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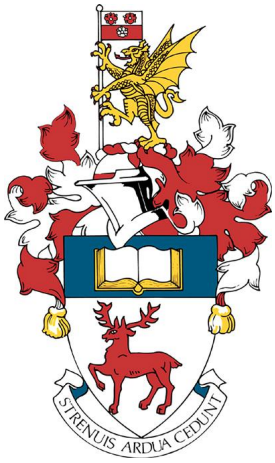

TITLE OF THE THESIS

by

AUTHOR

Supervised by SUPERVISOR

A thesis presented for the degree of DEGREE

DATE (i.e. September 2018)

TITLE OF THESIS

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Abstract

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I, THE AUTHOR declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

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4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Either none of this work has been published before submission, or parts of this work have been published as: [please list references below]:

Dedication

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Nomenclature

B_{WL}	breadth on waterline	$[m]$
C_T	total drag coefficient	[-]
C_{u_l}	lower value of CFL threshold	[-]
C_{u_u}	upper value of CFL threshold	[-]
D	experimental result	$[various]$
e_a^{ij}	approximate relative error between i^{th} and j^{th} solution	[-]
α	volume fraction	[-]
β	drift angle	$[rad]$
γ	non-dimensional yaw rate	[-]
δ	rudder angle	$[rad]$
δ_{ij}	Kronecker delta	[-]
δ_D	error in the experimental value	$[various]$
δ_{SN}	numerical error in simulated value	$[various]$
$\delta^*_{I_{km}}$	iterative error of the k^{th} variable at the m^{th} refinement	$[various]$
ϵ_{ij}	change between i^{th} and j^{th} corrected solutions	$[various]$
θ	pitch angle	$[rad]$
λ	scale factor	[-]
ψ	yaw angle	$[rad]$
ω	angular velocity $(2\pi/T)$	[rad/s]
Ω_{ij}	vorticity or rotation tensor	$[1/s]$
∇	displacement volume moulded	$[m^3]$

List of Abbreviations

CFD	Computational Fluid Dynamics
CFL	Courant–Friedrichs–Lewy
CMT	Circular Motion Test
CPU	Central Processing Unit
(D)DES	(Delayed) Detached Eddy Simulation
DOF	Degrees Of Freedom
DTMB	David Taylor Model Bassin
EASM	Explicit Algebraic Stress Model
FVM	Finite Volume Method
GCI	Grid Convergence Index
ITTC	International Towing Tank Conference
JBC	Japanese Bulk Carrier
JMU	Japan Marine United Corporation
KCS	KRISO Container Ship
KRISO	Korean Research Institute of Ships and Ocean Engineering
LES	Large Eddy Simulation
LS	Level Set
MARIN	Maritime Research Institute Netherlands
MMG	Mathematical Manoeuvring Model Group
MOERI	Maritime & Ocean Engineering Research Institute
NMRI	National Maritime Research Institute

Chapter 1

Introduction

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1.1 How to cite?

Use "\citet{pope2001turbulent}" for in text citation such as: Many books threat of the different turbulence models, for example, Pope (2001) give a thorough and comprehensive...

Use "\citep{pope2001turbulent}" for in text citation such as: The spectral tensor ϕ_{ij} is defined as the Fourier transform of the correlation function $R(\mathbf{r})$ (Pope, 2001).

1.2 Section of Introduction

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Chapter 2

Background

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2.2 Conclusion on Background

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Chapter 3

Theory

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3.1 Section of Theory

Two different coordinate systems are used in ship manoeuvring. A ship-fixed coordinate system (*oxyz*), fixed to the hull at the origin (*o*) and a space-fixed (*inertial*) coordinate system (*OXYZ*). For consistency with the experimental data available, the origin for the ship-fixed coordinate system is taken at midship, and not at the centre of gravity, for all simulations presented herein. The motions of the ship-fixed coordinate system are expressed relative to the space-fixed coordinate system.

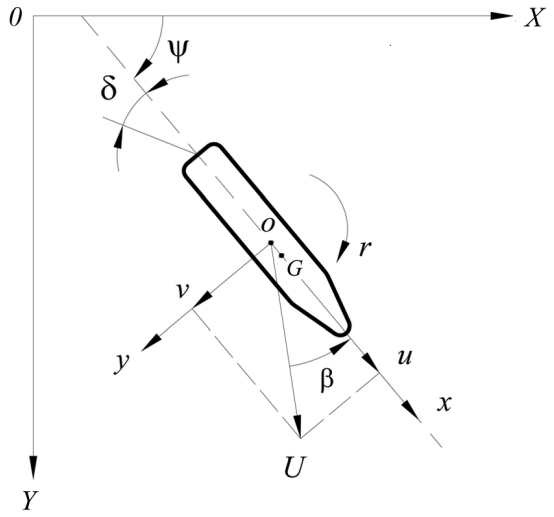

Figure 3.1: Space and ship-fixed coordinate system. Adapted from Luo et al. (2016).

In the ship-fixed coordinate system, x is pointing forward, y to starboard and z downwards. The origin of the space-fixed coordinate system is usually taken as lying on the undisturbed free surface. A positive yaw angle ψ is therefore defined as a *clockwise* rotation of the ship in the space-fixed coordinate system. Similarly, a positive drift angle β corresponds to the flow coming from starboard.

Chapter 4

Methodology

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4.1 Section of Methodology

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4.1.1 Sub-section of Methodology

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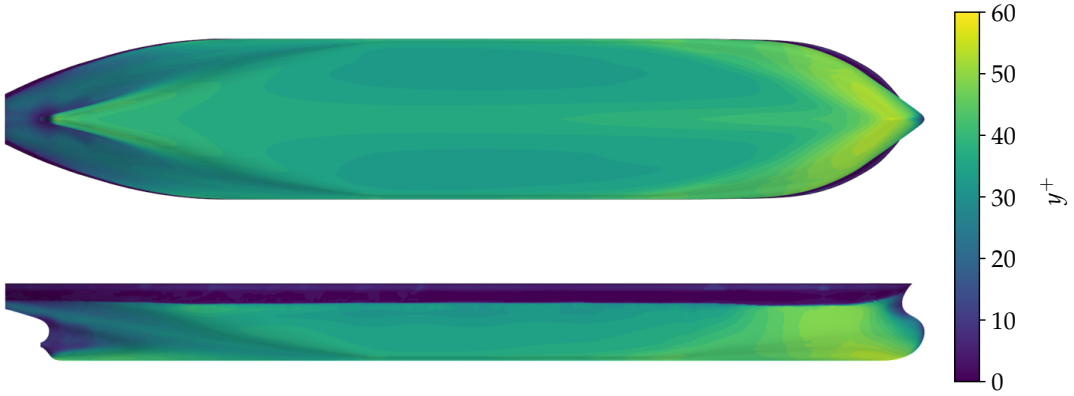

Figure 4.1: Bottom and profile view of the non-dimensional wall distance (y^+) on the KVLCC2 for the static drift simulation ($\beta = 0°$, $Fr = 0.142$).

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Table 4.1: Example of a threeparttable, useful for footnotes in tables.

Boundary	Quantity	Value
Inlet	-Turbulence Intensity	0.01
	-Turbulent Viscosity Ratio	10.0
	-Velocity	Wave[1]
	-Volume Fraction	Wave[1]
Outlet	-Turbulence Intensity	0.01
	-Turbulent Viscosity Ratio	10.0
	-Pressure	Wave[1]
	-Volume Fraction	Wave[1]
Hull	-Shear Stress	No-Slip
Deck	-Shear Stress	Slip
Tank Walls	-Shear Stress	Slip

[1] Star-CCM$^+$ uses flat-water waves when using the VOF model to specify the velocity, hydrostatic pressure and volume fraction at the boundaries.

Chapter 5

Chapter X

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5.1 Section of chapter X

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Chapter 6

Chapter XX

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Table 6.1: Another threeparttable example.

	X (N)	Y (N)	N (Nm)
$\hat{S}_{k1}$ (Fine)	-3.111	5.512	8.860
$\hat{S}_{k2}$ (Standard)	-3.094	5.502	8.8544
$\hat{S}_{k3}$ (Coarse)	-3.065	5.483	8.8540
Convergence[1]	M	M	M
$\boldsymbol{p}$ (apparent order)	**3.31**	**4.13**	**12.13**
$\hat{S}_{\text{ext}}^{21}$	-3.129	5.519	8.861
e_{a}^{21}	0.55	0.18	0.07
e_{ext}^{21}	0.56	0.14	0.01
$\mathbf{GCI}_{\text{standard}}^{21}$	**1.41**	**0.4**	**0.0074**

[1] M: monotonic convergence, O: oscillatory convergence, D: divergence

Chapter 7

Conclusion and Future Work

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7.1 Conclusions

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7.2 Recommendations for Future Work

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Appendix A

Writing Equations

The following present the details of the different turbulence closure models used. For a complete explanation of the implementation of the different models, refer to Siemens (2017).

A.1 Different Equations

Menter's formulation of the k-ω turbulence model is used (Menter, 1994), where the turbulent kinematic energy k is given by

$$\frac{Dk}{Dt} = \tau_{ij}\frac{\partial u_i}{\partial x_j} - \beta^\star \rho\omega k + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_{k1}\mu_t)\frac{\partial k}{\partial x_j}\right], \tag{A.1}$$

and the specific dissipation rate ω,

$$\begin{aligned}\frac{D\rho\omega}{Dt} = \frac{\gamma}{\nu_t}\tau_{ij}\frac{\partial u_i}{\partial x_j} - \beta\rho\omega^2 + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_\omega\mu_t)\frac{\partial \omega}{\partial x_j}\right] \\ + 2\rho(1-F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}\,.\end{aligned} \tag{A.2}$$

F_1 is a blending function that calculates the new model constants ϕ from the constant ϕ_1 and ϕ_2,

$$\phi = F_1\phi_1 + (1-F_1)\phi_2\,. \tag{A.3}$$

The turbulent viscosity is calculated using the turbulent kinetic energy and the specific dissipation rate

$$\nu_t = \frac{a_1 k}{\max(a_1\omega; \Omega F_2)}\,, \tag{A.4}$$

with

$$F_2 = \tanh(arg_2^2)\,, \tag{A.5}$$

where,

$$arg_2 = max\left(2\frac{\sqrt{k}}{0.09\omega y}; \frac{500\nu}{y^2\omega}\right) . \tag{A.6}$$

The constant of set ϕ_1 are (SST inner):

$$\kappa = 0.41 \qquad \beta^\star = 0.09 \qquad \beta_1 = 0.0750 \qquad \sigma_{k1} = 0.85$$
$$\sigma_{\omega 1} = 0.5 \qquad a_1 = 0.31 \qquad \gamma_1 = \beta_1/\beta^\star - \sigma_{\omega 1}\kappa^2/\sqrt{\beta^\star}$$

The constant of set ϕ_2 are (standard k-ϵ):

$$\kappa = 0.41 \qquad \beta^\star = 0.09 \qquad \beta_2 = 0.0828 \qquad \sigma_{k2} = 1.0$$
$$\sigma_{\omega 2} = 0.856 \qquad \gamma_2 = \beta_2/\beta^\star - \sigma_{\omega 2}\kappa^2/\sqrt{\beta^\star}$$

Appendix B

Other Tricks

B.1 Standard appendix

Boundary layer theory can be used to determine the required first cell height and the depth of the boundary layer for meshing. First the Reynolds number of the simulation is determined, using fresh water properties

$$Re_x = \frac{Ux}{\nu} = \frac{0.76 \cdot 2.9091}{1.138 \times 10^{-6}} = 1.94 \times 10^6 \,. \tag{B.1}$$

The wall distance can be calculated using the ITTC skin-friction correlation line

$$C_f = \frac{0.075}{(\log(Re_x) - 2)^2} = \frac{0.075}{(\log(1.94 \times 10^6) - 2)^2} = 4.078 \times 10^{-3} \,, \tag{B.2}$$

for $Re_x < 10^9$. The wall shear stress can be expressed as

$$\tau_w = \frac{1}{2}\rho U^2 C_f = \frac{1}{2} \cdot 999.1026 \cdot 0.76^2 \cdot 4.078 \times 10^{-3} = 1.176 \,. \tag{B.3}$$

From this the friction velocity can be calculated

$$u_* = \sqrt{\frac{\tau_w}{\rho}} = \sqrt{\frac{1.176}{9989.1026}} = 0.0343 \,. \tag{B.4}$$

And finally, the wall distance

$$y = \frac{y^+ \nu}{u_*} = \frac{30 \cdot 1.0034 \times 10^{-6}}{0.0343} = 0.000994m \,. \tag{B.5}$$

With a target y+ $\sim$ 30 the required first cell height is (this gives us the position of the first node, which is at the centre of the cell)

$$y = 0.00198m \;\sim\; 2mm \,. \tag{B.6}$$

The total boundary layer depth can be estimated using Schilchting formula for a turbulent boundary layer over a flat plate (Schlichting, 1979)

$$\frac{\delta}{x} = 0.37 Re_x^{-1/5} = 0.37 \cdot 1.94 \times 10^{6^{-1/5}} = 0.02044\,. \tag{B.7}$$

At the stern, the boundary layer depth will be

$$\delta = 0.02044 \cdot 2.9091 = 0.0595m\,. \tag{B.8}$$

B.2 Include code (Python and more)

```
from scipy.signal import butter, filtfilt

# Filter for experimental data
def butter_lowpass(cutoff, fs, order):
    nyq = 0.5 * fs
    normal_cutoff = cutoff / nyq
    b, a = butter(order, normal_cutoff, btype='low', analog=False)
    return b, a

def butter_lowpass_filter(data, cutoff, fs, order):
    b, a = butter_lowpass(cutoff, fs, order=order)
    y = filtfilt(b, a, data)
    return y
```

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