Experimental and Computational Investigation of Flow about Low Aspect Ratio Ellipsoids at Transcritical Reynolds Numbers

by

David B. Clarke

National Centre Maritime Engineering and Hydrodynamics

Submitted in fulfilment of the requirements
for the degree of
Doctor of Philosophy

University of Tasmania

December 2009

Declaration of originality and authority of access

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution. Except by way of background information and duly acknowledged in the thesis, and to the best of the candidates knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

This thesis may be made available for loan and limited copying in accordance with the Copyright Act 1968.

David B. Clarke

Abstract

As the role of unmanned underwater vehicles expands it becomes increasingly important to understand the nature of the fluid flow around them. This research examines the flow around two ellipsoids with generic shapes representative of streamline unmanned underwater vehicles (UUV). Although a significant body of work, both experimental and computational, exists for flow about spheroids the majority of this is for prolate spheroids with finer aspect ratio.

This research examines the flow around a 3–1 prolate spheroid and a 4.2–2–1 scalene ellipsoid. Many of the previous studies have focused on the major crossflow separation that occurs on a 6–1 prolate spheroid when placed at medium to large incidences. This study examines the flow around these bluffer bodies at low to moderate incidence in transcritical flow. These are the conditions that many UUV's spend the vast majority of their time operating in, and is thus of importance when assessing their operational envelope.

At low to moderate incidence a closed separation on the flank is found to be the dominant flow feature for the 3–1 spheroid and the 4.2–2–1 ellispoid. For the 4.2–2–1 ellipsoid at lower Reynolds numbers an open separation occurs on the flank upstream of the closed separation.

An extended length of attached flow on the suction side of the symmetry plane was observed for these models at incidence. The reasons for this attached flow despite a considerable length of adverse streamwise pressure gradient are identified to be due to the influence of the azimuthal pressure gradient on the boundary layer.

Ideally computational fluid dynamics (CFD) could be used to examine the flow about these shapes during the design process. However before this process is useful there needs to be an understanding of the strengths and weaknesses of the techniques being applied. Calculation of the three-dimensional flow around these vehicles presents a number of significant challenges including boundary layer transition and boundary layer separation off smooth doubly curved surfaces.

The experimental work has identified flow features and trends with Reynolds number; a considerable amount of quantitative data is also presented. The ability of CFD techniques to calculate the features and trends identified in the experimental work can be used as an

indication of their veracity. Numerical studies using two-equation turbulence models modified to allow predetermined regions of laminar flow are presented. Qualitative and quantitative comparisons between the measured and calculated results are presented. Limitations identified in the CFD modelling techniques used include: premature boundary layer separation at the rear of the model, typically on the pressure side; and separation of the laminar region prior to the measured transition region at low Reynolds numbers.

A number of experimental techniques were refined during this work. These include a quick and accurate method of applying discrete element boundary layer trip strips, which is particularly suited to three-dimensional shapes; improvements to a fast response total pressure probe; and an oil flow visualisation technique using a mixture that is close to neutrally buoyant and may be formulated to alter the viscosity over a large range.

Contents

Acknowledgements

The support of my employer, the Defence Science Technology Organisation (DSTO), has been pivotal to this research and is greatly appreciated. The head of the Maritime Platforms Division Hydrodynamics Group, Brendon Anderson provided unwavering support and encouragement. DSTO has funded the extensive array of equipment required for this research as part of a program to develop the capabilities of the Australian Maritime College Tom Fink Cavitation Tunnel.

Many of the staff at Boeing Australia have provided the support necessary for this research. The engineering drawings were produced by the Boeing Design Cell. John Xiberras was responsible for the engineering drawings for the spheroid, ellipsoid, model stings, internal balance housing, compound viewing windows, tare mount, and shroud for the support foil. These items often had a number of iterations so John's patience and perseverance were valuable. Vinh Nguyen created the drawings for the three-dimensional traverse and Derek Ramsay for the fast response probe. Adam Woollett assisted with the graphics for the spheroid, ellipsoid, internal balance and traverse.

The Boeing Manufacturing Cell manufactured all the above items except the ellipsoid and its internal balance housing. Many members of this cell were involved in this process. Of special note are Paul Vella and Paul Copper who are able to perform miracles with a mill, and Ken Morgan whose pursuit of perfection, vast knowledge and willingness to share it is appreciated.

The electronics and firmware for the three-dimensional traverse was designed and written by Sasha Smiljanic of the Boeing Electronics Cell and manufactured by the Boeing Electronics Cell. The responsiveness and cheerfulness of all members of the Boeing Engineering team at Fishermans Bend made the manufacture of these items a positive experience.

Engineering support at the cavitation tunnel was provided by Robert Wrigley: his ability to make problems go away was invaluable. Daniel Price assisted with the surface pressure measurements on the spheroid.

Thanks to Dr David Jones for translating Eichelbrenner and Michel's paper from French. The ellipsoid and internal balance housing were manufactured by Mark Harris, Peter Thornton, Richard Andrews, and Peter Worden from DSTO's Scientific Engineering Services Division.

Thanks to Hawk Lee and Dr Michael Roomina from Leap Australia who provided support for the Fluent CFD package.

Associate Professor Paul Brandner's diverse talents, knowledge and unrelenting commitment to his work, coupled with the deep wells of knowledge provided by Visiting Research Professor Greg Walker, created a formidable supervision team. Their friendliness, humour and support made this task a more pleasant experience.

Lastly I thank my partner Kris for her love, patience, understanding and support throughout this work.

Nomenclature

General

a_e	major axis length of spheroid or ellipsoid in x direction (m)
b_e	minor axis length of spheroid or ellipsoid in y direction (m)
c_e	minor axis length of spheroid or ellipsoid in z direction (m)
k	turbulent kinetic energy per unit mass, $\overline{u_i'u_i'}/2$ (m^2/s^2)
l	length of spheroid or ellipsoid in x_{bc} direction, $2a_e$ (m)
p	static pressure (Pa)
p_T	total pressure (Pa)
p'	unsteady component of static pressure (Pa)
p_{frtpp}	pressure measured by fast response total pressure probe (Pa)
p_{ref}	static pressure at reference point (Pa)
q_{ref}	dynamic pressure at reference point, $\rho u_{ref}^2/2$ (Pa)
u_{ref}	absolute velocity at reference point (m/s)
u_τ	friction velocity, $\sqrt{\tau_w/\rho}$ (m/s)
u, v, w	velocity in the x, y and z direction respectively (m/s)
u', v', w'	unsteady velocity component in the x, y and z direction respectively (m/s)
$A_{x_{bc}}$	maximum cross-section area of the model normal to x_{bc} (m^2)
C_p	non-dimensional pressure, $(p - p_{ref})/q_{ref}$
C_{τ_w}	non-dimensional wall shear stress, τ_w/q_{ref}
E	elastic modulus (Pa)
H	shape factor, δ^*/θ
N	number of samples
U_∞	freestream velocity (m/s)
V_e	volume of spheroid or ellipsoid model, $\frac{4}{3}\pi\, a_e\, b_e\, c_e$
Re_l	Reynolds number based on length, $U_\infty l/\nu$
Re_S	maximum strain rate Reynolds number
Re_{δ^*}	Reynolds number based on displacement thickness, $U_\infty \delta^*/\nu$

Re_θ	Reynolds number based on momentum thickness, $U_\infty\theta/\nu$
Re_Ω	maximum vorticity Reynolds number
x_{bc}	Cart. coord. aligned with major axis of body, origin at centre of model (m)
x_t	Cart. coord. aligned with longitudinal direction of the test section, origin at centre of test section (m)
$x_{\bar{\gamma}_i}$	streamwise location of $\bar{\gamma}_i$ in body coordinates (m)
y_{bc}	Cart. coord. aligned with horizontal minor axis of body, origin at centre of model (m)
y_t	Cart. coord. aligned with horizontal direction of the test section, origin at centre of test section (m)
y_P	distance from nearest wall (m)
y^+	non-dimensional distance from wall, $u_\tau y_P/\nu$
z_{bc}	Cart. coord. aligned with vertical minor axis of body, origin at centre of model (m)
z_t	Cart. coord. aligned with vertical direction of the test section, origin at centre of test section (m)
α	angle of incidence $(^\circ)$
γ	instantaneous intermittency of turbulence
$\bar{\gamma}$	time averaged intermittency of turbulence
$\bar{\gamma}_i$	time averaged intermittency of turbulence of a constant value i
δ	boundary layer thickness (m)
δ^*	displacement thickness, $\int_0^\infty (1-u(y)/u_0)\,dy$ (m)
ε	dissipation rate of turbulent kinetic energy (m^2/s^3)
θ	momentum thickness, $\int_0^\infty (u(y)/u_0)\,(1-u(y)/u_0)\,dy$ (m)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
ρ_W	density of water, at $20^\circ C$, $101.325\,kPa$ is $998.2\,kg/m^3$
τ_w	wall shear stress (Pa)
φ	azimuthal angle, measured from the symmetry plane on the windward side $(^\circ)$
φ_e	azimuthal angle mapped to an ellipse, measured from the windward side $(^\circ)$
ω	specific dissipation rate of turbulent kinetic energy $(1/s)$

Surface Pressure

k_{cont}	cavitation tunnel contraction function, weakly dependent on Reynolds number
k_{Rose}	calibration const. for the Rosemount differential pressure transducer (DPT) (Pa/V)
$k_{Validyne}$	calibration const. for Validyne DPT (Pa/V)
C_{P_i}	pressure coefficient at Port i, zero and temporally corrected
$\overline{C}_{P_i}$	time averaged C_{P_i}, equivalent to C_p
$C_{V_{i\_ref}}$	dimensionless coefficient used to calculate C_{P_i} at port i, zero corrected
P_i	pressure at Port i on the Scanivalve, no corrections (Pa)
P_{ref}	reference pressure for surface pressure measurements (Pa)
P_{i_ref}	zero corrected differential pressure measured by the Validyne DPT (Pa)
$P_{i\_ref\_corrected}$	zero and temporally corrected pressure determined from Validyne DPT (Pa)
$P_{i_{dynamic}}$	test section dynamic pressure when Validyne DPT connected to Port i (Pa)
Re_k	critical roughness Reynolds number
$V_{P_i - P_{ref}}$	Validyne DPT measurement resulting from pressure $P_i - P_{ref}$ (V)
$V_{P_{i_{Rose}}}$	Rosemount DPT measurement when Validyne DPT is connected to Port i (V)
$V_{P_{Rose\_zero}}$	zero for Rosemount DPT, obtained when water in the tunnel is stationary (V)
σ_i	standard deviation of sampled data for variable i
ε_i	estimated inaccuracy of variable i

Force Measurements and Calculations

α_t	pitching angle of model in tunnel coordinates $(^\circ)$
x_{eb}	Cart. coord. of external balance, parallel with x_t, different origin (m)
y_{eb}	Cart. coord. of external balance, parallel with y_t, different origin (m)
z_{eb}	Cart. coord. of external balance, parallel with z_t, different origin (m)
$\Delta x_{bc_{eb}}$	x position of body centre in external balance coordinates (m)
$\Delta z_{bc_{eb}}$	z position of body centre in external balance coordinates (m)
$A_{x_{bc}}$	area of the model projected onto the plane normal to the x_{bc} axis (m^2)
$A_{base_{x_{bc}}}$	area of the hole at the base of the model projected onto the plane normal to the x_{bc} axis (m^2)
$A_{foil_{z_{eb}}}$	cross sectional area of support foil normal to the z_t axis at $z_t = 40\,mm$ (m^2)
$A_{sting_{x_{eb}}}$	cross sectional area of sting at $x_{bc} = 161\,mm$ normal to the x_t axis (m^2)

C_F	force coefficient, $F/(q_{ref}A_{x_{bc}})$
C_{Ti}	moment coefficient, $T/(q_{ref}A_{x_{bc}}l)$
D	force parallel to flow direction at U_∞, drag (N)
F_i	force on external surfaces in the i direction due to flow (N)
Fm_i	force measured in the i direction due to flow (N)
Fmt_i	force measured in the i direction due to flow during tare correction (N)
L	force perpendicular to flow direction at U_∞, lift (N)
P_{base}	static pressure inside the model (Pa)
P_{eb}	internal pressure of the external balance housing (Pa)
Pt_{base}	static pressure inside the model during tare correction (Pa)
$\bar{P}_{lsf}$	average static pressure over the lower surface of the support strut (Pa)
$\bar{P}t_{lsf}$	average static pressure over the lower surface of the support strut during tare correction (Pa)
T_i	moment on external surfaces about the i direction due to flow (Nm)
Tm_i	moment measured about the i direction due to flow (Nm)
Tmt_i	moment measured about the i direction due to flow during tare correction (Nm)

Boundary Layer Survey

f_{dia}	1st resonant frequency of sensor diaphragm in air (Hz)
f_H	frequency of the Helmholtz resonator formed by probe cavity (Hz)
f_{wd}	1st resonant frequency of the probe considering only the mass of water and the stiffness of the diaphragm (Hz)
l_i	length of probe section with internal radius r_i (m)
l_z	axial distance from narrowest part of the conical section (m)
m_i	mass of water in probe section (kg)
m_{eff}	effective mass of water in probe at sensor diaphragm (kg)
p_{sen}	static pressure at the sensor (Pa)
p_{vap}	vapour pressure (Pa)
r_i	internal radius of probe section (includes probe tip and head) (m)
r_{cc}	radial variable for cylindrical coordinate system (m)
t_{sen}	thickness of sensor diaphragm (m)
w_i	average velocity of fluid in probe (m/s)
v_{ss}	speed of sound in water (m/s)
x_{tr}	Cart. coord. of traverse, parallel with x_t, different origin (m)

x_{trp}	estimate of location of boundary layer transition from pressure measurements (m)
y_{tr}	Cart. coord. of traverse, parallel with z_t, different origin (m)
$z_{cc}(r_{cc})$	height variable for cylindrical coordinate system, function of radial position (m)
z_{tr}	Cart. coord. of traverse, parallel with y_t, different origin (m)
C_{dia}	relative compliance of the diaphragm
E_{sen}	elastic modulus of sensor diaphragm (Pa)
K_{bm}	bulk modulus (Pa)
Re_D	Reynolds number based on sting diameter
V_i	volume of probe section (m^3)
Δp_{sen}	pressure applied to diaphragm movement to cause ΔV_{sen}, (Pa)
$\Delta p_{sen_{max}}$	pressure applied to diaphragm movement to cause $\Delta V_{sen_{max}}$ (Pa)
ΔV_{sen}	volume displaced by diaphragm movement (m^3)
$\Delta V_{sen_{max}}$	maximum volume displaced by diaphragm movement (m^3)
ξ	non-dimensional length used in plotting intermittency of turbulence
ρ_{dia}	density of sensor diaphragm (kg/m^3)
σ_c	cavitation number
θ_{cc}	azimuthal variable for cylindrical coordinate system (°)
θ_{tr}	rotation angle about y_{tr} (°)
ν_P	Poisson's ratio
ϕ_{tr}	rotation angle about z_{tr} (°)
ψ_{tr}	rotation angle about x_{tr} (°)
Subscript	
in	inlet section of probe including tip
con	conical section of probe between inlet and sensor section
sen	sensor sections of probe
trp	location of boundary layer transition estimated from the surface pressure distrubution

CFD

$a1$	constant used with SST turbulence model, set to 0.31
A_{blend}	constant used in calculating sharpness of blending for $\mu_{t,enh}$
$F1, F2$	blending functions for the SST turbulence model
H_Λ	estimate of shape factor allowing for the influence of crossflow
p_e	static pressure at the edge of the boundary layer (Pa)

$\overline{p}_w$	average static pressure at the wall (Pa)
u_Λ, v_Λ	velocity in the x_Λ and y_Λ direction respectively (m/s)
x_Λ	coordinate aligned with the external streamline (m)
y_Λ	coordinate in the crossflow direction (m)
z_Λ	coordinate normal to the surface (m)
y_P	distance to nearest wall, (m)
y^+	Wall y plus, non-dimensional parameter
Re_y	turbulent Reynolds number
Re_y^*	constant used in calculating sharpness of blending for $\mu_{t,enh}$
Re_θ	momentum thickness Reynolds number based
S	absolute value of the mean rate-of-strain tensor (1/s)
U_e	velocity outside the boundary layer (m/s)
U_Λ	velocity along the streamline at the edge of the boundary layer (m/s)
α^*	low Reynolds number correction for SST turbulence model
$\delta_{x_\Lambda}^*$	streamwise displacement thickness (m)
$\delta_{y_\Lambda}^*$	crossflow displacement thickness(m)
ΔRe_y	constant used in calculating sharpness of blending function
θ_{x_Λ}	streamwise momentum thickness (m)
θ_{xy_Λ}	influence of crossflow on $\theta_{x_\Lambda}^*$ (m)
λ_e	blending function used with enhanced wall treatment
λ_{hb}	Holstein-Bohlen parameter
μ_C	parameter used to calculate boundary layer properties
$\mu_{t,enh}$	blended turbulent viscosity used in with enhanced wall treatment $(Pa\,s)$
μ_{lam}	molecular viscosity $(Pa\,s)$
μ_t	turbulent viscosity in fully turbulent region $(Pa\,s)$
$\mu_{t,2layer}$	turbulent viscosity in near wall region $(Pa\,s)$
Ω	absolute value of the vorticity (1/s)

Subscript

Λ	coord. used in calculation of displacement thickness, x parallel to flow at boundary layer edge, z normal to surface.

Abbreviations

ADC	Analog-to-Digital Converter
AMC	Australian Maritime College
CFD	Computational Fluid Dynamics
DES	Detached Eddy Simulation
DSTO	Defence Science and Technology Organisation
DyPPiR	Dynamic Plunge-Pitch-Roll
DTP	Differential Pressure Transducer
FRTPP	Fast Response Total Pressure Probe
FSP	Full Scale Pressure
LES	Large Eddy Simulation
LDV	Laser Doppler Velocimeter
NACA	National Advisory Committee for Aeronautics
NNEMO	Newport News Experimental Model
PC	Personal Computer
PID	Proportional-Integral-Derivative
PIV	Particle Image Velocimetry
PVC	Peak Valley Counting
PVC	Polyvinyl Chloride
RANS	Reynolds Averaged Navier–Stokes
ROV	Remotely Operated Vehicle
URANS	Unsteady Reynolds averaged Navier–Stokes
UDF	User Defined Function
UDM	User Defined Memory
UUV	Unmanned Underwater Vehicle
VPI	Virginia Polytechnic Institute and State University