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

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Doctor of Philosophy

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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 ellipsoid. 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 particu-
larly 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.
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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, \(u_i'u_j'/2\) (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)

\(p_{frpp}\)  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)

\(u_t\)  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, \((p - p_{ref})/q_{ref}\)

\(C_{\tau w}\)  non-dimensional wall shear stress, \(\tau_{w}/q_{ref}\)

\(E\)  elastic modulus (Pa)

\(H\)  shape factor, \(\delta^*/\theta\)

\(N\)  number of samples

\(U_\infty\)  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, \(U_\infty l/v\)

\(Re_s\)  maximum strain rate Reynolds number

\(Re_{\delta^*}\)  Reynolds number based on displacement thickness, \(U_\infty \delta^*/v\)
Re$_{\theta}$ Reynolds number based on momentum thickness, $U_\infty \theta / v$
Re$_{\varepsilon}$ 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$\tilde{\gamma}_l$ streamwise location of $\tilde{\gamma}_l$ 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, $u_t y_P / v$
y$_C$ non-dimensional distance from wall, $u_t y_P / v$

$y_{bc}$ 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)

$\alpha$ angle of incidence ($^\circ$)
$\gamma$ instantaneous intermittency of turbulence
$\bar{\gamma}$ time averaged intermittency of turbulence
$\bar{\gamma}_l$ time averaged intermittency of turbulence of a constant value i
$\delta$ boundary layer thickness (m)
$\delta^*$ displacement thickness, $\int_0^\infty (1 - u(y)/u_0)\,dy$ (m)
$\varepsilon$ dissipation rate of turbulent kinetic energy ($m^2/s^3$)
$\theta$ momentum thickness, $\int_0^\infty (u(y)/u_0)(1 - u(y)/u_0)\,dy$ (m)
$\nu$ kinematic viscosity ($m^2/s$)
$\rho$ density ($kg/m^3$)
$\rho_w$ density of water, at 20°C, 101.325 kPa is 998.2 kg/m$^3$
$\tau_w$ wall shear stress (Pa)
$\varphi$ azimuthal angle, measured from the symmetry plane on the windward side ($^\circ$)
$\varphi_e$ azimuthal angle mapped to an ellipse, measured from the windward side ($^\circ$)
$\omega$ specific dissipation rate of turbulent kinetic energy (1/s)
Surface Pressure

\( k_{cont} \)  
\( k_{Rose} \)  
\( k_{Validyne} \)  
\( C_P \)  
\( C_{P_i} \)  
\( C_{V_i}^{ref} \)  
\( P_i \)  
\( P_{ref} \)  
\( P_{I,ref} \)  
\( P_{I,ref,corrected} \)  
\( P_{i,dynamic} \)  
\( Re_k \)  
\( V_{P_i-P_{ref}} \)  
\( V_{P_{Rose}} \)  
\( V_{P_{Rose,zero}} \)  
\( \sigma_i \)  
\( \epsilon_i \)

Force Measurements and Calculations

\( \alpha_t \)  
\( x_{eb} \)  
\( y_{eb} \)  
\( z_{eb} \)  
\( \Delta x_{bc,eb} \)  
\( \Delta z_{bc,eb} \)  
\( A_{x_{bc}} \)  
\( A_{base_{x_{bc}}} \)  
\( A_{foil_{z_{eb}}} \)  
\( A_{sting_{y_{eb}}} \)
$C_F$  force coefficient, $F/(q_{ref}A_{bc})$

$C_{Ti}$  moment coefficient, $T/(q_{ref}A_{bc}l)$

$D$  force parallel to flow direction at $U_\infty$, drag ($N$)

$F_i$  force on external surfaces in the $i$ direction due to flow ($N$)

$F_{mi}$  force measured in the $i$ direction due to flow ($N$)

$F_{mli}$  force measured in the $i$ direction due to flow during tare correction ($N$)

$L$  force perpendicular to flow direction at $U_\infty$, lift ($N$)

$P_{base}$  static pressure inside the model ($Pa$)

$P_{eb}$  internal pressure of the external balance housing ($Pa$)

$P_{tbase}$  static pressure inside the model during tare correction ($Pa$)

$\tilde{P}_{lsf}$  average static pressure over the lower surface of the support strut ($Pa$)

$\tilde{P}_{tlsf}$  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 ($Nm$)

$T_{mi}$  moment measured about the $i$ direction due to flow ($Nm$)

$T_{mli}$  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 ($m$)

$v_i$  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)

$z_{cc(rcc)}$ 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 (m³)

$\Delta p_{sen}$ pressure applied to diaphragm movement to cause $\Delta V_{sen}$, (Pa)

$\Delta p_{sen_{max}}$ pressure applied to diaphragm movement to cause $\Delta V_{sen_{max}}$ (Pa)

$\Delta V_{sen}$ volume displaced by diaphragm movement (m³)

$\Delta V_{sen_{max}}$ maximum volume displaced by diaphragm movement (m³)

$\xi$ non-dimensional length used in plotting intermittency of turbulence

$\rho_{dia}$ density of sensor diaphragm (kg/m³)

$\sigma_c$ cavitation number

$\theta_{cc}$ azimuthal variable for cylindrical coordinate system (°)

$\theta_{tr}$ rotation angle about $y_{tr}$ (°)

$v_p$ Poisson’s ratio

$\phi_{tr}$ rotation angle about $z_{tr}$ (°)

$\psi_{tr}$ 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 distribution

**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

$H_{\Lambda}$ estimate of shape factor allowing for the influence of crossflow

$p_{e}$ static pressure at the edge of the boundary layer (Pa)
average static pressure at the wall ($Pa$)

velocity in the $x_A$ and $y_A$ direction respectively ($m/s$)

coordinate aligned with the external streamline (m)

coordinate in the crossflow direction (m)

coordinate normal to the surface (m)

distance to nearest wall, (m)

Wall y plus, non-dimensional parameter

turbulent Reynolds number

constant used in calculating sharpness of blending for $\mu_{t,enh}$

momentum thickness Reynolds number based

absolute value of the mean rate-of-strain tensor (1/s)

velocity outside the boundary layer (m/s)

velocity along the streamline at the edge of the boundary layer (m/s)

low Reynolds number correction for SST turbulence model

streamwise displacement thickness (m)

crossflow displacement thickness (m)

constant used in calculating sharpness of blending function

streamwise momentum thickness (m)

influence of crossflow on $\delta^{*}_{x_A}$ (m)

blending function used with enhanced wall treatment

Holstein-Bohlen parameter

parameter used to calculate boundary layer properties

blended turbulent viscosity used in with enhanced wall treatment ($Pa s$)

molecular viscosity ($Pa s$)

turbulent viscosity in fully turbulent region ($Pa s$)

turbulent viscosity in near wall region ($Pa s$)

absolute value of the vorticity (1/s)

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

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