UNSTEADY TURBULENT SKIN FRICTION AND SEPARATION LOCATION MEASUREMENTS ON A MANEUVERING UNDERSEA VEHICLE

SERHAT HOSDER and ROGER L. SIMPSON

Department of Aerospace and Ocean Engineering
Virginia Tech.
Blacksburg, VA
INTRODUCTION

• Study of Unsteady Aerodynamics
  – *Important for dynamical performance of aircraft, submarines or missiles*
  – *There are significant differences between steady and unsteady aerodynamics*
  – *CFD techniques require physical models to resolve the complex flow structure*

• In This Work,
  – *Steady and Unsteady flow over a generic Suboff model is studied by means of skin friction measurement*
    • To understand the nature of the flow physics
    • To supply valuable data to the CFD simulations
DyPPiR

- **DyPPiR** Dynamic *Plunge-Pitch-Roll Model Mount*
- Three independent degrees of freedom:
  - +/-30° Plunge
  - +/-45° Pitch
  - +/-360° Roll
- All digitally controlled, thus allowing *general, high excursion* maneuvers
- 3000 PSI hydraulic actuators
Generic Suboff Model  \( L = 2.24 \, m \)

**Bow Region**  \( 0.0 \leq X / L \leq 0.23 \)

**Constant Diameter Region**  \( 0.23 \leq X / L \leq 0.75 \)

**Stern Region**  \( 0.75 \leq X / L \leq 1.0 \)

**Sail (When Placed)**  \( 0.21 \leq X / L \leq 0.31 \)
Model with hot-film sensors
Hot-film Sensors: How they measure the wall shear

\[ \bar{h} = \frac{\dot{q}}{lw(T_w - T_\infty)} = \frac{3}{2} Mk \left( \frac{\partial U/\partial y}{(3\alpha l)^{1/3}} \right)^{1/3} \]

\[ \tau_w = \mu \frac{\partial U}{\partial y} \propto \bar{h}^3 \]
Hot-film Sensor Calibrations 1

- On the constant diameter region of the model at 0 angle of attack
- Calibration speeds: 28.4 m/s, 29 m/s, 33.5 m/s, 42.7 m/s
- Boundary layer velocity profiles obtained at two stations \(x/L=0.25\) and \(x/L=0.59\) give \(\delta B. \, L. \, thickness\), \(\delta\) displacement thickness and \(\theta\) momentum thickness.
- By using a momentum integral equation, \(\theta\) distribution between two stations can be obtained:

\[
0.03138 \left[ \text{Re}_\alpha \ln \left( 1 + 9.337 \frac{\theta}{a} \right) \right]^{-0.2857} = \frac{d\theta}{dx}
\]
Hot-film Sensor Calibrations 2

- Use Ludwieg-Tilmann equation to get the skin-friction at the sensor locations
  \[
  \frac{C_f}{2} = 0.123 \times 10^{-0.678H} \left( \frac{U_e \theta}{\nu} \right)^{-0.268}
  \]

- Use King’s Law to get the calibration coefficients
  \[
  \frac{E^2}{(T_w - T_\infty)} = A + B \tau_w^{1/3}
  \]
U •  = 42.7 m/s, \( \text{Re}_L = 5.5 \times 10^6 \)

- Steady Measurements:
  - 14 angles of attack with 2 \( \infty \) increments
  - results for barebody and sail-on-side

- Unsteady Measurements:
  - Pitchup Maneuver: Linear Ramp from \( \alpha = 1 \infty \) to \( 27 \infty \) in 0.33 seconds
  - \( d \alpha/dt = 78 \) [\( \infty \)/second]
  - \( x_{cg}/L = 0.24 \)
  - results for barebody
Oil flow visualization, showing the crossflow separation topology on the constant diameter region of the model without sail at $\alpha=20^\circ$.

- $p$: primary separation line
- $s$: secondary separation line
Contour values of the skin friction coefficient around the sail region at $\alpha=15.3^\circ$.

The range of the $C_f$ levels indicate the complex flow structure in the vicinity of the sail.
Oil Flow Pattern Around the Sail at $\alpha = 15^\circ$

- Horseshoe type separation
- Separation line emanating from a 3-D point upstream of the sail and extending downstream
Conclusions for the Steady Results

- Flow over the barebody shows typical characteristics of the crossflow separation

- For sail-on-side case:
  - *On the non-sail side*, separation location trend closely follow the barebody
  - *On the sail-side*:
    - Flowfield strongly affected by the presence of the sail
    - Horseshoe type separation around the sail
    - Downstream of the sail, categorization of the separation locations difficult
    - Flow structure different from the crossflow separation
X/L=0.501, $C_f$ vs. $f$, Steady & Unsteady

Separation topology different between steady and unsteady flowfields
Comparison with Algebraic Time Lag Models

  \[ \alpha_{\text{eff}} = \alpha - \Delta \alpha_{\text{eff}} \]
  \[ \Delta \alpha_{\text{eff}} = \alpha^\prime \frac{x_{cg} - x}{U_\infty} \]

- Ericsson (1992):
  \[ \Delta t = \frac{x}{U_\infty} \]
  \[ \Delta \alpha_{\text{eff}} = \dot{\alpha} \frac{x_{cg} + x}{U_\infty} \]

Experimental results (solid symbols) do not match with the algebraic time lag model.
1st-Order Differential Time Lag Approximation

- Goman & Khrabov proposed in 1994.

- Wetzel and Simpson (1998) used in unsteady prolate spheroid study:

\[ \tau' \left( \frac{x}{L} \right) \frac{d \phi_{uns}}{dt'} + \phi_{uns} \left( \frac{x}{L}, t' \right) = \phi_0 \left( \frac{x}{L}, \alpha(t') \right) \]

\( \tau' \) \hspace{1cm} \text{first-order non-dimensional time lag}

\( \phi_{uns} \) \hspace{1cm} \text{approximation to the unsteady separation location}

\( \phi_0 \) \hspace{1cm} \text{quasi-steady separation location distribution}
First-order lag approximation fits the experimental data reasonably well
Time lags

- First-order non-dimensional time lags are obtained by fitting the model equation with the experimental unsteady separation location.

- \( \tau' \) vs. \( x/L \) trend different than the obtained for prolate spheroid.

- In the prolate spheroid study, trend was linear in \( x/L \).

\[
\begin{align*}
\text{• } \frac{x_{cg}}{L} &= 0.5 \text{ for prolate spheroid pitchup maneuvers} \\
\text{• } \frac{x_{cg}}{L} &= 0.24 \text{ for this study}
\end{align*}
\]
Conclusions for the Unsteady Results

• Separation topology different between steady and unsteady flowfields.

• Significant time lags occur between quasi-steady and unsteady separation locations.

• Algebraic time lag models do not match with the experimental data in this study.

• A first-order time lag model approximates the unsteady data reasonably well and non-dimensional time lags are obtained.

• Time lags may be influenced:
  – by the location of the model center of rotation \( x_{cg} \)
  – by the model geometry