University of Technology Sydney

Faculty of Engineering and Information Technology

An Investigation of Free Surface Hydraulic Structures Using Large Eddy Simulation and Computational Fluid Dynamics

Peter David McKellar Brady

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requirements for the degree of Doctor of Philosophy.

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Supervisors:

Adjunct Professor John Reizes

Dr Matthew Gaston

CERTIFICATE OF ORIGINALITY

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I also certify that the dissertation has been written by me. Any help that I have received in my research work and the preparation of the dissertation itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the dissertation.

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Nomenclature

English Symbols

Symbol	**Definition**
A	area
a	finite volume equation general coefficient variable
b, B	bottom face/cell
C_s	Smagorinsky constant
$C_{\varepsilon 1}$, $C_{\varepsilon 2}$, C_μ	closure constants for the $k-\varepsilon$ RANS model
c_{surf}	surface coefficient for VOF surface reconstruction
c_i and c_μ	constants of proportionality for the viscous and inertial “effects”
d	circular cylinder diameter, square cylinder side length
e, E	east cell face/cell
E_k	kinetic energy
$E(\kappa)$	energy as a function of wave number
F_E	ensemble average of a general function
f_i	inertial effects
f	general function
F_p	force due to pressure
F_{st}	surface tension forces
F_T	time average of a general function
F	volume fraction with VOF
F_ϑ	volumetric, spatial, average of a general function
f_μ	viscous effects
F_s	wall shear stress

G	filter function
$\mathbf{g}$	gravitation vector
H	channel height
h	depth from a reference point, for example when computing hydrostatic pressures
I_{∂}	general time integral for a variable ∂
k	turbulent kinetic energy
l	integral length
l_c	characteristic length
m	mass
n/N	north cell face/cell
N	cell count, number of experimental repetitions
$\mathbf{n}$	surface normal vector
P	a general point when discussing the finite volume method
p	thermodynamic pressure
p_h	hydrostatic pressure
S_{∂}	source term for variable ∂
s/S	south cell face/cell
S_{ij}	resolved strain rate tensor with LES
s_{ij}	strain rate tensor with RANS
$\overline{S}$	volume averaged source term
t	time (s); top cell face
T	time, when used in the temporal RANS average, or the top cell in the finite volume method
t_{ij}	viscous stress tensor with RANS models

U_i	average velocity in the *i*th direction
u_c	characteristic velocity
$\hat{u}_i$	filtered velocity with each hat representing one filtering iteration
u_i'	fluctuating velocity in the *i*th direction
u_i	instantaneous total velocity in the *i*th direction
u^+	non-dimensional wall velocity, $u^+ \triangleq \frac{U}{u_\tau}$
u, v, w	principle velocity components in a Cartesian reference frame
u_τ	wall velocity, $u_\tau \triangleq \sqrt{\frac{\tau_w}{\rho}}$
u	velocity vector (m/s)
U_∞	free stream velocity
w/W	west cell face/cell
x_i	*i*th coordinate direction
x	spatial coordinate vector
x, y, z	principle Cartesian coordinate axes
y^+	non-dimensional wall distance, $y^+ \triangleq \frac{u_\tau y}{\nu}$

Greek Symbols

Symbol	**Definition**
σ_k, σ_ε	closure constants for the $k-\varepsilon$ RANS model
θ	wall contact angel with VOF
ρ	density
Γ	diffusion coefficient when discussing the finite volume method
ε	dissipation rate
μ	dynamic viscosity

τ_{ij}	fluid stress tensor for a general fluid; specific Reynolds stress tensor with RANS
α	$\frac{1}{\mathrm{Re}}$
$\nu = \frac{\mu}{\rho}$	kinematic viscosity
η	Kolmogorov length
τ	Kolmogorov time scale
υ	Kolmogorov velocity scale
Δ	LES filter width
$\boldsymbol{\xi}$	point distance vector when filtering for LES
σ	surface tension coefficient
ν_T	turbulent viscosity
λ	wave length
κ	wave number
τ_w	wall shear stress
ϑ	volume
δ	a small increment of a variable, for example δx
ϕ, ψ, ξ	general variables used for the explanation of RANS correlations

Mathematical Operators

$\nabla \times$	curl operator
$\nabla \cdot$	divergence operator
∇	gradient operator
$\frac{D}{Dt}$	substantive derivative
$\mathbb{N}(u_i)$	Navier-Stokes operator with RANS

Δt	a small time increment
Δx	a small spatial increment
O	order operator

Subscripts

Symbol	**Definition**
i, j, k	directional indices
w	wall

Superscripts

Symbol	**Definition**
^{o}	indicates a variable at the current time step
$^{+}$	non-dimensional quantity
UP	variable computed from a first order upwind scheme
$2UP$	variable computed from a second order upwind scheme

Other Operators and Variables

Symbol	**Definition**
$\mathfrak{d}$	general scalar when discussing the finite volume method
$\mathfrak{X}$	blending factor for finite volume time integration
$\mathfrak{S}$	blending factor for the finite difference schemes between a first order upwind method and a higher degree scheme
$\mathfrak{K}$	geometric blending factor for central difference schemes
$\mathfrak{L}$	length from the centre of the cylinder to the outlet boundary
$\mathfrak{F}$	wall normal cell length.
$\mathfrak{D}$	two-dimensional distance of a point from a line

Non-dimensional Groups

Symbol	Definition
$\mathrm{Re} \triangleq \dfrac{u_c l_c}{\nu}$	Reynolds number based on a characteristic velocity and length
Re_τ	turbulent Reynolds number
Re_H	Reynolds number based on the channel height
$\mathrm{We} \triangleq \dfrac{\rho u_c^2 l_c}{\sigma}$	Weber number for describing surface tension

Acronyms

Acronym	Definition
2D	Two Dimensions
2OU	2nd Order Upwind
3D	Three Dimensions
CFD	Computational Fluid Dynamics
CFL	Courant-Freidrichs-Lewy
CPU	Central Processing Unit
DCP	Development Control Plans
DES	Detached Eddy Simulation
DFT	Digital Fourier Transform
DLES2	2nd Conference on Dynamic and Large Eddy Simulation
DNS	Direct Numerical Simulation
FS	Free Surface
GPT	Gross Pollutant Traps
HEC-RAS	Hydraulic Engineering Corp – River Analysis System
HR	High Resolution
HS	High Speed

ILES	Implicit Large Eddy Simulation
L&R	Abbreviation of papers by D Lynn and W Rodi (Lyn and Rodi, 1994, Lyn et al., 1995)
LDA	Laser Doppler Anemometry
LEP	Local Environment Plans
LES	Large Eddy Simulation
LES Dyn	Dynamic Large Eddy Simulation model
LES LD	Locally Dynamics Large Eddy Simulation model
LR	Low Resolution
LS	Low Speed
MAC	Marker And Cell
MILES	Monotonically Integrated Large Eddy Simulation
MR	Medium Resolution
PIV	Particle Image Velocimetry
PLIC	Piecewise Linear interface Construction
POTEO	Protection of the Environment Operations
PSD	Power Spectral Density
RAM	Random Access Memory
RANS	Reynolds Averaged Navier-Stokes
RMS	Root Mean Squared
SF	Single Fluid
SGS	Sub-Grid Scale
SIMPLEC	Semi-Implicit Method for Pressure Linked Equations - Corrected
SLIC	Single Linear Interface Construction
SMAG	Smagorinsky

SPH	Smoothed Particle Hydrodynamics
UNSW	University of New South Wales
UTS	University of Technology Sydney
VOF	Volume of Fluid
WT	Water Tunnel geometric configuration

Abstract

The work presented in this dissertation is essentially a thesis in three distinct parts (single fluid validation, two fluid validation and data analysis) rather than the established approach for the development of a novel computational fluid dynamics solver. First, the progression is a traditional one, in which an existing technique was applied to a new area and subsequently extended. Second, from detailed analysis of the large volume of data generated in the validation process, a number of insights were gained into the flow features of the prototypes investigated that extended beyond a traditional validation study and discovered a number of new physical phenomena.

Previous researchers have used monotonically integrated large eddy simulation (MILES) methods to investigate a range of flows including turbulent decay in rotary valve engines and rocket body dynamics. MLES methods have the distinct advantage over standard LES simulation techniques in that they promise to provide similar levels of detail and accuracy but at a fraction of the computational cost. However, to the author's knowledge these techniques have not been applied to the prototype problem of this thesis: cylinders in cross flow without and with free surfaces. Hence the *raison d'étre* of this thesis: to apply a faster yet equally accurate CFD method to a free surface problem via a validated single fluid investigation. Specifically, the progression was to first validate the method against a single right square cylinder in cross flow without a free surface and then to extend the method to a right circular cylinder in cross flow with a free surface.

With the right square cylinder without free surface the research focussed on the extensively studied configuration of a two dimensional square cylinder at a Reynolds number of 22×10^3. Despite the agreement of the validation parameters with published data, detailed examination of the flow field revealed inconsistencies in the modelled results. In particular the power spectrum decay of the data appear too "easy" to obtain, indicating possible flaws in the theoretical basis, while correlation data apparently supports a conclusion that the previous assumption of four diameters domain width is too narrow to provide an uncorrelated flow region.

The free surface physics of the circular cylinder model was captured with the volume of fluid method and was applied to Reynolds number flows based on cylinder diameter of between 27×10^3 and 54×10^3. These flows, at the provided grid resolution, push the

lower boundary of what can be called MILES, yet interpretations of the results indicates that the model is accurately capturing the physics of the flows.