Investigation of Reversal Phenomena in Forebody Vortex Manipulation by Forward Facing Nozzles

by

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B. Eng. (Aerospace)

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Martin Neuteboom, B. Eng.,
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January 17, 2003

Abstract

A water tunnel flow visualization study was performed on isolated forebody models of varying nozzle position and nosecone semi-apex angle to investigate a reversal phenomenon observed in forebody vortex manipulation using forward facing nozzles. The effects of blowing at different rates were examined at various angles of attack. Three categories of vortex manipulation were observed and named: low-blowing reversal, where relatively low blowing rates caused attachment of the vortex on the blowing side; switch, where moderate rates of blowing caused detachment of the vortex, and high-blowing reversal where high rates of blowing caused re-attachment. The occurrence of the two reversal categories was found to depend upon a combination of nozzle azimuth and axial location, semi-apex angle, and, to a lesser degree, angle of attack. It is hypothesized that vortex manipulation results from two competing effects of the blowing fluid: entrainment favoring attachment, and displacement favoring detachment. A CFD analyses was attempted to gather additional insight but no valid solution could be produced.

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Nomenclature

$$C_m = \text{mass flow rate coefficient of the nozzle fluid} = \frac{\rho Q_{jet}}{\rho V_{\infty} S_{ref}} = \frac{Q_{jet}}{V_{\infty} S_{ref}}.$$

$$C_{\mu} = \text{blowing momentum coefficient of the nozzle fluid} = \frac{\dot{m} V_{jet}}{\frac{1}{2} \rho V_{\infty}^2 S_{ref}} = \frac{2 Q_{jet}^2}{V_{\infty}^2 S_{ref} S_{jet}}$$

C_n = yawing moment coefficient. .

C_y = side force coefficient.

d = nozzle diameter.

D = nosecone base diameter.

$\dot{m}$ = nozzle fluid mass flow rate.

Q_{jet} = nozzle fluid volume flow rate.

R = radius at which nozzles are located.

S_{jet} = nozzle cross-sectional area

S_{ref} = nosecone base area.

T = period of alternating blowing cycle.

V_{jet} = nozzle fluid exit velocity.

V_{∞} = free stream velocity.

x = axial coordinate referenced to the nosecone apex

x_n = nozzle axial position referenced to the nosecone apex..

Greek Symbols

α = angle of attack.

β = angle of side slip.

θ = nozzle azimuthal location. Referenced to the windward meridian.

ρ = fluid density

σ = nosecone semi-apex angle.

τ = duration blowing is supplied to a particular nozzle during alternating blowing.

ω = angular frequency of alternating blowing in radians/second.

ω^* = reduced angular frequency = $\frac{\omega D}{V_{\infty}}$

Glossary

attached vortex	- vortex that is in the position closest to the forebody.
baseline vortex arrangement	-arrangement of the vortices about the forebody when no blowing is supplied.
blowing event	-one of five clearly observable characteristics in the flow field about the forebody when blowing is supplied to a forward facing nozzle. The five events include: crossover, low-blowing reversal, switch, escape and high-blowing reversal.
blowing fluid accumulation	- build up of nozzle fluid at the nozzle exit.
detached vortex	- vortex that is in the position furthest from the forebody

displacement effect	- the nozzle accumulation causes the path of flow to be displaced away from the forebody surface.
duty cycle	$= \tau/T$. The fraction of a complete cycle of oscillating blowing that a particular nozzle is on (Lee, 1995)
escape	-nozzle fluid escapes the shear layer and is convected downstream by the free stream.
high, higher, high position	- see detached vortex..
high blowing reversal	- reversal occurring at values of C_{μ} higher than for escape.
low, lower, low position	- see attached vortex.
low blowing reversal	- reversal occurring at values of C_{μ} lower than for escape.
reversal	- attachment of the vortex on the blowing side of the nosecone.

switch	- detachment of the vortex on the blowing side of the nosecone.
viscous fairing	- (Figure 2.1) displacement effect created by the accumulation. Flow passes over the accumulation and is therefore displaced from the forebody surface.
vortex manipulation category	- one of the three types of vortex manipulation observed as a result of forward nozzle blowing. They are: low-blowing reversal, switch , and high-blowing reversal.
vortex manipulation event	-a change in the asymmetric vortex arrangement from one of the two bistable arrangements shown in Figure 1.1 to the other as a result of nozzle blowing.
vortex manipulation regime	- range of C_{μ} for which one of switch, high level reversal, or low level reversal occurs.

Chapter 1: Introduction

The objective of this thesis is to extend the knowledge of forebody vortex manipulation on slender forebodies by blowing from forward facing nozzles. Forebody vortex manipulation is a form of alternative flight control for high performance fighter aircraft at high angles of attack. More specifically, the objective is to investigate a previously observed reversal of yawing moments and side forces when blowing momentum exceeds a certain threshold value.

When a slender, pointed body is placed in a flow at moderate to high angles of attack ($\alpha=35^\circ$ to 60°), flow tends to separate from the lee side. Separation occurs along two lines, one on the port side, one on the starboard side. The shear layer extending from each separation line tends to roll up into a vortex, giving one vortex on either side of the leeward meridian. For low angles of attack ($\alpha<30^\circ$) the vortices form symmetrically about the leeward meridian. At high angles of attack ($\alpha>30^\circ$), the symmetric vortex arrangement is not stable and the vortices assume an asymmetric configuration as shown in Figure 1.1. One vortex remains close to the body (*termed: low, lower, attached*) while the other is pushed further away from the body (*termed: high, higher, detached*). The relative velocity

near the surface of the body is greater on the side with the attached vortex. The static pressure is thus lower on the attached side and net force in the direction of the attached vortex results (Figure 1.1). Imperfections on the body surface or misalignments of the body's axis of symmetry with the freestream flow dictates which side is likely to have the attached vortex. The angle of attack at which asymmetry in the vortex arrangement begins to occur was found to be proportional to the semi-apex angle (σ) of the nosecone (Lowson and Ponton, 1992).

This vortex behavior occurs about the forebody of a high performance fighter aircraft having a slender nosecone. At high α , the rudder of such an aircraft is 'blanketed' by the wake of the wing and is ineffective at counteracting the yawing moments created by the asymmetric vortices. Many schemes have been proposed to either neutralize the effect of the asymmetric vortices or to use the yawing moments and side forces that they create, as means of extending flight control into the high- α regime.

An oscillating vortex manipulation approach, referred to as dynamic manipulation, has been proposed by E. Hanff of the National Research Council (NRC)(Alexan, 1992, Alexan et al., 1994). In principle the approach can be implemented using any scheme capable of manipulating the vortex arrangement. The vortices are switched from one stable arrangement shown in Figure 1.1. to the other at a relatively high frequency. If the vortices on both the port and starboard side are held in the attached

position for an equal amount of time during each cycle, the time-averaged side-forces and moments become zero and, if performed at a sufficient frequency, the aircraft will not experience any appreciable oscillations in yaw. The time-averaged side forces can be made to vary linearly by varying the share of each cycle during which a vortex is attached. This is referred to as the duty cycle (Figure 1.2). The potential to provide linear control of yawing moments and side forces makes dynamic manipulation attractive. In static schemes, nozzles, slots or structural devices are used to create an artificial steady vortex arrangement. Steady manipulation does not allow for linear control of side forces and moments. The dynamic manipulation approach proposed by Hanff, was first implemented by using forward blowing from axially aligned nozzles as shown in Figure 1.3 (Alexan et al. 1994). These experiments indicated that, using forward blowing, it was indeed possible to switch to the vortex arrangement at sufficiently high frequencies to obtain zero time-averaged side forces and yawing moment.

Forward blowing is a mechanically simple method for dynamic forebody vortex manipulation. It does not require moving parts such as active structural vortex manipulation devices, nor does it require significant change to an airframe design such as manipulation by slot blowing or aft facing nozzles. From Alexan's (1992) experiments implementing vortex manipulation by forward blowing it was discovered that relatively little blowing was required to switch the vortices from one stable arrangement to the other. Thus forward blowing is both viable and an advantageous method for dynamic

forebody vortex manipulation.

In recent wind tunnel experiments, performed by Lee (Lee et al. 2000) to further evaluate the effectiveness of dynamic manipulation, it was observed that side forces and yawing moments reversed signs when blowing exceeded a certain threshold value (Figure 1.5). Figure 1.4 indicates the sign convention used for blowing momentum coefficient (C_μ), yawing moment coefficient (C_n), and side force coefficient (C_y). A similar reversal phenomenon was also observed by Francois (2000) (Figure 1.6). An understanding of the cause of this reversal phenomenon, or at the very least the definition of the regime in which it occurs, is essential before forebody vortex manipulation by forward nozzle blowing can be implemented for practical use.

This thesis investigates both the regime and the cause of the reversal phenomenon. Water tunnel studies were conducted on a schematic forebody model to visualize flow about the body for a range of α , blowing momentum (C_μ), nosecone semi-apex angle (σ), nozzle azimuth location (θ) and axial nozzle location (x_n/D). Figure 1.4 shows how these parameters are defined. These studies proved useful for defining the regime of reversal. However, due to the small scale of the model, and lack of detailed flow measurements in the vicinity of the apex, the studies were inconclusive in determining the mechanism of reversal. CFD studies were also attempted in an effort to gain understanding but they were unsuccessful in producing valid solutions.

Further background to the current thesis work is provided in Chapter 2. It reviews earlier experiments at Carleton University and the NRC as well as other relevant papers. It also provides a brief summary of other forebody vortex manipulation schemes. Chapter 3 outlines the water tunnel experiments and CFD studies. Chapter 4 presents and briefly discusses the results of the experiments. Chapter 5 presents a hypothesis and discusses its relevance to the experimental observations. Chapter 6 includes recommendations for: successful design of forward facing nozzle configurations, improvements to the experimental set up and procedure, and future work. Chapter 7 presents the major conclusions of this thesis.

Chapter 2: Background

2.1 Forebody Vortex Manipulation by Forward Facing Nozzles

The fluid mechanics of manipulation of the forebody vortices by forward facing nozzles is not yet fully understood. Forward blowing is hypothesized to affect the vortices by creating a displacement effect on the blown side of the nosecone. The fluid leaving the nozzle acts as a 'viscous fairing' and displaces the attached vortex on the blown side into the higher position (Ericsson and Beyers, 2000)(Figure 2.1). The net result is a force and a moment away from the blown side of the nosecone. The appearance of the reversal phenomenon indicates that this hypothesis is not always valid.

The use of forward facing nozzles was also considered by Malcolm (1991). Malcolm suggests that forward nozzle blowing creates an entrainment effect at the exit of the nozzle where the jet velocity is high, while just upstream of the nozzle exit interaction within the shear layer creates a stagnation point. The effect of blowing on the vortex arrangement was found to be strongly dependent on C_{μ} and α . A combination of low α

and low C_{μ} favored attachment on the blown side. A higher value of C_{μ} at low α caused detachment. At high α blowing caused only detachment. Figure 2.2 shows the effect of α on moments and side force at a constant value of C_{μ} obtained by Malcolm(1991).

Malcolm hypothesizes that, at low α , attachment on the blowing side occurred at low values of C_{μ} because the nozzle fluid creates only a small disturbance upstream of the separation line. Flow accelerates over the disturbance delaying separation and thus favoring attachment on the blown side. Blowing at a high C_{μ} creates a large disturbance which is enough to promote early separation favoring detachment. At higher α , the separation lines are located closer to the windward meridian and are upstream of the nozzle exits. The disturbance created by blowing at any level forces the separation line on that side further upstream and detachment will always occur earlier on the blowing side .

Malcolm also observed that the nozzle fluid had to extend upstream to the apex of the cone in order to affect the vortices.

2.2 Other Forebody Vortex Manipulation Methods

In addition to forward facing nozzle blowing many other schemes have been proposed for the purposes of forebody vortex manipulation. Malcolm (1993) has presented a substantial review of the various techniques that were under consideration as

of 1993. Active structural devices, passive structural devices as well as a multitude of pneumatic methods have been considered. None of these methods have considered 'dynamic' manipulation of the forebody vortices.

Some of the active structural forebody vortex manipulation devices include a rotatable elliptical tip (Moskovitz et al. 1990)(Figure 2.3), deployable strakes (Malcolm, 1991, Malcolm and Ng, 1991, Malcolm et al 1989)(Figure 2.4), and a rotatable tip with fixed strakes (Malcolm, 1991)(Figure 2.5). In all of these methods the aim is to create a structural asymmetry near the apex of the forebody of the aircraft to force the vortices into a desired position.

Passive structural devices are usually strakes extending from the apex. The presence of forebody strakes increases the range of α for which a symmetric vortex arrangement is possible. The aim is to increase the range of symmetric vortices rather than to manipulate the vortices for the purposes of control.

In active strake methods, strakes are deployed from one side of the forebody or the other at a time. The strakes have a different effect on the vortex arrangement depending on their height and configuration. All strakes cause separation of the boundary layer. For small strake heights, the adverse pressure gradient is insufficient to maintain separation. Flow reattaches further downstream before separating to form a vortex. The

vortex separation line is pushed further downstream thus the vortex on the strake side is forced into the attached position. Larger strake heights produce complete separation of the boundary layer and the vortex on the strake side is forced into the detached position (Figure 2.6). Azimuthal positioning also influences the effect a strake has on the vortices. Figure 2.7 shows the effect of varying the azimuthal position of a strake. It may be that the reversal phenomenon associated with forward nozzle blowing occurs in a similar manner and may be dependent on the same parameters (i.e. the azimuthal position of the blowing fluid, and the height that it extends from the surface of the forebody).

It appears possible that alternating deployment of strakes between port and starboard would display the same characteristics as dynamic nozzle blowing. That is, active strake deployment would produce a zero time-averaged side force for a duty cycle of 50% and varying linearly as duty cycle changes.

Combining stationary strakes with nozzle blowing has also been considered (Malcolm 1991, Malcolm et al. 1989). In this scheme stationary strakes are used to force the vortices into a symmetric arrangement. Side force and moment are then created by blowing from either the port or the starboard nozzle to create asymmetry. Another scheme is the combination of nose blunting and nozzle blowing (Roos and Magness, 1993). Nose blunting has a similar effect to that of static strakes, that is to increase the maximum angle of attack at which symmetry is maintained. Blowing from either nozzle will induce

vortex asymmetry creating side forces.

Other blowing schemes have also received considerable attention. In addition to forward facing nozzles, blowing normal to the body surface, blowing aft, and blowing from tangential slots have all been considered (Malcolm, 1993). Slot blowing has received considerable attention (Hodgkins and Wood, 1998; Gee et al, 1995; Lanser and Meyn, 1994; Malcolm and Ng, 1991; and others). A thin film of air is blown over the body surface. This creates a Coanda effect on the blown side and draws the vortex on that side into the attached position. Moments and forces are toward the blown side (Figure 2.8). It was observed by Lanser and Meyn (1994) that as blowing momentum increases in this scheme, there is a dropping off of the yawing moment coefficient. CFD studies performed by Gee et al. (1995) suggest that at high C_{μ} , the blowing fluid is subject to compressibility effects. The flow is under expanded before leaving the slot at which point it expands. The result is to push flow away from the surface, decreasing the extent of asymmetry and diminishing the imbalance of forces. It is not indicated by Gee et al. (1995) whether this effect could be significant enough to ultimately cause a reversal of the vortex arrangement and the associated forces. Figure 2.9 indicates the effect of slot blowing at a) low C_{μ} , and at b) high C_{μ} .

2.3 Dynamic Forebody Vortex Manipulation

Several studies of dynamic vortex manipulation using forward blowing have been carried out to date.

2.3.1 Preliminary Water Tunnel Experiments

Preliminary experiments were conducted at Carleton University by Alexan (Alexan 1992, Alexan et al.1994). Alexan performed flow visualization and force measurement experiments on a schematic forebody model in a 12" by 12" water tunnel. The ogive-cylinder forebody had a length of 6 inches, a diameter (D) of 1 inch and $\sigma = 30^\circ$. Nozzles were located at $x_n/D = 0.25$ and $\theta = \pm 135^\circ$ from the windward meridian. A test section velocity of 7 cm/s was used. Figure 2.10 shows the model used by Alexan. The model was mounted on a sting equipped with strain gauges to measure the side forces and yawing moments. α could be varied from -5° to 70° .

Alexan determined that an asymmetric vortex arrangement occurred in the range of $30^\circ \leq \alpha \leq 60^\circ$ for this model. Using a relatively small value of blowing momentum coefficient ($C_\mu = 0.0013$), the vortices could be reliably switched from one stable arrangement to the other. Blowing from the nozzle on the side with the attached vortex

tended to push the vortex away from the surface and into the higher position with the other vortex assuming the lower position. Side force was away from the blown side.

Figure 2.11 shows C_n as a function of C_μ using the sign convention of Figure 1.3. Alexan used a solenoid valve to alternate the blowing between the nozzles. He determined the maximum reduced frequency ($\omega^*=0.16$) at which the vortices could switch completely between the two stable arrangements. The time-averaged side forces were found to be approximately zero when blowing was supplied for intervals of equal length to each nozzle. The experimentally determined, dimensionless parameters were applied to an actual sized, hypothetical, fighter aircraft. It was concluded that the dynamic vortex manipulation would cause only relatively small yaw oscillations for such an aircraft.

2.3.2 Wind Tunnel Experiments

Subsequent to these experiments, a geometrically similar model to that of Alexan (1992) was tested in a wind tunnel by Lee (1995) (1996). Lee's model was larger than Alexan's by a factor of 5. Figure 2.12 shows details of the model. The model was tested in the 2m x 3m wind tunnel at the NRC. It was found that in air and at higher Reynolds numbers, the same behaviour as found by Alexan could be achieved for lower values of C_μ (0.00066), and higher values of ω^* (0.32). This implied that the scheme was even more effective than found by Alexan. Lee also investigated the effect of varying the duty

cycle (τ/t) (Figure 2.13). The time averaged side force and yaw moment were found to vary linearly with duty cycle as expected. This confirmed that dynamic forebody vortex manipulation has the potential to offer linear control of side forces and yawing moments at high angles of attack.

2.3.3 Experiments on a Schematic Delta Wing Fighter

A full, schematic, fighter model was later tested by Lee (2000). The model consisted of a 65° delta wing and a forebody having $\sigma=12.8^\circ$. The tip of the nosecone was made to be interchangeable so that the effect of nozzle location could be examined. The forebody diameter measured 80mm and overall model length measured 943mm. Figure 2.14 shows this model. Experiments were conducted to investigate the effect of nozzle location, varying C_μ , and the interaction of the forebody vortices with the wing. It was found that interaction between the forebody vortices and the wing leading edge vortices tended to cause some additional lift and rolling moments when the duty cycle was less than 20% and greater than 80% (Figure 2.15). Increasing C_μ from zero with steady blowing was found to cause a steady yawing moment once the vortices had switched positions from the baseline arrangement ($C_\mu=0.0004$). Increasing C_μ beyond 0.0013 caused a steady decrease in the yawing moment until $C_\mu=0.0025$, at which point the moment switched signs (Figure 1.5). The reversed moment was equivalent in magnitude

to the previous, steady moment. Further increase in C_{μ} had no additional effect on the C_n and C_y for the range of C_{μ} tested.

Flow visualization with this forebody without the delta wing was conducted in a water tunnel at the University of Ottawa to explore the reversal effect. It was observed that blowing at low values of C_{μ} affected the vortices as described in Alexan's (1992) experiments. That is, blowing on the attached side caused detachment of the vortex, while the vortex on the non-blown side attached. Blowing at higher C_{μ} caused the detached vortex to reattach. This behaviour was similar to that observed in the wind tunnel for the aircraft model. This reversal phenomenon appeared to correspond with the nozzle fluid piercing the shear layer upstream of the nozzle exit. It was hypothesized that the nozzle stream piercing the shear layer acts as a rigid extension from the nosecone. Flow accelerates around this extension, creating a low pressure, thus delaying separation and forcing the vortex to assume the low position on the blown side.

Ericsson and Beyers (2000), suggest that the nozzle stream piercing the shear layer acts as a nose boom negating any blowing effect on the vortices. The vortices then return to their baseline configuration.

2.3.4 Experiments at ONERA

The Office National d'Etudes et Recherches Aeronautiques (ONERA) performed similar wind tunnel experiments to those by Lee (2000) (Francois, 2000). A 310mm base diameter cylindrical cone with $\sigma=15^\circ$ was used as a model (Figure 2.16). The forward facing nozzles were located at $\theta=\pm 115^\circ$. The nozzle openings were 0.9mm in diameter resulting in a local non-dimensional axial nozzle location (x_n/D) of 0.5. The purpose of these experiments was, again, to evaluate dynamic nozzle blowing and to essentially reproduce findings of the previous experiments, namely those performed by Lee (Lee et al. 2000) at the NRC.

Francois produced comparable results including the reversal phenomenon, however, with the peculiarity that side forces and moments were in the opposite direction to those obtained by Lee (Lee et al. 2000). That is low values of C_{μ} tended to favor attachment on the blown side while higher values tended to push the vortex away. Compare Figure 1.6, Francois's results to Figure 1.4 Lee's results. Francois does not speculate on the cause of the reversal phenomenon nor on the reason for the reversed signs of C_n and C_y . Francois's values of C_{μ} for the point of reversal appear to be comparable to Lee's ($C_{\mu}=0.0013$). However Francois uses the nozzle cross sectional area as the reference area, while Lee employs the wing area.

2.4 Present Work

To explain the reversal phenomenon, and to understand why reversal was apparent with the $\sigma=12.8^\circ$ nosecone model but not with the $\sigma=30^\circ$ nosecone model, a water tunnel flow visualization investigation was proposed as the subject of this thesis. The experiments were to encompass a variety of forebody models having a range of σ and at least two different axial nozzle locations. Steady blowing was to be supplied to one nozzle at a time, with C_μ gradually increased. Flow was to be marked by an upstream centerline dye streak and dyed blowing fluid. Visual observations were to be made and correlated to particular values of C_μ . This work was conducted and is presented in this thesis. At the conclusion of these experiments results similar to Francois's (2000) had not occurred. It was decided to conduct additional experiments examining the effect of nozzle azimuth angle (θ). A conclusive fluid mechanical explanation for the reversal phenomenon based on the water tunnel experiments alone was not found. Consequently a Computational Fluid Dynamic (CFD) study was undertaken but was unsuccessful in obtaining flow solutions.

Chapter 3:

Water Tunnel Experiments and CFD Studies

3.1 Overview and Purpose

Flow visualization experiments were conducted at the Department of Mechanical and Aerospace Engineering, at Carleton University. Experiments were conducted in a closed circuit water tunnel having a test section measuring 12" by 12" in cross-section, and 36" in length. Forebody models were outfitted with axially aligned, forward facing, nozzles located near the apex. The models were placed in the test section at high α . A dye stream was created upstream of the model, aligned with the model centerline and impinging on the model near the apex. Dyed blowing fluid was supplied to one of the nozzles and the flow rate varied. The effect of nozzle blowing on the asymmetric vortex arrangement was observed as a function of α , σ , θ , C_μ , and x_n/D . A total of six σ - x_n/D combinations were tested over a range of α , θ , and C_μ . At the conclusion of the water tunnel experiments computational fluid dynamic (CFD) studies were attempted but proved to be unsuccessful.

The purpose of the water tunnel experiments was to:

1. Determine the regime in which the reversal phenomenon occurs.
2. Obtain an explanation as to the cause of the reversal phenomenon.

3.2 Apparatus

3.2.1 Models

Figure 3.1 shows a typical forebody model used. The model consisted of an interchangeable tangent-ogive nosecone and a cylindrical extension. The models measured 1" in diameter and the cylindrical extension measured 5" in length. The individual nosecones varied in length from 2.25" to 4.4" depending on σ . Each nosecone was attached to the cylindrical extension by inserting the shank into the forebody extension and was held in place by the O-ring. This design is similar to Alexan's (1992) water tunnel models. The design was selected to allow easy interchange, and to permit variable roll of the nosecone. Both parts of the forebody were machined from 1" diameter plexiglass stock. Plexiglass was selected based on Alexan's models. Alexan selected plexiglass for its ability to transmit light, reasonable machinability, and the ability to obtain a smooth surface finish (Alexan 1992).

The nosecones were CNC machined by the Science Technology Center (STC) at

Carleton University. Axially aligned, forward pointing nozzles were drilled into each nosecone. First 1/16" diameter passages were drilled from the flat end through the majority of the nosecone. The final 1/32" diameter (d) nozzle openings were created by drilling from the apex end of the nosecone until reaching the 1/16" passage. The 1/16" passages were press fit with a short length of 1/16" o.d. brass tubing, extending beyond the aft surface of the nosecone. The brass tubing acted as a connector between the nozzles and the nozzle supply lines.

The cylindrical extension was bored to allow fitting of the shank and passage of the Tygon tubing which acted as the supply lines to the nozzles. The entire assembly was mounted on the sting and held in place by a set screw (Figure 3.4).

3.2.2 Choice of σ and xn/D

In total six nosecone geometries were tested. Fore and aft nozzle locations were tested for each of three different σ . Figure 3.2 shows the details of the nosecones. Table 3.1 presents the nosecone designations and parameters. The 60° apex angle ($\sigma=30^\circ$) nosecone corresponds to the initial water tunnel models (Alexan, 1992), the 25.6° ($\sigma=12.8^\circ$) apex angle nosecone corresponds to the schematic wind tunnel model for which reversal was observed (Lee, 2000), and the 42.8° ($\sigma=21.4^\circ$) apex angle nosecone was chosen as the mid-point between the other two nosecones.

An initial azimuth angle (θ) of 135° was chosen for each nozzle location based on the models of Alexan (1992) and Lee (2000). Additional azimuthal nozzle locations were achieved by rolling the nosecone so that the blown nozzle was at the desired azimuth.

Figure 3.3 shows the two different nozzle locations. The nozzle locations were determined by selecting two radial locations (R/D) that were maintained for each of the three values of σ . This meant that the actual values of x_n/D varied from nosecone to nosecone. The values of x_n/D for each nosecone are presented in Table 3.1. Maintaining two consistent R/D values simplified manufacturing of the nosecones while still producing qualitatively a fore and aft nozzle location for each σ . Position of the nozzle radial location was determined by approximately matching x_n/D for $\sigma=12.8^\circ$ to the values of x_n/D used by Alexan (1992) and Lee (2000). The aft nozzle location ($x_n/D=0.301$) corresponds approximately to that used by Alexan (0.25). Lee tested a variety of nozzle locations. The reversal phenomenon was observed to be more prevalent (occurred at lower values of C_μ) the closer the nozzles were to the apex. To ensure reversal was encountered in these experiments, forward nozzles were located as close to the apex as could be comfortably machined ($x_n/D=0.134$). This value of x_n/D at $\sigma=12.8^\circ$ was observed to cause reversal by Lee(2000). The $x_n/D=0.301$ corresponded to $R/D=0.066$ and $x_n/D=0.134$ corresponded to $R/D=0.030$.

3.2.3 Sting

A sting apparatus was designed and manufactured to mount the forebody in the test section. The sting apparatus allowed for adjustment of the orientation of the model in pitch and in yaw. In addition, it allowed for vertical movement of the model within the test section. This enabled the apex of the model to be centered horizontally and vertically within the test section regardless of the length of the model (dependent on σ) or the value of α . The sting in combination with the rollable nosecone gave the models 3 axis of rotation if needed.

Figure 3.4 and 3.5 show the sting assembly. The assembly was suspended from an existing, removable, portal of the water tunnel test section by a PVC compression fitting (Figure 3.5). By loosening the fitting the sting assembly could be moved vertically or rotated to produce side slip. When tightened the compression fitting locked the apparatus in place. The compression fitting was easily adjusted by hand and allowed for quick adjustments and realignment of the models.

α was controlled by adjusting the hand nut (2 in Figure 3.4). This caused the inner shaft (1) and attached bottom (5) plate to be raised or lowered relative to the outer shaft (3) and attached top plate (4). As the distance between the plates changed so did the angle of attack. Angle of attack was indicated by the protractor attached to the top plate. The models were mounted upside down in the water tunnel to avoid any upstream

interference from the shaft on the leeward flow.

The sting assembly was manufactured almost exclusively from brass with the exception of the outer shaft which was stainless steel. Stainless steel was used as stock of the desired inner and outer diameter dimensions was readily available. Brass was selected for the remainder of the model because of its machinability and corrosion resistance.

3.2.4 Dye Injection System

Dyed water was supplied from pressurized reservoirs to the upstream dye injector and to a nozzle. Figure 3.6 shows a schematic of the dye system. Figure 3.7 shows a photograph of the dye system. Compressed shop air was supplied through the control valve to the dye reservoirs through a network of copper and Tygon tubing. The pressure gauge indicated the supply air pressure which ranged from 0-3 psi(g). The reservoirs delivered dyed water through Tygon supply lines. Each supply line was master controlled by a needle valve. The main nozzle supply line was outfitted with an Omega Engineering Inc. rotameter-type flowmeter. The flowmeter was capable of measuring water flow rates between 0.012ml/min and 16.4ml/min. A conversion chart supplied by the manufacturer related the observed rotameter reading to an actual flow rate in ml/min. (Appendix A). Uncertainty in the flow rate correlation was $\pm 2\%$ average. Overall uncertainty in a typical flow rate value was $\pm 1.53 \times 10^{-3} \text{ ml} / \text{s}$ (from Appendix B).

In the test section, port and starboard supply lines passed from the brass tubing of the nosecones, through the cavity of the cylindrical extension, and were attached to two more lengths of brass tubing that passed through the test section portal. Blowing was supplied to one nozzle or the other by connecting the main nozzle supply line to either the port or starboard supply line. Flow rate was adjusted by a combination of the valve setting and the pressure supplied to the reservoirs. It was found that the valves were useful for coarse flow rate adjustments, while regulating the pressure provided fine adjustments.

An existing upstream portal in the top wall of the test section was used to mount the upstream dye injector. An upstream dye injector was manufactured by bending some 3/32" o.d. brass tubing into an 'L' shape. To fit the portal internal diameter, larger diameter brass tubing was soldered to the dye injector. The dye injector fit through the portal and was held in place by a brass compression fitting.

Figure 3.8 shows the set up of the test section from the side view.

3.2.5 Flow Marking

Stains were obtained from the Carleton University Department of Chemistry for use as flow markers. The stains were no longer in common use and were supplied at no cost. The stains used were Fisher Reagent Orange G, and Allied Chemical Nigrosin.

When mixed with water, Orange G ranged in color from yellow to dark orange depending on the concentration. Nigrosin ranged from purple to inky black. By mixing the dyes, brown colors could also be produced. Additional colors were also used at times and were produced by using food color.

3.2.6 Water Tunnel

The Department of Mechanical and Aerospace Engineering water tunnel was used. This closed-return water tunnel has a test section 12" by 12" by 36" long and is made from four plexiglass panels supported by a steel frame. Observations from four directions (top bottom and two sides) are possible. The top panel of the test section is outfitted with the two portals previously mentioned. For the experiments the water tunnel was filled to a level just beyond the top of test section. Flow is driven by an axial impeller that is in turn driven by a DC motor through a 47:1 gear reduction box. Motor speed is controlled digitally by a Siemens AC/DC inverter. Flow speed in the test section had a tendency to oscillate after the initial start up transient. After waiting for a period of about one hour the oscillations became negligible. Figure 3.9 shows the water tunnel.

3.2.7 Digital Camera and Lighting

Imaging of the flow was performed using a Nikon Coolpix 980 digital camera. The camera has an 3X optical lens having a focal length ranging from 7mm to 21mm. Images can be further enlarged up to 2.5 times by the digital zoom feature. The CCD array has an effective pixel count of 1.92 million pixels (1600 x 1200 pixels) and a total pixel count of 2.11 million pixels. The automatic white balancing eliminated the need for a flash or for any special lighting. The camera automatically adjusted the brightness of the image. In some instances the image was clearer than the real world visual observations. The camera's automatic focus could be set for close range, mid range or long range. For these experiments the close range setting, with a focus range of 2cm to infinity, was used. The camera was set on the tripod with the lens as close as possible to the test section. The typical focal-plane to model distance was approximately 30cm. The automatic focus function matched the focal length of the lens to this distance automatically. The depth of the field of view at this focal length setting was sufficient that the entire depth of the model and flow field was in focus. Blinds were created from sheets of bristol board and mounted above and behind the camera to eliminate reflections that appeared on the test section glass. Top view images were obtained by setting the focal plane of the camera approximately parallel to the forebody axis. The autofocus had difficulty focusing on the forebody when top view images were taken. Unfortunately only predefined focal lengths were permitted to be selected manually. Image focus was accomplished by selecting the 20cm focal length setting and adjusting the camera position to produce the clearest image.

Depth of the field of view was also a problem from this angle possibly due to refraction created by having the camera focal plane aligned at an angle to the Plexiglass. This method did not provide high quality focus.

3.3 Procedure

3.3.1 Setting and Determining Flow Velocity

For the water tunnel experiments the maximum test section flow velocity for which dye-diffusion was small was desired. Laminar dye-diffusion conditions were maintained to ensure clarity of flow visualization. The experimental motor speed was selected by setting the inverter to an arbitrary speed. A dye streak from the upstream dye injector was produced in the otherwise empty test section. The motor speed was then incremented until small perturbations in the dye streak were observed (transition). This was found to occur at a motor speed setting of ~ 25 radians/second. To ensure some margin, a setting of ~ 20 radians/second was used for the experiments.

With the model in place, velocity in the test section was measured. A ruler was set on the top of the test section aligned with the centerline but offset a small amount. Using a laser pointer mounted on a transverse apparatus (Figure 3.10), the location of the upstream dye injector exit was determined. The laser beam was then set an arbitrary distance downstream of the injector and its location was recorded relative to the injector

exit. A dye streak was created and then quickly shut-off. A stop watch was used to determine the elapsed time from when the valve was shut until the end of the dye streak passed the laser beam. This was repeated several times to obtain an average time. The velocity was then determined by dividing the distance between the injector and the downstream laser beam by the average time. The test section flow velocity was typically around $(5.4 \pm 0.3)\text{cm/sec}$.

3.3.2 Model Alignment

A repeatable method for aligning the model axis with the test section centerline after each adjustment was required. A plumb bob suspended through the upstream dye injector hole in the empty water tunnel was used to mark a point along the centerline of the test section. A line was drawn on the bottom Plexiglass panel of the test section, parallel to the side panels and passing through this point to mark the centerline. The distance from one wall to the centerline was carefully measured and the equivalent distance was marked on the upper wall of the water tunnel. This mark was used to mark an upper centerline for the test section. During operation, the exit of the upstream dye injector was aligned by eye with the upper and lower center lines. The model was then aligned so that its apex split the dye streak approximately equally. Yaw-alignment of the model was also confirmed by checking alignment of the apex with both the upper and lower center lines. Small errors in the yaw-alignment ($<1^\circ$) may have resulted but would

have had no significant effect on the measured values of C_μ (Lee et al., 2000).

Misalignment in yaw tends to favor attachment on the more windward side.

Due to the conflicting results of Lee et al. (2000), Alexan (1992), and Francois (2000), the expected behavior of the vortices for each nosecone was uncertain. The initial phase of the experiments was carried out to ascertain the sequence of events that occurred as C_μ was progressively increased for each of the six models. Also important was to determine the range of α for which vortex asymmetry was observed.

3.3.3 Baseline Tests

Baseline tests were performed on each nosecone. Models were aligned in the water tunnel and initially set to $\alpha = 20^\circ$. Flow was marked by the upstream dye injector. α was then increased in 5° increments. At each α , the vortex arrangement was observed to determine the range for which asymmetry was apparent. Based on these observations, an operating range of $\alpha = 35^\circ - 55^\circ$ was chosen for all further experiments. For detailed observations $\alpha = 55^\circ$ was chosen as at this α asymmetry was most prevalent.

3.3.4 Flow Documenting

After the α range of vortex asymmetry was found, the sequence of vortex events as C_μ increased from zero was determined. Each nosecone was set initially at $\alpha = 55^\circ$. Blowing was supplied to one nozzle over a range of flow rates and the effects on both the high and low vortex side were qualitatively observed. The nozzle flow rate at each vortex event was then measured using the flowmeter and converted to C_μ by equation 3.4 derived as follows:

Definition of blowing momentum coefficient:
$$C_\mu = \frac{\dot{m}_{jet} V_{jet}}{\frac{1}{2} \rho V_\infty^2 S_{ref}} \quad (3.1)$$

mass flow rate:
$$\dot{m}_{jet} = \rho V_{jet} S_{jet} \quad (3.2)$$

nozzle velocity:
$$V_{jet} = \frac{Q_{jet}}{S_{jet}} \quad (3.3)$$

Substituting 3.2 and 3.3 into 3.1 and simplifying yields:

$$C_\mu = \frac{2Q_{jet}^2}{V_\infty^2 S_{ref} S_{jet}} \quad (3.4)$$

Vortex events for each nosecone over the range of α were documented. Each event was approached from both lower and higher C_μ to account for any hysteresis effects.

A systematic database of images was obtained for each nosecone at $\alpha = 55^\circ$. Images

were captured at incremental values of C_μ . The annotated database of images may be found in the CD-Rom (Appendix C) at the back of the thesis.

3.3.5 Nozzle Azimuthal Location (θ)

The effect of azimuth location(θ) of the nozzles was also investigated. In addition to $\theta=135^\circ$, $\theta=95^\circ$, 115° , 155° , and 175° were investigated for the $\sigma=12.8^\circ$ and 21.4° nosecones. Azimuth angles were varied by rolling the nosecone so that the blown nozzle was in the desired azimuthal location. The effects of C_μ on both the high and the low vortex at each θ were examined for $\alpha=45^\circ$, 50° , and 55° . The nosecone was rolled in increments of 20° placing the nozzles at both $\theta=155^\circ$ and $\theta=115^\circ$ after the first increment and $\theta=95^\circ$ and 175° after the second increment. The model plane of symmetry was aligned with the free stream flow, and the baseline vortex configuration was observed. Blowing was supplied to one of the nozzles and the effects were recorded as before. The model was then perturbed a small amount ($<2^\circ$) in yaw to force the opposite baseline vortex arrangement. The effect of blowing from the same nozzle but on the reverse vortex arrangement was observed and recorded. The same nozzle was tested at all three values of α on both vortex arrangements before blowing was switched to the opposite nozzle and the procedure repeated for the complimentary value of θ .

3.4 CFD Studies

3.4.0 Overview

The flow visualization experiments did not lead to a conclusive explanation of the mechanics behind the reversal phenomena. CFD work was attempted to try to resolve details of the flow mechanics in the vicinity of the forebody apex and the nozzle exit, namely the velocity vectors and the pressure distribution. The initial study was to model the water tunnel experiments and attempt to replicate the results. Once this was achieved, the CFD models were to be scaled to roughly real world size and, using air as the working fluid, computed for a variety of Reynolds numbers. Additional parametric studies were proposed for alternative nosecone configurations including the one used by Francois.

Fluent was chosen for the flow solver as it was available within the department. Numeca Software's Hexpress was used for mesh generation. A satisfactory mesh, that provided sufficient flow resolution near the surface and in the vicinity of the nozzles, was found difficult to achieve. Once produced, there were errors in the mesh file that caused critical failures when employing the flow solver. A mesh of lesser resolution was generated and exported successfully to the flow solver, however, possibly due to the lack of resolution, solutions using it did not show the asymmetrical vortices. With more effort, it might have been possible to produce satisfactory results. Troubleshooting was complicated however, as it was difficult to determine whether errors were the result of

parameters in the mesh generating program, the flow solver, or due to computer system limitations. The CFD studies were abandoned after considerable effort as it did not appear that they were heading in a positive direction.

3.4.1 Mesh Generation

The mesh generator chosen was Numeca Software's Hexpress. Hexpress was designed to expedite the mesh generation portion of CFD. The user defines an operating domain, boundary conditions, the number of refinements (number of times an initial mesh is subdivided) and can specify target cell sizes for a given region or surface. The program divides the region into an unstructured hexahedral mesh. From a very coarse initial mesh (also specified by the user), the cells become progressively finer until they reach the surface of the model. Once a mesh is defined, the user may insert a boundary layer mesh with specified: initial cell size, growth factor and number of layers. Hexpress was used as it was offered on a trial basis to the department at the outset of the CFD trials. It appeared to be much simpler to learn and use than Gambit, the grid generator marketed by Fluent Inc. Learning to use the Numeca software was relatively easy but producing a workable mesh proved unsuccessful. Numeca provided a sample mesh (Figure 3.11) for the 12.8a nosecone (see Table 3.1 for definitions of nosecone designations) on which to base parameters for subsequent meshes. However, after many attempts, and much consultation with Numeca, no other successful mesh was produced. In all attempts one of the mesh generating steps failed.

3.4.2 Fluent Solutions

Fluent's laminar, steady, uncoupled solver was employed. The sample mesh of the 12.8a nosecone mesh was successfully exported to Fluent and simulations were run. As it was only a sample mesh, the cell size in the shear layer and in the vicinity of the nozzle was too coarse (Figure 3.11 b)) to produce asymmetry in the solution of either the baseline flowfield (no blowing) or when blowing was modeled. Figure 3.12 shows a cross section of the computed baseline flowfield at $x_n/D=0.46$. In Figure 3.12 a) velocity vectors are shown with constant length to indicate the direction of flow. A pattern resembling vortical motion is just visible but the vortices are symmetric about the forebody plane of symmetry. Figure 3.12 b) shows contours of the velocity magnitude which is also symmetrical about the forebody plane of symmetry. Figure 3.14 shows a plot of static pressure contours on the forebody surface looking a) axially along the forebody, and b) on the leeward side of the forebody. Again no asymmetry is visible.

Several means were attempted to trick the Fluent solution to produce asymmetry. First the inlet flow vector was given a small amount of side slip. This produced essentially the same flow field as in Figure 3.12. A solution modeling blowing was also attempted to force an asymmetrical solution. A value of C_μ known to affect the vortices was converted to a velocity and the velocity set as an inlet condition to the nozzle passage. The solution produced symmetrical vortices once more. Particle tracks of the fluid leaving the nozzle simply followed the flow within the symmetric vortex.

Finally, the entire volume was initialized with a velocity vector in side slip (z-direction in Figure 3.11). This resulted in the asymmetrical flow field shown in Figure 3.13 at $x_n/D=0.46$. Vortices can be observed on the leeward side of the forebody and appear to be asymmetrical. Figure 3.13 b) emphasizes this asymmetry with a plot of velocity magnitude contours for the same plane. Figure 3.15 shows contours of static pressure on the forebody surface corresponding to the asymmetrical solution. A region of higher pressure is visible on the starboard side which corresponds to the slightly more detached vortex in Figure 3.13 a). The solution shows signs of being a valid representation of the asymmetrical flow about the forebody however there are several reasons why this solution did not validate. Figure 3.16 shows that as x_n/D increases (moving further aft on the forebody), the solution becomes increasingly symmetrical about the forebody plane of symmetry. This is opposite to the water tunnel observations that the asymmetrical vortices diverged from each other and the forebody surface as the axial coordinate (x) increased. The water tunnel observations also noted that both vortices curve in the direction of the detached vortex side. In cross section, the position of both vortex centers should move counter clockwise about the forebody axis as x_n/D increases and the detached vortex should move radially away from the forebody surface. The CFD results show the vortex cores in approximately the same azimuthal location at each cross section and the detached vortex remains approximately the same radial distance away from the surface as well (Figures 3.14 a), 3.16 a) and b)). The solution may become less valid at higher values of x_n/D because the outlet boundary condition may have an influence on the solution upstream. This could be overcome by adding a long forebody

extension to the CFD model. The asymmetry may be visible simply due to the residual of the z-velocity initialization. Relative residual values of 5×10^{-5} were used for the x-, y-, and z-velocities. Perhaps with stricter convergence criteria the solution would become increasingly symmetric as the residual of the asymmetric initial condition diminished.

In light of the difficulties experienced in producing a mesh, Numeca forwarded a successful mesh with the desired parameters and cell refinement. Fluent was able to read the mesh file but with errors. Solutions failed before the first iteration was completed. At this point, it was not clear whether limitations in the computer network operating system, errors in Fluent input parameters, or errors in the mesh, were to blame for the failures. As it could take an unquantifiable amount of time to determine where the error lay, it was deemed prudent to abandon the CFD studies.

Chapter 4:

Results of Water Tunnel Experiments

4.1 Overview

Experiments were performed as described in Chapter 3. Five events resulting from blowing were observed:

1. *Low-blowing reversal:* The vortex on the blown side attaches at relatively low values of C_{μ} . No fluid escapes the shear layer
2. *Crossover:* Blowing fluid can be seen to cross the model axis and is drawn into the opposite vortex.
3. *Switch:* The vortex on the blown side detaches.
4. *Escape:* Fluid escapes the shear layer

5. *High-blowing reversal:* The vortex on the blown side attaches at relatively high value of C_{μ} . Fluid has escaped the shear layer.

It was found that in order to manipulate the vortex arrangement, fluid had to leave the nozzles with sufficient momentum to penetrate at least some distance upstream of the nozzle exit into the oncoming flow. To manipulate the vortices by high-blowing reversal, blowing fluid had to escape the shear layer.

Quantitative results are presented as plots of C_{μ} as functions of α and θ for the aforementioned events. Plots for different values of σ and x_n/D were generated and are discussed later in this chapter. It was observed that as α was increased, reversal became more prominent while the value of C_{μ} for which each blowing event occurred varied only slightly. As σ was decreased, the occurrence of reversal also increased. As θ was increased, the instance of reversal increased, C_{μ} for switch increased, C_{μ} for escape decreased, and at high θ , switch became impossible. As x_n/D was decreased at a particular value of σ , high-blowing reversal became more prominent and C_{μ} for all events decreased.

An assessment of uncertainty is also included in this chapter.

An explanation as to the cause of reversal was not found. Insight into the flow behaviour was limited by the small scale of the model and the absence of detailed flow measurements (i.e. velocity, pressure) in the vicinity of the apex.

4.2 Range of Asymmetry

An asymmetric vortex arrangement was observed for α ranging from 35° to 60° for $\sigma = 12.8^\circ$, and $\sigma = 21.4^\circ$. For $\sigma = 30^\circ$, asymmetry was observed for α ranging from 40° to 60° . This is in agreement with Lowson and Ponton, (1992) who concluded that α at which asymmetry occurs is approximately proportional to σ , and that above 60° the vortex arrangement becomes unstable. For all nosecones at $\alpha = 60^\circ$, asymmetry was observed but it was not stable. The breakdown point of the attached vortex moved forward toward the forebody apex. As it reached the apex, the high vortex moved into the attached position. The low vortex then began to reform, and forced the opposite vortex back into the high position. It appeared as though, in the absence of the second vortex, there was a preference for the low position. These observations were used to define an operating range for subsequent experiments of $40^\circ \leq \alpha \leq 55^\circ$, in 5° increments.

4.3 Blowing Events

For the range of parameters tested five events resulting from blowing were observed:

1. Low-blowing reversal: The vortex on the blown side attaches at relatively low values of C_μ . No fluid escapes the shear layer
2. Crossover: Blowing fluid can be seen to cross the plane of symmetry of the model and is drawn into the opposite vortex.
3. Switch: The vortex on the blown side detaches.
4. Escape: Fluid escapes the shear layer.
5. High-blowing reversal: The vortex on the blown side attaches at relatively high value of C_μ . Fluid has escaped the shear layer.

Figures 4.1 a) to e) show this sequence of events for the 12.8f, $\theta = 155^\circ$ case (see Table 3.1 for case designation convention) as an example. The 12.8f, $\theta = 155^\circ$ case displayed all of the five blowing events in sequence. Not all of these events occurred for every case. For example in some cases crossover occurred before low-blowing reversal (for example: 12.8a, $\theta = 155^\circ$), and others after switch (for example: 12a, $\theta = 95^\circ$).

Tables 4.1 and 4.2 indicate the occurrence of the reversal phenomena as well as instances where switching did not occur.

From these results it is evident that there are essentially three regimes of vortex manipulation. As implied, they are referred to as low-blowing reversal, switch, and high-blowing reversal. *Reversal* refers to the attachment of the vortex on the blown side. *Switch* refers to the detachment of the vortex on the blown side. Low-blowing reversal occurs when the vortex on the blown side attaches for a value of C_{μ} lower than the switch C_{μ} . High-blowing reversal occurs when the vortex on the blown side attaches after escape has occurred. *Escape* refers to the blowing fluid just escaping the shear layer. A fourth regime of vortex manipulation occurs at very high values of C_{μ} , but is neither a switch nor reversal. At these very high values of C_{μ} , the blowing fluid no longer affects the vortices and they assume their baseline (original, $C_{\mu}=0$) configuration.

4.4 Flow Visualization

Flow about the forebody remained laminar except at high values of C_{μ} where the blowing fluid appeared to break-up the vortices. At this level of blowing, the vortex configuration was still observable though the vortices were broken up (Figures 4.3c).

4.4.1 Crossover

When blowing was applied at a low rate, blowing fluid was entrained into the vortex core of the vortex on that side. As blowing increased, a point of crossover was reached where blowing fluid was also drawn into the opposite vortex core. This can be seen in many of the images in the database as well as in Figures 4.1 d) and e). Crossing over of the blowing fluid may occur either before or after the first vortex manipulation event is reached depending strongly on the values of θ , x_n/D , and to a lesser degree σ and α . From the data collected it is not believed that this crossing over of the blowing fluid has any effect on the vortices. For example in the 12.8f, $\alpha=55^\circ$, $\theta=115^\circ$ case, crossover occurred at a higher C_μ than for switch, while at $\theta=155^\circ$ crossover occurred at a lower C_μ . Both cases exhibited the same manipulation characteristics. It would appear that some blowing fluid was simply entrained by the opposite vortex.

4.4.2 Accumulation of the Blowing Fluid

At low values of C_μ all of the blowing fluid was drawn into the vortex core on the blown side. As C_μ was increased an *accumulation* of fluid at the nozzle exit appeared. This grew proportionally with C_μ until at some value the vortex arrangement was visibly affected. Some accumulation of fluid was required for all categories of vortex manipulation events. This is illustrated in Figures 4.2 a) to c) for the 12.8a nosecone at $\alpha=55^\circ$ and $\theta=135^\circ$ and is less visible but also observable in Figures 4.1a) to e). In Figure 4.2 a), C_μ is just below that required for low-blowing reversal. The enlargement of the

nozzle exit shows fluid exiting the nozzle normal to the forebody surface and being entrained into the vortex core on the blown side. No blowing fluid extends upstream of the nozzle exit and no accumulation occurs. In Figure 4.2 b) low-blowing reversal has occurred. Momentum of the blowing fluid exceeds the local momentum of the shear layer and blowing fluid penetrates upstream of the nozzle exit before being curved away from the surface and then convected downstream by the shear layer. This creates the 'accumulation' of fluid at the nozzle exit. In Figure 4.2 c) switch has occurred. Fluid extends even further upstream. When the accumulation became sufficiently large at a given nozzle location, crossover, and eventually, as C_μ was increased, escape occurred.

The size and shape of this fluid accumulation is dictated by the geometry of the shear layer. The geometry of the shear layer is dependent on the nosecone profile and on α . Moving the nozzle location within the shear layer by varying x_n/D or θ will also affect the shape of the accumulation and its position relative to the vortices. The size and shape relative to the nosecone, and the position of the accumulation within the nosecone should have a significant impact on how it affects the vortices.

4.4.3 Escape

Eventually, if blowing was increased to a sufficiently high value, some of the accumulated blowing fluid escaped the shear layer into the freestream (Figure 4.1 d) and 4.3 c)). Increasing the level of blowing beyond this point forced an increasing percentage of blowing fluid into the freestream resulting in less accumulation within the shear layer.

As more fluid escaped the shear layer, the curvature of the forward extreme of the accumulation diminished. The path of the fluid within the accumulation is deflected away from the surface until it's trajectory carries it into the freestream.

At some level of blowing beyond the initial point of escape, flow became disrupted such that the vortex cores appeared to be broken up (Figure 4.3 c)). The transition to this condition was not observed to have any effect on the vortex arrangement.

4.4.4 At Very High C_{μ} Vortices Return to Their Baseline Arrangement

Ultimately, at very high C_{μ} , all of the blowing fluid was found to pierce the shear layer with none of it accumulating. In this range of C_{μ} (~ 0.03), the vortices reverted to their baseline arrangement for the 21.4a, 30a, and 30f nosecones. Figure 4.3 c) shows this behaviour for the 30f low vortex case and the CD-Rom (Appendix C) also shows this behaviour for the 21.4a nosecone. These nosecones did not otherwise exhibit reversal. The observation shows some agreement with observations by previous researchers that the piercing jet nullifies the effect of blowing (Beyers and Ericsson, 2000). The reason this is not considered to be switch or reversal is because vortices only return to their baseline arrangement if they have already been manipulated away from that arrangement. For example: In the 30f, low vortex case, blowing is supplied to the low vortex and the vortices undergo switch (Figure 4.3 b). Continued blowing does not manipulate the vortices any further until at a very high C_{μ} where the jet from the nozzle

pierces the shear layer, the vortex on the blown side moves to the attached position, and the opposite vortex detaches (Figure 4.3 c)). For the same nosecone, if blowing is supplied to the detached vortex, that vortex remains detached as C_{μ} increases even when blowing fluid pierces the shear layer.

4.4.5 Observation of the Freestream Flow

The freestream dye streak split and wrapped about the forebody apex upstream of the blowing fluid accumulation. It was difficult to resolve any flow patterns in the short distance between the forebody apex and the blowing fluid accumulation. Flow tended to remain close to the surface on the leeside of the nosecone in the region between the apex and the blowing fluid accumulation. Upon encountering the blowing fluid accumulation, the branch of the dye streak on the nozzle side split and flowed around the accumulation, the majority of the flow appeared to remained close to the nozzle surface and as two streams splitting at the accumulation (This is observed in the top views of Figure 4.1c) and d)). As the flow passed the accumulation, it diverged from the surface and fed into the vortices.

As the vortices underwent low-blowing reversal, switch and even high-blowing reversal, no change in this flow pattern was observable. From visual observations it was impossible to determine the mechanism responsible for the reversal phenomena. The vortex manipulation mechanism must involve subtle differences in the pressure distributions and small changes in the particle velocity vectors near the apex.

4.4.6 Entrainment of the Freestream by the Blowing Fluid

It was observed, particularly for the range of C_μ beyond switch, that some of the freestream flow became entrained in the fluid leaving the nozzle (Figure 4.1 c), and 4.2 b)). Freestream fluid could be seen circulating within the accumulation before the point of escape. Beyond escape, some of the freestream flow escaped with the blowing fluid while a portion circulated within the accumulation. The remainder of the freestream flow passed around the accumulation and was drawn into the vortices.

4.4.7 High Vortex Draws In

In all cases, as a vortex manipulation point was approached, it was the high vortex that was drawn toward the body surface, while the attached vortex remained in the same position relative to the forebody. Once the vortices were parallel, the initially low vortex then moved away from the surface. This was regardless of which vortex blowing was supplied to. As switch was approached with increasing C_μ , this meant it was the vortex opposite to the blown vortex that was drawn toward the surface while the blown vortex remained in the same position. This is evident in the images in the CD-Rom database particularly for the 12f, $\theta=135^\circ$ low vortex case. If the attached vortex break down point moved forward, the detached vortex would begin to assume a lower position as discussed in section 4.1. It appeared as though the lower vortex position was the default position, and the higher position resulted from the low vortex pushing it into this position.

4.4.8 Stagnation Point

The windward stagnation point was observed to shift according to the vortex arrangement. The stagnation point was drawn toward the side with the attached vortex. This is logical since flow remains attached longer (i.e. to higher value of θ) on this side thus there is a low pressure which would draw the stagnation point toward that side. As blowing was applied and increased, the stagnation point moved away from the attached side. When there was a vortex manipulation, the stagnation point settled in closer to newly attached side.

4.5 Quantitative Observations

Quantitative results were plotted in terms of C_p as functions of α and θ at different values of σ and x_n/D .

4.5.1 Effect of α

Table 4.1 shows the occurrence of the reversal phenomena for the forward nozzle location at different combinations of α , θ and σ . It can be seen that as α increased the range of θ for which both high and low-blowing reversal occurred also increased. Similarly, Table 4.2 shows the occurrence of the reversal phenomena for the aft nozzle

location. Only low-blowing reversal occurred for the aft location and that was only for the $\sigma=12.8^\circ$ nosecone. The range of θ for which low-blowing reversal was observed increased with α as well. Quantitatively, α had only a minimal effect on the value of C_μ at which a particular event occurred. Figures 4.4 a) to c) show C_μ versus α for switch, escape, and reversal for $\theta=135^\circ$ for each nosecone. Figures 4.5 to 4.8 show C_μ versus nozzle azimuth position (θ) for each event at various α for the 12.8f, 12.8a, 21.4f and 21.4a nosecones. Because the 21.4a nosecone did not exhibit reversal it was deemed to be of little interest. Data collected at $\theta \neq 135^\circ$ was limited only to the highest and lowest α to confirm if reversal would occur and is therefore incomplete. The 30f and 30a nosecone were not examined for $\theta \neq 135^\circ$ and are not shown. Figures 4.10 to 4.13 show C_μ for each event at all α tested for each nosecone. It is clear that varying α had little effect on the shape of the C_μ versus θ curve. α tends to shift the curve in the vertical direction a small amount. The effect was more pronounced for nozzles in the aft location as can be seen in Figures 4.11a) and b). There is greater variation and shift in the curves as α varies.

There does not appear to be a consistent trend attributable to α . At different combinations of θ , σ , and x_n/D , C_μ does not show a consistent trend as α increases. θ , σ , and x_n/D must play a more significant role. From a design perspective, the somewhat small effect of α on C_μ required to manipulate vortices is desirable. The dependence of the reversal phenomena on α is undesirable.

4.5.2 Effect of σ

Semi-apex angle, σ had a significant effect on nozzle manipulation characteristics.

Table 4.1 shows that for lower σ , the instance of both high and low reversal increased.

There does not appear to be a clear trend in the value of C_{μ} for particular events associated with σ .

4.5.3 Effect of θ

θ had a strong effect on the manipulation characteristics of the nosecones. In Table 4.1 and 4.2 both high and low-blowing reversal became more prominent as θ increased. Switch did not occur at high values of θ for certain cases while at lower values it occurred in all cases. The disappearance of switch as θ increased was due to blowing reaching the point of escape before reaching the point of switch. Figures 4.5 to 4.8 show that as θ increased C_{μ} for switch increased, while C_{μ} for escape decreased. For the $\sigma=21.4^{\circ}$ nosecones, C_{μ} versus θ for switch and escape intersect at $\theta < 175^{\circ}$ and switch did not occur for $\theta = 175^{\circ}$. Switch did not occur after escape in any instance. If switch is caused by the pushing off of the blown vortex then this effect ultimately diminishes after escape.

4.5.4 Effect of Axial Nozzle Location (x_n/D)

Relative axial nozzle location (forward versus aft) had the most pronounced effect of the parameters tested on the vortex manipulation characteristic. High-blowing reversal occurred only with nozzles in the forward ($R/D = 0.03$) position. Low-blowing reversal was also more prominent with nozzles in the forward location. Actual values of x_n/D for the various nosecones are shown in Table 3.1. x_n/D is a critical factor for high-blowing reversal but is not sufficient on its own. High-blowing reversal was not experienced in the 30f ($x_n/D = 0.0529$), and 30a ($x_n/D = 0.119$) nosecones, although x_n/D for these two nosecones was less than for the 12.8f ($x_n/D = 0.134$) nosecone which exhibited the most instances of reversal. Reversal then depends on both x_n/D and σ . Lowering the value of x_n/D for a particular value of σ increases the likelihood of reversal.

C_{μ} for all other events increased as x_n/D was increased for each particular value of σ . (Figures 4.13 a) to d)).

4.6 Error Assessment

Sources of error and uncertainty include:

Calibration of the rotameter: Average error on flow rate $\pm 2\%$

Error in reading the rotameter: ($\pm \frac{1}{2}$ a division = $\pm 2\%$ avg.)

Overshooting C_{μ} that causes a particular effect: (± 1 division = $\pm 4\%$ avg.)

Possibility of hysteresis

Unsteady flow velocity in the test section

Inaccuracy in assessing the freestream flow velocity.

Asymmetry in the nozzle location.

Setting α : ($\pm 2.5^\circ$)

Setting θ : ($\pm 2.5^\circ$)

Alignment of the model in yaw. ($\pm 2^\circ$)

Alignment of the body in roll: ($\pm 2^\circ$)

Play in the sting mount. ($\sim +0.5^\circ$ in α)

Damage to the nosecone tip.

4.6.1 Hysteresis

Hysteresis was assessed by approaching C_{μ} for a particular event in both an ascending and descending manner. For crossover, switch, escape and reversal, values tended to agree within one increment on the rotameter scale. Values obtained in an ascending fashion had a tendency to be higher than those achieved in a descending manner implying that the discrepancy was likely due to the overshoot error. For low-blowing reversal ascending values were as much as 10 increments higher than descending values. This discrepancy is too large to be attributed to the overshoot error only and represents hysteresis. The possible cause of this hysteresis is discussed in section 5.2.1. The discrepancy creates a large uncertainty in the true value of low-blowing reversal. Plotted values of C_{μ} for the particular events were obtained by approaching the event

from lower values of C_μ .

4.6.2 Uncertainties in α

α was set using a protractor attached to the sting mount. There was separation between the protractor and the sting. The sting angle was observed by sighting at eye level from a distance as far away as possible. This resulted in a maximum error of $\pm 2.5^\circ$. The sting mount itself had some play in it as well due to the clearance between the shaft and the ABS fitting. The moment exerted by the weight of the model caused the shaft to rest at a small angle from the vertical. This led to a bias in α of about 0.5° . The total error on α was then $\pm 3^\circ$. As was illustrated in Figures 4.9-4.12, the effect of α on C_μ was small and the effect of these uncertainties is assumed negligible.

4.6.3 Uncertainties in Roll Angle

Roll alignment of the body was performed by aligning the marked top dead center of the model body with a centerline drawn on the sting. Top dead center of each nosecone and the model were marked at the time of manufacturing. There was a gap between the model body and the sting so again some judgement in the alignment was required. For $\theta = 135^\circ$ the markings were easily, and accurately aligned. Additional markings on the body were added to mark $\pm 20^\circ$ and $\pm 40^\circ$. These were added with less accuracy than the original top dead center marking. The error in θ for $\theta \neq 135^\circ$ is estimated to be $\pm 2.5^\circ$.

4.6.4 Uncertainties in Yaw Angle

Misalignment of the model in yaw had a tendency to favor attachment on the more windward side. The effect on the value of C_μ for a particular event was negligible for small perturbations in yaw except when alignment was near the point where the default position of the vortices was about to change. When small perturbations in yaw were used to force a particular vortex arrangement, they were chosen to be large enough that any further perturbation had a negligible effect on C_μ for a particular event. The maximum magnitude of these perturbations was approximately $\pm 2^\circ$.

4.6.5 Damage to the Nosecones

During the course of the experiments some damage to the tips of the $\sigma = 12.8^\circ$ nosecones occurred. It would be expected that vortex behaviour would be sensitive to irregularities in the geometry of the apex. Experiments performed before and after the damage occurred were compared and showed that C_μ for each event was unaffected.

4.6.6 Uncertainty in the Value of C_μ

Error in C_μ resulted from the measurement of the blowing flowrate (Q_{jet}) and from the measurement of the test section velocity (V_∞). Tolerances on the diameter of the

nozzles, and the model body were sufficiently high ($\pm 0.002''$ on the nozzle diameter (d) and $\pm 0.01''$ on the body diameter (D)) that their effect on the uncertainty of C_μ was negligible.

Uncertainty in the freestream velocity measurement resulted from the oscillation of the velocity in the test section, and coordinating the operation of the stop watch with: the closing of the freestream dye valve, and the visual cue of the dye streak passing the laser beam. Flow velocity in the test section was measured several times after a series of experiments was completed. A statistical mean and standard deviation was calculated. The velocity was determined with 95% certainty to be 5.39 ± 0.27 cm/s.

Uncertainty in the blowing flow rate includes the overshoot error, the reading error, and the uncertainty in the flow rate calibration. These resulted in a total uncertainty of $\pm 5\%$ on the blowing flow rate (Appendix B).

The propagation of these errors will vary with the blowing flowrate however, at a typical value encountered in these experiments of $Q_{jet} = 2.57$ ml/min (reading of 75 on the flowmeter), $C_\mu = 5.02 \pm 0.74 \times 10^{-3}$. This is a relative error of 14.7%. Calculations of these values are shown in Appendix B.

Chapter 5: Hypothesis and Discussion

The flow visualization observations, immediately lay to rest the hypothesis that blowing fluid piercing the shear layer acts as a solid obstruction. Reversal was observed at values of C_{μ} much lower than when such a jet is formed. Figure 4.1 e) shows that although blowing fluid escapes the shear layer, there is no jet piercing the shear layer at reversal. The observations indicate that in the range of blowing where such a jet is formed, the vortices are unaffected and return to their baseline arrangement as outlined by Ericsson and Beyer (2000).

Contrary to Malcolm's (1991) observations, the accumulation of blowing fluid was not required to reach the forebody apex in order to affect the vortices. For certain configurations (Figures 4.1 a) to e)) it does reach the apex. In other configurations (Figures 4.2 and 4.3) it does not. This is strictly dependent on the nozzle location and the angle of attack. The results also show a trend in low-blowing reversal that is opposite to that predicted by Malcolm's hypothesis. If attachment at low C_{μ} occurs when the accumulation is positioned upstream of the separation line then low-blowing reversal

would occur for low values of θ and α . From Tables 4.1 and 4.2 it can be seen that the opposite is true. Low-blowing reversal occurs at high values of θ and is more prevalent at higher values of α . As the accumulation occurs further downstream from the separation line, by increasing θ and α , low-blowing reversal becomes more likely.

5.1 Hypothesis

Three categories of vortex manipulation events exist and these were found to depend upon at least four parameters (θ , α , σ , and x_n/D). A hypothesis is proposed in the following paragraph to explain the relationship between the parameters and the vortex manipulation characteristics. The hypothesis relies in part on the fact that relatively rapidly moving fluid tends to entrain surrounding fluid, creating a region of reduced static pressure. The latter effect was observed experimentally and modeled by Wygnanski (1964) and Newman (1969).

At values of C_μ for which the vortex arrangement is not affected, fluid leaving the nozzle is simply drawn into the vortices (Figure 4.1 b) and 4.2 a)). At low-blowing reversal, the blowing fluid moving through the shear layer entrains some of the free stream flow, drawing the vortex on the nozzle side to the attached position (Figure 4.1 c) and 4.2 b)). At higher values of C_μ , the displacement effect of the accumulation supercedes the entrainment effect. Flow is pushed away from the surface by the accumulation which acts as a 'viscous fairing'. Switch occurs (Figure 4.1 d) and 4.2 c)).

Beyond escape (the stage at which blowing fluid escapes the shear layer into the freestream), the volume of fluid moving through the accumulation increases, the entrainment effect becomes dominant, and high blowing reversal occurs (Figure 4.1 e)). Blowing at very high values of C_μ , where the fourth vortex manipulation category is encountered, creates a small diameter jet that pierces the shear layer and produces little to no interaction with flow within the layer. The vortex arrangement then assumes the baseline arrangement (Figure 4.3 c).

Figure 5.1 is a graphical representation of the hypothetical competing effects of entrainment and displacement as functions of C_μ . At (1), the geometry of the nosecone (e.g. scratches, surface irregularities, etc.) favors detachment on the blowing side (shown as a small magnitude in the direction of detachment). Blowing is too low to have any effect on the vortices which remain in the baseline arrangement. Increasing C_μ creates an entrainment effect that is initially dominant over the displacement effect caused by the accumulation of the blowing-fluid (2) Low-blowing reversal occurs. The displacement effect grows more rapidly than the entrainment effect, however, and eventually dominates resulting in switch (3). At (4) escape occurs. The magnitude of the entrainment effect increases suddenly as flow now escapes the shear layer. The displacement effect also begins to decrease. At (5) the entrainment effect has once again surpassed the displacement effect and high-blowing reversal is observed. At some point (6) the entrainment effect begins to decrease until at some very high C_μ (8) both effects have diminished to approximately zero and the vortices return to their default arrangement

with the vortex in on the blowing side in the detached position (shown as a small magnitude in the direction of detachment).

In Figure 5.1 the scale for C_μ (horizontal axis) is based approximately on values obtained for the 21.4f, $\theta=155^\circ$ case. The vertical scale should be interpreted qualitatively only. That is, the relative magnitudes of the displacement and entrainment effects and the sense of the net effect are shown but there are no actual values for their magnitudes. For simplicity, the magnitude of each effect has been shown to vary linearly with C_μ for the most part in any particular range. In reality these curves could be of any form (i.e., quadratic, exponential, higher order polynomial, etc.). The magnitudes of the effects and the rate of change with respect to C_μ will vary with the nosecone parameters (θ , α , σ , x_n/D). These factors will be reflected in the net effect curve so that it may or may not intersect the horizontal axis in a given range. Thus certain categories of vortex manipulation events may or may not occur according to the hypothesis outlined here..

5.2 Discussion

The size, shape and position of the blowing fluid accumulation and its entrainment effects determine whether it has a reversal effect, no effect, or a switch effect on the vortices. As observed and presented in Tables 4.1 and 4.2, the position of the nozzles within the shear layer, determined by θ and x_n/D , has a significant effect on the

occurrence of both types of reversal. The geometry of the shear layer as determined by σ and α also has an effect on both types of reversal. If the accumulation forms near a critical point relative to the vortex position low-blowing reversal, switch or high-blowing reversal could occur at minimum values of C_μ . This is a possible explanation for the minimum points in Figures 4.5 to 4.8.

Several of the experimental observations are discussed in the following sub-sections.

5.2.1 Limitations on Reversal, Hysteresis in Low-Blowing Reversal

If the position of the accumulation is relatively distant from the axis of the vortex, the entrainment effect may be too weak to draw the vortex to the low position. This may be why reversal is only apparent for the more slender nosecones. The stouter nosecones produce vortices that diverge more strongly from each other and from the body. This places the vortex axes further from the accumulation. This could also explain the somewhat weak effect of low-blowing reversal. At the low values of C_μ , the amount of fluid circulating within the shear layer is small and the entrainment effect is small. The vortex position relative to the accumulation is crucial as to whether low-blowing reversal occurs or not. A small drift in the position of the vortices translates into a large difference in the magnitude of the entrainment effect on the vortex. This may explain why there are somewhat large discrepancies in repeat measurements for C_μ of low- blowing reversal

and why there exists some hysteresis. When approaching the threshold of low blowing reversal from a higher C_{μ} , the reversed vortex arrangement places the attached vortex closer to the blowing fluid. The entrainment effect experienced by this vortex is thus stronger at the same value of C_{μ} than if the vortex was detached. A lower value of C_{μ} is thus required to diminish the entrainment effect and enable detachment of the vortex. For nozzles in the aft position, low-blowing reversal has a tendency to occur over a wider range of θ . This could be because the magnitude of C_{μ} required to force reversal is larger and so the entrainment affects a larger region. For the aft nozzle location, low-blowing reversal occurs only for $\sigma=12.8^\circ$ because the combination of σ , and x_n/D happens to place the entrainment region in an effective position.

5.2.2 Convergence of Switch and Escape

The present hypothesis is in agreement with the observed convergence of switch and escape. Recall that as nozzle azimuth position (θ) was increased, the C_{μ} values to produce switch also increased, eventually converging with C_{μ} for escape. Values of θ beyond the convergence value did not exhibit switch. See Figures 4.5 and 4.8. Switch can only occur if sufficient fluid accumulates in the shear layer. Once escape is encountered the entrainment effect can only increase as more and more fluid moves through the shear layer. As C_{μ} for switch increases with θ , it approaches C_{μ} for escape. Once these values converge, switch is impossible because a sufficiently large displacement effect cannot

occur without first encountering escape and reduction of the net displacement effect.

5.2.3 Values of C_μ

The value of C_μ required to cause the observed effects is a function of the geometry of the wake, the axial component of velocity in the vicinity of the jet, and the nozzle location relative to the vortices.

For example if switch is dependent on the volume and shape of the fluid trapped within the shear layer, then fluid escaping this volume through crossover would have an adverse effect on C_μ for switch. For values of θ where crossover does not occur, lower values of C_μ for switch would be expected. Figure 5.2 shows agreement with this theory. As θ increases C_μ for crossover decreases, and C_μ switch increases.

The axial component of velocity in the vicinity of the nozzle exit is important as it is the momentum of fluid in the shear layer at this point that the blowing fluid momentum must overcome to affect the flow. If momentum at this point could be easily determined, then C_μ would be more correctly defined as the ratio of blowing momentum to this momentum. Any vortex manipulation event would then ideally occur at $C_\mu > 1$. The axial component of velocity is dependent on the nozzle location relative to the apex (x_n/D), α , and the circumference of the nosecone in the nozzle plane which essentially depends

upon R/D . The axial component of velocity will decrease with α as the component of the free stream flow vector resolved into the axial direction decreases. Flow is three-dimensional and so the velocity decreases due to viscous effects as flow moves both aft, and circumferentially about the nosecone. The factors x_n/D and R/D thus contribute to the actual shear layer momentum at the nozzle exit and it could be expected that these factors determine the sensitivity of vortex manipulation to C_μ .

5.2.4 Drawing in of the High Vortex

One observation that is particularly difficult to explain by the competing effects hypothesis is the apparent drawing in of the high vortex regardless of which vortex blowing is supplied to and regardless of which category of vortex manipulation is being encountered. For reversal, this observation can be explained by the entrainment effect of the blowing fluid. However when switch is approached and the non-blown vortex is drawn to the surface before the blown vortex detaches seems in contradiction to the displacement or 'viscous fairing' effect.

One possibility is that instead of displacing the vortex in the vertical plane, blowing displaces the vortex in the horizontal plane first leaving room for the detached vortex to move closer to the surface. The vortices were observed to move both horizontally and vertically as switch occurred.

Another possibility is that as C_μ increases and the accumulation expands, entrainment begins to have an effect on the opposite vortex drawing it parallel to the blown vortex before switch occurs. This hypothesis is not well supported by the experimental data or flow visualization observations however. If this hypothesis was true, then, in addition to the drawing in of the high vortex as switch was approached, the low vortex (which would be experiencing a dominant displacement effect) would be pushed away from the surface. In the flow visualization experiments, no change in position of the low vortex (or where low-blowing reversal occurs, its low-blowing reversal position) was observed until switch occurred.

The interaction of the two vortices that creates the stable asymmetrical arrangement forces one vortex to the high position, and one vortex to the low position. Perhaps as switch is approached the low vortex is displaced from the surface a small amount and the high vortex responds by moving down somewhat. The interaction between the vortices, causes the high vortex to push the low vortex back to the position closest to the surface while overall the relative asymmetry between the two vortices has decreased. This would have the appearance of the high vortex being drawn to the surface.

It could be stated that the attached position for some reason is the most stable position of the two possible vortex positions. The attached position must always be filled before the detached position can exist. This type of behaviour was certainly observed in the water tunnel experiments. When the attached vortex breakdown position moved

forward to the apex, the detached vortex assumed the low position until the initially attached vortex reformed. For whatever reason the attached position is always filled, it dictates that vortex manipulation can only occur by drawing in the high vortex first regardless of which vortex blowing is supplied to.

5.2.5 Francois's (2000) Results

Recall from Figure 1.6 that Francois (2000) also produced moments and side forces that reversed beyond a certain threshold value but the force and moment signs were opposite to the results produced by Lee (2000) in Figure 1.5. In Francois's results as C_{μ} was increased from zero the vortex on the blowing side attached at a particular value of C_{μ} ('low-blowing reversal' in the current thesis) and detached ('switch' in the current thesis) at a higher value. The 'reversed' results are explicable by considering the differences between Francois's model and Lee's, as well as the behaviour observed in the water tunnel experiments. Francois's model was similar to the 12.8f model in terms of σ and x_n/D . It differed in terms of θ and the profile shape (conical as opposed to a tangent-ogive). The profile shape would change the geometry of the wake region, changing the position of the vortices relative to the nozzles. As discussed, the different nozzle azimuth positions, place the nozzle exit and blowing fluid accumulation differently relative to the vortex. These factors would determine the type of reversal regimes possible, in this case low-blowing reversal and switch. The difference in the geometry of the wake would shift

the range of C_{μ} for which each of the competing effects dominates. Thus low-blowing reversal might have been possible in Francois's experiments for a range of C_{μ} that overlaps the range of switch or high-blowing reversal corresponding to the 12.8f nosecone of the present experiments. Francois, also used a different reference area for C_{μ} than either Lee (2000) or the present thesis. Because his cone was so large, using the base area would not be representative of the scale of the flow. Although it is not clearly defined in his paper, it would appear as though Francois used the nozzle cross sectional area rather than the wing surface area used by Lee. The fact that Francois's values of C_{μ} are comparable to those of Lee but causing the opposite yawing moments and forces, is simply due to coincidence. Because Francois studied a cone with a different nozzle configuration, and Lee studied a tangent-ogive, the results are not directly comparative in a quantitative sense.

5.2.6 Predictability of Behaviour

It is difficult to compare trends between different nosecone profiles. There are some trends consistent between nosecones such as: the preference for reversal at high θ , low x_n/D and low σ , or how C_{μ} for escape was intermediate between C_{μ} for switch and C_{μ} for high-blowing reversal. However, each nosecone tended to exhibit it's own unique vortex manipulation characteristic in the same way that airfoils of different profiles exhibit their own unique lift curves, pitching moment characteristics, etc. For a particular

nosecone there likely exists an optimum nozzle location for which C_{μ} for a particular vortex manipulation event is a minimum..

5.2.7 Dependence on θ

The dependence of reversal on θ could pose potential problems in real applications. During a manoeuvre of an aircraft, combinations of roll or sideslip may place a nozzle in an equivalent azimuth location to one causing reversal for the prevailing value of C_{μ} . The value of C_{μ} required to affect the vortices will vary significantly with the equivalent θ as well. If roll and sideslip angles are small this should not affect C_{μ} and the vortex behaviour significantly. If they are large enough, however, the value of C_{μ} must be appropriately adjusted to remain in the same category of vortex manipulation. This presents considerable complexity for control system design.

5.2.8 C_{μ} versus C_m

There is some disagreement in as to whether blowing momentum coefficient (C_{μ}) (used by Lee(1995, 2000), Francois (2000), Alexan (1992) and Malcolm (1991) for example) or mass flowrate coefficient (C_m) (used by Gee et al. (1995) and Lanser and Meyn (1994) for example, is the relevant parameter for forward nozzle blowing. In terms of this discussion, C_m should be relevant when considering displacement effects of

nozzle blowing, while C_μ is more relevant if considering the entrainment effect. The argument becomes moot however when plots of C_μ and C_m versus θ are compared for the same nosecone. Figure 5.3 a) shows C_μ versus θ for the 12.8f, $\alpha=55^\circ$, $\theta=135^\circ$ case while Figure 5.3 b) shows C_m for the same case. While the vertical scale is different the graphs show the same trends in both C_μ and C_m . The uncertainty as calculated in Appendix B will be lower for C_m as it depends on the measured quantities of Q_{jet} and v_∞ to the first order only.

5.3 Other Possible Hypotheses

It is possible that there are other competing effects on the vortices due to blowing in addition to entrainment and displacement. It is also possible that high-blowing reversal, switch and low-blowing reversal are caused by separate mechanisms. The observations support the current hypothesis outlined in section 5.1 but do not allow definitive conclusions that exclude all other possibilities. A reliable CFD study is necessary to confirm or disprove the hypothesis.

Chapter 6: Recommendations

Results of the current investigation are used to recommend guidelines for selecting a successful forebody vortex manipulation scheme using forward facing nozzles. Improvements to the experimental setup, and procedure, are suggested. Recommendations for future work are also included.

6.1 Recommendations for Design

From a design perspective, selecting an appropriate nozzle location is important. The observed three categories of vortex manipulation events offer a choice of three operating ranges of C_{μ} . Reliable vortex manipulation without encountering reversal of the side force and yawing moment is required. Low-blowing reversal shows some dependence on α , and shows substantial hysteresis, which does not make it a desirable operating regime. High-blowing reversal is predictable for the range of σ for which it is available. C_{μ} for high-blowing reversal must be exceeded by a large margin before blowing becomes ineffective again. This creates a good margin within which vortices can

be predictably manipulated. The disadvantage of high-blowing reversal is that it is not possible for all nosecone semi-apex angles (σ), and, it does not represent an efficient use of blowing fluid. A portion of the blowing fluid escapes into the freestream. Switch is perhaps the most preferable range to operate in. Switch is reliable, and occurred for every σ at both relative axial nozzle locations tested. Only at the highest value of θ and only for the 21.4° nosecone did switch not occur. Less fluid is required for switch than for high-blowing reversal which represents a more efficient use of nozzle fluid. In a real application, nozzle fluid is likely to be supplied from the compressor of the aircraft engine, so minimizing the amount of blowing fluid used is important. Placing the nozzles close the apex is advantageous in that it also reduces the amount of blowing fluid required to affect the vortices. The danger is that this places the nozzles in a region prone to reversal. The azimuthal location should then be selected to offer the maximum margin between switch and high-blowing reversal, and if possible to avoid low-blowing reversal altogether. For $\sigma=12.8^\circ$, the optimum θ would be 95° and for $\sigma=21.4^\circ$, $\theta=115^\circ$. An additional advantage is that for values of θ that meet these requirements, C_{μ} for switch is usually a minimum.

For real applications it will be difficult to predict the vortex manipulation characteristics exactly, as the shapes of actual fighter nosecones deviate from perfect tangent-ogives. Any proposed nozzle-forebody configuration should be tested thoroughly. Design considerations are as discussed in the preceding paragraph.

Another effect that may be encountered in real life designs is compressibility of the blowing fluid. As shown by Gee et al, [Gee et al.1995], if the nozzle fluid Mach number is high enough to cause compressibility, expansion at the nozzle exit could occur and possibly displace the vortex even well beyond the range of escape. At the values of C_{μ} typically required for switch however it is not expected that compressibility will be encountered.

6.2 Recommendations for Improving the Experimental Set Up and Procedure

The majority of the experimental set up was satisfactorily successful. Particularly impressive was the performance of the digital camera. There were two characteristics of the camera that could have been improved: the shutter speed, which was not fast enough in the available light to show oscillations in the dye streams at high C_{μ} ; and, the manual focus, which only had preset focal lengths and is the reason the top views for certain cases are not in focus. The camera had difficulty auto focussing on the forebody when capturing the top view. The manual focus was set to the predefined focal length of 20cm. The position of the camera was then adjusted to create an image with the best focus. A more flexible manual focus option would have improved the focus of these images.

The Plexiglass models, were manufactured satisfactorily, however for future models it is recommended that a different material be selected. There were a few disadvantages to the Plexiglass. The brittleness of the Plexiglass allowed the fine tips of the 12.8 nosecones to be damaged easily. A more durable material (plastic or corrosion resistant metal) may not have been damaged so easily. Another disadvantage was the transparency of the Plexiglass. At times, this made observation of the flow unclear, as there was no solid background to give contrast to the dye streaks. As well, distorted images of background objects appeared in the nosecones. The visibility of the nozzles, nozzle supply passages, and flow on the opposite side of the nozzle from the desired view plane confused observations. Opaque models are recommended for the future. Models should be light in colour to contrast with the dye and to reflect the available lighting thereby eliminating possible dark zones in the test section.

In retrospect selecting an axial nozzle location based on x_n/D instead of R/D would have allowed for a more accurate assessment of the effect of varying σ . It is recommended for future parametric studies (scale models or CFD) involving different values of σ that x_n/D be held constant.

6.3 Recommendations for Future Work

It is recommended that the hypothesis proposed in section 5.1 be investigated further through CFD analyses. Simulations modelling the water tunnel experiments should be conducted and pending those results, simulations should then be performed on actual sized models in airflow, at realistic Reynolds numbers. Additional experiments could be performed to investigate the effect of each of the design parameters (θ , σ , and x_n/D) in greater detail.

Chapter 7: Conclusions

From the current thesis work it can be concluded that:

- Flow visualization was inconclusive in determining the fluid mechanics of the reversal phenomena. Nevertheless a hypothesis which qualitatively explains the experimental observations has been proposed.
- Three vortex manipulation event categories exist: low-blowing reversal, switch, and high-blowing reversal. A fourth event, where the blowing jet pierces the shear layer but does not affect the vortices, allowing them to return to the baseline arrangement also exists.
- A particular nosecone and nozzle arrangement may be subject to all, some or none of these manipulation events depending on x_n/D , θ , σ and to a lesser extent α .
- The value of C_μ or C_m for which a particular vortex manipulation event

occurs depends on xn/D , θ , σ and α .

- The following factors favor both high- and low-blowing reversal:
 - low σ
 - high θ
 - lower xn/D for a particular value of σ
 - high α
- Switch is favored by:
 - low θ
 - low xn/D
- Blowing fluid must overcome the momentum of the shear layer in order for a vortex manipulation event to occur. Switch cannot occur once escape has occurred. Thus the maximum value of C_μ at which switch can occur, and the minimum value of C_μ at which high-blowing reversal can occur is the value of C_μ corresponding to escape.
- The proposed hypothesis is consistent for the most part with the experimental observations but CFD studies should be performed before it is accepted.

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Tables

Designation	σ	R/D	x_n/D
12.8f	12.8	0.030	0.134
12.8a	12.8	0.066	0.301
21.4f	21.4	0.030	0.0779
21.4a	21.4	0.066	0.175
30f	30.0	0.030	0.0529
30a	30.0	0.066	0.119

Table 3.1 Nosecone models, designations and parameters.

Forward		Nozzle Azimuth Position (θ)				
σ	α	95	115	135	155	175
21.4	45	-	h	h	h	h, ns
	50	-	h	h	h	h, ns
	55	h	h	h	h, l	h, l, ns
12.8	45	h	h	h	h	h, l
	50	h	h	h, l	h, l	h, l
	55	h	h	h, l	h, l	h, l

Key: - only switch occurred
h high-blowing reversal occurred
l low-blowing reversal occurred
ns no switch occurred

Table 4.1: Occurrence of high- and low-blowing reversal as a function of α , σ and θ for nozzles in the **forward** nozzle location.

Aft		Nozzle Azimuth Position (θ)				
σ	α	95	115	135	155	175
21.4	45	-	-	-	ns	ns
	50	n/a	n/a	-	n/a	n/a
	55	-	-	-	-	ns
12.8	45	-	-	-	l	l
	50	-	-	-	l	l
	55	-	l	l	l	l

Key: - only switch occurred
h high-blowing reversal occurred
l low-blowing reversal occurred
ns no switch occurred

Table 4.2: Occurrence of high- and low-blowing reversal as a function of α , σ and θ for nozzles in the **aft** nozzle location. High-blowing reversal did not occur for nozzles in the aft location.

Figures

Figure 1.1: Two stable vortex patterns and direction of the resultant side force in a cross-flow plane of a forebody at high angle of attack *Reproduced from Figure 1 of Lee et al. (1996)*

Figure 1.2: Concept of the dynamic manipulation of forebody vortices *Reproduced from Figure 1 of Lee et al. (2000)*.

Figure 1.3: Forward blowing (plan view) showing the adopted sign conventions.

Figure 1.4: Definitions of α , σ , θ , x_n , d , R and V_∞ .

a) Yawing moment

b) Side force

Figure 1.5: Time-averaged a)moment and b) side force coefficients as C_μ varies as obtained by Lee (2000). Reproduced from Figure 7 Lee et al. (2000).

Figure 1.6: Time-averaged yawing moment as C_μ varies obtained by Francois (2000). Starboard blowing only is shown. *Reproduced from Figure 4 Francois (2000).*

Figure 2.1: Hypothesized effect of forward blowing. *Reproduced from Figure 16 of Ericsson and Beyers, 2000.*

(a) $x/d = 0.5$

(b) $x/d = 1.0$

Figure 2.2: Yaw moment as a function of α at $C_\mu=0.03$ using forward facing nozzles at two different axial locations: a) $x/D=0.5$ and b) $x/D=1.0$. *Reproduced from Figure 43 of Malcolm (1991).*

Figure 2.3: Rotatable elliptical tip. *Reproduced from Figure 1 of Moskovitz et al. (1990).*

Figure 2.4: Deployable strakes. *Reproduced from Figure 19 of Malcolm (1991).*

Figure 2.5: Rotatable tip with strakes. *Reproduced from Figure 3 of Malcolm and Ng (1991).*

Figure 2.6: The effect of strake height on the cross flow pattern. *Reproduced from Figure 8 of Malcolm (1993).*

Figure 2.7: Effect of azimuthal strake location on yawing moment coefficient. *Reproduced from Figure 7 of Malcolm (1991).*

Figure 2.8: Effect of slot blowing on the boundary layer. *Reproduced from Figure 16 of Malcolm and Ng (1991).*

Figure 2.9: Effect of overblowing on the flow in the vicinity of slots used for vortex manipulation; computed velocity vectors in the cross flow plane. *Reproduced from Figure 8 of Gee et al. (1995).*

Figure 2.10: Alexan's (1994) water tunnel model. *From Figure 1 of Alexan et al. (1994).*

Figure 2.11: C_n as a function of C_{μ} as obtained by Alexan (1992) in water tunnel experiments using a $\sigma=30^\circ$, $x/D=0.25$, $\theta=135^\circ$, forebody. Moment is away from the blowing side. *From Figure 4.10(a) of Alexan (1992)*

Figure 2.12: Details of the wind tunnel model used by Lee (1996) and based on the water tunnel model used by Alexan (1994). *From Figure 4 of Lee et al. (1996).*

Figure 2.13: Time-averaged side force and yawing moment for zero side slip as functions of duty cycle at different values of α . *Reproduced from Figure 9 Lee et al. (1996).*

NOTE (1) Dimension represents the length of the ogive profile between the forebody apex and the point of tangency with the cylindrical fuselage.

Figure 2.14: Schematic delta wing model used in wind tunnel experiments by Lee (2000). Reproduced from Figure 3 of Lee et al. (2000).

Figure 2.15: Typical variation of time-averaged forces and moments with duty cycle for the delta wing model used by Lee (2000) in wind tunnel experiments. *Reproduced from Figure 6 of Lee et al. (2000).*

Figure 2.16: Cone-cylinder model used in wind tunnel experiments by Francois (2000).
Reproduced from Figure 1 of Francois (2000).

Figure 3.1: Forebody model. Dimensions are in inches.

Figure 3.2: Nosecone profiles. Dimensions are in inches.

Figure 3.3: Fore and aft nozzle locations Dimensions are in inches..

Figure 3.4: Sting apparatus and model.

Figure 3.5: Sting apparatus and water tunnel portal.

Figure 3.6: Schematic of Pressurized Dye System

Figure 3.7: Top view of the water tunnel test section showing the experimental set-up of the dye injection system.

Figure 3.8: Test section side view

Figure 3.9: Water tunnel.

Figure 3.10: Laser transverse and set-up used to measure test section flow velocity

Figure 3.11 Sample mesh for the 12.8a nosecone. **a)** surface mesh **b)** cross sectional plane at $x_1/D=0.46$ (aft of the nozzle exits).

Figure 3.12 Results of CFD analysis using Fluent for the 12.8a nosecone with **initial z-velocity = 0.0 cm/s**. $\alpha=55^\circ$, $V_\infty = 5.4$ cm/s. **a)** Velocity vector field on the leeside at $xn/D=0.46$. **b)** Contours of velocity magnitude at $xn/D=0.46$. Red = higher magnitude Blue = lower magnitude.

Figure 3.13: Results of CFD analysis using Fluent for the 12.8a nosecone with **initial z-velocity = 5.4 cm/s**. $\alpha=55^\circ$, $V_\infty = 5.4$ cm/s. **a)** Velocity vector field on the leeside at $xn/D=0.46$. **b)** Contours of velocity magnitude at $xn/D=0.46$. Red = higher magnitude Blue = lower magnitude.

Figure 3.14. Surface pressure contours of the 12.8a nosecone CFD model. **Initial velocities = 0cm/s.** a) axial view and b) leeside. Blue = lower pressure, green = higher pressure.

Figure 3.15. Surface pressure contours of the 12.8a nosecone CFD model. **Initial z-velocity = 5.34cm/s.** a) axial view b) leeside. Blue= lower pressure, green = higher pressure.

Figure 3.16: Velocity vector field on the leeside for the 12.8a nosecone CFD model with initial z -velocity=5.34 cm/s at **a)** $xn/D=2.52$ and **b)** $xn/D=3.31$. Flowfield becomes increasingly more symmetric as xn/D increases.

Figure 4.1a) Nosecone 12.8f, $\alpha=55^\circ$, $\theta=155^\circ$, $C\mu=0$. **Baseline** vortex configuration. Near vortex is in the detached position (right vortex in top view).

Figure 4.1 b) Nosecone 12.8f, $\alpha=55^\circ$, $\theta=155^\circ$, $C\mu=5.24 \times 10^{-5}$. Blowing is supplied to the near vortex (right vortex in top view). The vortex arrangement remains **unaffected**.

Figure 4.1 c) Nosecone 12.8f, $\alpha=55^\circ$, $\theta=155^\circ$, $C\mu=5.62 \times 10^{-3}$. **Low-blowing reversal** has occurred. Near vortex attaches (right vortex in top view). Blowing is supplied to the near vortex.

Figure 4.1 d) Nosecone 12.8f, $\alpha=55^\circ$, $\theta=155^\circ$, $C\mu=1.54 \times 10^{-2}$. **Switch and crossover** have occurred. The near vortex detaches (right vortex in top view). Blowing is supplied to the near vortex.

Figure 4.1 e) Nosecone 12.8f, $\alpha=55^\circ$, $\theta=155^\circ$, $C\mu=4.55 \times 10^{-2}$. **High-blowing reversal** has occurred. Fluid has escaped the shear layer. Near vortex attaches (right vortex in top view). Blowing is supplied to the near vortex.

Figure 4.2 a) Nosecone 12.8a, $\alpha=55^\circ$, $\theta=135^\circ$, $C\mu=2.92 \times 10^{-2}$. **Before low-blowing reversal**. Blowing is supplied to the near nozzle. Flow exiting the nozzle, exits normal to the surface. No blowing fluid penetrates upstream.

Figure 4.2 b) Nosecone 12.8a, $\alpha=55^\circ$, $\theta=135^\circ$, $C\mu=5.13 \times 10^{-3}$. **Low-blowing reversal** has occurred. The near vortex attaches. Flow now penetrates upstream of the nozzle exit. The entrainment effect (just visible in the enlargement) dominates favoring attachment on the blown side.

Figure 4.2 c) Nosecone 12.8a, $\alpha=55^\circ$, $\theta=135^\circ$, $C\mu=1.08 \times 10^{-2}$. **Switch** has occurred. Significant accumulation of the blowing fluid is visible. Displacement effect dominates promoting detachment of the near vortex.

Figure 4.3 a) Nosecone 30f, $\alpha=55^\circ$, $\theta=135^\circ$, $C_\mu=0$. Baseline vortex arrangement.

Figure 4.3 b) Nosecone 30f, $\alpha=55^\circ$, $\theta=135^\circ$, $C_\mu=1.13 \times 10^{-2}$. Switch has occurred. The far vortex detaches. Blowing is supplied to the far vortex.

Figure 4.3 c) Nosecone 30f, $\alpha=55^\circ$, $\theta=135^\circ$, $C_\mu=6.51 \times 10^{-2}$. **Piercing jet effect.**
Vortices resume the baseline arrangement. Blowing also disrupts the flow so the vortices appear broken. Blowing is supplied to the far vortex.

Figure 4.4 a) $\theta=135^\circ$, C_{μ} versus α for **switch** for various nosecones.

Figure 4.4 b) $\theta=135^\circ$, C_{μ} versus α for **escape** for various nosecones.

Figure 4.4 c) $\theta=135^\circ$, C_{μ} versus α for **high-blowing reversal** for various nosecones.

Figure 4.5 a) Nosecone12.8f, $\alpha=45^\circ$. C_{μ} for switch, escape, low- and high-blowing reversal, as nozzle azimuth position (θ) varies.

Figure 4.5 b) Nosecone12.8f, $\alpha=50^\circ$. C_{μ} for switch, escape, low- and high-blowing reversal, as nozzle azimuth position (θ) varies.

Figure 4.5 c) Nosecone 12.8f, $\alpha=55^\circ$. C_{μ} for switch, escape, low- and high-blowing reversal, as nozzle azimuth position (θ) varies.

Figure 4.6 a) Nosecone 21.4f, $\alpha=45^\circ$. C_{μ} for switch, escape high- and low-blowing reversal, as nozzle azimuth position (θ) varies. Note the convergence of switch and escape as θ increases. Low-blowing reversal does not occur.

Figure 4.6 b) Nosecone 21.4f, $\alpha=50^\circ$. C_{μ} for switch, escape high- and low-blowing reversal, as nozzle azimuth position (θ) varies. Note the convergence of switch and escape as θ increases Low-blowing reversal does not occur.

Figure 4.6 c) Nosecone 21.4f, $\alpha=55^\circ$. C_{μ} for switch, escape high- and low-blowing reversal, as nozzle azimuth position (θ) varies. Note the convergence of switch and escape as θ increases

Figure 4.7 a) Nosecone12.8a, $\alpha=45^\circ$. C_μ for switch, escape and low-blowing reversal, as nozzle azimuth position (θ) varies. High-blowing reversal does not occur.

Figure 4.7 b) Nosecone12.8a, $\alpha=50^\circ$. C_μ for switch, escape and low-blowing reversal, as nozzle azimuth position (θ) varies. High-blowing reversal does not occur.

Figure 4.7 c) Nosecone 12.8a, $\alpha=55^\circ$. C_μ for switch, escape and low-blowing reversal, as nozzle azimuth position (θ) varies. High-blowing reversal does not occur.

Figure 4.8 a) Nosecone 21.4a, $\alpha=45^\circ$. C_μ for switch and escape as nozzle azimuth (θ) varies. Note convergence of Switch and escape as θ increases.

Figure 4.8 b) Nosecone 21.4a, $\alpha=55^\circ$. C_μ for switch and escape as nozzle azimuth (θ) varies.

Figure 4.9 a) Nosecone 12.8f Comparison of C_μ for **switch** as nozzle azimuth position (θ) varies at $\alpha=45^\circ$, 50° , and 55° .

Figure 4.9 b) Nosecone 12.8f Comparison of C_{μ} for **escape** as nozzle azimuth position (θ) varies at $\alpha = 45^\circ$, 50° , and 55° .

Figure 4.9 c) Nosecone 12.8f. Comparison of C_{μ} for **high-blowing reversal** as nozzle azimuth position (θ) varies at $\alpha = 45^\circ$, 50° , and 55° .

Figure 4.10 a) Nosecone 21.4f. Comparison of C_{μ} for **switch** as nozzle azimuth position (θ) varies at $\alpha = 45^\circ$, 50° , and 55° .

Figure 4.10 b) Nosecone 21.4f. Comparison of C_{μ} for **escape** as nozzle azimuth position (θ) varies at $\alpha = 45^\circ$, 50° , and 55° .

Figure 4.10 c) Nosecone 21.4f. Comparison of C_{μ} for **high-blowing reversal** as nozzle azimuth position (θ) varies at $\alpha = 45^\circ$, 50° , and 55° .

Figure 4.11 a) Nosecone 12.8a.. Comparison of C_{μ} for **low-blowing reversal** as nozzle azimuth position (θ) varies at $\alpha = 45^\circ$, 50° , and 55° .

Figure 4.11 b) Nosecone 12.8a.. Comparison of C_{μ} for **switch** as nozzle azimuth position (θ) varies at $\alpha = 45^\circ$, 50° , and 55° .

Figure 4.11 c) Nosecone 12.8a. Comparison of C_{μ} for **escape** as nozzle azimuth position (θ) varies at $\alpha = 45^\circ$, 50° , and 55° .

Figure 4.12 a) Nosecone 21.4a. Comparison of C_{μ} for **switch** as nozzle azimuth position (θ) varies at $\alpha=45^\circ$, 50° , and 55° .

Figure 4.12 b) Nosecone 21.4a. Comparison of C_{μ} for **escape** as nozzle azimuth position (θ) varies at $\alpha=45^\circ$, 50° , and 55° .

Nosecone: $\blacktriangle$ 12f $\triangle$ 12a $\blacksquare$ 21.4f $\square$ 21.4a
Figure 4.13 a) $\alpha=55^\circ$, Comparison of C_{μ} for **switch for various nosecones.**

Nosecone: $\blacktriangle$ 12f $\triangle$ 12a $\blacksquare$ 21.4f $\square$ 21.4a
Figure 4.13 b) $\alpha=55^\circ$, Comparison of C_{μ} for **escape for various nosecones.**

Nosecone: $\blacktriangle$ 12f $\triangle$ 12a $\blacksquare$ 21.4f
Figure 4.13 c) $\alpha=55^\circ$, Comparison of C_{μ} for **low-blowing reversal for various nosecones.**

Nosecone: —▲— 12f —■— 21.4f

Figure 4.13 d) $\alpha=55^\circ$, Comparison of C_{μ} for **high-blowing reversal** for various nosecones.

Figure 5.1: Graphical representation of the competing effects in vortex manipulation resulting in three manipulation categories. **1)** Baseline arrangement prefers the detached vortex on the blowing side. Geometric asymmetry near the apex creates a weak detachment effect. **2)** Low-blowing reversal: Blowing fluid has begun to penetrate upstream of the nozzle exit. Blowing fluid passing through the accumulation creates a weak entrainment effect that dominates. The displacement effect of the accumulation begins to grow. **3)** Displacement effect has surpassed the entrainment effect. Switch is observed. **4)** Escape occurs. The displacement effect has reached its maximum. There is a jump in the entrainment effect as more fluid is suddenly able to pass through the shear layer. **5)** High-blowing reversal: Beyond escape, the entrainment effect continues to grow with C_μ while the displacement effect decreases. The entrainment effect becomes dominant causing reversal. **6)** The entrainment effect reaches a maximum. Fluid exiting the nozzle approaches the form of a concentrated jet. **7)** The displacement effect due to blowing reaches zero. Factors that determined the default vortex configuration favouring detachment remain. **8)** Fluid exiting the nozzle has become a concentrated stream and pierces the shear layer with minimal effect on it. Vortices assume the default arrangement.

Figure 5.2 12.8f, $\alpha=55^\circ$. Example of C_{μ} for crossover and switch. As C_{μ} for crossover decreases, C_{μ} for switch increases.

Figure 5.3 a) 12.8f, $\alpha=55^\circ$, $\theta=135^\circ$. C_{μ} for switch, escape, low- and high-blowing reversal.

Figure 5.3 b) 12.8f, $\alpha=55^\circ$, $\theta=135^\circ$. C_m for switch, escape, low- and high-blowing reversal. a) C_{μ} , and b) C_m , show the same trends as θ is varied. C_m has a larger vertical scale.

Appendix A: Correlated Flow Table for the Omega Engineering Inc. Rotameter

Correlated Flow Table

Fluid water

Tube Size 1

Density 0.99980 grams/ml

Float Type Glass & Stainless Steel

Viscosity 1.0020000 cp

Serial No. 14657-14660

Date 09/14/1999

Measured & flowing at 1.00 atm and 70 °F

R at 0= 1.93 R at 50= 13.44 R at 100= 25.81

FLOW ML/MIN GLASS SCALE	FLOW ML/MIN S.S.	FLOW ML/MIN GLASS SCALE	FLOW ML/MIN S.S.	FLOW ML/MIN GLASS SCALE	FLOW ML/MIN S.S.	FLOW ML/MIN GLASS SCALE	FLOW ML/MIN S.S.	FLOW ML/MIN GLASS SCALE	FLOW ML/MIN S.S.
0.0120	1	0.0645	26	1.67	51	5.52	76	10.8	
0.0153	2	0.0825	27	1.80	52	5.72	77	11.0	
0.0191	3	0.103	28	1.92	53	5.91	78	11.3	
0.0234	4	0.127	29	2.05	54	6.11	79	11.5	
0.0283	5	0.154	30	2.17	55	6.32	80	11.8	
0.0337	6	0.183	31	2.30	56	6.52	81	12.0	
0.0398	7	0.217	32	2.44	57	6.72	82	12.2	
0.0464	8	0.253	33	2.57	58	6.93	83	12.5	
0.0537	9	0.293	34	2.70	59	7.14	84	12.7	
0.0617	10	0.337	35	2.84	60	7.34	85	13.0	
0.0704	11	0.385	36	2.98	61	7.55	86	13.2	
0.0798	12	0.437	37	3.13	62	7.76	87	13.5	
0.0899	13	0.493	38	3.27	63	7.98	88	13.7	
0.101	14	0.553	39	3.42	64	8.19	89	13.9	
0.113	15	0.617	40	3.58	65	8.40	90	14.2	
0.125	16	0.686	41	3.73	66	8.62	91	14.4	
0.138	17	0.760	42	3.89	67	8.83	92	14.6	
0.153	18	0.838	43	4.06	68	9.05	93	14.9	
0.168	19	0.921	44	4.22	69	9.27	94	15.1	
0.184	20	1.01	45	4.40	70	9.49	95	15.3	
0.201	21	1.10	46	4.57	71	9.71	96	15.5	
0.219	22	1.20	47	4.75	72	9.93	97	15.8	
0.238	23	1.32	48	4.94	73	10.1	98	16.0	
0.258	24	1.43	49	5.13	74	10.4	99	16.2	
0.279	25	1.55	50	5.33	75	10.6	100	16.4	

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Appendix B: Propagation of Measurement Uncertainty in C_μ

The uncertainty (u) in $C\mu$ is a combination of the bias limit (b) and the precision limit (p):

$$u = \sqrt{b^2 + p^2}$$

The bias limit of $C\mu$ is expressed as:

$$b = \sqrt{\sum_{m=1}^M \left(\frac{\partial C\mu}{\partial x_m} b_{x_m} \right)^2}$$

where x_m represents the individual parameters comprising $C\mu$. The bias limit of the individual parameters (b_{x_m}) is:

$$b_{x_m} = \sqrt{\sum_{k=1}^K b_k^2}$$

b_k are the bias limits introduced by each step of the measuring process for a particular parameter.

Similarly the precision limit on $C\mu$ is:

$$p = \sqrt{\sum \left(\frac{\partial C\mu}{\partial x_m} p_{x_m} \right)^2}$$

$$p_{x_m} = 2\sigma_{sd,x_m}$$

Where:

σ_{sd,x_m} = standard deviation in repeat measurements of parameter x_m .

The bias limits for the various parameters in $C\mu$ are:

- Q_{jet} -reliability of the flow rate calibration= $\pm 2\%$ average.
-overshoot of $C\mu$ for a particular event $\approx +1$ rotameter graduation = ± 0.065 ml/min average.
- S_{jet} -manufacturing tolerance in the nozzle area = ± 0.01 "
- S_{ref} -manufacturing tolerance in the reference area = ± 0.002 "

For a typical rotameter reading of 75 or 2.57 ml/min:

$$b_1 = \frac{2.57 \text{ ml} / \text{min}}{60 \text{ s} / \text{min}} \times 0.02 = 8.566 \times 10^{-4} \quad \text{Uncertainty in flow rate calibration}$$

$$b_{Q_{jet}} = \sqrt{(8.566 \times 10^{-4})^2 + (1.0833 \times 10^{-3})^2} = 1.53 \times 10^{-3} \text{ ml} / \text{s} \quad \text{Overshoot bias.}$$

$$b_2 = \frac{.065 \text{ ml} / \text{min}}{60 \text{ s} / \text{min}} = 1.0833 \times 10^{-3} \quad \text{Overall bias on } Q_{jet}.$$

The tolerances on the nozzle diameter and body diameter are high. The bias propagated to b_{s_n}

and $b_{S_{ref}}$ will be small compared to $b_{Q_{jet}}$, and so these biases will be neglected. The bias limit on $C\mu$ becomes:

$$b_{c\mu} = \left(\frac{4Q_{jet}}{S_{jet}S_{ref}V_{\infty}^2} \right) (b_{Q_{jet}})$$

$$b_{c\mu} = \left(\frac{4 \cdot \frac{2.57 \text{ cm}^3 / \text{min}}{60 \text{ s} / \text{min}}}{4.948 \times 10^{-3} \text{ cm}^2 \cdot 5.067 \text{ cm}^2 \cdot (5.396 \text{ cm} / \text{s})^2} \right) \cdot (1.53 \times 10^{-3} \text{ cm}^3 / \text{s})$$

$$b_{C\mu} = 3.591 \times 10^{-4}$$

The precision limit comes from V_∞ exclusively.

$$\bar{V}_\infty = 5.396 \text{ cm / s}$$

$$\sigma_{sd, V_\infty} = 0.1367 \text{ cm / s}$$

$$p_{v_\infty} = 2 \times 0.1367 = 0.2734 \text{ cm / s}$$

The precision limit in $C\mu$ becomes:

$$p_{C\mu} = \left(\frac{-2 \cdot 2Q_{jet}^2}{S_{jet} S_{ref} V_\infty^3} \right) (p_{V_{jet}})$$

$$p_{C\mu} = \left(\frac{-4 \cdot \left(\frac{2.57 \text{ cm}^3 / \text{min}}{60 \text{ s / min}} \right)^2}{4.948 \times 10^{-3} \text{ cm}^2 \cdot 5.067 \text{ cm}^2 \cdot (5.396 \text{ cm / s})^3} \right) (0.2734 \text{ cm / s})$$

$$p_{C\mu} = -5.093 \times 10^{-4}$$

The total uncertainty in $C\mu$ becomes:

$$u = \sqrt{(3.591 \times 10^{-4})^2 + (-5.093 \times 10^{-4})^2}$$

$$u = 6.232 \times 10^{-4}$$

Appendix C: CD-Rom Database of Images

Flow_Visualization_Images.html

The attached CD-Rom, file: **Flow_Visualization_Images.html** presents flow visualization images for the various nosecones in an HTML format. The images included in the database were selected to illustrate the various observations discussed in chapter 4 and to illustrate the vortex manipulation characteristics for each nosecone. Since some of the nosecones displayed similar vortex manipulation characteristics, not all cases are included. When a case is omitted a link to a similar case is included with reference to all other cases exhibiting the same behavior. For each nosecone, images are presented at incremental values of blowing at $\theta=135^\circ$, and $\alpha=55^\circ$ unless otherwise noted. A summary of the manipulation characteristics is included for each case. The effect of blowing on both the high and the low vortex side is shown for most of the cases. Blowing supplied to the vortex causing the greatest number of vortex manipulation events is presented first for each case.

For examples of:**see:**

–	low-blowing reversal	12.8a high vortex,
12.8f $\theta=155^\circ$ high vortex
–	high-blowing reversal	12.8f low vortex,
12.8f $\theta=155^\circ$ high vortex
21.4f low vortex

-
–	switch	any
–	entrainment (visible)	12.8a high vortex
–	high vortex drawing in as
switch is approached.	12.8f low vortex
–	return of the vortices to the
baseline arrangement at
high C_μ	21.4a low and high vortex
–	crossover	any top view
–	escape	any case