Low drag aerodynamic attitude control for high-speed missiles using transpiration

Kathryn Zbierajewski

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A Thesis

Entitled

Low drag aerodynamic attitude control for high-speed missiles using transpiration.

By

Kathryn Zbierajewski

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master of Science Degree in Mechanical Engineering

_________________________________
Dr. T. Terry Ng, Committee Chair

_________________________________
Dr. Sorin Cioc, Committee Member

_________________________________
Dr. Abdollah Afjeh, Committee Member

_________________________________
Dr. Patricia R. Komuniecki, Dean
College of Graduate Studies

The University of Toledo

August 2010
An Abstract of
Low drag aerodynamic attitude control for high-speed missiles using transpiration.

By
Kathryn Zbierajewski

As partial fulfillment of the requirements for the Masters of Science degree in Mechanical Engineering

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This CFD study investigates the effectiveness of transpiration channels for attitude control of a high-speed missile. The channel geometry is progressively adjusted based on the flow results from CFD studies to develop an optimized configuration. Additional sensitivity studies are conducted with the chosen best channel geometry on the effects of geometric parameters, Mach number, and angle-of-attack (AOA). In order to compare the control moments generated and the drag induced by the transpiration channels with the more commonly used spoiler, the Mach number and AOA CFD sensitivity studies are repeated on a generic spoiler geometry. The CFD study shows that the transpiration channels generate the control moments desired, but at a smaller magnitude and with much less drag than the spoilers. Once optimized, the performance of the transpiration channels is relatively insensitive to small changes in geometric parameters. The one exception is the channel cross sectional area, where the larger the channel cross-sectional area the larger the control moment produced. Lowering the Mach number and increasing the AOA both decrease the magnitude of the pitch moment produced, while yaw decreases and roll increases with increase in AOA. Similarly, the spoiler studies show decreased pitch moment with lower speed and increased AOA.
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Chapter 1

1 Introduction

There are currently many different systems used for attitude control and maneuverability of missiles. The current systems, such as spoilers, strakes, fins, and canards, are effective in producing moments on the body but also produce considerable drag and require bulky deployment systems. A low drag deployable attitude control mechanism is desired for this application. The solution explored herein is the use of passive transpiration channels on the missile body. The channels change the flowfield around the body thereby altering the pressure distribution and resultant force or moment on the body. Duca [1] performs an initial numerical study of this concept for his thesis in 2008 with attractive results. The current investigation is conducted to more deeply understand the effect of channel geometry on the channel performance. The missile used is the one given for the AIMSS project, outlined in Figure 4-1 below.
Chapter 2

2 Analysis

The transpiration channel investigation is conducted to reveal the capability of transpiration channels to provide attitude control moments on a body. There are many other methods of control in use today, as well as other investigational methods being developed. External structures, such as spoilers or fins, as well as methods of passive porosity and discrete suction or blowing, are discussed below.

External Structures

Traditional methods of yaw and pitch control for slender bodies have relied on external structures to interact with the flow around the body. Patel, et al. [2] investigated the maneuvering capabilities provided by deployable micro-actuators such as tubes, bumps, fences, and vortex generators. These tests determined that fences, or spoilers, are the most effective at producing the desired control moments. Patel, et al. [3, 4] went on to show that deployable miniature spoilers, fins integrated with deployable spoilers, and boattails with active spoilers are capable of producing aerodynamic control comparable to traditional control surfaces such as hinged fins and ailerons. They have been proven to be effective for control force generation but also have a few drawbacks. They protrude
into the freestream flow to alter the flow field and pressure distribution within, but the large surface area that contacts the flow also produces large drag. There are packaging issues as well, such as where the spoilers can be placed so as to not interfere with other components. In order to be utilized as active control mechanisms, the spoilers must be deployed when such control forces are needed. This calls for additional hardware and auxiliary power for the deployment mechanism and space for undeployed spoilers. Strakes, fins, and canards impose these same drag and packaging penalties. These issues have led to the development of other control techniques. [5, 6]

Aerodynamic Plasma Actuation

The physics behind plasma generation, or ionizing air through single dielectric barrier discharge (SDBD), is presented by Enloe et al. [7, 8]. Electrodes are positioned on the body so as to produce an electric field gradient. The presence of this gradient instigates the production of plasma, which generates a body force on the surrounding air. This body force acts to change the effective aerodynamic shape of, and thus pressure distribution over, the surface on which the actuator is located. Research has been conducted utilizing plasma actuators for various aerodynamic applications. [9, 10, 11, 12]

Discrete Suction/Blowing

Discrete suction involves removing flow from the boundary layer through tiny holes located along the aerodynamic surface. The holes are individually controlled to produce a periodic perturbation prior to separation. This perturbation acts to produce a 3-D,
spanwise variation at the separation line, which in turn forms counter-rotating vortices that entrain high-momentum fluid onto the surface. In this way, separation is delayed by a very small input that triggers a natural stability in the separated flow. Discrete suction has been used to control shear flow unsteadiness and leading edge flow separation. [13, 14, 15]

Similarly, adding mass flow to the flow field through the body surface, whether as a jet or slot, has been implemented to control yaw forces on slender bodies at high angles of attack. This blowing interacts with the vortices that form downstream of the body, enabling a controlled force to be generated. [16, 17, 18]

Passive Porosity

Passive porosity was originally intended as a way to control boundary layer-shock interaction, the idea of which dates back to the early 1980's. It affects the boundary layer downstream of a shockwave by providing a cavity through which air circulates to control the interaction between boundary layer air and air from the impinging shockwave. This technology can be applied to supersonic jet engines, transonic airfoils, transonic aircraft parts, or supersonic vehicles. The concept relies on pressure gradients to drive flow through very small passages thus altering the flow field near the surface. The concept has been applied for other purposes such as drag reduction, aerodynamic control, correction of forebody asymmetries, and film cooling of high temperature parts. [19, 20, 21, 22, 23]
Chapter 3

3 Transpiration Channels

The transpiration channel method instituted in this study can be considered a combination of suction and blowing. It involves bleeding freestream flow at one location and injecting that flow back into the freestream at another location through a channel that is controlled with a valve. Passive transpiration is naturally driven by pressure gradients between the bleed location and injection location; in this case, the inlet and exit of the transpiration channel, located on the body tube surface and boattail surface, respectively.

A similar combination of suction and blowing was investigated by Liu et al.[24] for flow transition control. These numerical studies were conducted on an airfoil. Applying suction at the leading edge (L.E.) allows for control of the flow transition position. The channel shape investigated is a slot; the slot width is a variable in the tests. Combining the L.E. suction with blowing at the trailing edge reduces drag on the body as compared with suction only.

Experimental research has been conducted by Orbital Research, Inc. in conjunction with the University of Toledo, investigating the potential of using transpiration for control through reconfigurable porosity. The background is outlined in AIAA 2003-3665 [25]
and the experiment is summarized in AIAA 2004-2695 [26]. The concept utilizes microelectromechanical systems (MEMS)-based microvalves to energize the boundary layer and delay flow separation. The patterns of numerous microvalves are distributed along the control surfaces, such as wings or tailfins, as well as around the boattail region, with results showing the possibility of pitch, yaw, and roll control. These positive results lead to the expansion of the concept from this initial approach to a concept validation study by Duca [1], to the AIMSS based testing conducted herein. The two main changes in application include operating speed and scale. The 2003 research was conducted at low subsonic speed, while the mission envelope for the AIMSS research is high-speed operation. Secondly, the microvalve implementation of transpiration channels is expanded to large, strategically located channels placed only around the boattail section of the missile.

As evidenced by the initial numerical simulations mentioned earlier, investigation of aerodynamic control through boattail transpiration is in its infancy. No other research was found which offered evidence of optimal channel geometry for the intended missile-type application. The starting point then for this research is simply that the transpiration concept can be effective and effects are dependent upon channel location.
Chapter 4

4 Computational Method

The initial investigation to optimize a passive transpiration channel for the AIMSS missile is completed using 3D, double precision, pressure based implicit Navier-Stokes CFD using the Spallart-Almaras turbulence model. The operating conditions are those given for the project primary cruise; 70,000 ft altitude, Mach 4, 0 degrees angle-of-attack (AOA) with fluid properties corresponding to atmospheric conditions at such, shown in Table 4-1 below.

**Table 4-1: Atmospheric Properties at Cruise Altitude**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity of Sound</td>
<td>295.9294 m/s</td>
</tr>
<tr>
<td>Missile Velocity</td>
<td>1183.7176 m/s</td>
</tr>
<tr>
<td>Density</td>
<td>0.071742 kg/m³</td>
</tr>
<tr>
<td>Viscosity</td>
<td>0.000014286 kg/m·s</td>
</tr>
<tr>
<td>Total Pressure</td>
<td>683916 Pa</td>
</tr>
<tr>
<td>Static Pressure</td>
<td>4487.7 Pa</td>
</tr>
<tr>
<td>Ttotal</td>
<td>915.2414 K</td>
</tr>
<tr>
<td>Tstatic</td>
<td>217.9 K</td>
</tr>
<tr>
<td>Gas Constant ©</td>
<td>287.0379 J/kg-K</td>
</tr>
<tr>
<td>Reynolds Number</td>
<td>3019775</td>
</tr>
<tr>
<td>Cp</td>
<td>1005.726 J/kg-K</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>0.019611 W/m·K</td>
</tr>
</tbody>
</table>

The domain for the computation is a rectangular solid starting 30 in. before the nose of the missile and extending 330 in. beyond the missile, for a total axial length of 600 in. The yz-plane is 300 in x 300 in, with the centerline of the missile centered in this plane.
The coordinate system for all configurations follows Figure 4-2 and Figure 4-3 below, with the origin at the nose of the missile. The sign convention is adjusted to correspond to the standard aerodynamics convention, i.e. positive moments are pitching nose-up, yawing nose-right, rolling clockwise.

Figure 4-1: Baseline Missile Model

Figure 4-2: Computational Domain: Top View
The boundary conditions on this domain consist of a massflow driven inlet plane, pressure driven outlet plane, and pressure-far-field along the four axial bounding planes. The solutions are run until convergence with first-order discretization and SIMPLE pressure-velocity coupling.

The internal packaging of the model is unknown, therefore, the center of gravity (CG) around which to calculate moments is also unknown. The CG is assumed to be the midpoint of the missile. This assumption is held constant throughout all of the CFD analyses.

4.1 Baseline
An important characteristic of CFD is that the accuracy of the result is dependent on many factors such as turbulence model used, computational domain, mesh size, and how the mesh is distributed. This leads to perhaps the main limitation of CFD in that the result will need to be validated at the very least for certain conditions. This is typically accomplished using experimental data. Since there is at present no experimental result available for the configuration, the initial CFD investigation is set at zero degrees AOA where forces and moments should be zero except for the drag. The base model configuration is the AIMSS missile complete with delta wing and cruciform tail without any transpiration channels or spoilers. The baseline flow is investigated using different computational domains, grid sizes, and grid arrangements. Figure 4-4 and Figure 4-5 below show some examples of the baseline flow field results.

Figure 4-4: Contours of Static Pressure; Baseline XY Plane
The results show a shock wave off the nose of the craft at approximately 20 degrees (slightly less than 20 degrees) inclined to the body centerline. There are additional shocks at the delta wing and tail fin locations. There is an expansion wave over the 20 degree declined boattail surface producing a low-pressure region along the trailing surface of the missile followed by a higher-pressure wake region. The wake mixes out by 7 diameters downstream.

The flow field results obtained using different grids are visually similar, but the forces and moments show differences. Table 4-2 shows a comparison of the results from two different grids. All forces and moments except the drag should theoretically be zero, and any non-zero value shown is a result of imperfections in the meshing. Results of Grid 1 reveal small but notable deviations from the theoretical zero with the exception of yawing moment coefficient, which shows a relatively large deviation. This is suspected to be a result of small asymmetries in the grid. Grid 2 shows results that are significantly
improved over Grid 1. The main difference is that Grid 2 (even with a 30% lower cell count) is more symmetrically distributed than Grid 1. The drag coefficients of the two grids are close, due likely to the relative large magnitude of the grid that minimizes the effects of small grid imperfections.

Table 4-2: Grid Comparison Results

<table>
<thead>
<tr>
<th>Baseline Configuration</th>
<th>Grid 1</th>
<th>Grid 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Count</td>
<td>2641769</td>
<td>2037180</td>
</tr>
<tr>
<td>Pitching Moment Coef.</td>
<td>-2.520e-3</td>
<td>1.002e-9</td>
</tr>
<tr>
<td>Yawing Moment Coef.</td>
<td>-2.376e-2</td>
<td>-1.095e-10</td>
</tr>
<tr>
<td>Rolling Moment Coef.</td>
<td>3.327e-4</td>
<td>1.005e-12</td>
</tr>
<tr>
<td>Lift Coefficient</td>
<td>-1.108e-3</td>
<td>-5.449e-11</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td>3.245e-1</td>
<td>3.198e-1</td>
</tr>
<tr>
<td>Side Force Coefficient</td>
<td>3.185e-3</td>
<td>1.070e-10</td>
</tr>
</tbody>
</table>
Chapter 5

5 Results and Discussions

5.1 Transpiration Channels

The first phase of transpiration channel investigation involves comparison between different general channel geometries. The goal is to find a near optimum geometry that offers a balance between performance (production of moments on the body) and simplicity (for manufacturing considerations). For yaw and pitch control, the transpiration channel is centered between two of the tail fins. Since only a single channel will be included, the grid will necessarily be asymmetric with the associated potential for errors. As such, the difference between the grids for different channel designs is limited mostly to modifications of the channel grid.

Fourteen channel designs are investigated and named channels B through O. The channel shapes evolve from a simple constant cross-section circular arc into more complicated designs as flow results are attained. The channel A designation is reserved for the geometry chosen for further sensitivity studies. Channels B through F are simulated on the initial geometry boattail: 14 degrees declined over 6 inches in the axial direction. Channels G through O, as well as the ‘downselect’ channel A, are simulated on the
updated boattail: 20 degrees declined over 4.11 inches in the axial direction. The following characteristics are studied to establish performance comparisons:

- Channel Cross-Sectional Radius
- Inlet Profile
- Single Throat Nozzle
- Number of Channels
- Slotted Channel
- Two Throat Nozzle

The performance goal of the transpiration channel is the production of a moment (yaw, pitch, roll, or a combination) on the missile. In determining the best performing channel design the simulated flow fields are analyzed for compliance with physics and the resulting moment magnitudes are compared.

5.2 Channel Cross-Sectional Radius Sensitivity

The initial designs are torus shaped (Figure 5-1); this geometry represents one of the simplest designs and serves as the starting point for the investigation. The channel cross-sectional radius affects both the massflow ingested by the channel and the boattail surface area that is affected by the channel flow. It also alters the channel wall surface area on which the channel flow pressure acts.

5.2.1 Channel B

The channel design labeled B is an attempt to scale a channel investigated in an earlier thesis [1] from a University of Toledo student to the current application geometry. The
dimensions from the copied channel are not complete and some geometry is assumed. It is a single swept arc with constant circular cross section, as seen in Figure 5-1 below.

![Figure 5-1: Channel B Dimensions, 0.8 in. Channel Radius](image)

The channel inlet requires almost 90 degrees of turn that does not happen immediately.

Investigation of Figure 5-2 above shows that the flow separates at the inlet and a recirculation forms at the upstream edge of the inlet. This results in an effective area at the inlet that is significantly smaller than the physical area. Once past the recirculation...
zone the flow maintains a subsonic velocity in the direction of the channel until the channel exit. At this point it joins the freestream flow without causing separation from the boattail surface. The channel jet does however slow the flow downstream of the channel exit to below the velocity on the rest of the boattail surface and produces a moment on the body. The pressure contours in Figure 5-3 support the data from the vector plot above.

![Figure 5-3: Contours of Static Pressure: Channel B](image)

5.2.2 Channel C

The channel C is the channel B with a 50% increase in channel cross-sectional radius. This is an attempt to achieve a higher massflow within the channel and greater momentum at the exit where the jet enters the freestream flow. A greater momentum at the exit can separate the flow over the boattail surface, which will produce much higher
pressures than where the flow is attached including the opposite side of the boattail. A moment on the body is therefore produced. The geometry is shown in Figure 5-4 below.

Figure 5-4: Channel C Dimensions, 1.2 in. Channel Radius

Figure 5-5 shows that similar flow behavior as in channel B occurs with the flow separates at the exit and not turning into the channel inlet immediately, a recirculation zone at the upstream edge of the inlet, and subsonic flow through the remainder of the channel to the exit. There is an additional recirculation area halfway through the channel axially, at the inner radius of the channel arc. This is due to over-aggressive turning in
the channel. The channel flow is choked at the inlet effective throat and forms a jet within the channel. The higher momentum jet continues in a direction towards the outside wall of the channel arc (nearly normal to and towards the body centerline) instead of turning with the channel. The flow is forced to turn when it meets the channel wall and re-circulating flow fills the void at the inside of the channel’s arc. At the boattail surface the flow does not separate as anticipated. The pressure contours in Figure 5-6 support the concl from the vector plot above.

**Figure 5-6: Contours of Static Pressure: Channel C**
5.2.3 Performance Comparison: B and C

Table 5-1: Moment Coefficient Results; Baseline, Channel B, Channel C

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>B</th>
<th>C</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw</td>
<td>-3.076e-2</td>
<td>-3.421e-2</td>
<td>11.20%</td>
</tr>
<tr>
<td>Pitch</td>
<td>-3.132e-3</td>
<td>2.674e-3</td>
<td>-185%</td>
</tr>
<tr>
<td>Roll</td>
<td>-3.815e-4</td>
<td>-4.880e-4</td>
<td>27.91%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2653292</td>
<td>2519529</td>
<td></td>
</tr>
</tbody>
</table>

The moment results for channels B and C are summarized in Table 5-1 above. The forces produced by channel B cause a nose down pitching moment, indicating a camber effect over the boattail. The nose left yawing moment indicates higher surface pressures from the channel, which is inconsistent with the pitch results. This is attributed to mesh asymmetries, as discussed for the baseline configuration. The channel C simulation produces the intended results, namely higher surface pressures near the channel causing a nose up pitch and nose left yaw. The torus design proves to be mostly ineffective regardless of the air passage size. The pressure distribution is altered only in small areas near the entrance and exit with little air flow through the passage. As such, no significant control force can be expected. The velocity results indicate that the entrance angle is too steep resulting in the flow mostly separated and bypassing the channel. A recirculation zone is generated inside the passage at the entrance when the air stream descends down slightly over the opening and eventually impinges on the back-end of the entrance to create a small high pressure region.

5.3 Inlet Profile Evolution
The two configurations studied thus far have experienced difficulty ingesting flow due to the turn angle required to enter the channel. Here, a progression of alterations to each channel leads to the next, starting with channel C and leading to channels D, E, F, and G (Figure 5-7, Figure 5-10, Figure 5-13, Figure 5-16). The purpose of changing the inlet design is to produce smooth flow into, through, and out of the channel, without separated flow regions.

5.3.1 Channel D

The upstream half of channel C is changed to a straight 20 degrees from axial decline that meets with the arc section to form channel D. This modification provides a shallower inlet angle than Channels B and C in order to minimize inlet separation and increase the inlet flow. The circular cross-section radius and downstream half of the channel is left unchanged.

Figure 5-7: Channel D Dimensions
Figure 5-8 above shows that the flow readily enters the new channel inlet, expanding and accelerating slightly over the inlet edge and maintaining flow in the direction of the channel until reaching the arc section. At the outside wall of the turn a shock wave causes an adverse pressure gradient that causes separation and recirculation at the walls. The separation at the inside wall moves upstream until becoming steady towards the beginning of the arc. The recirculation at the inside wall of the arc extends to the channel exit, sustained by the aggressive turn angle of the channel. The center of the channel flow maintains its direction through the shock (between the separated regions) until reaching the outer wall of the arc where it is turned to the exit. The flow that makes it out of the channel exit is quickly turned and accelerated by the high momentum freestream flow but does affectively slow the flow over the boattail surface as compared to the undisturbed regions. The pressure contours in Figure 5-9 support the data from the vector plot above.
5.3.2 Channel E

A relatively strong shock occurs in channel D where the declined section meets the circular arc section. For channel E, a horizontal (axial) section is added between the two to further graduate the turning through the channel.

Figure 5-10: Channel E Dimensions
Figure 5-11 above reveals that the declined inlet section for channel E behaves the same as that for channel D. When the flow reaches the horizontal section the wall forced turn produces a shock wave and an adverse pressure gradient that causes separation and recirculation at the walls. The separation at the inside wall moves upstream until becoming steady towards the beginning of the horizontal section. The flow is able to reattach before the arc section where subsonic speeds are maintained until the exit. Again, the exiting flow joins the freestream and slows the flow considerably over the boattail surface. The pressure contours in Figure 5-12 support the flow pattern revealed by the vector plot above.
5.3.3 **Channel F**

The recirculation region at the inside of the circular arc affects the velocity of the flow entering the freestream at the channel exit. To prevent this recirculation, the radius of the arc section in channel F is increased to ease the severity of turning required in that section of the channel.
As shown in Figure 5-14 above, well-behaved inlet flow passes through a shock wave at the turn to the horizontal section. The increased arc radius of the exit section does not prove to remove the recirculation zone, as the shock at the turn to the arc section still causes separation at the inside wall. The separation moves upstream until becoming steady towards the beginning of the arc section. The increased arc does, however, allow the flow to reattach to the inside wall of the channel before reaching the exit. Flow exits the channel through the full cross section and mixes with the freestream flow. The pressure contours in Figure 5-15 support the flow pattern revealed by the vector plot above.
5.3.4 Performance Comparison: D, E, and F

Table 5-2: Moment Coefficient Results; Baseline, Channel D, Channel E, Channel F

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>Channel D</th>
<th>Channel E</th>
<th>Channel F</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw</td>
<td>-4.500e-2</td>
<td>-4.973e-2</td>
<td>-4.659e-2</td>
<td>10.52% D to E; -6.32% E to F</td>
</tr>
<tr>
<td>Pitch</td>
<td>1.541e-2</td>
<td>2.298e-2</td>
<td>2.160e-2</td>
<td>49.13% D to E; -6.00% E to F</td>
</tr>
<tr>
<td>Roll</td>
<td>9.725e-4</td>
<td>1.240e-3</td>
<td>9.349e-4</td>
<td>27.48% D to E; -24.59% E to F</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2680775</td>
<td>2311988</td>
<td>2329236</td>
<td></td>
</tr>
</tbody>
</table>

The moment results for channels D through F are summarized in Table 5-2 above. The progression from D to E proves to alleviate excessive separation caused by aggressive turning from the inlet section to the outlet section. The channel F proves to further minimize separation at the turn to the arc exit, however, since the internal channel flow is not slowed as much as in channel E, the moments produced by channel F are not as large. The most effective of these designs, or that producing the largest moments on the body, is channel E. It decelerates both the flow within the channel and that over the boattail,
producing the highest pressure gradients between the channel side and the other sides of the missile.

5.4 Alternate Missile Geometry

The initial geometry of the missile boattail is modified at this point. The angle from axial is changed from 14 degrees to 20 degrees. The axial distance decreases from 6 inches to 4.11 inches to maintain the same diameter on the rear-facing surface.

5.4.1 Channel G

The previous best performing channel design is E. To set a new comparison standard, channel E is transposed to the new missile geometry to become channel G. The channel is shifted rearward on G so that the centers of the channel inlet and outlet are the same distances from the boattail leading edge as in E. Since G is shifted downstream on the missile body, the moment arm on which the pressures act is longer, potentially increasing the resultant moment.

Figure 5-16: Channel G Dimensions
The flow behavior in G is very similar to that in E (see Figure 5-17 above) since it is the same geometry. The flow readily enters the channel inlet, expanding and accelerating slightly over the inlet edge and maintaining flow in the direction of the channel. When the flow reaches the horizontal section wall it is not turned very sharply so the shock at the bottom of the channel is weak. There is no separation at the bottom of the channel, and the expansion around the turn at the top of the channel is strong enough to overcome the adverse pressure gradient formed by the shock on the lower side. The flow does not separate until the inside edge at the beginning of the arc section where a normal shock produces another region of adverse pressure gradient. The flow is able to reattach before the channel exit, and the exiting flow joins the freestream and slows the flow over the boattail surface. The pressure contours in Figure 5-18 support the flow pattern revealed by the vector plot above.
5.4.2 Performance Comparison: E and G

Table 5-3: Moment Coefficient Results; Baseline, Channel E, Channel G

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>Channel E</th>
<th>Channel G</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw</td>
<td>-4.973e-2</td>
<td>-4.388e-2</td>
<td>-11.76%</td>
</tr>
<tr>
<td>Pitch</td>
<td>2.298e-2</td>
<td>2.742e-2</td>
<td>19.36%</td>
</tr>
<tr>
<td>Roll</td>
<td>1.240e-3</td>
<td>1.331e-3</td>
<td>7.34%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2311988</td>
<td>2707366</td>
<td></td>
</tr>
</tbody>
</table>

The moment results for channels E and G are summarized in Table 5-3 above. In comparing channel E to channel G there are slight differences in the predicted separation zones within the channel. The differences do not appear to have a large effect on the overall performance of the channel. The increase in pitching moment for channel G can most likely be attributed to the longer moment arm resulting from channel axial location.
In comparison to the torus channels, the performance of Channels D, E, F and G is notably better. Each of the channels possesses a shallower entrance angle compared with the initial torus design. The velocity distribution shows that the modified design results in a more favorable entrance condition and subsequently significantly higher air flow. Supersonic flow is maintained over the straight portion of the passage. At the entrance to the curved portion, the flow slows down at the outer curvature and the relatively high turn angle results in a shock and a high pressure region at the wall. In comparison to the torus design, the pressure is altered over a much larger region.

5.5 Single Throat Nozzle Channel

One of the transpiration study concepts is to use the channel exit flow to cause flow separation over the boattail surface. If the exiting flow is supersonic, it will expand around the channel exit plane and accelerate over the boattail surface, contrary to the intended results. A supersonic diffuser is intended to choke the supersonic channel flow and decelerate it further, maintaining subsonic flow at the channel exit. The design of a supersonic diffuser is, however, not trivial in this situation where the flow is three-dimensional and contains tight turns. For the current study a rough design is obtained according to one-dimensional analysis; the area ratios across the converging and diverging sections follow the isentropic throat area ratio equation dependent upon flow Mach number and gamma (Equation 5-1).
\[
\frac{A^*}{A} = M \left( \frac{\gamma + 1}{2} \frac{\left( \frac{1}{\gamma - 1} \right)}{1 + \frac{\gamma - 1}{2} M^2} \right)
\]

**Equation 5-1**

5.5.1 Channel H

The channel H is evolved from the earlier channels by adding a convergent-divergent section before the circular arc exit (Figure 5-19). The exit radius (1 in) is chosen so that the hole does not cover more than half of the boattail surface. The throat is calculated for an exit Mach number of 0.29. The inlet radius is chosen to be consistent with the earlier channels (1.2 in.), which, by area ratios, calls for Mach 2.65 at the inlet.

![Figure 5-19: Channel H Dimensions](image)
The design Mach number at the inlet of the nozzle section is less than that of the freestream flow. Figure 5-20 above shows that this causes an adverse pressure gradient from the freestream flow to the channel inlet. Separation occurs at the leading edge of the channel inlet and does not reattach until after the turn to the horizontal section. The flow is choked through this effective inlet area and becomes subsonic until accelerating through the convergent section to the throat. The flow chokes at the throat and accelerates through the following divergent section. A normal shock slows the flow to subsonic speeds and it continues smoothly through the arc section to the exit. The pressure contours in Figure 5-21 support the vector plot above.
The inlet radius of channel H is increased to 1.75 in for channel I to increase the inlet Mach number to 3.5. The remaining dimensions are unchanged from the H configuration (Figure 5-22).

Figure 5-22: Channel I Dimensions
The design Mach number at the inlet section is again less than that of the freestream flow. Figure 5-23 above shows that similar behavior to that seen in channel H is repeated by channel I. The adverse pressure gradient from the freestream flow to the channel inlet causes separation at the leading edge of the channel inlet that does not reattach until the convergent section of the nozzle. The flow is choked through this effective inlet area and becomes subsonic until accelerating through the convergent section to the throat. The flow chokes at the throat and accelerates through the following divergent section. A normal shock slows the flow to subsonic speeds and it continues smoothly through the arc section to the exit. The pressure contours in Figure 5-24 support the vector plot above.
5.5.3 Channel J

The inlet to the channel is declined 20 degrees. A flow speed of Mach 4 is assumed
approaching the turn. Using the turn angle and Mach angle at this speed, a new speed of
Mach 6.1 is calculated after the turn. The x-component of this Mach (5.7) is used with
the channel I inlet radius (1.75 in) to calculate the throat radius and an exit radius of 1 in
defines the flow speed at the channel exit (Figure 5-25).

Figure 5-24: Contours of Static Pressure: Channel I

Figure 5-25: Channel J Dimensions
Flow naturally follows a favorable pressure gradient. Since trying to slow supersonic flow through a convergent nozzle presents an adverse pressure gradient, the field stabilizes with a subsonic speed before the convergent section, as shown in Figure 5-26 above. This allows for a favorable pressure gradient as the flow accelerates to the throat. The subsonic inlet speed again produces an adverse pressure gradient and separation at the inlet. The very large area ratio between the inlet and throat calls for very slow velocities entering the convergent section, contributing to the swirling seen at the entrance to the nozzle. The pressure contours in Figure 5-27 support the vector plot above.
Figure 5-27: Contours of Static Pressure: Channel J

5.5.4 Performance Comparison: H, I, and J

Table 5-4: Moment Coefficient Results; Baseline, Channel H, Channel I, Channel J

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>Channel H</th>
<th>Channel I</th>
<th>Channel J</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw</td>
<td>-3.290e-2</td>
<td>-3.529e-2</td>
<td>3.627e-2</td>
<td>7.28% H to I; 2.76% I to J</td>
</tr>
<tr>
<td>Pitch</td>
<td>7.430e-3</td>
<td>1.171e-2</td>
<td>-4.914e-3</td>
<td>57.66% H to I; -58.05% I to J</td>
</tr>
<tr>
<td>Roll</td>
<td>-7.533e-4</td>
<td>5.917e-5</td>
<td>-3.720e-4</td>
<td>-107.85% H to I; 528.65% I to J</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2545552</td>
<td>2702364</td>
<td>2738235</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-4 shows that all three channels produce a nose up pitching moment and nose left yawing moment which is indicative of regions of high pressure in the channels. The channels produce comparable performance results to each other; however, they do not perform as well as prior, simpler channels. For this reason, the single throat nozzle is not investigated further.
5.6 Single Channel vs. Three Adjacent Channels vs. a Slot Channel

The comparison between three separate circular channels and one slotted channel is intended to compare a more versatile design (three channels) to a simpler one (slot). There is roughly the same cross sectional area between the two designs. Included in this study is the effect of the number of channels to bridge the gap between earlier single channel designs and the eventual multiple-channel configuration.

5.6.1 Channel K1

A shallower channel design than seen thus far is required in order to put three channels adjacent to each other circumferentially (Figure 5-28). The shape is chosen to be simple but proven effective in earlier results. There is a 20 degree decline from horizontal inlet section followed by a circular arc to the exit on the boattail surface. The perimeter of the channel exit is tangent to the leading edge of the boattail surface to maximize downstream surface area.

Figure 5-28: Channel K Dimensions
From Figure 5-29 above, the flow entering the channel makes a smooth turn from the freestream, expanding slightly over the upstream edge and slowing at the turn forced by the downstream edge wall. The flow maintains supersonic velocities in the direction of the channel until reaching the circular arc. At the bottom of the channel there is a shock where the flow is turned by the wall. The adverse pressure gradient caused by the shock initializes separation at the top and bottom of the channel which propagates upstream until stabilizing at the beginning of the arc section. The flow on the bottom of the channel reattaches shortly downstream while the top maintains its separation, both due to the wall turning. The channel flow meets the freestream flow at the channel exit. There is a small expansion over the downstream edge of the channel exit but the majority of the flow over the boattail is slowed by the exiting channel flow. The pressure contours in Figure 5-30 support the vector plot above.
5.6.2 Channel K

The multiple channel design is comprised of three adjacent channels identical to the single K1 channel. The center channel is situated with its centerline along a plane 45 degrees from horizontal (xz plane), centered between two fins as the other channel designs are. The two additional channels are located at planes inclined 22.5 degrees and 67.5 degrees from horizontal to flank the center one evenly (Figure 5-31).
Figure 5-32: Vectors of Velocity Colored by Mach Number: Channel K, 22.5 Deg., Vectors Scaled x5

Figure 5-33: Vectors of Velocity Colored by Mach Number: Channel K, 45 Deg., Vectors Scaled x5
Figure 5-34: Vectors of Velocity Colored by Mach Number: Channel K, 67.5 Deg., Vectors Scaled x5

Figure 5-32 through Figure 5-34 show cross sections at three different azimuthal positions, each through the center of one of the three channels. The flow entering the channels again makes a smooth turn from the freestream, expanding slightly over the upstream edge and slowing at the turn forced by the downstream edge wall. The flow maintains supersonic velocities in the direction of the channel until reaching the circular arc. At the bottom of the channel there is a shock where the flow is turned by the wall. This adverse pressure gradient caused by the shock initializes separation at the top of the channel which propagates upstream until stabilizing at the beginning of the arc section. This recirculation area effectively decreases the area, slowing the main flow through the channel until the exit plane. The channel flow meets the freestream flow at the channel exit. There is a small expansion over the downstream edge of the channel exit but the majority of the flow over the boattail is significantly slowed by the exiting channel flow. All three channels show the same behavior. The region immediately behind the channels experiences the slowest flow, but the affected region expands circumferentially just past
the fin on either side of the channels. The pressure contours in Figure 5-35 through Figure 5-37 support the data from the vector plot above.

Figure 5-35: Contours of Static Pressure: Channel K, 22.5 Deg.

Figure 5-36: Contours of Static Pressure: Channel K, 45 Deg.
5.6.3 Channel L

The slot design of channel L is derived from the channel K configuration (Figure 5-38). The axial channel cross-section dimensions are consistent between the two. Channel L, however, is not simply channel K with the material between channels removed. The process for constructing the two configurations in the solid modeling program is different, resulting in slight differences between the two. The channel K is constructed by sweeping the round channel cross-section along the axial path of the channel, keeping the circle center point on a plane inclined from horizontal about the missile centerline. The channel L is constructed by rotating the axial cross-section around the centerline and chamfering the left and right end-faces to create half circle sides (Figure 5-39). In this scenario, the left and right bounding points are along the same plane, instead of the center of the arc. In both cases the circumferential maximum distance between the left and right channel faces changes along the axial direction. The channels ‘fan out’ from each other with the narrowest point at the deepest part of the channel.
Figure 5-38: Channel L Dimensions

Figure 5-39: Channel L Sections
Figure 5-40: Vectors of Velocity Colored by Mach Number: Channel L, 22.5 Deg., Vectors Scaled x5

Figure 5-41: Vectors of Velocity Colored by Mach Number: Channel L, 45 Deg., Vectors Scaled x5
The flow behavior seen in L is consistent with that seen in K (see Figure 5-40 through Figure 5-42 above). Since channel L has a greater area (normal to flow direction), higher flow speeds are attained in the circular arc section than is seen in the constricted circular channel flow. The effects over the boattail are slightly different as well. The slow flow seen behind the separate channels in K is not quite as slow in L but extends across the circumferential width of the channel. The overall affect is also seen circumferentially just beyond the bounding fins. The pressure contours in Figure 5-43 through Figure 5-45 support the vector plot above.
Figure 5-43: Contours of Static Pressure: Channel L, 22.5 Deg.

Figure 5-44: Contours of Static Pressure: Channel L, 45 Deg.
The moment results for channels K1, K and L are summarized in Table 5-5 above. The channels and slot are located in the y-positive z-positive quadrant. The high pressure regions created by the channels cause a negative moment in the z-direction, which corresponds to pitch nose up, and positive moment in the y-direction, corresponding to yaw nose left (see Table 5-5). Increasing the single K channel to three K channels increases but does not triple the magnitude of the moments. The pitch moment created by the slot L more than doubles that of channels K. The yaw moment created by the slot
L is 40% greater than that of channels K. The large advantage of the slot L is credited to higher pressures on the inside wall of the channel rather than its influence over the boattail surface. The K configuration actually produces higher pressures on the boattail surface but this is a smaller area than the channel wall. The higher pressure in the slot L is due to the decrease in cross sectional area as the depth of the slot increases. At supersonic conditions this slows the flow and increases the local static pressure.

Alternately, the cross section of the three channels is a circle swept along a declined then arced path; the area does not change with change in channel depth but is constant on planes normal to flow direction. The pressure is also seen to increase on the channel wall in the arc exit region. This pressure is resultant from turning the flow as is common to pipe flow.

5.7 Two Throat Nozzle System Channel

The concept for two throats follows the approach used in a transonic or supersonic wind tunnel. For the wind tunnel, the incoming flow is subsonic and the first convergent section accelerates the flow to the first throat where it is choked. The following divergent section continues to accelerate the flow at supersonic speeds until the cross-sectional area, and thus speed, is held constant through the test section. The second convergent section decelerates the supersonic flow but the second throat is larger than the first throat. This is to allow sufficient flow through the channel even with the strongest possible shock between the first and second throats. The second divergent section again accelerates the still supersonic flow but the fluid is brought to subsonic speeds across a normal shock. The area ratios across the converging and diverging sections are designed
according to the isentropic throat area ratio equation dependent upon flow Mach number and gamma (Equation 5-1).

5.7.1 Channel M

The 20 degree decline straight inlet section from previous channel designs is maintained in channel M. The inlet Mach number (0.6) and radius (0.75 in) are design choices for calculating the throat radius. The supersonic section Mach number (2) is chosen to calculate the radius of such, and the Mach number (1.3) at the second throat is chosen to calculate its radius. The exit radius (1 in.) is chosen as a balance between minimizing the channel area on the boattail surface and sufficiently slowing the flow. The Mach number at the end of the second divergent section and flow velocity after the normal shock are calculated. Axial distances are chosen to produce cone angles for well behaving flow defined in textbooks from empirical data.

Channel M proved to be difficult to simulate properly in CFD. Channels N and O converged before channel M, and their results led to abandoning efforts towards channel M.

5.7.2 Channel N

The design theory applied to channel M is consistent for channel N. The design Mach numbers are however different to require greater area ratios between adjacent sections. This helps to decrease the effects of errors from using geometric areas instead of effective areas caused by boundary layers in the area ratio calculations.
Figure 5-46: Vectors of Velocity Colored by Mach Number: Channel N, Vectors Scaled x3

Figure 5-46 above shows that the inlet area is closed down by separated flow in the declined section. The separation is forced by downstream cross-sectional areas that control the mass flow. The incoming flow slows significantly as it expands past the recirculation and approaches the first throat at subsonic speed. The convergence and following divergence of the channel wall accelerates the flow to sonic speeds at the throat and decelerates the flow back to subsonic speeds through the constant area section to the second throat. The flow again accelerates with the curvature of the channel wall through the second nozzle section where a shock slows the flow at the beginning of the exit arc. A small separated region is caused by the turning of the wall at the inside radius of the arc. As seen in the other designs there is a small expansion over the downstream edge of the channel exit but the majority of the flow over the boattail is significantly slowed by the exiting channel flow. The pressure contours in Figure 5-47 support the vector plot above.
Channel O maintains the same area ratios and axial distances as channel N; however, since the inlet is a shallower 10 degree decline it does not extend as deep into the missile, and the exit is a straight 10 degree incline instead of a circular arc. The intent is to compare a shallow straight exit to the arc sections used previously. The shallower exit section forces a shallower channel overall (a comparable axial distance is desired) causing two design changes from channel N. The shallower channel will create forces at a longer distance from missile centerline to increase the magnitude of the moment on the body while the straight incline exit section may not experience the wall forces seen when turning the flow.
Figure 5-48: Vectors of Velocity colored by Mach Number: Channel O, Vectors Scaled x2

Figure 5-48 shows that channel O behaves similarly to channel N from the inlet to the second throat. The inlet area is closed down by separated flow forced by downstream cross-sectional areas that control the massflow. The incoming flow slows significantly as it expands past the recirculation and approaches the first throat at subsonic speed. The flow accelerates and decelerates back to subsonic speeds through the first throat and maintains speed through the constant area section. The flow again accelerates with the curvature of the channel wall through the second nozzle section but unlike in channel N, no shock occurs past the second throat. The flow exits the channel at supersonic speeds and smoothly joins the freestream over the boattail. The flow speed over the boattail downstream of the channel exit is close to that of the flow exiting the channel, which is significantly slower than the flow speed over the opposing side of the boattail. The pressure contours in Figure 5-49 support the vector plot above.
5.7.4 Performance Comparison: M, N, and O

Table 5-6: Moment Coefficient Results; Baseline, Channel M, Channel N, Channel O

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>Channel N</th>
<th>Channel O</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw</td>
<td>-2.000e-2</td>
<td>-2.921e-2</td>
<td>46.07%</td>
</tr>
<tr>
<td>Pitch</td>
<td>1.184e-2</td>
<td>1.371e-2</td>
<td>15.78%</td>
</tr>
<tr>
<td>Roll</td>
<td>-6.293e-4</td>
<td>-3.515e-4</td>
<td>-44.15%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2710215</td>
<td>2710969</td>
<td></td>
</tr>
</tbody>
</table>

The moment results for channels N and O are summarized in Table 5-6 above. The two throat nozzle channels do effectively change the flow characteristics over the boattail section of the missile, as well as produce forces on the channel walls from internal channel pressures. The different configurations perform comparably well with each other, but like the single throat nozzles, do not provide any performance advantage to offset the cost and difficulty of production associated with the complicated geometry.
The simpler designs have shown larger moment results eliminating the need to investigate further the two throat nozzle approach.

5.8 Note on Moment Asymmetries

A rather important observation that has not been addressed is the asymmetry between the pitch and yaw forces. The channel is located at 45 degrees (centered between tailfins), however, the pitch and yaw moments are not identical. This can be attributed to the asymmetry of the mesh. In the case of the mesh, the forces are calculated by summing the pressure and viscous forces on the wall zone, and unequal numbers of grid points on opposing sides of the missile result in phantom forces. The exact magnitudes of moments induced by each channel is not necessarily as important as the flow behavior observed, and the errors within the mesh are assumed to be smaller than the moment differences between geometries. The mesh symmetry is addressed in all following simulations.

5.9 Channel Geometry Downselect

The previous simulations compare performance among considerably different channel geometries. From these results, the channel G shape is chosen as the best performing shape and is carried forward for further studies. This G channel shape is slightly modified and renamed A, the baseline channel shape. Channel A can be seen in Figure 5-50 below.
Instead of running a single channel to analyze the flowfield, the following studies compare specific channel operating conditions, i.e. pitch configuration and roll configuration. Initially, two channels, one on each side of the top fin, are used for the pitch configuration and four channels, one on the same side of each fin, are used for the roll configuration. These geometries inhibited the mesh symmetry for the tail section of the mesh. Initially the tail sections were only yaw symmetric for the pitch configuration and completely non-symmetric for the roll configurations. Repeating the simulation on one of the roll configurations with a new, rotated mesh showed much better results of the pitch and yaw moments (closer to zero). The Table 5-7 below summarizes the moment results seen for the same geometry simulated with two different meshes; one is yaw symmetric at the tail section, one is rotated around the missile centerline.

Figure 5-50: Baseline A Channel for Parametric Studies (all dimensions in inches or degrees)
Table 5-7: Moment Coefficient Results; Mesh Comparison of Four Channel Roll Configurations

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>Yaw Symmetric Mesh</th>
<th>Roll Symmetric Mesh</th>
<th>Percent Difference</th>
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</thead>
<tbody>
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<td>Yaw</td>
<td>-1.081e-3</td>
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<td>-100.29%</td>
</tr>
<tr>
<td>Pitch</td>
<td>7.747e-5</td>
<td>2.850e-6</td>
<td>-96.32%</td>
</tr>
<tr>
<td>Roll</td>
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<td>16.15%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2462039</td>
<td>2440856</td>
<td></td>
</tr>
</tbody>
</table>

5.10 Numerical Model

Since the pitch and roll configurations affect the mesh symmetry, the parametric studies are conducted on configurations closer to the assumed final configuration. All cases have eight channels, one located on each side of each fin. The channels sweep along planes parallel to the planes of the fins (xy and xz planes) and the channel centerline is shifted 1.75 inches from the centerline of the fins. The configurations for pitch and roll controls are displayed in Figure 5-51. For the pitch configuration, the top two channels are left open and the remaining six channels are blocked with a wall at the end of the horizontal section of the channel, similar to the valve to be used for channel deployment. The roll configuration consists of one channel on the same side of each fin left open and the remaining four closed.
Figure 5-51: Control Channel Locations
The computational domain blocks used can be seen in Figure 5-52 below. The method for meshing is as follows:

- The mesh is divided into 16 blocks.
- The front of the domain, from the inlet extending to 1 inch upstream of the tailfins, has four blocks reflected across pitch and yaw planes.
- The center of the domain, from 1 inch upstream of the tailfins through most of the wake region behind the missile to 100 inches downstream of the missile, has eight blocks reflected across the pitch and yaw planes and also the 45 degree planes in between (there are 8 pie pieces from the yz cross sectional view).
- The back of the domain has four blocks with the same symmetry as the front
Figure 5-52: Grid blocks; example of mesh symmetry
For each parametric study, the front and back of the domains remain unchanged and the respective meshes are identical from run to run. The center section has one channel in each of the eight blocks and the meshes are identical between blocks (the geometry and the mesh are reflected). This ensures that the entire mesh is symmetric along planes of interest and will not interfere with the desired moments.

The boundary conditions and operating conditions are consistent with the previous geometry investigation simulations, as summarized in Table 4-1.

5.11 Baseline

There are three channel conditions being considered as the baseline: (1) no channels, (2) all eight channels open, and (3) all eight channels closed. The baseline A channel from Figure 5-50 is used for these simulations. The open and closed conditions are used to determine the lowest drag option for the nominal operation point (i.e. no control moment). The baseline results are summarized in Table 5-8 and Figure 5-53 through Figure 5-56 below.

<table>
<thead>
<tr>
<th>Force Coefficient</th>
<th>No Channels</th>
<th>8 Channels Open</th>
<th>8 Channels Closed</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drag</td>
<td>0.320</td>
<td>0.341</td>
<td>0.309</td>
<td>6.65%; -9.38%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2037180</td>
<td>2905276</td>
<td>2905276</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5-53: Vectors of Velocity Colored by Mach Number: Channel A, 8 Channels Open, Vectors Scaled x3

Figure 5-54: Contours of Static Pressure: Channel A, 8 Channels Open
The result shows that the nominal operating condition is to close all eight channels for the lowest drag. The flow field results show that high pressure regions in the turning section of the open channels result in larger drag than the closed channels, which show lower pressures in that same turning section.
5.12 Geometric Parameter Studies

To further optimize the baseline channel A geometry, studies are conducted on the following geometric parameters:

- Circumferential Location
- Inlet and Outlet Location (Channel Length)
- Inlet and Outlet Angles
- Channel Cross-Sectional Area

The ‘two open channel’ pitch configuration is the comparison point for the parametric studies, all of which are simulated with the top two channels open for pitch nose up.

5.12.1 Circumferential Location

The circumferential location for this study refers to the distance of the channel centerline from the fin centerline. The missile geometry and the channel depth define the boundaries for possible circumferential location. The baseline distance is 1.75 inches. This value is increased to 2.25 inches, or from 8.75% of the missile diameter to 11.25% of the diameter. Table 5-9 below summarizes the results.

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>Baseline Pitch, 1.75 inches</th>
<th>2.25 inches</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitching</td>
<td>4.375e-2</td>
<td>4.476e-2</td>
<td>2.33%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2905276</td>
<td>2868724</td>
<td></td>
</tr>
</tbody>
</table>

The channel effectiveness does not appear to be very sensitive to the circumferential location of the channel. Since the geometry confined boundary mentioned above is not
very large, this is not a parameter from which large performance changes can be obtained.

5.12.2 Inlet and Outlet Location

The inlet location, which refers to its axial location along the missile body, is addressed first. The horizontal section of the channel is extended three inches to shift the inlet location three inches upstream. All of the other geometry remains unchanged. Table 5-10 below summarizes the results.

<table>
<thead>
<tr>
<th>Table 5-10: Moment Coefficient Results; Inlet Axial Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment Coefficient</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Pitching</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
</tr>
</tbody>
</table>

The exit location is shifted axially downstream by lengthening the horizontal section of the channel, this time by only one inch due to the limited boattail surface area available. The results are summarized in Table 5-11 below.

<table>
<thead>
<tr>
<th>Table 5-11: Moment Coefficient Results; Exit Axial Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment Coefficient</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Pitching</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
</tr>
</tbody>
</table>

Again, the channel effectiveness does not appear to be very sensitive to the axial location of the inlet or outlet of the channel. While there is a considerable amount of available space to move the inlet upstream, extending the channel by almost 15% afforded no
appreciable advantage. Implementing longer channels introduces more manufacturing and integration challenges than can be offset by minor performance improvements. Moving the exit downstream worsens the channel performance. The original design channel outlet is therefore located as far upstream as possible to maintain transpiration effects.

5.12.3 Inlet and Outlet Angles

The inlet angle refers to the angle of the axis of the inlet section relative to the free-stream. This angle is changed to 18 degrees while the axial length of the inlet section remains the same. The channel is thus shallower than the original through the horizontal section, and the horizontal section meets with the exit arc farther downstream to preserve the original arc geometry and location. Table 5-12 below summarizes the results.

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>Baseline, Pitch</th>
<th>18 Deg. Inlet Angle, Pitch</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitching</td>
<td>4.375e-2</td>
<td>4.663e-2</td>
<td>6.59%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2905276</td>
<td>2862784</td>
<td></td>
</tr>
</tbody>
</table>

The outlet section of the channel is a circular arc. To vary the outlet angle, the radius of this arc is increased by roughly 50%. The location of the outlet and all other channel geometry is maintained from the original channel geometry. The results are summarized in Table 5-13 below.
Table 5-13: Moment Coefficient Results; Outlet Angle

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>Baseline, Pitch</th>
<th>Increased Arc Radius, Pitch</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>4.375e-2</td>
<td>3.618e-2</td>
<td>-17.29%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2905276</td>
<td>2865852</td>
<td></td>
</tr>
</tbody>
</table>

The adjustments made to the inlet angle produce small changes while the changes made to the outlet angles produce negative results. It could be worth investigating exit angle changes in the opposite direction of those studied here to possibly find positive results. Reducing the radius of the outlet section will decrease the wall surface area where high pressure is seen, possibly reducing the control moment.

5.12.4 Channel Cross-Sectional Area

The channel has a constant circular cross section swept along the channel path. The diameter of the cross section is increased by 25% while maintaining the location of the channel centerline. Table 5-14 below summarizes the results.

Table 5-14: Moment Coefficient Results; Channel Cross-Sectional Area

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Baseline, Pitch</th>
<th>Increased Channel Diameter, Pitch</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitching moment</td>
<td>4.375e-2</td>
<td>6.577e-2</td>
<td>50.34%</td>
</tr>
<tr>
<td>Drag</td>
<td>3.170e-1</td>
<td>3.168e-1</td>
<td>-0.06%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2905276</td>
<td>2947444</td>
<td></td>
</tr>
</tbody>
</table>

Of all of the parameters investigated, increasing the diameter of the channel cross-section produces the largest effect on pitching moment and, surprisingly, little effect on drag. This parameter has limits defined by the area of the boattail surface and the available
channel depth constrained by internal hardware. However, as can be seen here, relatively small changes result in large performance differences.

The goal of the geometric parameter studies is to identify a best performing geometry to conduct further studies on flight parameters. The channel diameter has the largest impact on channel performance with little-to-no impact on drag; hence the larger diameter channel is simulated henceforth.

5.13 Flight Parameter Studies

All previous simulations have been conducted at the primary trajectory cruise operating point. Only one control option was implemented, i.e. pitch control from opening the top two channels. There are, however, other operating conditions of interest. The flight parameters under consideration include:

- Four Channel Pitch Control
- Mach Number
- Angle-of-attack
- Yaw and Roll Control

These simulations are performed on the large diameter variation of channel A. Results from the first operating condition investigation determine the largest control magnitude four channel pitch configuration, which is then used for the remainder of investigations. The primary cruise, as stated previously, is Mach 4 and zero degrees AOA. All $\Delta C_m$ values reference the ‘8-channels closed’ nominal operating condition.
5.13.1 Four Channel Pitch Control

The first to be simulated is a four open channel pitch configuration to determine which channels surrounding the pitch fins add to the desired pitching moment. The top four channels are left open for the first simulation, while the top two and two under the pitch fins are left open for the second. The results are summarized in Table 5-15 and Figure 5-57 through Figure 5-59 below.

![Diagram](image)

- Open valve
- Closed valve

**Table 5-15: Moment Coefficient Results; Two Channel Pitch versus Four Channel Pitch**

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>Top Two Channels Open, Pitch</th>
<th>Top Four Channels Open, Pitch</th>
<th>Top Two Channels and Two Channels Under Pitch Fin Open, Pitch</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>4.375e-2</td>
<td>1.072e-2</td>
<td>7.720e-2</td>
<td>-75.51%; 76.48%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2905276</td>
<td>2905276</td>
<td>2905276</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5-57: Contours of Static Pressure, Missile Surface: Channel A, Top 2 Channels Open for Pitch

Figure 5-58: Contours of Static Pressure, Missile Surface: Channel A, Top 4 Channels Open for Pitch
The results show that the largest pitching moment is achieved by opening the top two channels and the two channels directly below the pitch fins, as opposed to opening the top four channels. Lower pressures are seen on the side of the fin adjacent to the open channel. Opening the channels under the fins removes flow from the freestream causing the flow under the fin to accelerate. This results in low pressure under the pitch fin and a downward force supporting the nose up pitch. This configuration, with the top two channels and two channels under the pitch fins open, is implemented for the following simulations.

5.13.2 Mach Number

Since the missile is not operating at the maximum designed Mach number at all time, additional simulations are run at a lower supersonic velocity and a subsonic velocity. The results are summarized in Table 5-16 and Figure 5-60 below.
Table 5-16: Moment Coefficient Results; Large Diameter Channel, Four Channel Pitch, Mach Variation

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>Mach 4</th>
<th>Mach 2.5</th>
<th>Mach 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>1.121e-1</td>
<td>2.324e-1</td>
<td>1.115</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2947444</td>
<td>2947444</td>
<td>2947444</td>
</tr>
</tbody>
</table>

Figure 5-60: Delta Pitching Moment vs. Mach Number for Channels in Pitch Configuration

The magnitude of the $\Delta C_m$ decreases as the freestream flow speed increases. This is due to the faster increase in the magnitude of free-stream dynamic pressure than control moment. The channels produce the intended results at all flow speeds.

5.13.3 Angle-of-attack

All prior simulations are run at zero degrees angle of attack. To investigate other possible operating conditions, both the baseline eight closed large diameter channels configuration and the four large diameter channels pitch configuration are run at 5
degrees AOA and –5 degrees AOA. The results are summarized in Table 5-17, Table 5-18, Figure 5-61, and Figure 5-62 below.

Table 5-17: Moment Coefficient Results; Large Diameter Channel Baseline, Eight Channels Closed, AOA Variation

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>-5 Degrees</th>
<th>0 Degrees</th>
<th>5 Degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>4.266e-1</td>
<td>N/A</td>
<td>-4.258e-1</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2905276</td>
<td>2905276</td>
<td>2905276</td>
</tr>
</tbody>
</table>

Table 5-18: Moment Coefficient Results; Large Diameter Channel, Four Channel Pitch, AOA Variation

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>-5 Degrees</th>
<th>0 Degrees</th>
<th>5 Degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>5.618e-1</td>
<td>1.121e-1</td>
<td>-3.320e-1</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2947444</td>
<td>2947444</td>
<td>2947444</td>
</tr>
</tbody>
</table>

Figure 5-61: Pitching Moment Coefficient vs. AOA for Baseline Channels Closed Configurations
Figure 5-62: Delta Pitching Moment Coefficient vs. AOA for Pitch Configuration

In the baseline configuration, the negative pitch moment (nose down) for 5 degrees AOA and the positive pitch moment (nose up) for –5 degrees AOA indicate an aerodynamically stable configuration. For the pitch configuration, the channels produce the intended nose up pitch moment through the range of -5 to 0 degrees. The magnitude of the moment decreases as AOA increases (Table 5-18) since the aerodynamically stable baseline missile produces nose up pitching moment at negative AOA (works with channels) and nose down pitching moment at positive AOA (works against channels). The $\Delta C_{\text{in}}$ is less at positive AOA than at negative AOA because the top two channels are not as effective at positive AOA since the missile body interferes with the flow into the channels (Figure 5-62).

In addition to pitch control, the four channels yaw configurations (pitch channel configuration rotated 90 degrees for yaw) and four channels roll are run at 5 degrees AOA and –5 degrees AOA. The yaw results can be found in Table 5-19 and Figure 5-63.
through Figure 5-65 below. The roll results can be found in Table 5-20 and Figure 5-66 through Figure 5-68 below.

Table 5-19: Moment Coefficient Results; Large Diameter Channel, Four Channel Yaw, AOA Variation

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>-5 Degrees</th>
<th>0 Degrees</th>
<th>5 Degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yawing</td>
<td>1.024e-1</td>
<td>1.146e-1</td>
<td>1.030e-1</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2947444</td>
<td>2947444</td>
<td>2947444</td>
</tr>
</tbody>
</table>

Figure 5-63: Yawing Moment Coefficient vs. AOA for Yaw Configuration

Figure 5-64: Delta Pitching Moment Coefficient vs. AOA for Yaw Configuration
Figure 5-65: Delta Rolling Moment Coefficient vs. AOA for Yaw Configuration

The magnitude of the yaw moment is lower at AOA (both positive and negative) than during level flight. Small $\Delta C_m$ and $\Delta C_l$ (relative to baseline closed channel configuration) are generated at non-zero angles of attack. The attitude of the missile affects the flow into, through, and around the channels, thus influencing the magnitude of the resulting moments, similarly for positive and negative AOA.

Table 5-20: Moment Coefficient Results; Large Diameter Channel, Four Channel Roll, AOA Variation

<table>
<thead>
<tr>
<th>Moment Coefficient</th>
<th>-5 Degrees</th>
<th>0 Degrees</th>
<th>5 Degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling</td>
<td>1.284e-2</td>
<td>1.210e-2</td>
<td>1.279e-2</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2947444</td>
<td>2947444</td>
<td>2947444</td>
</tr>
</tbody>
</table>
Figure 5-66: Rolling Moment Coefficient vs. AOA for Roll Configuration

Figure 5-67: Delta Pitching Moment vs. AOA for Roll Configuration
The magnitude of the roll moment is greater at AOA (both positive and negative) than at level flight. Small $\Delta C_m$ and $\Delta C_n$ (relative to baseline closed channel configuration) are generated at non-zero angles of attack. The attitude of the missile affects the flow into, through, and around the channels, thus influencing the magnitude of the resulting moments, similarly for positive and negative AOA.

Figure 5-68: Delta Yawing Moment Coefficient vs. AOA for Roll Configuration
Chapter 6

6 Spoilers

Using transpiration channels as a means of attitude control is a relatively new research topic; alternatively, spoilers have been used for attitude control for quite some time. The following simulations provide a reference point for comparing the effectiveness of the transpiration channels to the spoilers.

6.1 Numerical Model

The mesh for the spoiler simulations is identical to the grid blocks used in the 8 channel simulations in all regions besides the eight blocks surrounding the tail of the missile (see Figure 5-52). Just as those blocks changed between channel configurations, they are changed for each different spoiler size. The grids are, however, identical between the pitch and roll configurations. All eight spoilers are present geometrically in the mesh so that the eight grid blocks are symmetric. To run specific spoiler configurations, the desired spoilers are set to a wall boundary condition while the rest are left as interior fluid surfaces that do not affect the flow.
Figure 6-1: Spoiler Dimensions

The drawings shown in Figure 6-1 only include one spoiler. The number and location of spoilers present in the simulations depends on the body moment required. The possible locations are similar to the transpiration channels (Figure 5-51); pitch up has four
spoilers, two between each set of fins on the upper half of the missile (different from the channels which open only two channels for pitch, unless otherwise specified), while roll has four spoilers, each on the same side of each fin.

The boundary conditions and operating conditions are consistent with the previous channel investigation simulations, summarized in Table 4-1.

6.2 Baseline

The baseline configuration for these studies is the baseline missile (body, wings and tail fins) and does not contain any spoilers. Since the body moments for this configuration are trivial, presented in Table 6-1 below is the drag result that will be compared with the drag results with spoilers.

<table>
<thead>
<tr>
<th>Table 6-1: Force Coefficient Results; Spoiler Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Force Coefficient</strong></td>
</tr>
<tr>
<td>Drag</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
</tr>
</tbody>
</table>

6.3 Spoiler Height

The dimensions of the spoiler are presented in Figure 6-1. The effect of the spoiler height is the focus of these studies. The span and thickness are held constant between designs and only the radial height changes. The smallest spoiler size is represented in the dimensioned drawing in Fig. 70. The two additional heights simulated are 0.75 in and 1.00 in.
The first result to note is the pitching and rolling moments induced by the presence of the spoilers, and the second is the drag. These values are first compared to the baseline configuration (no spoilers or channels) and then to the best performing channel configuration. These results are presented in Table 6-2 through Table 6-4.

**Table 6-2: Force and Moment Coefficient Results; 0.5 in. Spoiler and Transpiration Channels**

<table>
<thead>
<tr>
<th>Moment / Force Coefficient</th>
<th>Baseline</th>
<th>0.5 in Spoiler</th>
<th>Percent Difference</th>
<th>Transpiration Channels</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch (in Pitch Configuration)</td>
<td>N/A</td>
<td>1.624e-1</td>
<td>N/A</td>
<td>1.121e-1</td>
<td>44.83%</td>
</tr>
<tr>
<td>Drag in Pitch Configuration</td>
<td>3.208e-1</td>
<td>3.445e-1</td>
<td>7.39%</td>
<td>3.304e-1</td>
<td>4.27%</td>
</tr>
<tr>
<td>Roll (in Roll Configuration)</td>
<td>N/A</td>
<td>3.220e-5</td>
<td>N/A</td>
<td>-1.210e-2</td>
<td>-99.73%</td>
</tr>
<tr>
<td>Drag in Roll Configuration</td>
<td>3.208e-1</td>
<td>3.440e-1</td>
<td>7.23%</td>
<td>3.311e-1</td>
<td>3.90%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2597380</td>
<td>2838516</td>
<td>2947444</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 6-3: Force and Moment Coefficient Results; 0.75 in. Spoiler and Transpiration Channels**

<table>
<thead>
<tr>
<th>Moment / Force Coefficient</th>
<th>Baseline</th>
<th>0.75 in Spoiler</th>
<th>Percent Difference</th>
<th>Transpiration Channels</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch (in Pitch Configuration)</td>
<td>N/A</td>
<td>2.335e-1</td>
<td>N/A</td>
<td>1.121e-1</td>
<td>108.32%</td>
</tr>
<tr>
<td>Drag in Pitch Configuration</td>
<td>3.208e-1</td>
<td>3.588e-1</td>
<td>11.85%</td>
<td>3.304e-1</td>
<td>8.60%</td>
</tr>
<tr>
<td>Roll (in Roll Configuration)</td>
<td>N/A</td>
<td>8.103e-5</td>
<td>N/A</td>
<td>-1.210e-2</td>
<td>-99.33%</td>
</tr>
<tr>
<td>Drag in Roll Configuration</td>
<td>3.208e-1</td>
<td>3.573e-1</td>
<td>11-38%</td>
<td>3.311e-1</td>
<td>7.91%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2597380</td>
<td>2881100</td>
<td>2947444</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6-4: Force and Moment Coefficient Results; 1.0 in. Spoiler and Transpiration Channels

<table>
<thead>
<tr>
<th>Moment / Force Coefficient</th>
<th>Baseline</th>
<th>1 in Spoiler</th>
<th>Percent Difference</th>
<th>Transpiration Channels</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch (in Pitch Configuration)</td>
<td>N/A</td>
<td>3.066e-1</td>
<td>N/A</td>
<td>1.121e-1</td>
<td>168.07%</td>
</tr>
<tr>
<td>Drag in Pitch Configuration</td>
<td>3.208e-1</td>
<td>3.757e-1</td>
<td>17.11%</td>
<td>3.304e-1</td>
<td>13.71%</td>
</tr>
<tr>
<td>Roll (in Roll Configuration)</td>
<td>N/A</td>
<td>7.603e-5</td>
<td>N/A</td>
<td>-1.210e-2</td>
<td>-99.37%</td>
</tr>
<tr>
<td>Drag in Roll Configuration</td>
<td>3.208e-1</td>
<td>3.746e-1</td>
<td>16.77%</td>
<td>3.311e-1</td>
<td>13.14%</td>
</tr>
<tr>
<td>Mesh Cell Count</td>
<td>2597380</td>
<td>2931760</td>
<td></td>
<td>2947444</td>
<td></td>
</tr>
</tbody>
</table>

The spoilers clearly produce larger pitching moments as the size of the spoiler increases. All three chosen spoilers also produce a larger pitching moment than the best performing channel configuration, on the order of 42% greater for the 0.5 in. spoiler up to 170% for the 1 in. spoiler. The channels do, however, produce a larger rolling moment (about 2 orders of magnitude larger) and less drag than all of the chosen spoiler sizes, which potentially represent large advantages of transpiration channels over spoilers for attitude control.

6.4 Flight Parameter Studies

As with the first stages of the transpiration channel investigation, all previous spoiler simulations have been conducted at the primary trajectory cruise operating point. There are, however, other operating conditions of interest. The flight parameters under consideration include:

- Mach number
- Angle-of-attack
These simulations are performed on the largest height spoiler, with the top four spoilers deployed for pitch control. The primary cruise, as stated previously, is Mach 4 and zero degrees AOA. All $\Delta C_m$ values reference the ‘baseline no spoilers’ operating condition.

6.4.1 Mach Number

Since the missile will be operating at lower speeds than Mach 4, additional simulations are run at a lower supersonic velocity and a subsonic velocity. The results are summarized in Table 6-5 and Figure 6-2 below.

| Table 6-5: Moment Coefficient Results; Large Height Spoiler, Four Spoiler Pitch, Mach Variation |
|-----------------------------------------------|-----------------|-----------------|-----------------|
| Moment Coefficient | Mach 4 | Mach 2.5 | Mach 0.5 |
| Pitching | 3.066e-1 | 4.526e-1 | 3.082 |
| Mesh Cell Count | 2931760 | 2931760 | 2931760 |

Figure 6-2: Delta Pitching Moment vs. Mach Number for 4 Spoilers in Pitch Configuration
While magnitude of the produced moment decreases as the freestream flow speed decreases, the pitching moment coefficient increases. This means that the freestream dynamic pressure decreases faster than the magnitude of the moment as freestream Mach reduces. Nevertheless, the spoilers produce the intended results at all flow speeds.

6.4.2 Angle-of-attack

To investigate further possible flight conditions, both the baseline no-spoiler configuration and the four spoiler pitch configuration are run at 5 degrees AOA and –5 degrees AOA, as is done in the transpiration channel study. The results are summarized in Table 6-6, Table 6-7, Figure 6-3, and Figure 6-4 below.

| Table 6-6: Moment Coefficient Results; Spoiler Baseline, No Spoilers, AOA Variation |
|----------------------------------|-----------------|-----------------|-----------------|
| Moment Coefficient               | -5 Degrees      | 0 Degrees       | 5 Degrees       |
| Pitching                         | 4.154e-1        | N/A             | -4.154e-1       |
| Mesh Cell Count                  | 2597380         | 2597380         | 2597380         |

| Table 6-7: Moment Coefficient Results; Large Height Spoiler, Four Spoiler Pitch, AOA Variation |
|----------------------------------|-----------------|-----------------|-----------------|
| Moment Coefficient               | -5 Degrees      | 0 Degrees       | 5 Degrees       |
| Pitching                         | 7.844e-1        | 3.066e-1        | -1.655e-1       |
| Mesh Cell Count                  | 2931760         | 2931760         | 2931760         |
In the baseline no-spoiler case, a nose up attitude results in a nose down pitch and a nose down attitude results in a nose up pitch. This indicates an aerodynamically stable base configuration. The 4 spoiler pitch configuration repeats the behavior of the channels for the AOA study. The direction of the pitching moment remains nose-up throughout the
range from –5 to 0 degrees. The magnitude of the moment decreases as AOA increases since the aerodynamically stable baseline missile produces nose up pitching moment at negative AOA (works with spoilers) and nose down pitching moment at positive AOA (works against spoilers).
Chapter 7

7 Conclusions

The effectiveness of transpiration channels for attitude control of a high-speed missile has been studied. The purpose of the initial CFD investigation is to find the best geometric shape for each section of the transpiration channel. The results show that the entrance to the channel should be smooth without over-aggressively turning the flow for best flow ingestion. The channel should gently progress to the exit section to prevent separation and flow constriction. The results show that greater moments are produced by pressure on the inside walls of the channel than by surface pressure gradients generated on the boattail due to disruption of the channel exit flow. For this reason, an aggressive exit, such as the circular arc, is beneficial, as turning the flow produces forces on the channel walls and thus moments on the missile body.

The parametric studies explore the performance sensitivity of the channels to small adjustments to the optimized geometry found during the initial investigation. The results show that among those studied the only parameter to produce large performance differences is the channel cross-sectional diameter. This means that the amount of mass flow through the channel is more influential in determining the magnitude of the moment
produced than the subtle behaviors of the flow inside the channel (keeping in mind that the other modifications made did not severely alter the flow behavior in the channel).

The flight parameter studies look at the performance of the channels at different flight conditions than those used for during the initial study, namely different flow Mach number and missile AOAs. Changing the flow Mach number proves only to affect the magnitude of the moment that the channels produce, but does not inhibit their effectiveness. The channels also prove to work at different AOAs (within a small range) but moments produced by other components of the missile also factor into the missile behavior.

A small study on spoiler performance is conducted for comparison with the transpiration channel results. The spoiler studies reveal no new information to the field; larger spoilers produce greater attitude control moments along with greater drag. They are effective at different flow Mach numbers and AOAs, but as seen with the transpiration channels, moments produced by other components of the missile also factor into the missile behavior.
References


Appendix A

Parametric Study Plots

Figure A-1: Vectors of Velocity Colored by Mach Number: Channel A, 2.25 In., Vectors Scaled x3
Figure A-2: Contours of Static Pressure: Channel A, 2.25 In.

Figure A-3: Vectors of Velocity Colored by Mach Number: Channel A, Inlet Moved Upstream, Vectors Scaled x2
Figure A-4: Contours of Static Pressure: Channel A, Inlet Moved Upstream

Figure A-5: Vectors of Velocity Colored by Mach Number: Channel A, Inlet Moved Downstream, Vectors Scaled x3
Figure A-6: Contours of Static Pressure: Channel A, Inlet Moved Downstream

Figure A-7: Vectors of Velocity Colored by Mach Number: Channel A, 18 Degree Inlet Angle, Vectors Scaled x3
Figure A-8: Contours of Static Pressure: Channel A, 18 Degree Inlet Angle

Figure A-9: Vectors of Velocity Colored by Mach Number: Channel A, Increased Arc Radius,
Vectors Scaled x3
Figure A-10: Contours of Static Pressure: Channel A, Increased Arc Radius

Figure A-11: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, Vectors Scaled x3
Figure A-12: Contours of Static Pressure: Channel A, Increased Channel Diameter

Figure A-13: Contours of Static Pressure, Missile Surface: Channel A, Increased Channel Diameter, Top 2 Channels and 2 Channels Under Pitch Fins Open for Pitch
Figure A-14: Contours of Static Pressure, Missile Surface: Channel A, Increased Channel Diameter, Yaw Configuration

Figure A-15: Contours of Static Pressure, Missile Surface: Channel A, Increased Channel Diameter, Roll Configuration
Figure A-16: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, Mach 2.5, Vectors Scaled x10

Figure A-17: Contours of Static Pressure: Channel A, Increased Channel Diameter, Mach 2.5
Figure A-18: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, Mach 0.5, Vectors Scaled x2

Figure A-19: Contours of Static Pressure: Channel A, Increased Channel Diameter, Mach 0.5
Figure A-20: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, 8 Channel Closed, AOA 5 Degrees, Vectors Scaled x3

Figure A-21: Contours of Static Pressure: Channel A, Increased Channel Diameter, 8 Channel Closed, AOA 5 Degrees
Figure A-22: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, 4 Channel Pitch, AOA 5 Degrees, Vectors Scaled x10

Figure A-23: Contours of Static Pressure: Channel A, Increased Channel Diameter, 4 Channel Pitch, AOA 5 Degrees
Figure A-24: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, 4 Channel Yaw, Channels Above Pitch Fins, AOA 5 Degrees, Vectors Scaled x3

Figure A-25: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, 4 Channel Yaw, Channels Below Pitch Fins, AOA 5 Degrees, Vectors Scaled x3
Figure A-26: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, 4 Channel Yaw, Channels Right of Yaw Fins, AOA 5 Degrees, Vectors Scaled x3

Figure A-27: Contours of Static Pressure: Channel A, Increased Channel Diameter, 4 Channel Yaw, AOA 5 Degrees
Figure A-28: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, 4 Channel Roll, AOA 5 Degrees, Vectors Scaled x3

Figure A-29: Contours of Static Pressure: Channel A, Increased Channel Diameter, 4 Channel Roll, AOA 5 Degrees
Figure A-30: Contours of Static Pressure, Missile Body: Channel A, Increased Channel Diameter, 4 Channel Roll, AOA 5 Degrees

Figure A-31: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, 8 Channel Closed, AOA -5 Degrees, Vectors Scaled x3
Figure A-32: Contours of Static Pressure: Channel A, Increased Channel Diameter, 8 Channel Closed, AOA -5 Degrees

Figure A-33: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, 4 Channel Pitch, AOA -5 Degrees, Vectors Scaled x10
Figure A-34: Contours of Static Pressure: Channel A, Increased Channel Diameter, 4 Channel Pitch, AOA -5 Degrees

Figure A-35: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, 4 Channel Yaw, Channels Above Pitch Fins, AOA -5 Degrees, Vectors Scaled x3
Figure A-36: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, 4 Channel Yaw, Channels Below Pitch Fins, AOA -5 Degrees, Vectors Scaled x3

Figure A-37: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, 4 Channel Yaw, Channels Right of Yaw Fins, AOA -5 Degrees, Vectors Scaled x3
Figure A-38: Contours of Static Pressure: Channel A, Increased Channel Diameter, 4 Channel Yaw, AOA -5 Degrees

Figure A-39: Vectors of Velocity Colored by Mach Number: Channel A, Increased Channel Diameter, 4 Channel Roll, AOA -5 Degrees, Vectors Scaled x3
Figure A-40: Contours of Static Pressure: Channel A, Increased Channel Diameter, 4 Channel Roll, AOA -5 Degrees

Figure A-41: Contours of Static Pressure, Missile Body: Channel A, Increased Channel Diameter, 4 Channel Roll, AOA -5 Degrees
Figure A-42: Vectors of Velocity Colored by Mach Number: Spoiler Baseline, No Spoilers, Vectors

Scaled x3

Figure A-43: Contours of Static Pressure: Spoiler Baseline, No Spoilers
Figure A-44: Vectors of Velocity Colored by Mach Number: 0.5 In. Spoiler Pitch, Vectors Scaled x10

Figure A-45: Contours of Static Pressure: 0.5 In. Spoiler Pitch
Figure A-46: Contours of Static Pressure, Missile Surface: 0.5 In. Spoiler Pitch

Figure A-47: Vectors of Velocity Colored by Mach Number: 0.5 In. Spoiler Roll, Vectors Scaled x10
Figure A-48: Contours of Static Pressure: 0.5 In. Spoiler Roll

Figure A-49: Contours of Static Pressure, Missile Surface: 0.5 In. Spoiler Roll
Figure A-50: Vectors of Velocity Colored by Mach Number: 0.75 In. Spoiler Pitch, Vectors Scaled x10

Figure A-51: Contours of Static Pressure: 0.75 In. Spoiler Pitch
Figure A-52: Contours of Static Pressure, Missile Surface: 0.75 In. Spoiler Pitch

Figure A-53: Vectors of Velocity Colored by Mach Number: 0.75 In. Spoiler Roll, Vectors Scaled x10
Figure A-54: Contours of Static Pressure: 0.75 In. Spoiler Roll

Figure A-55: Contours of Static Pressure, Missile Surface: 0.75 In. Spoiler Roll
Figure A-56: Vectors of Velocity Colored by Mach Number: 1.00 In. Spoiler Pitch, Vectors Scaled x10

Figure A-57: Contours of Static Pressure: 1.00 In. Spoiler Pitch
Figure A-58: Contours of Static Pressure, Missile Surface: 1.00 In. Spoiler Pitch

Figure A-59: Vectors of Velocity Colored by Mach Number: 1.00 In. Spoiler Roll, Vectors Scaled x10
Figure A-60: Contours of Static Pressure: 1.00 In. Spoiler Roll

Figure A-61: Contours of Static Pressure, Missile Surface: 1.00 In. Spoiler Roll
Figure A-62: Vectors of Velocity Colored by Mach Number: 1.00 In Spoiler Pitch, Mach 2.5, Vectors
Scaled x10

Figure A-63: Contours of Static Pressure: 1.00 In Spoiler Pitch, Mach 2.5
Figure A-64: Vectors of Velocity Colored by Mach Number: 1.00 In Spoiler Pitch, Mach 0.5, Vectors Scaled x5

Figure A-65: Contours of Static Pressure: 1.00 In Spoiler Pitch, Mach 0.5
Figure A-66: Vectors of Velocity Colored by Mach Number: Spoiler Baseline, No Spoilers, AOA 5 Degrees, Vectors Scaled x3

Figure A-67: Contours of Static Pressure: Spoiler Baseline, No Spoilers, AOA 5 Degrees
Figure A-68: Vectors of Velocity Colored by Mach Number: 1.00 In Spoiler Pitch, AOA 5 Degrees,
Vectors Scaled x10

Figure A-69: Contours of Static Pressure: 1.00 In Spoiler Pitch, AOA 5 Degrees
Figure A-70: Vectors of Velocity Colored by Mach Number: Spoiler Baseline, No Spoilers, AOA -5 Degrees, Vectors Scaled x3

Figure A-71: Contours of Static Pressure: Spoiler Baseline, No Spoilers, AOA -5 Degrees
Figure A-72: Vectors of Velocity Colored by Mach Number: 1.00 In Spoiler Pitch, AOA -5 Degrees, Vectors Scaled x10

Figure A-73: Contours of Static Pressure: 1.00 In Spoiler Pitch, AOA -5 Degrees