Bauhaus-Universität Weimar

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

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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

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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.

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Dario Milani
Weimar, den 05. Dezember 2017

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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.

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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

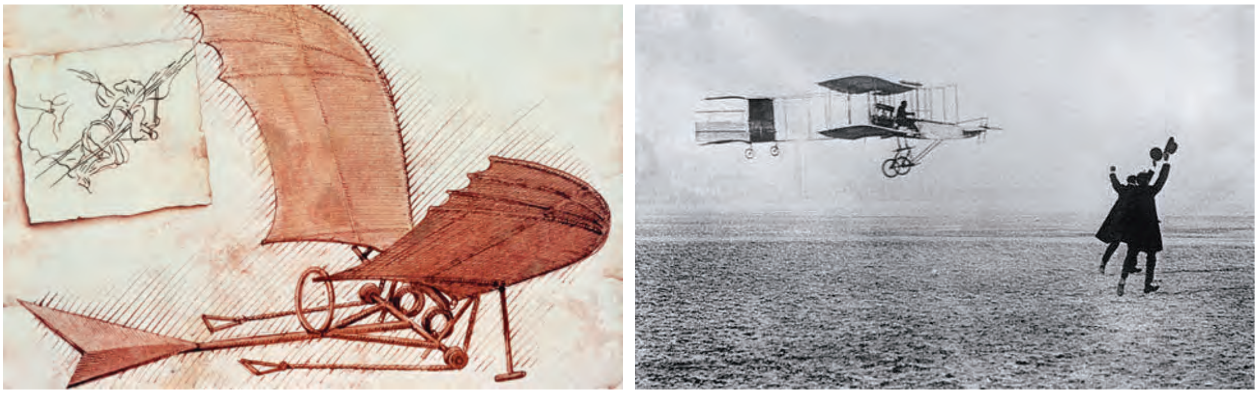

Figure 1.1: (Left) Leonardo da Vinci, flying machine sketch (Picture courtesy of Seven Shades of Black). (Right) Wrights brothers' glider being tested (Credit: Public Domain via britannica.com).

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,