Aerodynamic control of slender bodies at high angles of attack

Vijaya Sirangu

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A Thesis

entitled

Aerodynamic Control of Slender Bodies at High Angles of Attack

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for
the Master of Science Degree in Mechanical Engineering

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Experimental and numerical investigations have been conducted on the aerodynamic control and maneuvering of slender bodies at high angles of attack. The study was conducted on an U.S. NAVY countermeasure concept projectile termed GuiDED Missile, and rectangular aftbody strakes were used to control the flow at high angles of attack. Forebody geometries studied include O-give, hemisphere and elliptical geometries. The optimal forebody design was based on maximum strake-induced mean yawing moment obtainable, minimum natural flow asymmetry, and minimum forebody-induced flow oscillation. The results show that the most effective flow control at high angles of attack is achieved with the O-give nose forebody geometry.

For the O-give nose geometry, impacts of various body components including fairings, forebody wings and aftbody fins on the overall control performance were investigated. Effects of strake height, length, axial and azimuthal locations were studied, and an optimal rectangular strake planform was determined. Off-surface flow visualizations were conducted to study the flow fields associated with O-give, hemisphere and elliptical forebody geometries, and the optimal strake in combination with O-give forebody.
Numerical simulations using FLUENT were conducted at low angles of attack for the baseline model with O-give and hemispheric forebodies. Simulations were performed at different Mach numbers for the O-give nose. The results obtained from the simulations were compared to that of the experiments.
To my mother, father, brother and grandmother for their love, patience, support and encouragement they have been giving me throughout my life.

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## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>α</td>
<td>angle of attack, degrees</td>
</tr>
<tr>
<td>θ</td>
<td>azimuthal angle, degrees</td>
</tr>
<tr>
<td>Cn</td>
<td>yawing moment coefficient, Yaw Moment/ (Q<em>Aref</em>Lref)</td>
</tr>
<tr>
<td>Cy</td>
<td>side force coefficient, Side Force/ (Q<em>Aref</em>Lref)</td>
</tr>
<tr>
<td>C_N</td>
<td>normal force coefficient</td>
</tr>
<tr>
<td>Q</td>
<td>freestream dynamic pressure, Pa</td>
</tr>
<tr>
<td>A_{ref}</td>
<td>reference area for non-dimensional aero-coefficients, m^2</td>
</tr>
<tr>
<td>L_{ref}</td>
<td>reference length for non-dimensional aero-coefficients, m</td>
</tr>
<tr>
<td>AoA</td>
<td>angle of attack, degrees</td>
</tr>
</tbody>
</table>
CHAPTER 1

Introduction

1.1 - Motivation

Due to recent missile threats to commercial and military aircrafts, countermeasure devices are being investigated for aircraft self-defense. One concept of such device is the GuiDED Missile. A GuiDED Missile is an unmanned vehicle that carries an explosive war head and contains means for controlling its trajectory. The flight system uses the data from the targeting or the guidance system to maneuver the missile in flight, allowing it to mediate inaccuracies in the missile or to follow a moving target. These high performance combat missiles need to operate at high angles of attack, which may result in the loss of control or vehicle stability due to aerodynamic instabilities. Thus it is desired to maintain aerodynamic control over the aero structure by using flow control techniques. The flow control techniques needed are based on speed, flight envelop, required maneuverability, region of travel (subsonic or supersonic) and angle of attack. These techniques are employed to modify the flow around the missile body in accordance with the flight requirements.
This thesis reports the experimental and numerical investigations into the aerodynamic forces and moments acting on a generic missile body at high angles of attack. Forebodies with O-give, hemisphere and elliptical cross sections were investigated to optimize the payload volumes and operational control at high angles of attack. The missile configuration is further optimized by testing the body with combinations of fairings, forebody wings and aftbody fins. The flow control technique employed is rectangular strake.

1.2 - Aerodynamic Models and Test Arrangements

This section presents a brief description of the aerodynamic models and the test section of the wind tunnel in which the experiments are conducted. All the tests are conducted in the low speed subsonic wind tunnel at the University of Toledo. The closed loop circuit has a rectangular test section of 3-ft. x 3-ft. The model is supported by a C-strut on a turntable. An internal force balance is incorporated in the model to measure forces and moments. The five component balance has two components each for the pitch and yaw axes, and one component for roll, which is not considered in the present study. The angle of attack of the models is varied from -4° to 60°.

1.2.1 - Baseline Model with O-give, Hemispheric and Elliptical Forebodies.

Three models with the same cylindrical body but different forebodies are shown in Figure 1.1. Detailed dimensions of each model are given in later discussions. All models have the same aftbody length of 19.84” and a nominal forebody length of 2.32”. The fineness ratio of the overall body is 8.42. An initial study with a strake mounted in-between the forebody and aftbody is conducted to determine the most effective forebody geometry for detailed investigations.
Figure 1.1 - Baseline Model with O-give, Elliptical and Hemisphere Forebodies
1.2.2 - Missile Body with Fairings, Forebody Wings and Aftbody Fins.

The missile body was tested with combinations of typical vehicle components including fairings, forebody fins and aftbody wings. The components are shown in Figure 1.2. Detailed dimensions of all components will be given in later discussions.

![Missile Body with Fairings, Forebody Wings and Aftbody Fins](image)

**Figure 1.2 - Fairings, Forebody Wings and Aftbody Fins attached to the Missile body.**

1.3 – Slender Body Flow Separation

As a slender body of revolution is pitched through the angle-of-attack range from 0° to 90°, it experiences four distinct flow patterns that reflect the diminishing influence of the axial flow component [3]. These flow patterns are depicted in Fig.1.3.
At low angles of attack \((0 \leq \alpha \leq \alpha_{sv})\), the flow is attached. The cross flow effect in this region generates a thick viscous layer on the leeside. For a blunt nose in this region local flow separation can occur. At intermediate angles of attack \((\alpha_{sv} \leq \alpha \leq \alpha_{AV})\), the flow begins to separate and rolls up into symmetric vortex pair on the leeward side as sketched in Fig. 1.4. As the angle of attack increases further \((\alpha_{AV} \leq \alpha \leq \alpha_{UV})\), asymmetric flow separation occurs as shown in Fig. 1.5.
It has long been recognized that asymmetric vortex shedding can occur on bodies of revolution at high angles of attack [1, 7-9]. Bryson [5] was one of the first researchers to link the vortex separation with the nose cone geometry. Due to the natural flow asymmetry, a side force is generated in a nominally symmetric flow condition as depicted.
in Fig. 1.6. At very high angle of attack in the range \((\alpha_{UV} \leq \alpha \leq 90\,\text{deg})\) unsteady vortex shedding occurs and resembles a two-dimensional cylinder normal to the flow.

1.4 – High Angle of Attack Flow Control Methodology

The asymmetric evolution of the wake on the leeward side is responsible for the presence of an unwanted side force. Experiments have been carried out with a variety of add-on devices to assess their effectiveness in reducing the side force on aircraft. The devices included surface roughness, helical trip, modifications in the nose geometry rotation of the tip [4], among others.

Ericsson and Beyer [12] conducted comprehensive studies of separation asymmetry by investigating conical, O-give and blunt nose geometries. Before attempting to transfer existing forebody flow control capability for use on missile bodies, the influence of the forebody on the asymmetric flow over the cylindrical aftbody has to be taken into account.
On long pointed bodies the vortex asymmetry, and thus the side force, usually begins at the nose, and the vortices are shed at a relatively rapid rate to give alternating side-force cells on the long, slender bodies [10, 11]. The pointed geometry also offers increased directional stability under high-alpha conditions, in addition to better normal force characteristics [22]. Ericsson and Reding [3] determined that a slight bluntness of the nose causes the asymmetric vortices to develop at the rear of the body, and alternating vortex shedding does not occur readily. In this case, the side force cells are much larger and can cover the entire cylindrical aft body. If the nose is sufficiently blunt a nose induced separation of the axial flow will occur [13]. Thus, from the above discussions it is clear that the nose design has significant influence on the asymmetry of flow over the entire body at high angles of attack.

The control of asymmetric flow separation on missiles is necessary because in the absence of such control, the maneuvering at high angles of attack would experience large lateral moment changes. Rao [14] suggested the possibility of manipulating the steady-state vortex system characteristics of slender bodies at high angles of attack to generate controlled side force by using jet blowing on a forebody shape characterized by a high fineness ratio. Yaw control up to 120° is demonstrated by Hodgkin and Wood [15] by using a slot optimized for the periodic vortex shedding region. For control in the regions of high vortex asymmetry, short slots near the forebody apex were most efficient, while for control at higher angles of attack, short slots further aft were acceptable. Another method is the use of helical trip first suggested by Scruton and Walsh [16], which has been used rather successfully in reducing vortex-induced instability of structures susceptible to wind-excited oscillations. With the helical trips the flow is forced to
separate at varying peripheral locations along the length of body to result in vorticity flux variations along the length. This prevents the shed vorticity from concentrating into discrete two-dimensional cores, thereby suppressing the unsteady cross-force. Modi [4] showed a nose boom to be effective in the reduction of side forces. Tajfar [17], Stahl [18], Viswanath [19] and Brandon [20] are examples of using nose geometry modifications to control the vortices.

Strakes were designed with the intent of fixing the flow separation location along the length of the forebody [23]. In some flight regimes, the flow can be partially controlled by employing small strakes, which fix the boundary layer separation point and assist in making the leeward vortices symmetric or more deterministic [21]. Rao et al. [14] suggested two alternative modes of strake deployment. An asymmetric deployment (i.e., one strake deployed at a time) can force a strongly asymmetric vortex pattern and thus generates a side force that is, controllable via strake deflection. Another method is the simultaneous deployment (i.e., both strakes deployed), which will establish a symmetrical pair of augmented vortices, from which a controlled side force is generated via antisymmetric (or differential) strake deflection. They concluded that dual strakes were effective, but a single strake has approximately the same control if located in the correct position. Ng [24] performed surface oil flow visualizations which revealed that the presence of strake alters the position and the shape of the separation line. These findings suggest that the strake at the tip not only minimizes the interaction of the tip vortices, but also forces the origin of the separation line to move to the tip. The results also show that the effectiveness of the strake decreases when moved farther downstream from the nose. Ng [25] showed that the amplification of the asymmetry takes place mostly at the nose.
apex and proposed that blunting the nose would have a similar effect of reducing the flow interaction as the strake. Lopera et al. [26] investigated effects of azimuthal and axial positions of the strake as well as the strake planform on the flow control of a relatively short missile body. He concluded that the most effective location for the yaw control was at 90° and 270° (left and the right meridians). Also, he concluded that the strake is effective in the position close to the nose seam where the forebody ends. Furthermore, out of the fourteen different strake planforms tested, the most effective strake in producing large yaw control is the rectangular strake planform.

1.5 - Effect of Wings, Fins and Fairings - Literature Survey

Slender wings with sharp leading edge are featured in many designs of modern high speed fighter aircraft to provide a high degree of maneuverability at subsonic speeds [28]. Fairings are sometimes attached to missile body for stability. These stationary surfaces are used to provide stability and (some) lift during missile flight. Ziada [27] investigated the effect of fins on vortex shedding from the cylinder in cross-flow. He concluded that the addition of fins enhances the process of vortex shedding. It is also shown that the fins increase the correlation length and the amplitude of velocity fluctuation at the vortex shedding frequency. Daniel [29] states that the missile control fins have been, and are arguably still, the most efficient means of controlling a tactical missile and guiding it to the target. They can generate the required maneuvering force either by a direct action near the center of gravity, as in a mid-wing control missile, or through rotation of the missile to higher angles, as in canard or tail control missiles.
1.6 - Flow Control Methodology in Present Work

From the discussions in section 1.4, it is known that a strake can provide required control in the high angle-of-attack regime. Deployable strakes are small flow control devices that are typically deployed at the nose. The strake used in the present study is asymmetrically deployable as depicted in Figs. 1.7 and 1.8. The deployed strake lifts the vortex up and away from the surface on the strake side thereby modifying the entire vortex pattern. The resulting pressure difference induces a side force in a controlled manner.

Figure 1.7 - Effect of the strake on the leeward side vortex
Chapter 2 presents effects of forebody geometry on the yawing moment and side force generated on a slender body missile at high angles of attack.

Chapter 3 discusses effects of various combinations of components including fairings, forebody wings and aftbody fins on the baseline flow and control.

Chapter 4 presents the yaw control of using aftbody strake and the optimum strake configuration at high angles of attack.

Chapter 5 presents flow visualization results of different forebody geometries and yaw control with strake.

Chapter 6 presents numerical simulations of the baseline model with O-give and hemispheric nose geometries in the subsonic region.
CHAPTER 2

The Effects of Nose Geometry on Yaw Moment and Side Force on a Slender Body Missile

2.1- Introduction

In this chapter effects of nose geometry on yawing moment and side force are studied. Experiments were conducted initially to investigate the nose geometry that provides the desired baseline and control characteristics at high angles of attack. Further testing is then conducted with the most suitable nose geometry. Experiments are conducted with three nose geometries: (1) hemispheric, (2) elliptical and (3) tangent O-give.

2.2 - Aerodynamic Models

The model tested was a 70% scale model of a missile configuration designed by Orbital Research Inc. Figure 2.1 show the hemispheric, elliptical and O-give nose models. The overall length of the model is 22.16 inch. The O-give nose has a length that is equal to the base diameter of 2.63 in., the hemisphere nose has a length that is equal to the base radius of 1.315 in., and the elliptical nose has an ellipticity of 3 that results in a length of 0.867 in.
Figure 2.1 – O-give, Elliptical and the Hemisphere Nose Geometries.

Figure 2.2 - Detailed dimensions (in inches) of the overall model with different forebodies.
2.3 - Wind Tunnel Experiments

The experiments were conducted at a free stream velocity of 18.5 m/s, and Reynolds number of 78 x 10^3 based on the model maximum diameter. The Static tests were conducted for angles of attack ranging from -40° to 60° at 2° increments. Two thousand samples were taken at a sampling rate of 200 samples per second, corresponding to a sample-period of 10sec. All experiments were repeated three times to verify the repeatability of the measurements, and the measurements were found to be repeatable.

2.3.1 – Effect of Forebody Geometry on Yawing Moment and Side Force Coefficient

Figures 2.3 and 2.4 depict respectively the baseline yawing moment and side force coefficients for the three nose geometries. Positive values indicate rightward yawing moment and side force, while negative values indicate left-ward yawing moment and side force.

It can be observed from Figures 2.3 that the hemisphere nose exhibits yaw asymmetry from α = 30° to 60°, while the same occurs for the elliptic and O-give nose from α = 40° to 60°. The magnitude of the yawing moment produced by the hemisphere nose reached 50% higher than those of the elliptic and O-give noses. Figure 2.4 shows the variation of side force with angle of attack. The side force behaviors follow basically that of the yawing moment.
Figure 2.3 – Baseline yawing moment for O-give, elliptic and hemisphere forebodies.

Figure 2.4 - Baseline Side Force Coefficient for O-give, elliptic and hemisphere forebodies.
2.3.2 - Yaw Control with Strake.

Experiments were conducted by placing a strake at 90° and 270°, with 0° being the windward meridian from pilot’s view as shown in Figure 2.5. Effects of strake height, length, axial position and azimuthal angle will be presented in chapter 4. In this section only the effectiveness of one particular strake (height 5-mm and length 15-mm) in relation to the forebody geometry will be discussed.

Figure 2.5: Pilot’s view of Missile
The notations used in the graph with color code are given below:

Figure 2.6 – Effect of strake on yawing moment for the model with hemispheric, elliptical and O-give nose
Figure 2.7 – Effect of strake on side force for the model with hemispheric, elliptical and O-give nose

Results of the yawing moment and the side force coefficients of the model with different nose geometries are shown in Figures. 2.6 and 2.7. The strake is mounted in-between the forebody and aftbody at a distance of 2.32-in from the nose apex. At angles up to $\alpha = 20^\circ$, the flow was symmetric and no significant yawing moment or side force was observed.

From Figure 2.6 it is clear that for $\alpha$ greater than $30^\circ$, the controlled yawing moment achieved by the single aftbody strake was much larger and predictable for the O-give nose than those of the hemispheric and elliptical nose geometries. The O-give nose generated a maximum yawing moment that is about 50-60% higher compared to the hemisphere and elliptic geometries. For the O-give nose geometry, the right ($90^\circ$) and
the left (270°) yawing moments were similar in magnitude but opposite in direction. The elliptical nose generated controlled yawing moment more effectively than the hemisphere nose for angles greater than 30°. It is evident from the graphs that controlled yawing moments were generated with the aftbody strake regardless of the nose geometry.

Figure 2.7 shows the side force coefficients for the baseline and cases with strake. The side force behavior follows the same trend as the yawing moment. The results show that for \( \alpha \) greater than 30°, the aftbody strake with the O-give nose produces controlled sides forces 30-50% greater than the other forebody geometries.

2.4 – Baseline Flow Oscillations

In section 2.3.1, it was observed that there is a great similarity between the O-give and elliptical nose geometries in regard to the baseline mean yawing moment and side force behaviors. In this section, the flow oscillations in both cases were taken into account to determine the best nose geometry for further study.

An unsteady flows over the slender body can be expected to cause force and moment fluctuations. In the experiments conducted oscillations in the pitch and yaw planes were revealed by the root-mean-square (rms) values of the respective force balance voltage outputs. Results of the oscillations are shown in Figure. 2.8
Figure 2.8 shows no significant flow oscillations for all cases for $\alpha$ up to 10°. At higher angles of attack, the oscillation in yaw is significantly higher than in pitch. Both elliptic and hemisphere geometries produce large oscillations in yaw as the angle of attack increases. The O-give geometry on the other hand, produces relatively small oscillations at all angles of attack. Thus, taking into account both the mean and oscillatory results, the O-give nose exhibits the most desirable and predictable baseline behaviors for control applications.
2.5 – Present Chapter Conclusions

1. The O-give and elliptic forebody geometries exhibit a relatively small baseline asymmetry compared with the hemispheric case.

2. The hemisphere nose geometry generates significant baseline yawing moment and side force at medium-to-high angles of attack.

3. The experiments conducted with the control strake showed that the O-give nose produces the highest controlled yawing moment and side force among the three nose geometries.

4. The magnitude of flow oscillation is smallest for the O-give nose geometry when compared with the others.

It is concluded that the O-give nose geometry is most suitable for producing controlled and predictable yaw moment and side force at high angles of attack. Thus, further study will be conducted with the O-give forebody geometry.
CHAPTER 3

Effects of Common Missile Components on the Baseline flow and Control

3.1 – Introduction

While the general configuration of the missile is a slender cylindrical main body, often attached to the body are wings, fins and fairings. These components are intended to provide, among the other functions, static stability, lift and covers for necessary hardware. In this chapter, various combinations of components are tested in order to determine their effects on the baseline flow behaviors and control effectiveness of the strake.

The design of a missile depends on several factors such as payload, operating range and the speed of travel (subsonic or supersonic). The design tested in the present study consists of wings mounted near the forebody; control fins that are located to the rear of the missile, and combination of both. Fairings are attached to the body to act as covers for the fin tilting mechanism.
3.2 - Aerodynamic Models

Dimensions of the body fairings, forebody wings and aftbody fins are illustrated in Figures 3.1 through 3.3. All dimensions are in inches.

Figure 3.1 - Dimensions of the forebody fairing

Figure 3.2 - Dimensions of the aftbody fairing
Figure 3.3 - Dimensions of the wings and fins

All dimensions are in inches unless noted.
3.3 - Wind Tunnel Experiments

Tests were performed at a free stream velocity of 18.45 m/s and Reynolds number of 78 x $10^3$ based on the model diameter. Two thousand samples are taken at a sampling rate of 200 samples per second resulting in sampling period of 10 sec. All the experiments are conducted twice to verify repeatability of the measurements. The measured forces and moments are found to be consistent and repeatable.

The following are the test cases without control:

- a. Body-Alone-Ogive
- b. Body-Alone-Ogive-Fairings
- c. Body-Wings-Ogive
- d. Body-Wings-Ogive-Fairings
- e. Body-Fins-Ogive
- f. Body-Fins-Ogive-Fairings
- g. Body-Wings-Fins-Ogive
- h. Body-Wings-Fins-Ogive-Fairings

The following are the test cases with control:

- i. Body-Alone-Ogive-ST
- j. Body-Alone-Ogive-Fairings-ST
- k. Body-Wings-Ogive-ST
- l. Body-Wings-Ogive-Fairings-ST
- m. Body-Fins-Ogive-ST
3.3.1 – Effect of Fairings on the Baseline Asymmetry

Figure 3.4 shows the yawing moment of the baseline O-give nose case, with and without fairings. From the graph it can be observed that while the fairings do reduce the magnitude of flow asymmetry at high angles of attack, they do not eliminate the asymmetry. Same observation is made for side force coefficient.
3.3.2 - Effect of Forebody Wings, Aftbody Fins and Combination of Both on Flow Control

The notations used in the graph with color code are given below:

- Body-Alone-Ogive
- Body-Alone-Ogive-Fairings
- Body-Wings-Ogive
- Body-Wings-Ogive-Fairings
- Body-Fins-Ogive
- Body-Fins-Ogive-Fairings
- Body-Wings-Fins-Ogive
- Body-Wings-Fins-Ogive-Fairings

Figure 3.5 - Yaw moment coefficient for various combination of components
Figure 3.5 present respectively the yawing moment of various configurations. The offset from zero that is visible in the graph is due to misalignment of the fins. It can be observed that the asymmetry is reduced for the models with wings. The addition of tail fins changes the flow behavior but does not increase or reduce the natural asymmetry.

3.3.3 - Effects of Forebody Wings and Aftbody Fins on the Control

Effects of fins and wings on the yawing moment and side force produced by a control strake are illustrated in Figures. 3.6 and 3.7.

![Coefficient of Yawing Moment vs Angle of Attack](image)

Figure 3.6 - Yawing moment coefficient for various configurations with control strake
From Figures 3.6 and 3.7, it is evident that the tail fins do not have a significant effect on the strake induced controlled yaw and side force. On the other hand, the presence of forebody wings significantly reduces the effectiveness of the strake control.
3.3.4 - Effect of Forebody Wings at different locations from the nose apex

Since in the previous section it is observed that the forebody wings can significantly reduce the control effectiveness, they are moved downstream to 203-mm and 238-mm from the nose apex to determine if that will result in improvements. Tests are conducted with and without strake.

The notations used in the graphs without control are:

Position 1: At a distance of 58.92-mm from the nose apex

Position 2: At a distance of 203-mm from the nose apex

Position 3: At a distance of 238-mm from the nose apex

Figure 3.8 - Yaw moment coefficient vs. Angle of attack for various positions of forebody wings without control Strake
Figure 3.9 - Yaw moment coefficient vs. Angle of attack for various positions of forebody wings with control strake.

Figure 3.10 - Side force coefficient vs. Angle of attack for various positions of forebody wings without control strake.
Figure 3.11 - Side force coefficient vs. Angle of attack for various positions of forebody wings with control strake.

Figures 3.8, 3.9, 3.10 and 3.11 present the yawing moment and side force coefficients for various positions of the forebody wings with and without control strake. From the graphs it can be seen that the change in the position of the wings does not improve the baseline flow or control effectiveness. The offset that is observed from zero in the graphs is due to the misalignment of the fins.
3.4 - Present Chapter Conclusions

1. The fairings attached to the main body reduce but do not eliminate the baseline asymmetry.

2. Tail fins have minimal effect on the baseline asymmetry and control effectiveness of strake.

3. Forebody wings reduce the baseline asymmetry but adversely affect the control effectiveness of the strake.

Based on the results, the forebody wings are eliminated from further studies.
CHAPTER 4

Yaw Moment Control at High Angles of Attack by Using Aftbody Strake

4.1 - Introduction

In this chapter, effects of strake height, length, axial location and azimuthal angle are investigated.

The missile configuration used for the investigation is shown in Figure 4.1. The configuration contains tail fins and fairings but no forebody wings.
4.2 - Wind Tunnel Experiments

The strakes used in the study are mounted behind the forebody as shown in Figure 4.2. As such they are termed as aftbody strakes. In reference to cylindrical coordinates, there are three parameters that define the strake location: radial, axial and angular. Angular location is the position of the strake around the cylindrical body, and is often referred as the azimuthal location. Radial position is the height of the strake. Axial location is determined by the location of the strake in relation to the nose tip along the body axis. A rectangular strake planform is used in the study.
4.3.1 - Effect of Strake Height and Length

This section presents results of the yawing moment and side force coefficients for various strake heights and lengths. Dimensions of the strake are given as Height * Length in mm.

The wind tunnel test matrix for the strake study with regard to the height is shown in Table below:

Table 4.1 - Strake Test Matrix with respect to Height
<table>
<thead>
<tr>
<th>Test No</th>
<th>Height (mm)</th>
<th>Length (mm)</th>
<th>Azimuth (deg)</th>
<th>AoA (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT - 1</td>
<td>3</td>
<td>15</td>
<td>90 and 270</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 2</td>
<td>5</td>
<td>15</td>
<td>90 and 270</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 3</td>
<td>8</td>
<td>15</td>
<td>90 and 270</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 4</td>
<td>10</td>
<td>15</td>
<td>90 and 270</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 5</td>
<td>12</td>
<td>15</td>
<td>90 and 270</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 6</td>
<td>14</td>
<td>15</td>
<td>90 and 270</td>
<td>-4 to 60</td>
</tr>
</tbody>
</table>

The notations used in the graph with color code are given below:
Figure 4.3 - Effect of the strake deployment height on the yaw for Body-Fins-Ogive-Fairings-ST

Figure 4.4 - Effect of the strake deployment height on the side force for Body-Fins-Ogive-Fairings-ST
Figures 4.3 and 4.4 show the effects of strake height on the yawing moment and side force coefficients. The strake is mounted in-between the forebody and aftbody and positioned at 90° and 270°. The results show that a strake 3-mm in height does not produce significant control. With strake heights above 3-mm a significant control with symmetric leftward and rightward yawing moments can be produced. As, the deployment height of the strake increases, the yawing moment generated also increases. An increase from 12-mm to 14-mm in height does not produce significant increases in the control moment. Thus, the strakes height should be between 3-mm and 14-mm.

The wind tunnel test matrix for the strake study with regard to the length is shown in Table 4.2

<table>
<thead>
<tr>
<th>Test No</th>
<th>Height (mm)</th>
<th>Length (mm)</th>
<th>Azimuth (deg)</th>
<th>AoA (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT - 1</td>
<td>8</td>
<td>10</td>
<td>90 and 270</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 2</td>
<td>8 and 12</td>
<td>15</td>
<td>90 and 270</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 3</td>
<td>8 and 12</td>
<td>20</td>
<td>90 and 270</td>
<td>-4 to 60</td>
</tr>
</tbody>
</table>
Since it is observed that strakes of height 8 and 12-mm produced reliable control; these strake heights are used in combination with various lengths to determine the optimum strake shape.

The notations used in the graph with color code are given below:

- Body-Fins-Ogive-Fairings-ST-810-90
- Body-Fins-Ogive-Fairings-ST-810-270
- Body-Fins-Ogive-Fairings-ST-815-90
- Body-Fins-Ogive-Fairings-ST-815-270
- Body-Fins-Ogive-Fairings-ST-820-90
- Body-Fins-Ogive-Fairings-ST-820-270
- Body-Fins-Ogive-Fairings-ST-1215-90
- Body-Fins-Ogive-Fairings-ST-1215-270
- Body-Fins-Ogive-Fairings-ST-1220-90
- Body-Fins-Ogive-Fairings-ST-1220-270
Figure 4.5 - Effect of the strake length on the yaw for Body-Fins-Ogive-Fairings-ST

Figure 4.6 - Effect of the strake length on the side force for Body-Fins-Ogive-Fairings-ST
Figures 4.5 and 4.6 show the effects of strake length on the yawing moment and side force coefficients. It is observed that a strake length of 15-mm produces significant control at angles of attack up to $\alpha = 50^\circ$ for both strake heights of 8 and 12 mm. Strakes with length of 10-mm and 20-mm are all less effective than the 15-mm case. This indicates that there is an optimal length that positions the vortices at the most effective positions.

In summary, the effect of changing the deployment height is more pronounced than that of changing the strake length. The strake of height 12mm and length 15mm is chosen as the best strake geometry for the model.

4.3.2 - Effect of Axial Location

This section presents the wind tunnel test results of the effect of axial location of the strake.

The wind tunnel test matrix for the strake study with regard to the location is shown in table 4.3.
Table 4.3 - Strake Test Matrix with respect to Axial Location

<table>
<thead>
<tr>
<th>Test No</th>
<th>Height &amp; Length (mm)</th>
<th>Axial Location (mm)</th>
<th>Azimuth Angle (deg)</th>
<th>AoA</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT - 1</td>
<td>12*15</td>
<td>59</td>
<td>90 and 270</td>
<td>-4 and 60</td>
</tr>
<tr>
<td>WT - 2</td>
<td>12*15</td>
<td>64</td>
<td>90 and 270</td>
<td>-4 and 60</td>
</tr>
<tr>
<td>WT - 3</td>
<td>12*15</td>
<td>69</td>
<td>90 and 270</td>
<td>-4 and 60</td>
</tr>
</tbody>
</table>

Figure 4.7 - The effect of axial location of the strake on yawing moment for Body-Fins-Ogive-Fairings-ST
Figure 4.8 - The effect of axial location of the strake on side force for Body-Fins-Ogive-Fairings-ST

The effect of strake axial location is studied by placing the strake at different axial locations downstream from the forebody. Figures 4.7 and 4.8 show the yawing moment and side force coefficients associated with different strake axial locations. The results indicate that the largest yaw control is obtained when the leading edge of the strake is mounted in-between the forebody and aftbody. The farther, the strake is moved downstream of the forebody, the less the control magnitude.

4.3.3 - Effect of the Azimuthal Angle

The effect of the azimuthal angle is determined by rotating the strake azimuthally around the model. The azimuthal location of the strake is measured from pilot’s point of view, with 0° being the windward meridian and the angle increases in the counter-clockwise direction.
The wind tunnel tests are conducted with the strake of 12-mm in height and 15-mm in length, and, mounted in-between the forebody and aftbody or a distance of (59-mm from the nose apex). Azimuthal angles from $0^\circ$ to $110^\circ$ at $10^\circ$ increments are examined.

The wind tunnel test matrix for the strake study with regard to the Azimuthal Location is shown in Table 4.4

Table 4.4 - Strake Test Matrix with respect to Azimuthal Angle.

<table>
<thead>
<tr>
<th>Test No</th>
<th>Height &amp; Length (mm)</th>
<th>Axial Location (mm)</th>
<th>Azimuth Angle (deg)</th>
<th>AoA</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT - 1</td>
<td>12*15</td>
<td>59</td>
<td>10</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 2</td>
<td>12*15</td>
<td>59</td>
<td>20</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 3</td>
<td>12*15</td>
<td>59</td>
<td>30</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 4</td>
<td>12*15</td>
<td>59</td>
<td>40</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 5</td>
<td>12*15</td>
<td>59</td>
<td>50</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 6</td>
<td>12*15</td>
<td>59</td>
<td>60</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 7</td>
<td>12*15</td>
<td>59</td>
<td>70</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 8</td>
<td>12*15</td>
<td>59</td>
<td>80</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 9</td>
<td>12*15</td>
<td>59</td>
<td>90</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 10</td>
<td>12*15</td>
<td>59</td>
<td>100</td>
<td>-4 to 60</td>
</tr>
<tr>
<td>WT - 11</td>
<td>12*15</td>
<td>59</td>
<td>110</td>
<td>-4 to 60</td>
</tr>
</tbody>
</table>
The notations used in the graphs with color code are given below:

Figure 4.9 - The effect of azimuthal angle up to $\theta = 50$ deg on yawing moment
Figure 4.10 - The effect of azimuthal angle from $\theta = 60$ to 110 deg on yawing moment.

Figure 4.11 - The effect of azimuthal angle from $\theta = 0$ to 110 deg on side force coefficient.
Figures 4.9, 4.10 and 4.11 show the yawing moments and side forces associated with the strake at different azimuthal angles. The largest yawing moment and side force are produced when the strake is placed in the range of $\theta = 70^\circ$ to $90^\circ$. From $\alpha = 42^\circ$ to $60^\circ$ significant yaw moments and side forces are obtained. Strakes mounted at azimuthal angles less than $70^\circ$ and greater than $90^\circ$ are less effective in producing the desired control. The control attained by mounting the strake at angle $90^\circ$ has the same magnitude as the strake at $270^\circ$, with the former produces a negative or rightward yawing moment and the latter exhibits positive or the leftward yawing moment.

4.4 - Present Chapter Conclusions

1. Aftbody strakes can provide significant yawing moment and side force at high angles of attack.

2. The strake of height 12-mm and length 15-mm produced the highest controlled yawing moment and side force. A change in the height has more pronounced effect than a change in length of the strake.

3. The optimum axial location of the strake is in-between the forebody and aftbody.

4. The most effective azimuthal location of the strake is at an angle in the range $\theta = 70^\circ$ to $90^\circ$ (and $250^\circ$ and $270^\circ$).
CHAPTER 5

Flow Visualizations: Effects of Forebody Geometry on Baseline Flow and Yaw Control with Strake

5.1 - Introduction

This chapter presents results of the off-surface flow visualization study conducted to investigate effects of forebody nose geometry on the baseline flow and yaw control at high angles of attack. Flow Visualization is an experimental method of examining the flow pattern around the body by injecting dye, smoke, oil flow or sublimation methods. In the wind tunnels, smoke has been successfully used to trace vortex flows at low speeds.

5.2 - Aerodynamic models:

Flow Visualization is conducted on the baseline case with O-give, hemispheric and elliptical nose geometries. Fig. 5.1 shows the regions that are investigated.
5.3 - Wind Tunnel Experiments

The baseline flow and strake induced behaviors are examined at 50° angle of attack. This angle is chosen based on the yawing moment and side force results. For the yaw control, the strake of 8-mm in height and 15-mm in length, located in-between forebody and aftbody, and at 90° azimuthal angle is being studied.

The smoke flow technique is used in visualizing the vortex position and structure around the body. A laser sheet is used to show the cross section of the flow. The laser sheet is aligned normally to the model's longitudinal axis.

5.3.1 - Baseline Case Investigation: Hemispheric, Elliptical and O-give Forebodies.

Laser sheet visualizations are conducted at 6 different locations along the length of the model. Location 1 and 2 are upstream of the strake. Location 1 at 1" from the nose apex, location 2 at 2", location 3 at 4", location 4 at 5.5", location 5 at 7.5" and location 6 at 12.5".
Figure 5.2 shows the pictures of the O-give, hemispheric and elliptical nose geometries at location 1. A pair of symmetric vortices is observed over the O-give nose at section 1. The vortices appear to be equal in strength and symmetric in position. In contrast, there are no observable vortices over either the hemispheric or elliptical nose at this location.
Figure 5.3 - Section 2 for O-give, elliptical and hemisphere nose geometries.

Figure 5.3 shows the flows at section 2. Flows over both the O-give and hemisphere noses show two well-defined symmetric vortices. The vortices formed over the O-give nose are better defined and closer to the body compared to hemispheric nose. In contrast, the vortices around the elliptical nose are strongly asymmetric with the right vortex situated far above the surface compared to the left.
Figure 5.4 - Section 3 for O-give, Hemisphere and Elliptical Nose Geometries.

Figure 5.4 shows the flows at section 3. The flows over the O-give and hemisphere nose geometries show approximately symmetric vortices. The spacing between the vortices is smaller for the O-give nose than that of the hemisphere nose. For the elliptical nose, the flow becomes unsteady with the left and right vortices oscillating between the two asymmetric patterns shown in Figures 3(a) and 3(b).
Figure 5.5 shows the flow at section 5. It is observed that the flows over both the O-give and hemispheric noses have become asymmetric but remain steady. The flow oscillations over the elliptical nose becomes more pronounced than at section 4, and multiple vortex pairs can now be seen.
Figure 5.6 shows the flow field at section 6. Strong asymmetric vortices are now observed on all three models. The O-give nose flow remains steady. The flow over the elliptical nose however becomes oscillatory with multiple vortex pairs, similar to the case hemispheric nose.
5.3.2 - Yaw Control: Aftbody Strake on O-give nose

The flow of O-give nose geometry with an aftbody strake is investigated. The flow is examined at the sections shown in Figure 5.1. The flow visualization is conducted at 50° angle of attack. A strake of height 8-mm and length 15-mm is mounted in-between the forebody and aftbody at an azimuthal angle of 90°.

Figure 5.7 - Section 1 to 6 for O-give nose geometry with control strake.
Figure 5.7 shows sections 1 to 6 along the length of the O-give nose model with control strake. There is no observable effect due to the strake, as the strake is mounted downstream of the location. A pair of symmetric vortices is observed at section 1 as in the baseline case. Section 2 is close to the strake that is deployed on the right side of the model (pilot’s view). The strake lifts the right vortex off the surface and the left vortex moves closer to the model. As, the flow progresses along the length of the model, the distance and thus the asymmetry between the left and the right vortices increase.

5.4 - Present Chapter Conclusions

1. The onset of flow asymmetry occurs sooner for the elliptical nose geometry in comparison with the O-give and hemispheric geometries.

2. Flow oscillations and multiple vortex pairs are observed over the elliptical and hemispheric nose geometries but not the O-give nose, which is in agreement with the force oscillation measurements.

3. The strake with O-give forebody is effective in producing control force by forming vortices that are lifted off the strake-side surface in a controlled manner.
CHAPTER 6

Numerical Simulations of the Baseline Model with O-give and Hemisphere Forebodies

6.1 - Introduction

This chapter presents results of the forebody nose geometry effects on the flow. In the simulations, exact governing equations are time-averaged or modified into a set of equations that are computationally less expensive to solve. These modified equations contain unknown variables. Turbulent models are necessary to determine the variables in terms of known quantities. The choice of turbulence model depends on considerations such as the physics encompassed in the flow, the established practice for a specific class of problem, the level of accuracy required, the available computational resources, and the amount of time available for the simulation.

6.2 - Body Configuration, Boundary Conditions and Initial Conditions

Computations were performed for steady, 3D subsonic flow over the baseline model with the O-give and hemispheric nose geometries. The simulations are performed at Mach nos.
of 0.05 and 0.6. The former matches the wind tunnel test speed, while the latter provides indications of whether the wind tunnel results can be projected to the operational Mach number.

An adiabatic no slip boundary condition is applied at the body surface and the computational outer boundary is maintained at the freestream conditions. Far-Field boundary conditions specify the Mach number on the surfaces except at the missile body which is considered as wall. The computational domain is large enough to capture the flow around the missile body. Second-order accuracy in time and second-order accuracy in space are used in the computations. The flow is initially set to freestream and advanced in time through the previously obtained solution.

6.3 - Numerical Method

In the present study, the steady three dimensional Reynolds Averaged Navier-Stokes equations are solved with the Spalart-Allmaras turbulence model. Boussinesq hypothesis is employed to relate the mean stress to the mean velocity gradients. The advantage of this method is the relatively low computational cost for the computation of the $\mu_t$ (turbulent viscosity). The disadvantage of this method is that it assumes $\mu_t$ as an isotropic scalar quantity, which is not strictly true. An alternative to the above method is the use of Reynolds Stress Model to solve the transport equations for each of the terms in the Reynolds stress tensor that necessitates solving five transport equations in 2D and seven in 3D which increases the computational time.
Spalart-Allmaras model has only one transport equation whereas in k-ω and k-ε have two transport equations to be solved. The Spalart-Allmaras turbulence model is used to save the computational time and resources.

The model solves a modeled transport equation for kinematic eddy (turbulent) viscosity. Using the current density data the turbulent viscosity \( \mu_t \) is found and hence the Reynolds stress terms via Boussinesq hypothesis. This model embodies a relatively new class of one-equation models in which it is not necessary to calculate a length scale related to the local boundary layer thickness unlike the RSM. The Spalart-Allmaras model is designed specifically for the aerospace applications involving the wall-bounded flows [32].

6.4 - Computational Domain and Grid

A cylindrical computational domain is created with the missile body in the centre. Based on the results of similar studies, the computational domain, with 10 times and 15 times the characteristic length upstream and downstream respectively, is large enough to capture the flow. As the flow is subsonic the information of the flow propagating both upstream and downstream are equally important. The computational domain has 10 orthogonal rows with 1.00 propagation ratio. Tetrahedral mesh is used for the computational domain.

6.5 - Computational Results: Low Angles of Attack

In this section the flows at angles of attack \( \alpha = 0^\circ, 5^\circ \) and \( 15^\circ \) are analyzed. The baseline cases with the hemispheric and the O-give nose geometries are simulated. Simulations also are carried out for the O-give nose at different Mach numbers.
6.5.1 - Baseline with O-give and Hemisphere Forebodies at M = 0.05

The following are the simulations performed on the model:

Table 6.1 - Test Matrix for Baseline Study

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Mach No</th>
<th>Equations and conditions</th>
<th>Status</th>
<th>AoA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body-Alone-Ogive</td>
<td>0.05</td>
<td>3-D, Steady, Implicit, Spalart-Allmaras</td>
<td>Converged</td>
<td>0, 5 and 15</td>
</tr>
<tr>
<td>Body-Alone-Hemi</td>
<td>0.05</td>
<td>3-D, Steady, Implicit, Spalart-Allmaras</td>
<td>Converged</td>
<td>0, 5 and 15</td>
</tr>
</tbody>
</table>

The computational domain of the O-give and hemispheric forebodies is shown in Figs. 6.1, 6.2 and 6.3
Figure 6.1 - Subsonic mesh computational domain

Figure 6.2 - Baseline model with O-give nose geometry
Figure 6.4 shows effect of angle of attack on pressure contours. The static pressure contours show a stagnation region near the nose and low-pressure region on the upper surface. At \( \alpha = 0^\circ \), the pressure is uniformly distributed near the nose region. As angle of attack increases there is significant change in pressure distribution over the surface that results in the variation of the forces produced.
Figure 6.4 - Pressure contours for the O-give nose at angles of attack $\alpha = 0^\circ$, $5^\circ$ and $15^\circ$

Figure 6.5 shows the velocity contours for the O-give nose at angles of attack $\alpha = 0^\circ$, $5^\circ$ and $15^\circ$. Fig 6.6 shows the vectors of the velocity magnitude for the Ogive geometry at angles of attack $\alpha = 0^\circ$, $5^\circ$ and $15^\circ$. The flow behaves as expected, with the separated region at the tail being captured clearly.
Figure 6.5 - Velocity Contours for O-give nose at $\alpha = 0^\circ$, $5^\circ$, and $15^\circ$
At Mach 0.05, $\alpha = 0^\circ$

At Mach 0.05, $\alpha = 5^\circ$

At Mach 0.05, $\alpha = 15^\circ$

Figure 6.6 – Vectors of velocity magnitude for O-give geometry
The pressure contours, velocity contours and vectors of velocity magnitude for the hemisphere geometry are shown in Figs. 6.7 and 6.8. Fig. 6.9 shows the vectors of velocity magnitude for Hemisphere geometry at angles of attack \( \alpha = 0^\circ, 5^\circ \) and \( 15^\circ \). The results show that, at this range of angle of attack, the flow is similar to that of the O-give geometry except at the nose apex.

![Figure 6.7 – Pressure Contours for the Hemisphere Geometry](image)

At Mach 0.05, \( \alpha = 0^\circ \)

At Mach 0.05, \( \alpha = 5^\circ \)

At Mach 0.05, \( \alpha = 15^\circ \)
At Mach 0.05, $\alpha = 0^\circ$

At Mach 0.05, $\alpha = 5^\circ$

At Mach 0.05, $\alpha = 15^\circ$

Figure 6.8 - Velocity Contours for Hemisphere Geometry
At Mach 0.05, $\alpha = 0^\circ$

At Mach 0.05, $\alpha = 5^\circ$

At Mach 0.05, $\alpha = 15^\circ$

Figure 6.9 - Vectors of Velocity Magnitude for Hemisphere Geometry
Table 6.2 - Numerical for the Ogive and Hemisphere Geometries Numerical Data at Mach 0.05

<table>
<thead>
<tr>
<th>Angle of Attack (deg)</th>
<th>Drag</th>
<th>Normal Force Coefficient ($C_N$)</th>
<th>Side Force Coefficient ($C_Y$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-give</td>
<td>0</td>
<td>0.581986</td>
<td>-0.014673536</td>
</tr>
<tr>
<td></td>
<td>5</td>
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<td>1.2667501</td>
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<tr>
<td>Hemisphere</td>
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<td>0.42376729</td>
<td>-0.013475122</td>
</tr>
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<td>0.68845283</td>
<td>0.41293463</td>
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<tr>
<td></td>
<td>15</td>
<td>0.61117977</td>
<td>1.2791935</td>
</tr>
</tbody>
</table>

Table 6.3 - Experimental Results at Mach 0.05

<table>
<thead>
<tr>
<th>Angle of Attack (deg)</th>
<th>Drag</th>
<th>Normal Force Coefficient ($C_N$)</th>
<th>Side Force Coefficient ($C_Y$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-give</td>
<td>-0.1312</td>
<td>0</td>
<td>0.0139</td>
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<tr>
<td></td>
<td>5.9489</td>
<td>0.3483</td>
<td>0.0675</td>
</tr>
<tr>
<td></td>
<td>15.9474</td>
<td>1.3456</td>
<td>-0.052</td>
</tr>
<tr>
<td>Hemisphere</td>
<td>-0.09034</td>
<td>0</td>
<td>-0.001</td>
</tr>
<tr>
<td></td>
<td>5.99182</td>
<td>0.3733</td>
<td>0.0145</td>
</tr>
<tr>
<td></td>
<td>15.9448</td>
<td>1.395</td>
<td>0.056</td>
</tr>
</tbody>
</table>
Figure 6.10 - Comparison of normal force coefficient of numerical and experimental data for baseline case with O-give and hemisphere geometries.

Force coefficients from CFD simulations are compared to the experimental results in Table 6.2 and Fig. 6.10. The small but finite side-forces shown in Table 6.2 are due to numerical and experimental uncertainties as they should be zero in theory. It can be observed that the numerical and experimental results are in reasonable good agreement for all the three angles of attack.
6.5.2 - Simulations of the Baseline case with Ogive nose at M 0.6

The practical application of the missile is to operate in subsonic region at Mach No. 0.6. In this section simulations of the baseline case with the O-give nose are carried out at Mach number 0.6.

As shown in Figs. 6.11 and 6.12, the distribution of pressure on missile body, vortex pattern and the wake region for the baseline case with O-give geometry at Mach 0.6 is similar to those at Mach 0.05. This suggests that results from the wind tunnel tests can be scaled to the operational Mach number of 0.6 with reasonable accuracy. This is confirmed by the M=0.6 results in Table 6.3 that show similar normal force coefficients as in Table 6.2 for M = 0.05.

![Figure 6.11 - Pressure contours for Ogive geometry at Mach 0.6](image)

At Mach 0.6, $\alpha = 0^\circ$

At Mach 0.6, $\alpha = 5^\circ$

At Mach 0.6, $\alpha = 15^\circ$

Figure 6.11 - Pressure contours for Ogive geometry at Mach 0.6
At Mach 0.6, $\alpha = 0^\circ$

At Mach 0.6, $\alpha = 5^\circ$

At Mach 0.6, $\alpha = 15$ deg

Figure 6.12 - Velocity contours for Ogive geometry at Mach 0.6
Table 6.4 - Numerical Data of Baseline Case with Ogive Geometry at Mach No. 0.6

Numerical Data at Mach 0.6

<table>
<thead>
<tr>
<th>Mach No</th>
<th>Angle of Attack (deg)</th>
<th>Drag</th>
<th>Normal Force Coefficient ($C_N$)</th>
<th>Side Force Coefficient ($C_Y$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0</td>
<td>0.51902127</td>
<td>- 0.00950079</td>
<td>0.01236145</td>
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<tr>
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<td>5</td>
<td>0.54171414</td>
<td>0.39587526</td>
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<td>0.55130161</td>
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<td>0.00471079</td>
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</tbody>
</table>

6.7 - Present Chapter Conclusions

1. Simulations at $M = 0.05$ produce results that are in reasonable good agreement with the experimental ones.

2. Simulations at $M = 0.6$ suggests that the experimental results can be scaled to the operational Mach number of 0.6
Conclusion

Experimental and numerical investigations have been conducted on the aerodynamic control and maneuvering of slender bodies at high angles of attack. Rectangular strakes were used for vortex flow control. Forebody geometry and various body components including fairings, forebody wings, and aftbody fins were studied to assess their impacts on the overall performance of the control strake.

Experiment results showed that the O-give forebody geometry possesses the most desirable baseline and control characteristics compared to the hemispheric and elliptical nose geometries. The results reveal that tail fins and fairings have relatively small effects on the baseline flow and control performance, while forebody wings reduce the baseline asymmetry but also render the strake ineffective. A strake of height 12-mm and length 15-mm, mounted at a distance of 59-mm from nose apex, and at azimuthal angle 90° is shown to produce the highest controlled yawing moment and side force.

Off-surface flow visualizations show that, in contrast to the hemispheric and elliptical geometries, the O-give geometry induces no flow oscillations at high angles of attack, which is in agreement with the force and moment measurements. Numerical results show that the wind tunnel results at M = 0.05 can be scaled to the operational Mach number of 0.6.
References


