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# Application of Computational Fluid Dynamics to Two-Dimensional Downwind Sail Flows



THE UNIVERSITY OF AUCKLAND  
NEW ZEALAND

A DISSERTATION  
SUBMITTED TO THE DEPARTMENTS OF MECHANICAL ENGINEERING AND ENGINEERING SCIENCE  
OF THE UNIVERSITY OF AUCKLAND  
IN PARTIAL FULFILMENT OF THE REQUIREMENTS  
FOR THE DEGREE OF  
DOCTOR OF PHILOSOPHY

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August 2006

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# Abstract

The research detailed in this thesis investigates the practical application of Computational Fluid Dynamics (CFD) to downwind sail design. Simulations were performed using CFX-5, an unstructured commercial CFD package. The research focuses on the performance of the SST and  $k-\omega$  turbulence models which were judged to be CFX-5's most appropriate turbulence models for downwind sail flows. Two-equation turbulence models are viewed as the most appropriate model type for sail simulations, they capture a significant amount of the flow physics whilst providing turnaround times for sail simulations of less than one day.

CFD simulations were compared with experimental data for a flat plate at shallow angles of incidence. This test case holds particular relevance to sail flows since both flows are affected by leading edge separation bubbles which form due to knife-edge separation at sharp leading edges. The CFD captures this leading edge bubble well, with the SST model predicting the length of the bubble with 7% of the experimental value.

Wind tunnel data was gathered for two-dimensional downwind sail sections for the purpose of CFD validation. A preliminary wind tunnel study was carried out using a low aspect ratio model. The tests were prone to three-dimensional effects and only three-dimensional CFD simulations were capable of successfully reproducing the flow. High aspect ratio wind tunnel test results were also conducted in an effort to obtain nominally two-dimensional wind tunnel data. Surface pressures were measured using Pressure Sensitive Paint (PSP), however due to the low dynamic pressure of the tests error appeared in the data and comparison with the CFD was poor. Results show that CFD is capable of qualitatively reproducing downwind sail flows, the leading and trailing edge separation regions were captured and the CFD results compared well with wind tunnel flow visualisation.

Finally, CFD simulations were used to investigate the two-dimensional downwind sail design space through a parametric study of sail draft and camber. Results show that increasing camber increases both lift and drag a trend that also is evident in three-dimensional sail designs. It is also shown that gains can be made by using designs with draft values as far aft as 60% which helps reduce the extent of trailing edge separation. This parametric design study illustrates how CFD can be used successfully to analyse design trends and rank designs.

The research presented illustrates how CFD can be used in the design process but also that care must be made in validating the method. Through this study the relative strengths and weaknesses of the turbulence models are better understood. Whilst CFD cannot yet be reliably used for downwind sail performance prediction, it is still a useful tool for investigating the flow structure which leads to better understanding of the design space.

# Acknowledgements

My greatest appreciation goes out to Professor Margot Gerritsen whose investment in me over many years has been considerable. Through undergraduate, Masters and Ph.D. theses Margot has supported me and has provided a solid base for my academic development. Her kindness in continuing to advise me after her move from Auckland to Stanford University was vital to the course of my Ph.D. Margot has readily gone out of her way for me and I appreciate that greatly. Moreover, her advise is always well thought out and clear whilst also provides room for discovery and individual thought. Margot, I thank you and I look forward to continuing doing research with you.

Much thanks goes to Professor Peter Jackson whose supervision in this Ph.D. was extremely valued and reflective of his considerable experience and knowledge. Peter's thoughtful questions and answers always motivated me to explore the topic deeply and challenged me to question results from new directions.

Burns Fallow has been my mentor in the sail design industry for many years. From giving me the opportunity as an undergraduate to perform my work experience at North Sails, through to his valued advice on this thesis. Burns has provided me with many valuable experiences and shared much of his esteemed knowledge of sail design.

Acknowledgement must also be provided to Technology New Zealand who supported me through TIF fellowship contract NSLX9901. Similarly thanks goes to The University of Auckland's Doctoral Scholarship program.

Finally I would like to thank my friends and family who have always provided me with a warm and exciting life outside of my studies. Sharon, Dave, Jocelyn, Heather and Philippa, your love, support and sacrifice is cherished.

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# List of Symbols and Abbreviations

## Chapter 1

$a$	mean-line designation; fraction of the chord from leading edge over which loading is uniform at the ideal angle of attack
ACC	America's Cup Class
CFD	Computational Fluid Dynamics
FEA	Finite Element Analysis
LDA	Laser Doppler Anemometry
NASA	National Aeronautics and Space Administration
PC	Personal Computer
RANS	Reynolds Averaged Navier-Stokes
RMS	Root Mean Squared
SYR	Stanford Yacht Research
TIF	Technology for Industry Fellowship
TFWT	Twisted Flow Wind Tunnel
VPP	Velocity Prediction Program

## Chapter 2

$\alpha_i$	induced reduction of the angle of attack due to three-dimensional effects
$\beta$	apparent wind angle
$\Gamma$	circulation
$\lambda$	leeway angle
$A$	wing / sail area
$AR$	aspect ratio
$c$	chord length
$C_{L(2D)}$	lift coefficient (two-dimensional flow)
$C_{L(3D)}$	lift coefficient (three-dimensional flow)
$DSP$	displacement of an ACC yacht
$D_{Aero}$	aerodynamic drag force

$F_D$	driving force
$F_H$	heeling force
$F_S$	hydrodynamic side force
$F_{T(Aero)}$	total aerodynamic force
$F_{T(Hydro)}$	total hydrodynamic force
$h$	wing / sail span
$L$	measured length of an ACC yacht
$L_{Aero}$	aerodynamic lift force
$O_{CE}$	Center of Effort
$R$	resistance
$S$	measured upwind sail area of an ACC yacht
$V_A$	apparent wind velocity
$V_S$	boat velocity
$V_T$	true wind velocity
$y_{back}$	the perpendicular distance between the sail and the chordline halfway between $x_d$ and the trailing edge
$y_{front}$	the perpendicular distance between the sail and the chordline halfway between the leading edge and $x_d$
$y_{max}$	the greatest perpendicular distance between the sail and the chordline
$x_d$	the chordwise location of $y_{max}$
IACC	International America's Cup Class
RNG	Renormalisation Group

### Chapter 3

$\alpha$	closure coefficient for the production of $\omega$
$\beta$	closure coefficient for the dissipation of $\omega$
$\beta^*$	closure coefficient for the dissipation of $k$
$\psi$	blending parameter for the NAC term
$\delta$	displacement thickness
$\delta_{ij}$	dirac delta function
$\epsilon$	dissipation of turbulent kinetic energy per unit mass
$\phi$	unknown variable
$\kappa$	Von Karman's constant
$\nu$	kinematic viscosity, $\nu = \frac{\mu}{\rho}$
$\nu_T$	eddy viscosity
$\mu$	dynamic viscosity
$\rho$	density
$\sigma$	closure coefficient for the turbulent transport
$\sigma_d$	closure coefficient for cross diffusion



$\sigma_\epsilon$	closure coefficient for the turbulent transport of $\epsilon$
$\sigma_k$	closure coefficient for the turbulent transport of $k$
$\sigma_\omega$	closure coefficient for the turbulent transport of $\omega$
$\tau$	Reynolds shear stress
$\tau_{ij}$	Reynolds (or turbulent) stress tensor
$\tau_w$	shear stress at the wall
$\omega$	specific rate of dissipation of turbulent kinetic energy
$a$	finite volume coefficients
$A$	face area
$a_1$	Bradshaw's coefficient
$b$	boundary condition vector
$B$	log-law constant
$C_{\epsilon 1}$	closure coefficient for the production term in the $\epsilon$ -equation
$C_{\epsilon 2}$	closure coefficient for the dissipation term in the $\epsilon$ -equation
$C_\mu$	closure coefficient for the eddy viscosity
$f$	current face of the control volume
$F_1$	cross-diffusion blending function
$F_2$	SST blending function
$I$	turbulence intensity
$ip$	integration point
$k$	turbulent kinetic energy
$L$	characteristic mean-flow length scale
$l_{mix}$	mixing length of the turbulent eddies
$N$	the Navier-Stokes operator
$n$	upstream node
$nb$	the set of neighboring nodes
$p$	instantaneous pressure
$p_t$	total pressure
$p_d$	dynamic pressure
$P$	mean-flow pressure
$p'$	turbulent pressure fluctuations
Re	Reynolds number, $Re = \frac{\rho U_\infty L}{\mu}$
$S_{ij}$	mean rate-of-strain tensor
$t$	time
$t_{ij}$	viscous stress tensor
$T$	time-scale for Reynolds averaging
$u$	instantaneous velocity
$U$	mean-flow velocity
$u'$	turbulent velocity fluctuation
$U^+$	dimensionless velocity, $U^+ = \frac{U}{u_\tau}$
$u_\tau$	friction velocity, $u_\tau = (\tau_w/\rho)^{1/2}$

$u_{mix}$	mixing velocity of the turbulent eddies
$U_\infty$	freestream velocity magnitude
$V$	volume of the control volume
$\Delta y$	perpendicular distance between the wall and the first grid point
$y$	distance to the nearest wall
$y^+$	non-dimensional wall distance, $y^+ = \frac{u_{\tau y}}{\nu}$

AIAA	American Institute of Aeronautics and Astronautics
AMG	Algebraic Multigrid
ASM	Algebraic Stress Models
BSL	the Baseline model
CTR	Centre for Turbulence Research
DES	Detached Eddy Simulation
DNS	Direct Numerical Simulation
ILU	Incomplete Lower Upper factorisation
LES	Large Eddy Simulation
LRN	Low Reynolds Number
NAC	Numerical Advection Control
PDE	Partial Differential Equation
SST	Shear Stress Transport

## Chapter 4

$\alpha$	angle of attack
$A$	surface area
$C_D$	drag coefficient, $C_D = \frac{D}{1/2\rho U_\infty^2 A}$
$C_L$	lift coefficient, $C_L = \frac{L}{1/2\rho U_\infty^2 A}$
$C_P$	pressure coefficient, $C_P = \frac{P}{1/2\rho U_\infty^2}$
$D$	drag force
$L$	lift force
$N$	non-dimensional grid spacing
$u$	velocity in the chordwise direction
$u'$	turbulent velocity fluctuations in the chordwise direction
$u_{RMS}$	RMS of the $u$ velocity fluctuations
$v$	velocity in the direction perpendicular to the plate
$v'$	turbulent velocity fluctuations in the direction perpendicular to the plate
$v_{RMS}$	RMS of the $v$ velocity fluctuations
$w$	velocity in the spanwise direction
$w'$	turbulent velocity fluctuations in the spanwise direction
$w_{RMS}$	RMS of the $w$ velocity fluctuations

$x$  chordwise dimension  
 $X_R$  reattachment length  
ZPG Zero Pressure Gradient

## Chapter 5

- 2D Two Dimensional  
3D Three Dimensional

## Chapter 6

- $A$  PSP calibration coefficient  
 $B$  PSP calibration coefficient  
 $\phi$  Phase angle  
 $I$  light intensity at pressure  $p$   
 $I_0$  light intensity at pressure  $p_0$   
 $L_*$  Length of a particular flow region (leading edge bubble, recovery region or trailing edge separation region)  
 $p_0$  wind-off pressure  
 $X_R$  Reattachment length of the leading edge bubble (% $c$ )  
 $X_S$  Trailing edge separation position (% $c$ )
- PSP Pressure Sensitive Paint

## Chapter 7

- $\beta$  apparent wind angle  
 $\varepsilon_A$  aerodynamic drag angle
- $C_T$  total force coefficient  
 $C_{DF}$  driving force coefficient  
 $C_{DS}$  drag coefficient scaled by the arc length  
 $C_{HF}$  heeling force coefficient  
 $C_{L_{\max}}$  maximum lift coefficient  
 $C_{LS_{\max}}$  maximum lift coefficient scaled by the arc length  
 $s$  arc length  
 $V_{MG}$  velocity made good (the yacht's velocity component in the direction of the next mark)  
 $SF$  foot length  
 $SLE$  leech length  
 $SLU$  luff length  
 $SMG$  mid girth length  
 $SSA$  measured downwind sail area