean and hourly mean respectively at a height 10m above the ground in open type terrain. The first two values should be considered for design if thunderstorms are frequent in the area concerned. The third value corresponds to an hourly mean value usually underestimates the structural response due to small scale events.

The site wind speed may be calculated by multiplying the basic wind speed with the appropriate factors to account for effects of exposure, aerodynamic shape as well as any dynamic response. A factor that accounts for the effects of probability may also be included if the design reliability was higher than the value that is obtained from

the 2% annual probability of exceedance for buildings of similar usage. The factors for altitude and terrain roughness have to be determined again through experimental means. The reason is that the winds that result from thunderstorms deviates from the traditional boundary layer profile and that the effect of terrain roughness is less pronounced compared to the monsoon wind. It should be noted that the abovementioned factors from the codes of practice for monsoon wind may still be conservative in some cases.

7.5.2 Dynamic component

The dynamic component of the building response includes all the dynamic effects due to wind action. When design against monsoon wind, this component considers the buffeting effect of the fluctuating wind speed. The calculation of the peak response due to this fluctuating component can be determined through the Gust Response Factor (GRF) method which was developed by Davenport (1961). This method has been widely accepted for the calculation of peak response of building structures with consideration of wind stochastic component.

The effects of dynamic wind actions are usually not considered in structural design unless the building is deemed to be dynamically sensitive. The building height needs to be above 100m or that its natural frequency falls below 1Hz in order to satisfy this criterion. Most modern building codes do allow such considerations and they group all dynamic effects into a coefficient C_{dyn} . This coefficient C_{dyn} is named the dynamic response factor and is assigned a value of 1.0 for all structures that are not classified as dynamically sensitive. The procedure that leads to the eventual value of C_{dyn} incorporates the GRF method in the calculation.

For the dynamic component for building response due to thunderstorms, the dynamic behaviour includes the effects due to the non-stationary mean as well as the stochastic component. The non-stationary mean results in fluctuation at lower frequency range and will not significantly contribute to the dynamic effect on a building compared to that of stochastic component. Therefore, the dynamic effect of the non-stationary mean wind is ignored with preference to the stochastic component which can also be viewed as the main contributing factor to the buffeting effect.

7.6 Implementation of design framework

The guideline for the design against winds resulting from thunderstorm events has been proposed in the previous sections. It is specified that both the non-stationary and the stochastic component of thunderstorm should be considered. It is noted that the framework follows closely the procedures for calculating the along wind response due to monsoon winds. Based on the analysis procedures using the Holmes and Oliver's model, a stochastic thunderstorm model has been established based on regression analysis. The wind load design against thunderstorms can then be carried out based on the assumption of a spectrum that accurately can be described during a typical downburst event. The Davenport spectrum used in the GRF method is replaced by the stochastic thunderstorm spectrum for wind load design against thunderstorms.

In this chapter, a single degree of freedom (SDOF) structure for wind load considering the effects of thunderstorms is demonstrated. The structure is of 15m height and the detailed properties are given in the Figure 7.1.

Figure 7.1 SDOF test structure

The wind load considered in the calculation is quasi-static and time-dependent. The response due to quasi-static wind load arises from the assumption of steady wind force. The time-dependent wind shows the non-stationarity and the effect of the gust wind on the dynamic behaviour of the structure in addition to the quasi-static wind load.

The magnitude of dynamic response due to wind generated by the code can be assessed by comparing the dynamic amplification factor of each selected thunderstorm data with GRF. The dynamic amplification factor of the structural response of SDOF structure is computed based on the thunderstorm time-history data. The dynamic response of the SDOF system subjected to different time-histories is calculated using the MATLAB program which utilizing the Duhamel's Integral. The peak factor used in GRF method is taken as unity for the purpose of comparison.

Figure 7.2 Dynamic and quasi-static response of SDOF structure

The typical thunderstorm wind speed time-history with the structural responses is shown in Figure 7.2. The actual dynamic response and the quasi-static response of the SDOF structure are depicted in the same figure. In the figure, the dynamic amplification factor is found to be 1.036. The input variables for the GRF method takes into account the site conditions such as the statistics of the collected monsoon wind data at a height of 15m. Given a level of 10% turbulence intensity, the GRF of 1.269 computed by the equations (7.3) to (7.7) when the Davenport spectrum is referenced. The Davenport spectrum is shown to be the governing spectrum even in the case of thunderstorms.

Data	Dynamic amplification factor
25-Mar-05	1.088
26-Mar-05	1.088
02-Apr-05	1.109
03-Apr-05	1.118
04-Apr-05	1.079
16-Apr-05	1.110
21-Apr-05	1.166
06-May-05	1.093
14-May-05	1.140
19-May-05	1.166
21-May-05	1.086
24-May-05	1.138

Table 7.1 Dynamic amplification factors of SDOF subjected to time-histories

The dynamic amplification factors of the SDOF structure subjected to different storm time-histories are summarized in Table 7.1. The values as shown vary due to the strong uniqueness of each thunderstorm time history. This uniqueness may be translated in terms of variability of the strength and storm path for each individual event. However, it should be pointed out that the difference in amplification may be attributed to the contribution of the non-stationary mean wind speed. This also implies that the non-stationary mean wind speeds do not significantly contribute to the resonant effect of the stochastic component of thunderstorm.

The peak structural response is calculated by the GRF method using an appropriate wind spectrum as input function. It is found that for all thunderstorm data tested, the structural response predicted by the GRF value of 1.269 by using the Davenport spectrum is very similar to the dynamic amplifications displayed by the dynamic response that is due to the wind speed time histories collected over a height of 15m.

Based on the findings from the comparison between the GRF value and the dynamic amplification factor, it is concluded that the dynamic effects is not

significant and the response predicted using the GRF method, which is implemented in the codes for design against monsoon winds, is conservative compared to that of the thunderstorm downburst. It is observed that the dynamic effects are mostly due to the resonant response of the structure due to narrowband excitation by the stochastic component rather than the slow varying non-stationary mean. The added dynamic responses that are found in thunderstorms are usually mild, due to the low frequency of the variation of the non-stationary mean. The non-stationary mean varies much slower than the stochastic component and usually consideration of the quasi-static response is a good approximation of the actual response. The quasi-static response may be calculated based on the ordinary provisions of any wind loading code. The resonant response that is due to narrowband excitation will include the effect that is due to any different terrain or gust size that has been taken into account.

Therefore, the dynamic response of stiff structures due to thunderstorms may be treated as an approximate quasi-static response based on site wind speed of a return period of 50 years. The choice of suggested averaging scheme is the 3-sec gust based on recommendations of the Australian/New Zealand wind loading code AS/NZS1170 (2002). Modifications should be made on the parameters to take into account the contribution from thunderstorms as well as the monsoons which jointly govern the wind environment of Singapore for different times of the year.

Chapter 8: Conclusion and Recommendations

This report presents a study of the stochastic thunderstorm component that is based on a new method of extraction. The data from a wind mast situated in the Nanyang Technological University (NTU) campus has been used in this study. This method is based on the theoretical model proposed by Holmes and Oliver (2000) simulating the physics expected of a thunderstorm downburst. The results from this new method have been compared with the results obtained from the moving average technique.

8.1 Conclusion

The usual method of applying the moving average of a suitable averaging window has several shortcomings. It is a numerical technique that does not have any physical reason behind it and it also tends to remove some of the frequency content that belongs to the lower frequency range. However, the new method requires more parameters like the spatial information on the rough proximity of the storm cell such that the horizontal profile of the wind speed follows the one predicted by the theory. This means that every thunderstorm data has to have the time-history compared against the theoretical profile. Some thunderstorm data may not be useful in providing information if the storm occurs far away from the collection site. In all, the new method requires a higher level of understanding into each storm event. Moreover, the effect of varying storm path on the magnitude of wind speeds recorded is difficult to deduce because the terrain roughness of the site is difficult to model. The amount of data collected is not enough to make a sound conclusion and the uncertainties of the storm parameters contributes to the difficulty. The use of Holmes and Oliver's model in obtaining the stochastic component may have

physical reasons but its use has been proved to be discouraging because the storm parameters need to be known for each individual event.

The stochastic component is also checked for stationary and Gaussian properties and is found to be similar to that of produced by 1-min moving average. The assumption of the Davenport spectrum is found to be conservative when thunderstorms are considered. However, more samples may be needed to reach a conclusion on the validity of using the Holmes' model in the extraction process. An expression for the wind spectrum of the stochastic thunderstorm component is proposed through the analysis of the data collected.

The provisions in the wind loading codes are reviewed and concepts are borrowed in the formulation of a design framework that accommodates the design of wind load due to thunderstorms. The Gust Response Factor method using a peak factor of unity is used to compare with any suspected dynamic effects due to non-stationary mean of thunderstorm time-histories and it is found to be satisfactory. The Gust Response Factors computed are found to be conservative when compared against structural response of a SDOF structure subjected to time-history loadings. A framework for design against thunderstorms is proposed based on the results from the tested data.

8.2 Recommendations

Thunderstorm occurrence has been a random process and its effect on wind loading of structures has not been included in most codes of practice. The severity of thunderstorms varies from country to country and its damage potential is dependent on the storm path. This non-uniformity has made research and codification difficult.

The wind mast at NTU has been immensely useful in capturing wind speeds during thunderstorms and allowing further understanding into the wind speed time-histories during thunderstorms. However, wind speeds have been observed to be mild in Singapore and capturing an extreme event is very unlikely.

Future research may focus on the understanding of the flow structure of a thunderstorm. This includes the use of wind tunnel facilities in actual simulated thunderstorm wind flow experiments and three-dimensional Computational Fluid dynamics software in computer analysis. The effect of ground roughness on downburst wind speeds may be investigated by the use of wind tunnel testing. The construction of an urban terrain model is extremely useful in investigating the effects of a thunderstorm downburst in an urban city environment.

Appendix A: Histograms of stochastic components

Figure A.1 Histograms of stochastic components from 25th Mar - 16th Apr 05

Figure A.2 Histograms of stochastic components from 21st Apr - 24th May 05

Appendix B: Spectra of stochastic components

Figure B.1 Spectra of stochastic components from 25th Mar - 16th Apr 05

Figure B.2 Spectra of stochastic components from 21st Apr - 24th May 05

References:

AS/NZS, Structural design actions, Part 2: Wind actions. AS/NZS 1170.2. 2002. Standards Australia/New Zealand.

BSI, Code of basic data for the design of buildings. Loading, Part 2, Wind loads: CP3. British Standards Institution; 1972 [chapter V].

BSI, British standard: loads for buildings, Part 2. Code of practice for wind loads: BS6399. British Standards Institution; 1997.

BSI, British standard: Eurocode 1: Action on structures- Part 1-4: General actions- Wind actions: BS EN 1991-1-4. British Standards Institution; 2005.

Caracena F, Holle RL, Doswell FA, Microbursts- A Handbook for Visual Identification. U.S. Dept. of Commerce, NOAA/ERL/NSSL, 1989.

Chen L, Letchford CW, Parameter study on the response of the CAAR building to downbursts in the time domain. 11th International Conference on Wind Engineering, Lubbock, Texas, 2-5 June, 2003.

Chen L, Letchford CW, A deterministic-stochastic hybrid model of downbursts and its impact on a cantilevered structure. Engineering Structures 2004; 26: 619-629.

Choi ECC, Extreme wind characteristics over Singapore- an area in the equatorial belt. Journal of Wind Engineering and Industrial Aerodynamics 1999; 83: 61-69.

Choi ECC, Wind characteristics of tropical thunderstorms. Journal of Wind Engineering and Industrial Aerodynamics 2000; 84: 215-226.

Choi ECC, Hidayat FA, Gust factors for thunderstorms and non-thunderstorm winds. Journal of Wind Engineering and Industrial Aerodynamics 2002; 90: 1683-1696.

Choi ECC, Tanurdjaja A, Extreme wind studies in Singapore- an area with mixed weather system. Journal of Wind Engineering and Industrial Aerodynamics 2002; 90: 1611-1630.

Choi ECC, Hidayat FA, Dynamic response of structures to thunderstorm winds. Prog. Struct. Engrg Material 2002; 4:408-416; John Wiley & Sons, Ltd.

Choi ECC, Field measurement and experimental study of wind speed profile during thunderstorms. Journal of Wind Engineering and Industrial Aerodynamics 2004; 92:

275-290.

Clough RW, Penzien J, Dynamics of Structures, second edition, McGraw-Hill Inc, 1993.

Davenport AG, The application of statistical concepts to the wind loading of structures. Proceedings of the Institute of Civil Engineers 1961: 19:449-472.

Draft Singapore Standard, Code of practice for wind loading on structures. 2002. Spring Singapore.

Engineering Sciences Data Unit, Calculation methods for along-wind loading. Part 3. Response of buildings and plate-like structures to atmospheric turbulence. ESDU Item 88019.

Fujita TT, The downburst. Report of Projects NIMROD and JAWS. University of Chicago, 1985.

Fujita TT, Andrews AFB microburst. SMRP Research Paper 205. University of Chicago, 1985.

Gomes L, Vickery BJ, On thunderstorm wind gusts in Australia, Civ. Eng. Trans. Ind. Eng. Aust. 18(1976) 33-39.

Hjelmfelt MR, Structure and life circle of microburst outflows observed in Colorado. Journal of Applied Meteorology 1988; 27:900-27.

Holmes JD, Modeling of extreme thunderstorm winds for wind loading of structures and risk assessment, in: Larsen, Larose, Livesey (Eds.), Wind Engineering into the 21st century, Balkema, Rotterdam, 1999.

Holmes JD, Oliver SE, An empirical model of a downburst. Engineering Structures 2000; 22: 1167-1172.

ISO, International standard: Wind actions on structures, ISO4354:1997. International Standards Organisation; 1997.

Kareem A, Analysis and modeling of wind effects on structures. IWEF workshop on CWE/CFD for Prediction of Wind Effects on Structures. Colorado State University, Fort Collins, Colorado, 9 August, 1996.

Lutes LD, Sarkani S, Random vibrations: analysis of structural and mechanical systems. Elsevier Butterworth-Heinemann 2004.

Osguera RM, Bowles RL, A simple analytic 3-dimensional downburst model based on boundary layer stagnation flow. NASA Technical memorandum 100632, July 1988.

Poreh M, Cermak JE, Flow characteristics of a circular submerged jet impinging normally on a smooth boundary. Sixth Annual Conference on Fluid Mechanics, Austin, Texas, September 1959.

Simiu E, Scanlan H, Wind effects on structures: an introduction to wind engineering. Second Edition. John Wiley & Sons 1986.

Stull R, Meteorology for Scientists and Engineers. Second Edition. Gary Garlson 2000.

Twisdale LA, Vickery PJ, Research on thunderstorm wind parameters. Journal of Wind Engineering and Industrial Aerodynamics 41(1992) 545-556.

Vicroy DD, Assessment of microburst models for downdraft estimation. Journal of Aircraft 1992: 29: 1043-8.

Whittingham HE, Extreme wind gusts in Australia, Bulletin No 46, Bureau of Meteorology, Melbourne, Australia, 1964.

Wood GS, Kwok KCS, An empirically derived estimate for the mean velocity profile of a thunderstorm downburst. 7th AWES workshop. Auckland, 1998.