Chapter 7

Conclusions

Steady and the unsteady turbulent surface flow on a generic submarine model was studied. Hot-film sensors with constant temperature anemometers were used to measure the steady and the unsteady wall shear magnitudes over the model surface. Three-dimensional separation locations were determined from the minima of the skin-friction magnitudes. Steady skin-friction magnitudes were obtained at fourteen steady angles of attack. The dynamic plunge-pitch-roll model mount (DyPPiR) was used to simulate the pitchup maneuvers. The pitchup maneuver was a linear ramp from 1 ° to 27 ° in 0.33 seconds. Mean wall static pressures were measured at 10 ° and 20 ° angles of attack. Qualitative examination of the steady surface flow topology was done by using the oil-flow visualization pictures.

Two model configurations were studied in both the steady and the unsteady experiments: The barebody case and the sail-on-side case. The barebody case is the axisymmetric configuration of the model and can also be thought as a missile body or to a certain extent fuselage of an aircraft. Therefore, results obtained for the barebody case may be applied to many geometries with similar shapes. The sail-on-side measurements were performed with the sail fixed at the circumferential position $\phi = 270°$. Pitchup maneuvers for the sail-on-side case simulate the turning maneuver of a submarine. All the tests were conducted at $Re_L = 5.5 \times 10^6$ with a nominal wind tunnel speed of $42.7 \pm 1\%$ m/s. For the experiments, slotted walls with an open-air-ratio of 38% are used to reduce the blockage effects. However, some steady pressure and hot-film data at certain angles of attack were also acquired with solid walls for the purpose of comparison.

For the range of conditions at which the tests are conducted, steady results over the barebody show that the flow on the leeward side of the model can be characterized by the crossflow separation. The first clear detection of the primary separation locations are at the stations downstream of $x/L = 0.638$ at $\alpha = 5.1\,^{\circ}$. As the angle of attack increases, the primary separation line moves upstream and at a specific x/L location moves towards the windward side. At $\alpha = 11.3\,^{\circ}$, the onset of the secondary separation can be observed on the stern region. The secondary separation line migrates upstream and towards the leeward side with increasing angle of attack. The flat circumferential skin-friction profile on the stern region indicates the low speed separated flow which is also consisted with the oil-flow pattern of this region. This flat profile makes the identification of the true minimum and thus the separation location difficult for the stern region. A weak separation and reattachment of the flow on the nose region of the model can also be observed at high angles of attack.

The results of the sail-on-side case are evaluated in two separate regions, the region with no sail (between $\phi = 0\,^{\circ}$ and $180\,^{\circ}$) and the region with the sail (between $\phi = 180\,^{\circ}$ and $360\,^{\circ}$). 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. The primary separation locations of the non-sail region start to deviate from the barebody results having an offset in the leeward direction at angles of attack starting from $\alpha = 15.3^{\circ}$. On the other hand, secondary separation locations of the non-sail region are shifted in the leeward direction compared to the secondary separation locations of the barebody case at all angles of attack.

Downstream of the sail, 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. Compared to the separation topology of the barebody and the non-sail region of the sail-on-side case, the separation location trend as a function of x/L and α shows significant differences. Two minima in C_f vs. ϕ distributions on the leeward side of the sail region can be observed for certain angles of attack and x/L locations. The first minima measured from $\phi = 180\,^{\circ}$ can be observed only at a certain range of angles of attack, while second minima is detected at all angles of attack starting from $\alpha = 5.1\,^{\circ}$. 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.

The comparison of the barebody pressure measurements made with the solid walls and the slotted walls shows the blockage effect in the solid wall case, especially at $\alpha = 20\,^\circ$. On the leeward side of the model, the circumferential pressure gradient is found to be approximately zero over the regions of flow separation. One can think of using the flat pressure profile in regions of separation to locate the separation locations, however it is difficult to determine the exact point where this flat pressure distribution begins.

Unsteady skin-friction distributions of the barebody case and the non-sail region of the sail-on-side case show similar trends compared to the steady distributions of each. For these regions at high instantaneous angles of attack, the dominant flow feature on the leeward side of the model can again be characterized by the crossflow separation. However, the unsteady crossflow topology is different than the corresponding quasi-steady one; the primary separation formation occurs at higher angles of attack compared to the steady ones at which the onset of the first steady primary separation is observed. Also, at an instantaneous pitch angle for a specific x/L location, the primary unsteady separation starts more leeward compared with the steady case. No clear secondary separation is observed for the unsteady maneuvers. For the barebody and the non-sail region of the sail-on-side case, the difference in the separation topology originates from the fact that the unsteady separation location lags the unsteady separation.

As also seen in the steady case, the unsteady separation structure of the sail side is different from the unsteady crossflow separation topology observed on the barebody and the non-sail region of the sail-on-side case. From the results obtained for this region, it can be concluded that unsteady separation patterns do not follow the quasi-steady data with a time lag. A lag definition as described for the unsteady crossflow separation may not be appropriate for the sail side separation topology based on the results obtained in this study.

Time lag models were used to approximate the unsteady separation data of the barebody case and the non-sail region of the sail-on-side case. Algebraic time lag model results do not match with the barebody experimental results. This indicates the complex nature of the unsteady flow separation over the Suboff model. The first-order differential time lag model of Goman and Khrabrov [35] approximates the unsteady data reasonably well and captures the time-varying nature of the unsteady crossflow separation locations. Therefore, this model may be used as part of the unsteady aerodynamic models used to describe the physics of such flows.

Time lags that are obtained by fitting the model approximation with the experimental unsteady data have a unique variation along x/L that does not match with the one obtained from the prolate spheroid study of Wetzel and Simpson [3]. In this study, time lag values are approximately constant along most part of the constant diameter region whereas in the prolate study, a linear trend increasing in the downstream direction is observed. However, the model center of rotation and the model geometry are different between two cases. This may imply the influence of these two parameters on the time lags. Further study has to be done in order to investigate the effect of these parameters.

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