Chapter 1

Introduction

1.1 Motivation

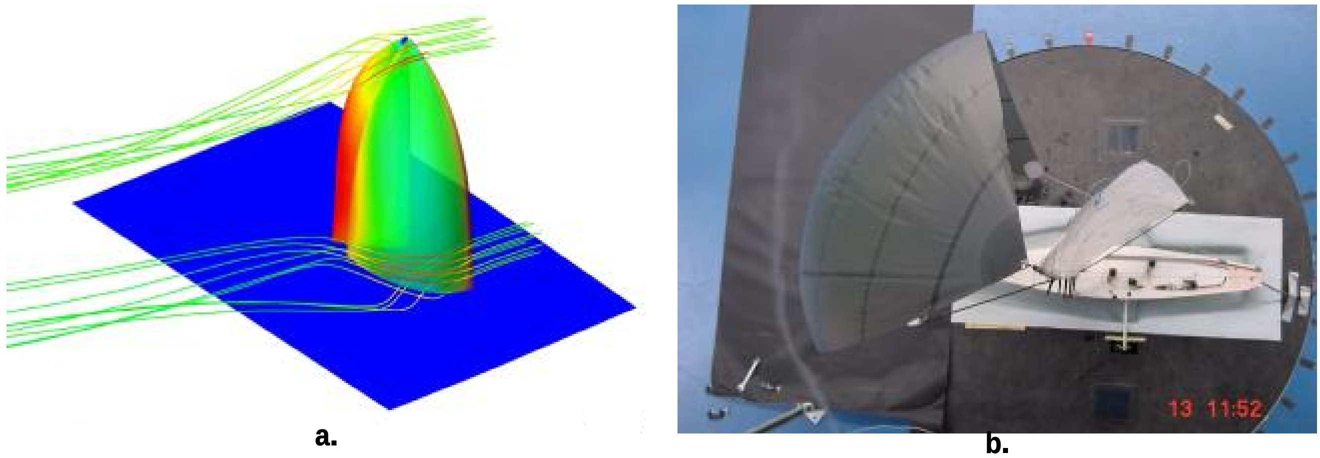
With the rapid advancement and increasing a¤ordibility of high-end computers, engineers and designers are increasingly tempted to invest in computational methods. However unlike many other aspects of yacht and sail design, downwind sail development is yet to make use of Computational Fluid Dynamics (CFD) tools. The downwind sail design process is largely analytical, based around incremental developments and experiences with past designs. Recently wind tunnel testing has become an integral part of high performance downwind sail development and with the current rate of increase of CFD technology and computer power the inclusion of CFD in the sail design process is inevitable.

Figure 1.1: Americas cup yachts sailing downwind under spinnaker.

Figure 1.2: The University of Auckaland's Twisted Flow Wind Tunnel.

It is common for sail designers to rely almost entirely on computational approaches in the design of upwind sails. Wind tunnel tests are inaccurate for upwind studies due to di¢culties in producing a realistic in‡ow and trimming the sails accurately. Upwind sails involve predominantly attached ‡ow for which computational methods are well established. Such aerodynamic design codes are most commonly based on the vortex lattice method [1] and can provide three-dimensional solutions for the ‡ow past genoa/mainsail con…gurations in less than a minute on a common desktop PC. Consequently extensive parametric design studies can be carried out using a large number of design variables. However inviscid panel methods are only valid for close-hauled sailing conditions where the ‡ow remains attached. In fact their inability to predict leading edge and trailing edge separation makes the application of panel methods for performance prediction questionable even in close-hauled conditions. Consequently they are seldom relied upon for aerodynamic input to velocity prediction programs (VPPs).

There are several clear advantages of CFD over wind tunnel testing. Wind tunnel testing is plagued by inaccuracies in the model construction and in obtaining the correct sail trim. Also since wind tunnel models are much smaller than real sails, scaling errors are introduced, both in terms of the inviscid/viscid behavior (Reynolds number) and in the deformation of the model under load (density scaling). Di¢culties are also found in creating the ‡ow conditions since the problem is complicated by the twisted apparent wind pro…le that is created as the yacht travels within the atmospheric boundary layer. At present only two wind tunnels in the world have the facility to reproduce twisted ‡ow for sailing yachts; the twisted ‡ow wind tunnel (TFWT) [2] at The University of Auckland's Yacht Research Unit and a similar tunnel in California developed by Oracle BMW racing.



a. b.

Figure 1.3: Examples of ‡ow visualisation techniques. a. Streamlines plotted with CFD. b. Wind tunnel smoke stream visulaisation

Perhaps the most signi…cant advantage of CFD is in visualisation of the ‡ow. Flow visualisation techniques in the wind tunnel are time-consuming, expensive and inaccurate, whereas with a computer model the ‡ow can be examined in detail with streamlines, velocity vectors and contours plotted with relative ease. This allows a more comprehensive analysis of design changes and a better understanding of the physics involved in the ‡ow. By using CFD designers can learn not just about performances of di¤erent sail shapes, but they can also begin to understand why a sail performs well - or poorly - and possibly make further improvements based on these …ndings.

The prospect of obtaining accurate numerical solutions for the ‡ow past downwind sails is enticing for a sail designer. However there are also many downsides to computational modelling and consequently - for downwind sails at least - CFD is yet to play a signi…cant role in the design process. The computational demands for a CFD model for a three-dimensional sail are considerable. Grid accurate analysis requires a computation grid in excess of 10 million nodes and consequently many gigabytes of computer memory is required. For downwind sails the angle of attack is large (approximately $30^{\pm}$ to the chord line) compared to upwind sails and the presence of large and unsteady separated regions makes the solution process di¢ cult. Simulations must use a transient solver and time steps small enough to resolve the transient behavior. Even with state-of-the-art supercomputers simulations of this ‡ow problem inevitably take days, or even weeks to solve.

As mentioned, CFD simulations of the three-dimensional ‡ow past downwind sails require top-of-the-line computer resources and long solution times. Therefore to perform a comprehensive validation study with suitable grid- and time step-convergence studies for a three-dimensional model would require exorbitant computer resources and inappropriate solution times considering the time frame of the Ph.D. project. Therefore since three-dimensional solutions are impractical it was decided to study ‡ows around two-dimensional downwind sail sections, that is, to investigate the performance of turbulence models for ‡ows around thin highly cambered airfoils. Two-dimensional simulations require only a fraction of the computer resources and involve the essence of the physics of three-dimensional sail ‡ows. Flow separation is the most demanding feature of the ‡ow physics and simplifying the problem from three- to two-dimensions does not make the prediction of ‡ow separation any easier. Further discussion of the di¤erences and similarities between two- and three-dimensional sail ‡ows is provided in Section ??.

Perhaps the largest obstacle to the simulation of accurate sail ‡ows is the phenomenon of turbulence, a phenomenon that cannot be simulated exactly (without vast computer resources) and must be modelled using a turbulence model. Turbulence models are notoriously unreliable for ‡ows that involve ‡ow separation and numerous validation studies have illustrated that dramatically di¤erent results can be achieved depending on the choice of turbulence model [3]. Consequently it is unwise to embark upon a computational design program for a ‡ow as complex as a downwind sail con…guration without …rst performing an in depth investigation into the relative preformance of the available turbulence models. In order to be con…dent of results and understand their limitations it is necessary to …rst validate the method carefully and develop a good understanding of the physics involved. This is the essence of the motivation for the thesis; *to gain an in depth understanding of the physics involved downwind sail ‡ows and to determine the most suitable computation method for downwind sail analysis.*

1.2 Previous related studies

To the knowledge of the Author there have been no publications to date on the validation of computational methods for highly cambered foils that are representative of downwind sail ‡ows. In fact it is di¢cult to …nd a ‡ow case that involves all the typical ‡ow features of downwind sail ‡ows. Other high-lift foils such as aircraft take-o¤ and landing con…gurations and front and rear wings on race cars involve the same design goal of maximising lift while ignoring the in‡uence of drag, however these foils are allowed to have slots to sustain attached ‡ow. Downwind sail ‡ows - with their large unsteady wakes - resemble ‡ows past circular cylinders more closely than most high-lift devices.

In order to simulate viscous ‡ows involving separation it is necessary to model the boundary layer of the sail. *Bailey* (1999) [4] developed upon the work of *Jackson and Fiddes* (1995) [5] using a two-dimensional panel code coupled to integral boundary layer methods to compute two-dimensional sail ‡ows. Bailey's model was capable of predicting turbulent transition, leading edge separation and boundary layer separation. However it was found that the methods used were only applicable to low camber sails at moderate angles of attack. Unfortunately extension of such a coupled method to three dimensions is a di¢cult and as yet unexplored task.

The work of *Jackson and Fiddes* (1995) highlighted the importance of accurately representing the leading edge bubble that often forms as air passes the lu¤ of a sail [5]. Jackson and Fiddes modelled the leading edge bubble using a geometric approximation that assumed that the bubble shape was elliptical. This approximation is inadequate since leading edge bubbles have complicated shapes that will not necessarily collapse into a generic function. Jackson and Fiddes also expressed the need for good experimental data on the problem in order to provide a better understanding of the bubble shape and dynamics [5].

Following Jacskon and Fiddes' request for experimental data on leading edge bubble *Crompton* (2001) performed wind tunnel tests on a ‡at plate a shallow angle so of incidence [6]. Surface pressures were recorded using pressure tappings and laser doppler anemometry (LDA) was used to measure velocities and normal turbulent stresses in the leading edge bubble and in the developing turbulent boundary layer downstream of the point where the leading edge bubble reattaches. This study answers many questions with regard to the shape and structure of the leading edge bubble, but unfortunately it provides little insight into the behavior of trailing edge separation of the type that occurs in downwind sail ‡ows.

Whilst a wealth of experimental data exists for two-dimensional airfoil sections - including airfoils past stall - there is little data available for sections representative of two-dimensional sails shapes. There have been just two signi…cant investigations into the behavior of the ‡ow past two-dimensional sail sections, *Milgram* (1971, 1978) and *Wilkinson* (1984, 1989, 1990).

Milgram (1971) performed water tunnel tests for thin cambered plates shaped according to the NACA 65 and $a = 0:8$ mean lines [7]. The data is presented is in the form of lift, drag and pitching moment, all measured using the force balance. The experiments used Reynolds numbers of $6;9$ and 12 £ 10^5 and camber ratios of 0.120, 0.129, 0.150 and 0.180. Large chord lengths were used relative to the width of the tunnel so that high Reynolds numbers could be achieved, consequently the aspect ratio of the models was just 2.2. For such low aspect ratio sections and large camber ratios spanwise three-dimensionalities are likely and Milgram was unable to assess the extent of their in‡uence [7]. In 1978 Milgram tested the NACA $a = 0:8$ mean line at camber ratios of 0.12 and 0.15 in the same fashion as the 1971 tests, however this time he also measured the forces for the sections with circular and elliptical masts of di¤erent diameters [8].

Wilkinson (1984) tested the NACA 63 and $a = 0:8$ mean lines with a circular mast attached in the same manner as Milgram, however unlike Milgram he also measured the surface pressure distributions and boundary layer pro…les (1990) [9, 10, 11]. Wilkinson was the …rst to paint a detailed description of the behavior of the ‡ow past sails with reference a universal description of the pressure distribution (Figure XXX). Neither Milgram or Wilkinson reported witnessing vortex shedding in their experiments. Regular vortex shedding from a IACC mainsail has been witnessed by the Author using smoke ‡ow visualisation in the University of Auckland's Twisted Flow wind tunnel. Smoke ‡ow visualisation for spinnakers and gennakers does not show clear vortex shedding, but rather a chaotic and unsteady wake region. The lack of regular shedding for these sails is thought to be due to the very low aspect ratios of these sails. Initial CFD investigations carried out in 2000 were unsteady with periodic vortex shedding, therefore it is expected that model tests of two-dimensional downwind sail sections will also exhibit vortex shedding [12]. The largest camber values tested by Wilkinson and Milgram were 20% and 18% respectively and at these high cambers it is surprising that vortex shedding was not present. However since the chord lengths were small the frequency of vortex shedding would be in the order of 5-20Hz for a Strohal numbers of 0.1-0.4 and hence it is possible that vortex shedding was present but that it's e¤ect was lost due to low sample rates.

Unfortunately, due to errors associated with three-dimensional e¤ects, the available experimental data for two-dimensional sail sections is insu¢cient both in terms of quality and detail if one's goal is to reliably validate a computation method. In order to discern di¤erences in the performance of di¤erent turbulence models it is necessary to have data that is …rstly accurate enough so that the di¤erences between the di¤erent turbulence models is more signi…cant than the error in the data itself and secondly it is important to have a range of di¤erent ‡ow variables to examine in order to enable better understanding of the behavior of the models.

1.3 Present contributions

The overall purpose of the current work is to gain an in depth understanding of the physics involved in downwind sail ‡ows and to determine the most suitable computation method for downwind sail analysis.

In order to achieve this goal the research pursues three speci…c aims: The …rst one was to assess the performance of di¤erent turbulence models for leading edge bubbles of the type found in downwind sail ‡ows. This was achieved by comparing CFD simulations with the wind thunnel results of Crompton [6]. The second aim was to perform wind tunnel experiments for several two-dimensional downwind sail sections in order to develop further understanding of the ‡ow features and to provide a database of results suitable for turbulence model validation. The …nal aim was to assess the performance of di¤erent turbulence models for our downwind sail test suite from the wind tunnel experiments.

The present research began in 2000 with a study of the current downwind sail design methodology and proceedures of North Sails New Zealand Ltd and Team New Zealand Ltd. This involved investigation into the design parameters and goals, wind tunnel testing, the computational tools - both aerodynamics and structural FEA - and the manufacturing process itself. The result of the study was a list of speci…cations for the basic input and output parameters for a CFD program and details as to how such a tool would …t into the design process. Following on from this study work was carried out investigating the suitability of di¤erent computational methods for downwind sail analysis and design. Initial a wide range of di¤erent methods were investigated from panel codes to advanced turbulence simulations (LES, DES) and it became apparent that CFD codes based on the Reynolds Averaged Navier-Stokes (RANS) equations were the most applicable. A literature review was then carried out investigating a wide range of RANS based turbulence models considering the suitability of the models based both on accuracy and simulation e¢ciency. The review focused on validation studies that have been carried out for ‡ows involving features that are relevant to sail ‡ows, e.g., airfoils near maximum lift, ‡ows involving adverse pressure gradients and boundary layer separation, ‡ows with high streamline curvature, unsteady vortex shedding and three-dimensional e¤ects such as tip vortices. This literature review is documented in *Collie et al.* (2001) [13], the key aspects of this study are also presented in Chapter ??.

Subsequent work speci…cally addressed the three aims listed above, the validation of CFD methods for the leading edge bubble for ‡at plates, wind tunnel testing of downwind sail sections, and comparison of CFD results with the wind tunnel results. As a …nal extension to the project a parametric design study was carried out looking at a range of downwind section designs. This study was used to illustrate how CFD can be employed in the downwind sail design process and to gain a better understanding of the in‡uence of di¤erent design paramenters.

1.4 Thesis outline

A description of the basic principles of yachts sailing downwind and the physics involved with downwind sails is presented in Chapter ??. This chapter is intended to provide the reader with insight into the design goals and obstacles related to downwind sails and to provide familiarity to the ‡ow problem. Chapter ?? describes issues related to turbulence and turbulence models and presents the results from a review of literature related to turbulence model validation. Chapter ?? describes the numerical method used in the CFD simulations and the key aspects of the solver. The validation study for the ‡at plate at shallow incidence is presented in Chapter ??. A preliminary wind tunnel and CFD study of the ‡ow past a two-dimensional downwind sail section is presented in Chapter ??. This study details initial e¤orts to guage the performance of di¤erent turbulence models for downwind sail ‡ows and to determine the nature of complications that are inevitable whenever wind tunnel experiments are carried out. Chapter ?? presents the validation study for two-dimensional downwind sail sections. This chapter presents the results from wind tunnel tests carried out at NASA ames in conjunction with Stanford Yacht Research. It then goes on to compare CFD results with the wind tunnel data and to assess the strengths and weaknesses of the di¤erent turbulence models. The most suitable turbulence model is then selected and used to perform a parametic analysis of downwind sail designs. This study is presented in Chapter ??. The …nal chapter summarises the thesis, draws conclusions and suggests opportunities for further research.

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