

Bauhaus-Universität Weimar

Concepts of Adaptivity for Vortex Particle Methods and Applications to Bluff Body Aerodynamics

DISSERTATION

zur Erlangung des akademischen Grades
Doktor-Ingenieur (Dr.-Ing.)

an der Fakultät Bauingenieurwesen
der Bauhaus-Universität Weimar

vorgelegt von
Dario Milani
geboren am 1. Juli 1989
in Desio, Italien

Mentor: Prof. Dr. Guido Morgenthal

Tag der Disputation
19.10.2018

To my father
&
to my beautiful family

“...l’amor che move il sole e altre stelle”

“...the Love that moves the sun and other stars”

Dante Alighieri, The Divine Comedy

Acknowledgements

First and foremost, my gratitude goes to my supervisor Prof. Guido Morgenthal. I need to thank you prof for choosing me to conduct this interesting project and for relying on me to start the wind tunnel activities in our new facility. I realize just now, after three years, how your supervision empowered my skills and taught me how to manage scientific challenges rigorously and independently.

I am very grateful to Ilia Marchevsky from the Bauman Moskow State Technical University for his contribution on my knowledge in Computational Fluid Dynamics. Ilia, your passion for science and your objective criticism on problems made worthy all of our Skype discussions late in the night. Moreover, thanks to Kseniia Kuzmina for coming with Ilia to visit me in Weimar and for working together on Panel Methods. I truly hope that our collaboration continues in the future.

Many thanks to ALL of my colleagues in MSK. Samir Chawdhury, thank you for sharing the office with me, being supportive and for dealing wisely with my stress in dark times. Christopher Taube, thank you for your support, for your empathy and for saving me from spending whole nights in the office. I truly hope I am going to find colleagues like you guys on my way. Wang Wai, thank you for our philosophical discussions on the sense of life and for always being there to help. Thanks also to my precious colleagues Amir Hossein Arshian, Sebastian Rau, Hans-Georg Timmler, Normann Hellermann, Jakob Taraben, Tajammal Abbas, Anne-Marie Nöthlich and Jutta Lorenz.

Many thanks to my Italian friends “dei posteriori” for being there. Particularly, thanks to Matteo Lazzarotto, Federico Cutturini, Andrea Pinnavaria, Alessandro Bruno, Luca Guastaferrero and Dario (2) Tremolada. Anywhere I go guys, I carry you in my heart.

Infinite thanks to my beautiful family. Grazie mille a mia madre Pierina, a mio padre Renato e ai miei fratelli Walter e Simone. There are no words able to describe the power of the love which unify us.

Finally, thanks to you Maria Grazia. I don't know where you have found such strength all this time. Your music, your being yourself, your spreading attention and careful support fulfilled me with joy during this journey.

Solemn declaration

I do solemnly declare that I have made this work without undue assistance from third parties and without the use of other than referenced sources. Data and concepts acquired from other sources directly or indirectly are identified by referencing the source.

Other people were not involved in the development of content and material of the present work. In particular, I have not used any paid help of mediation or counseling services (promotion consultants or other persons). No one has received directly or indirectly monetary benefit from me for any work in connection with the content of the submitted dissertation.

The work has been neither submitted to any other Examining Authority in Germany nor abroad in the same or similar style.

I certify on my honor that I have said the whole truth and that I concealed nothing.

Ehrenwörtliche Erklärung

Ich erkläre hiermit ehrenwörtlich, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus anderen Quellen direkt oder indirekt übernommenen Daten und Konzepte sind unter Angaben der Quellen gekennzeichnet.

Weitere Personen waren an der inhaltlich-materiellen Erstellung der vorliegenden Arbeit nicht beteiligt. Insbesondere habe ich hierfür nicht die entgeltliche Hilfe von Vermittlungs- bzw. Beratungsdiensten (Promotionsberater oder anderer Personen) in Anspruch genommen. Niemand hat von mir unmittelbar oder mittelbar geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen.

Die Arbeit wurde bisher weder im In- noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

Ich versichere ehrenwörtlich, dass ich nach bestem Wissen die reine Wahrheit gesagt und nichts verschwiegen habe.

Dario Milani
Weimar, den 05. Dezember 2017

Contents

List of Symbols	xiii
List of Tables	xvii
List of Figures	xix
1 Introduction	1
2 Wind Effects on Civil Structures	7
2.1 Introduction	7
2.2 Characteristics of atmospheric wind	7
2.3 Wind actions on slender structures	11
2.4 Structural scales and wind scales	13
2.5 Summary	15
3 Modeling of Wind Effects	17
3.1 Introduction	17
3.2 Modeling of aerodynamic and aeroelastic problems	17
3.2.1 Structural modeling	18
3.2.2 Modeling of aerodynamic problems	21
3.2.3 Modeling of aeroelastic problems	26
3.3 Adaptive numerical modeling	31
3.3.1 On adaptivity in grid based methods	32
3.3.2 Adaptivity in meshless methods	34
3.4 Summary	36

4	The Vortex Particle Method	39
4.1	Introduction	39
4.2	Analytical formulation	39
4.3	Spatial discretization	41
4.4	Temporal discretization and diffusion	42
4.5	Surface discretization and particle initialization	44
4.5.1	Vorticity boundary values	44
4.5.2	Discretization of the boundaries and numerical solution	45
4.5.3	Mechanism of particle releasing	49
4.6	Particle remeshing	50
4.7	Convergence and resolution of classical VPM	51
4.8	Computational cost of VPM	53
4.9	Summary	55
5	Novel Method for Localized Resolution Control	57
5.1	Introduction	57
5.2	Localized control of spatial resolution	58
5.3	Localized control of temporal resolution	60
5.3.1	Accuracy of time integration	60
5.3.2	Time integration substepping	62
5.3.3	Analysis of substepping	64
5.4	Zonation	64
5.4.1	Spatial zonation for remeshing	66
5.4.2	Temporal zonation for substepping	67
5.5	Localized full resolution control	68
5.6	On the discretization of immersed boundaries	70
5.6.1	Numerical schemes discretizing the boundaries	70
5.6.2	Potential flow — comparative study	72
5.6.3	Single vortex point position — comparative study	78
5.7	Summary	81

6	Validation of Adaptive Schemes	83
6.1	Introduction	83
6.2	The impulsive start of circular cylinder at $Re = 3000$	83
6.2.1	Convergence of original scheme	85
6.2.2	Convergence of adaptive remeshing	87
6.2.3	Convergence study of substepping	90
6.2.4	Convergence study of fully adaptive scheme	90
6.3	The flat plate	94
6.3.1	Description of the model	95
6.3.2	Computation of flutter derivatives	96
6.3.3	Prediction of critical wind speed	99
6.4	Summary	100
7	Applications	101
7.1	Introduction	101
7.2	Static force coefficients of Great Belt East Bridge	101
7.2.1	Description of the Great Belt East Bridge	102
7.2.2	Numerical model	102
7.2.3	Experimental model and experimental set-up	104
7.2.4	Comparison of simulations using adaptivity and experiments	106
7.2.5	Discussion	108
7.3	Vortex-Induced Vibrations of Alcónetar Bridge	109
7.3.1	Vortex-Induced Vibrations of the structure	109
7.3.2	Simulation model	111
7.3.3	Application of fully adaptive scheme — static simulations	111
7.3.4	Dynamic response reduced by deflectors	121
7.3.5	Discussion	122
7.4	Aeroelastic response of a T-shaped energy harvester	124
7.4.1	Power extraction from Limit Cycle Oscillations	124
7.4.2	Experimental model	125
7.4.3	Numerical model	128
7.4.4	Adapted simulations compared against experiments	129
7.4.5	Discussion	134
7.5	Summary	135

8	Conclusions	137
8.1	Summary	137
8.2	Scientific contribution	140
8.3	Outlook	141
	Appendix	142
A	Numerical Schemes to compute the Boundary Vorticity	143
A.1	Introduction	143
A.2	Boundary value problem in Vortex Particle Method	143
A.2.1	Integral equation for vortex sheet intensity	144
A.3	Numerical schemes for vortex sheet intensity computation	147
A.3.1	Scheme with piecewise-constant solution (<i>sch</i> ₂ , <i>sch</i> ₃)	148
A.3.2	Scheme with discontinuous piecewise-linear solution (<i>sch</i> ₄)	149
A.3.3	Finite Element type numerical scheme (tangent) (<i>sch</i> ₅)	150
A.3.4	Finite Element type numerical scheme (normal) (<i>sch</i> ₀ , <i>sch</i> ₁)	151
A.3.5	FEM type approach with discontinuities extraction (<i>sch</i> ₆)	152
A.4	Summary	154
	Bibliography	154

List of Symbols

$\mathbf{f}_{\text{struc}}$	Vector of structural forces [N]	18
\mathbf{f}_{aero}	Vector of aerodynamic forces [N]	18
\mathbf{p}	Vector of nodal coordinates [m]	19
\mathbf{M}	Mass matrix [kg]	19
\mathbf{C}	Damping matrix [kg/s]	19
\mathbf{K}	Stiffness matrix [kg/s ²]	19
\mathbf{y}	Vector of modal coordinates [m]	19
Φ	Modal matrix [-]	19
ζ_j	Modal damping ratio of j -th mode [-]	19
ω_j	Modal circular frequency ratio of j -th mode [rad/s]	19
N_{struc}	Number of degrees of freedom [-]	20
c_1	Mass proportional constant [s ⁻¹]	20
c_2	Stiffness proportional constant [s]	20
ρ	Fluid density [kg/m ³]	22
\mathbf{u}	Velocity vector [m/s]	22
p	Pressure [N/m ²]	22
ν	Kinematic viscosity [m ² /s]	22
Re	Reynolds number [-]	22
F_L	Lift force [N]	25
F_D	Drag force [N]	25
F_M	Pitching moment [Nm]	25
C_L	Lift coefficient [-]	25

C_D	Drag coefficient [-]	25
C_M	Moment coefficient [-]	25
L	Cross sectional width — chord [m]	25
H	Cross sectional height [m]	25
B	Transversal length — depth [m]	25
u_∞	Modulus of velocity at infinity [m/s ²]	25
f_{shed}	Vortex shedding frequency [Hz]	25
St	Strouhal number [-]	25
c_f	Correction factor used for blockage [-]	26
S_H	Surface perpendicular to the free stream flow [m ²]	26
S_{WT}	Surface of the testing area [m ²]	26
\tilde{k}	Surface of the testing area [-]	26
\mathbf{x}	Vector of coordinates [m]	26
h	Heave displacement [m]	28
α	Pitch displacement [°]	28
H_i^*	Aerodynamic derivatives of lift force [-], ($i = 1, \dots, 4$)	29
A_i^*	Aerodynamic derivatives of pitch moment [-], ($i = 1, \dots, 4$)	29
K	Reduced frequency [-]	29
Ψ	Stream function [m ² /s]	40
\mathbf{e}_x	Normalized vector along x [-]	40
\mathbf{e}_y	Normalized vector along y [-]	40
\mathbf{e}_z	Normalized vector along z [-]	40
\mathcal{F}	Fluid domain $\in \mathcal{R}^2$	41
N_{part}	Number of particles [-]	41
Γ_i	Circulation [m ² /s]	42
δ	Dirac function [-]	42
\mathbf{K}	Velocity kernel [1/m]	42
N_t	Number of timesteps [-]	42
Δt_0	Unrefined timestep duration [s]	42

C_1	Coefficient-1 [-]	43
C_2	Coefficient-2 [-]	43
\mathcal{B}	Immersed body boundary $\in \mathcal{R}^2$	44
\mathcal{G}	Immersed body $\in \mathcal{R}^2$	44
\mathbf{n}	Normalized vector perpendicular to the surface [-]	44
$\boldsymbol{\tau}$	Normalized vector tangent to the surface [-]	44
\mathbf{I}	Induced velocity [m/s]	45
N_{pan}	Number of panels [-]	45
Δs_j	Panel length of j -th panel [-]	45
\mathbf{b}	Vector of known velocity influence on the panels [-]	46
\mathbf{M}	Connectivity matrix [-]	46
d_j	Distance to the panel j at which the particles are released [m/s]	50
M'_4	Third order projection kernel [-]	50
ξ	Normalized nodal distance [-]	51
CC	Computational cost [-]	54
Δx_0	Underlying grid spacing [m]	58
Δy_0	Underlying grid spacing [m]	58
l_{sp}	Spatial resolution level [-]	58
\mathbb{Z}	Set of integer numbers	59
$\Delta x_{l_{sp}}$	Adapted grid spacing [m]	59
$\Delta y_{l_{sp}}$	Adapted grid spacing [m]	59
Err	Solution error [-]	61
l_{ti}	Temporal resolution level [-]	62
\mathbb{N}	Set of natural numbers	62
s	Substep counter [-]	63
r_i	Particle distance to the immersed body [m]	66
R_{sp}	Reference length in spatial adaptation [m]	66
a_{sp}	Linear coefficient in spatial adaptation [-]	66
b_{sp}	Global resolution parameter in spatial adaptation [-]	66

b_{ti}	Global resolution parameter in temporal adaptation [-]	67
a_{ti}	Linear coefficient in temporal adaptation [-]	67
R_{ti}	Reference length in temporal adaptation [m]	67
$a_{sp,ti}$	Linear coefficient in full adaptation [-]	68
$b_{sp,ti}$	Baseline resolution control parameter in full adaptation [-]	68
κ	Curvature [1/m]	73
J_{pan}	Number of additional panels [-]	75
I_E	Integral error [-]	85
I_{TU}	Turbulence intensity [%]	106

All the symbols which are not present in this list are declared within the text.

List of Tables

2.1	Geometrical similarities between structural and flow feature scales	14
5.1	Schematic of the activities in different zones	63
5.2	List of boundary element method schemes and main characteristics	71
7.1	The Great Belt East Bridge; experimental conditions during static sectional model test	106
7.2	The Alcónetar Bridge; summary of numerical (static) simulations	113
7.3	The Alcónetar Bridge; summary of numerical (dynamic) simulations	121
7.4	T-shaped energy harvester; details and dimensions of the system	125
7.5	T-shaped energy harvester; experimental conditions during free vibration and aeroelastic tests.	128
7.6	T-shape energy harvester; comparison of simulations for critical wind speed identification	130

List of Figures

1.1	Aerodynamics in history; Da Vinci’s flying machine and Wright brothers’ flight	1
1.2	Aerodynamics in history; The collapse of Tacoma Bridge due to interaction with wind	2
2.1	Schematic of wind patterns of largest geometrical scales projected on the Earth’s surface	8
2.2	Schematic of the temporal scales associated with Wind Engineering	9
2.3	Scheme of Atmospheric Boundary Layer thickness and wind velocity profile	10
2.4	Slender structures sensitive to aeroelastic instabilities	11
2.5	Davenport’s Wind Loading Chain	11
2.6	Sketch of dynamic response of slender structures	13
2.7	Perspectives of the Stonecutters Bridge and overview of structural scales and flow feature scales involved	16
3.1	Representation of Rayleigh damping	21
3.2	Impulsively started circular cylinder resolved with a grid based method and a gridless method	23
3.3	Portion of a bridge with typical cross section and nomenclature of the reference dimensions used for non-dimensionalization.	25
3.4	Grid distortion on an angular point of a simple geometry during adaptation	33
3.5	Flowchart of adaptive meshfree methods	35
4.1	Sketch of the immersed boundary problem	45
4.2	Surface discretization using linear panels	46
4.3	Potential solution on the uniformly discretized circular cylinder by sch_0 and sch_2	49
4.4	Particle initialization mechanism	50

4.5	Footprint of the third order projection kernel in 2D	51
4.6	Algorithms for the N-body problem associated with the computation of particle velocities	54
5.1	Projection footprints of two particles p_1 and p_2 belonging to different spatial resolution zones	59
5.2	Study of Euler time integration; the 2-particles problem	61
5.3	Schematic of substepping procedure	62
5.4	Study of substepping on Euler time integration; the 2-particles problem	65
5.5	Schematic of zonation proposed for spatial resolution around an immersed body	67
5.6	Schematic of zonation proposed for temporal resolution control around an immersed body	68
5.7	The fully adaptive strategy; mapping of refinement levels for space and time	69
5.8	Potential solution on the uniformly discretized circular cylinder by sch_0 and sch_1	72
5.9	Study of the potential flow solution on 2D geometries	74
5.10	Representation of smoothly varying discretization	75
5.11	Study of non-uniform panel discretization topologies; part I	76
5.12	Study of non-uniform panel discretization topologies; part II	77
5.13	Representation of abruptly varying discretization	78
5.14	Study of discontinuous panel discretization refinements	79
5.15	Representation of the particle position with respect to the panel	79
5.16	Study of the solution in presence of a single wake vortex	80
6.1	Impulsively started circular cylinder at $Re = 3000$; drag curve of references	84
6.2	Impulsively started circular cylinder at $Re = 3000$; classical scheme	86
6.3	Impulsively started circular cylinder at $Re = 3000$; spatially adapted solution; part I	88
6.4	Impulsively started circular cylinder at $Re = 3000$; spatially adapted solution; part II	89
6.5	Impulsively started circular cylinder at $Re = 3000$; temporally adapted solution; part I	91
6.6	Impulsively started circular cylinder at $Re = 3000$; temporally adapted solution; part II	92

6.7	Impulsively started circular cylinder at $Re = 3000$; fully adapted solution	93
6.8	Impulsively started circular cylinder at $Re = 3000$; summary of simulations	94
6.9	Flat plate $L : H = 25 : 1$; forced vibrations; schematic	95
6.10	Flat plate $L : H = 25 : 1$; heave forced simulations with and without adaptivity	97
6.11	Flat plate $L : H = 25 : 1$; computation of aerodynamic derivatives	98
6.12	Lillebælt suspension bridge; computation of critical wind speed using flutter derivatives from a flat plate $L : H = 25 : 1$ simulation	99
7.1	The Great Belt East Bridge; artistic view	102
7.2	The Great Belt East Bridge; cross-sectional model for numerical simulations	103
7.3	The Great Belt East Bridge; static force coefficients	104
7.4	The Great Belt East Bridge; experimental model, set-up and smoke visualization	105
7.5	The Great Belt East Bridge; comparing full adapted simulations against experimental output	107
7.6	The Alcónetar Bridge; view of structure and details	110
7.7	The Alcónetar Bridge; effects of wind deflectors	110
7.8	The Alcónetar Bridge; cross-sectional model	112
7.9	The Alcónetar Bridge; instantaneous velocity vectors during adaptation	114
7.10	The Alcónetar Bridge; comparison of time averaged velocity profiles across the wind deflectors	116
7.11	The Alcónetar Bridge; contour plots of time averaged velocity and error field	117
7.12	The Alcónetar Bridge; contour plots of time averaged velocity and error field around structural details	118
7.13	The Alcónetar Bridge; contour plots of velocity fluctuation field and error field	119
7.14	The Alcónetar Bridge; contour plots of velocity fluctuation field and error field around structural details	120
7.15	The Alcónetar Bridge; dynamic simulations with and without guide vanes	123
7.16	T-shaped energy harvester; Limit Cycle Oscillation	125
7.17	T-shaped energy harvester; details of model and experimental set up	126
7.18	T-shaped energy harvester; identification of modal frequency and damping	127
7.19	T-shaped energy harvester; lateral view of the fluttering system using smoke particles generator.	128

7.20	T-shaped energy harvester; contour plots and particle maps during the development of the oscillations	129
7.21	T-shaped energy harvester; numerical simulations; part I	131
7.22	T-shaped energy harvester; numerical simulations; part II	132
7.23	T-shaped energy harvester; comparison of experimental and numerical displacements at respective critical conditions	133
7.24	T-shaped energy harvester; comparison of computational time required for the critical wind-speed estimation	134
A.1	Sketch of the immersed boundary problem	144
A.2	Schematic representation of linear shape functions of the first order	151
A.3	Schematics of discontinuous basis functions	153

Chapter 1

Introduction

Aerodynamics has always reflected the desire of human beings to exceed their limits. As such, it first appeared with the attempt to create flying machines with Leonardo da Vinci and with the studies leading to the first successful flight by the Wright Brothers, as in Figure 1.1. Since then

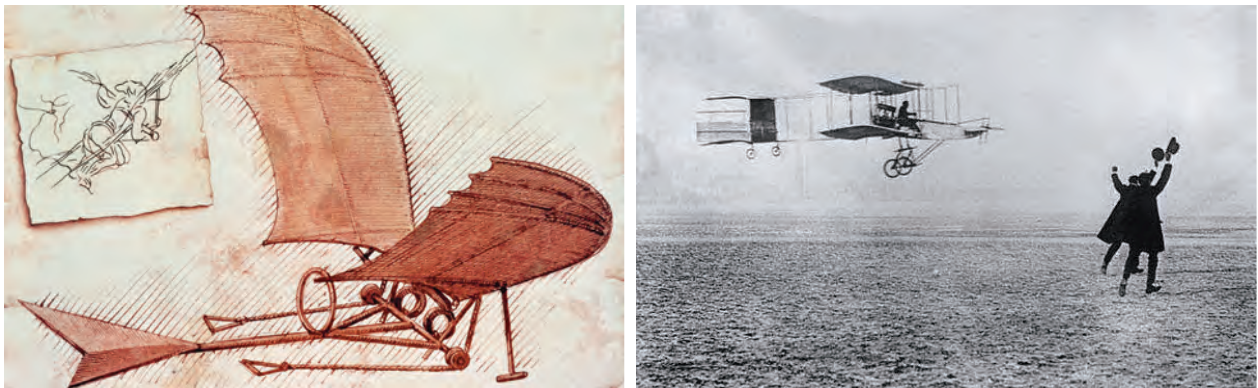


Figure 1.1: (Left) Leonardo da Vinci, flying machine sketch (Picture courtesy of Seven Shades of Black). (Right) Wrights brothers' glider being tested (Credit: Public Domain via britannica.com).

it has been clear that the study of air motion would have been the chance for the man to move forward. Nowadays, the motion of fluids, of which air is a confined subdomain, is a concern in most engineering and natural science practices ranging from automotive to biomedical engineering e.g. in [293]. In automotive, engineers study air and fluids to design performant and safe cars ([140]) and to enhance the efficiency of thermal engines ([125, 40]), whilst in biomedical engineering, engineers model and study the motion of blood in our circulatory system to forecast problems such as thrombosis and to understand how diseases spread ([18, 287]). Among other engineering practices, in aeronautics air notably plays the crucial role of sustaining flight, but also undergoes a continuous development connected with e.g. drag reduction ([51, 286, 213]), flight stability, control and maneuverability of flying machines ([181, 226]). These concerns are also reflected in naval architecture ([5]) and extend to ocean engineering ([90]), climate studies and meteorology e.g. in [199, 212].

Civil and wind engineering, main focus of this research work, first experienced the complexity of flow phenomena with the spectacular yet catastrophic collapse of the Tacoma Narrows Bridge in 1940 (cf. Figure 1.2), in which the structure collapsed due to the effects of a moderate wind.



Figure 1.2: (Left) The collapsed Tacoma Bridge in 1940 (Picture of Barney Elliott; The Camera Shop). (Right) New bridge from 2007 (Credit: Public Domain via wikipedia.org).

This event constitutes a turning point in civil engineering as it forced engineers to comprehend and to account for the complex effect of air on structures. Since then, wind effects on civil structures has become a major concern during the design phase of slender structures such as bridges and practically constitutes a burden in civil engineering art work aiming to connect distant lands and cultures, which has to be overcome.

Experimental studies such as Wind Tunnel Tests (WTT) constitute a reliable reference for studying the underlying phenomena and effects because they allow the direct measurement of fluid induced forces on the model and of flow properties. For this reason experimental studies and WTT are evergreens in aerodynamics as they constitute the ultimate validation of a method or a design in a large range of applications e.g. in [211]. Such tests are however time-consuming, expensive and subject to Reynolds number effects. The application of numerical methods therefore offers an appealing alternative to support the design as they allow the straightforward test of several configurations at substantially low times and costs. Moreover, numerical simulations can be efficiently coupled with shape optimization algorithms, which allow the exploration of several configurations until the optimal design solution is found.

Numerical methods studying the motion of fluids around bluff bodies with complex shapes and structural details using Computational Fluid Dynamics (CFD) offer on the other hand a viable alternative and are of significant interest in many of the engineering applications mentioned above. The main advantages of numerical approach are connected with time and cost savings, as well as the opportunity to access to the measures in the entire domain, which in Wind Tunnel Tests require the installation of intrusive and expensive equipment.

The criticality of enhanced design of structures is inherently connected with the capacity to predict the effect of the smaller structural details, as they might affect critically the aerodynamic behavior thus pressure and forces. Whilst flow features of different scales are typical of bluff body flows ([80]), bodies that exhibit different geometrical scales pose a particular challenge to the efficient and accurate resolution of the fluid dynamic problem. The significant effect that such small details can have on the overall aerodynamic behavior of structures has been reported ([49, 253, 260, 302]). In [207] the effect of handrails on the aerodynamics of bridge decks is highlighted whilst studies of small scale appendages designed to modify the flow can be found in [206, 154, 284] for wind screens and in [128, 21, 153] for flaps. Examples of small-scale features to reduce wind response of structures are spirals on chimneys and guide vanes in bridge decks ([75]) as studied later in this thesis.

Among CFD methods, Vortex Particle Methods (VPM) have been found to be accurate and comparatively efficient techniques for simulating 2D bluff body aerodynamics problems around complex geometries. However, their popularity in CFD was limited by several objections. Common objections to the usage of Vortex Particle Methods are

- (I) lack of modeling techniques for unresolved sub-grid scales,
- (II) difficulty of adding viscous effects,
- (III) complexity of velocity evaluation,
- (IV) “excessive” self adaptivity,

which have however been addressed. (I) Vortex Particle Methods present unachievable characteristic of producing small eddies and to proliferate them to model turbulent sub-grid scales without inherent numerical dissipation. A common approach in Vortex Methods designed for engineering applications is the filtering of the vorticity field, thus producing sub-grid scale dissipation ([111]), as in Large Eddy Simulations (LES). Moreover, Mansfield ([186]) proposed a Smagorinsky sub-grid scale model for the filtered equations and later a dynamic eddy diffusivity LES-like model ([187]). In order to provide small scale models such as turbulence models Guermond in [123] proposed to couple vortex methods with grid based methods. Such coupling discretizes the fluid nearby the geometry with a grid based methods and applies appropriate boundary layer models while the far field is represented by Lagrangian particles. This strategy exploits the inherent ability of the velocity pressure models to resolve the boundary layer, and the self adaptivity of vortex methods for the wake which then evolves without numerical dissipation. However, such methods lead to difficult modeling techniques making them of interest for a restricted range of applications e.g. in rotor aerodynamics ([299]). (II) The difficulty in adding viscous effects is a consequence of their Lagrangian formulation, which results to be less prone to discretization than grid based methods. (III) The complexity of velocity evaluation is related to the resolution of the N -body problems, which requires to perform N^2 operations to compute each particle velocity. More affordable scalings have been proposed with the Fast Multiple Method and Vortex In Cell method, which both reduce the problem to $N \log N$ operations. (IV) The self adaptivity is a peculiarity which makes Vortex Method generally very appealing. Their grid-free formulation provides a natural self-adaptivity where vortex particles tend to cluster in regions of significant flow features ([80]). The “excessive” self adaptivity has been questioned in many works such as [131] and [159] because of Lagrangian grid distortions and the resulting inaccuracies as also analyzed in [82]. This led to the introduction of pseudo-grids as presented and discussed in [221], [308] and [156]. The application of pseudo-grids allows the re-initialization of the particle map to obtain a certain Lagrangian grid distortion in order to guarantee sufficient particle overlaps required for vorticity support ([79], [240], [139] and [155]). Moreover, applying pseudo-grids does not compromise the self adaptive nature of these methods. The technique of particle reinitialization, often referred to as remeshing, is currently used in most of the current implementations and constitutes in itself an interesting platform for further development of adaptive techniques.

More recent implementations of remeshing improve the accuracy of the numerical solution and its efficiency e.g. in [300]. However, information related to the immersed body geometry and the relative geometrical scale of its components can be exploited to control the remeshing and thus arrive at a means to actively adapt the particle map.

In view of more advanced design of structures to be confronted with wind, it is required to provide adaptivity to numerical methods which depict all the relevant features to conduct a more precise analysis of the structural response to wind actions. Therefore, the objective of this work is to introduce an adaptive strategy for simulations of bluff body flows with Vortex Particle Methods which adapts to whichever geometrical complexity and allows to consider the influence of structural details in modifying the aeroelastic performance of the structure. Such requirement is translated in the following points to be developed:

- to provide means to balance accuracy and computational efficiency in resolving flows dominated by features of different scales, specifically arising from complex geometries,
- to retain versatility of classical VPM, as it does not require large pre-processing effort, which would be required instead for grid based methods,
- to identify margins of improvement of the existing surface discretization technique in order to enable high resolution nearby the boundaries.

This is achieved through a spatial adaptivity facilitated by a staggered remeshing and a temporal adaptivity linked to it. The proposed method employs the geometrical properties of the immersed body to independently guide the adjustment of particle spacing through remeshing and time step length through a substepping scheme. Both components are linked to a fully adaptive method through a zonation of the solution domain and the inherent link between spatial and temporal discretization.

After a thorough validation, the capabilities of the adaptive strategy are demonstrated on several applications to demonstrate their versatility in dealing with different problems and structures. Among the applications considered, the study of the vortex shedding from the two arches of the Alcónetar bridge is relevant to show the influence of small structural details on the bridge response. In fact, the Vortex-Induced Vibrations which occurred during the erection of the arches had been effectively suppressed by welding deflector-type guide vanes. The resolution of the complex flow physics in an efficient manner represents the numerical challenge. It is reported how the proposed adaptive strategy allows the accurate prediction of the influence of wind deflectors at a fifth of the time spent when using the equivalent classical VPM implementation.

This thesis is organized as follows. An introduction to aerodynamic and aeroelastic problems is presented in Chapter 2, with emphasis on the performance of slender bridges facing wind being the major motivation and the current application of this work. Afterwards, Chapter 3 reviews and compares methods for the analysis of aerodynamic and aeroelastic phenomena on slender structures performed by numerical, experimental and analytical methods. Moreover, the comparison extends to specific aspects of numerical modeling including adaptive strategies built on other numerical methods, i.e. Finite Volumes Methods (FVM), Finite Element Methods (FEM) and Vortex Methods (VM). The review proceeds in Chapter 4 with the mathematical formulation of the Vortex Particle Method (VPM), the numerical method characterizing the resolution of the aerodynamic problem herein treated. The classical formulation of the VPM is augmented with known considerations and results about performance and resolution. Chapter 5 contains the core of the present research work, the contribution of which is mainly twofold:

- it introduces variable temporal and spatial discretization techniques. These are used to resolve the smaller scales of the fluids in “relevant zones” of the fluid volume,