Università degli Studi di Genova

Doctoral Thesis

Transient phenomena induced by thunderstorm outflows on slender structures

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Stefano Brusco

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UNIVERSITÀ DEGLI STUDI DI GENOVA

Abstract

PhD program in Civil, Chemical and Environmental Engineering
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Doctoral Thesis

Transient phenomena induced by thunderstorm outflows on slender structures

by Stefano Brusco

The climatology at mid-latitudes (for instance, Europe) is dominated by both extra-tropical depressions at the synoptic scale and by mesoscale thunderstorm outflows (also called downbursts). Thunderstorm outflows are non-stationary phenomena, complex and potentially devastating, which strongly differ from synoptic winds under many points of view (genesis, scale, duration above all). Consequently, the induced wind fields are highly different. Modern codes and guidelines are mainly based on the cyclonic model, because of the persistent lack of knowledge about thunderstorm outflows, in particular concerning full-scale measurements. On the other hand, severe wind damage is often induced by downbursts, especially concerning low- and medium- rise structures (e.g., cranes, small turbines, light poles, low-canopies).

The present PhD Thesis is collocated within the framework of the ERC THUNDERR Project. It investigates aspects connected with the aerodynamic loading of structures subjected to thunderstorm outflows, particularly focusing on the transient aerodynamics and transient aeroelasticity. This is firstly pursued through the definition of analytical formulations which, starting from compatible vertical wind fields, permit to evaluate the aerodynamic wind loading by using the strip and quasi-steady theory. The application of the procedures on selected slender test structures shows that a crucial role is played by thunderstorm-induced variations of the wind angle of attack, which may increase or reduce the structure response. The second part of the Thesis is devoted to an extensive experimental campaign carried out at the multiple-fan wind tunnel of the Tamkang University, Taipei, which is able to simulate unsteady flows. The sectional model of a sharp-edged square cylinder, equipped with 94 pressure taps, is investigated and numerous configurations of the flow parameters are considered in order to study the effects of acceleration on the aerodynamic loads and on the vortex-shedding from the body. The drag coefficients and the fluctuating cross-flow force coefficients connected with vortex shedding are found to be either comparable or definitely lower than their corresponding values for steady flows. Furthermore, discontinuities of the shedding frequency are present during the transients and their number and magnitude appear to be connected with the acceleration of the flow.

This Thesis is dedicated to the memory of
Professor Giovanni Solari

“*Wish you were here*”

Pink Floyd, 1975

Contents

List of Symbols

$\overline{A}$	mean of the random variable A
$\tilde{A}$	median of the random variable A
$E\left[A^n\right]$	moment of order n of A
$E\left[\left(A-\overline{A}\right)^n\right]$	central moment of order n of A
$< A >$	ensemble mean of A

U	wind speed
V_X	anemometric component of the wind directed from West to East
V_Y	anemometric component of the wind directed from South to North
γ	time-varying angle of attack
ρ	air density

$\overline{U}$	slowly-varying mean wind speed - classical decomposition
U'	wind speed fluctuation - classical decomposition
σ_U	slowly-varying standard deviation of the fluctuation - classical decomposition
I_U	slowly-varying turbulence intensity - classical decomposition
$\tilde{U}'$	reduced turbulent fluctuation - classical decomposition

$\overline{u}$	slowly-varying mean wind speed - directional decomposition
$\overline{\beta}$	slowly-varying direction of the mean wind speed - directional decomposition
u'	longitudinal turbulence component - directional decomposition
v'	lateral turbulence component - directional decomposition
σ_u	slowly-varying longitudinal standard deviation - directional decomposition
σ_v	slowly-varying lateral standard deviation - directional decomposition
I_u	slowly-varying longitudinal turbulence intensity - directional decomposition
I_v	slowly-varying lateral turbulence intensity - directional decomposition
$\tilde{u}'$	longitudinal reduced turbulent fluctuation - directional decomposition
$\tilde{v}'$	lateral reduced turbulent fluctuation - directional decomposition

x, y	alongwind and crosswind axes
X, Y	principal directions of the cross-section
n_1	natural frequency of the first mode
m_1	modal mass of the first mode
ξ_1	structural damping of the first mode
ψ_1	modal shape of the first mode
b	reference dimension of the body
$\overline{c}_D$	mean drag coefficient
$\overline{c}_L$	mean lift coefficient
$\overline{c}'_D$	angular derivative of the mean drag coefficient
$\overline{c}'_L$	angular derivative of the mean lift coefficient

u'_{eq}	longitudinal equivalent turbulent fluctuation

v'_{eq}	lateral equivalent fluctuation
$\tilde{u}'_{eq}$	longitudinal equivalent reduced turbulent fluctuation
$\tilde{v}'_{eq}$	lateral equivalent reduced turbulent fluctuation
$S_{\tilde{u}'_{eq}}$	PSD of the longitudinal equivalent reduced turbulent fluctuation
$S_{\tilde{v}'_{eq}}$	PSD of the lateral equivalent reduced turbulent fluctuation
$F_{\tilde{U}'_{eq}}$	Fourier transform of $\tilde{U}'_{eq}$
$F_{\tilde{u}'_{eq}}$	Fourier transform of $\tilde{u}'_{eq}$
$F_{\tilde{v}'_{eq}}$	Fourier transform of $\tilde{v}'_{eq}$
f_D	drag force per unit length
f_L	lift force per unit length
q_x, q_y	displacements along the x- and y- axes
q_X, q_Y	displacements along the X- and Y- axes
q_t	total displacement
ξ_{ay}	aerodynamic damping in the cross-wind direction
Sc	Scruton number
a_G	galloping coefficient
$\overline{u}_{cr}$	critical wind speed
$\tilde{\boldsymbol{M}}$	principal mass matrix
$\tilde{\boldsymbol{C}}$	principal damping matrix
$\tilde{\boldsymbol{K}}$	principal stiffness matrix
$\tilde{\boldsymbol{\Psi}}$	principal modal matrix
$\tilde{\boldsymbol{F}}$	vector of the principal wind actions
$\overline{\boldsymbol{f}}$	mean wind force
$\boldsymbol{f'}$	wind force associated with the incoming turbulence
$\boldsymbol{f_a}$	motion-induced force
$\tilde{\boldsymbol{C}}_{\boldsymbol{a}}$	principal aerodynamic damping matrix
$\boldsymbol{c_a}$	aerodynamic damping matrix
$\tilde{\boldsymbol{K}}_{\boldsymbol{a}}$	principal stiffness damping matrix
$\boldsymbol{k_a}$	aerodynamic stiffness matrix
$\boldsymbol{A}$	dynamic matrix
c_a	added mass coefficient
c_m	inertia coefficient
K_a	acceleration parameter
U_W	filtered wind speed through continuous wavelet transform-based technique
a_W	flow acceleration estimated through continuous wavelet transform-based technique
P_{dyn}	reference dynamic pressure
ΔP_D	difference of pressure in the alongwind direction
ΔP_C	difference of pressure in the crosswind direction
$c_{\Delta P_D}$	resistance coefficient
$c_{\Delta P_L}$	lift pressure coefficient
c_L	lift coefficient

P_s	static pressure
n_{VS}	shedding frequency
S	Strouhal number

Part I

Preliminaries

Chapter 1

Introduction

1.1 Mixed climatology: extra-tropical depressions and thunderstorms

Wind is the most destructive natural phenomenon, producing more fatalities and damage than any other natural event (Solari, 2019). Wind actions on structures are crucial to be determined for the social safety and economy. Guidelines and national codes support designers to protect structures to withstand wind actions with specific sections devoted to them. These are based on the model of the extra-tropical depression, or extra-tropical cyclone, whose effects dominate the climatology of large part of the world (Solari, Burlando, et al., 2020). Extra-tropical depressions are well known in their genesis and evolution (Figure 1.1). Their effects have consequences on a large horizontal scale (synoptic scale), being their geographical extensions in the order of thousands of kilometers and lasting for days. Their study in the course of the years allowed Alan Garnett Davenport to formulate the classical solution of the dynamic alongwind response of structures (Davenport, 1961).

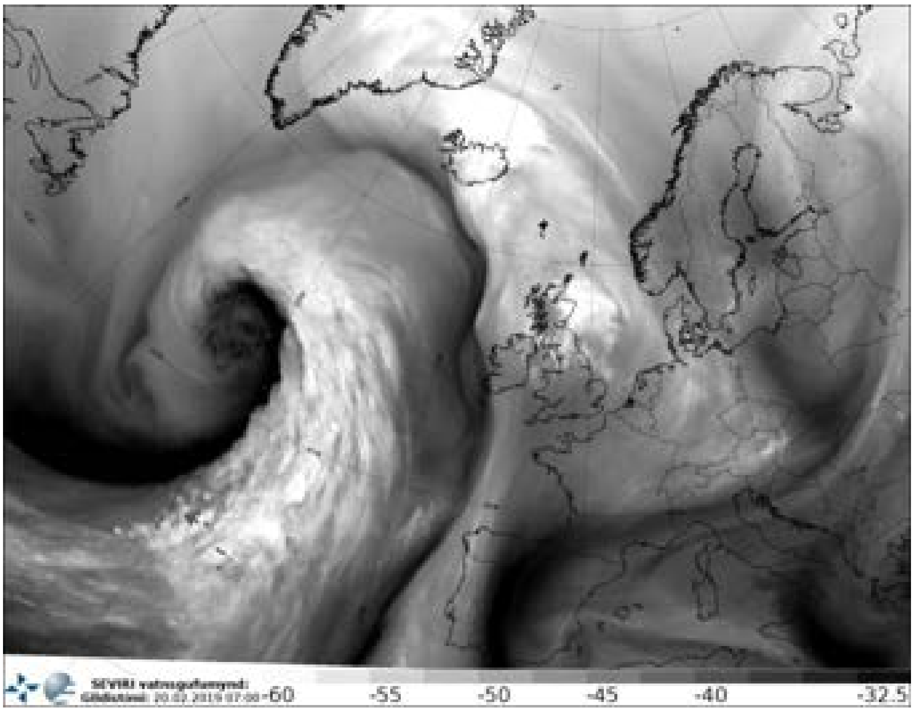


FIGURE 1.1: Extra-tropical depression on the Atlantic Ocean; source: *https://weatheritalian.wordpress.com.*

Davenport's formulation considers the wind generated from an extra-tropical depression (synoptic wind) in a neutral atmospheric condition, assuming that the wind velocity in a time interval between 10 minutes and 1 hour may be studied as a stationary Gaussian process (Van der Hoven, 1957). Moreover, its vertical profile is assumed to grow with the height, generating an atmospheric boundary layer with a depth in the order of 1-3 $[Km]$. Considering the turbulence as small, and neglecting the effect of the quadratic term of the fluctuation, the wind velocity may be converted into an aerodynamic action which, in turn, is still Gaussian. The aerodynamic loading is applied on a structure which is considered as linear. This permits to consider also the dynamic response as a Gaussian quantity, which is investigated by studying the up-crossings of a threshold, considered as rare and independent. The resulting probability density function (PDF) is sharp and narrow, allowing its mean value to be representative of the maximum response. This process, nowadays robust and consolidated, is known as the *Davenport chain*. It constitutes the foundation of the whole set of guidelines and codes in the world to evaluate wind actions on structures.

However, the climatology at mid-latitudes (for instance, Europe) is dominated either by extra-tropical depressions and by mesoscale thunderstorm outflows or downbursts (Solari, 2020). These are non-stationary phenomena, complex and potentially devastating, which strongly differ from synoptic winds. Knowledge about thunderstorms has been gained in the early 1950s, when Byers, an American meteorologist, led the *Thunderstorm Project* (1946-1947). A thunderstorm is a cloud or a cluster of clouds that produces thunder, lightning, heavy rain. It may also give rise to hail, tornadoes and strong winds, the downbursts. Thunderstorm clouds are named Cumulonimbus. The final report of the project (Byers and Braham, 1949) describes the evolution of the cell through three stages. The first one is the cumulus stage (on the left in Figure 1.2), in which hot and moist air moves towards the top of the troposphere. This is strictly associated with a high level of instability of the atmosphere. The second stage (in the middle of the picture) is the mature one. This phase is linked to the high impact weather factors (lightning, tornadoes, downbursts...) mentioned before. Finally, a downdraft of cold air impinges over the terrain, generating a sudden wind field and a drop of temperature. Eventually, the thunderstorm loses strength in the final dissipation stage (on the right of Figure 1.2). The entire process may last less than 30 minutes.

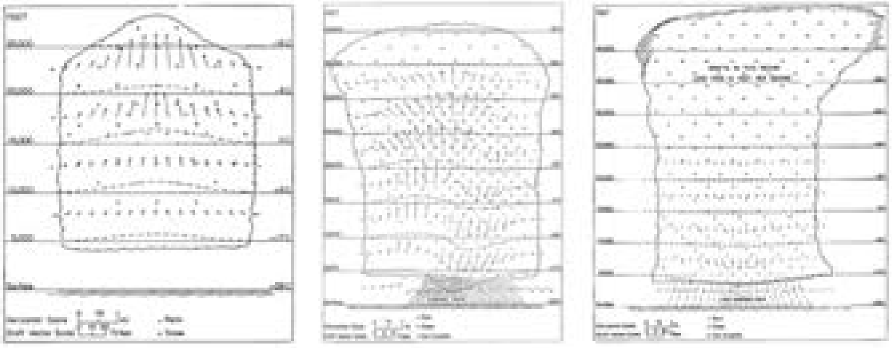
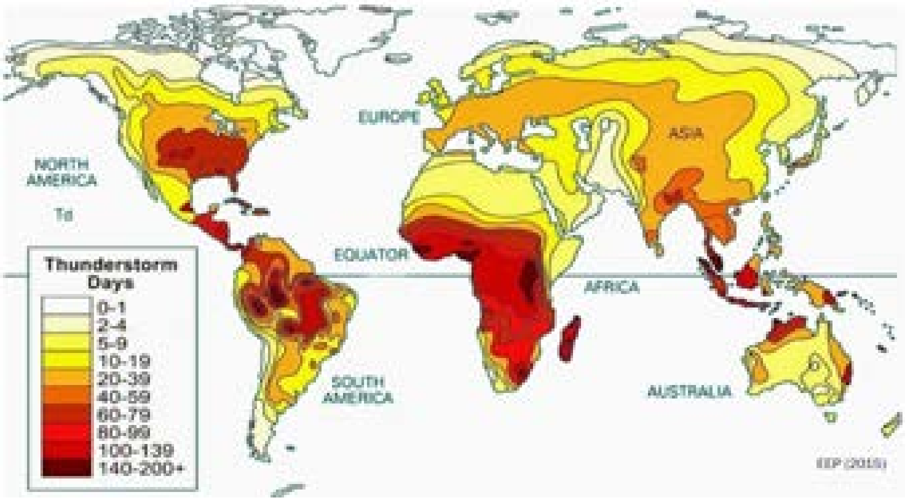
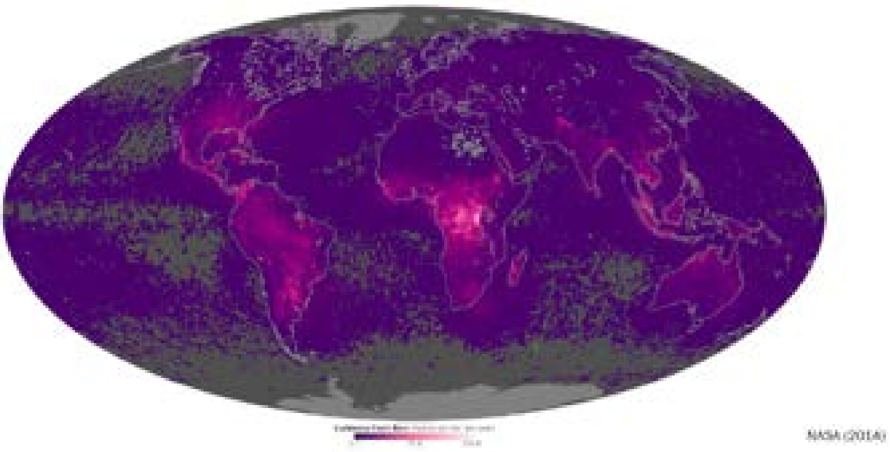


FIGURE 1.2: The cycle of the evolution of a thunderstorm cell; the figure is after (Byers and Braham, 1949).

Every year, 16 millions of thunderstorms strike the Earth's surface. At any given time, there are 2000 thunderstorm cells active (Solari, 2019). Their global distribution is represented in Figure 1.3A, which highlights that the regions crossing the Equator are the ones most likely to be subjected to the action of a high number of thunderstorms. This is associated with the high instability of the atmosphere in this area. The outcome is also reflected by the global map of lightning (Figure 1.3B), which points out the same regions as before. This is unsurprising, since it has been said that lightning constitutes one of the major high impact weather factors related to to thunderstorms.



(A) Global downburst climatology; the figure is after *Electrical Engineering Portal*.



(B) Global lightning distribution; the figure is after *NASA*.

FIGURE 1.3: Global maps associated with thunderstorms.

Pictures of thunderstorms coming from three different continents (Australia, America and Europe) are furnished in Figure 1.4. Often, thunderstorms are associated with wind of limited magnitude. On the other hand, their dangerousness has been firstly noted one hundred year ago, when the aviation started to be developed. In the history, there have been many dramatic accidents of aircraft and dirigibles entered thunderstorms and crashed, following the action of the updraft or of the downdraft. This was actually the reason of the development of the *Thunderstorm Project*.

(A) Thunderstorm in Brisbane, Australia (2016); source: *www.centrometeoitaliano.it* .

(B) Thunderstorm in Kansas, US (2014); source: *www.express.co.uk* .

(C) Thunderstorm in Sergnano, Italy (2019); source: *www.cremaonline.it* .

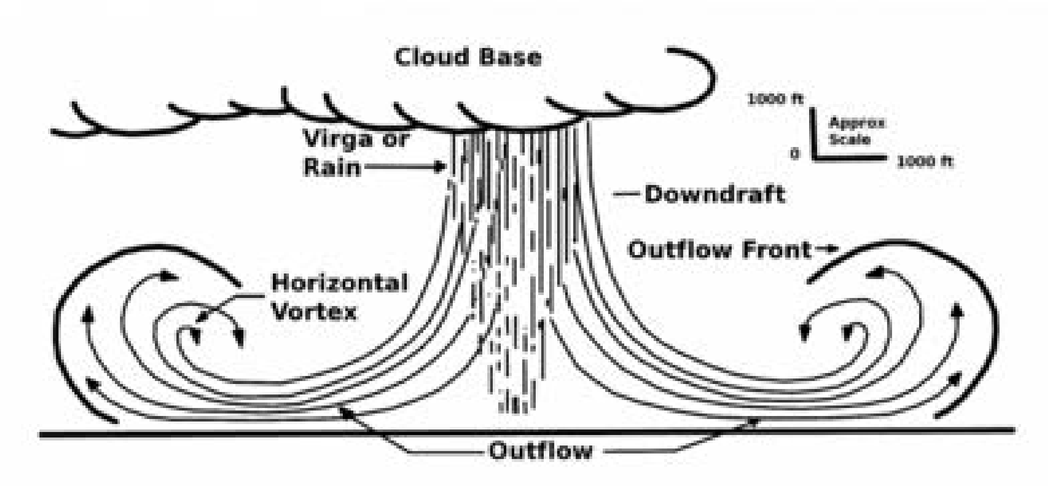
FIGURE 1.4: Pictures of thunderstorms from three continents.

Hence, after the Fifties, thunderstorms have been studied in order to make the flights safer, as it is discussed in the next section. On the other hand, awareness about the importance about thunderstorm outflows arose also in the Wind Engineering community. Davenport himself (Davenport, 1968) recognised the need for more specific studies for these phenomena, which may be treated separately from synoptic winds. This concept was considered by Gomes and Vickery, while developing the map of the extreme wind speeds in Australia (Gomes and Vickery, 1978). They separated thunderstorm outflows from non-thunderstorm ones, and carried out independent analyses for each of the sub-sets. Eventually, they derived the mixed statistical model, which provided the expected design wind velocity concerning a certain return period for thunderstorm outflows and for non-thunderstorm winds. Nowadays, there is a spread conviction that wind speeds associated with high return period are, for mixed wind climate regions, often induced by thunderstorm outflows. In particular, Letchford, Mans and Chay (Letchford, Mans, and Chay, 2002) pointed out the importance of thunderstorm winds in Australia (taking up the findings obtained by Gomes and Vickery and by (Whittingham, 1964)), US, South Africa and Argentina. Also (Solari, 2014), stated that "*design wind velocities with mean return periods greater than 10-20 years are often associated with such phenomena*".

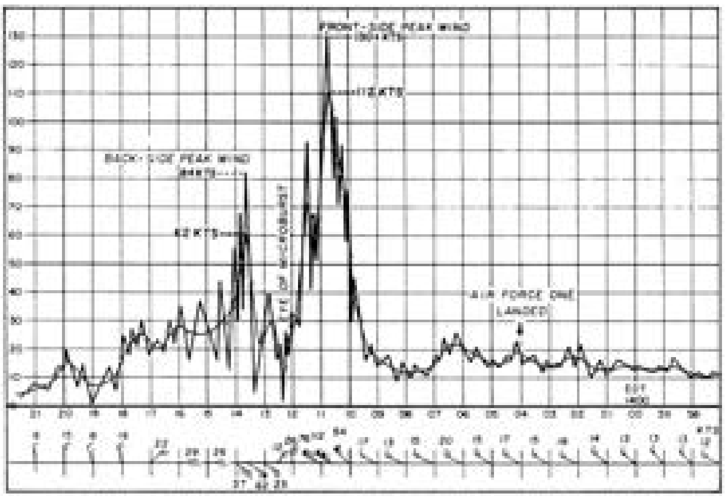
Extra-tropical depressions and thunderstorms are profoundly different phenomena under many points of view (genesis, scale, duration ...). This fact has to be reflected on the relevant wind fields, which in fact are anything but similar. General characteristics of the wind field relative to thunderstorm outflows are provided in the next paragraph.

1.2 Thunderstorm outflows or downbursts

In the Seventies and in the Eighties, three projects were launched in US by the national government, to support full-scale measurements of thunderstorm outflows. These are named NIMROD (Northern Illinois Meteorological Research on Downburst, 1978), JAWS (Joint Airport Weather Studies, 1982) and MIST (Microburst and Severe Thunderstorms, 1986). They provided an extensive set of data about the wind field associated with thunderstorm outflows. One of the most prominent scientist in the field has been Fujita, who, also collaborating with Wakimoto, realised that the downdraft impacting Earth's surface produces radial outflow and ring vortices (Fujita, 1981; Fujita and Wakimoto, 1981; Fujita, 1985; Fujita, 1990). Fujita himself called the whole ensemble as "*downburst*" (Figure 1.5A), distinguishing the cases of a "*macro-burst*" and of a "*micro-burst*". The first is characterised by a size greater than 4 [Km], whereas the seconds is smaller in size.



(A) Downburst.

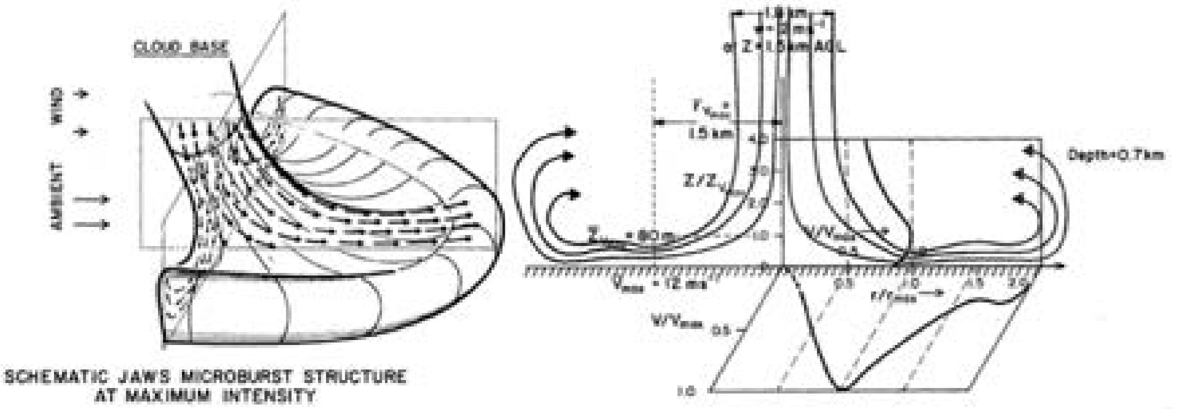


(B) Time-history of a thunderstorm outflow.

FIGURE 1.5: Scheme and measurements by Fujita; the figures are after (Fujita, 1985).

Furthermore, Fujita provided a fundamental additional contribution, providing a link between meteorological aspects and wind field properties. He reported a time-history of a wind speed signal recorded on the 1^{st} of August 1983 by an anemometer close to the ground at the Andrews Air Force Base (Figure 1.5B). The time-history is highly different than what usually

related to a synoptic wind, being characterised by an evident non-stationarity. Moreover, the intensity of the wind speed appears as high, exhibiting a gust speed up to 149 [*mph*]. Fujita noted that the wind speeds relevant to thunderstorm outflows are lower than the ones induced by a tornado. However, tornadoes are much rarer and smaller, therefore downbursts may well have a strong impact on the safety of structures.
In the same years, Hjelmfelt (Hjelmfelt, 1988; Hjelmfelt et al., 1989) has been another prominent scientist in the field of thunderstorm. He focused on the causes, morphology and life cycle of thunderstorms. In particular, he provided articulated schemes of the wind field induced by a thunderstorm, focusing on the possible effects of a background wind speed (Figure 1.6A), and furnishing average values of structural features of thunderstorm outflows (Figure 1.6B).



(A) Action of the ambient wind on the wind field of the downburst.

(B) Wind field generated by a thunderstorm.

FIGURE 1.6: Schemes relative to the structure of thunderstorm outflow; the figures are after (Hjelmfelt, 1988).

Moreover, he clarified a concept already anticipated by (Goff, 1976). The vertical profile of a thunderstorm outflow does not increase with the height, as for a synoptic wind. It has a nose-like profile that increases up to a certain level, and then decreases (Figure 1.7).

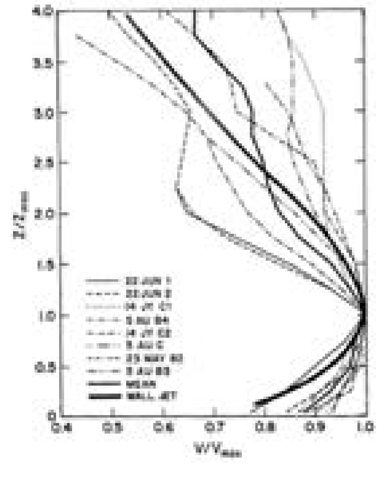


FIGURE 1.7: Vertical wind profile of a thunderstorm outflow; the figure is after (Hjelmfelt, 1988).

The amount of measurements gathered in the years and, even more, the use of Doppler radar to detect thunderstorms and tornadoes allowed a strong reduction of accidents induced by downbursts on jets and flights, as documented by *The Washington Post* in 2014 (Figure 1.8).

Capital Weather Gang

Defeating the downburst: 20 years since last U.S. commercial jet accident from wind shear

By Mike Smith

FIGURE 1.8: Article by *The Washington Post* in 2014.

However, Doppler radar could not prevent the damage induced by thunderstorm outflows on structures and forests (Figure 1.9).

FIGURE 1.9: Trees felled by straight-line winds in Minnesota, 2011; source: *www.nssl.noaa.gov.*

In particular, structures may deeply suffer the action of thunderstorm outflows. This seems true for low- and medium-rise structures and building. The nose-like profile is strongly enhanced in correspondence of their elevation, reaching high wind speeds that cannot be predicted by employing the model of the extra-tropical depression. Figure 1.10 proposes a representation of this statement. Two structures, a medium-rise one (a crane) and a tall one (the World Financial Center in Shanghai), are subjected to possible vertical wind fields associated with a synoptic wind (in blue, with legend ETD = extra-tropical depression) and to a thunderstorm outflow (in red, T = thunderstorm). This picture points out that the low- and medium- rise building is exposed to wind actions that are much greater than the ones induced by blue profile. Conversely, a tall building may be less affected by that discrepancy, since for high elevations the synoptic winds dominates in terms of speed and, consequently, in terms of loading.

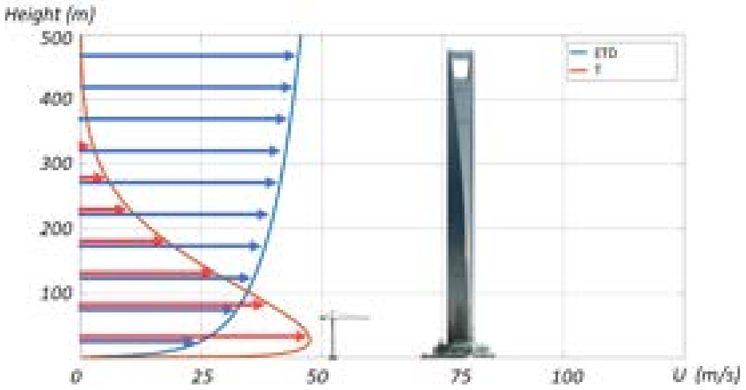
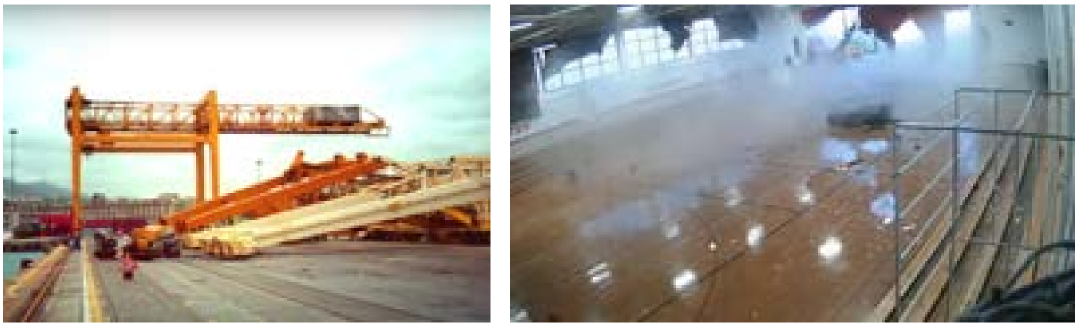


FIGURE 1.10: Comparison between vertical profiles caused by an extra-tropical depression and a thunderstorm; the figure is after (Lerzo, 2018).

Also in the light of what expressed before concerning the design wind speed, it is unsurprising to note that severe wind damage of low- and medium- rise structures (namely cranes, small turbines, light poles, canopies, ...) is often associated with thunderstorm outflows (Figure 1.11).



(A) Seaport of Genoa, 1994, (Solari, 2020). (B) Gym in North Carolina, 2020; source: *www.cnn.com*.

FIGURE 1.11: Damage caused by downbursts.

(A) Iowa, 2020; source: *www.accuweather.com*. (B) South Brazil, 2006; the figure is after (Alminhana, Albermani, and Mason, 2016).

FIGURE 1.12: Transmission lines collapsed following downbursts.

To this point, a striking comment has been made by (Kwon and Kareem, 2009), who stated that: "... *the traditional velocity profile does not exist; rather it bears an inverted velocity profile with its maxima near the ground potentially exposing low- to mid-rise structures to* *higher wind loads.*". Real structures that mostly suffer the largest number of collapses and the most extensive damage due to thunderstorms are transmission lines and towers (Figure 1.12). In the last twenty years, numerous scientists put effort to study the effects of thunderstorm outflows on structures. In particular, traditional wind tunnels have been modified to allow the reproduction of peculiar aspects of the phenomenon, first and foremost the non-stationarity. Moreover, novel facilities have been realised to simulate their phenomenon in a bigger scale. This is the case of the WindEEE Dome (Figure 1.13), where the phenomenon is reproduced by a jet on the ceiling of the dome which impinges over the floor, as a downburst over the Earth's surface.

FIGURE 1.13: Simulation of a downdraft in the WindEEE Dome, at the University of Western Ontario; source: *www.navigator.innovation.ca*.

However, today there is not yet a shared and common view about the representation and the modeling of thunderstorm outflows. In fact, these topics are still full of uncertainties (Solari, 2014). Thunderstorm outflows are complex phenomena, for which it is difficult to propose simple and reliable models, able to capture their prominent characteristics, as accomplished for the synoptic winds. Moreover, their short duration and limited extension do not allow the traditional wind monitoring networks to detect their passage. Indeed, these are usually realised with stations placed at 50-100 [Km] one from the other, and the output of such measurements is usually a mean value over a period of time, which is between 10 minutes and 3 hours. This choice is implicitly linked to the synoptic winds, and therefore thunderstorm measurements are lost.

The absence of robust field data and the limited knowledge about a model to represent thunderstorm outflows are also reflected into the definition of methods to evaluate the loading and response of structures subjected to these events. In fact, there cannot be yet a shared and established chain to support designers to protect structures, as the *Davenport chain* allows for synoptic winds. There are codes (e.g., ASCE 7-16) which perform a separation between thunderstorm and non-thunderstorms storms, enabling the separation of the phenomena. On the other hand, to make matters worse, it might happen that in the rare cases in which the mixed statistical analysis is made, the thunderstorm-induced wind speeds are used as the input for the traditional *Davenport chain*. This constitutes a huge distortion, which completely rules out the noteworthy differences between synoptic and thunderstorm winds.

In the last years, since 2007, the WinDyn Group (Wind Engineering and Structural Dynamics Research Group) of the University of Genoa has been persevering the study of thunderstorm outflows. After the first years of research, the European Research Council (ERC) has granted Prof. Giovanni Solari and his Research Group an Advanced Grant 2016. Generalities about this topic are provided in the following section.

1.3 The ERC THUNDERR Project

The ERC Advanced Grant 2016 led to the project THUNDERR (Figure 1.14), "*Detection, simulation, modeling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures*". It is an acronym, since THUNDER stands for THUNDERstorm, and the last R points out the Roar with which the project aims at tackling the subject.

FIGURE 1.14: ERC Advanced Grant 2016.

This prestigious grant has been assigned to Prof. Giovanni Solari, the Principal Investigator of the project, after the remarkable results obtained during four previous/ongoing projects. The first and the second are the European projects "*Wind and Ports*", (Solari, Repetto, et al., 2012), and "*Wind, Ports and Sea*", (Repetto et al., 2018). The third has been supported by Compagnia di San Paolo, "*Wind Monitoring, simulation and forecasting for the smart management and safety of port, urban and territorial systems*". The fourth has been granted by the Italian Ministry for Instruction, University and Research, "*Measurement and representation of wind actions and effects on structures*" (PRIN 2015 - 2019).
The first two focused on the safe management and risk assessment of the main ports in High Thyrrenian Sea. An extensive wind monitoring network has been realised, equipped with 28 ultrasonic anemometers in the Ports of Genoa, La Spezia, Livorno, Savona, Bastia, and L' Île-Rousse (Figure 1.15). Moreover, three LiDAR profilers and three meteorological stations have been installed as well.

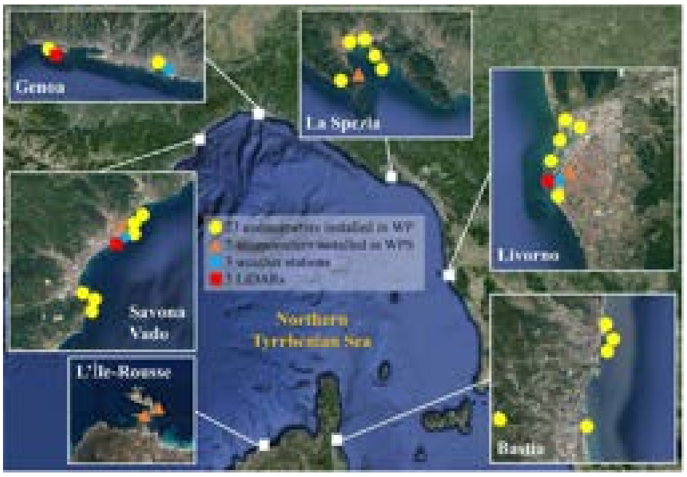
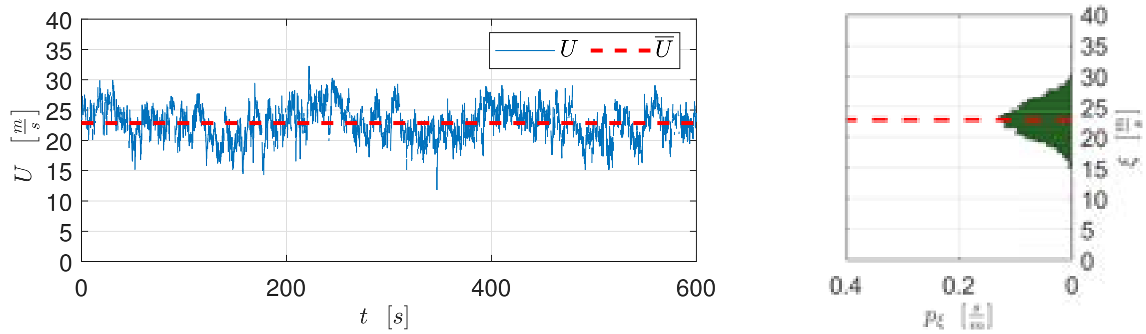


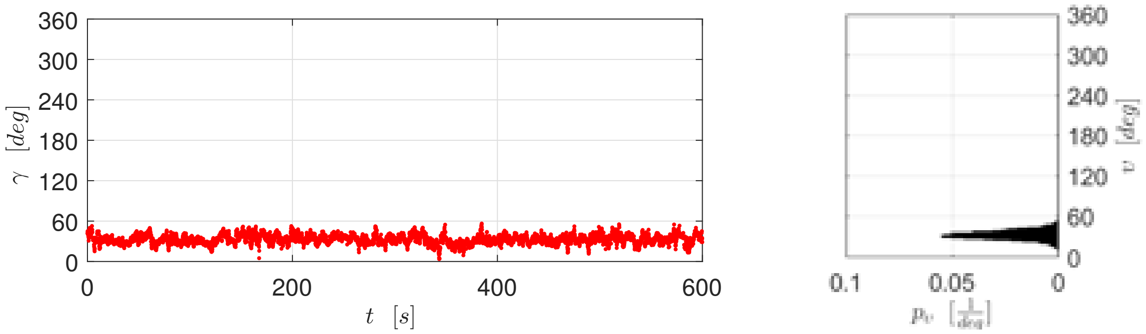
FIGURE 1.15: Wind monitoring network in the northern Thyrrenian Sea; WP shortens "*Wind and Ports*", while WPS means "*Wind, Ports and Sea*".

The anemometers were mounted on high-rise towers or on antenna masts at the top of building, at heights never lower than 10 $[m]$ and in positions were no local effects could contaminate the measures. The sampling frequency for the anemometers is 10 $[Hz]$, except for the devices in Bastia, whose sampling frequency is set at 2 $[Hz]$. The precision of wind measurements is up to 0.01 $\left[\frac{m}{s}\right]$ for its intensity and up to 1 $[degree]$ for the direction. As it is clarified by Figure 1.15, the anemometers are quite close to each other in a single port area. The first analyses carried out on the huge amount of data pointed out a typical mixed climatic condition (Solari, 2014). Different wind phenomena interest the area, as testified by the anemometer recordings (Figures 1.16, 1.17). These two graphs show the time-histories of the wind speed U and of the flow direction γ, as well as their relevant PDFs. The red dashed line in the plots of the wind speed draws the mean value of U, $\overline{U}$. It was then possible to distinguish between signals associated with extra-tropical depressions and thunderstorms.



(A) Time-history of the wind speed.

(B) PDF of the wind speed.



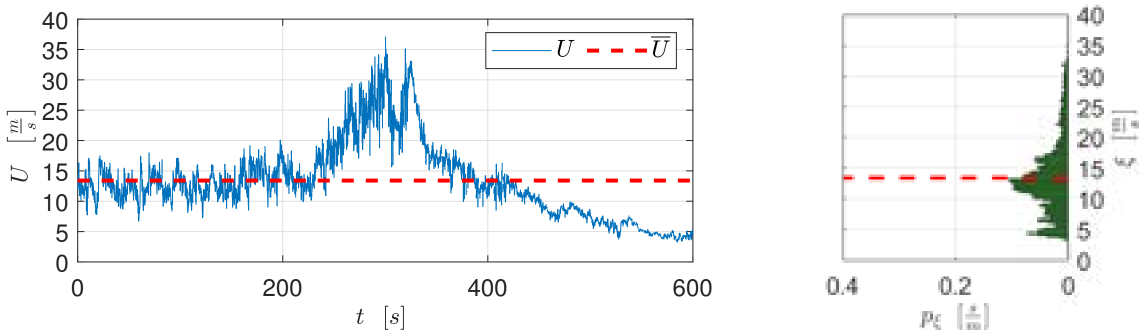
(C) Time-history of the direction.

(D) PDF of the direction.

FIGURE 1.16: 10-minute signal associated with an extra-tropical depression, recorded in Livorno.

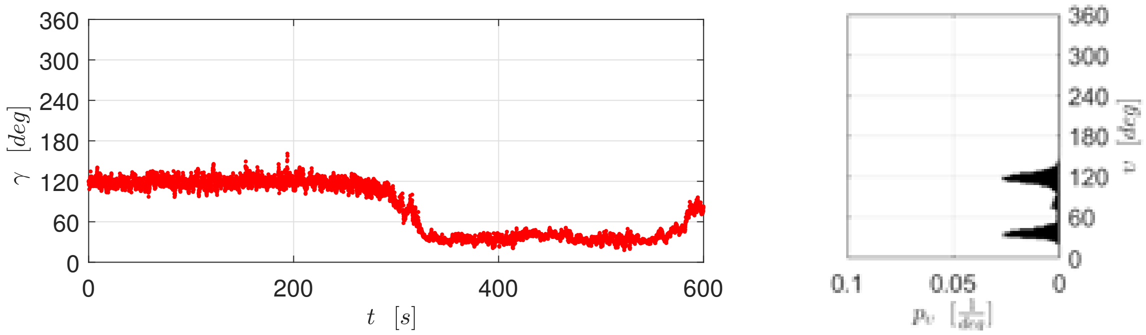
The first ones are characterised by large mean wind velocities and small gust factors. The fluctuating part of the signal may be considered as a realisation of a stationary and Gaussian process. The wind direction is regular in time.

Events caused by thunderstorm outflows are usually associated with small mean wind speeds and large gust factors. The relevant turbulence is a non-stationary and non-Gaussian random process. The wind direction may exhibit remarkable changes. A third family of wind signals concerns stationary and non-Gaussian events, named as gust fronts (Solari, 2014).



(A) Time-history of the wind speed.

(B) PDF of the wind speed.

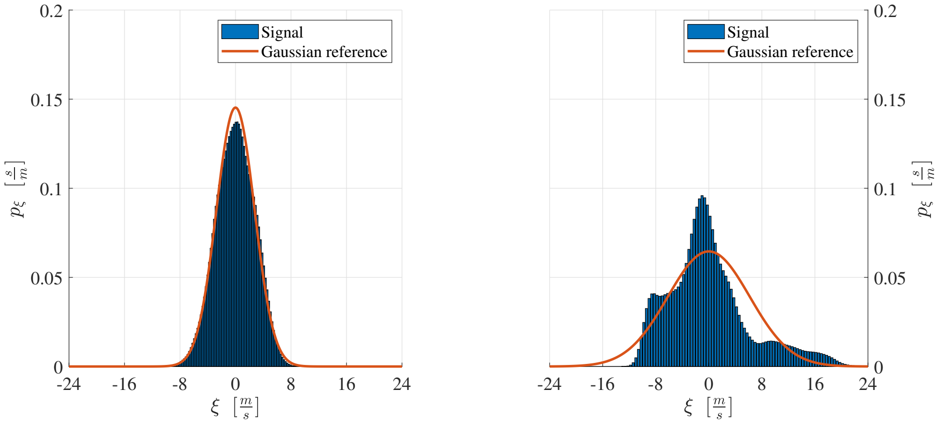


(C) Time-history of the direction.

(D) PDF of the direction.

FIGURE 1.17: 10-minute signal associated with a thunderstorm, recorded in La Spezia on 25^{th} of October, 2011.

Figure 1.18 shows an even more direct comparison between the PDFs of the residual fluctuation (which is the signal subtracted of its mean value) of the event recorded in Livorno and in La Spezia. The orange line is the Gaussian reference, drawn by imposing the same mean and the standard deviation of the sample.



(A) Synoptic wind in Livorno.

(B) Thunderstorm outflow in La Spezia.

FIGURE 1.18: PDF of the fluctuating component of U, U', and comparison with the Gaussian reference for the two events shown before.

Thunderstorms have been classified considering the duration (Burlando, Zhang, and Solari, 2018), defining time-scales of 10-minute, 1- and 10-hour.

Initially, 93 transient events have been extracted from the database (Solari, Burlando, et al., 2015). In a second phase, more than 250 transient recordings have been gathered (Zhang, Solari, De Gaetano, et al., 2018). The first extreme wind speed analyses carried out after 6 years of measurements revealed that wind events with a high return period in specific locations of the High Thyrrenian Sea (namely Livorno and La Spezia) are likely to be associated with thunderstorm outflows (Zhang, Solari, Yang, et al., 2018). As a matter of fact, the mixed extreme distribution for high return period tends to coincide with the thunderstorm distribution. Not to distinguish between the two phenomena leads to an ensemble distribution which underestimates the extreme peak wind speed, particularly for high return period.

The other two projects mainly focused on downburst wind field and wind loading of structures. In particular, concerning to this latter task, it was observed that thunderstorm outflows are transient events and, usually, the dynamic response to such phenomena is evaluated by response spectrum technique (as in the case of earthquakes). This inspired a new line of research, firstly taken up by converting the wind measurements into an identically coherent wind field for single-degree of freedom systems (Solari, De Gaetano, and Repetto, 2015). Besides, the study has been extended to multi-degree of freedom systems (Solari, 2016), introducing suitable methods to take the aerodynamic admittance into account. Moreover, time-domain analyses (Solari, Rainisio, and De Gaetano, 2017) showed that the probability density function of the maximum value of the structural response induced by thunderstorm outflows is more spread than the one associated with synoptic winds.

The THUNDERR project aims at firstly dealing with the thunderstorm as a physical phenomenon, seeking the definition of an unitary model. To pursue this aim, the monitoring network has been enhanced with the installation of new 10 ultrasonic anemometers at the end of 2019 in Genoa. Furthermore, a Windcube 400S pulsed LiDAR scanning system by Leosphere has been installed in the Port of Genoa on 18^{th} of April 2018. Secondly, it pursues the definition of methods to evaluate thunderstorm-induced loading on structures and to assess the dynamic response. In particular, the THUNDERR Project aims at developing three complementary methods to evaluate the wind-induced loading. These are the response spectrum technique, time-domain analysis and the non-stationary random dynamics by the evolutionary power spectral density (EPSD) model. As far as the already mentioned response spectrum technique is concerned, its results have been checked with the time-domain solutions, providing a satisfying agreement (Solari and De Gaetano, 2018). Besides, an evolutionary spectral density model of thunderstorm outflows has been proposed in 2020 (Roncallo and Solari, 2020).

This PhD Thesis is collocated in this branch of the project. In particular, it concerns thunderstorm-induced loading on slender structures through numerical and experimental methods. Deeper details about its outline are provided in Chapter 2.

Chapter 2

Outline of the Thesis

This chapter illustrates from a general viewpoint the structure of the Thesis.

The Thesis deals with the transient aerodynamics and transient aeroelasticity of slender structures subjected to thunderstorm outflows. These topics have extreme relevance with regards the wind loading and the dynamic response of slender structures to transient events.

Bluff-body aerodynamics is the discipline that establishes the principles to transform the undisturbed flow field into a pressure or force field acting on a bluff-body. The wind-induced pressure and forces acting on a structure are usually evaluated by assuming the flow to be incompressible and by invoking the strip and quasi-steady theory (Kawai, 1983). This allows one to derive them from the knowledge of the kinetic pressure (i.e. the kinetic energy per unit volume, $\frac{1}{2}\rho U^2$) of the undisturbed wind field and of adequate pressure and force coefficients, which are treated as constant quantities and estimated in wind tunnels reproducing steady flows. This procedure is well-consolidated when studying effects on structures induced by synoptic winds, which have indeed steady characteristics in both wind speed and direction. On the other hand, the transient nature of thunderstorm outflows might subvert its application, making the coefficients time-varying functions, as the kinetic pressure. Consequently, the aerodynamic actions would have to be evaluated through convolution products. It is unclear whether these effects associated with thunderstorm outflows have to be taken into account in the assessment of the structural response. Concerning this topic, a deep discussion is ongoing within the Wind Engineering community.

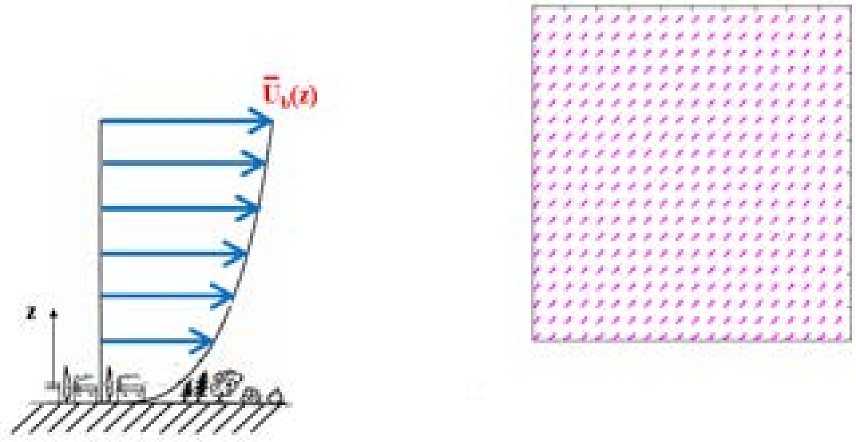
Conversely, at the author's best knowledge, transient aeroelasticity is still a subject completely ignored in the literature, if not by isolated papers which highlight the interest towards the topic (Kareem and Wu, 2013). Aeroelastic phenomena may lead to various types of structural instability, exposing the structure to high risk of collapse (e.g., resonant vortex-shedding in lock-in regime, galloping, flutter, torsional divergence). The potential insurgence of such phenomena is always studied by considering that a long time (usually, in the order of minutes) is provided to the fluid and the structure to interact between them, allowing the building-up of the instability. This situation seems to well picture the effects of synoptic winds on structure, whereas it might be questionable in presence of thunderstorm outflows.

Transient aerodynamics and transient aeroelasticity are investigated in the following, with two different approaches. The first aims at investigating both the transient aerodynamics and transient aeroelasticy of slender structures to determine the relevant aerodynamic loading and dynamic response. Their definition is accomplished by invoking the strip and quasi-steady theory, which permits to use the traditional aerodynamic coefficients. This is made by implicitly considering that the passage of the gust front is moderately slow (Solari et al., 2015; Zhang et al., 2018; Mason, Yang, et al., 2016). Consequently, any sort of effect on the bluff-body aerodynamics induced by the change of wind speed and direction is neglected. In this phase, vortex-shedding phenomenon is neglected in the analyses and the aeroelasticity is investigated by considering the transversal galloping. Conversely, the second approach challenges the application of the strip and quasi-steady theory, exploring the effects of accelerating flows on structures. This is firstly investigated by analysing anemometric signals, and estimating

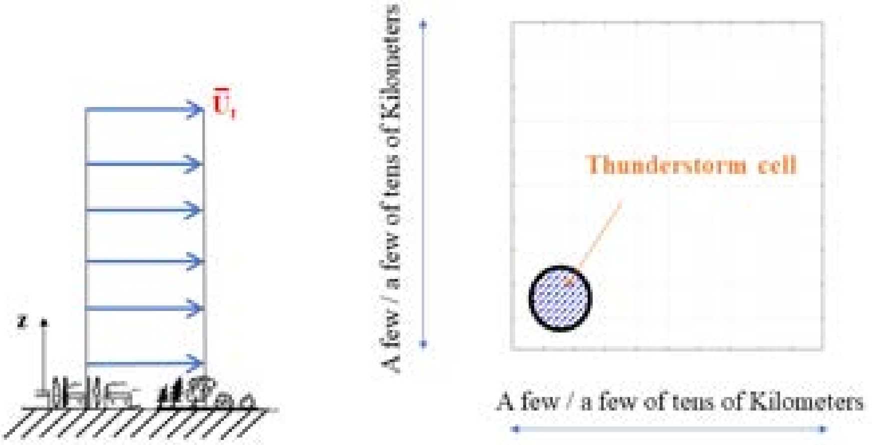
acceleration-induced forces. Moreover, an experimental campaign has been carried out in the multiple-fan wind tunnel of the Tamkang University, in Taipei, on a rigid model. Therefore, in this case the aeroelasticity has not been investigated, and the analyses concern the transient aerodynamics only. The acceleration reproduced in the wind tunnel are consistent with thunderstorm anemometric measurements. The results obtained are not omni-inclusive of the whole set of cases investigated in the first part of the Thesis. However, they provide first precious pieces of information about the reliability of the methodology adopted in there.
Therefore, it seems justified the separation of the Thesis in two distinct parts, named as "*On the dynamic response of slender structures through the strip and quasi-steady theory*" (Part II) and "*Effects induced by accelerating flows on rigid slender structures*" (Part III). A general and brief introduction to them is given in the two following sections, depicting how these are articulated.

2.1 On the dynamic response of slender structures through the strip and quasi-steady theory

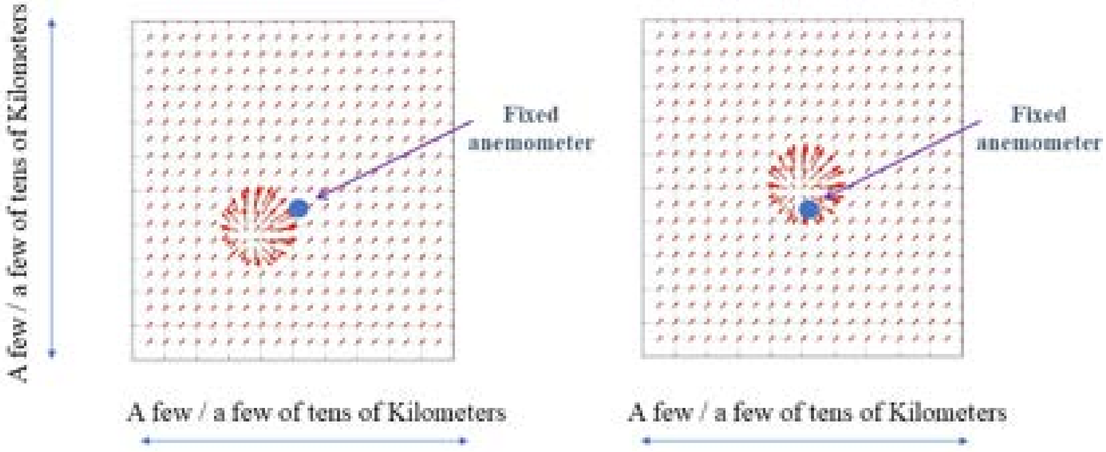
In the Thesis, the aerodynamic loading and the dynamic response of slender structures are evaluated through time-domain analyses. Well-suitable techniques are introduced to take the non-stationarity of the wind speed into account, but also to consider other interesting aspects related to thunderstorm outflows, above all the potential change of the direction of the wind event. In fact, literature is rich about methodologies to define a slowly-varying mean wind speed from a signal of a thunderstorm outflow, which is separated from the residual non-stationary fluctuation. The first authors to put forward this separation have been (Choi and Hidayat, 2002), who applied a simple moving average technique. This has been followed by many other techniques, often more advanced and complicated, for instance involving wavelets, e.g. (Su, Huang, and Xu, 2015). On the other hand, the same effort has not been devoted to study the role of the change of the direction. This has been discussed from a qualitative point of view, e.g. (Holmes et al., 2008). This is induced by the simultaneous actions of wind fields associated with different nature. In fact, the wind field directly induced by the downdraft (Figures 1.6B) is not the only one acting, but is potentially flanked by other two effects. These are the background wind speed (Figure 2.1A, as already noted by (Hjelmfelt, 1988) and discussed in Chapter 1), and the translational wind speed (associated with the traveling thunderstorm cell), when the downburst is non-stationary (Figure 2.1B). Therefore, the passage of a non-stationary downburst thunderstorm cell nearby an anemometer is reflected by a sudden change of direction detected by the device (Figure 2.1C).



(A) Wind field associated with a background wind.



(B) Wind field associated with a traveling thunderstorm cell.



(C) Overall wind field, in two different instants.

FIGURE 2.1: Qualitative wind fields induced by a thunderstorm outflows.

In spite of the peculiarity of this phenomenon, there is not yet a model to study the structural dynamic response which considers this characteristic in explicit form.
The first chapter of Part II, Chapter 3, aims at this purpose. As deepened in this chapter, the choice of neglecting the variation of the angle of attack in the process of signal decomposition has induced several shortcomings. It oriented the dynamic response of structures to thunderstorm outflows to be considered in an alongwind, invariant direction only. On top of that, the traditional separation between alongwind and crosswind response was prevented. To overcome this drawback, Chapter 3 investigates whether directionality effects may instead play a role in the structural dynamic response, giving rise to an increase of the maximum displacement. As a consequence, Chapter 3 is entitled as "*Directional buffeting of slender structures subjected to thunderstorm outflows*".
Moving to Chapter 4, its aim is an attempt to answer questions about the effects of the non-stationarity of the wind speed and of the angle of attack on the building-up of aeroelastic instabilities (tranversal galloping). As far as the wind speed is concerned, it is unclear whether a phenomenon of short duration as a thunderstorm outflow is sufficient to trigger an instability. Nonetheless, the role of the variation of the angle of attack appears striking again. In fact, its variation may give rise to rapid alternations of stable or unstable conditions, in a classic synoptic study. Chapter 4 is entitled as "*Transient aeroelasticity of slender structures*

subjected to thunderstorm outflows" and basically extends the methodology of Chapter 3 taking aeroelastic effects into account.
As mentioned earlier on, these two chapters neglect the effects of vortex-shedding around the body. This choice is made to focus on the role played by the directionality effects on a generalised quasi-steady formulation of the aerodynamic forces. In this way, the influence of the sudden change of directionality of the force on buffeting forces (Chapter 3) and galloping (Chapter 4) can be deeply analysed without the influence of vortex-shedding effects, usually challenging to be included in an all-encompassing model. Both chapters investigate the subject of the dynamic response of slender structures in a complete analogy with the traditional formulation for synoptic winds. In fact, they allow a separation between the alongwind and crosswind forces. Moreover, the hypothesis of small turbulence is made. These choices open the doors to a robust comparison between synoptic winds and thunderstorm outflows in terms of wind loading and structural response.
In the framework of this part of the Thesis, signals acquired by anemometers are converted into compatible vertical wind fields through suitable pseudo-deterministic approaches, e.g., Equivalent Wind Spectrum Technique (Solari, 1988; Piccardo and Solari, 1998), adequately applied on stationary and Gaussian components of the original signal. This choice allows the burdensome Monte Carlo technique to be avoided, and permits to clarify whether the phenomenon might be of interest from a physical point of view. The wind fields are employed to evaluate the aerodynamic wind loading on selected slender structures invoking the strip and quasi-steady theory (Figure 2.2). The dynamic response is eventually numerically evaluated in the state-space domain.

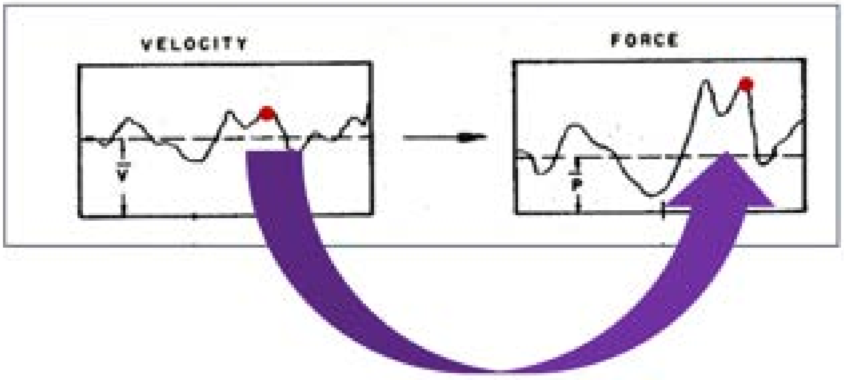


FIGURE 2.2: Strip and quasi-steady theory. The picture in the background is after (Davenport, 1961).

2.2 Effects induced by accelerating flows on rigid slender structures

As mentioned in the overture of this chapter, the application of the strip and quasi-steady theory to evaluate thunderstorm-induced effects on structures constitutes an important debate in the Wind Engineering community (Figure 2.3). In this sense, a striking comment has been made by (Letchford and Chay, 2002): "*It remains to be seen whether it is possible to retain*

the large database of pressure coefficients obtained in boundary layer flow and apply an appropriate 'design' thunderstorm wind speed profile". In fact, literature about this topic is quite limited and fragmentary (Solari, 2020) and generally disregarded from accelerations typical of thunderstorm outflows. The pioneer of this subject has been Sarpkaya, who realised himself a device to allow a rapid growth of the flow speed from zero to a certain value (Sarpkaya, 1963; Sarpkaya, 1966). The tests performed on a circular cylinder and a flat plate led to an increase of the drag coefficient of about 25 %, if compared with the steady condition. (Sarpkaya and Ihrig, 1986), studying a square cylinder, found that the overshooting coefficients of the drag and lift coefficient are strongly dependent on the incidence angle. Subsequently, as deeply described in Chapter 6, other researchers tried to deepen the subject (Okajima, Matsumoto, and Kimura, 1997; Katsura, 1997). In the meanwhile, as anticipated in Chapter 1, the interest for thunderstorm outflows in the Wind Engineering community grew (Letchford, Mans, and Chay, 2002), and researchers came up with new techniques to reproduce downbursts in laboratories. At the beginning, these were limited to suitable modifications of already existing wind tunnels. This is the case of the realisation of stationary wall jets (Chay and Letchford, 2002), followed by their traveling version, aiming at the reproduction of a moving downburst (Letchford and Chay, 2002). In the same years, another remarkable paper, this time concerning the technique of the pulsed wall jet, has been proposed (Mason, Letchford, and James, 2005).
Following these attempts, modifications were directly made on the traditional axial flow of the wind tunnel, as the stationary (Lin and Savory, 2006) and non-stationary slot jet technique (Lin, Orf, et al., 2007), or the introduction of a plate suddenly introduced in the oncoming flow (Butler and Kareem, 2007). In parallel, albeit with aims that were not related to the reproduction of downbursts, the realisation of multiple-fan wind tunnels with individually controlled fans began to step up (Cao et al., 2002).

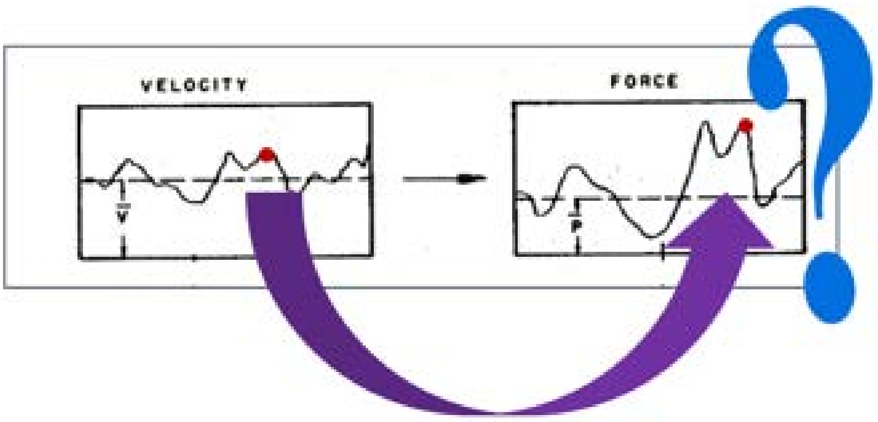


FIGURE 2.3: Questioning the application of the strip and quasi-steady theory. The picture in the background is after (Davenport, 1961).

A multiple-fan wind tunnel is a facility characterised by a wall of fans, whose dimension is limited with respect to classic fans of a traditional wind tunnel. Figure 2.4 shows the comparison between the 31-foot diameter wooden fan of the Altitude Wind Tunnel (Figure 2.4A, NASA) and three models of the prototype fan for the multiple-fan wind tunnel of the Tamkang University, in Taipei, whose characteristic length is 22 [*cm*].

(A) Altitude Wind Tunnel (AWT) Fan, 1944; source: *www.nasa.gov*.

(B) Three models of the prototype fan, for a multiple-fan wind tunnel.

FIGURE 2.4: Wind tunnel fans.

A discussion of the potential effects relative to the flow acceleration on the aerodynamic loading is given in the first chapter of Part III, Chapter 5. This is followed by the estimation of thunderstorm-induced accelerations, evaluated from fifteen selected anemometric signals by adopting a tailored technique. Besides, this chapter also offers remarks about how the procedure for the definition of a "mean" wind speed in a transient event is a procedure which is unlikely to always fit under any condition, but has to be related with its application. Chapter 5 is named as "*Estimation of thunderstorm-induced mean wind speeds and accelerations through continuous wavelet-based procedures*".

Subsequently, a wind tunnel testing campaign has been undertaken to investigate the effects of accelerating flows on structures. This has been carried out in Taipei (January 2020 - August 2020), at the Tamkang University Multiple-fan wind tunnel (TKU-MKWT) (Figure 2.5). A sectional model of a square cylinder is the object of the investigation. It is equipped with 94 pressure taps and it is studied for zero incidence only.

The analyses of the huge amount of data have been divided in two main elaborations. The first concerns the effect induced by the acceleration on the aerodynamic drag, while the second focuses on vortex-shedding around the body in transient conditions. Three chapters of the Thesis are devoted to the description of the wind tunnel test campaign and of the relevant analyses. The first one, Chapter 6, is a general elucidation about the characteristics of the facility and of the wind tunnel model, providing information about the choice of the flow parameters. It is entitled as "*Wind tunnel tests*". It is followed by Chapter 7, which deals with the definition of the aerodynamic drag in steady and unsteady conditions, eventually proposing a comparison between the two cases. It is named as "*Aerodynamic drag of a square cylinder in steady and unsteady conditions*". The corresponding analyses carried out on vortex-shedding are presented in Chapter 8, entitled as "*Vortex-shedding on a square cylinder in steady and unsteady conditions*".

The final part of the Thesis, Part IV, includes Chapter 9, "*Final remarks and future perspectives*", which expresses the general conclusions of the work, drawing possible future perspectives following this Thesis.

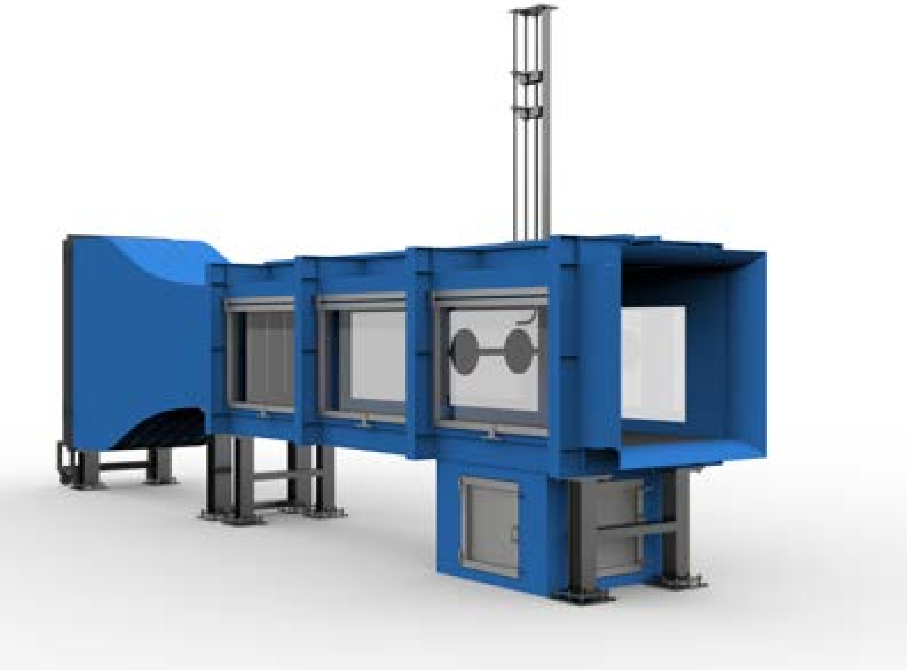


FIGURE 2.5: Render of the TKU-MFWT with the model installed.