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

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Abstract

Steady and unsteady flow over a generic SUBOFF model is studied. The skin friction magnitudes are measured by using hot-film sensors each connected to a constant temperature anemometer. The local minima in the skin friction magnitudes are used to obtain the separation locations. Steady results are presented for two model configurations: barebody and sail-on-side case. Unsteady results are given for the barebody case. The dynamic plunge-pitch-roll model mount (DyPPiR) is used to simulate the pitchup maneuvers. The pitchup maneuver is a linear ramp from 1° to 27° in 0.33 seconds. Steady results show that the flow structure on the leeward side of the barebody can be characterized by the crossflow separation. In the sail-on-side case, the separation pattern of the non-sail region follow the barebody separation trend closely. The flow on the sail side is strongly affected by the presence of the sail and the separation pattern

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is different from the crossflow separation. Unsteady results show significant time lags between unsteady and steady separation locations. These effects produce the difference in separation topology between the unsteady and steady flow fields. A first-order time lag model approximates the unsteady separation locations reasonably well and time lags are obtained by fitting the model equation with the experimental data.

Nomenclature

- A = hot-film sensor calibration coefficient, Equation (4)
- B = hot-film sensor calibration coefficient, Equation (4)
- a =model radius of the constant diameter region
- C_f = skin friction coefficient
- C_p = pressure coefficient

$$E$$
 = time-averaged voltage value

- F = generalized steady and quasi-steady aerodynamic vector function
- G = generalized unsteady aerodynamic vector function
- H = shape factor
- \bar{h} = mean heat transfer film coefficient

$$L = model length$$

- Re_a = radius based Reynolds number, $U_{\infty}a/\nu$
- Re_L = length based Reynolds number, $U_{\infty}L/\nu$
- Re_{θ} = momentum thickness based Reynolds number, $U_{\infty}\theta/\nu$

t'	= non-dimensional time, tU_{∞}/L
t_{ref}	= reference time, L/U_{∞}
T_{∞}	= free-stream temperature
T_w	= hot-film sensor temperature
U_e	= boundary layer edge velocity
U_{∞}	= free-stream velocity
x	= model longitudinal position from nose
x_{cg}	= location of center of rotation
z	= DyPPiR plunge ordinate
α	= model center angle of attack and DyPPiR pitch angle
α_{eff}	= effective angle of attack, $\alpha_{eff} = \alpha - \Delta \alpha_{eff}$
$\dot{\alpha}$	= dimensional pitch rate
$\Delta \alpha_{eff}$	= incremental effective angle of attack
β	= sideslip angle
δ	= boundary layer thickness
δ^*	= displacement thickness
ν	= kinematic viscosity
$ au_w$	= wall shear stress
au'	= first order time lag in non-dimensional units
θ	= momentum thickness
ϕ	= circumferential location on the model surface

 ϕ_{sep} = separation location

 ϕ_{uns} = approximation to the unsteady separation location, Equation (8)

 ϕ_0 = quasi-steady separation location, Equation (8)

I. Introduction

The study of truly unsteady, high-excursion and high-Reynolds Number separated flows over undersea vehicles, aircraft or missiles has become of great importance in the analysis and the improvement of the dynamic performance. Because of highly complex, threedimensional, turbulent and separated nature, standard stability derivative techniques fail to capture the nonlinearities in these flows and computational fluid dynamics (CFD) techniques need physical models that can resolve the complexities of such flow fields in order to get accurate and more reliable results. Suitable simulation of the time-dependent maneuvers in the wind tunnels is not only important for understanding the physics of complex flow phenomena, but also supplies the necessary information required for developing the realistic unsteady physical flow models. The DyPPiR (**Dy**namic **P**lunge-**Pitch-Roll**) model mount, computer controlled, three degrees of freedom robotic arm at the Stability Wind Tunnel of Virginia Tech, provides the unique capability of performing pre-programmed, general, high-excursion, large scale, high Reynolds Number, and unsteady maneuvers.^{1,2}

Dynamic testing has been an important part of design and validation of various types of craft for decades. Typically these techniques are only *quasi-steady*, relying on very small

amplitude sinusoidal oscillations that can describe small-excursion maneuvers reasonably well.³ As discussed by Wetzel and Simpson,⁴ there is a significant difference between quasi-steady and unsteady aerodynamics. In a quasi-steady approach, the aerodynamics of a maneuvering body are dependent only on the instantaneous state of the model (α angle of attack, β sideslip angle, control surface deflections, etc.), whereas in fully general unsteady aerodynamics, explicit time dependency, or history effects are also included. Mathematically the distinction between quasi-steady and unsteady aerodynamics can be shown as follows: steady, $\mathbf{F}(\alpha, \beta, ...)$; quasi-steady, $\mathbf{F}[\alpha(\mathbf{t}'), \beta(\mathbf{t}'), ...]$; and fully unsteady $\mathbf{G}[\mathbf{t}', \alpha(\mathbf{t}'), \dot{\alpha}(\mathbf{t}'), \beta(\mathbf{t}'), \dot{\beta}(\mathbf{t}'), ...]$ where \mathbf{F} and \mathbf{G} can be a dominant flow feature such as separation location. Here t' is the non-dimensional time given by Etkin:⁵

$$t' = \frac{t}{t_{ref}} = \frac{tU_{\infty}}{L}.$$
(1)

In the above equation, t_{ref} represents the time for the flow to pass over a model: L/U_{∞} . The history effects mainly cause time lags or leads between the unsteady and the corresponding instantaneous quasi-steady flow fields, which can be quantified by measuring flow separation locations or the aerodynamic loads on a body undergoing time-dependent maneuvers.

Among the previous studies, the unsteady crossflow separation location measurements on a maneuvering 6:1 prolate spheroid model by Wetzel³ can be considered as the most similar work to the one presented here in terms of the experimental measurement technique and the unsteady, high-excursion maneuvers performed. In his work, he has determined significant lags in the unsteady flow separation locations on the prolate spheroid undergoing pitch-up and turning maneuvers compared with the steady data. Wetzel and Simpson⁴ also found that a first-order lag model fits the unsteady data. A review of some other relevant studies of three-dimensional, unsteady aerodynamic experiments on various bodies has been given in Wetzel and Simpson,⁴ and Hosder.⁶

In the present work, unsteady turbulent flow separation on a maneuvering undersea vehicle is studied. Hot-film sensors were used to measure the surface skin friction magnitude values over the body surface. Local minima of the skin friction magnitude values are used to determine the separation locations.⁷ Steady skin friction measurements were obtained for different model-center angle of attacks. Unsteady maneuvers include the ramp pitchup maneuvers simulated by the DyPPiR. Surface oil flow visualizations were also used in order to examine the steady surface flow topology and the separation locations qualitatively. Both steady and unsteady tests were performed for two model configurations: The barebody (axi-symmetric case) and the body with the sail. In this paper, the steady results for both cases are presented while the unsteady results and discussion are given for the barebody case.

II. Experimental Apparatus and Techniques

II.A. Wind Tunnel and the DyPPiR

Virginia Tech Stability Wind Tunnel with 1.8×1.8 m square test section has been used for the experiments. The tunnel is a closed-return, closed test section subsonic facility powered by 450-kW dc motor driving a 4.27 m long propeller. Tunnel, with a maximumspeed of 80 m/s, has a very low free-stream turbulence level of 0.03^{\%}.¹ To eliminate flow blockage effects, a slotted wall test section was used with 38% open area ratio. The Dynamic Plunge, Pitch and Roll actuator (DyPPiR) is installed in the Virginia Tech Stability Wind Tunnel (Figure 1). This computer controlled model mount DyPPiR has three degrees of freedom: plunge with a vertical range of 1.5 m from the tunnel centerline, pitch with a range of $\pm 45^{\circ}$ and (with recently made improvements) roll with a range of $\pm 360^{\circ}$. The three hydraulic actuators give the DyPPiR power to force a maximum model load of 45 kg and 250 kg of hardware at rates approaching to 9 m/s in plunge and 120 degs/s in pitch. By the combined motion of pitch and plunge actuators, the DyPPiR can perform maneuvers around an arbitrary center of rotation, which is important for obtaining the correct lateral velocities across the aircraft and the submarines. These unique features of the DyPPiR allows one to simulate the pre-programmed, general, highexcursion, rapid, time-dependent maneuvers and to keep the model in desired location and orientation in steady testing as well. The coordinate nomenclature for the DyPPiR and the model is given in Figure 2. Note that the circumferential location ϕ is measured from the windward line of symmetry in the counter-clockwise direction.

II.B. Wind Tunnel Model

The light weight model has a generic SUBOFF undersea vehicle geometry with a scaled length (L) of 2.24 m. The model has a bow region for $0.0 \le (x/L) \le 0.23$, a constant diameter region for $0.23 \leq (x/L) \leq 0.75$ and an afterbody (stern) region for $0.75 \leq (x/L) \leq 1.0$. Figure 3 shows the model geometry with the hot-film sensor locations. The sail can be detached, resulting in the axis-symmetric configuration of the model which can be thought as a missile or to a certain extent an aircraft fuselage geometry More sensors have been used near the body-sail junction region to resolve the complex structure of the separated flow. Oil flow visualization pictures also have been used in order to determine the optimum sensor locations.

The barebody measurements were performed by using 15 sensors located at certain positions on the long row (Figure 3). The same sensors were used in the sail-on-side case throughout the whole circumferential locations. The remaining sensors were used near the sail region in order to resolve the flow structure. For the sail-on-side configuration, the chord line of the sail is aligned with the circumferential location $\phi = 270^{\circ}$. At its maximum thickness location, the sail extends from $\phi = 262^{\circ}$ to 278° and is placed between x/L = 0.21 and x/L = 0.31.

The sail is mounted on a movable ring integrated into the model structure and can be rotated and fixed to any desired circumferential location. Both in steady and unsteady testing, the skin friction distribution on the whole surface of the model with desired circumferential spacing can be obtained by using only one row of sensors on the model surface. The model is rotated with a certain roll angle in one direction while the sail is rotated in the opposite direction with the same amount. By this action, while changing the circumferential location of the row of sensors, the model geometry and the alignment relative to the free-stream for a specific pitch angle and sail location is kept constant. A small gap between the model and the sail was kept in order the sail to be moved on top of the sensors without any contact. This gap was sealed properly and without giving any fillet effect for every roll angle before the data were taken.

In order fix the transition location on the model and further guarantee a Reynolds-number insensitive separation, trip posts of 0.76 mm high cylinders with 1.28 mm diameter, 2.5 mm spaced apart, were placed on the model nose part at x/L = 0.10. Two rows of the same trip posts were put on the lower and the upper surfaces of the sail in the spanwise direction. The rows were located 0.64 cm (measured on the surface) away from the leading edge of the sail.

II.C. Hot-film Sensors and the Calibration

To measure the skin friction, hot-film sensors designed and documented by Simpson *et* $al.^8$ are used. The sensors are made of Balco foil (70% nickel, 30% iron) and the main sensing part is a spiral of 5.1 mm in diameter. These directionally insensitive hot-film sensors have been designed to measure the magnitude of the skin friction as described in Simpson *et al.*⁸ The sensors heat the near-wall fluid by forced convection. Because of the similarity between the gradient transport of momentum and scalars (heat), heat transfer in the fluid gives a measure of the wall shear. The mean film coefficient \bar{h} is proportional to the cube root of the near wall velocity gradient, which is thus proportional to the wall shear τ_w . Hot-film sensors were operated with Miller-type non-linearized constanttemperature anemometers.⁹ The same sensor-anemometer set-up was used by Wetzel³ in his prolate spheroid study. He reported a flat frequency response out to roughly 200 Hz. Because of relatively low frequency response and large sensor size (diameter of 5.1 mm), the sensors are insensitive to high-frequency, small-scale turbulent fluctuations. However, the frequency response is high enough to resolve the time-history of the spatially-averaged skin friction values in unsteady maneuvers.

The hot-film sensors that are used in the actual tests have been calibrated on the constant diameter part of the model at zero angle of attack. By removing the sail during the calibrations, axi-symmetric flow around the model was maintained. Boundary Layer velocity profiles on the constant diameter region of the model were taken at four calibration speeds: 24.4 m/s, 29 m/s, 33.5 m/s and 42.7 m/s. Measurements for each speed were made at two stations. The first station was at the upstream location of the constant diameter region (x/L = 0.25) and the second station at the downstream part (x/L = 0.59). By using the boundary layer velocity profiles, the boundary layer thickness δ , displacement thickness δ^* , momentum thickness θ and the shape factor H at each station were calculated by taking into account the transverse wall curvature effect which was discussed in White.¹⁰ The velocity measurements in the streamwise direction between these two stations also showed that the boundary layer edge velocity U_e could be taken as constant along the constant diameter region of the model. To determine the θ distribution between two measurement stations, the following momentum integral equation was used:

$$0.03138 \left[Re_a \ln \left(1 + 9.337 \frac{\theta}{a} \right) \right]^{-0.2857} = \frac{d\theta}{dx}.$$
 (2)

This equation was obtained by using the approach in Kays and Crawford¹¹ and by making necessary modifications to include the transverse curvature effects. Equation 2, which represents an initial value problem, has been solved numerically by using *Modified Euler's Method* in order to determine the momentum thickness distribution. As the initial value for the momentum thickness, the θ value measured at the second station was used. After obtaining the θ distribution, skin friction coefficient at each sensor location has been obtained by using *Ludwieg-Tillmann equation*:

$$\frac{C_f}{2} = 0.123 \times 10^{-0.678H} \left(\frac{U_e \theta}{\nu}\right)^{-0.268}.$$
(3)

The calibration C_f values were obtained for $1010 \le Re_{\theta} \le 4900$. For the calibration, the hot-film version of King's Law was used:

$$\frac{E^2}{(T_w - T_\infty)} = A + B(\tau_w)^{1/3}.$$
(4)

Here, E is the time-averaged voltage value obtained from a hot-film sensor connected to a constant temperature anemometer, T_w stands for the sensor temperature and T_∞ for free-stream temperature of the flow in the tunnel. The purpose of the calibration is to determine the coefficients A and B in Equation 4. For finding these coefficients, E and corresponding τ_w values obtained at the calibration speeds were used to make a linear regression. In Equation 4, the change in the free-stream temperature will also cause a change in the calibration coefficients A and B. Since the temperature of the stability tunnel is ambient and can not be controlled, the calibration procedure was repeated as the tunnel temperature changed. In order to minimize the uncertainty in the skin friction measurements due to the free-stream temperature change for the barebody case, the calibration coefficients for each sensor have been re-calculated for every roll angle position of the model before taking steady data and performing unsteady maneuvers for that specific roll angle. The free-stream temperature change was at most $\pm 0.5 \text{ C}^{\circ}$ between each roll angle position and this was included in the overall uncertainty calculations. For the measurements with the sail, calibration coefficients for each sensor were re-calculated approximately in every 10 roll angle by simply detaching the sail from the body and applying the calibration procedure to the barebody.

II.D. Steady Measurements and the DyPPiR Maneuvers

All the skin friction measurements were done with a tunnel speed of $42.7 \pm 1\%$ m/s. For these experiments, the Reynolds number based on the model length (Re_L) was 5.5×10^6 . The oil flow visualizations were taken at $Re_L = 4.5 \times 10^6$. Ahn¹² showed that there exists a critical Reynolds number of 2.5×10^6 for the flow past a 6:1 Prolate Spheroid at different angles of attack. Above this critical value, as the Reynolds number increases, the crossflow separation is fully turbulent and the separation lines do not change their circumferential location but stretch to the upstream of the body. Since the Reynolds numbers used in hot-film measurements and the oil-flow visualizations of the case discussed in this paper are both well above the critical value, quantitative data from the hot-film measurements and the qualitative observations from the oil-flow visualizations should supply information for the same flow pattern and the separation structure.

Measurements of the skin friction in steady experiments and unsteady maneuvers were performed for two model configurations: barebody and sail-on-side cases. In the barebody case, both steady and unsteady skin friction data were acquired between $\phi = 0^{\circ}$ and 180° in the circumferential direction with 10° increments on the windward side and for every 2° on the leeward side. For the sail-on-side case, measurements were made between $\phi = 0^{\circ}$ and 360°. The ϕ increment was again 2° on the leeward side in order to locate the crossflow separation locations with low uncertainty. On the windward side, measurements were made with 10° increments except the region between $\phi = 270^{\circ}$ and 292° where C_f was measured every 2° to resolve the surface flow structure in the vicinity of the sail.

Steady hot-film measurements were taken at 14 angles of attack starting from 0.9° . The last angle covered was 27.6°. The difference between each steady angle of attack ranged from 1.9° to 2.2° . These angles are shown by solid square symbols in Figure 4. Besides obtaining the steady surface flow structure over the model, the results of the steady data at these angles of attack were also used to construct the quasi-steady data to be used in a first-order lag model, which will be described in Section III.

Unsteady results were obtained for the pitchup maneuvers. The pitchup maneuver per-

formed for the present work is a simple linear ramp from 1 ° to 27 ° in 0.33 seconds. Figure 4 shows the DyPPiR pitch angle and plunge location feedback for the pitchup maneuvers. The DyPPiR pitch angle is also the instantaneous angle attack measured at the model center of rotation. Note that the actual maneuver starts at t' = 3.00. The maneuvers were performed with a constant pitch rate of 78 degs/s and the model center of rotation was at $x_{cg}/L = 0.24$. For each ϕ orientation of the model, the pitchup maneuver was executed for 10 times. Unsteady skin friction values at each x/L measurement station were calculated for each repetition and the final values were obtained by ensemble averaging. Further details about the unsteady data reduction may be found in Hosder.⁶

II.E. Uncertainties in Measured Quantities

The steady skin friction magnitudes have an uncertainty of $\pm 6\%$ for random uncertainties at 20:1 odds. For the unsteady skin-friction magnitudes, uncertainty is $\pm 8\%$. The uncertainty in the determination of the separation locations is $\pm 2^{\circ}$.

III. Results and Discussion

III.A. Steady Results

III.A.1. Barebody skin-friction measurements

For the range of conditions mentioned in section II.D., steady results over the barebody show typical characteristics of the crossflow separation. Figure 5 shows the oil flow visualization of the near-wall fluid over the constant diameter region of the model in the barebody case and qualitatively describes the crossflow separation topology. Skin-friction lines converge along the separation lines and from this figure two separation lines can be identified on the leeward side of the model. The one closer to the windward side is defined as the primary separation and the other as the secondary separation line.

Figure 6 gives the skin-friction C_f distribution vs. circumferential location on the model surface ϕ at $\alpha = 15.3$ ° for different x/L stations. Barebody results are represented by the filled symbols. At this pitch angle, x/L = 0.266 is the first station at which a minimum in the C_f distribution can be detected. This minimum indicates the primary separation location at $\phi = 146$ °. Starting from this station, the primary separation can be clearly seen as the most windward of the C_f distribution at all the other x/Lstations downstream. As x/L increases, the primary separation location moves towards the windward side. It is also interesting to see the nearly flat profile at the vicinity of the minimum point for the last station x/L = 0.863 located on the stern region. This profile indicates separated low speed fluid in this complex flow region between $\phi \simeq 100^{\circ}$ and 130° which makes the identification of the true minimum difficult. The secondary separation location can be obtained by finding the second minimum in each C_f vs ϕ distribution after a certain pitch angle. At $\alpha = 15.3^{\circ}$, the secondary separation can clearly be observed starting from x/L = 0.638. The secondary separation location moves in the leeward direction with increasing x/L.

Figure 7 shows the C_f vs. ϕ distribution for all the pitch angles covered in the steady measurements at x/L = 0.501, both for barebody and sail-on-side case. In the barebody case, $\alpha = 7.2^{\circ}$ is the first pitch angle at which a primary separation has been observed at $\phi = 146^{\circ}$. As α increases, the primary separation location moves windward and reaches to $\phi = 120^{\circ}$ at $\alpha = 27.6^{\circ}$. The secondary separation can be identified starting from $\alpha = 15.3^{\circ}$ and moves leeward with increasing pitch angle. The results given above indicate that at a specific x/L station, the primary separation location moves windward while the secondary separation location in the leeward direction as α is increased. At a certain pitch angle, the primary separation location will move windward and the secondary separation location leeward as we go downstream in x/L.

III.A.2. Sail-on-side skin-friction measurements

In Figures 6 and 7, open symbols stand for the C_f vs. ϕ distributions of the sail-on-side case. It is more appropriate to evaluate the results of the sail-on-side case in two separate regions; the region with no sail (between $\phi = 0^{\circ}$ and 180°) and the region with the sail

(between $\phi = 180^{\circ}$ and 360°). In the first region, the origin and the variation of the primary and the secondary separation lines as a function of x/L and α show the same characteristics as defined for the barebody case. This implies that the main flow feature on the non-sail region is the cross flow separation. Although the general trend is the same, in Figure 6, for the stations $x/L \geq 0.501$ at $\alpha = 15.3^{\circ}$, the locations of the primary and the secondary separations are slightly different from the barebody separation locations. They are more leeward compared to the barebody locations. The same difference can also be observed in Figure 7 for $\alpha \geq 15.3^{\circ}$ at x/L = 0.501. Figure 8 shows the variation of the primary separation location with α for three different x/L stations. As can be seen from this figure, the primary separation locations of the barebody case and the non-sail region of the sail-on-side case are approximately the same within uncertainties up to $\alpha = 15.3^{\circ}$.

The flow structure on the sail side of the model is much different than the one observed for the non-sail side. The flow field in this region is strongly affected by the presence of the sail. In Figure 6, in the sail region, a minimum can be located at four stations: x/L = 0.306, 0.345, 0.434, and 0.501. Corresponding ϕ locations are 224°, 220°, 212°, and 210°. This may indicate a separation at these stations. However, for the rest of the stations downstream, this minimum vanishes. A second minimum in C_f can be seen at x/L = 0.345 and the rest of the stations downstream. This minimum has an approximately constant ϕ location of $256 \pm 2^{\circ}$ between x/L = 0.501 and the last station x/L = 0.863. The same trend can also be observed in Figure 7. A minimum in C_f for $\alpha = 9.3^{\circ}$, 11.3° , 13.2° , and 15.3° at $\phi = 216^{\circ}$, 216° , 208° , and 208° respectively can clearly be located. The second minimum starts from $\alpha = 5.1^{\circ}$ and has a constant circumferential location of $256^{\circ} \pm 2^{\circ}$ between $\alpha = 13.2^{\circ}$ and 27.6° . The results on the sail side indicate that the flow field does differ from the crossflow separation structure observed for the barebody and non-sail region of the sail-on-side case. Therefore the categorization of the separation locations as the primary or the secondary is not clear and may not reflect the real flow structure of this region.

The flow in the vicinity of the sail-body junction is dominated by the horseshoe type separation. This can be clearly seen from Figure 9 which shows the oil-flow pattern in the leeward side of the sail region at $\alpha = 15$ °. The separation line emanating from a three-dimensional stagnation point upstream of the sail extends from both leeward and windward side of the sail and travels downstream. The separation line on the leeward side of the sail can be seen along the converging skin friction lines in Figure 9. Although the flow topology near the onset of the horseshoe separation is different from that of the crossflow separation,¹³ both show similar characteristics of separated flows downstream: there is a strong convergence of the limiting streamlines on the surface and there are concentrated regions of vorticity in the flow. This may raise the ambiguity about the identification of the separation pattern downstream of the sail. Figure 10, shows the C_f contours around the sail region at $\alpha = 15.3$ °. Note that the blank areas are the regions where no data were acquired. The vertical blank between $x/L \simeq 0.22$ and $x/L \simeq 0.26$ designates the ring area where the sail is mounted. In this plot, a low velocity region can be noticed at around x/L = 0.27 and $\phi = 245^{\circ}$ which also matches with the oil flow visualization results at that location. C_f on the hull takes relatively large values at regions closer to the sail.

III.A.3. Barebody pressure measurements

In order to determine the circumferential behavior of the mean pressure in the separated flow regions, steady pressure distributions are compared with the skin-friction variations at the same x/L locations. Figure 11 shows this comparison for the barebody case at x/L = 0.501 and $\alpha = 21.4$ °. A favorable pressure gradient was observed on the windward side of the model. The leeward side of model can be thought as a pressure recovery region. However due to the crossflow separation on the leeward side of the model, the general C_p trend does not follow a monotonic increase. A common characteristic of the pressure distributions in the vicinity of the separation locations can be observed: the mean pressure values are approximately constant over the separated fluid regions. This flat C_p region extends over the primary and the secondary separation locations. As discussed in Wetzel *et al.*,⁷ although the pressure data are used often to indicate the existence of massive separation, it is not a good indicator of the separation location. This is due to the fact that the crossflow separation is the result of local flow phenomena, but pressure at a given point in space is strongly influenced by the entire flow field. One can think of using the flat pressure profile in regions of separation to locate the separation, however it is difficult to determine the exact point where this flat pressure distribution begins.

III.B. Unsteady Results

III.B.1. Unsteady separation topology

In this paper, the unsteady results will be presented for the barebody case. One of the methods to investigate the difference between the steady and the unsteady flow over the model is to compare the steady C_f vs. ϕ distribution obtained at a certain pitch angle α with the unsteady one acquired at the corresponding instantaneous pitch angle $\alpha(t')$. Figure 12 shows the steady primary and secondary separation locations and the unsteady primary separation locations at three angles of attack. Steady primary and secondary separation lines can be observed at $\alpha = 13.2$ °, however no separation is detected for the unsteady case at the corresponding instantaneous angle of attack. As the angle of attack is increased, the onset of unsteady primary separation line can be seen, which is more leeward and downstream compared to the steady one. No clear unsteady secondary separation can be detected even at the highest angle of attack covered in the experiments. Figure 11 shows the steady/unsteady circumferential skin-friction comparison at x/L = 0.501 and $\alpha = 21.4$ °. The primary separation location for the steady data is $\phi = 122$ °, while the unsteady primary separation occurs at $\phi = 138$ °. The steady data have a secondary separation at $\phi = 148^{\circ}$ while no secondary separation is observed for the unsteady case. The difference between the C_f magnitudes should also be noted. Especially in the leeward region between 150° and 180°, this difference is significant, with steady values being higher than the unsteady ones.

These results show that in unsteady flows the separation topology is different from the one in an equivalent steady configuration. This difference originates from the fact that the unsteady separation location lags the steady separation. This can be clearly seen from Figure 13 where the quasi-steady and the unsteady primary separation locations are plotted against the non-dimensional time t' for different x/L stations. In this figure, the horizontal distance between the unsteady and the steady separation location is an indication of the presence of a time lag. Since the maneuvers were performed with a constant pitch rate, the instantaneous pitch angle is a linear function of t'. By considering this fact in examining Figure 13, it can also be thought that at an instantaneous pitch angle, for a specific x/L location, the unsteady separation starts more leeward compared with the steady case. This explains the cause of difference between the steady and the unsteady and the unsteady and the steady case.

III.B.2. Time lag models

To understand, why a lag exists; as described by Wetzel and Simpson,⁴ one should examine the path of a fluid particle during the maneuver. During the pitchup maneuver, a fluid particle originally starts its trajectory on the windward side of the model at a lower angle of attack. Therefore, the particle experiences a less severe adverse pressure gradient along its path, and can travel farther around the leeside before separating when compared with a similar particle in a steady flow field.

The main interest is to be able to model or approximate the time lags associated with the unsteady flow fields. Algebraic time lag modeling was a commonly used approach in the previous studies. Most of the algebraic time lag models are based on finding an effective angle of attack α_{eff} by using the descriptions of the flow kinematics. If a model rotates about some point x_{cg} at a constant pitch rate $\dot{\alpha}$, a relative velocity normal to the model axis $\dot{\alpha}(x - x_{cg})$ will exist at other x/L locations in addition to the velocity of the wind relative to the point of rotation. By using this fact, Montividas et al.¹⁴ approximated an effective angle of attack as

$$\alpha_{eff} = \alpha - \Delta \alpha_{eff},\tag{5}$$

where

$$\Delta \alpha_{eff} = \dot{\alpha} \frac{x_{cg} - x}{U_{\infty}}.$$
(6)

However, this approximation did not describe the unsteady effects in their flow field associated with the onset of asymmetric vortex shedding at high angles of attack on ogive cylinders. Ericsson¹⁵ also studied the same problem and extended the effective angle of attack idea by including convective lag effects in the flow field. He used the fact that a vortex at a downstream station of the apex of the model (ogive cylinder) will react to the changed flow conditions at the apex at a time Δt later. He also approximated that the disturbances originating at the apex of the model would propagate downstream with the free-stream velocity U_{∞} which would give $\Delta t = x/U_{\infty}$. By using this result in Equation 6, Ericsson¹⁵ obtained:

$$\Delta \alpha_{eff} = \dot{\alpha} \frac{x_{cg} + x}{U_{\infty}}.$$
(7)

Equation 7 did approximate the lags in asymmetric vortex shedding on the pitching ogive cylinder successfully.

In this study, $\Delta \alpha_{eff}$ has been calculated both from the experimental results and Equation 7 for four different x/L locations. Since the pitch rate has a constant value of 78 degs/s, the lag Equation 7 gave constant $\Delta \alpha_{eff}$ values for each x/L locations. For calculating $\Delta \alpha_{eff}$ from the experimental results, certain number of unsteady separation locations ϕ_{sep} and corresponding instantaneous pitch angles $\alpha(t')$ have been selected from the data. Then the same ϕ_{sep} values for the steady data and the corresponding steady pitch angles have been picked. For a specific ϕ_{sep} , the difference between the instantaneous pitch angle and the steady pitch angle has been calculated as the effective angle of attack increment. The $\Delta \alpha_{eff}$ results obtained from Equation 7 and the experimental data have been compared in Figure 14. As can be seen from this figure, there is a significant difference between experimental $\Delta \alpha_{eff}$ and the one calculated from Equation 7. Especially for the stations $x/L \ge 0.501$, the magnitudes of the experimental $\Delta \alpha_{eff}$ are twice as much higher than that of obtained by using the model Equation 7. Also, although the pitch rate is constant, experimental $\Delta \alpha_{eff}$ does change with the instantaneous pitch angle thus with the time. This comparison shows the difference between the lags in the unsteady crossflow separation over the model used in the present experiment and the flow field associated with the asymmetric vortex shedding on the ogive cylinder.

Goman and Khrabrov¹⁶ have developed a first order time lag model in order to approximate the time history of a dominant flow feature such as separation location in general unsteady flows. They applied this model to pitching two-dimensional airfoils, delta wings and the unsteady aerodynamics of a complex fighter aircraft configuration as well. They used the separation location as an internal state variable, and defined the forces and moments as functions of this state variable. For a given maneuver, by obtaining the time history of this state variable, they were able to calculate the unsteady force and moments.

Wetzel and Simpson⁴ implemented an extended version of this model for approximating the time varying nature of the unsteady separation locations over the maneuvering prolate spheroid. The approximation successfully fit the experimental unsteady separation locations and non-dimensional time lag values for different x/L stations of the prolate spheroid were obtained. The same extended version of the first-order differential lag model has been used in this study in order to approximate the unsteady primary separation locations over the model without sail undergoing pitchup maneuvers:

$$\tau'\left(\frac{x}{L}\right)\frac{d\phi_{uns}}{dt'} + \phi_{uns}\left(\frac{x}{L}, t'\right) = \phi_0\left(\frac{x}{L}, \alpha(t')\right). \tag{8}$$

In Equation 8, ϕ_{uns} represents the approximation to the unsteady separation location and τ' stands for the first order non-dimensional time lag. The quasi-steady separation location distribution, ϕ_0 can be obtained from the steady separation data at each $\alpha =$ $\alpha(t')$. Note that both the quasi-steady separation location ϕ_0 and the approximation to the unsteady separation location ϕ_{uns} do also vary in x/L. This is the difference between the extended version and the original time lag model of Goman & Khrabrov.¹⁶ In the original version, a single point of separation was considered. However, for the present study and the prolate spheroid case, since the crossflow separation occurs along a line rather than a point (Figure 12), ϕ_{uns} and ϕ_0 were also functions of x/L. It should also be noted that the time lag τ' in Equation 8 is taken as an unknown and is identified by fitting the model equation with the experimental data.

Equation 8 mainly correlates the unsteady separation locations to the quasi-steady data by the time lag τ' . In the solution procedure, the quasi-steady separation distribution ϕ_0 was obtained by fitting a cubic spline to the steady data. The independent variable was t'in the fitting procedure. As the initial value for ϕ_{uns} , the first steady separation location in the steady data was used. For each x/L station, the model equation was solved with different values of the τ' in an iterative manner. The root mean square error between the approximated and experimental unsteady data was calculated at each iteration and the τ' that gives the smallest error has been chosen for that specific x/L location. The details of the solution procedure can be found in Hosder.⁶ Figure 13 shows the results of the time lag model approximation to the unsteady data at x/L = 0.306, 0.570, and 0.774 respectively. In these figures, the first-order lag model approximation fits the measured unsteady separation locations reasonably well.

 τ' values obtained from the model equation fits for different x/L locations are shown

in Figure 15. Note that all the stations were not used in calculating the time lags. At the stations $x/L \leq 0.266$, no unsteady separation location at any instant of time was observed. At the last station x/L = 0.863, the determination of the unsteady separation location was not accurate enough because of the flat nature of the C_f profile near the minimum, as discussed in the steady results section. In Figure 15, near the model rotation point $x_{cg}/L = 0.24$, time lag value is close to zero indicating that the quasisteady data follows the unsteady data closely. Then an increase until x/L = 0.43 can be seen. Since there are not enough points in this region, the nature of this increase (linear or non-linear) can not be determined accurately. After this point, the time lag stays approximately constant between x/L = 0.43 and x/L = 0.774, taking an average value of 1.40. At x/L = 0.819, this value drops to 1.24.

The trend of τ' along the model length in this study is different from the one obtained for the prolate spheroid by Wetzel and Simpson.⁴ In that case, τ' increased almost linearly over the length of the prolate spheroid model to a value of about 3 at x/L = 0.8. For those pitchup maneuvers, the model center of rotation point was at x/L = 0.5, whereas in this study the rotation point is at x/L = 0.24. Also the SUBOFF model has a different geometry from the prolate spheroid, having a relatively large length of a constant diameter before the model stern. Both of these differences may cause the time lag versus x/L to be different.

One plausible explanation of the different time lag trends may be that time is required for the upstream boundary layer vortical fluid to be convected around the body to displace inviscid fluid and form a leeside separation vortex structure with the same separation location as the steady case. One can observe this unsteady accumulation of vortical fluid in flow visualization studies such as shown by Gadel-el-Hak and Ho.¹⁷ After the beginning of a transient motion, the separated flow region requires some time to be filled with vortical fluid.

This hypothesis explains to some extent why the time lags in the prolate spheroid case are so much larger at the same downstream x/L than the SUBOFF results. For the prolate spheroid, the model diameter downstream of the point of rotation continuously decreases towards the tail. In non-dimensional terms, a greater volume of vortical fluid must be convected and gathered to fill the leeside separation region than for the constant diameter SUBOFF model. Because the SUBOFF model does have a constant diameter region, the time lags within this region of this model length should be about the same, as is observed.

IV. Conclusions

Steady and unsteady skin friction magnitudes have been measured over the SUBOFF model by using hot-film sensors. The minima of the skin friction vs. ϕ distribution at each x/L measurement station have been used to locate the separation locations. The steady results obtained for the barebody case show that the flow on the leeward side of the model can be characterized by the crossflow separation. For the sail-on-side case, the steady flow over the non-sail region of the model also show the basic characteristics of the

crossflow separation, and the C_f vs. ϕ distributions follow the barebody results closely. The flow structure on the sail side is strongly affected by the presence of the sail. The oil flow pictures show the horseshoe type of flow separation around the sail. The separation location variation as a function of α and x/L is different from the one obtained for the barebody case. Therefore, the flow field on the sail side may not be characterized by the crossflow separation.

The unsteady data over the barebody show that the unsteady separation topology is different from the one observed in the steady case. At the same angle of attack, no secondary separation location was observed for the unsteady data whereas the steady data have both primary and secondary separations. Unsteady data also showed significant time lags between the unsteady and steady flow separation locations. Algebraic time lag model results did not match with the experimental results. This indicates the complex nature of the unsteady flow separation over the SUBOFF model. The first-order time lag model of Goman and Khrabrov fits the unsteady data reasonably well. Time lags obtained from this model have a unique variation along x/L that does not match with the one obtained for the prolate spheroid geometry.⁴ The apparent reason for different time lags between two cases is that the time to displace the volume of leeside inviscid fluid during a maneuver with vortical separated fluid is different for different geometries and points of rotation.

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References

- Simpson, R. L. Unsteady Aero-Hydrodynamics for Maneuvering Aircraft, Submarines and Automobiles. Report VPI-AOE-253, Department of Aerospace and Ocean Engineering, Virginia Tech, November 1997.
- Simpson, R. L. "Some Experience with the Dynamic-Plunge-Pitch-Roll (DyP-PiR) Mount in Unsteady Aerodynamics Research", AIAA-2002-0170, 40th AIAA Aerospace Sciences Meeting, January 14-17, 2002.
- [3] Wetzel, T. G. and Simpson, R. L. Unsteady Flow over a 6:1 Prolate Spheroid. Report VPI-AOE-232, DTIC no: ADA3071412XSP, Department of Aerospace and Ocean Engineering, Virginia Tech, 1996.
- [4] Wetzel, T. G. and Simpson, R. L. Unsteady Crossflow Separation Location Measurements on a Maneuvering 6:1 Prolate Spheroid. AIAA Journal, 36(11):2063–2071, November 1998.

- [5] Etkin, B. Dynamics of Atmospheric Flight. Wiley, New York, 1972.
- [6] Hosder, S. Unsteady Skin-Friction Measurements on a Maneuvering DARPA2 SUBOFF Model. M.S. Thesis, Department of Aerospace and Ocean Engineering, Virginia Tech, June 2001. (Electronic version available at http://scholar.lib.vt.edu/theses/available/etd-06152001-121441/).
- [7] Wetzel, T. G., Simpson, R. L., and Chesnakas, C. J. Measurement of Three-Dimensional Crossflow Separation. AIAA Journal, 36(4):557–564, April 1998.
- [8] Simpson, R. L., Walker, D. A., and Shinpaugh, K. A. Description of a 1000 Sensor Constant Current Anemometer System for Locating Three Dimensional Turbulent Boundary Layer Separations. Report VPI-AOE-185, DTIC no: ADA2508273XSP, Department of Aerospace and Ocean Engineering, Virginia Tech, December 1991.
- [9] Miller, J. A. A Simple Linearized Hot-Wire Anemometer. Journal of Fluids Engineering, 98(3):550–557, 1976.
- [10] White, F. M. An Analysis of Axissymmetric Turbulent Flow Past a Long Cylinder. ASME Journal of Basic Engineering, 94:200–206, March 1972.
- [11] Kays, W. M. and Crawford, M. E. Convective Heat and Mass Transfer. McGraw-Hill, New York, 1980.
- [12] Ahn, S. An Experimental Study of Flow Over a 6 To 1 Prolate Spheroid at In-

cidence. PhD Thesis, Department of Aerospace and Ocean Engineering, Virginia Tech, October 1992.

- [13] Yates, L. A. and Chapman, G. T. Streamlines, Vorticity Lines and Vortices Around Three Dimensional Bodies. AIAA Journal, 30(7):1819–1826, July 1992.
- [14] Montividas, R. E., Reisenthel, P., and Nagib, H. N. "The scaling and Control of Vortex Geometry Behind Pitching Cylinders". AIAA Paper 89-1003, 1989.
- [15] Ericsson, L. E. Unsteady Flows. In *Tactical Missile Aerodynamics: General Topics*, pages 490–493. edited by M. J. Hemsch, Progress in Astronautics and Aeronautics, AIAA, Washington D.C., 1992.
- [16] Goman, M. and Khrabrov, A. State-Space Representation of Aerodynamic Characteristics of an Aircraft at High Angles of Attack. *Journal of Aircraft*, **31**(5):1109– 1115, 1994.
- [17] Gad-el Hak, M. and Ho, C. M. Unsteady Flow Around an Ogive Cylinder. AIAA Journal of Aircraft, 23(6):520–528, 1986.

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