The University of Toledo

College of Engineering

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY: Russell Stucke

ENTITLED: High Angle-of-Attack Yaw Control Using Strakes on Blunt-Nose Bodies

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Mechanical Engineering

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This study explores control of a blunt-nose slender body aircraft at high angles of attack. To maximize the operational envelope and maximum payload capabilities two nose geometries were studied, hemispherical and elliptical, to determine stability and control at high angles of attack. Preliminary flow investigation indicates that at high angles of attack the elliptical nose was more stable than the hemispherical nose due to the forebody airflow and vortex interaction on the aircraft body. (Studies were carried out at Mach 0.1.) Generation and control of phantom yaw was studied using strakes of varying sizes and shapes, rectangular and triangular. The elliptical nose responded linearly to both shapes, while the hemispherical only responded beneficially to the triangular strake designs. Ultimately yaw control was optimized for both models using triangular shaped strakes,
yawing moment was maximized for the elliptical nose ($C_n = 2.07$) and the hemispherical nose ($C_n = 2.2$). The combination of the elliptical nose with triangular shaped strakes offered the most dynamic and versatile combination.
Dedication

To my parents, thank you for all of the support (financial and emotional) that you have given me over the years. I am forever indebted to you. Thank you for curiosity I was raised with and the inspiration to continue my education.

To my friends Dave, Alex, Jeff, Jerry, and Sam thanks for the good times, the support, and the continual help you have offered and given.
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Chapter One

Introduction

1.1 Motivation

Recent events have shown that missile threats are an ever-increasing risk to commercial and military aircraft. Intelligent enemy missiles with automatic decoy rejection technology are now ignoring devices currently used on aircraft to deceive and deflect the missile threats. The new intelligent technology, along with the lack of an aggressive countermeasure, exploits the aircraft’s deficiency in providing blanket protection. To alleviate the defense deficiency, the Air Force is currently developing a countermeasure device intended for self-protection of slow moving aircraft to actively seeks and destroy incoming missiles.

The Destructive Expendable (DEX), the new countermeasure, assumes the shape of a small rocket powered projectile. The DEX is integrated with an onboard computer system to predict and intercept the flight path of any missiles at a safe distance from the aircraft. Design compatibility of the DEX is requested to be similar to the current on-board flare dispenser system currently used by Air Force aircraft. Anticipated to enter the air stream at high angles of attack, the DEX is required to be effective in the destruction of the incoming missiles by having efficient warhead payload and controllability at high angles of attack. It is
within these limitations set by the design constraints, that the DEX needs to be optimized for both payload volumes through forebody design and have effective operational control at high angles of attack.

1.2 Identification of Problem

The DEX is projected to enter the air stream immediately at high angles of attack, approximately thirty to seventy degrees of pitch. As noted by Modi [29], as well as several other researchers, cylinders at incidence have four distinct flow fields on the leeward side of the body. They include fully attached flow from approximately zero to ten degrees, symmetric leeward vortex flow from ten to thirty degrees, asymmetric vortex flow from approximately thirty to sixty degrees, and bistable flow from sixty to ninety degrees. While many factors dictate the formation, behaviors, and occurrence of the vortices, the primary influence is the nose design.

Operating an aircraft at high angles of attack involves considerable risk. At the third range of airflow, from thirty to sixty degrees of incidence, vortices create the most prominent effects on the control of the DEX. Asymmetric vortices appear in the third range creating pressure differentials in the lateral plane across the aircraft body, which in turn create uneven side forces around the body and hence the term “phantom yaw” [47]. The phantom yaw can be great enough to necessitate special methods to control the aircraft at high angles of attack. Typically rudders and tail fins are used for control purposes, but due to washout the traditional methods are not likely choices. Another idea is thrust vectoring control, however limited thrust time will deeply inhibit the amount of control available. An efficient choice to
control the side forces is through controlling or modifying the vortices to the advantage of the aircraft by the use of strakes, spoilers, or other methods.

The primary motive for developing vortex control techniques is to provide for a robust yaw control at high angles of attack. Research provided by Modi [29], showed the side force created by the vortices can be on the same magnitude as the normal force, therefore the need to eliminate the potentially negative result, or manipulate the known flow characteristics to be advantageous exists. The robust yaw control created by vortex control could then allow the DEX to be maneuvered and steered when rudder control and other resources are ineffective at high angles of attack.

The proposed solution is through controlled manipulation of the vortices by a mechanical system such as a strake or surface control on the aft body, near the vortex initiation points. A thorough investigation of the flow physics is needed for understanding the air surrounding the DEX body and how the vortices created by the aircraft can be influenced by the location, size, and orientation of the mechanically controlled vortex generator. Controlled vortices can then provides a method of controlling the local side force on the forebody and the resulting yawing moment of the entire aircraft.

1.3 Literature Survey

One of the first investigations on the flow phenomenon of slender bodies was conducted by Allen and Perkins [1] in 1951. Letko [24] soon followed with quantitative measurement of side forces, and Bryson [8] was one of the first researchers to link the vortex separation to the nose cone geometry (1959). Due to the demand to increase the flight envelope of aircraft, especially that of missiles and other slender body aircraft, much research
has been done since the first investigations. Three areas, specifically the cause, reducing the side force, and controlling the vortices have been the main areas of interest.

1.3.1 Literature Survey - Causes and Parameters Affecting the Cross Flow

A major issue greatly disputed and studied amongst the aerospace field was determining the original cause of the asymmetric vortices. Hydrodynamic forces and nose tip geometry were both commonly debated as the cause of the asymmetry. Bernhardt et al [4] questionably related the vortex asymmetry to Reynolds number; however, this was done at a fixed angle of attack with varying Reynolds number, effectively leaving Reynolds Number as the only varied parameter. Keener and Chapman [22] gave hydrodynamic instability as the cause by stating it was a result of the vortices crowding together as the apex angle decreased. Ericsson [15] however compared the results of Keener and Chapman’s with several other studies to determine that the cause of flow asymmetries is micro-asymmetries in the nose cone. The advent of CFD codes later backed-up Ericsson’s conclusion when it was found by Degani and Levy [11] that a small disturbance was needed at the tip of the aircraft to create the asymmetry in the computational wake flow.

Much research has also been completed on the parameters needed to generate the asymmetric forces. For conical noses, Modi et al. [29], Keener and Chapman [22], along with Lowsone and Ponton [25], found that the smaller the apex angle of the nose the larger the side force created. This suggested that a blunter nose would benefit the aircraft by reducing or helping control the side force generation. That idea was also theorized later by an Ericsson and Beyers [16] study noting that it was nearly impossible to predict the controlling factor of the asymmetry, but noted that a blunted nose would help in the controlling process of the associated forces. The study presented in this paper includes very blunt noses,
hemispherical and elliptical nose, with large side forces present, suggests that many other factors can affect side force generation.

Modi’s [29] extensive study into nose geometry also demonstrated that at high angles of attack the induced side force from the vortices had roughly the same magnitude as the normal force, and that the resulting direction of the force was due to many different factors. Modi most prominently suggested that the most important and influential factor in generating vortex formation parameters was the design of the nose geometry.

### 1.3.2 Literature Survey - Reduction of the Side Forces

Though the exact cause or parameters that directly control vortex asymmetry are still unknown, many researchers have tirelessly attempted to control the forces produced. Rao [29] [36] effectively reduced the side force using a helical groove on a pointed ogive nose. The approach did not completely eliminate the side force but drastically reduced it. Tajfar [43] and Stahl et al. [42] approached this concept using elliptic cross sections of the body to reduce the asymmetry, while Visawanth [44] along with Brandon and Nguyen [7] used the same approach to reduce the side force generation, but did so by altering the cross section of the nose only. Each of the studies involving altering of the cross section of the nose or body did show decrease in side force generation; however it was only for limited regions of incidence. Overall, when compared to cylindrical cross section studies at large ranges of incidence, there were only slight advantages in the overall performance of the elliptical cross section.
1.3.3 Literature Survey – Controlling the Side Forces

Asghar et al. [2] tried controlling, or in his terms “suppress” the asymmetric forces. Asghar et al. did this using a strake on the leeward meridian. Asghar’s brief but effective use of a strake is a technique that is largely in use today. As seen in the F/A-18, strakes or vortex generators, as they are sometimes called, are added structures to control the location and formation of the vortices. Strakes are one of the more prominent methods used, however many other techniques such as pressurized blowing and suction, rotating nose tips, and micro-asymmetries have also been studied. Cornelius and Lucius [10] used the method of vortex control via pneumatic methods, which proved to be effective in altering the formation of the vortices and the side forces involved. Bernhardt and Williams [3] followed suit using a blowing technique and achieving the same results. The drawback to pneumatic and blowing of air is the added complexity of the system. Unless enough of a pressure difference can be manipulated from within the aircraft’s natural pressure differentials, a pump system must be added. Rotating nose tips were studied by Maynes and Gebert [26]. In their study, a rotating nose tip with varying number of strakes attached was used. Their findings concluded that the method was effective in reducing the side force by 80%, but was limited to below the critical angle where absolute instability may occur.

1.4 Literature Survey - Specific Topics of Interest to the Present Investigation

As briefly mentioned, several researchers have attempted to control/suppress the side force generation of the aircraft. The following sections are a more in-depth discussion of relevant research and studies that relate more closely to the present study, namely nose geometry and strake use.
1.4.1 Nose Geometry effects/Size and Shape

The most simplistic alteration to the slender body aircraft to modify the flow would be a modification of the nose geometry. No moving parts or mechanical operations would be needed; therefore much interest has been garnered in this area. The most often studied nose is that of ogive or conical design, which is significantly different from the hemispherical and flat ellipse nose designs used in this study.

Tajfar [43], Stahl [42], Visawanath [44], and Brandon [7] are examples of using nose geometry modifications to control the vortices. All of their research primarily emphasized the use of elliptical cross-sections, but limited benefit was realized from the forebody alteration. The primary conclusion each of the researchers came to is; that at specific ranges, usually small exclusive sets, the elliptical nose design was beneficial. In the studies data comparison, a body with a hemispherical nose often performed nearly the same.

More extreme changes in the nose geometry to control the side force generation were conducted by Rao [36] and Moskovitz [30]. Rao used an ogive nose with helical grooves machined into the nose. Several different designs for the helical grooves were used, and all performed quite well to effectively change the flow around the body. Since no adjustment can be made mid-flight, a helical nose device must be a preplanned for flight. Moskovitz [30] used a similar approach only on a smaller scale. He used a micro asymmetry on the nose as a flow effector. Contrary to the approach of making the entire nose elliptic, he only made a small portion of the nose tip elliptic, mechanical rotation of the nose tip was then used to control the vortices.

Similar to the helical nose grooves, chinned forebodies are heavily researched [48] and even implemented in today’s aircrafts, most notably the SR-71. Chined forebodies were
found to create stronger vortices, which affect the eventual vortex breakdown and bursting [50].

Ericsson and Beyers [16] did one of the more comprehensive studies of separation asymmetry and nose geometry using both conical, ogive, and blunt combinations of nose geometry. In general, the research shows that among all factors associated with the vortex asymmetry nose design indeed is probably the most influential one. Ericsson and Beyers suggest that more pronounced nose bluntness would allow for more control over the vortex formation, by allowing for a smaller area for formation.

While extensive research in the area of nose geometry has been conducted, little if any has been done on geometry pertaining to this study. The vast difference in nose designs results in a principle difference in the fluid flow around the nose. The much smaller conical and ogive nose generated vortices near the nose tip that are small and close in proximity with respect to the vortex size. However, the DEX’s blunt nose at high angles of attack will generate vortices further aft of the forebody with the vortices are very far apart relative to their size.

1.4.2 Strake Use to Modify Flow

Modi et al. [29] in 1984 briefly studied the strake method to control the formation of vortices. Rao et al. [37] in 1987 did extensive research with single and dual strakes. They concluded that dual strakes were effective, but a single strake had about the same control if located in the right position. Rao et al. used strakes that were part of the integrated forebody nose design, such that when the strakes were not used they were rotated into the nose. This
inclusive design was well conceived but too cumbersome and complicated. Nonetheless, good information came from his research about the size and location of the strakes.

Chen et al. [9], Ng [31, 33], Gangulee and Ng [18], and Boone [6] have all done extensive research in the area of strakes and pivotable strakes on the forebody. Ng [31] concluded that the closer the strake to the apex, the larger their effects are on the amplification of the vortex asymmetry. Ng and Malcolm [33] implemented an active control system of rotatable nose strakes on a mock up of the F/A-18. The control was proved to successfully modify the vortex generation and side forces involved.

One study done by Smith [40] from Eidetics International was a comprehensive and complete study of strakes on a nose boom. Though the control was not located directly on the nose or the body of the aircraft, noticeable effects and control were demonstrated.

One of the most complete reports to date of actively using strakes to control an air vehicle was demonstrated in a paper by Patel et al. [35]. In the work Patel et al. used flow effectors to modify the flow around a missile. The flow effectors acted as airflow manipulation devices for the flow around the missile, and were controlled by a closed loop control system. This closed loop control system allocated the use of eight different strakes and actuated them at separate times to control the flow. This study, while the most recent and thorough study involving active stake control on the forebody, does not involve the use of a blunt nose vehicle.

1.4.3 Strake Size and Location

Modest amounts of research have gone into the actual optimal location of the strakes; most studies instead research the feasibility and usage of strakes. Since the formation of vortices is dependent upon many variances including nose geometry, the most effective
location of a strake is specifically dependent on each model. Rao et al. [37] did conclude that for a single strake placed on the nose the optimum azimuthal range on most conical and ogive shape nose cones was approximately between 105-115 degrees from the windward meridian. Ng, Y.T. [34] also found that as a strake was placed further down the nose, the less effect it had on changing the vortex.

1.5 Scope and Objectives

The foregoing discussion leads to the following aims of this investigation:

- Determine the baseline airflow surrounding each DEX geometry using flow visualization techniques. Flow visualization will be used to find the separation points, reveal the formation of the vortices (symmetric or asymmetric), and determine causes for variances between the flow for each geometric configuration.
- Evaluate basic flow controlling devices to alter flow around DEX body to control yawing moment.
- Determine optimal locations for the flow controlling devices.
- Evaluate a small test matrix of basic shapes of the flow effector to further determine the ability and capabilities of vortex control on the DEX
- Determine optimum DEX configuration and effectiveness of vortex controlling method to control induced yaw.
1.6 Thesis Outline

The remaining parts of this thesis are organized in the following manner:

- In-depth descriptions of the setups used to carry out the current study, the measurement and control equipment used and some technical specifications of the testing facility are discussed in chapter two.

- Chapter three discusses the baseline flow characteristics, both on the surface of the DEX and the off-surface vortices.

- Chapter four discusses two methods for vortex modification and analyzes the best choice for the DEX.

- A more in-depth study to determine the optimal location of the chosen vortex generator is presented in chapter five.

- A small test matrix of strakes to determine the effectiveness of the strake on the DEX body is examined in chapter six.

- Conclusions and recommendations for future research are presented in chapter seven.

- All appendices to complement the information given in the chapters.
Chapter Two

Methodology

2.1 DEX model

Figure 2-1 shows schematics of the DEX model. The model tested was a 150% scale model of the intended DEX proposed by Orbital Research Inc. The scaling-up was done to provide more space for the internal sting balance used. The outside diameter of the main body of the model was three inches, the length was twelve inches, and the fin length was three-and-three-quarter inches by three inches.

In tandem with this study on vortex control, Orbital Research Incorporated of Cleveland (ORI), Ohio previously performed a fundamental study on the nose geometry. Two nose designs were determined via a CFD study to maximum nose volume and stability at medium to high alpha. Dimensions of the nose geometries as well as the main body can be seen in Figure 2-1. The hemispherical nose has a radius of one-and-a-half inches. The elliptical nose had an eccentricity of 0.33 (eccentricity equals minor axis divided by major axis), a radius of one-and-a-half inches, and a displacement of one-half inches. Aerospace grade aluminum was used as the construction material, and to aid in the flow visualization the model was painted a flat black color. Pictures of the models can be seen in Figure 2-2.
Figure 2-1: DEX dimensions.

Figure 2-2: DEX model pictures.
2.2.1 Overview of the Test Facility

Tests were performed at the University of Toledo 3-by-3 Subsonic Wind Tunnel. The tunnel is a closed-loop design. A 14-blade, variable-pitch fan coupled to a 150 hp electric motor drives the airflow. A variable speed motor allows the tunnel to reach over 150 mph (300 ft/s). The test section is 3' x 3' in cross-section. Two tempered-glass sidewalls and a large Plexiglas window on the ceiling provide easy access for flow visualizations. The model support incorporates a turntable, a C-strut, and a round-sting mount to allow independent variations of pitch, yaw, and roll angles. To facilitate remote model positioning automated adjustment via remote control was incorporated into the turntable drive. Additionally, a computer monitors tunnel dynamic pressure and temperature continuously during an experiment. The flow in the test-section is very uniform, with a turbulence level of about 0.5% outside of the wall boundary layers. A side door upstream of the flow straighteners and contraction section provides access to different parts of the tunnel. A picture of the wind tunnel can be seen in figure 2-3.
2.2.2 Test Section and Mounting

The DEX model was mounted using an internal sting balance that is correspondingly mounted to a C-strut on the turntable plate. The internal sting balance was used to measure force and moment. It was designed and built for the tests by the University of Toledo. The balance was designed with 5 modules, two each measuring moments in the pitch and yaw planes while the remaining module measures the rolling moment (not used in this study since little rolling moment is expected). Using the principle of Wheatstone’s bridge, summation and differencing of the voltage measurements through a circuit allow the normal and side forces, in addition to the moments, to be computed. Each section used four strain gauges.
connected as a full bridge to reduce temperature effects and to increase sensitivity. The mounted force and moment balance can be seen in figure 2-4.

![Strain Gage Diagram](image)

**Figure 2-4:** University of Toledo’s internal sting balance.

The mounting bracket that connects the internal sting balance to the C-strut has a built-in 15-degree offset. The bracket can be rotated to align the model in different roll angles. When the mounting bracket is rotated down, the angle of attack can be changed from 0 to 50 degrees by sliding the bracket along the C-strut. When the sting mount is rotated to the side, the angle of attack can be changed from -35° to 65° using the motorized turntable. Pictures of the model mounted for data acquisition and flow visualization can be seen in Figures 2-5 and 2-6.
The turntable plate rotates to allow testing at multiple angles during wind tunnel tests, and is adjustable at the wind tunnel control panel. Angles of attack for tests conducted range
from zero to sixty-four degrees. No blockage or wall corrections were made due to the lack of a reliable correction method for three-dimensional objects at high angles of attack. Since the projected model profile is relatively small compared to the cross-section of the test section, the application is low-speed, and the Reynolds number is \( \text{Re} = 1.64 \times 10^5 \), the correction needed is assumed to be small. Pictures of the turntable can also be seen in Figures 2-5 and 2-6.

### 2.3.1 Data Acquisition Instrumentation and Procedure

Outputs of the strain gage circuits, thermocouple, flow rate sensor, and angle of attack were monitored using a LabVIEW control program and a National Instruments data acquisition card. The LabVIEW program combined the measurements of the wind tunnel conditions, signal conditioning, data acquisition, and data reductions. The software was developed by UT personnel for the tests and used in conjunction with a National Instruments data acquisition card. A strain gauge conditioning unit was used to provide excitations voltage to the balance bridges and to amplify the output signals. The outputs of the signal conditioner were routed to the A/D board inside a Dell Pentium 4 computer. The National Instruments 16-bit data acquisition card allows for sampling rates of 100,000 samples/sec. A sampling rate of 200 Hz was chosen for this experiment with the number of scans set at 5,000. The resulting twenty-five seconds of sample were then averaged to obtain the voltage output from each of the four Wheatstone bridge circuits. Simultaneously, readings were also taken on the wind tunnel’s temperature, wind speed, and the turntable’s angle. A picture of the data acquisitions software’s front page can be seen in Figure 2-7 below.
2.3.2 Primary Equations Used

Due to the nearly linear relationship between strain and voltage, the linear relation of bending moment to the strain provided an easy way of determining the moment at each strain gage location. Pretest calibration of the strain gauges yields a static sensitivity coefficient. Determination of the coefficient was done using simple weights and by relating the voltage to each applied moment. The coefficient obtained in the calibration is then multiplied by the voltage readout from the Wheatstone bridge to generate the moment value at each of the four strain gauge locations.
Equations:

To aid in the discussion of the equations used, refer to the strain gauge setup in Fig. 2-4. Each equation used was based on the voltage difference between the baselines “no strain” voltage to the voltage with strain applied.

\[ V_r = e - e_o \]

\( V_r \) = Voltage difference  
\( e \) = Balance Voltage  
\( e_o \) = No strain Voltage

The voltage difference is then multiplied by the predetermined coefficient to give the measured moment at the strain gage location.

\[ M_1 = V_r \times (C_1) \]

\( M_1 \) = Moment measured at strain gage 1  
\( C_1 \) = Coefficient for Strain gage 1

Moments from the other three strain gages are also determined. Similar equations can be deduced using the same notation but varying the moment value inputs.

\[ M_2 = V_r \times (C_2) \]

\( M_2 \) = Moment measured at strain gage 2  
\( C_2 \) = Coefficient for Strain gage 2

\[ M_3 = V_r \times (C_3) \]

\( M_3 \) = Moment measured at strain gage 3  
\( C_3 \) = Coefficient for Strain gage 3

\[ M_4 = V_r \times (C_4) \]

\( M_4 \) = Moment measured at strain gage 4  
\( C_4 \) = Coefficient for Strain gage 4

From the measured moment at each strain gage location, the equivalent force, force location, force coefficients, moment and moment coefficients can be determined using the following equations.
Normal force and Side force are determined by subtracting the difference between the two corresponding measured moments, and then dividing by the distance between them.

Normal Force = \( N \)

\[
\Delta X = \text{distance between gage 1 and gage 2} \quad N = \frac{(M_2 - M_1)}{\Delta X}
\]

Side Force = \( Y \)

\[
\Delta Y = \text{distance between gage 3 and gage 4} \quad Y = \frac{(M_4 - M_3)}{\Delta Y}
\]

The location of the force can then be determined, with respect to one of the gages, by subtracting the ration of the moment and force from the distance to the gage.

Normal Force Location = \( X_N \)

\[
X_N = X_2 - \frac{M_2}{N}
\]

\( X_2 = \text{distance to gage two from the balance tip} \)

Side Force Location = \( X_Y \)

\[
X_Y = X_4 - \frac{M_4}{Y}
\]

\( X_4 = \text{distance to gage four from the balance tip} \)

Non-dimensional coefficients are determined by dividing the normal or side force for by the dynamic pressure \( Q \) multiplied by the cross sectional area of the DEX.

Normal Force Coefficient = \( C_N \)

\[
C_N = \frac{N}{Q \times A_{ref}}
\]

Side Force Coefficient = \( C_Y \)

\[
C_Y = \frac{Y}{Q \times A_{ref}}
\]

The corresponding moments for both the normal and side force are the calculated forces multiplied by the distance from the center of mass.
Pitching Moment = \( M_p \)
\[ M_p = N \times X_{cm} \]

\( X_{cm} \) = Distance from measured force to center of mass

Yawing Moment = \( M_y \)
\[ M_y = S \times X_{cm} \]

\( X_{cm} \) = Distance from measured force to center of mass

The non-dimensional coefficients for the moments are determined by dividing the calculated moments by the product of the dynamic pressure, cross sectional area, and diameter (Note: a more appropriate scale is the length rather than the diameter, however Orbital Research Inc. requested this data measurement) of the DEX.

Pitching Moment Coefficient
\[ C_M = \frac{M_p}{Q \times A_{ref} \times D} \]

Yawing Moment Coefficient
\[ C_n = \frac{M_y}{Q \times A_{ref} \times D} \]

\( D \) = diameter of DEX

2.4 Flow Visualization

Due to the limited amounts of study done on the configurations presented in this study, the airflow around the DEX was visualized using oil film surface flow visualization and laser sheet/off-surface flow visualization.

2.4.1 Oil Film/Surface Flow Testing

Oil film testing was done to determine the flow separation lines and near surface flow patterns directly on the DEX. For the experiments Zyglo Penetrant ZL-37 and a 100-Watt
Magnaflux black light were used. Zygloy penetrant, when illuminated by a black light, emits a bright green color. When the DEX model coated with the translucent oil is placed in the air flow, accumulation of the oil occurs at the regions where flow separation occurs. Once the black light is shined on the model, surface flow patterns can be seen on the model indicating the flow field near the surface of the DEX. Figure 2-8 show a picture of the oil and the black light used. Further investigation and discussion of this process will be presented in later sections.

![The luminescent oil and black light.](image)

**Figure 2-8:** The luminescent oil and black light.

### 2.4.2 Laser Sheet/Off-Surface Flow Testing

Off-surface flow visualization was done using a low-power laser diode and a Delta 3000 remotely controlled smoke machine. The smoke machine is placed upstream of the test section and the flow straighteners to minimize disturbance. When the smoke machine is activated, the air flowing past the test section is laced with the smoke from the smoke machine, and then lit up by the laser sheet along the models axis. Both the laser and smoke machine are integrated parts of the wind tunnel system and have remotes located near the test section to adjust the associated settings. Each is placed on grid tables that allow for
adjustments to place each apparatus in the most effective position for flow visualization. The smoke machine can adjust its location in “X” and “Y” directions, the laser can be adjusted in “X” and “Y” directions as well as roll angle. The laser can be seen in Figure 2-9, and the smoke machine in Figure 2-10. The laser sheet technique and its results will be discussed in later sections.
Figure 2-9: Smoke machine used in flow visualization process.

Figure 2-10: Smoke machine used in flow visualization process.
Chapter Three  
Baseline Flow Investigation

3.1 Introduction

Tests were conducted at the University of Toledo 3-ft x 3-ft wind tunnel to evaluate the airflow patterns created naturally by the baseline DEX configurations. Flow visualization techniques along with side force, normal force, and related moments were obtained from wind tunnel tests to study the baseline flow. Photographs of the vortex and surface flow structures, as well as the generated forces aid in determining the phantom yaw origin as well as the optimal control methods in later sections.

For consistency, off-surface flow visualization was done at constant axial locations for comparison between models. Figure 3-1 designates cross sectional locations where most flow visualization photographs were taken. The photos in this section were taken at thirty and fifty degrees of inclination for comparison of vortex growth and symmetry.

![Figure 3-1: Flow visualization locations for laser sheet technique.](image)
To aid in discussion, Figure 3-2 displays the cross sectional pattern created by airflow across a slender body at high angles of attack. The figure shows steady airflow with symmetric vortices on the leeward side of the circular cross section. Notice both primary and secondary separation points occur on a body in cross flow, as well as a stagnation line where flow converges.

![Diagram of cross section flow]

**Figure 3-2**: Cross section flow around DEX model, [figure taken from ref. 17].

### 3.2.1 Hemispherical Nose DEX: Off-Surface Flow Visualization

The off-surface flow visualization was performed at a speed that allows for sufficient smoke density. Tests were conducted at 64 ft/s, or approximately 0.056 Mach, and a Reynolds number of Re = .056 x 10^-6. (See appendix A for calculation). Figure 3-3 is the
leeward flow of the hemispherical nose DEX at an angle of incidence of thirty degrees. It can be seen in the figure that no asymmetry in the flow along the axis of the DEX at this angle of attack. The vortices appear to be symmetric and remain close to the DEX until section D-D.

**Figure 3-3:** Off-surface flow visualization for hemispherical DEX at thirty degrees angle of attack.
Figure 3-4 shows the flow visualization pictures of the DEX model with hemispherical nose at fifty degrees angle of attack. Vortex pairs can be seen in section A-A, with noticeable asymmetry observed at section B-B. The right side vortex appears to be higher than the left. The asymmetry persists further downstream through section D-D.

Figure 3-5 is a picture of the off-surface flow visualization taken along the axial direction of the DEX body near the nose, at fifty degrees angle of attack. In the figure, separation of the boundary layer is present just past the apex of the nose, but reattachment is
also seen about an inch past the separation point leaving a bubble of recirculation. Hsieh [20] also observed the presence of a separation bubble on a hemispherical nose.

![Recirculation Bubble](image)

**Figure 3-5:** Axial off surface flow visualization for hemispherical DEX.

### 3.2.2 Hemispherical Nose DEX: Surface Flow Visualization

Surface flow visualization was performed using the oil film method at 0.1 Mach and a Reynolds number of $\text{Re} = 0.164 \times 10^6$. The DEX model was placed on the mount at fifty degrees angle of attack. Figure 3-6 shows the leeward side surface of the hemispherical nose DEX. (Note: the wind direction is coming out of the photograph).
From Fig. 3-6, the primary and secondary separation points can be seen. The primary separation points are from the initial separation of attached flow from the DEX, and are located approximately ninety degrees from the leeward meridian. Secondary separation points are from the flow reattachment to leeward side of the cylinder and separating again from the cylinder. The secondary separation line continues until the far aft body (Reference Figure 3-2 for aid in the flow structure).

3.2.3 Hemispherical Nose DEX: Flow Summary

Flow around the DEX with the hemispherical nose at high incidences is asymmetric with a circulation bubble directly after the nose. The flow coming over the nose initially becomes separated and then reattaches itself to the DEX body. Additionally from the surface flow visualization, it can be seen that the vortex pair impinges on the DEX body until just
past the fins creating the possibility that a large amount of force could be exerted over the entire aft body. Figure 3-7 shows a schematic of the overall flow around the hemispherical nose DEX.

**Figure 3-7:** Composite sketch of hemispherical DEX model airflow.
3.3.1 Elliptical Nose DEX - Off-Surface Flow Visualization

The off-surface flow visualization was performed at the same conditions as the hemispherical nose DEX. Wind tunnel speed was at 64 ft/s, or approximately 0.056 Mach, and a Reynolds number of $\text{Re} = 0.056 \times 10^6$. The DEX model was placed on the mount at two different angles of attack: thirty and fifty degrees.

![Off-Surface flow visualization for baseline elliptical nose at thirty degrees angle of attack.](image)

Figure 3-8: Off-Surface flow visualization for baseline elliptical nose at thirty degrees angle of attack.
Figure 3-8 is a summary of the flow around the elliptical nose DEX at thirty degrees of attack. Similarly to the hemispherical nose DEX, the elliptic nose configuration at high incidence creates vortices. The vortices are essentially symmetric.

Further investigation of the elliptical nose can be seen in Figure 3-9, with the DEX pitched at an angle of attack of fifty degrees. From the progression of photos virtually no
asymmetry is seen at cross section. Vortex body size is similar to the hemispherical DEX, but with no asymmetry. After section A-A no clear vortex center is present, which may be an indication of vortex bursting.

A picture of the axial cross section flow, Figure 3-10, demonstrates that unlike the hemispherical model, the flow coming off the elliptical nose does not reattach at high angle of attack.

![Axial off surface flow visualization of elliptical DEX.](image)

**Figure 3-10:** Axial off surface flow visualization of elliptical DEX.

### 3.3.2 Elliptical Nose DEX: Surface Flow Visualization

The surface flow at fifty degrees angle of attack is shown in Figure 3-11. Primary separation points are in the same location as the hemispherical DEX, approximately ninety degrees from the windward meridian. The secondary separation points are more visible with the right separation point drawn closer to the leeward meridian than in the hemispherical nose DEX. The secondary separation lines also converge to a point before the fin.
3.3.3 Elliptical Nose DEX: Flow Summary

Flow around the DEX with the elliptical nose at high incidences is symmetric with no circulation bubble directly after the nose. Surface flow visualization indicates the possibility that at 50 degrees angle of attack the vortices separate or burst approximately one-half inch before the fin attachment point. Figure 3-12 shows a schematic of the overall flow around the elliptical nose DEX.

Figure 3-11: Leeward side surface flow visualization for elliptical nose DEX.
**3.4 Baseline Force Generation Data**

The data was taken at the University of Toledo’s subsonic wind tunnel at 0.1 Mach with a Reynolds number of $0.164 \times 10^6$, at angles of attack every two degrees from zero to sixty-four degrees. Data for both the baseline hemispherical and elliptical nose DEX are used to determine stability and the level of control each DEX possesses.
3.4.1 Normal Force and Pitching Moment

Figure 3-13 upper shows the normal force coefficient for the DEX model. The normal force is approximately linear from zero to fourteen degrees angle of attack, with relatively little difference between the hemispherical model and the elliptical model. Above fourteen degrees there is a reduction in the rate of increase of the normal force with the angle of attack.

The pitching moment graph in Figure 3-13 lower shows the same trends as that of the normal force graph. Both DEX models show similar behaviors with respect to normal force and pitching moment. The small difference in the projected area of each nose is accounts for the higher normal force and pitching moment of the elliptical nose.
Figure 3-13: Normal Force and pitching moment coefficient values from zero to sixty-four degrees angle of attack for both the hemispherical and elliptical nose DEX.
3.4.2 Side Force and Yawing Moment

Figure 3-14 shows the measured side force and yawing moment coefficients for the hemispherical and elliptical nose DEX. The data indicates that up to forty-two degrees the hemispherical DEX generates a negative side force, which corresponds to a force to the left direction of the DEX. Above forty degrees the hemispherical DEX generates a positive side force, or force to the right of the DEX. The corresponding yawing moment coefficient of the Hemi nose DEX generates a similar pattern due to a center of pressure upstream of the center of gravity. The center of pressure for side force occurs at an average of about 1.95 inches upstream of the center of gravity.

Other trends seen from the data is that the hemispherical nose DEX generates side force early, approximately at eighteen degrees, with the force rising and declining rapidly until forty-five degrees. At forty-five degrees the side force switches from negative to positive or from the left direction to a right direction. The side force above forty-five degrees remains relatively unchanged until fifty-eight degrees where a dramatic increase is seen.

The elliptical DEX data in Figure 3-14 lower show that a nearly neutral side force coefficient and yawing moment coefficient are present until fifty-two degrees. Above fifty-two degrees large increases in the side force coefficient and yawing moment coefficient are visible. The center of pressure is at 2.02 inches upstream of the center of gravity.

For comparison, the side force coefficients and yawing moment coefficients are plotted against each other in Figure 3-15. Note that the elliptical nose DEX appears much more stable when compared to the hemispherical nose DEX.
Figure 3-14: Side Force and yawing moment values from 0 to 64 degrees angle of attack for both the hemispherical and elliptical nose DEX.
Figure 3-15: Cross comparison of both DEX models side force and yawing moments values from 0 to 64 degrees angle of attack.
3.5 Flow Investigation Summary

Combining flow visualization and data from the experiments, a few conclusions about the flow can be made.

Flow Visualization:

- From the off-surface flow visualization vortex generation is present in both models, however only the hemispherical model displays asymmetry in the vortex formation.
- Vortices appear to be fully formed over the hemispherical nose DEX for the entire body, but may have bursted for the elliptical nose DEX before the fins at very high angles of attack.
- The forebody flow is a major phenomenon separating the two models: the recirculation bubble present on the hemispherical nose DEX, and pure flow separation on the elliptical nose DEX.

Wind Tunnel Data:

- The hemispherical nose DEX generates significant side forces at an early range angle of attack, and has unstable behavior at high angles of attack.
- The elliptical nose DEX has little side force generation from vortex interaction with apparent instabilities only at very high angles of incline.
- Both DEX models appear to enter a less stable phase above fifty-five degrees angle of attack.

The above summarized points lead to the conclusion that the moderate bluntness of the hemispherical DEX allows the vortices to communicate with one another, thereby introducing large amounts of asymmetry. Furthermore, instabilities in the hemispherical
DEX could be further attributed to the forebody recirculation bubble, but the exact extent or cause is not certain. On the contrary, the elliptical nose DEX with its extreme bluntness creates the vortices at an early stage on the wide forebody that do not interact with each other to generate asymmetric forces.
Chapter Four

Preliminary Yaw Control Study

4.1 Introduction

Two flow control techniques, strake and spoiler, were tested to determine which would be more effective at altering the vortex pattern and the associated yawing moment. Each technique was chosen based on past uses in aerodynamics applications. Strakes are often used for controlled separation and generation of vortices, while spoilers are used for boundary layer deflection. Examinations of the off surface and surface flows, and force data were used to determine the optimum control for the DEX body.

For comparison purposes the strake and the spoiler were the same dimensions, one inch in length and one-quarter inch in height as shown in Figure 4-1. Pictures of the two flow modifiers mounted on the elliptical nose DEX can be seen in Figures 4-2. Based on a previous study by Rao et al. [36], the strake was mounted approximately one hundred and thirty-five degrees from the leeward meridian. For this initial test, the strake control was mounted on the right side of the DEX approximately one inch from the nose tip. The spoiler was also mounted just aft of the forebody at the same angular location. Mounting of the modifiers was done using clear plastic tape. Caution was used in the taping as to not disturb the boundary layer around the strake or spoiler.
4.2.1 Hemispherical DEX with Flow Modifiers - Flow Visualization

An examination of cross-section C-C of the laser sheet technique for the hemispherical model and the baseline is provided in Figure 4-3. Figure 4-3 upper displays the baseline flow; while Figure 4-3 left displays the hemispherical model DEX model with spoiler controls and Figure 4-3 right displays the strake control.
Baseline off-surface flow at fifty degrees of incline for the hemispherical model at cross section C-C.

Off-surface flow at fifty degrees angle of attack for hemispherical model with spoiler flow effector (left) and the strake flow effector (right). Cross-sections B-B and C-C.

**Figure 4-3:** Hemispherical DEX off surface flow visualization cross comparison of flow effectors at fifty degrees angle of attack.

From the figures, a couple of observations can be made. The spoiler flow effector generates a slight increase in vortex separation from the DEX body, but with negligible increase in asymmetry. The strake generates approximately the same size vortices as the spoiler, but the right vortex is separated much further from the DEX body when compared to the effects of the spoiler.
Baseline hemispherical DEX surface flow at fifty degrees angle of attack.

Surface flow at fifty degrees angle of attack for the hemispherical models with spoiler flow effector (left) and the strake flow effector (right).

**Figure 4-4:** Hemispherical flow control surface flows cross comparison at fifty degrees angle of attack.

The surface flow visualization is shown above in Figure 4-4. The spoiler flow modifier (above – left), when added to the hemispherical nose DEX, noticeably disrupted the secondary flow. There are no longer well defined secondary separation lines. For the strake-controlled model (above – right), a more differentiated surface flow from the baseline is apparent. The right secondary separation line is visible and closely follows the strake location along the DEX axis past attachment of the fins. The left secondary separation line also appears to be pushed away from the leeward meridian. Overall, the strake generates a significant asymmetry in the leeward surface flow.
4.2.2 Hemi-Nose DEX – Normal Force and Pitching Moment

Figures 4-5 display the normal and pitching moment graphs for the hemispherical nose DEX with the proposed control methods against the baseline values. The normal force and pitching moment results show that neither measurement has changed significantly by the controls. Both the normal force and pitching moment behave in a similar fashion as the baseline case. The small increases in normal force and pitching moments can be attributed to an increase in cross sectional area as well as the instability attributed to increased vortex formation.
Figure 4-5: Normal Force and Pitching Moment Calculations for hemispherical nose DEX with preliminary flow control methods.

4.2.3 Hemispherical Nose DEX – Side Force and Yawing Moment

The side force and yawing moment for the hemispherical DEX are plotted in Figure 4-6. The results show that the spoiler has a neutralizing effect on the asymmetric side force up to an angle of attack of approximately thirty degrees. Above this angle the side force
measurement gradually declines toward a negative coefficient value of $C_m = 0.2$. Above forty degrees angle of attack, the spoiler produces a force that is in the opposite direction to that of the baseline.

The strake flow modifier, when compared to the spoiler, creates a much different effect. It can be seen that a strake placed on the right side of the DEX creates a force to the left. Through the range of incidence from thirty to sixty-four degrees of incline the strake produces a yawing moment consistently greater than the baseline value. Correspondingly, the moment arm to which the force is applied is also altered. For the spoiler the center of force is closer to the center of gravity by approximately 0.09”, while the strake produced no change in the center of force.
Figure 4-6: Side force and yawing moment calculations for hemispherical nose DEX with preliminary flow control methods.
4.3.1 Elliptical DEX with Flow Modifiers - Flow Visualization

Baseline off-surface flow at fifty degrees of incline for the elliptical model at cross section C-C.

Off-surface flow at fifty degrees angle of attack for elliptical model with spoiler flow effector (left) and the strake flow effector (right). Cross-sections C-C and C-C.

**Figure 4-7:** Elliptical DEX off-surface flows visualization cross comparison of flow effectors at fifty degrees angle of attack.

An examination of cross-section C-C of the laser sheet technique for the elliptical model and the baseline is provided in Figure 4-7. Figure 4-7 upper displays the baseline flow, while Figure 4-7 left displays the elliptical model DEX model with spoiler controls and Figure 4-7 right displays the strake control. From the figures several observations can be made. Compared to the hemispherical DEX, the spoiler generates less separation and less asymmetry on the elliptical DEX. The strakes when placed on the DEX generate the same
reaction from both models: greater separation and larger asymmetry. When located on the upper right quadrant of the DEX, the strake generates a right high vortex for each model.

Baseline elliptical DEX surface flow at fifty degrees angle of attack.

Surface flow at fifty degrees angle of attack for the elliptical models with spoiler flow effector (left) and the strake flow effector (right).

**Figure 4-8:** Elliptical flow control surface flows cross comparison at fifty degrees angle of attack.

The surface flow visualization for the elliptical nose DEX is shown in Figure 4-8. The spoiler flow modifier (above – left), when added to the elliptical nose DEX, does not noticeably disrupted the secondary flow. For the strake-controlled model (above – right), a more differentiated surface flow from the baseline is apparent especially towards the tail end. The right secondary separation line is pushed father leeward, while the left secondary
separation line appears to move windward. Overall, the strake generates a significant asymmetry in the leeward surface flow.

4.3.2 Elliptical Nose DEX – Normal Force and Pitching Moment

Figure 4-9 shows the measured normal force and pitching moment for the two control techniques versus the baseline. Little effect was noticed on the normal force and the pitching moment for both the strake and the spoiler. Results of both the strake and the spoiler closely followed the baseline side force coefficient and yawing moment coefficient.
Figure 4-9: Normal Force and pitching moment values for Elliptical nose DEX with preliminary flow control methods.
4.3.3 Elliptical Nose DEX – Side Force and Yawing Moment

Preliminary side force and yawing moment results for the elliptical-nose model are plotted in Figure 4-10. The spoiler control technique for the elliptical nose DEX is the less effective one based on both the side force and yawing moment coefficient. While the trends with angles of attack for both controls are similar, the strake has a significantly larger effect on the elliptical-nose DEX. Above ten degrees of incline the side force generated with the strake increases significantly from the baseline until an angle of attack of thirty-five degrees, and then gradually levels off at forty-five degrees. The characteristic of a generated force to the left when the strake is on the right is consistent with that of the hemispherical model.

The trend seen in the yawing moment closely mimics that of the side force. A negative moment is generated from the negative force that acts 1.97 inches upstream of the center of gravity. The strake also provides additional control above fifty degrees angle of attack.
Figure 4-10: Side Force and Yawing moment values for Elliptical nose DEX with preliminary flow control methods.
4.4 Preliminary Study Conclusion

Based on the flow visualization and force results, the combination of the elliptical nose DEX and strake offers the most linear control. The spoiler appears to have no significant impact on the elliptical nose DEX. For the hemispherical nose DEX, the spoiler did neutralize the phantom yaw. While a valid discovery, the ultimate goal of this project is to control the DEX via a manipulation of the asymmetry of the vortex flow. Therefore, the choice method to control the DEX will be the strake. Determination of the optimal size and location of the strake is discussed in the following chapter.
Chapter Five
Detailed Study of the Strake

5.1.1 Introduction

The data and flow visualization of the DEX with flow controls indicate good side force control was obtained with the strake. Further investigation was done to determine the range of usefulness and physical requirements of the strake to generate beneficial control. The goal was to obtain a better understanding of size and shape requirements and position that a strake needs to be placed in order to effectively control the DEX.

5.1.2 DEX Strake location

In reference to cylindrical coordinates, there are three parameters that define the strake location: radial, axial, and angular. Figure 5-1 displays the coordinates on the DEX body. Angular location for the DEX, which is the placement of the strake around the DEX circular body, is also denoted as the azimuthal location. Radial location is governed by the height of the strake. Axial location is determined by the location of the strake in relation to the nose tip along the axis of symmetry.
5.1.3 Strake notation

A notation system was devised to accurately keep track of the data gathered. A couple of examples are listed in Fig. 5-2.

Figure 5-1: Strake location variables.

Figure 5-2: Notation use for DEX strake testing.
The first letter denotes the nose geometry used: “H” for hemispherical and “E” for elliptical. “Strake” is placed in the notation to indicate the flow effector used. The letter after the flow effector designation, either A through F or S through W, denotes the strake design. Following the strake design is the azimuthal location designation, ranging from zero to three hundred and fifty degrees. The notation is used in all the graphs and figures in this chapter to decipher and accurately keep track of the data.

5.1.4 Axial Location

Few studies have focused on the axial location of the strake. Ng et al. [34] and Ng [31] both note that the strake location relative to the nose is the determining factor of the effectiveness of the strake; however, both studies used tangent ogive nose geometry. Upon evaluation of the surface flow visualization and the flowfield composites, the vortex initiation point is approximately one to two inches from the tip of the nose. It is then theorized that the most effective location to place a strake is in this region. For the initial testing the strake was placed approximately one inch from the nose, however a new position of one and a half inches was later proved to be more effective.

Figure 5-3 examines the side force and yawing moment generated with the new positioning of the strake. The original placement of the strake is denoted as “H-Strake-1 inch” and the new placement is denoted as “H-Strake-1.5 Inch”. In both cases the side force coefficient and the yawing moment coefficient advantages of the further aft placement can be seen at higher angles of attack. The further aft position prevented the induced side force from switching directions at high angles of attack and also generates a larger positive yawing moment than the initial strake position. The moment arm of the force was moved an additional two tenths of an inch past the center of gravity. The new aft positioning, denoted
as “H-Strake-1.5 Inch” in the plots, will be the standard position for all subsequently tested strakes.

Figure 5-3: Axial position study.
5.2.1 Optimal Azimuthal Location

The effect of strake azimuthal location has been studied extensively. A strake too close to the leeward meridian may result in separation before the strake, while too close to the windward meridian the airflow may reattach and subsequently reduce the control effectiveness. Rao et al. [36], for example, studied both single and dual strakes on a tangent ogive nose slender body. Rao determined that the optimal azimuthal location for strake was roughly one hundred and fifteen to one hundred and twenty degrees from the windward meridian. It was theorized that this location was the optimal due to upstream placement of the strake from the natural flow separation location. The approach used in this study was to identify the optimal location using flow visualization, and data acquisition.

5.2.2 Test Procedure

Figure 5-4 illustrates the coordinate system for the azimuthal dimension used in this study. The angular orientation is based from the view of the DEX’s tail fins facing the DEX nose. With zero degrees at the windward meridian and the angle increasing in a clockwise fashion, the left side of the DEX is at the positive ninety degree mark, the right side of the DEX the two hundred and seventy degree mark, and the leeward meridian one hundred and eighty degrees.
Figure 5-4: Angular coordinate system used for determination of azimuthal location.

The optimum location of the strake was determined by rotating the strakes azimuthally around the DEX. The strake one inch in length and one-fourth inch in height. Ten-degree increments were marked on the DEX body, and flow visualization was performed at each increment. Photos were taken at each ten-degree azimuthal increment at the first three axial cross sections. A total of thirty-five strake positions were tested on each of the DEX configurations. Figure 5-5 shows a picture of the DEX model with the incremental distances marked on the body. The picture is for the case with the strake located at the leeward meridian, or one hundred and eighty degrees.
5.2.3 Off-Surface Flow Visualization Results

For each quadrant of the strake position the maximum vortex displacement was noted. The following sections examine a sequence of photos corresponding to strake positions for maximum vortex displacement. Additionally, photos of the strake at the windward (0 degrees) and leeward (180 degree) meridians are included for comparison.

In this chapter only C-C cross sections are displayed. Similar flow reactions to the strake location are seen in the upstream locations, A-A and B-B, with the effect at section C-C being more pronounce due to the downstream growth of the vortices. Appendix B contains photographs for sections A-A and B-B.
5.2.4 Hemispherical Nose DEX Strake Location

Figure 5-6: Azimuthal location testing of hemispherical nose DEX Cross Section C-C.
In Fig. 5-6, only photos of the maximum vortex control locations are displayed to efficiently convey the influence of the strake location on the vortices. Photos with the strake at the windward and leeward meridians are also shown. A comparison of the vortex flow at cross section C-C, with the strake in the optimal locations of each quadrant can be seen.

At 50 degrees angle of attack the baseline asymmetry for this model favored a right vortex high configuration (Figure 3-3) i.e., the right vortex situates farther from the surface compared to the left. In figure 5-6(a) and 5-6(b), with the strake at the windward and leeward meridians respectively, no flow bias can be seen.

Figures 5-6(c) and 5-6(d) are the corresponding sixty and three hundred degree locations of the strake on the windward side of the DEX. Figure 5-6(c) has the strake on the left side of the DEX, and the left vortex is situated slightly higher from the surface than the right vortex. Figure 5-6(d) has the strake on the right side of the DEX, which produces the opposite effect on the vortices with the strake on the left.

When the strake is moved to the upper quadrants of the DEX a similar but magnified response is achieved. Figure 5-6(d) shows that the left vortex is now positioned higher that the right when the strake is at the one hundred and twenty degree mark. With the strake at the two hundred and forty degree location, shown in Fig. 5-6(e), the right vortex is now higher. This is parallel to that of the strake at one hundred and twenty degrees. In each case the vortex is positioned higher on the side of the strake, however the maximum upward displacements of the left and right vortices occurred at one hundred and twenty degrees and two hundred and forty degrees respectively.
5.2.5 Elliptical Nose DEX

Figure 5-7 displays sequences of photographs of the azimuthal test for the elliptical nose DEX at 50 degrees angle of attack. In the sequence shown, only photos of the maximum vortex control are displayed to efficiently convey the influence of strake location on the vortices. Photos with the strake at the windward and leeward meridians are also shown.

In figures 5-7(a) and (b) an even more symmetric vortex pair than that of the baseline configuration. The left and right vortices, with the strake at zero and one hundred and eighty degrees appear to be at approximately the same height.

With the strakes at sixty and three hundred-degree positions, Figures 5-7(c) and (d) show a significant degree of vortex asymmetry. In each case, the vortex is positioned higher on the side of the strake. The largest effect of the strakes is seen at the positions of one hundred and twenty and two hundred and forty degrees, shown respectively in figure 5-7(e) and (f).
a) Strake angle 0° (windward meridian)  

b) Strake angle 180° (leeward meridian)  

c) Strake angle 60° (bottom left quadrant)  

d) Strake angle 300° (bottom right quadrant)  

e) Strake angle 120° (upper left quadrant)  

f) Strake angle 240° (upper right quadrant)  

**Figure 5-7**: Azimuthal location testing of elliptical nose DEX at section C-C. At fifty degrees angle of attack.
5.2.6 Azimuthal Study Summary

From the study, it is apparent that the elliptical nose DEX shows similar vortex flow patterns per strake position as the hemispherical nose DEX. There was no change in the most effective strake locations around the axis for both DEX models, with the most effective positions being at one hundred and twenty and two hundred and forty degrees. This coincides with the positions noted by Modi et al [29]. Strakes at windward and the leeward meridians also produced a neutralizing vortex structure, which was hypothesized by several researchers.

Overall, the elliptical nose DEX showed the largest influence of the strake on the off-surface flow along with the most symmetric response to opposing placements of the strake. The largest influence of the strake is seen at one hundred and twenty degrees and two hundred and forty degrees, these two placements will be used for further testing of the control.

Figure 5-8 displays a final comparison of the baseline vortex flow for the hemispherical nose DEX compared to the strake affected flow at two hundred and forty degrees and one hundred and twenty degrees. Additionally, Figure 5-9 displays a similar final comparison for the elliptical nose DEX.
Figure 5-8: Hemispherical nose DEX controlled and baseline flow.
Figure 5-9: Elliptical nose DEX controlled and baseline flow comparison.
5.3  **Hemispherical Nose DEX - Azimuthal Location Validation.**

To validate the off-surface flow visualization results, a brief study of the azimuthal location was conducted using the side force coefficient and the yawing moment coefficient. One hundred and twenty degrees from the windward meridian was determined to be the most effective for vortex modification, therefore the largest side force should be seen at the same strake position. To see if the assumption was correct three positions of the strake were tested: 230, 240, and 265 degrees. From Figure 5-10 it is seen that indeed the expected results are rendered. Although, the differences are slight, both the side force coefficient and yawing moment coefficient for the 240 degree location are consistently greater than the other two azimuthal locations tested.
Figure 5-10: Hemispherical nose azimuthal location validation.
6.1 Introduction

Side force and induced yawing moment created by strakes of different shapes varying in height and length were measured. The strake designs were all chosen on the possibility of being used on a DEX, with size being the major factor involved. Much larger strakes could be tested but were not due to anticipated space restrictions within the aircraft body. If the DEX were to use as an actuated vortex generator it would need to be retractable. Too large of a strake, the interior space needed to house the actuation device would be too large and the actuation method too cumbersome.

Shown in Figure 6-1 is the baseline strake used for previous testing. It is denoted as Strake “A”. Several variations of Strake A are used, varying in length and height and are denoted as Strakes B through F. These strakes were tested as alternatives to Strake A to determine if smaller strakes could out-perform or perform similar to larger strake sizes. Alternative to strakes A-F are strakes S-W. These strakes are triangular in shape, with the exception of strake S. These strakes were designed to be similar to nose boom strakes and other vortex generation devices typically seen on slender bodied aircraft.
Figure 6-1: Strake dimensions.
Note: Due to the vast amount of experimental data gathered, the focus of the experiment being on the side force and yawing moment, and minimal strake influence on normal force and pitching moment, the full sets of normal force coefficient graphs and pitching moment coefficient graphs are located in Appendix D. Only selected results will be presented below.

Data for each strake was acquired with the wind tunnel at 0.1 Mach, $Re = 1.64 \times 10^5$, and the angle of attack from zero to sixty-four degrees in two-degree increments. Each strake was tested at the 120 degrees azimuthal location ($\theta = 120^\circ$) and the opposing 240 degrees azimuthal location ($\theta = 240^\circ$).

6.2.1 Hemispherical Nose DEX – Strakes A-F – $\theta = 120^\circ$

Several key phenomena can be observed from the data acquired for strakes A-F at $\theta = 120^\circ$ (Figure 6-2). Principally, the baseline asymmetry is reversed due to the strake placement on the left side of the DEX. The result for each strake follows similar form, with maximum side force peaking at approximately thirty degrees angle of attack. A force reversal affect is observed for all strakes except A. The side force switches directions above forty degrees angle of attack, from a force in the right direction to a force to the left. Above forty degrees of incline each strake, with the exception of strake A, averages a side force coefficient of approximately $C_Y = 0.25$.

The yawing moment coefficient reflects the same trends, in that Strake A produces the largest and best behaved yawing moment coefficient. For instance, strake E generates a large negative yawing moment from thirty degrees angle of attack to forty-five degrees angle of attack, and then has a directionally varying yawing moment from forty-five degrees to sixty-four degrees of incline.
Figure 6-2: Hemispherical DEX strakes A through F at 120 degrees azimuthal.
6.2.2 Hemispherical Nose DEX – Strakes A-F – $\theta = 240^\circ$

Placing a strake at the azimuthal location of $\theta = 240^\circ$ result in an opposite side force with similar values compared with the case of $\theta = 120^\circ$. Strake A at this location enhances the baseline asymmetry. The corresponding side force coefficient is increased by thirty-three percent over the baseline from zero to thirty nine degrees of incline, and an average side force coefficient of $C_Y = 0.25$ is generated from thirty nine degrees to sixty-four degrees. Strake E, with the maximum length tested along with strake A, generates the second highest side force. However strake B, which has the same height as strake A, performs poorly and does not produce significant changes on the baseline value side forces. The most notable poor performers were strakes C and D. These strakes produce relative small side forces from thirty-five to fifty-five degrees angle of attack, and a side force reversal at higher angles.

Strakes A and E generate the highest yawing moment. No well-behaved controls are garnered using strakes, C, D, and F.
Figure 6-3: Hemispherical DEX strakes A through F at 240 degrees azimuthal.
6.2.3 Hemispherical Nose DEX – Strakes A-F - Summary

Results from testing strakes A-F at 240 degrees azimuthal indicate that, with perhaps the exception of strake A, the baseline asymmetry is too strong for any of the controls to completely overcome over the entire range of angle of attack. For strakes that are effective, it is obvious that the length of the strake plays an important role for controlling the hemispherical nose DEX. Maximum length strakes, strakes A and E, produced the most beneficial side force generation, while the shorter strakes, strakes C, B, D and F, generated small side forces and often increase the instability of the DEX. On average, strakes A-F move the center of force toward the center of gravity by approximately 0.07”. Strakes A and E had the opposite effect of lengthening the moment arm by an average of 0.33”, moving the baseline distance of 2.11 inches to 2.44 inches.

6.2.4 Hemispherical Nose DEX – Strakes S-W – $\theta = 120^\circ$

Strakes S-W, as shown in Figures 6-4 and 6-5, offer substantially different results compared to the rectangular shaped strakes. The maximum side force coefficient for Strake S is approximately 2, compared to Strake A that only had a maximum side force coefficient of 1.05. The yawing moment coefficient, with a maximum value near $C_n = 2.5$, has an increase of 250% over strake A. Unlike the rectangular strakes, there is an absence of side-force direction reversal. Strake S, the largest strake, generates significantly higher side force than any other strake with a near-linear force increase with angles above twenty-four degrees. A maximum side force coefficient of 2 is attained by strake S at fifty-two degrees of incline. Strake V generates the highest yawing moment among all strakes until an angle of attack of forty-eight degrees. This is due to Strake V having the furthest aft center-of-force. At
approximately 3.95 inches, Strake V is one-half inch farther than the other strakes center-of-force, which accounts for the largest yawing moment coefficient.

Figure 6-4: Hemispherical DEX strakes S through W at 120 degrees azimuthal.
6.2.5 Hemispherical Nose DEX – Strakes S-W – $\theta = 240^\circ$

In Figure 6-5 upper, it is evident that until approximately thirty-degrees triangular strakes placed at $\theta = 240^\circ$ are ineffective and even create predictable adverse amounts of side force. Above thirty-three degrees side force is generated to the opposing side of the strake, with the maximum side force generation being produced by the largest strakes, S and W.

In parallel with the side force measurements, the yawing moment coefficient yields similar behaviors with the exception of strake T generating the most yawing moment. Only the smallest strakes T and V generate the yawing moment without switching direction over the entire angle of attack range.
Figure 6-5: Hemispherical DEX strakes S through W at 240 degrees azimuthal.
6.2.6 Hemispherical Nose DEX – Strakes S-W – Summary

Strakes S-W generate obvious increases in side force and yawing moment that surpasses the naturally generated asymmetric force. Additionally a shift in the center of force away from the center of gravity, by an average of up to one-half inch, also incurred. With a strake placed on the right side of the DEX at $\theta = 240^\circ$, a reversal in side force direction can be seen at medium angles of attack. This can be attributed to strong baseline vortex asymmetry. No clear indication to the effect of strake size is found. The largest strakes produced the largest side force, but the smallest strake generated the largest moment due to a shift in the center of force.

6.3.1 Elliptical Nose DEX – Strakes A-F – $\theta = 120^\circ$ and $240^\circ$

The rectangular strakes on the elliptical DEX, results shown in Figures 6-6 and 6-7, offer predictable linear side force generation and related yawing moment. Similar to the hemispherical DEX, the longest strakes, A and E, generate the most side force. Strakes B, C, D, and F, generate similar side force and yawing moment magnitudes. The yawing moment coefficient and normal force coefficient generated for the elliptical nose DEX is on the same order of magnitude as the hemispherical nose DEX, but with a much more linear behavior and no apparent directional reversal.

Results for the strake location of 120 degrees azimuthal are presented in Figure 6-7. The side force and yawing moment are similar in magnitude but opposite in direction to those at 240 degrees.
Figure 6-6: Elliptical DEX strakes A through F at 120 degrees azimuthal.
Figure 6-7: Elliptical DEX strakes A through F at 240 degrees azimuthal.
6.3.2 Elliptical Nose DEX – Strakes S-W – $\theta = 120^\circ$ and $240^\circ$

For the elliptical DEX model with triangular shaped strakes, results shown in Figures 6-8 and 6-9, an increase in side force generation from 100 to 200% is seen over strakes A-F. Strakes S-W again shows predictable side force generation above twenty degrees of incline. Each strake shows varying magnitudes of side force and yawing moment, depending upon the strake size. Strakes S and W, the largest strakes by size, generate the most side force coefficient and yawing moment. Strake T, the smallest strake by size, generates the smallest side force for the entire rage tested. For all strakes, the average center of pressure creates a longer moment arm by approximately three tenths of an inch.
Figure 6-8: Elliptical DEX strakes S through W at 120 degrees azimuthal.
Figure 6-9: Elliptical DEX strakes A through F at 240 degrees azimuthal.
6.3.3 Elliptical Nose DEX – Strakes A-F and S-W – Summary

The elliptical nose DEX with strakes of both rectangular and triangular shape creates linear and stable side force and yawing moment. The rectangular strakes enhance the side force control, with maximum forces garnered towards the longest strakes. Additionally, Strakes A-F appear to have little-to-no effect on the center of pressure, only minimally altering the center of force location by approximately 0.05” on average. Strakes S-W generate significantly more force than the rectangular strakes. The larger strakes generate more side force, but the smaller strakes increase the moment arm slightly more.

6.4 Test Conclusion

Results from the tests indicate the following:

*Hemispherical Nose DEX:*

The hemispherical nose DEX appears to have very strong, yet unstable baseline vortex flow. Strakes A-F were marginally capable of altering and varying the amounts of side force and yawing moment, but not in a controlled and linear fashion. Additionally it was determined that a minimum size is needed for the control to take effect, with the most important size parameter being the length of the strake. Adverse effects of strakes A-F occurred when generated forces would switch directions.

With strakes S-W the hemispherical DEX is capable of producing twice as much side force compared to strakes A-F. Stability is however still an issue, which indicates a strong baseline influence. Strakes S–W also show a limited range in the forces able to be generated, leaving little room for the needed variations in force output. Strakes placed on the right side
of the hemispherical DEX appear to result in a less stable control than strakes placed on the left side of the DEX, which further suggests the strong influence of the bias in the baseline asymmetry.

**Elliptical Nose DEX:**

The elliptical nose DEX baseline configuration generated little asymmetric side force and yawing moment. Both rectangular and triangular strakes produced well-behaved side force and yawing moment that are comparable to the maximum side force generated on the hemispherical DEX. The Strakes A-F results also indicate that strake length is the major influencing factor for the effectiveness of rectangular strakes, similar to the hemispherical DEX. The largest strakes produced linear and stable side force with no directional reversal. The Triangular strakes produced nearly 2.5 times the side force than the rectangular strakes.
Chapter Seven
Conclusions and Future Work

7.1 Conclusions

A detailed study was carried out on the yaw control of a blunt nose body at high angles of attack. The resulting airflow around each forebody was thoroughly studied. Results from the study revealed the following.

1. The moderate bluntness of the hemispherical DEX allows the vortices to be dependent upon one another, introducing large amounts of asymmetry. Furthermore, instabilities in the hemispherical DEX could be further attributed to the forebody recirculation bubble, but the exact extent or cause is not certain. On the contrary, the elliptical nose DEX with its extreme bluntness creates the vortices at an early stage on the wide forebody that do not interact or create asymmetric forces.

2. Based on the flow visualization and force results, the strake generated the most desirable results. The strake when compared to the spoiler offered a more significant controlled side force. For the hemispherical nose DEX, the spoiler did neutralize the phantom yaw. While a valid discovery, the ultimate goal of this project is to control the DEX through manipulation of the vortex flow. When used on both the hemispherical
nose DEX and the elliptical nose DEX, the strake offered an increase in side force generation and yawing moment and therefore the method.

3. From the acquired force data it is apparent that the hemispherical nose DEX has a very strong, yet unstable baseline vortex flow. Strakes A-F were marginally capable of altering and varying the amounts of side force and yawing moment, but not in a controlled and linear fashion. Strakes S-W on the hemispherical DEX were capable of producing twice as much side force compared to strakes A-F. Stability is however still an issue, which indicates a strong baseline influence. Strakes used on the hemispherical DEX also show a limited range in the generated forces, leaving little room for the needed variations in force output.

4. The optimized combination for control is with the strake and the elliptical nose DEX. The elliptical nose DEX baseline configuration generated little asymmetric side force and yawing moment, however the vortices welcomed manipulation and control. Both rectangular and triangular strakes produced well-behaved side force and yawing moment that are comparable to the maximum side force generated on the hemispherical DEX. Strakes A-F results also indicate that strake length is the major influencing factor for the effectiveness of rectangular strakes, similar to the hemispherical DEX. The largest strakes produced linear and stable side force with no directional reversal. The Triangular strakes produced nearly 2.5 times the side force than the rectangular strakes.
7.2 Recommendations for Future Work

Results from this study are promising, but only serve as a preliminary step for future developments. To reach the final goal of an aggressive and highly maneuverable countermeasure, more studies need to be conducted. Based purely on the results from this study, the following are recommended.

- Eliminate all further study of the hemispherical nose DEX. The study proved that is was unstable and had highly dominant baseline flow asymmetry.
- For the elliptical nose DEX: expand the test matrix to a much broader range of strakes to minimize the size requirement.
- Conduct a dynamic experiment in which the strake deployment time and flow response time will be studied to further identify the correct control parameters.
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Appendix A

Mach and Reynolds Number Calculations


The follow equations and calculations are used to determine Mach number and the related Reynolds Number.

Speed of Sound:

\[ a = \sqrt{\gamma RT} \]

\[ a = \sqrt{1.4 \left( \frac{287 \text{ kg m}^2}{\text{s}^2} \right) - 298 \text{K}} \]

\[ a = 346.03 \frac{\text{m}}{\text{s}} \Rightarrow 1135.26 \frac{\text{ft}}{\text{s}} \]

Wind tunnel test speed of approximately 0.1 Mach is used for all data acquisition and some flow visualization procedures.

\[ M = \frac{V_s}{a} \Rightarrow Ma = V_s \]

\[ 0.1 \left( 346.03 \frac{\text{m}}{\text{s}} \right) = V_s \]

\[ V_s = 34.6 \frac{\text{m}}{\text{s}} \Rightarrow 113.5 \frac{\text{ft}}{\text{s}} \]

Flow visualization using later sheeting technique was done at M=.056.

\[ M = \frac{V_s}{a} \Rightarrow Ma = V_s \]

\[ M= \text{Mach number} = 0.1 \]

\[ V_s= \text{Free Stream Velocity} \]

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0.056 \left( \frac{346.03 \text{ m}}{s} \right) = V_s

V_s = 19.05 \frac{\text{ m}}{s} \Rightarrow 64.0 \frac{\text{ ft}}{s}

The Calculated Reynolds number data acquisition:

\[ \text{Re} = \frac{V_s D}{\nu} \]

\[ \text{Re} = \frac{34.6 \frac{\text{ m}}{s} \times 0.0762 \text{ m}}{1.60 \times 10^{-5} \frac{\text{ m}^2}{s}} \]

\[ \text{Re} = 1.64 \times 10^5 \]

The Calculated Reynolds number for off-surface flow visualization:

\[ \text{Re} = \frac{V_s D}{\nu} \]

\[ \text{Re} = \frac{19.05 \frac{\text{ m}}{s} \times 0.0762 \text{ m}}{1.60 \times 10^{-5} \frac{\text{ m}^2}{s}} \]

\[ \text{Re} = 0.9184 \times 10^5 \]
Appendix B

Azimuthal Location pictures (Reference Chapter 5)

a) Strake angle 0° (windward meridian)  b) Strake angle 180° (leeward meridian)

c) Strake angle 60° (bottom left quadrant) d) Strake angle 300° (bottom right quadrant)

e) Strake angle 120° (upper left quadrant) f) Strake angle 240° (upper right quadrant)

Figure B-1: Azimuthal location testing of hemispherical nose DEX at section A-A. Angle of attack fifty degrees.
Figure B-2: Azimuthal location testing of hemispherical nose DEX at section B-B. Angle of attack fifty degrees.
**Figure B-3:** Azimuthal location testing of hemispherical nose DEX at section C-C. Angle of attack fifty degrees.
Figure B-4: Azimuthal location testing of elliptical nose DEX at section A-A. Angle of attack fifty degrees.
a) Strake angle 0° (windward meridian)  
b) Strake angle 180° (leeward meridian)

c) Strake angle 60° (bottom left quadrant)  
d) Strake angle 300° (bottom right quadrant)

e) Strake angle 120° (upper left quadrant)  
f) Strake angle 240° (upper right quadrant)

**Figure B-5:** Azimuthal location testing of elliptical nose DEX at section B-B. Angle of attack fifty degrees.
Figure B-6: Azimuthal location testing of elliptical nose DEX at section C-C. Angle of attack fifty degrees.
Figure C-1: Normal Force Coefficient and Yawing Moment Coefficient for Hemispherical Nose DEX for Strakes A-F at 120 degrees azimuthal.
Figure C-2: Normal Force Coefficient and Yawing Moment Coefficient for Hemispherical Nose DEX for Strakes A-F at 240 degrees azimuthal.
Figure C-3: Normal Force Coefficient and Yawing Moment Coefficient for Hemispherical Nose DEX for Strakes S-W at 120 degrees azimuthal.
Figure C-4: Normal Force Coefficient and Yawing Moment Coefficient for Hemispherical Nose DEX for Strakes S-W at 240 degrees azimuthal.
Figure C-5: Normal Force Coefficient and Yawing Moment Coefficient for Elliptical Nose DEX for Strakes A-F at 120 degrees azimuthal.
Figure C-6: Normal Force Coefficient and Yawing Moment Coefficient for Elliptical Nose DEX for Strakes A-F at 240 degrees azimuthal.
Figure C-7: Normal Force Coefficient and Yawing Moment Coefficient for Elliptical Nose DEX for Strakes S-W at 120 degrees azimuthal.
Figure C-8: Normal Force Coefficient and Yawing Moment Coefficient for Elliptical Nose DEX for Strakes S-W at 240 degrees azimuthal.