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

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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-ω 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.

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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

α_i	induced reduction of the angle of attack due to three-dimensional effects
β	apparent wind angle
Γ	circulation
λ	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

α	closure coefficient for the production of ω
β	closure coefficient for the dissipation of ω
β^*	closure coefficient for the dissipation of k
ψ	blending parameter for the NAC term
δ	displacement thickness
δ_{ij}	dirac delta function
ϵ	dissipation of turbulent kinetic energy per unit mass
ϕ	unknown variable
κ	Von Karman's constant
ν	kinematic viscosity, $\nu = \frac{\mu}{\rho}$
ν_T	eddy viscosity
μ	dynamic viscosity
ρ	density
σ	closure coefficient for the turbulent transport
σ_d	closure coefficient for cross diffusion

σ_ϵ	closure coefficient for the turbulent transport of ϵ
σ_k	closure coefficient for the turbulent transport of k
σ_k	closure coefficient for the turbulent transport of ω
τ	Reynolds shear stress
τ_{ij}	Reynolds (or turbulent) stress tensor
τ_w	shear stress at the wall
ω	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 ϵ-equation
$C_{\epsilon 1}$	closure coefficient for the dissipation term in the ϵ-equation
C_μ	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	instanteous pressure
p_t	total pressure
p_d	dynamic pressure
P	mean-flow pressure
p'	turbulent pressure fluctions
Re	Reynolds number, $\text{Re} = \frac{\rho U_\infty L}{\mu}$
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_τ	friction velocity, $u_\tau = (\tau_w/\rho)^{1/2}$

u_{mix}	mixing velocity of the turbulent eddies
U_∞	freestream velocity magnitude
V	volume of the control volume
Δy	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	Dettached 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

α	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
ϕ	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

β	apparent wind angle
ε_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