

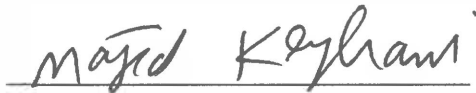
To the Graduate Council

I am submitting herewith a thesis written by Charles Roy McConnell Jr entitled "Experimental Aerodynamic Analysis of a Wing-Flap System with Delta Vortex Generators." I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aerospace Engineering.

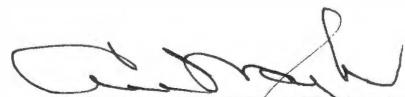


Robert Bond, Major Professor

We have read this thesis and
recommend its acceptance:



Acceptance for the Council:



Vice Chancellor and Dean of
Graduate Studies

Thesis
2005
, m22

**Experimental Aerodynamic Analysis of a Wing-Flap System
with Delta Vortex Generators**

A Thesis Presented
for the Master of Science Degree
The University of Tennessee, Knoxville

Charles Roy McConnell Jr
December 2005

ACKNOWLEDGEMENTS

I would like to express volumes of thanks to all those involved in helping me through the process of completing my thesis research. I would like to express my deepest gratitude to Dr. Bond who has always been there to consult with on troubling issues and to just sit and have a chat with. He has been instrumental in helping to fund this research and his willingness to assist me was more than I could have expected. He has been a valued mentor, teacher, motivator, and friend; I am very thankful for having had the opportunity to work with him on this research.

To my committee members, Dr.'s Milligan and Keyhani, I am thankful that you have been able to be a part of this research and I am even more thankful of the influences that you have had on my education. If not for the educational impressions made upon me by you, I would not be able to consider my experiences at the University of Tennessee nearly as valuable as they have been. I would also like to thank the Department of Mechanical, Aerospace and Biomedical Engineering at the University of Tennessee; the faculty and staff have always been there to assist me.

There have been a handful of educators in my life that have had a memorable influence on my desire to learn and on my commitment to achieve. Most importantly is Dr. Eric Klumpe, if not for him there is no doubt that I would not be where I am today in obtaining a career as an Aerospace Engineer.

I would also like to thank my wife, Jennifer. Her grace has always amazed me and her compassion for others influences me to recognize my own faults and want to be a

better person. Her support in my pursuit of this degree has been unwavering and she has been my motivation when I've been overwhelmed by the graduate school experience. I have been blessed by the gift of her and I would not be where I am today if it were not for that blessing. I would also like to thank my family, I appreciate their encouragement and pride in my pursuit of this degree. I am thankful that there has always been a place for me in the family business and even more thankful that they have been so supportive of my desire to leave that life and become an engineer.

ABSTRACT

Experimental Aerodynamic Analysis of A Wing-Flap System with Delta Vortex Generators

By Charles McConnell Jr

The principle idea upon which the use of vortex generators (VGs) is based has been to control flow separation. The characteristic of VGs has been used to improve lift and alter the stall characteristics of aircraft and has been a relatively common practice for many years. Due to the seemingly limitless range of VG geometries and arrangements, which are largely dependant upon the desired aerodynamic performance, there has been a broad investigation into VG application.

The purpose of this experimental investigation has been to collect data to be used to establish the effects of various delta shaped vortex generators (delta-VGs) geometries and locations for comparison with a baseline model. The data for this research were collected using the University of Tennessee subsonic wind tunnel and were used to produce aerodynamic information including coefficients for lift, drag and pitching moment.

In this research program it was found that delta-VGs mounted along the flap-hinge line produced little effect on lift. It was believed that flow separation was either induced by the delta-VGs or that separation simply occurred before the delta-VGs could aide in the flow characteristics on the model. Testing with the delta-VGs near the leading edge of the model produced significant aerodynamic benefit regardless of the delta-VG arrangement. Continued experiments on some of the more beneficial arrangements

identified that the length and the spacing between the delta-VGs produced results that could improve the maximum lift coefficient, the angle of attack at which it occurred and improved the lift to drag ratio. In the case of a $\frac{3}{4}$ " length delta-VG with a 2" spacing and a 60° sweep angle, improvements by as much as 57% from the baseline were observed in $C_{L_{max}}$. The separation region for this configuration was also delayed by 4° . These experiments also revealed that decreasing the spacing between delta-VGs increased the magnitude of the lift to drag ratio and in some cases extended the angle at which the maximum lift to drag ratio occurred.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION	1
CHAPTER 2: LITERATURE REVIEW	3
CHAPTER 3: EXPERIMENTAL APPARATUS	7
3.1 UTK Subsonic Wind Tunnel	7
3.2 Wind Tunnel Instrumentation and Equipment	7
3.3 Calibration of Test Equipment	9
3.4 Two Dimensional Wind Tunnel Model	11
CHAPTER 4: EXPERIMENTAL PROCEDURE.....	13
4.1 Experimental Test Procedure	13
4.2 Experimental Data Acquisition Procedure.....	14
4.3 Experimental Determination of Aerodynamic Coefficients.....	15
4.4 Experimental Placement of Vortex Generators.....	15
4.5 Error Estimation for Experimental Data.....	16
CHAPTER 5: RESULTS AND DISCUSSION	20
5.1 Baseline Model Data.....	20
5.2 Length Comparison of Vortex Generators at Flap-Hinge Line.....	22
5.3 Spacing Comparison of Vortex Generators at Flap-Hinge Line	22
5.4 Additional Geometries of Vortex Generators at Flap Hinge Line.....	23
5.5 Surface Comparison of Leading Edge Vortex Generators.....	23
5.6 Length Comparison of Leading Edge Vortex Generators.....	25
5.7 Spacing Comparison of Leading Edge Vortex Generators	26

CHAPTER 6: CONCLUSIONS.....	28
LIST OF REFERENCES	31
APPENDIX.....	33
VITA.....	107

LIST OF TABLES

Table	Page
4.1.1 Experimental Test Matrix	34
4.5.1 Calculation of Error in Lift	34
4.5.2 Calculation of Error in Drag	34
4.5.3 Calculation of Error in Pitching Moment	35
4.5.4 Error in Dynamic Pressure, Effect on Lift	35
4.5.5 Error in Dynamic Pressure, Effect on Drag	35
4.5.6 Error in Dynamic Pressure, Effect on Pitching Moment	36
4.5.7 Tabulated Error Values	37
4.5.8 Total Error	38
5.7.1 Data Comparison for α -Dependent Data, $\delta = 0^\circ$	39
5.7.2 Data Comparison for α -Dependent Data, $\delta = 10^\circ$	40
5.7.3 Data Comparison for δ -Dependent Data, $\alpha = 10^\circ$	41

LIST OF FIGURES

Figure	Page
3.1.1 Schematic of UTK Subsonic Wind Tunnel	42
3.3.1 Centerline Velocity Distribution vs Time	43
3.3.2 Vertical Velocity Distribution vs Position	44
3.3.3 Horizontal Velocity Distribution vs Position	45
3.3.4 Horizontal Variation in Turbulence Intensity %	46
3.3.5 Vertical Variation In Turbulence Intensity %	47
3.3.6 Variation of Turbulence Factor with Turbulence Intensity from Hot-Wire Measurements	48
3.3.7 Repeatability in Pyramidal Balance, No Load	49
3.3.8 Repeatability in Pyramidal Balance, 25 Pound Load on Lift Cell	49
3.3.9 Repeatability in Pyramidal Balance, 5 Pound Load on Drag Cell	50
3.3.10 Repeatability in Pyramidal Balance, 5 Pound Load on Pitching Moment Cell	50
3.3.11 Hysteresis Test on Pyramidal Balance Strain Gauge, Negative Loading	51
3.3.12 Positive Loading of Lift Load Cell	51
3.3.13 Positive Loading of Drag Load Cell	52
3.3.14 Positive Loading of Pitching Moment Load Cell	52
3.4.1 Schematic of Model Components	53
3.4.2 Leading Edge Angled View of Wing-Flap System with Delta-VGs Looking Downstream	54
5.1.1 Baseline Model α dependent Lift Coefficient, $\delta = 0^\circ$	55

5.1.2	Baseline Model α dependent Drag Coefficient, $\delta = 0^\circ$	55
5.1.3	Baseline Model Drag Polar, $\delta = 0^\circ$	56
5.1.4	Baseline Model α dependent Moment Coefficient, $\delta = 0^\circ$	56
5.1.5	Baseline Model α dependent Lift Coefficient, $\delta = 10^\circ$	57
5.1.6	Baseline Model α dependent Drag Coefficient, $\delta = 10^\circ$	57
5.1.7	Baseline Model α dependent Moment Coefficient, $\delta = 10^\circ$	58
5.1.8	Baseline Model δ dependent Lift Coefficient, $\alpha = 0^\circ$	58
5.1.9	Baseline Model δ dependent Drag Coefficient, $\alpha = 0^\circ$	59
5.1.10	Baseline Model δ dependent Moment Coefficient, $\alpha = 0^\circ$	59
5.1.11	Baseline Model δ dependent Lift Coefficient, $\alpha = 10^\circ$	60
5.1.12	Baseline Model δ dependent Drag Coefficient, $\alpha = 10^\circ$	60
5.1.13	Baseline Model δ dependent Moment Coefficient, $\alpha = 10^\circ$	61
5.2.1	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, α -dependent Lift Coefficient, $\delta = 0^\circ$	61
5.2.2	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, α -dependent Drag Coefficient, $\delta = 0^\circ$	62
5.2.3	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, Drag Polar, $\delta = 0^\circ$	62
5.2.4	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, α -dependent Moment Coefficient, $\delta = 0^\circ$	63
5.2.5	Size Comparison at 2.5" Spacing, Flap-Mounted VGs Lift / Moment Coefficients, $\delta = 0^\circ$	63
5.2.6	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, α -dependent Lift Coefficient, $\delta = 10^\circ$	64
5.2.7	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, α -dependent Drag Coefficient, $\delta = 10^\circ$	64

5.2.8	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, α -dependent Moment Coefficient, $\delta = 10^\circ$	65
5.2.9	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, δ -dependent Lift Coefficient, $\alpha = 0^\circ$	65
5.2.10	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, δ -dependent Drag Coefficient, $\alpha = 0^\circ$	66
5.2.11	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, δ -dependent Moment Coefficient, $\alpha = 0^\circ$	66
5.2.12	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, δ -dependent Lift Coefficient, $\alpha = 10^\circ$	67
5.2.13	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, δ -dependent Drag Coefficient, $\alpha = 10^\circ$	67
5.2.14	Size Comparison at 2.5" Spacing, Flap-Mounted VGs, δ -dependent Moment Coefficient, $\alpha = 10^\circ$	68
5.3.1	Size Comparison of 1/4" Flap Mounted VGs, α -dependent Lift Coefficient, $\delta = 0^\circ$	68
5.3.2	Size Comparison of 1/4" Flap Mounted VGs, α -dependent Drag Coefficient, $\delta = 0^\circ$	69
5.3.3	Size Comparison of 1/4" Flap Mounted VGs, α dependent Drag Polar $\delta = 0^\circ$	69
5.3.4	Size Comparison of 1/4" Flap Mounted VGs, α dependent Moment Coefficient, $\delta = 0^\circ$	70
5.3.5	Size Comparison of 1/4" Flap Mounted VGs, α dependent C_L / C_M Coefficient, $\delta = 0^\circ$	70
5.3.6	Size Comparison of 1/4" Flap Mounted VGs, α dependent Lift Coefficient, $\delta = 10^\circ$	71
5.3.7	Size Comparison of 1/4" Flap Mounted VGs, α dependent Drag Coefficient, $\delta = 10^\circ$	71
5.3.8	Size Comparison of 1/4" Flap Mounted VGs, α dependent Moment Coefficient, $\delta = 10^\circ$	72

5.3.9	Size Comparison of ¼" Flap Mounted VGs, δ dependent Lift Coefficient, $\alpha = 0^\circ$	72
5.3.10	Size Comparison of ¼" Flap Mounted VGs, δ dependent Drag Coefficient, $\alpha = 0^\circ$	73
5.3.11	Size Comparison of ¼" Flap Mounted VGs, δ dependent Moment Coefficient, $\alpha = 0^\circ$	73
5.3.12	Size Comparison of ¼" Flap Mounted VGs, δ dependent Lift Coefficient, $\alpha = 10^\circ$	74
5.3.13	Size Comparison of ¼" Flap Mounted VGs, δ dependent Drag Coefficient, $\alpha = 10^\circ$	74
5.3.14	Size Comparison of ¼" Flap Mounted VGs, δ dependent Moment Coefficient, $\alpha = 10^\circ$	75
5.4.1	Size Comparison of Flap Mounted VGs, α dependent Lift Coefficient, $\delta = 0^\circ$	75
5.4.2	Size Comparison of Flap Mounted VGs, α dependent Drag Coefficient, $\delta = 0^\circ$	76
5.4.3	Size Comparison of Flap Mounted VGs, α dependent Drag Polar $\delta = 0^\circ$	76
5.4.4	Size Comparison of Flap Mounted VGs, α dependent Moment Coefficient, $\delta = 0^\circ$	77
5.4.5	Size Comparison of Flap Mounted VGs, α dependent Lift / Moment Coefficient, $\delta = 0^\circ$	77
5.4.6	Size Comparison of Flap Mounted VGs, α dependent Lift Coefficient, $\delta = 10^\circ$	78
5.4.7	Size Comparison of Flap Mounted VGs, α dependent Drag Coefficient, $\delta = 10^\circ$	78
5.4.8	Size Comparison of Flap Mounted VGs, α dependent Moment Coefficient, $\delta = 10^\circ$	79
5.4.9	Size Comparison of Flap Mounted VGs, δ dependent Lift Coefficient, $\alpha = 0^\circ$	79

5.4.10	Size Comparison of Flap Mounted VGs, δ dependent Drag Coefficient, $\alpha = 0^\circ$	80
5.4.11	Size Comparison of Flap Mounted VGs, δ dependent Moment Coefficient, $\alpha = 0^\circ$	80
5.4.12	Size Comparison of Flap Mounted VGs, δ dependent Lift Coefficient, $\alpha = 10^\circ$	81
5.4.13	Size Comparison of Flap Mounted VGs, δ dependent Drag Coefficient, $\alpha = 10^\circ$	81
5.4.14	Size Comparison of Flap Mounted VGs, δ dependent Moment Coefficient, $\alpha = 10^\circ$	82
5.5.1	Leading Edge Surface Comparison 2.0" Spacing, $\frac{1}{2}$ " VGs, α -dependent Lift Coefficient, $\delta = 0^\circ$	82
5.5.2	Leading Edge Surface Comparison 2.0" Spacing, $\frac{1}{2}$ " VGs, α -dependent Drag Coefficient $\delta = 0^\circ$	83
5.5.3	Leading Edge Surface Comparison 2.0" Spacing, $\frac{1}{2}$ " VGs, α -dependent Drag Polar, $\delta = 0^\circ$	83
5.5.4	Leading Edge Surface Comparison 2.0" Spacing, $\frac{1}{2}$ " VGs, α -dependent Moment Coefficient $\delta = 0^\circ$	84
5.5.5	Leading Edge Surface Comparison 2.0" Spacing, $\frac{1}{2}$ " VGs, α -dependent Lift / Moment Coefficient, $\delta = 0^\circ$	84
5.5.6	Leading Edge Surface Comparison 2.0" Spacing, $\frac{1}{2}$ " VGs, α -dependent Lift Coefficient $\delta = 10^\circ$	85
5.5.7	Leading Edge Surface Comparison 2.0" Spacing, $\frac{1}{2}$ " VGs, α -dependent Drag Coefficient $\delta = 10^\circ$	85
5.5.8	Leading Edge Surface Comparison 2.0" Spacing, $\frac{1}{2}$ " VGs, α -dependent Moment Coefficient $\delta = 10^\circ$	86
5.5.9	Leading Edge Surface Comparison 2.0" Spacing, $\frac{1}{2}$ " VGs, δ -dependent Lift Coefficient $\alpha = 0^\circ$	86
5.5.10	Leading Edge Surface Comparison 2.0" Spacing, $\frac{1}{2}$ " VGs, δ -dependent Drag Coefficient $\alpha = 0^\circ$	87

5.5.11	Leading Edge Surface Comparison 2.0" Spacing, ½" VGs, δ-dependent Moment Coefficient $\alpha = 0^\circ$	87
5.5.12	Leading Edge Surface Comparison 2.0" Spacing, ½" VGs, δ-dependent Lift Coefficient $\alpha = 10^\circ$	88
5.5.13	Leading Edge Surface Comparison 2.0" Spacing, ½" VGs, δ-dependent Drag Coefficient $\alpha = 10^\circ$	88
5.5.14	Leading Edge Surface Comparison 2.0" Spacing, ½" VGs, δ-dependent Moment Coefficient $\alpha = 10^\circ$	89
5.6.1	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Lift Coefficient, $\delta = 0^\circ$	89
5.6.2	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Drag Coefficient, $\delta = 0^\circ$	90
5.6.3	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Drag Polar, $\delta = 0^\circ$	90
5.6.4	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Moment Coefficient, $\delta = 0^\circ$	91
5.6.5	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Lift / Moment Coefficient, $\delta = 0^\circ$	91
5.6.6	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Lift Coefficient, $\delta = 10^\circ$	92
5.6.7	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Drag Coefficient, $\delta = 10^\circ$	92
5.6.8	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Moment Coefficient, $\delta = 10^\circ$	93
5.6.9	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, δ-dependent Lift Coefficient, $\alpha = 0^\circ$	93
5.6.10	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, δ-dependent Drag Coefficient, $\alpha = 0^\circ$	94
5.6.11	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, δ-dependent Moment Coefficient, $\alpha = 0^\circ$	94

5.6.12	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, δ -dependent Lift Coefficient, $\alpha = 10^\circ$	95
5.6.13	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, δ -dependent Drag Coefficient, $\alpha = 10^\circ$	95
5.6.14	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, δ -dependent Moment Coefficient, $\alpha = 10^\circ$	96
5.6.15	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent C_{Lmax} , $\delta = 0^\circ$	96
5.6.16	Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Lift to Drag Ratio, $\delta = 0^\circ$	97
5.7.1	Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Lift Coefficient, $\delta = 0^\circ$	98
5.7.2	Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Drag Coefficient, $\delta = 0^\circ$	98
5.7.3	Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Drag Polar, $\delta = 0^\circ$	99
5.7.4	Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Moment Coefficient, $\delta = 0^\circ$	99
5.7.5	Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Moment Coefficient vs Lift Coefficient, $\delta = 0^\circ$	100
5.7.6	Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Lift Coefficient, $\delta = 10^\circ$	100
5.7.7	Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Drag Coefficient, $\delta = 10^\circ$	101
5.7.8	Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Moment Coefficient, $\delta = 10^\circ$	101
5.7.9	Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, δ -dependent Lift Coefficient, $\alpha = 0^\circ$	102
5.7.10	Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, δ -dependent Drag Coefficient, $\alpha = 0^\circ$	102

5.7.11	Lower Surface, Leading Edge, 1/2" VG Space Comparison, δ -dependent Moment Coefficient, $\alpha = 0^\circ$	103
5.7.12	Lower Surface, Leading Edge, 1/2" VG Space Comparison, δ -dependent Lift Coefficient, $\alpha = 10^\circ$	103
5.7.13	Lower Surface, Leading Edge, 1/2" VG Space Comparison, δ -dependent Drag Coefficient, $\alpha = 10^\circ$	104
5.7.14	Lower Surface, Leading Edge, 1/2" VG Space Comparison, δ -dependent Moment Coefficient, $\alpha = 10^\circ$	104
5.7.15	Lower Surface, Leading Edge, 1/2" VG Space Comparison, α -dependent $C_{L_{max}}$, $\delta = 0^\circ$	105
5.7.16	Lower Surface, Leading Edge, 1/2" VG Space Comparison, α -dependent Lift to Drag Ratio, $\delta = 0^\circ$	106

LIST OF SYMBOLS

AR - aspect ratio

b - model span (in)

c - model chord (in)

C - coefficient

g – gravity (ft/s^2)

h – height (in of H_2O)

P – pressure (in of H_2O)

q - dynamic pressure (lb/ft^2)

r – radius (in)

V – velocity (ft/s)

S - model planform area (ft^2)

Subscripts

D - drag

e - exit

i - inlet

LE - leading edge

L - lift

max - maximum

M - pitching moment

m - mean

t - stagnation

Greek Letters

α - angle of attack (deg)

δ - flap angle (deg)

ρ - density (slug/ft³)

ω - error

Other symbols

" - inches

∞ - free stream

CHAPTER 1: INTRODUCTION

Vortex generators (VGs) have long been used as high-lift devices by developing improved lift or pressure distribution characteristics on an aircraft. The geometry of these devices has been quite diverse in their location, size, shape, and is largely dependent upon the desired aerodynamic performance. The principle idea, upon which the use of VGs is motivated by, is the control of flow separation. VGs are used in the prevention or delay of flow separation by energizing the boundary layer, which is an important concern in aircraft design. It is possible for a vortical flow to greatly increase momentum transfer in the boundary layer, delaying flow separation.

Thin delta shaped VGs (delta-VGs), oriented as typical delta-wing would be in normal flight, and was the focus of this experiment. This choice was motivated by the concept of vortex lift as generated by delta wings. The higher pressure on the lower surface of a delta-wing at a positive angle of attack will separate from the leading edge and tend to turn up into the low pressure upper surface. This turning flow tends to curl up into a region of high vorticity giving rise to vortex lift. By introducing delta-VGs, oriented at various locations upstream into the flow, a study was performed on effect, if any, these vortices had on the aerodynamic characteristics of an established model.

The aerodynamic characteristics of a wing-flap airfoil served as a model for baseline comparison with various delta-VG geometries. These data were acquired through wind tunnel experimentation and used in determining coefficients for lift, drag and pitching moment. Utilizing various delta-VGs, an identical procedure was used to

obtain the same type of data. The data collected was used to establish the effects of various delta-VG geometries for comparison with the baseline model and to each other.

CHAPTER 2: LITERATURE REVIEW

The process of imparting momentum into the boundary layer for the purpose of delaying flow separation can be achieved by ensuring transition of the flow from laminar to turbulent. According to Bertin [1], the fact that a turbulent boundary layer can flow without separation into regions of much steeper adverse pressure gradients, than can a laminar boundary layer has been well established. This is due to the greater momentum transfer within the boundary layer caused by the turbulent mixing.

The application of vortex generators (VGs) is motivated by their lack of complicated parts and low cost as a device for altering flow separation characteristics. The unifying theme amongst all VGs is that the generation of vortices can be used to enhance momentum transfer into the retarded flow of the near-the-wall regime. It is this desired effect that make VGs such a promising tool in aircraft design as a device for lift improvement at high angles of attack. As an aide to lift, the use of this device can result in the critical angle of attack occurring at significantly higher values, by delaying the stall condition. It can also serve to promote a prolonged stall region, rather than the traditional sharp decline in lift production which is traditionally subsequent to stall. Much of the research with VGs involves determining the effects that geometry, location, size and spacing have on the aerodynamic characteristics of flow over a body.

The scope of high lift devices, however, is not limited to vortex generators and according to Lin, Robinson, McGhee, and Valarezo [2] “High-Lift systems have traditionally been mechanically complex, generally consisting of some combination of leading-edge slats and multiple trailing-edge flaps. As an attempted solution to alleviate

the complexity and cost of high lift devices conventional, vane-type, passive vortex generators (VGs) have long been used to increase near-wall momentum through the momentum transfer from the outer flow to the wall region.” By using vortex generators consisting of the vane type, set at an angle of incidence to the local flow, the production of an array of streamwise trailing co-rotating and counter-rotating vortices were tested in their experiments Lin et al. [2]. According to Tai [3], “The principle of boundary layer control by VGs relies on the increased mixing between the external stream and the boundary layer due to longitudinal vortices produced by VGs. Fluid particles with high momentum in the streamwise direction mix with the retarded viscous flow inside the boundary layer; thereby the mean streamwise momentum of the fluid particles in the boundary layer is increased. This process provides a continuous source of reenergization to counter the natural boundary layer retardation and growth caused by viscous friction and adverse pressure gradients.” In experiments involving vane-type VGs both trapezoidal and delta geometries have been used Lin et al. [2]. It is this delta type that is of interest due to their aerodynamic characteristics.

The aerodynamic characteristics of delta wings have the effect of producing counter-rotating vortices inboard of the low pressure surface. While flying at low speeds delta wing aircraft must produce these vortices for adequate lift production and by increasing the angle of attack it is possible to achieve the necessary lift due to the vortex lift component. According to Buchholz and Tso [4], “the delta wing produces large vortex lift at high angles of attack, which allows for its flight at low speed conditions.” These vortices are generated when the high-pressure air on the lifting surface spills over the edge and wraps up in to a rotational structure atop the low pressure surface. Based on

the aerodynamic characteristics of the delta wing the use of delta wing vortex generators (delta-VGs) is thought to be a suitable choice for VG.

In an effort to overcome the adverse pressure gradient causing flow separation experiments have been conducted to determine the benefits of varying physical placement of VGs. The effectiveness of a flap, for example, as it deflects fluid flow would be greatly benefited by delay or prevention of flow separation. It is thought that by placing VGs along the leading edge of the flap, as done by Storms and Ross [5] and Lin et al. [2] in their experiments, the boundary layer would be strengthened by enhancement of streamwise momentum. Storms et al. [5] noted that wishbone type VGs added to the flap reduced flow separation at high flap deflections. Results for Storms et al. [5] experiment included an increase in C_{Lmax} of 17% with the use of cove tabs and vortex generators when compared to the baseline data from their experiment. It has also been reported that vane type trapezoidal and delta VGs were effective in certain configurations Lin et al. [2]. Placement of VGs has also been evaluated towards the leading edge of the main airfoil chord. Barrett and Farokhi [6], experiments determined that a ramp type VG had an optimal location of 5 - 15% behind the leading edge and were effective in preventing the stall condition. The experiments by Barrett et al [6] showed an increase in C_{Lmax} of 13.5% and a delay in the stall condition of approximately 2 degrees.

There have been many experiments done on VGs, most of which address not only the location but involve analysis as to an appropriate size or aspect ratio to be used. According to Nowak and Solies [7], a typical sizing for delta-flap VGs ranges from an AR of 1 – 2 with a chord of $\frac{1}{4}$ - $\frac{1}{3}$ of the main wing chord. However, it was also stated

that “the delta flap must be positioned such that it protrudes outside the boundary layer or any area of flow separation into the healthy, high energy, airflow surrounding the aircraft wing Nowak et al. [7].” While this theory is most likely the safest approach to VG sizing, research has suggested that VGs that are a fraction of the boundary layer thickness can still provide momentum transfer over a region several times their own height and in experiments it is determined that VGs as small as 0.18% of the total chord were effective in specific locations Lin et al [2].

The spacing between VGs is also a concern in much of the experiments on VGs. One reason for this is that there is typically a drag penalty associated with their use. Some experiments have obtained results where it was discovered that with an increase in the number of VGs there was an incremental increase in drag as well as an increase in lift coefficient Nowak et al. [7]. This finding clearly demonstrates the importance of the effect of VG spacing. However, experiments also show that, while there is a lift coefficient benefit, the difference between VG aspect ratio and spacing lack a significant sensitivity to these parameters Nowak et al. [7]. In their experiments [7] a radical improvement in the stall condition was found and after C_{Lmax} was reached, lift coefficients near this value were maintained for a wide range of angles of attack.

The use of VG devices in aviation is an established practice with proven benefits. However, the review of the referenced work suggests that further investigation in VG configurations could be beneficial based on the potential rewards of such endeavors. This is no small part due to the almost limitless range of devices based on the multitude of possible configurations.

CHAPTER 3: EXPERIMENTAL APPARATUS

3.1 UTK Subsonic Wind Tunnel

The facilities at UTK included an open return subsonic wind tunnel with an open test section, a sketch of which can be found in the Appendix Figure 3.1.1. Note that all figures can be found in the appendix. The test section was 24" in width, 24" height and a 40.5" length with a free jet design. A flat sheet of acrylic was installed at the bottom of the test section at a location of $\frac{1}{2}$ " above the lower test section limit with a width of 24" and a length of 27". The sheet served to shield the balance mechanism from the flow field. The wall effect this arrangement had on the experimental data was ignored, since the difference between various model configurations were of primary interest. Velocities as high as 10" of H₂O were obtained in the wind tunnel giving a maximum dynamic pressure ($q_{\max}$) of 52 lb/ft² or, based on standard atmospheric conditions at 803.8 ft, $V_{\max} = 211$ ft/s for typical flow conditions.

3.2 Wind Tunnel Instrumentation and Equipment

The large subsonic wind tunnel at UTK was equipped with an inclined manometer for determination of the dynamic pressure. During tunnel operation the static pressure was measured upstream of the converging section. The measured static pressure was assumed to be equivalent to the total pressure, Equation 3.2.1, because of low tunnel velocity upstream of the convergent section.

$$P_{te} = P_e + \frac{1}{2} \rho_{\infty} V_{\infty}^2 \rightarrow P_{te} = P_e \quad (3.2.1)$$

The test section static pressure (P_i), represented in Equation 3.2.2, and was measured as the pressure in the room containing the test section.

$$P_{ti} = P_i + \frac{1}{2} \rho_{\infty} V_{\infty}^2 = P_{te} \quad (3.2.2)$$

From this information, the dynamic pressure was determined by the difference between these two pressures. As a result, the dynamic pressure was calculated by Equation 3.2.3.

$$q_{\infty} = \frac{1}{2} \rho_{\infty} V_{\infty}^2 \rightarrow P_i - P_e = gh\rho_{H_2O} \quad (3.2.3)$$

An IFA 300 constant temperature anemometer (CTA) and ThermalPro v4.5 software for the IFA 300 were used to measure mean and fluctuating velocity components, turbulence and temperature. The IFA 300 system was expandable to 16 channels, which provided up to 300 kHz frequency response, depending upon the sensor used. A hot film probe was used for calibration in this research in conjunction with the CTA. Each module was designed with a built in thermocouple circuit for measuring fluid temperature and for making temperature corrections. All operations, including setup, calibration and data acquisition are software controlled via an RS-232 interface.

An Aerolab Pyramidal Strain Gauge Balance was used to resolve resultant aerodynamic force into individual components of lift, drag and pitching moment through independent load cells. The loads sensed by the force balance were translated into data with the use of a strain gauge model 2150 from Vishay Instrument Division. InstaCal software from Measurement Computing and hardware for converting voltage to A/D counts, card number PCIM-DAS1602/16, allowed for computer control of the strain gauge. DAS wizard allowed the data to be directly integrated into an Excel spreadsheet.

3.3 Calibration of Test Equipment

The use of the IFA 300 constant temperature anemometer first required calibration of the sensor-probe at known atmospheric conditions. The calibration was done with Thermal Systems Inc model 1125 velocity calibrator, where the sensor was placed in an air stream of known atmospheric pressure, temperature and total pressure. After the atmospheric conditions were established, tests were run to determine dynamic pressure. This process was repeated over a range of velocities for a complete data set, which completed the data collection required for calibration of the hot film probe. With software control of the IFA 300, via ThermalPro, this data was incorporated into the program calibration section allowing for a survey of the test section flow characteristics.

Before experiments were run using the model, it was desired to quantify the flow characteristics in the empty test section. The experiments began with a velocity measurement at the midpoint of the test section entrance, or the exit of the convergent section, for a period of two minutes. The results of this test demonstrated a fluctuation in the velocity profile as shown in Figure 3.3.1. Through the use of this information, an experimental test time of twenty seconds was determined to be satisfactory in capturing the cycle of fluctuations in the flow characteristics. A series of experiments were also conducted at the test section entrance to determine the horizontal and vertical centerline velocity distributions as well as the turbulence intensity distribution. The centerline velocity distributions were collected at a velocity of approximately 100 ft/s or 2.7" H₂O, based on standard atmosphere. With the use of a constant temperature anemometer (CTA) the test section inlet was traversed in one inch increments. The velocity profiles obtained from these tests can be found in Figures 3.3.2 – 3.3.3. There was a temperature

gradient in the wind tunnel test section from the top of the nozzle exit to the bottom. This characteristic was a result of both outside temperature air and cooler air near the floor available at the inlet. This temperature gradient may also explain the decreasing slope of the vertical temperature distribution, Figure 3.3.3. These tests also obtained information to be used in calculating the average turbulence intensity, Figures 3.3.4 – 3.3.5. A turbulence intensity percent was obtained for both the horizontal and vertical tests; the worst of these had a value of 0.889 %. Through the use of this value and Figure 3.3.6, a corresponding wind tunnel turbulence factor of 1.7 was obtained.

Determination of a practical tunnel test velocity was achieved, with the model in the test section at $\alpha = 0$ and $\delta = 0$, by accelerating the tunnel velocity to about $0.9 V_{\max}$. The model was turned through a high α and δ , and a decrease in flow velocity to 5.0" of H₂O was observed. As a result, a test velocity of 4.5" was implemented during experimentation. This ensured a safe margin so that all test could be performed at the same dynamic pressure. Based on the prescribed test conditions, a maximum Reynolds number of $Re = 6.5 \times 10^5$ was obtained and was calculated using the standard atmosphere at 803.8 ft. When including the turbulence factor, this yielded an effective Re of 1.0×10^6 .

The use of the strain gauge balance with separate channels corresponding to lift, drag and pitching moment also required calibration to obtain accurate corresponding values for applied force. The balance sent a voltage signal to the software controlled strain gauge set at 10 volts digital counts. This allowed for separate load cell conversion of volts to pounds force or in pounds moment. A sample rate of 2000 at 100 hertz at a setting of ± 5 volts allowed for a testing duration of 20 seconds. By attaching a known

mass to the balance, a test was performed to determine the repeatability of data acquisition with the strain gauge balance. By repeatedly taking data of a loaded and unloaded balance, illustrated in Figures 3.3.7 – 3.3.10, the drift between separate tests was determined to be minimal. A hysteresis test was performed, shown in Figure 3.3.11 that illustrated a bilinear characteristic of negative loading of the strain gauge balance. These studies also illustrated that there was not any hysteresis in the system. In order to load the balance in a positive direction, a pulley system was used to pull upwards on the balance for further calibration testing. This process also made it possible to isolate each load cell for calibration into number of analog/digital (A/D) counts per pound. The results of this study, shown in Figures 3.3.12 – 3.3.14, also illustrated that positive loading of the balance was linear as opposed to being bilinear when negatively loaded. The results of this investigation gave corresponding values of A/D counts to pounds of lift, drag and pitching moment. With the model attached to the force balance and before any aerodynamic loading, data was acquired with the strain gauge balance to separate the model weight from aerodynamic force measurements. This process was performed prior to each startup of the wind tunnel.

3.4 Two Dimensional Wind Tunnel Model

A flat plate wing-flap model with chord (c) = $9\frac{5}{16}$ inches, span (b) = $17\frac{3}{4}$ inches, maximum thickness ($t_{\max}$) = $\frac{1}{2}$ inches and a leading edge radius (r_{Le}) = $\frac{1}{4}$ inches was fabricated from polyethylene. These dimensions resulted in $S = 1.18 \text{ ft}^2$ and an aspect ratio (AR) = 1.86. The bottom aft portion of the flap was milled so as to taper the trailing edge of the model. A schematic of the model is available in Figure 3.4.1. The wing-flap

system was joined with a flush mounted piano hinge and flush mounted screws. The centerline of the hinge was located at 0.52c. A pair of endplates, used to reduce wing-tip effects, was fabricated from 0.125" aluminum sheets and attached with flush mounted screws to the wing. By cutting a constant radius slot into the aluminum, the hinged flap could be turned through a range of angles. A desired flap angle was set into position with a screw on each side of the model that put the flap in a bind with the endplate. The leading edges of the endplates were also given a radius allowing for less disturbance of the air stream. A series of delta shaped vortex generators (delta-VGs) were cut from 0.02" thick aluminum sheet. Three of the geometries had a sweep angle of 60° and lengths of $\frac{3}{4}$ ", $\frac{1}{2}$ " and $\frac{1}{4}$ " while a sweep angle of 30° was also manufactured from the $\frac{1}{2}$ " length for further testing. The $\frac{1}{4}$ " length 60° sweep delta-VGs bent upwards at angles of 45° were also developed for testing. An illustration of delta-VG configurations can be found in Figure 3.4.2.

CHAPTER 4: EXPERIMENTAL PROCEDURE

4.1 Experimental Test Procedure

The process of making a comparison of the effects the delta shaped vortex generators (delta-VGs) had on lift, drag and pitching moment coefficients began with testing the model in a baseline configuration without the use of the VGs. Through preliminary testing of this baseline of the model, data was obtained for developing lift, drag and pitching moment coefficients. The objective of this experiment, being to compare various vortex generator configurations with the baseline data, led to choosing specific values for angle of attack (α) and flap deflection (δ) based on the critical value for the α -dependant lift coefficients. This served as a reference for developing the test matrix shown in Table 4.1.1. Through the use of the test matrix, data for the lift, drag and pitching moment coefficients as a function of both α and δ were obtained. Testing of the baseline model also established a reference for future comparisons. By choosing a test value near the critical value of α -dependant lift data, a comparative analysis was more insightful as to the effects of various VG configurations in the regime near flow separation.

By conducting multiple tests with the baseline model it was also possible to verify the repeatability of the data acquisition system. Having established a baseline for the aerodynamic characteristics of the model, the Test Matrix for developing lift, drag and pitching moment coefficients was repeated for the various delta-VG configurations.

4.2 Experimental Data Acquisition Procedure

The procedure for utilization of the data acquisition system was initiated by warming-up the Strain Gauge apparatus for a period of approximately 24 hours. This greatly exceeded the manufacturer's recommendation of 1 hour and ensured maximum electric stability. A mercury barometer was also used before each test to determine the atmospheric pressure for future Re calculations.

With the model oriented at $\alpha = 0^\circ$ and $\delta = 0^\circ$, the data acquisition system was used to record reference values for each load cell. This was done before the model underwent any aerodynamic loading and allowed the weight of the model to be factored out of component force data collected during aerodynamic testing. At this point the wind tunnel was started and the test section dynamic pressure increased to 4.5" of H_2O measured by a manometer. Once this condition was reached the experimental Test Matrix procedure, Table 4.1.1, was initiated.

Once the model was aerodynamically loaded, the angle of attack (α) was verified with a small laser light that contained a beam splitter. The laser was attached to the model and pointed onto a set of fixed alignment points corresponding to the desired α . This method became necessary since the counter for the control of α located on the pyramidal balance proved to be unreliable. The determination of δ was made possible by a series of reference lines drawn on the inside surface of the endplates. These reference lines corresponded to known values of flap deflection, and were aligned with the upper surface of the flap. Following data acquisition at the desired angles, these angles were rechecked to verify accuracy.

4.3 Experimental Determination of Aerodynamic Coefficients

The computer driven data acquisition software was used to measure the strain gauge conditioner voltages and collect the A/D counts for each component of lift, drag, and pitching moment. The determination of aerodynamic forces was obtained by subtracting reference values for the weight of the model from the data acquired for the lift, drag and pitching moment forces and applying the established conversions of force or moment to these values. The resulting values of force for lift, drag and pitching moment were used along with established values for area (S) and test dynamic pressure to determine the coefficients for lift, drag and pitching moment.

4.4 Experimental Placement of Vortex Generators

In this phase of experimentation the vortex generators were arranged so that the delta tips were extended in the direction of flow from their base at the 0.54c flap hinge line and at 0.013c position measured from the model leading edge. At this point, the test matrix was implemented and the experimental data acquisition procedure was followed to obtain the experimental values of the force coefficients.

Various vortex generator sizes and geometries were tested to determine the effect they had on lift, drag and pitching moment coefficients. These included delta-VGs with sweep angles of 60° and lengths of $\frac{3}{4}$ ", $\frac{1}{2}$ " and $\frac{1}{4}$ ", a 60° sweep angle and a $\frac{1}{4}$ " length bent 45° upwards and a $\frac{1}{2}$ " length with a 30° sweep angle. The testing of the delta-VGs at both the 0.54c and the 0.013c position involved varying space between each VG. This space was measured from the centerline of the model to the centerline of each delta-VG with the initial delta-VG aligned with the model centerline. The process of varying the

location, length and spacing allowed for aerodynamic analysis on the effect of these vortex generators.

4.5 Error Estimation for Experimental Data

The utility of the collected experimental data was quantified by an assessment of the accuracy of the equipment and procedure. The object of the experimental analysis was to determine changes in aerodynamic coefficients caused by the geometry changes. Because the focus of the experiment was on changes in values and not the actual values, interference that would cause the values to differ from free flight C_L , C_D and C_M were assumed to be present for both baseline and modified tests and could thus be neglected. These errors included effects induced by the acrylic sheet located towards the floor of the test section. This sheet would have a wall effect influence on the model. It was assumed that during testing that these would be identical in effect for the base and modified model geometries. It was also assumed that dimensional inconsistencies in delta-VG placement are small and thus irrelevant in the analysis of error.

The bulk of the systematic errors involved in experimentation leading to the calculation of force coefficients involve α , δ , q_∞ , and the fluctuation in A/D counts. The fluctuation in A/D counts accounts for minor changes in voltage reading for a constant load or balance condition. Each of these parameters has a unique effect depending upon the component of force being analyzed. The approach used to combine or total these errors involved the use of Equation 4.5.1 for each coefficient.

$$\omega_R = \left[\left(\frac{\partial R}{\partial x_1} \omega_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} \omega_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} \omega_n \right)^2 \right]^{1/2} \quad (4.5.1)$$

The term ω_R refers to the error in R, where R referred to the quantity being analyzed.

The term $\frac{\partial R}{\partial x_n}$ refers to the change in the quantity being analyzed with respect to some

independent parameter which was multiplied by the error in the independent

parameter ω_n .

The error analysis involving data collected from the baseline model was used to make the calculations for the entire experiment. It was assumed that specific errors for various geometries involving the delta-VGs were of the same order magnitude.

The use of Equation 4.5.1 applied to C_L is shown in Equation 4.5.2.

$$\omega_{C_L} = \left[\left(\frac{\partial C_L}{\partial q_\infty} \omega_{q_\infty} \right)^2 + \left(\frac{\partial C_L}{\partial \alpha} \omega_\alpha \right)^2 + \left(\frac{\partial C_L}{\partial \delta} \omega_\delta \right)^2 + \left(\frac{\partial C_L}{\partial a/d} \omega_{a/d} \right)^2 \right]^{1/2} \quad (4.5.2)$$

The differential term $\frac{\partial C_L}{\partial \alpha}$, corresponded to the α -dependent lift curve slope of the straight line segment from 0° to 9° obtained from Figure 5.1.1. For the purpose of error calculation, the lift curve slope was approximated as being linear. The ω_α term was an estimation of the accuracy in obtaining the angle of attack. This value was estimated to be $\pm 0.25^\circ$.

The analysis of the differential term $\frac{\partial C_L}{\partial \delta}$ involved taking the slope of the straight line segment for the δ -dependant C_L , Figure 5.1.8, test for $\alpha = 0^\circ$. The ω_δ term was an estimation of the accuracy of obtaining a specific value for δ . This value was estimated to be $\pm 0.25^\circ$.

The dynamic pressure (q) in this experiment included errors from two sources. The first of these was in the density of water, since it is slightly temperature dependent. This gave an error in density of ± 0.004 due to the temperature dependence of H_2O . The other was that there was a slight fluctuation in tunnel dynamic pressure. The error in the height of H_2O taken from the manometer was taken to be ± 0.03 " during data acquisition, which was the maximum fluctuation allowed. From this information, the error in C_L with respect to q_∞ is formulated in Equation 4.5.3

$$\left(\frac{\partial C_L}{\partial q_\infty} \omega_{q_\infty} \right)^2 = \left(\frac{\partial C_L}{\partial \rho_{H_2O}} \omega_{\rho_{H_2O}} \right)^2 + \left(\frac{\partial C_L}{\partial h} \omega_h \right)^2 \quad (4.5.3)$$

In analyzing the error term $\frac{\partial C_L}{\partial A/D}$, it was necessary to convert established values for A/D counts per pound to C_L per A/D counts. From Equation 4.5.4 it was possible to obtain a value for C_L counts per pound with q_∞ and S being predetermined values.

$$L = \frac{1}{2} \rho_\infty V_\infty^2 S C_L = q_\infty S C_L, \quad (4.5.4)$$

The experimentally determined value for A/D counts per pound lift, obtained in the calibration procedure, being $\frac{A/D}{lb} = 809$ (1/lb) and the calculated value from Equation

4.5.4 of $\frac{C_L}{lb} = 0.0364$ (1/lb), it was possible to obtain a value or $\frac{\partial C_L}{\partial A/D} = \frac{0.0364}{809} = 4.0 \times$

10^{-5} . In determining a value for the term $\omega_{A/D}$ an approach was used that required taking the standard deviation of all the baseline model tests and choosing the largest value of these for lift. Once the largest standard deviation value was determined it was desired to

factor in the number of data points that were taken for each test. By taking a 95% confidence interval of the standard deviation the $\omega_{A/D}$ was determined to be ± 125 counts.

A similar procedure was implemented for the error analysis in C_D and C_M . For the calculation of $\frac{\partial C_D}{\partial \alpha}$ and $\frac{\partial C_M}{\partial \alpha}$ required a slightly different approach since the data was non-linear. As a suitable approximation, a tangent line was drawn at $\alpha = 10^\circ$ and the slope of these lines were used as a measure of the error. Although this process could have been done at each angle to obtain the associated error at each point, it was assumed that choosing data that would yield the largest error would be a reasonable estimate of a maximum error and is an overestimate of the error at most angles. For $\frac{\partial C_D}{\partial \delta}$ and $\frac{\partial C_M}{\partial \delta}$ a linear trend line was imposed on the data to obtain a representative value for the error. The process of producing the error values is shown in Tables 4.5.1 – 4.5.6 and the final results are in Tables 4.5.7 – 4.5.8

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Baseline Model Data

The analysis of the base model revealed the aerodynamic characteristics that served as a reference for comparison to modified configurations. The data for the baseline model can be found in Figures 5.1.1 – 5.1.13. All plots containing baseline data contain error bars to help visualize the magnitude of the changes from baseline data. For the baseline data a maximum lift coefficient of, $C_{L_{\max}} = 0.39$ as indicated in Figure 5.1.1, was found to occur at 11° angle of attack with no flap deflection. This value was obtained by averaging the $C_{L_{\max}}$ values from two independent tests. A distinct characteristic of the model was the negative camber effect, evident by the negative lift coefficient at zero angle of attack. Also from Figure 5.1.1, it can be seen that the point of zero lift occurs at 1.5° angle of attack. Assuming that the lower portion of the lift curve slope is linear, the average lift curve slope was calculated from the average experimental data to be 0.04. However, the lift curve slope of the model tended to be slightly non-linear and in fact had a slightly concave up appearance. According to Barlow, Rae and Pope [8] this is a typical phenomenon encountered with low aspect ratio airfoils.

The drag of the baseline model, presented in Figure 5.1.2, identifies a $C_{D_{\min}} = 0.066$, at 2° , which was quite near the angle of attack for zero lift. Utilizing the averaged data from the two tests for lift and drag, the lift to drag ratio was calculated and is shown in Figure 5.1.3. Based on these data, $(L/D)_{\max} = 3.01$ and occurs at approximately 9.5° .

All pitching moment data was taken about the $\frac{1}{4}$ chord and initially the model has a positive pitching moment, shown in Figure 5.1.4. As the angle of attack was increased

the moment quickly transitioned to negative. Data for the C_M shows an inflection point near the stall condition in the range near $\alpha = 11^\circ$.

Having established the baseline data for the lift, drag and pitching moment an investigation of the effect of flap deflection was performed. The first set of plots were obtained with 10° of flap deflection. For these plots, data was taken at $\alpha = 2^\circ$ increments and increased to 1° in the areas where instability was eminent. Future comparisons would yield more insight into the effect various delta VGs had on the aerodynamic characteristics in this high C_{Lmax} range. These data can be found in Figures 5.1.5 – 5.1.7, and as expected a positive C_L occurs throughout the tests and there are increases in the magnitudes for C_{Lmax} , C_{Dmin} and C_M . An interesting revelation in the C_D was that it increased nearly linearly as α was increased. When compared to data for the flap angle (δ) = 0° , the C_{Lmax} for $\delta = 10^\circ$ was approximately 59% higher with a reduction of 2° in α , while C_{Dmin} increased by only 7%.

Experimentation through a range of flap settings was done to establish a baseline for comparison. Two separate tests were done, one of which with $\alpha = 0^\circ$ and the other with $\alpha = 10^\circ$ and with the flap angle (δ) being deflected through a range of angles, from 0° to 30° . The results for this data can be found in Figures 5.1.8 – 5.1.10 and Figures 5.1.11 – 5.1.13 respectively. Of interest from these data is that for $\alpha = 0^\circ$, Figure 5.1.8, the flap could be turned through a high degree of angles before the wing began to stall and that there was a near linear increase in lift with α .

5.2 Length Comparison of Vortex Generators at Flap-Hinge Line

The initial delta-VG experiments were run with the VGs at the flap-hinge line to quantify the effect of different delta-VGs on the aerodynamic characteristics of the wing-flap system. Delta-VGs with a sixty degree sweep angle and lengths of $\frac{3}{4}$ ", $\frac{1}{2}$ " and $\frac{1}{4}$ " were tested with a spacing of 2.5". This spacing was measured from the centerline of each VG, with the initial VG being lined up with the centerline of the model. The final results can be found in Figures 5.2.1 – 5.2.14 along with a comparison to the baseline model. As shown in these figures, there was no measurable difference in lift or drag. While there was a measurable improvement in the pitching moment, this data was not the primary focus of the research. With no improvement in lift or drag any change in the pitching moment was of little importance and in such cases will not be addressed further. In the case of Figure 5.2.9, for the $\frac{3}{4}$ " and $\frac{1}{2}$ " cases where $\alpha = 0^\circ$ and δ was varied, there was a slightly measurable decrease in the lift coefficient as α gets larger.

5.3 Spacing Comparison of Vortex Generators at Flap-Hinge Line

Although there was no improvement in the aerodynamic characteristics of the model a further study was conducted into the effect of spacing, to see if more VGs would improve performance. The results of this test can be seen in Figures 5.3.1 - 5.3.14. Again, there appears to be no measurable benefit from doubling the number of VGs, with a change in spacing to 1.25" from 2.5". Due to these results, no further experiments on spacing were conducted.

5.4 Additional Geometries of Vortex Generators at Flap Hinge Line

Testing was also done with additional geometries to develop a beneficial flap-hinge line configuration. Delta-VGs with a 30° sweep angle and a length of $\frac{1}{2}$ " and a 60° sweep angle VG with a $\frac{1}{4}$ " length was bent upwards at an angle of 45° to increase the angle of attack. Both of these geometries were tested at a spacing of 2.5". The results of these tests are shown in Figures 5.4.1 – 5.4.14. In the cases of the α -dependent tests, Figures 5.4.1 – 5.4.8, there was not a significant lift effect but in regions of higher angles of attack there was a slight decrease in C_D . The C_M data demonstrates an overall increase in magnitude; however, this data was secondary to the effects of lift and drag and therefore will not be investigated further. In the cases for the δ -dependent tests, Figures 5.4.9 – 5.4.14, some locations had noticeable decreases in lift and drag. However, these aerodynamic changes were extremely limited and based on this information no further investigation was done. It was believed that the reason for the failure of the delta-VGs to have a beneficial effect on lift or drag was because the placement of the VGs at the 0.54c position was after the flow had separated.

5.5 Surface Comparison of Leading Edge Vortex Generators

In testing delta-VGS at the leading edge, where the base of the VGs were located at the 0.013c position of the model, an approach similar to the 0.054c tests was taken. Initially, however, tests were run to determine the aerodynamic differences between putting the delta-VGs on the top and bottom surface of the model. Using the $\frac{1}{2}$ " length VGs with a 60° sweep angle, tests for the α -dependent and the δ -dependent arrangements were conducted, the results of which can be found in Figures 5.5.1 – 5.5.14. In the case

of Figure 5.5.1, the α -dependent C_L plot illustrated a significant benefit leading edge VGs can have. The use of these VGs on the lower surface, showed the largest improvement, and increased $C_{L_{\max}}$ by as much as 43% when compared to the base model. Both surface arrangements delayed the stall condition, with the lower surface mounted VGs occurring at a slightly higher α than the upper surface arrangement. Further tests of α -dependent configurations were done with $\delta = 10^\circ$, Figure 5.5.6, and illustrated the significance induced vortices had on improving lift characteristics. By allowing for higher angles of attack and increased lifting force these VGs produce a desirable effect in landing situations where flaps are employed. An unexpected result was that the onset of the stall condition was followed by a more gradual loss in lift. There was not a significant drag penalty in any of the tests for these arrangements. The drag polar, Figure 5.5.3, identified that there was not an increase in the magnitude of the lift to drag ratio. However, for both surface cases there was an increase in $(L/D)_{\max}$ and in the case of the lower surface $(L/D)_{\max} = 3.18$, which occurred near $\alpha = 11^\circ$ where the base model $(L/D)_{\max}$ occurred near 10° . When evaluating lift at angles near $\alpha = 0^\circ$ there was little to no measurable effect the VGs had compared to the baseline model and this was confirmed by the data, observable in Figures 5.5.9 and 5.5.10 where δ was varied and $\alpha = 0^\circ$. This was an expected result since delta-wings require high angles of attack to generate vortices of enough strength for low speed flight. Tests done where δ was varied and $\alpha = 10^\circ$, also served to further illustrate the influence delta-VG induced vortices had on controlling separation. In Figure 5.5.12 this effect was made clear by the significant increase in flap deflection before the onset of the stall condition. This figure also identifies that the stall condition was approached more gradually than the base line data. The moment data for

the α -dependent tests, Figures 5.5.4, 5.5.5 and 5.5.8, illustrated smaller values for the slope than that of the baseline model and an extension of the angles where there was positive pitch before transition to negative. The δ -dependent tests, Figures 5.5.11 and 5.5.14, not only decreased the slope of the moment data but change in data was nearly linear. All moment data for the surface tests identified an increased pitching moment when compared to the baseline. Based on the results of the surface experiments, all future tests were done with the delta-VGs on the lower surface. It was believed that placing the VGs on the lower surface allowed for greater penetration into the free stream and resulted in better vortex interaction with the model.

5.6 Length Comparison of Leading Edge Vortex Generators

The next phase of experiments focused on the effect various lengths had on the aerodynamic properties of the model. By using delta-VGs with 60° sweep angles and lengths of $\frac{3}{4}$ ", $\frac{1}{2}$ " , $\frac{1}{4}$ " and by using a 30° sweep angle with a length of $\frac{1}{2}$ ", the data for varying the length was collected and can be seen in Figures 5.6.1 – 5.6.16. When compared to the base-line model all VG lengths used showed improvement. When compared to each other the various delta-VG tests suggest, with the exception of the $\frac{3}{4}$ " VG, only a marginal difference in the effect length has on lift, drag and pitching moment. The data for the $\frac{3}{4}$ " delta-VG indicated an improved lift to drag ratio, which can be attributed to the reduced drag illustrated in Figure 5.6.2. Based on the data presented in Figure 5.6.15, it was clear that $C_{L_{max}}$ for the various VGs were comparable in magnitude, but in the case of the $\frac{3}{4}$ " length VG it occurs later in terms of angle of attack. Figure 5.6.16 illustrates the L/D ratio as a function of α and for the $\frac{3}{4}$ " VG it occurs at a

comparatively lower α . However, it was significantly larger in magnitude than other length VGs. Although there seems to be a slight advantage in using the $\frac{3}{4}$ " length VG, it was decided that the $\frac{1}{2}$ " length VG with a 60° sweep angle would be used for further investigation into the effect of delta-VG spacing on the model aerodynamic properties.

5.7 Spacing Comparison of Leading Edge Vortex Generators

The effect spacing had on the aerodynamic properties was compared using spacing of 4.5", 2.5", 2.0" and 1.5", the data for which can be found in Figures 5.7.1 – 5.7.16. Evaluating the α -dependent data where $\delta = 0^\circ$ and $\delta = 10^\circ$, the case of a 1.5" space between VG centerlines, Figure 5.7.3, yielded the greatest improvement in $(L/D)_{\max}$ and the L/D ratio. It also had the most effect on the moment data by decreasing the severity of the transition from positive to negative. The least beneficial arrangement was the 4.5" spacing, most likely due to a reduced number of induced vortices. In terms of lift, spacing of 2.5" and 2.0" were virtually identical to the 1.5" arrangement. However, the drag polar data in Figure 5.7.3 clearly indicated that the 1.5" arrangement was optimal by comparison. Similar to previous results there was virtually no change in results where α was small, which was demonstrated best by Figures 5.7.9 – 5.7.11. The data in Figure 5.7.15 suggests that as the space between the VGs was decreased, the measured effect was within the limits of error of $C_{L\max}$. However, the values of α where $C_{L\max}$ occurred tended to decrease as the spacing was increased. Further analysis of the data, Figure 5.7.16, illustrated the lift to drag ratio and the approximate angles at which $(L/D)_{\max}$ occur. It seems that in the 1.5" spacing arrangement there was a significant lift benefit compared to the drag penalty. However, the value where $(L/D)_{\max}$ occurred was slightly

lower at $\alpha \approx 10^\circ$ than in other cases where $11^\circ \leq \alpha \leq 12^\circ$. By conducting tests at various spacing of delta-VGs, the number of vortices produced seemed to be an important consideration. In the case of the 1.5" spacing arrangement, the highest lift to drag ratio was produced as well as the highest value for C_{Lmax} . In the case of the 4.5" spacing, the reduced number of vortices showed a reduction in the lift to drag ratio but allowed for the onset of the stall condition to be delayed to larger angles of attack. A comparison of C_{Lmax} , C_{Dmin} and $(L/D)_{max}$ for all leading edge cases is available in Table 5.7.1 -5.7.4

CHAPTER 6: CONCLUSIONS

This research was primarily concerned with establishing the differences in aerodynamic properties of a base-line model configuration with various delta-VG geometries. This was achieved through wind tunnel experimental data to compare results in lift, drag and pitching moment. Conclusions drawn from this research were:

- 1) Flap mounting of the delta-VGs showed little effect in lift characteristics on the various lengths and spacing used in vortex generator analysis. It was believed that separation occurred before this location and could therefore not improve the lift. There was a measurable impact on the moment data; however, without improvements in lift or drag the moment data was of little interest. However, the moment data suggests that there was likely some level of vortex generation.
- 2) All arrangements of leading edge delta shaped vortex generators had a greater production of total lift that did the base-line model. This can be directly attributed to the effect of inducing vortices prior to separation and resulting in attachment to the model surface.
- 3) In testing the leading edge for determination of upper or lower surface mounting of delta-VGs, the lower surface proved to be better. It was believed that this was due to the fact that as the angles of attack were increased the lower surface

arrangement allowed for earlier and greater interaction into the free stream than did the upper surface.

- 4) While testing various length delta-VGs at the leading edge of the model it was determined that, in comparison to the base-line data, the delta-VGs increased the total lift produced. In comparing the different length VGs to each other there were only small differences on the magnitude of lift produced but that stall was both delayed to higher angles of attack and prolonged in terms of a subsequent loss in lift. There were also varying improvements in the critical angle.
- 5) In making a comparison to the baseline data, further investigation of the space between delta-VGs of the same length revealed that more VGs improved the magnitude of $C_{L_{\max}}$ and delayed the stall condition to higher angles of attack. This test also revealed that as the number of VGs were reduced, there was a reduction in the magnitude $(L/D)_{\max}$ accompanied with an increase in the angle where $(L/D)_{\max}$ occurred. This characteristic also reached a limit and as the distance between VGs was increased further the magnitude of $(L/D)_{\max}$ increased and the angles at which it occurred decreased.
- 6) The pitching moment data for all leading edge VG data denoted that there was an increase in the pitching moment. In the α -dependent cases there was a pitch-up condition that extended to higher angles of attack than the baseline data. The δ -dependent data illustrated a nearly linear change in moment with flap deflection.

- 7) Experiments ran with the 3/4" delta-VGs on the lower surface for the α -dependent tests and with $\delta = 0^\circ$ showed an increase from baseline data in $C_{L_{max}}$ of 45% and a delay in the stall condition by 8° was observed. Results from Storms et al. [5] and Barrett et al. [6] showed an increase of 13.5% and 17% in $C_{L_{max}}$, with a delay in the stall condition of 2-3 degrees. There were obvious differences in the improvements found by other researchers which could be attributed to the different aerodynamic systems used in experimentation. The research by Nowak et al. [7] and the data found in this research both noted a gradual decrease in lift after the maximum lift values were obtained.

LIST OF REFERENCES

LIST OF REFERENCES

- 1) Bertin, John J. *Aerodynamics for Engineers*, 4th Ed. New Jersey: Prentice Hall, 2002.
- 2) Lin, John C., Robinson, Stephen K., McGhee, and Robert J., Valarezo, Walter O., "Separation Control on High-Lift Airfoils via Micro-Vortex Generators." *Journal of Aircraft*, Vol. 31, No. 6, 1994, pp. 1317-1323.
- 3) Tai, T. C., "Effect of Midwing Vortex Generators on V-22 Aircraft Forward Flight Aerodynamics." *Journal of Aircraft*, Vol. 40, No. 4, 2003, pp. 623-630.
- 4) Buchholz, Mark D., and Tso, Jin, "Lift Augmentation on Delta Wing with Leading Edge Fences and Gurney Flap." *Journal of Aircraft*, Vol. 37, No. 6, 2000, pp. 1050-1057.
- 5) Storms, Bruce L., and Ross, James C., "An Experimental Study of Lift Enhancing Tabs on a Two Element Airfoil." *Journal of Aircraft*, Vol. 32, No. 5, 1995, pp. 1072-1078.
- 6) Barrett, Ron, and Farokhi, Saeed, "Subsonic Aerodynamics and Performance of a Smart Vortex Generator System, *Journal of Aircraft*, Vol.33, No. 2, 1996, pp. 396-398.
- 7) Nowack, D.K., and Solies, U. P., "Wind Tunnel Tests of a High Lift Generation and Stall Spin Recovery System." *Journal of Aircraft*, Vol. 37, No. 3, 2000, pp. 383 – 389.
- 8) Barlow, Jewel B., Rae, William H., and Pope, Alan, *Low Speed Wind Tunnel Testing*, 3rd Ed. New York: John C Wiley and Sons, Inc., 1999.

APPENDIX

APPENDIX

Table 4.1.1: Experimental Test Matrix

Parameter	Range (Degrees)
Angle of Attack, α Flap Angle, δ	$0 \leq \alpha \leq 20$ $\delta = 0$
Angle of Attack, α Flap Angle, δ	$0 \leq \alpha \leq 20$ $\delta = 10$
Angle of Attack, α Flap Angle, δ	$\alpha = 0$ $0 \leq \delta \leq 30$
Angle of Attack, α Flap Angle, δ	$\alpha = 10$ $0 \leq \delta \leq 35$

Table 4.5.1: Calculation of Error in Lift

$\delta = 0^\circ$		$\delta = 10^\circ$		$\alpha = 0^\circ$		$\alpha = 10^\circ$	
α	Lift	α	Lift	δ	Lift	δ	Lift
0	-0.0499	0	0.2860	0	-0.05432	0	0.38245
9	0.33853	8	0.60905	21	0.63579	8	0.57189
$dC_L/d\alpha$	0.04317	$dC_L/d\alpha$	0.04038	$dC_L/d\delta$	0.03286	$dC_L/d\delta$	0.02368

Table 4.5.2: Calculation of Error in Drag

$\delta = 0^\circ$		$\delta = 10^\circ$		$\alpha = 10^\circ$		$\alpha = 10^\circ$	
α	Drag	α	Drag	δ	Drag	δ	Drag
0	0.06962	0	0.07050	0	0.07489	0	0.13028
9	0.11317	8	0.15340	21	0.12221	8	0.16721
$dC_D/d\alpha$	0.00484	$dC_D/d\alpha$	0.01036	$dC_D/d\delta$	0.00225	$dC_D/d\delta$	0.00462

Table 4.5.3: Calculation of Error in Pitching Moment

$\delta = 0^\circ$		$\delta = 10^\circ$		$\alpha = 10^\circ$		$\alpha = 10^\circ$	
α	Moment	α	Moment	δ	Moment	δ	Moment
0	0.0072	0	-0.03702	0	0.002559	0	-0.03926
9	-0.016	8	-0.04923	21	-0.07575	8	-0.06717
$dC_M/d\alpha$	0.0025	$dC_M/d\alpha$	0.00153	$dC_M/d\delta$	0.00373	$dC_M/d\delta$	0.00349

Table 4.5.4: Error in Dynamic Pressure, Effect on Lift

$\rho \text{ H}_2\text{O}$ (slug/ft ³)	g (ft/s ²)	h (ft)	S (ft ²)	q_∞ (lb/ft ²)	Lift @ 10 (deg)	C_L	$dC_L/d\rho$	dC_L/dh
1.932	32.17	0.3775	1.179	27.662	10.518	0.380	0.19823	1.020797
1.932	32.17	0.3725	1.179	27.295	10.518	0.385		
1.935	32.17	0.375	1.179	27.521	10.518	0.382		
1.928	32.17	0.375	1.179	27.422	10.518	0.383		

Table 4.5.5: Error in Dynamic Pressure, Effect on Drag

$\rho \text{ H}_2\text{O}$ (slug/ft ³)	g (ft/s ²)	h (ft)	S (ft ²)	q_∞ (lb/ft ²)	Drag @ 10 (deg)	C_D	$dC_D/d\rho$	dC_D/dh
1.932	32.17	0.3775	1.179	27.662	3.4941	0.126	0.06585	0.3391
1.932	32.17	0.3725	1.179	27.295	3.49415	0.128		
1.935	32.17	0.375	1.179	27.521	3.49415	0.127		
1.928	32.17	0.375	1.179	27.422	3.49415	0.127		

Table 4.5.6: Error in Dynamic Pressure, Effect on Pitching Moment

ρ_{H_2O} (slug/ft ³)	g (ft/s ²)	h (ft)	S (ft ²)	q_∞ (lb/ft ²)	PM@ 10 (deg)	C_D	$dC_M/d\rho$	dC_M/dh
1.932	32.17	0.3775	1.179	27.662	- 0.0332	- 0.4508	0.0006	0.0032
1.932	32.17	0.3725	1.179	27.296	- 0.0332	- 0.4569		
1.935	32.17	0.3750	1.179	27.5218	- 0.0332	- 0.4531		
1.928	32.17	0.3750	1.179	27.4223	- 0.0332	- 0.4548		

Table 4.5.7: Tabulated Error Values

Parameter	Calculated Value	Parameter	Estimated Value
$\frac{\partial C_L}{\partial \alpha}$	0.043166	ω_α	± 0.25 (deg)
$\frac{\partial C_L}{\partial \delta}$	0.040381	ω_δ	± 0.25 (deg)
$\frac{\partial C_L}{\partial \rho_{H_2O}}$	0.1982304	$\omega_{\rho_{H_2O}}$	± 0.004 (slug/ft ³)
$\frac{\partial C_L}{\partial h_{H_2O}}$	1.02079	$\omega_{h_{H_2O}}$	± 0.0025 (ft)
$\frac{\partial C_L}{\partial A/D}$	0.00004	$\omega_{A/D}$	± 125 (A/D counts)
$\frac{\partial C_D}{\partial \alpha}$	0.010363	ω_α	± 0.25 (deg)
$\frac{\partial C_D}{\partial \delta}$	0.004616	ω_δ	± 0.25 (deg)
$\frac{\partial C_D}{\partial \rho_{H_2O}}$	0.06585	$\omega_{\rho_{H_2O}}$	± 0.004 (slug/ft ³)
$\frac{\partial C_D}{\partial h_{H_2O}}$	0.33909	$\omega_{h_{H_2O}}$	± 0.0025 (ft)
$\frac{\partial C_D}{\partial A/D}$	0.000033	$\omega_{A/D}$	± 89 (A/D counts)
$\frac{\partial C_M}{\partial \alpha}$	0.00258	ω_α	± 0.25 (deg)
$\frac{\partial C_M}{\partial \delta}$	0.00373	ω_δ	± 0.25 (deg)
$\frac{\partial C_M}{\partial \rho_{H_2O}}$	0.0006	$\omega_{\rho_{H_2O}}$	± 0.004 (slug/ft ³)
$\frac{\partial C_M}{\partial h_{H_2O}}$	0.0032	$\omega_{h_{H_2O}}$	± 0.0025 (ft)
$\frac{\partial C_M}{\partial A/D}$	0.000041	$\omega_{A/D}$	± 190 (A/D counts)

Table 4.5.8: Total Error

ω_{c_L}	ω_{c_D}	ω_{c_M}
± 0.016	± 0.004	± 0.008

Table 5.7.1: Data Comparison for α -dependent Data, $\delta = 0^\circ$

α -dependent tests, $\delta = 0^\circ$						
	Critical Angle (C_{Lmax})	C_{Lmax}	(L/D) max	Increase in Critical Angle from Baseline (deg)	Increase in C_{Lmax} from Baseline (%)	Increase in (L/D)max From Baseline (%)
Baseline	11	0.392	3.010			
Upper Surface 1/2" VG 2" Spacing	16	0.509	3.025	5	29.604	0.485
1/4" VG 2" Spacing	16	0.531	3.003	5	35.182	-0.234
1/2" VG 4.5" Spacing	18	0.531	3.189	7	35.374	5.928
1/2" VG 2.5" Spacing	18	0.550	3.057	7	40.181	1.553
1/2" VG 2.0" Spacing	17	0.556	3.183	6	41.632	5.728
30° Sweep 1/2" VG 2.0" Spacing	19	0.563	3.112	8	43.510	3.389
1/2" VG 1.5" Spacing	17	0.564	3.646	6	43.819	21.110
3/4" VG 2" Spacing	19	0.569	3.575	8	44.994	18.758
In order from Lowest to Highest Lift Coefficient						

Table 5.7.2: Data Comparison for α -dependent Data, $\delta = 10^\circ$

α -dependent tests, $\delta = 10^\circ$						
	Critical Angle (C_{Lmax})	C_{Lmax}	(L/D) max	Increase in Critical Angle from Baseline (deg)	Increase in C_{Lmax} from Baseline (%)	Increase in (L/D)max From Baseline (%)
Baseline	9	0.623	4.538			
Upper Surface 1/2" VG 2" Spacing	12	0.659	4.554	3	5.777	0.346
1/4" VG 2" Spacing	12	0.689	4.289	3	10.653	-5.484
1/2" VG 4.5" Spacing	12	0.683	4.684	3	9.686	3.220
1/2" VG 2.5" Spacing	14	0.705	4.489	5	13.237	-1.079
1/2" VG 2.0" Spacing	14	0.715	4.620	5	14.776	1.799
30° Sweep 1/2" VG 2.0" Spacing	14	0.721	4.496	5	15.746	-0.922
1/2" VG 1.5" Spacing	14	0.711	4.875	5	14.159	7.417
3/4" VG 2" Spacing	14	0.728	5.480	5	16.901	20.768

Table 5.7.3: Data Comparison for δ -dependent Data, $\alpha = 10^\circ$

δ -dependent tests, $\alpha = 10^\circ$						
	Critical Angle (C_{Lmax})	C_{Lmax}	(L/D) max	Increase in Critical Angle from Baseline (deg)	Increase in C_{Lmax} from Baseline (%)	Increase in (L/D)max From Baseline (%)
Baseline	9	0.591	3.483			
Upper Surface 1/2" VG 2" Spacing	32	0.768	3.477	21	30.032	-0.166
1/4" VG 2" Spacing	23	0.849	3.731	12	43.729	7.101
1/2" VG 4.5" Spacing	24	0.823	3.725	13	39.198	6.942
1/2" VG 2.5" Spacing	31	0.883	3.810	20	49.348	9.382
1/2" VG 2.0" Spacing	27	0.879	3.855	16	48.780	10.687
30° Sweep 1/2" VG 2.0" Spacing	32	0.904	3.907	21	52.967	12.162
1/2" VG 1.5" Spacing	31	0.886	4.130	20	49.977	18.558
3/4" VG 2" Spacing	29	0.896	4.144	18	51.554	18.967

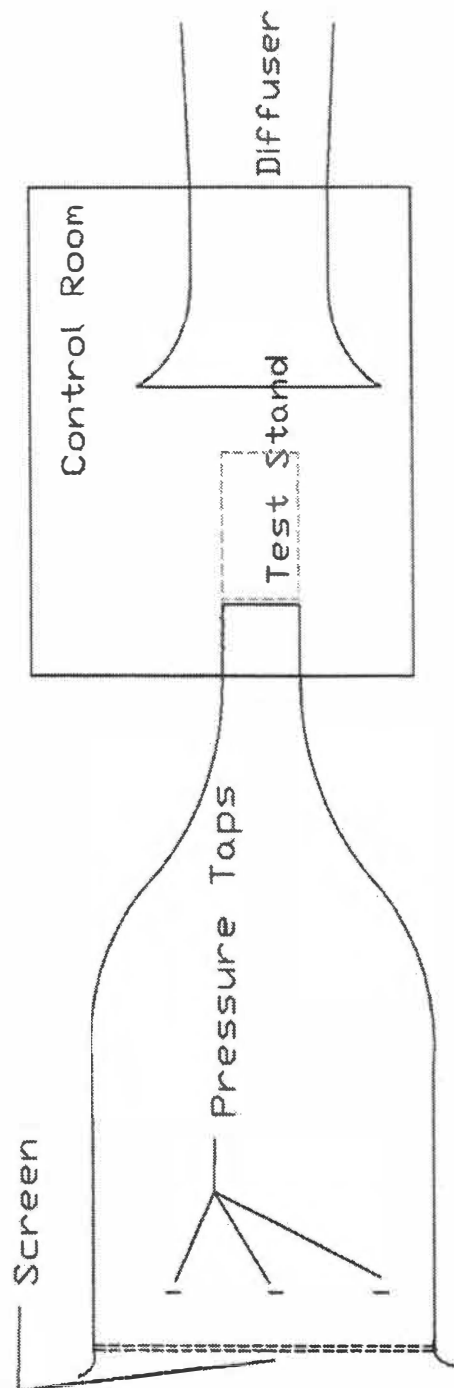


Figure 3.1.1: Schematic of UTK Subsonic Wind Tunnel

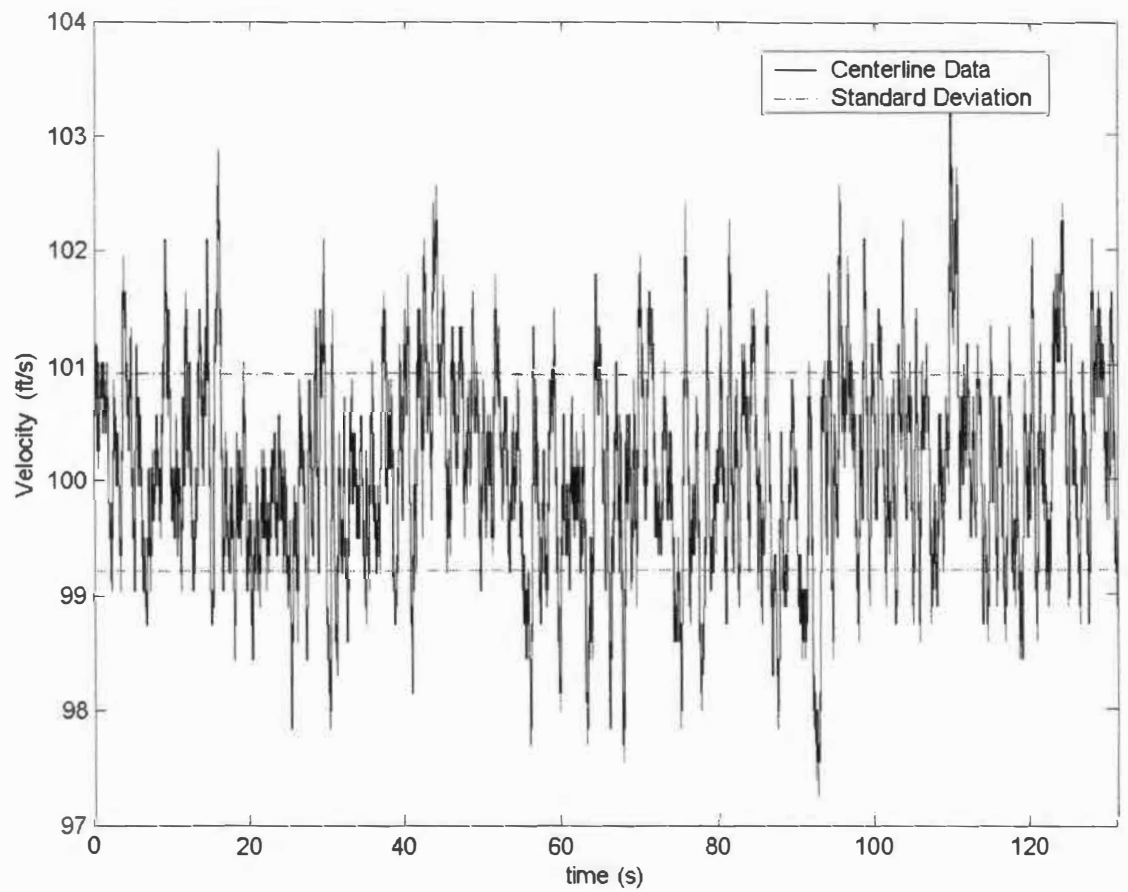


Figure 3.3.1: Centerline Velocity Distribution vs Time

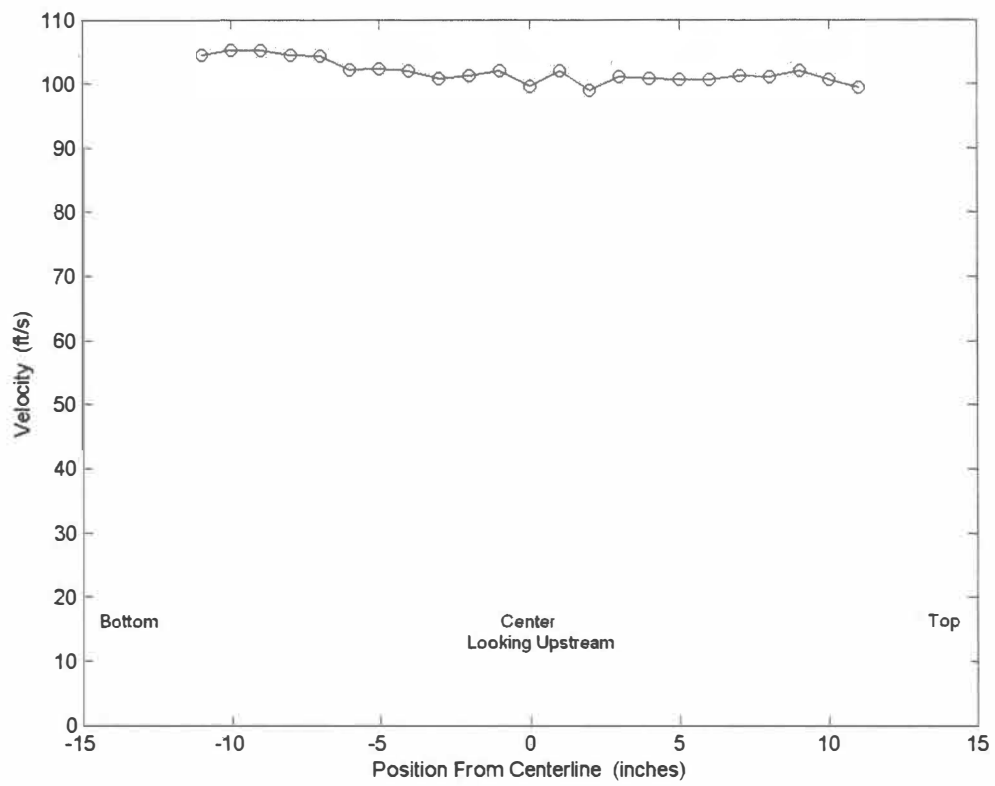


Figure 3.3.2: Vertical Velocity Distribution vs Position

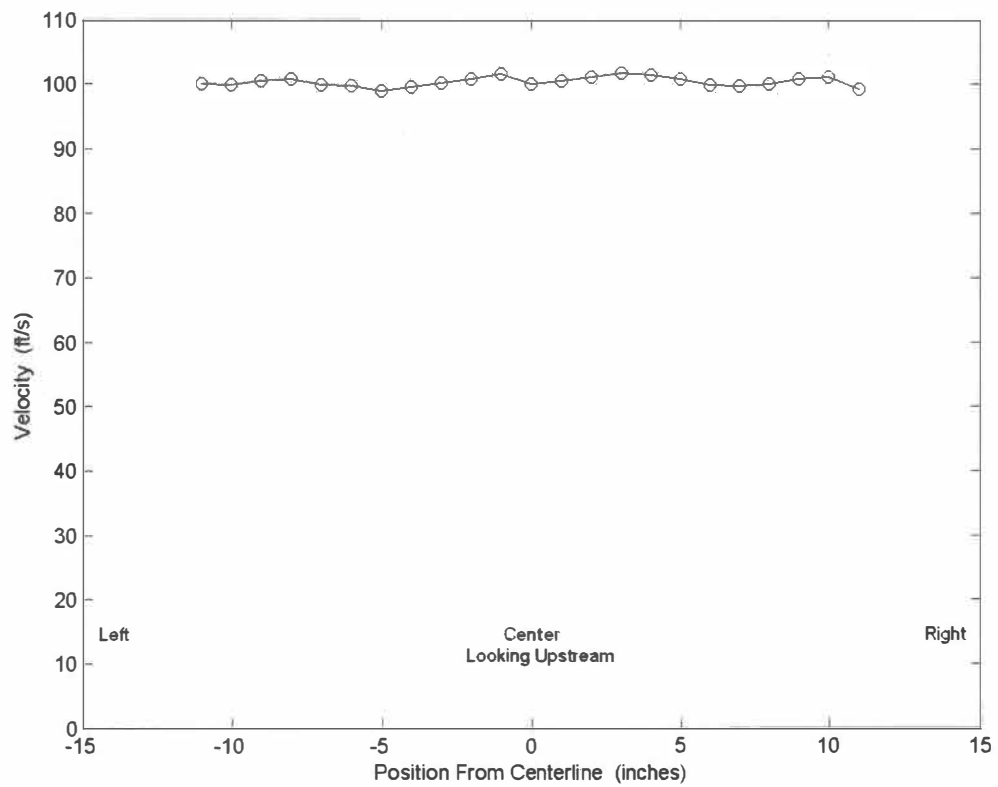


Figure 3.3.3: Horizontal Velocity Distribution vs Position

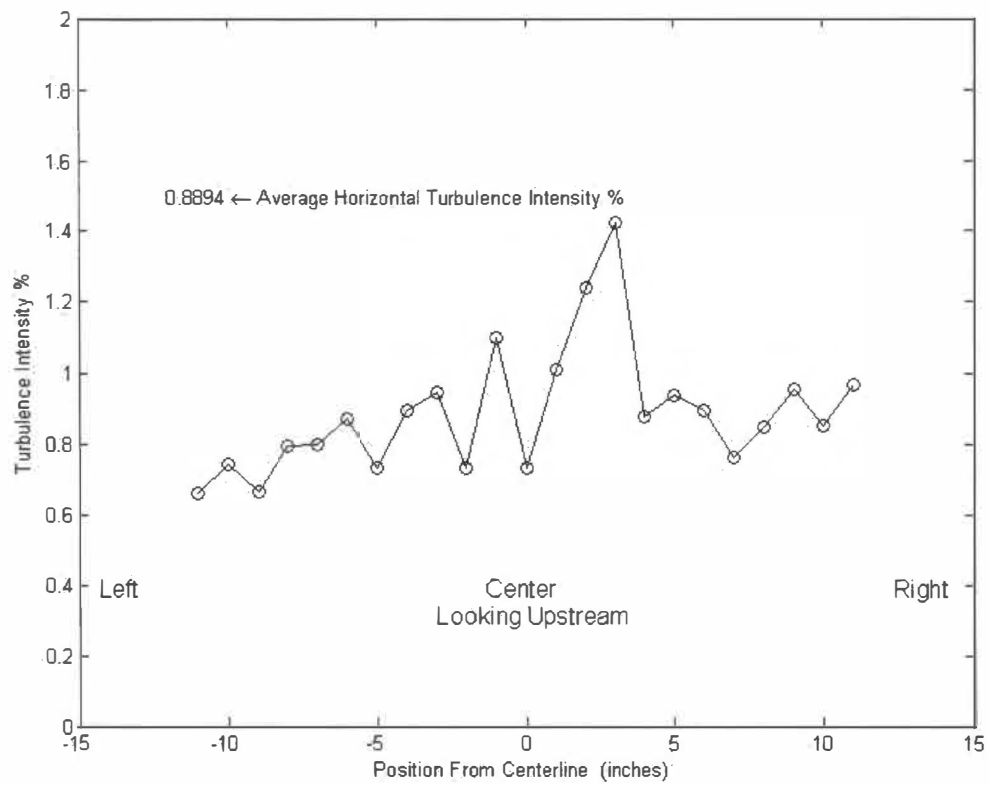


Figure 3.3.4: Horizontal Variation in Turbulence Intensity %

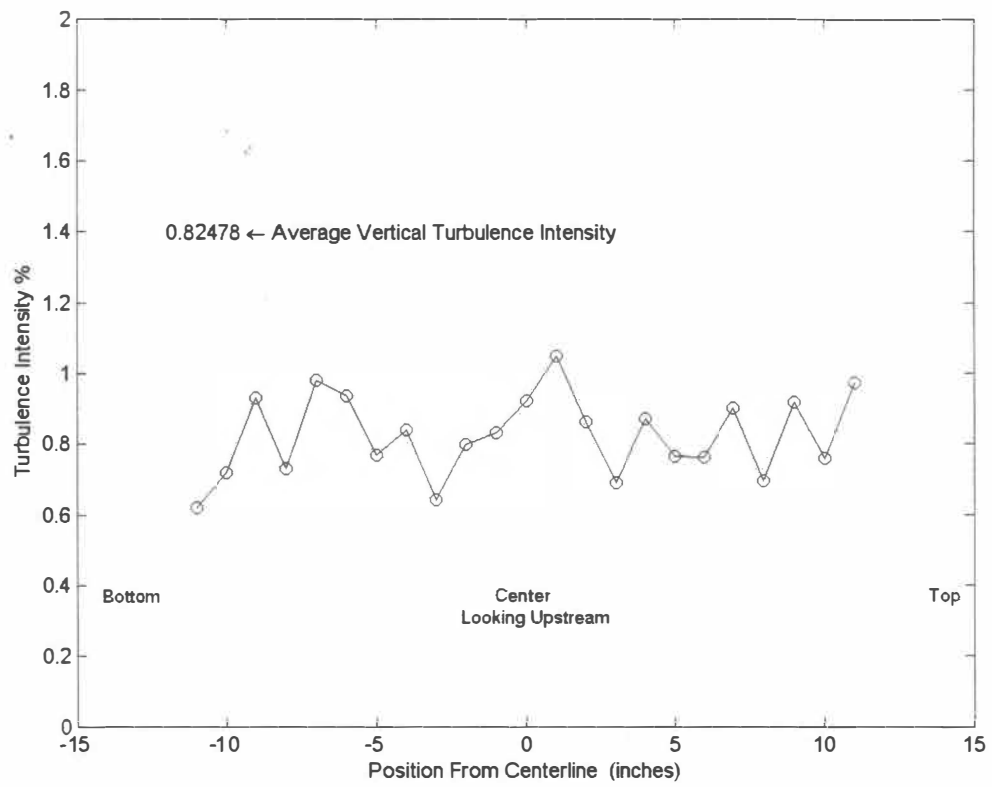


Figure 3.3.5: Vertical Variation In Turbulence Intensity %

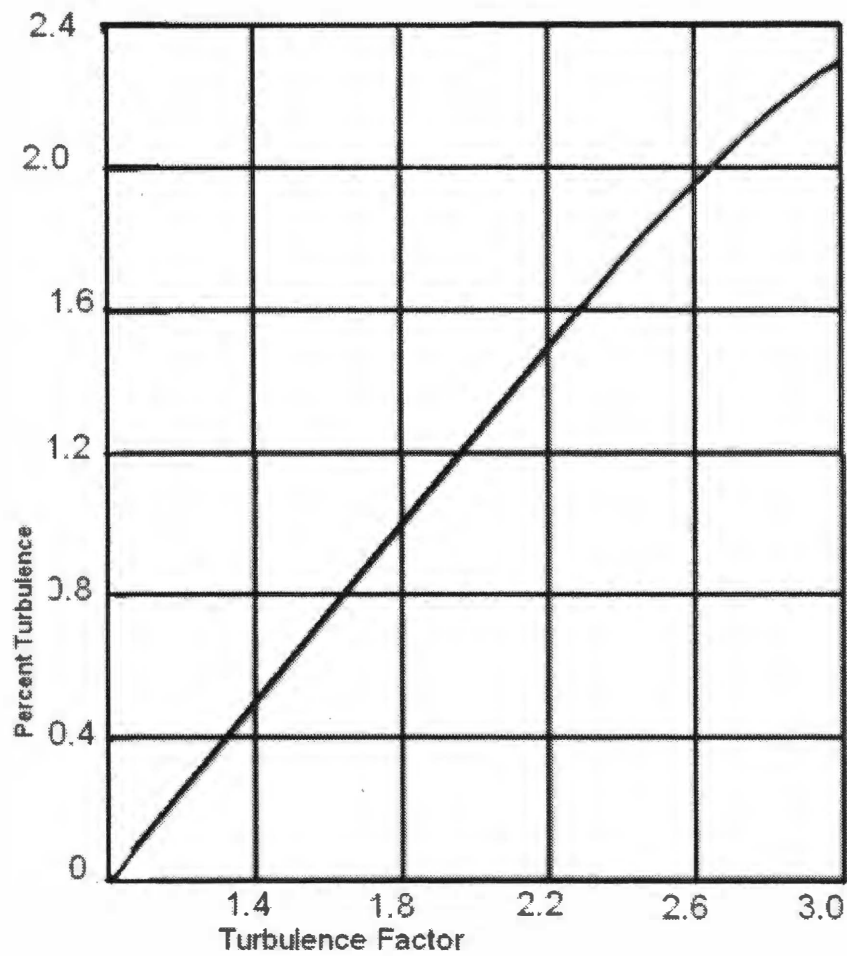


Figure 3.3.6: Variation of Turbulence Factor with Turbulence Intensity from Hot-Wire Measurements

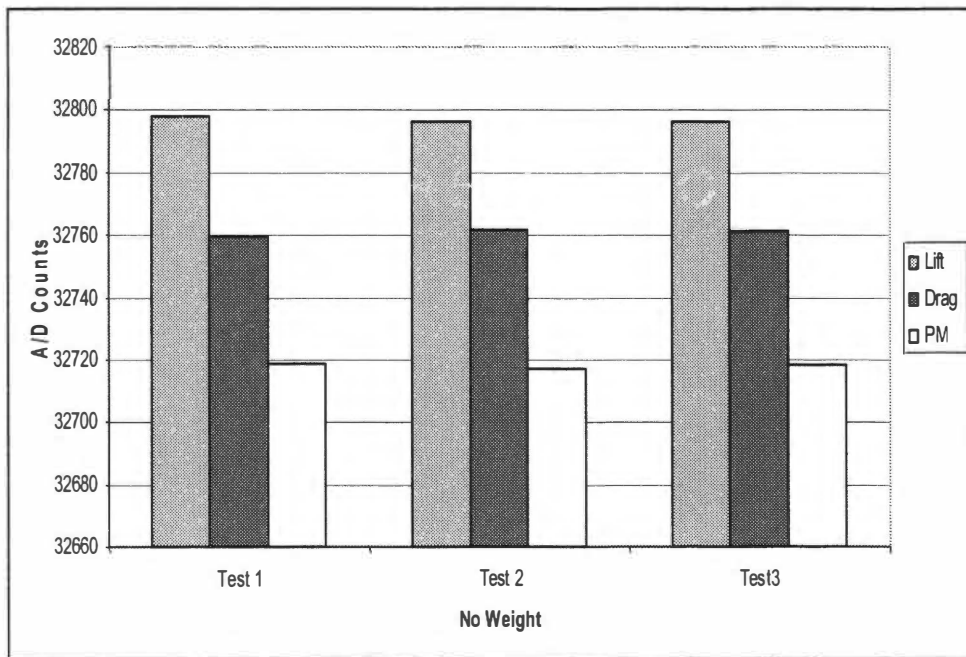


Figure 3.3.7: Repeatability in Pyramidal Balance, No Load

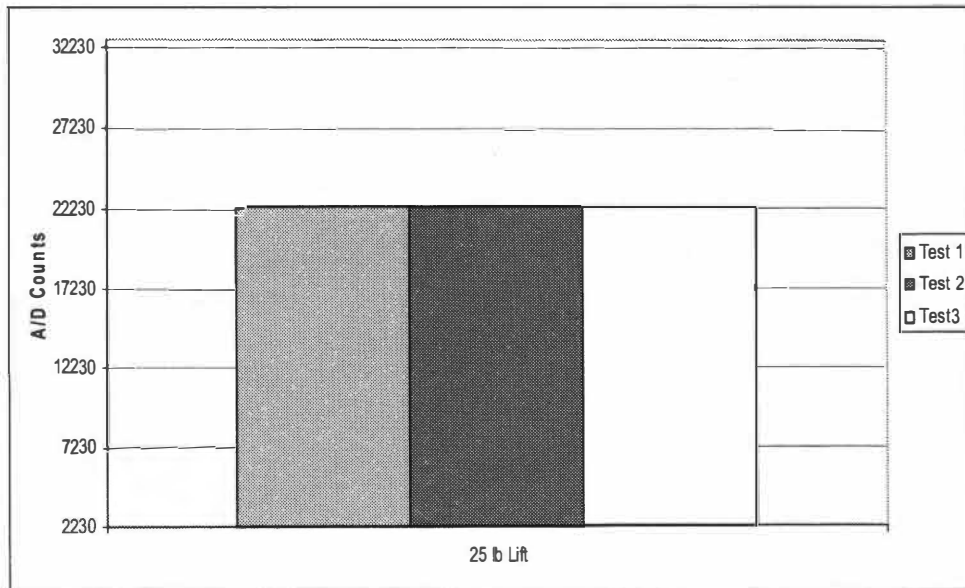


Figure 3.3.8: Repeatability in Pyramidal Balance, 25 Pound Load on Lift Cell

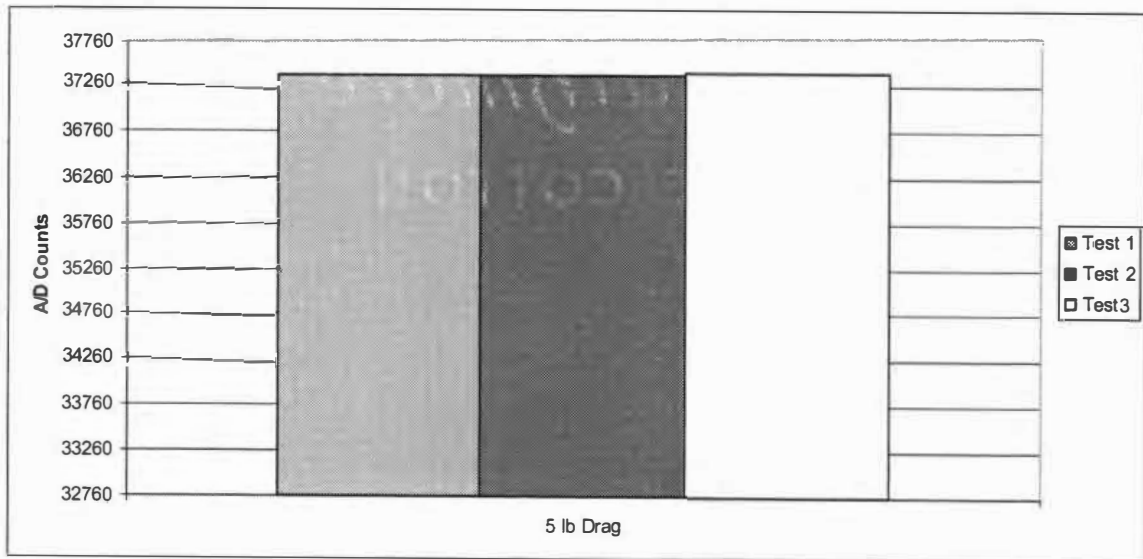


Figure 3.3.9: Repeatability in Pyramidal Balance, 5 Pound Load on Drag Cell

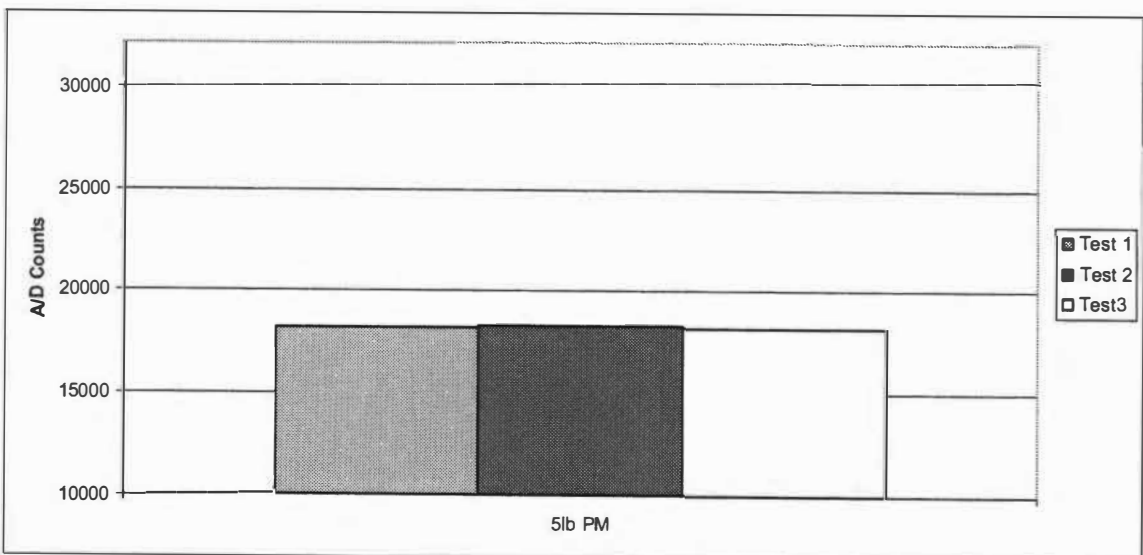


Figure 3.3.10: Repeatability in Pyramidal Balance, 5 Pound Load on Pitching Moment Cell

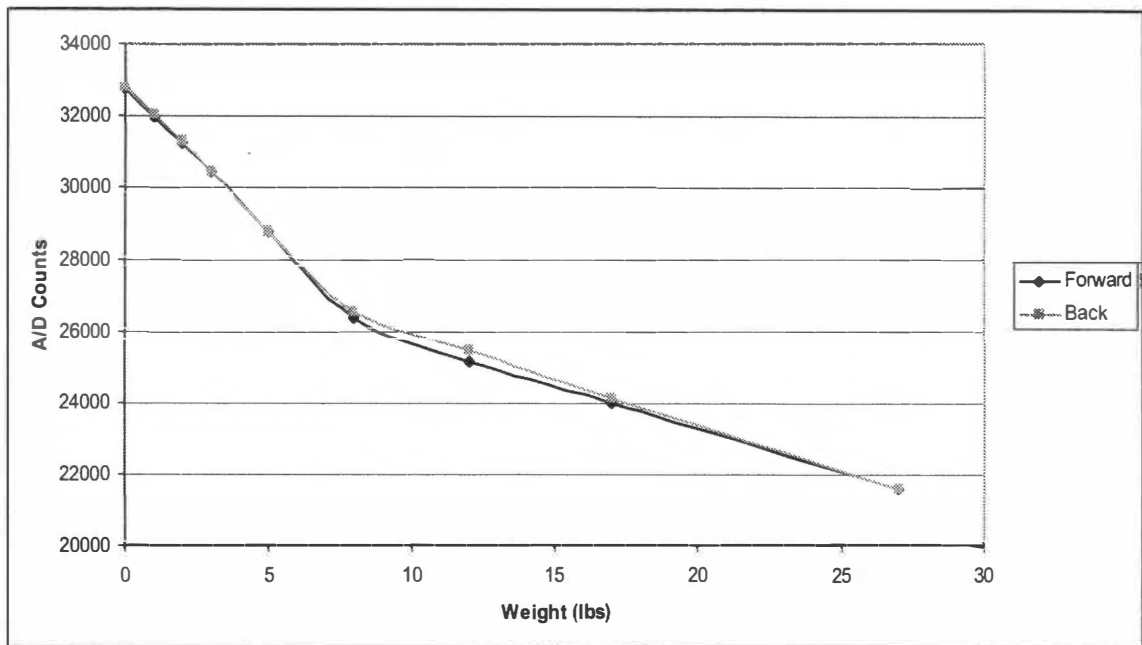


Figure 3.3.11: Hysteresis Test on Pyramidal Balance Strain Gauge, Negative Loading

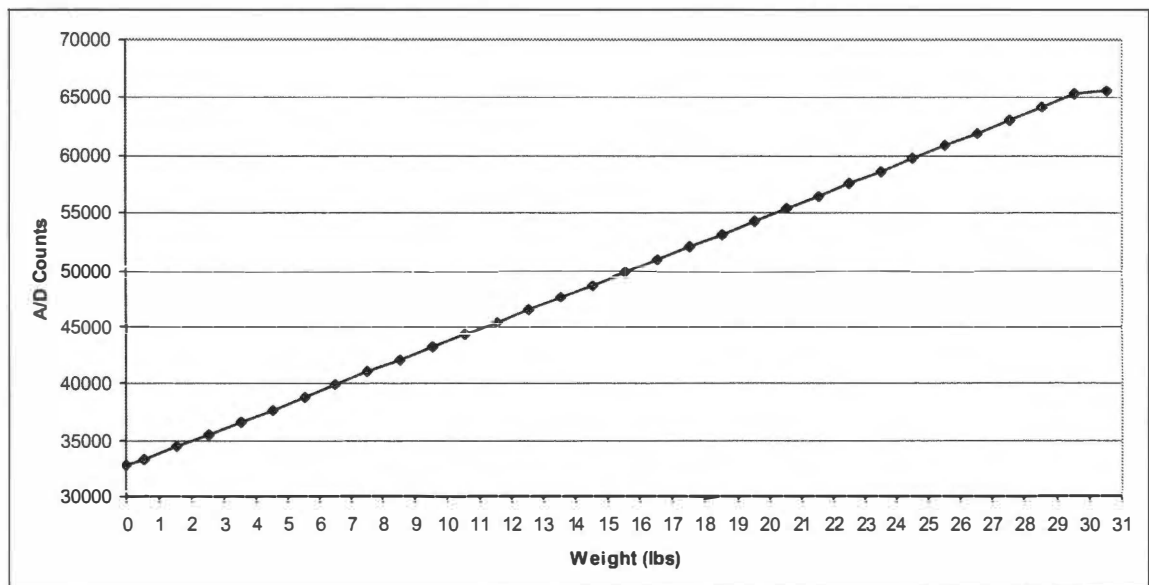


Figure 3.3.12: Positive Loading of Lift Load Cell

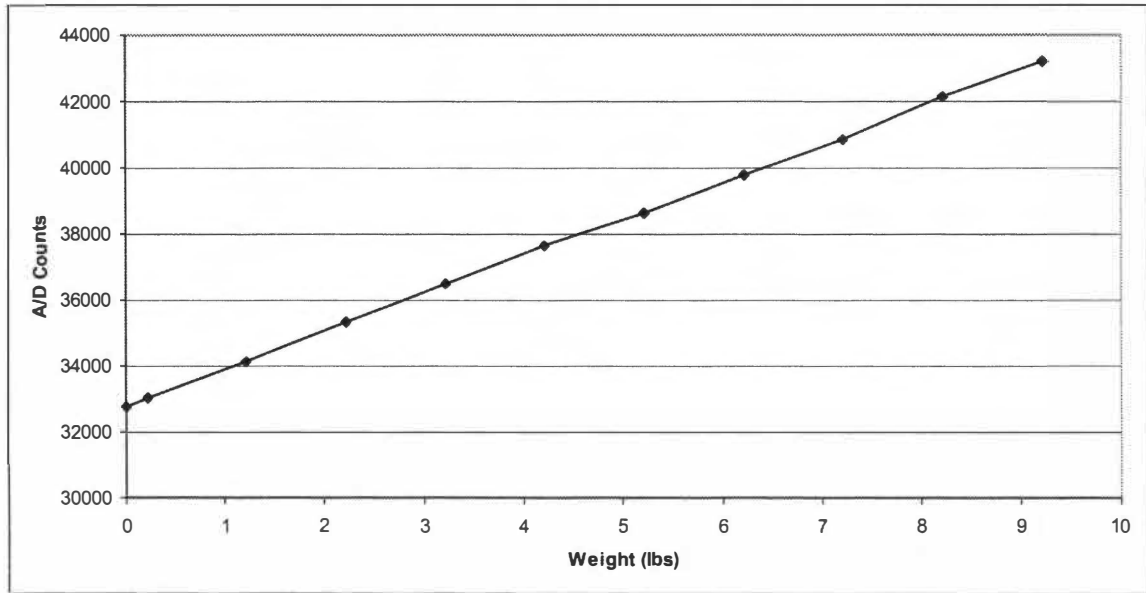


Figure 3.3.13: Positive Loading of Drag Load Cell

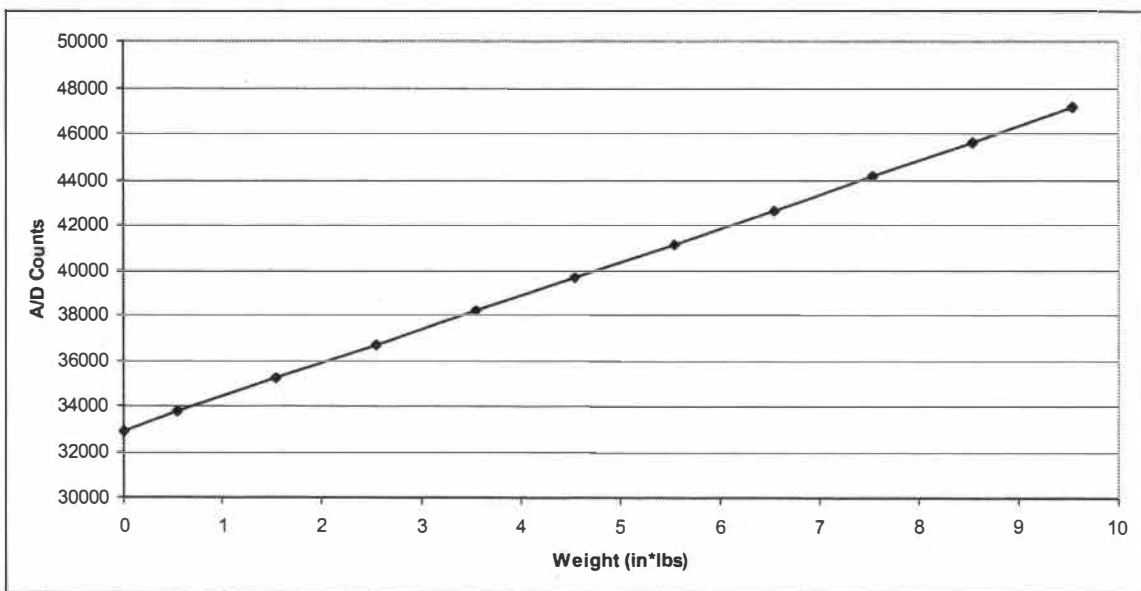


Figure 3.3.14: Positive Loading of Pitching Moment Load Cell

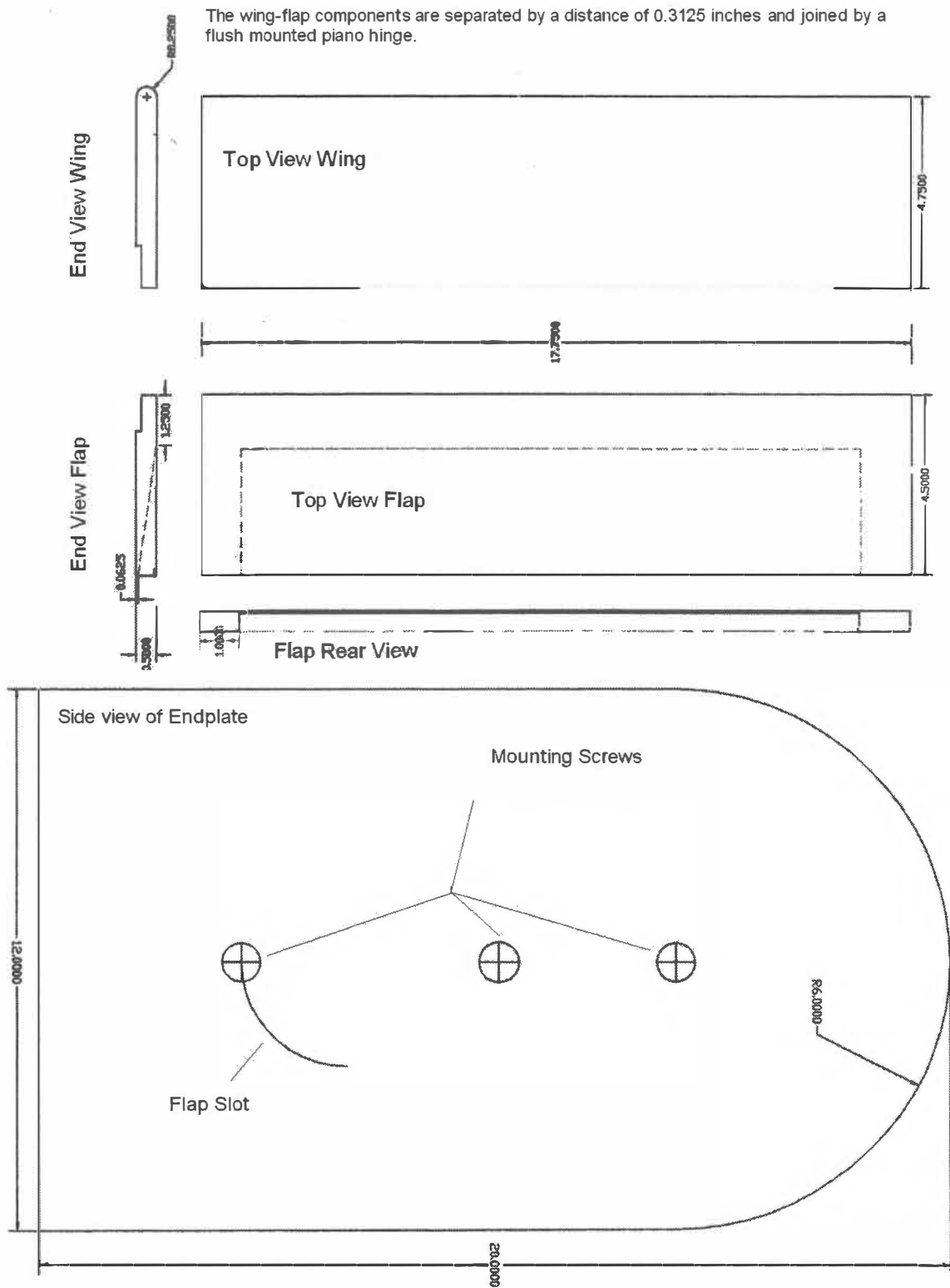


Figure 3.4.1: Schematic of Model Components

Flap-Hinge Line Mounting of 0.5 Inch Delta-VGs

Leading Edge Lower Surface Mounting of
0.5 Inch Delta-VGs

Figure 3.4.2: Leading Edge Angled View of Wing-Flap System with Delta-VGs
Looking Downstream

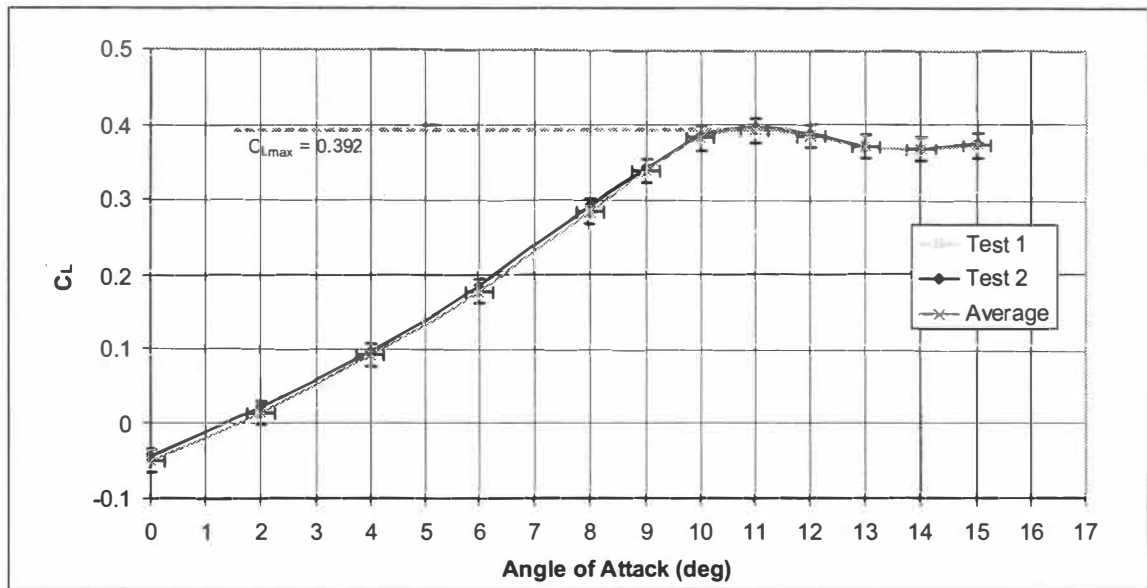


Figure 5.1.1: Baseline Model α dependent Lift Coefficient, $\delta = 0^\circ$

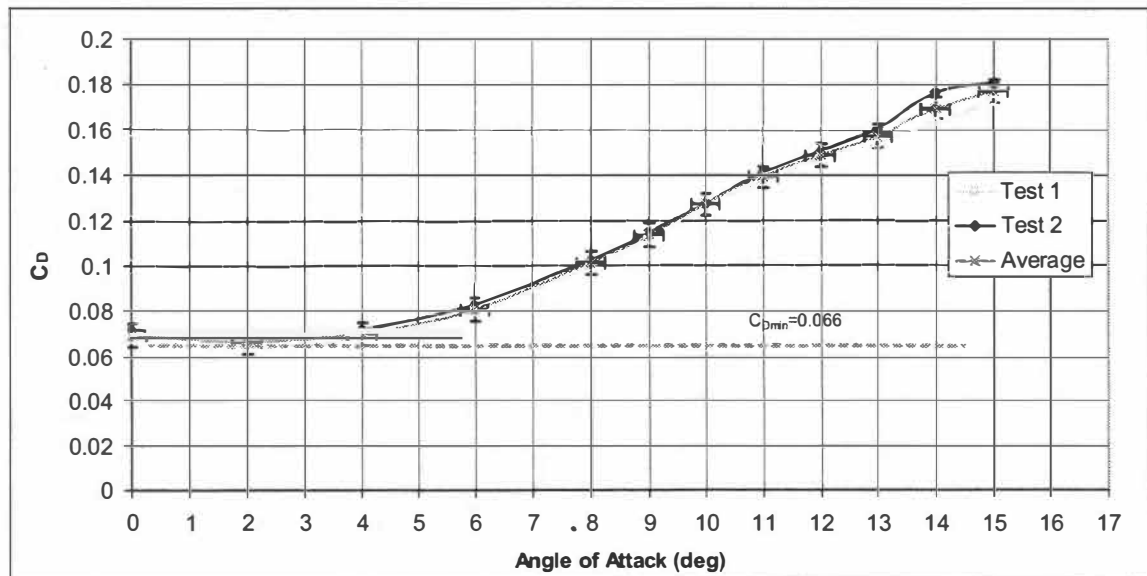


Figure 5.1.2: Baseline Model α dependent Drag Coefficient, $\delta = 0^\circ$

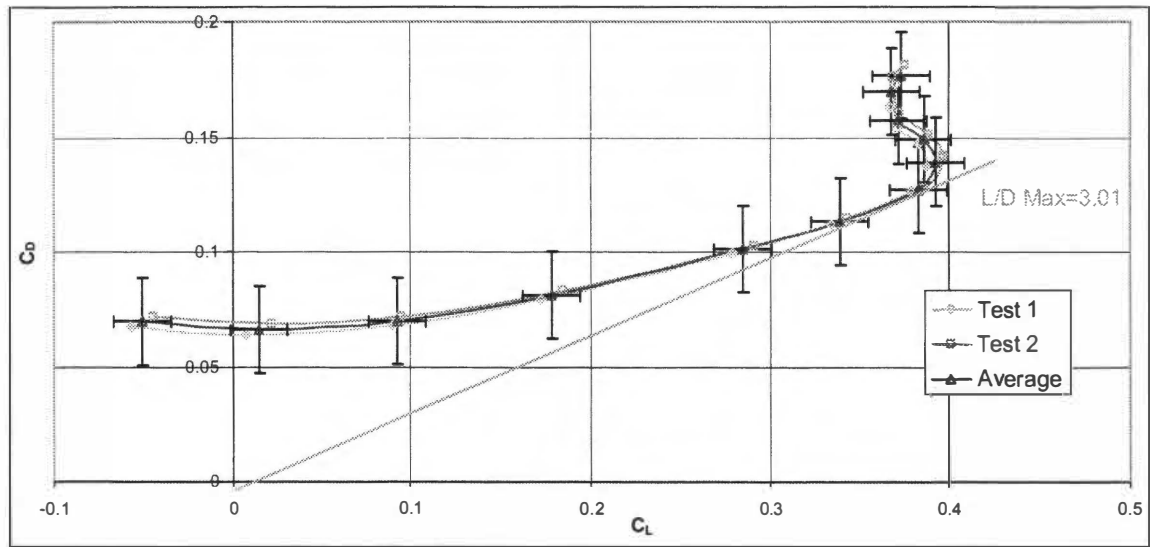


Figure 5.1.3: Baseline Model Drag Polar, $\delta = 0^\circ$

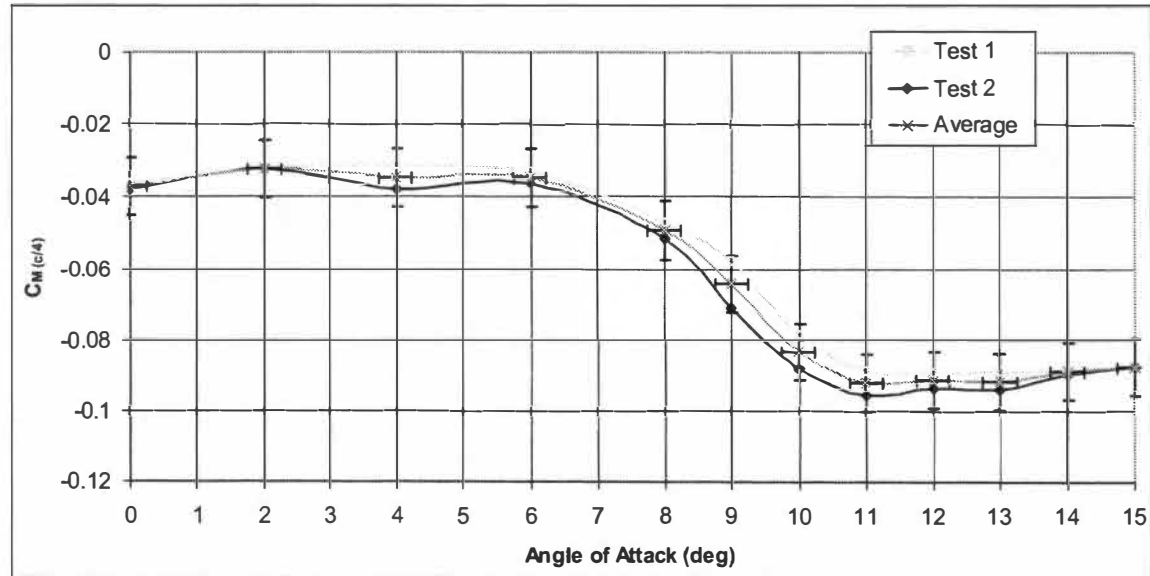


Figure 5.1.4: Baseline Model α dependent Moment Coefficient, $\delta = 0^\circ$

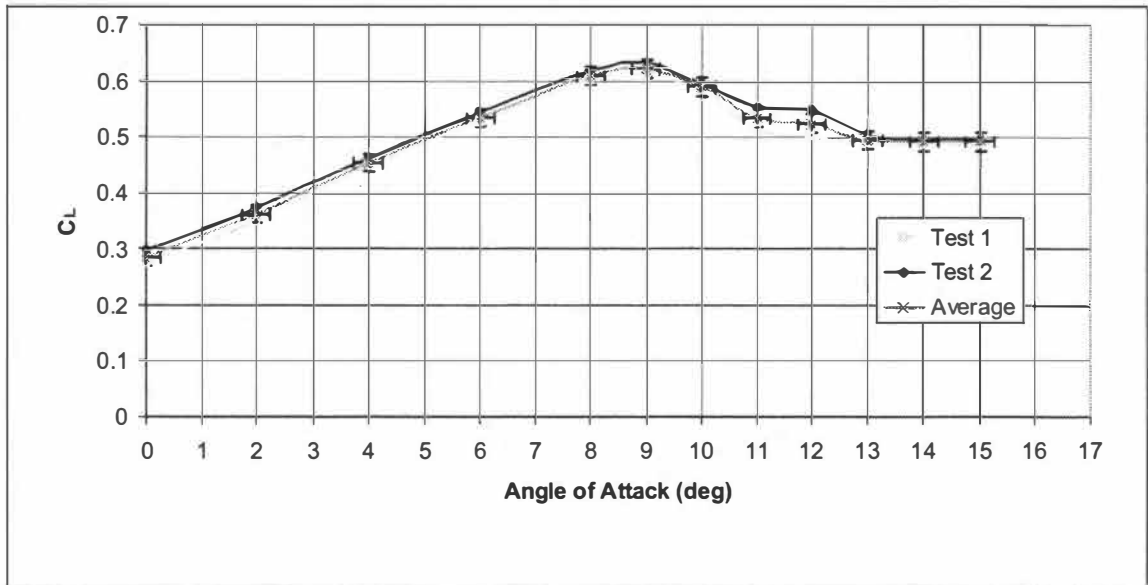


Figure 5.1.5: Baseline Model α dependent Lift Coefficient, $\delta = 10^\circ$

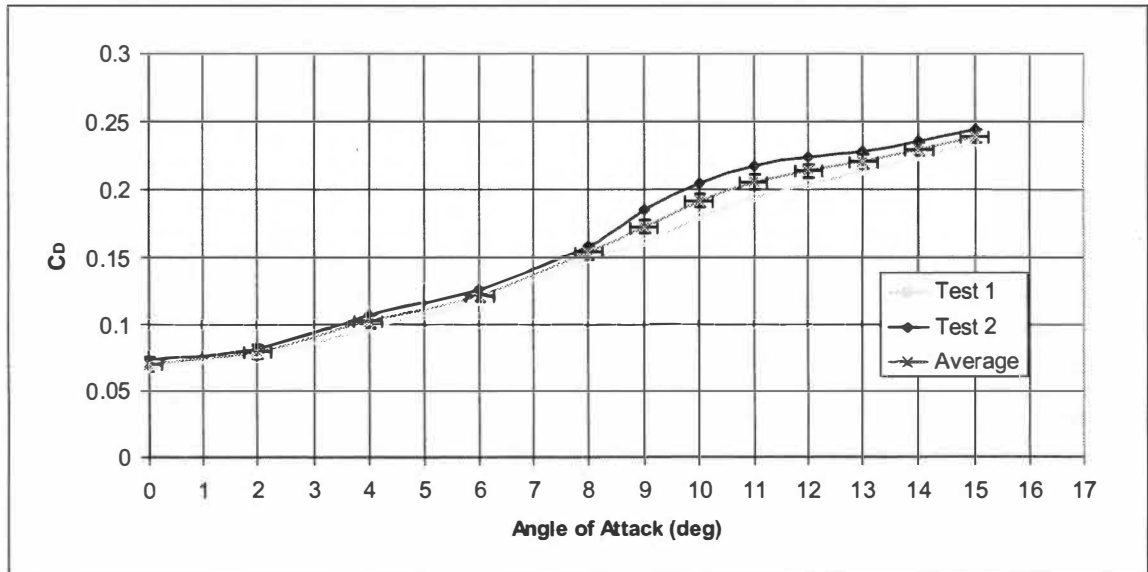


Figure 5.1.6: Baseline Model α dependent Drag Coefficient, $\delta = 10^\circ$

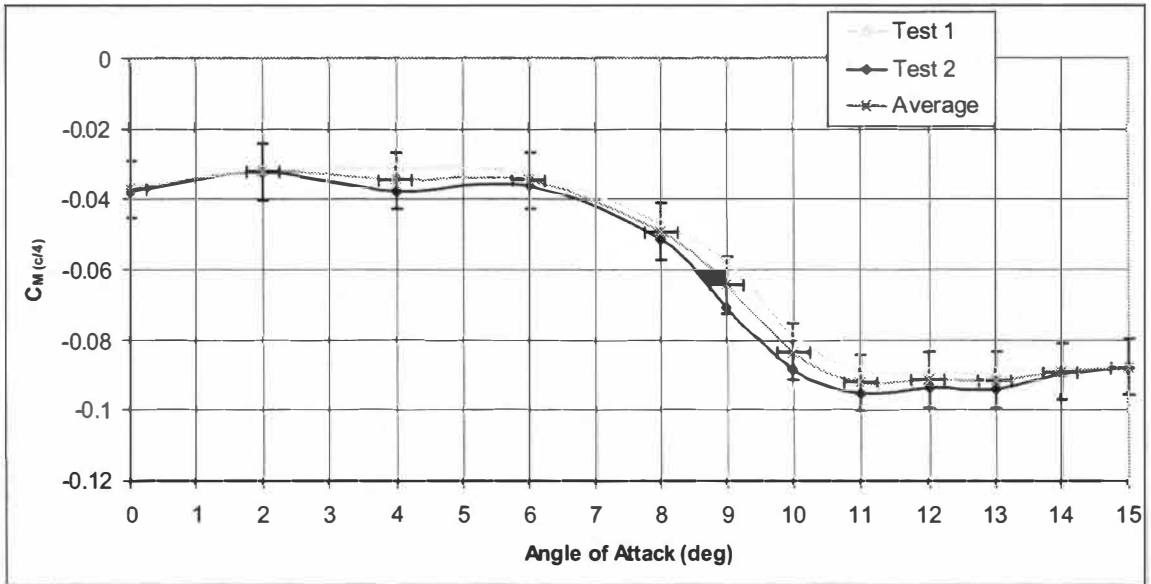


Figure 5.1.7: Baseline Model α dependent Moment Coefficient, $\delta = 10^\circ$

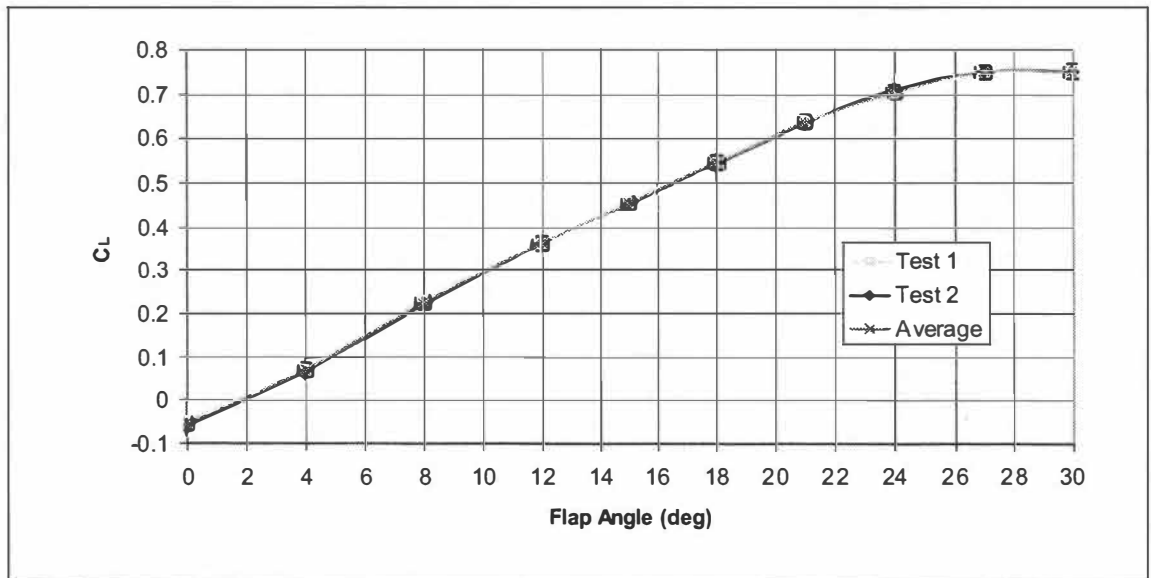


Figure 5.1.8: Baseline Model δ dependent Lift Coefficient, $\alpha = 0^\circ$

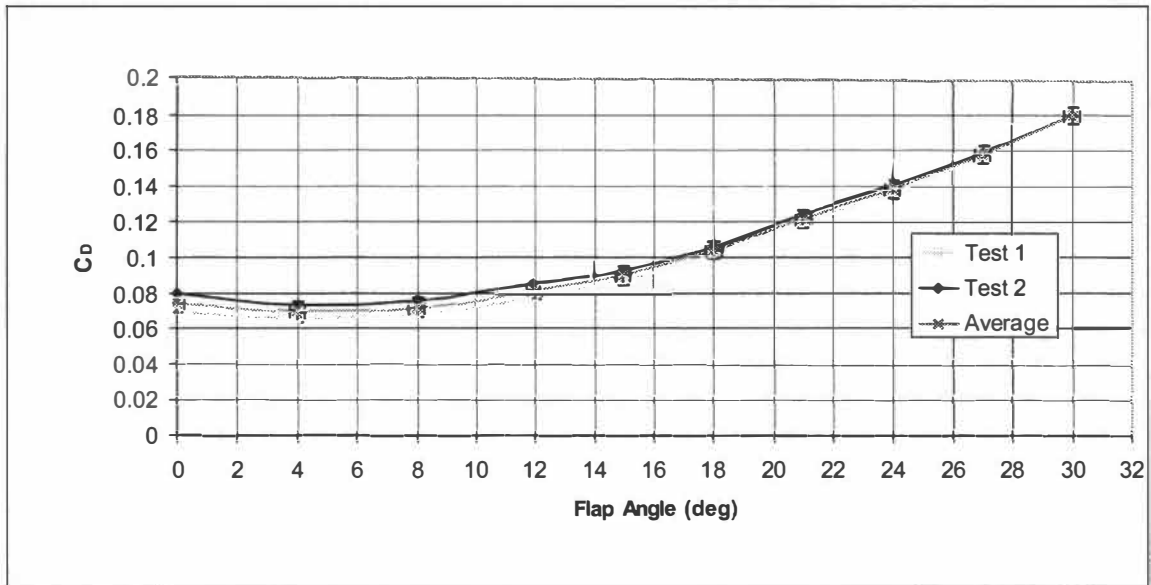


Figure 5.1.9: Baseline Model δ dependent Drag Coefficient, $\alpha = 0^\circ$

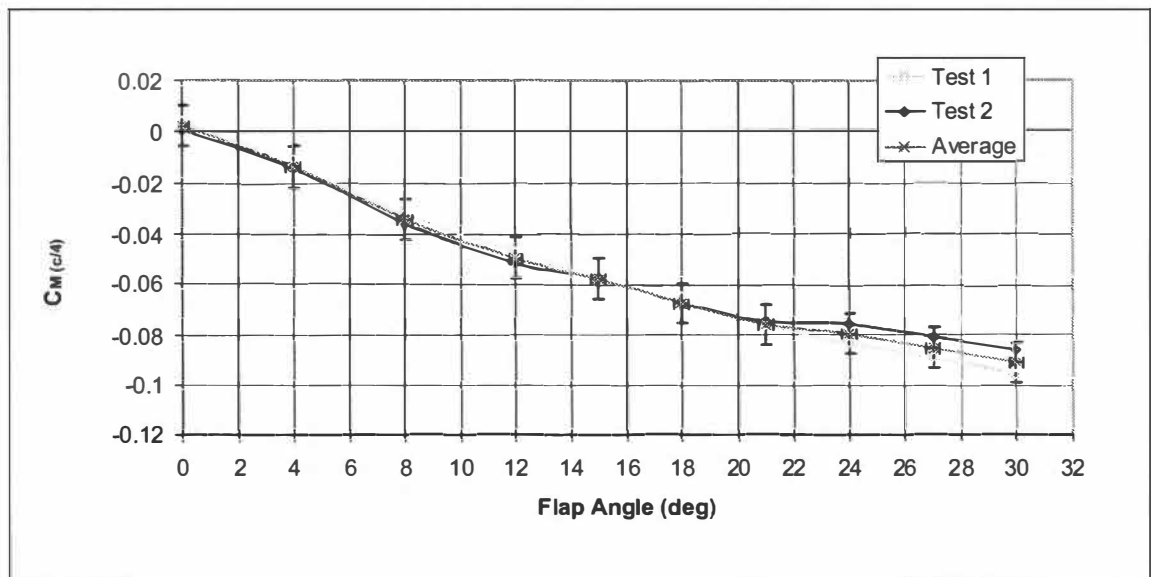


Figure 5.1.10: Baseline Model δ dependent Moment Coefficient, $\alpha = 0^\circ$

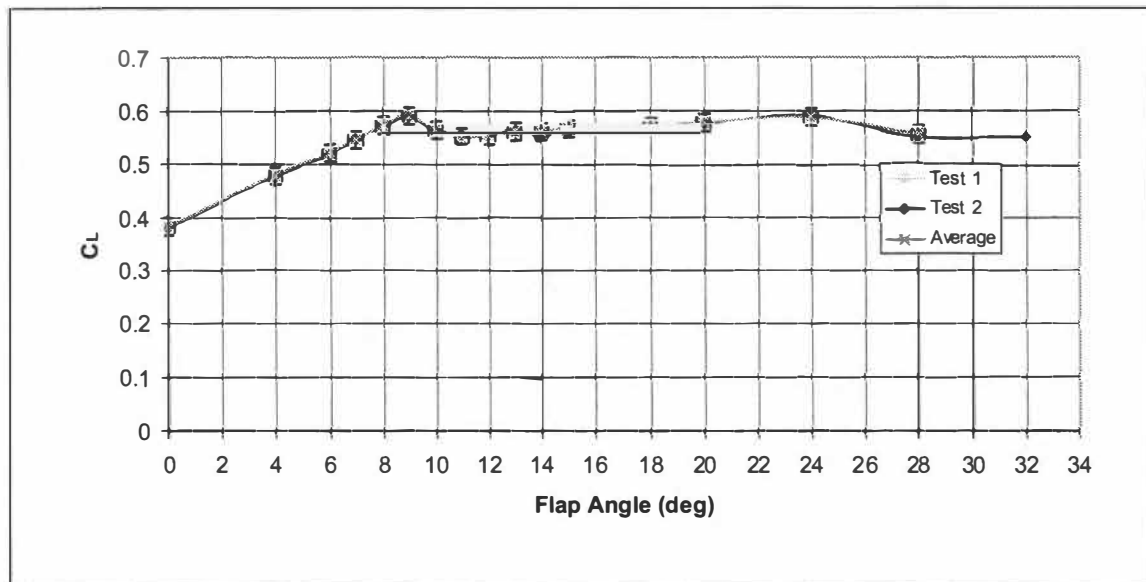


Figure 5.1.11: Baseline Model δ dependent Lift Coefficient, $\alpha = 10^\circ$

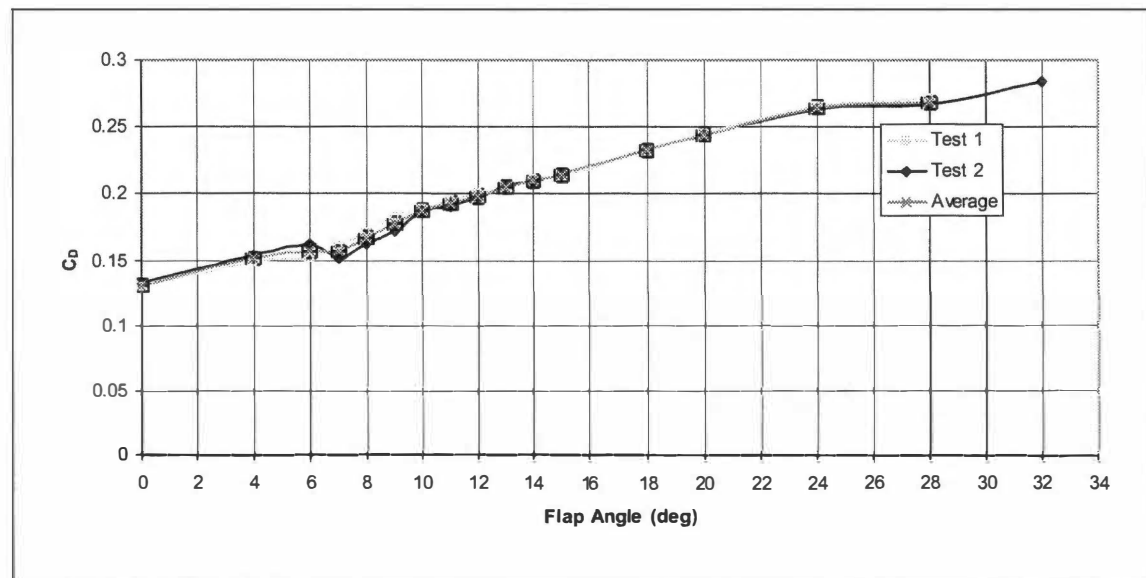


Figure 5.1.12: Baseline Model δ dependent Drag Coefficient, $\alpha = 10^\circ$

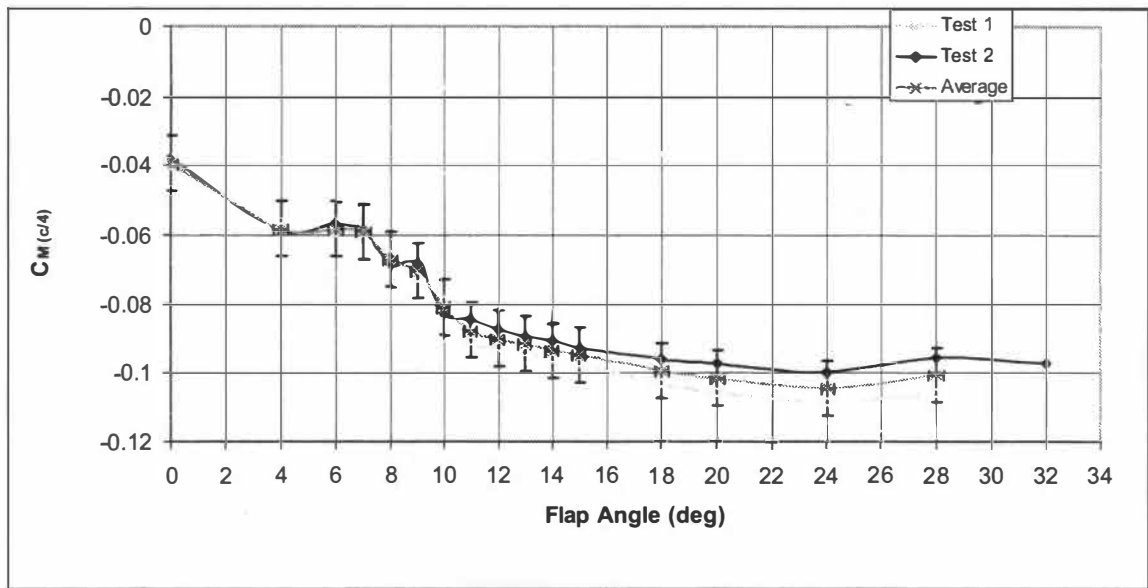


Figure 5.1.13: Baseline Model δ dependent Moment Coefficient, $\alpha = 10^\circ$

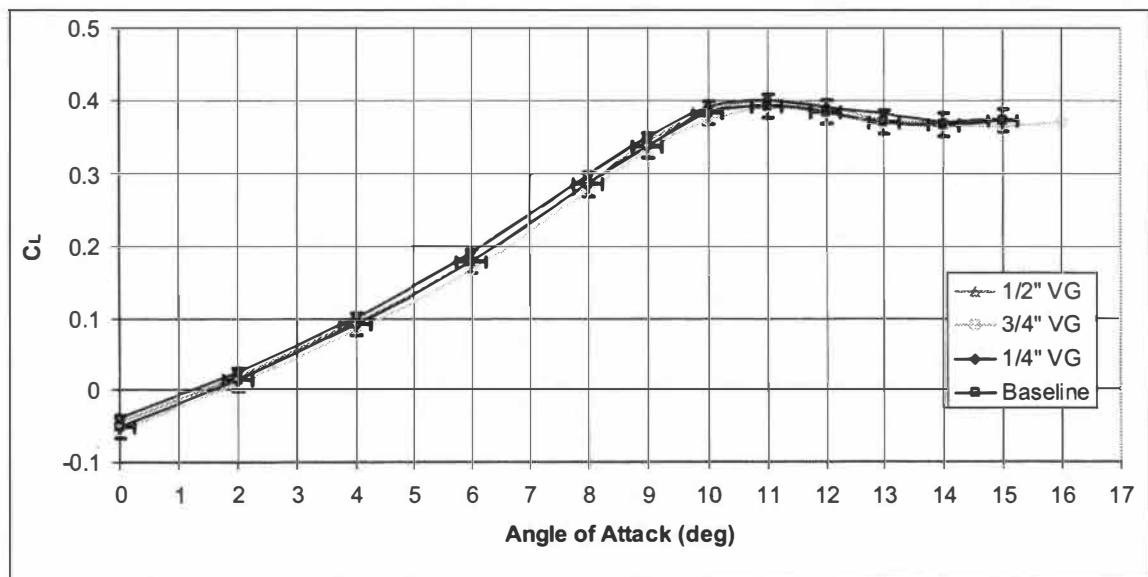


Figure 5.2.1: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, α -dependent Lift Coefficient, $\delta = 0^\circ$

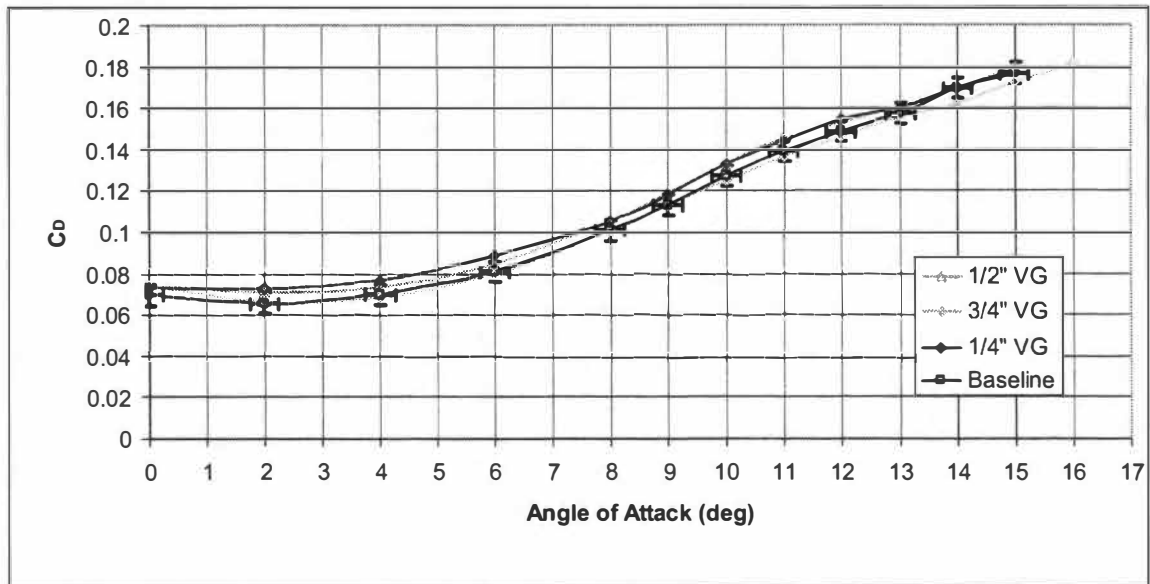


Figure 5.2.2: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, α -dependent Drag Coefficient, $\delta = 0^\circ$

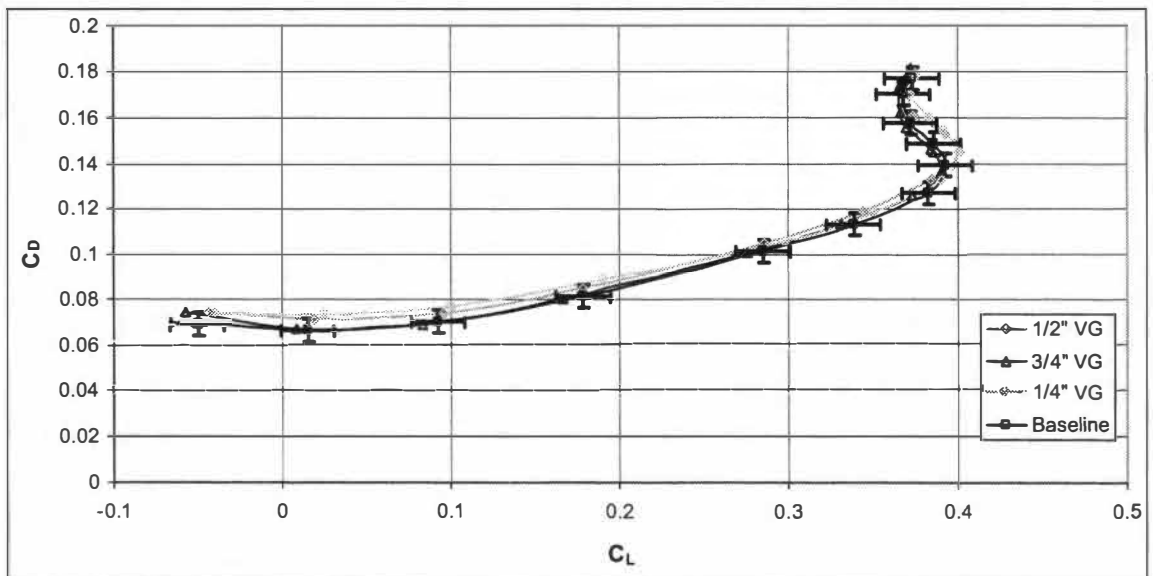


Figure 5.2.3: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, Drag Polar, $\delta = 0^\circ$

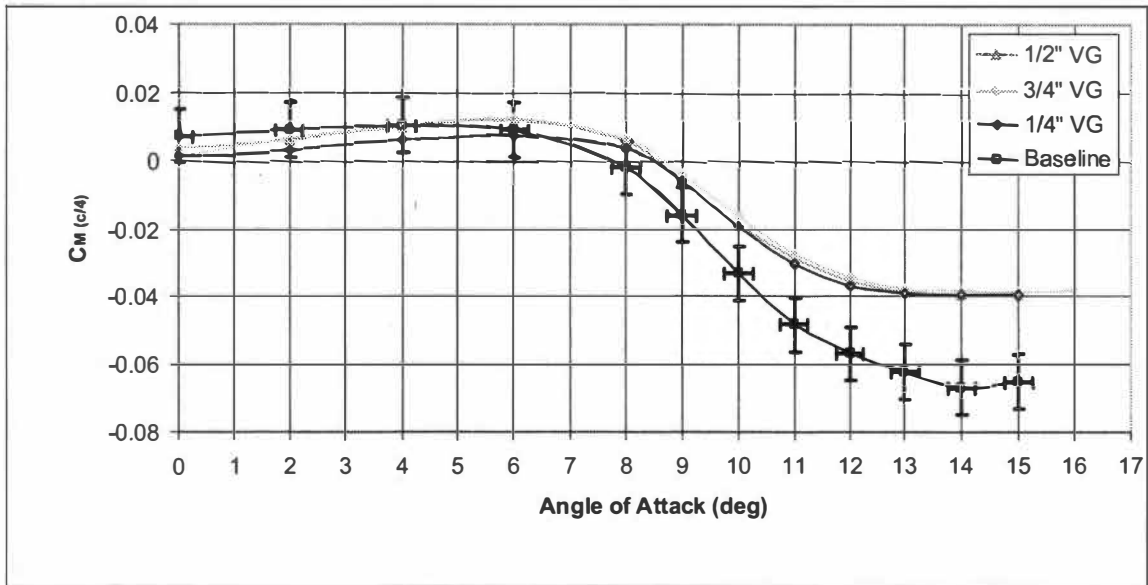


Figure 5.2.4: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, α -dependent Moment Coefficient, $\delta = 0^\circ$

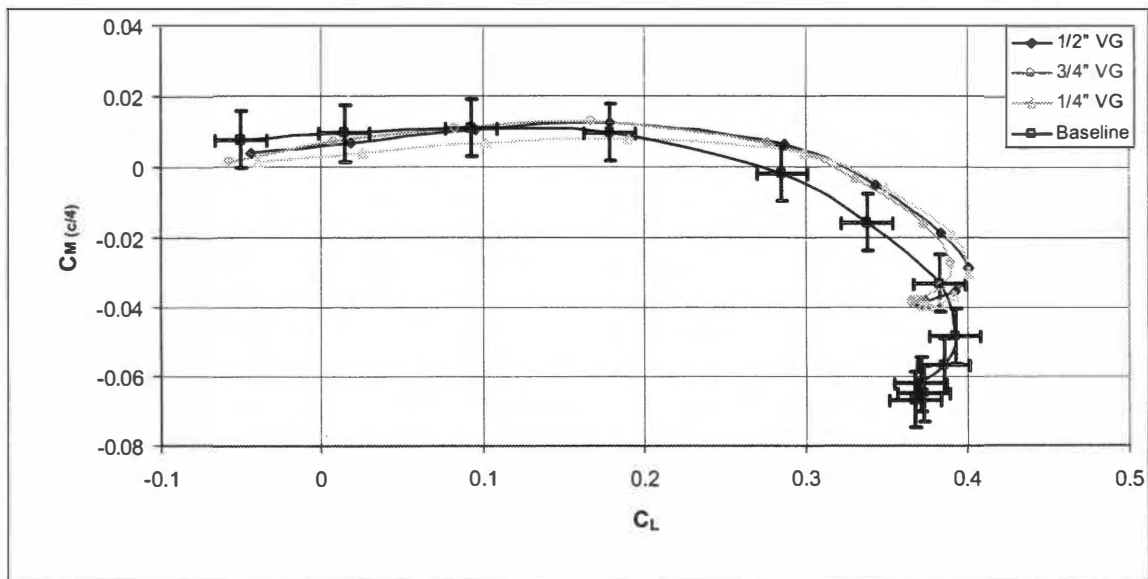


Figure 5.2.5: Size Comparison at 2.5" Spacing, Flap-Mounted VGs Lift / Moment Coefficients, $\delta = 0^\circ$

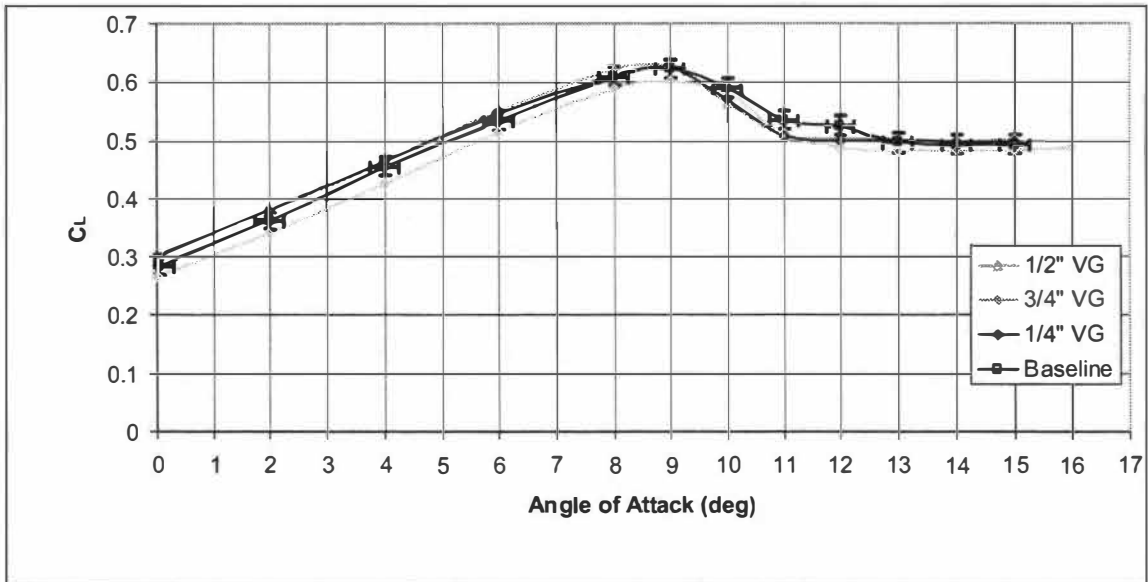


Figure 5.2.6: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, α -dependent Lift Coefficient, $\delta = 10^\circ$

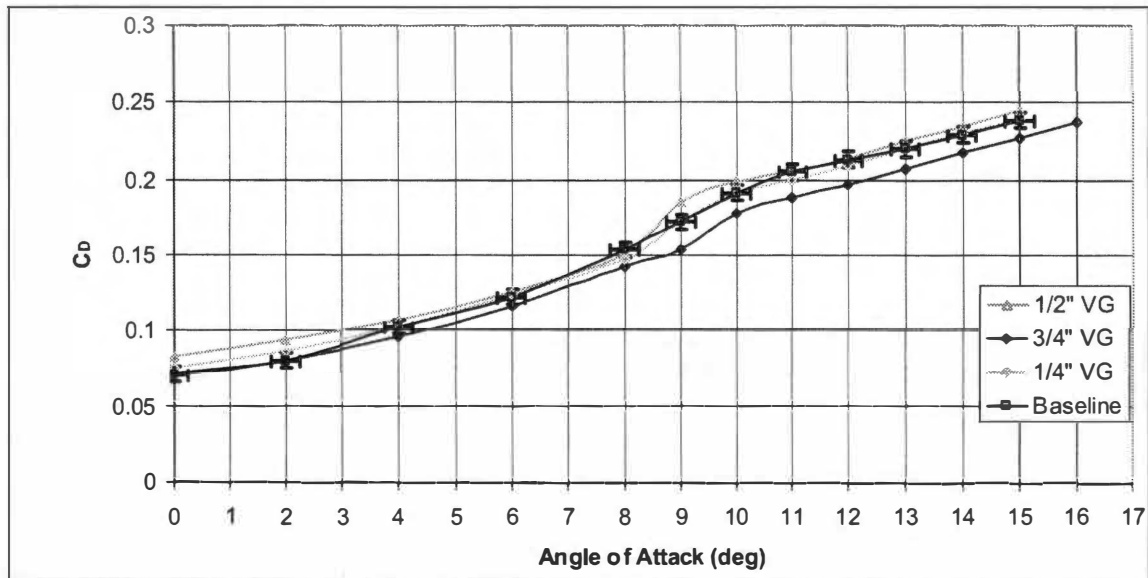


Figure 5.2.7: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, α -dependent Drag Coefficient, $\delta = 10^\circ$

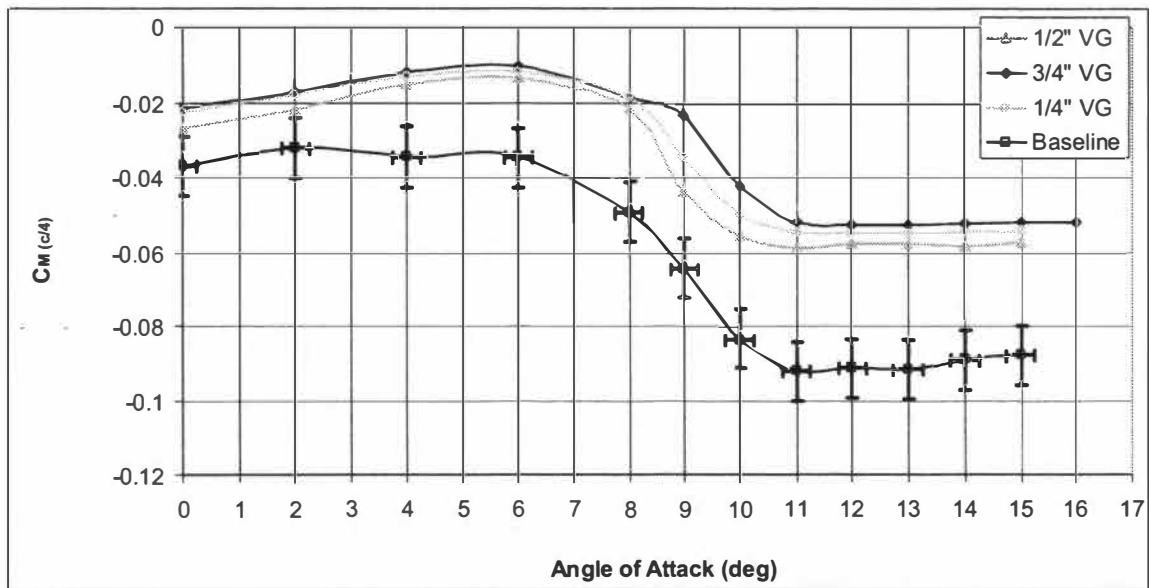


Figure 5.2.8: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, α -dependent Moment Coefficient, $\delta = 10^\circ$

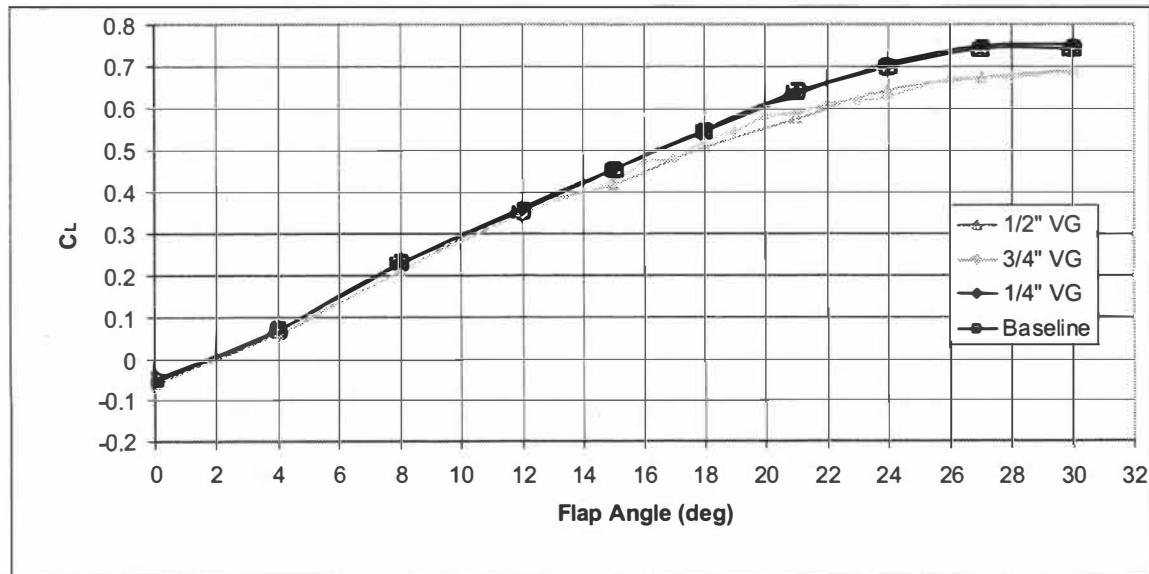


Figure 5.2.9: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, δ -dependent Lift Coefficient, $\alpha = 0^\circ$

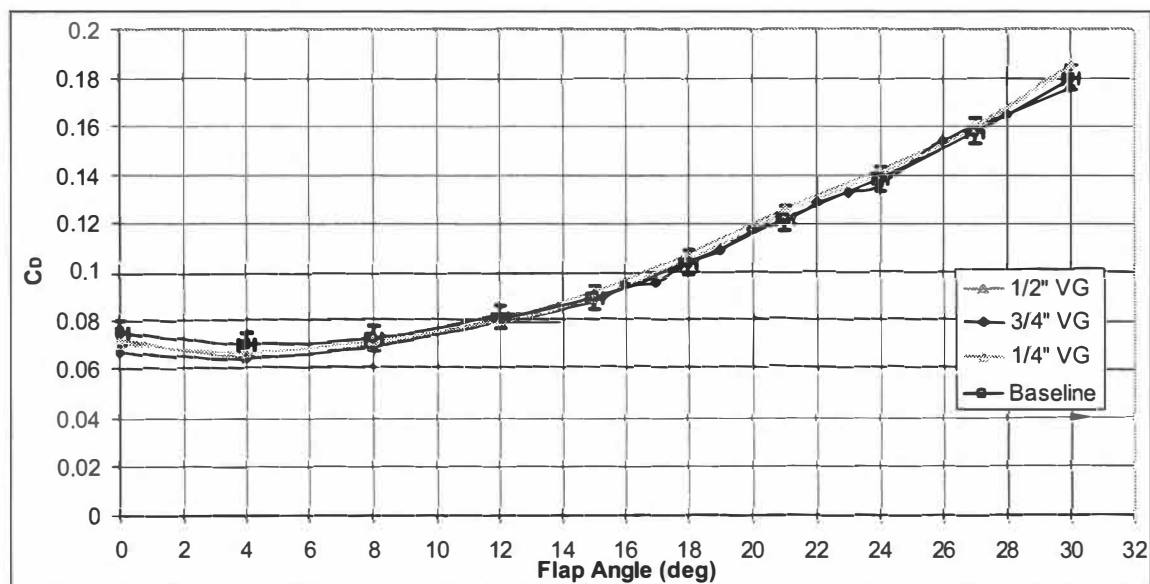


Figure 5.2.10: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, δ -dependent Drag Coefficient, $\alpha = 0^\circ$

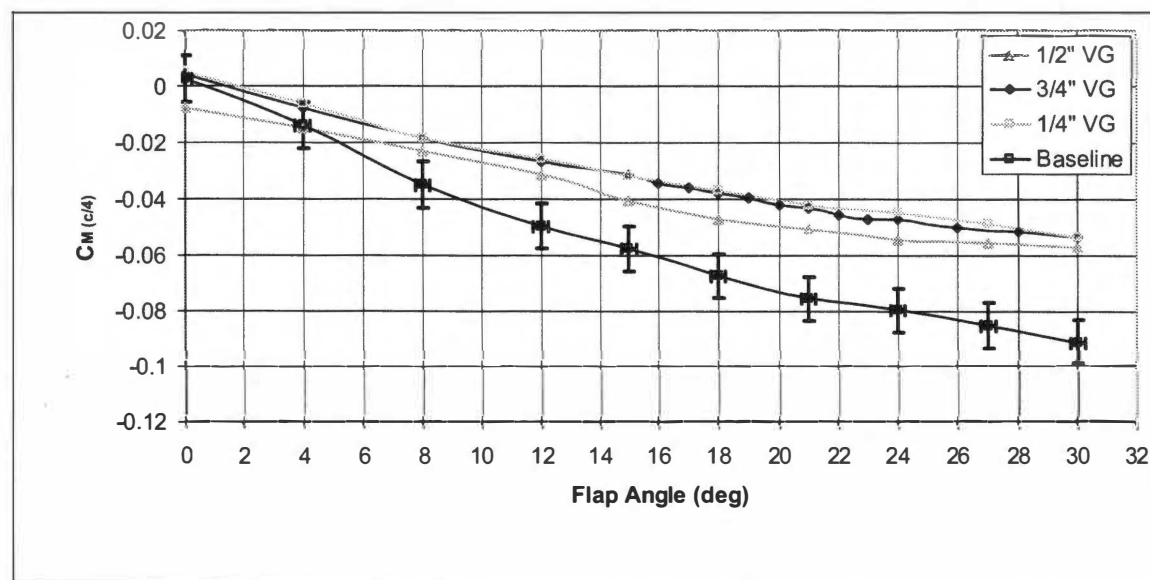


Figure 5.2.11: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, δ -dependent Moment Coefficient, $\alpha = 0^\circ$

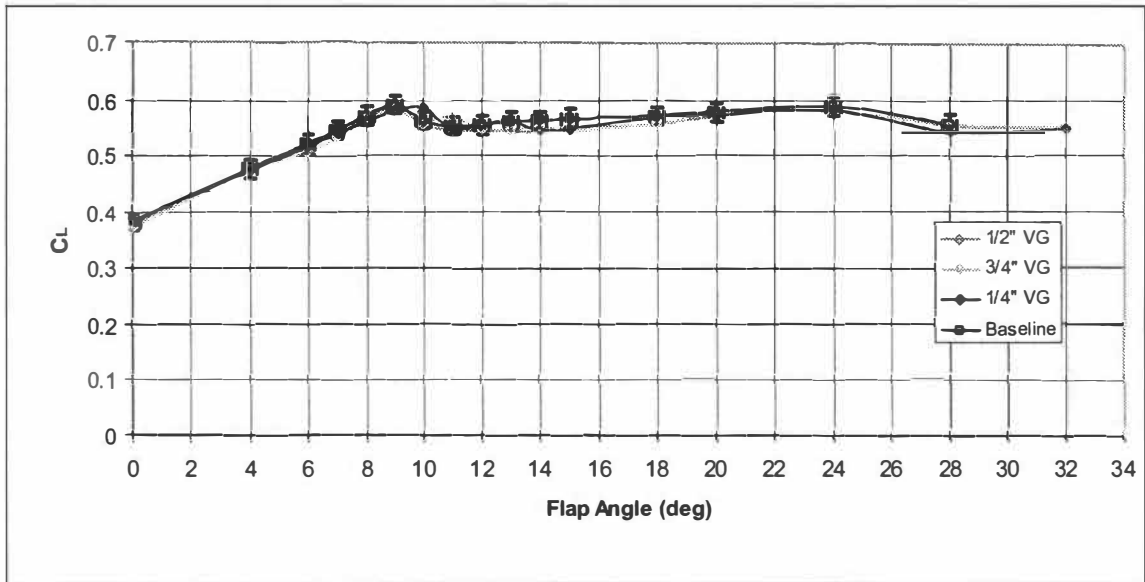


Figure 5.2.12: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, δ -dependent Lift Coefficient, $\alpha = 10^\circ$

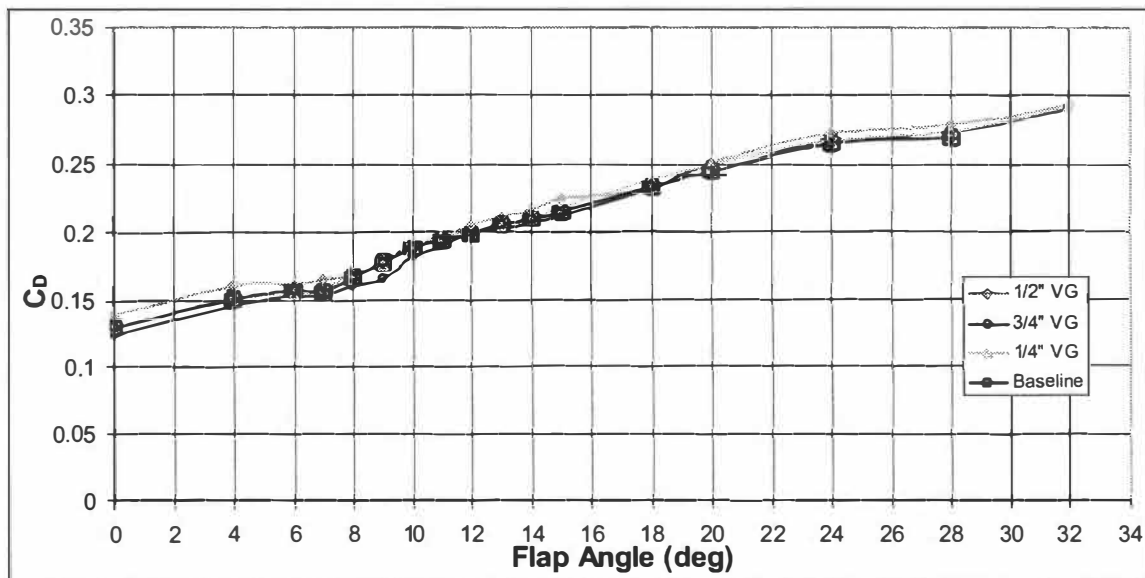


Figure 5.2.13: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, δ -dependent Drag Coefficient, $\alpha = 10^\circ$

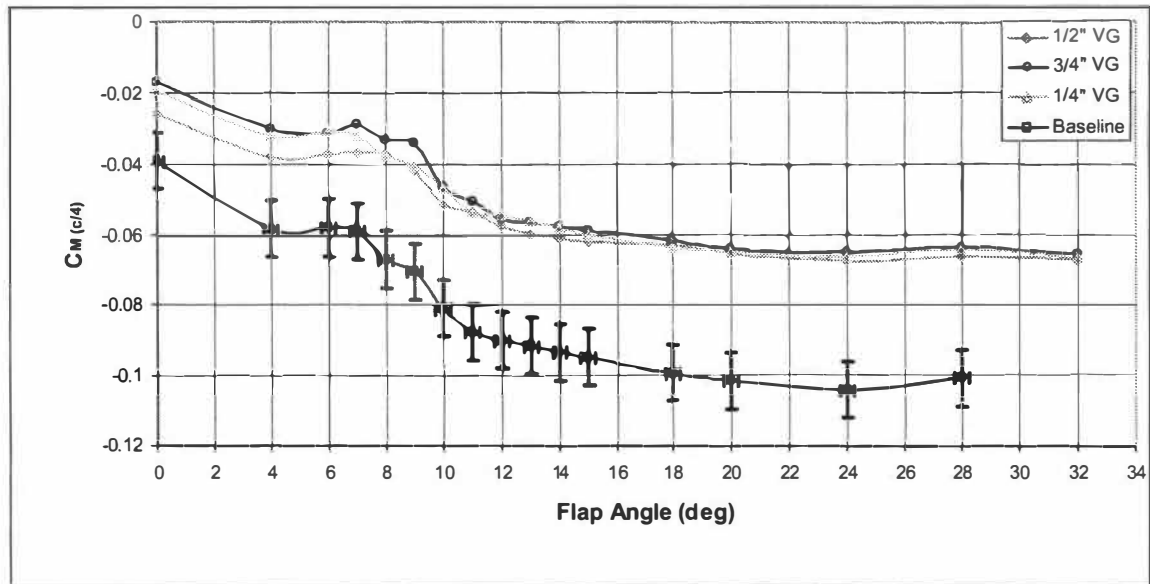


Figure 5.2.14: Size Comparison at 2.5" Spacing, Flap-Mounted VGs, δ -dependent Moment Coefficient, $\alpha = 10^\circ$

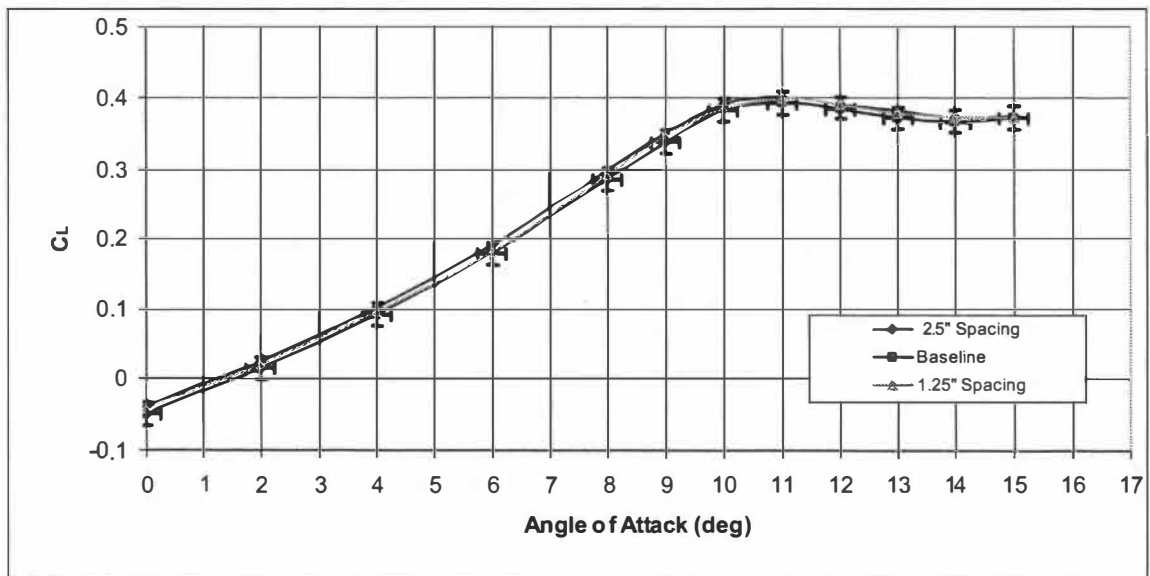


Figure 5.3.1: Size Comparison of 1/4" Flap Mounted VGs, α -dependent Lift Coefficient, $\delta = 0^\circ$

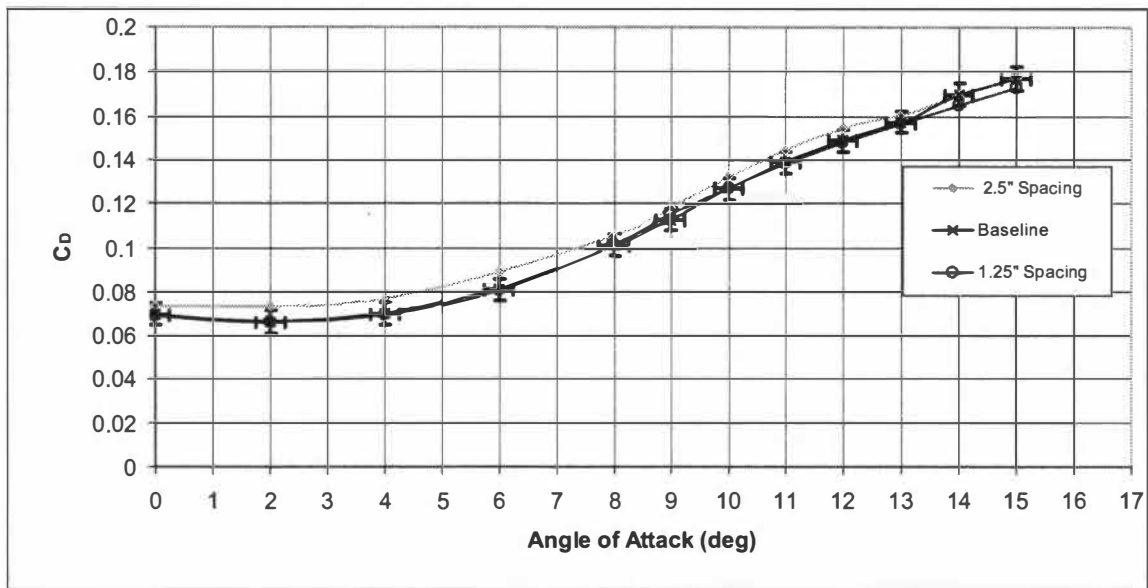


Figure 5.3.2: Size Comparison of 1/4" Flap Mounted VGs, α -dependent Drag Coefficient, $\delta = 0^\circ$

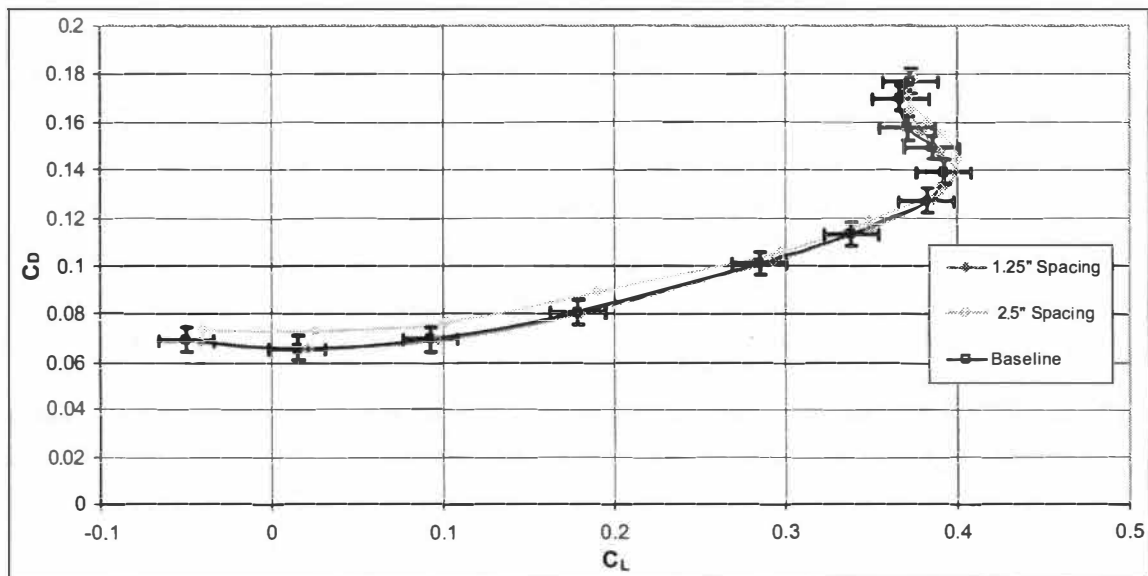


Figure 5.3.3: Size Comparison of 1/4" Flap Mounted VGs, α dependent Drag Polar $\delta = 0^\circ$

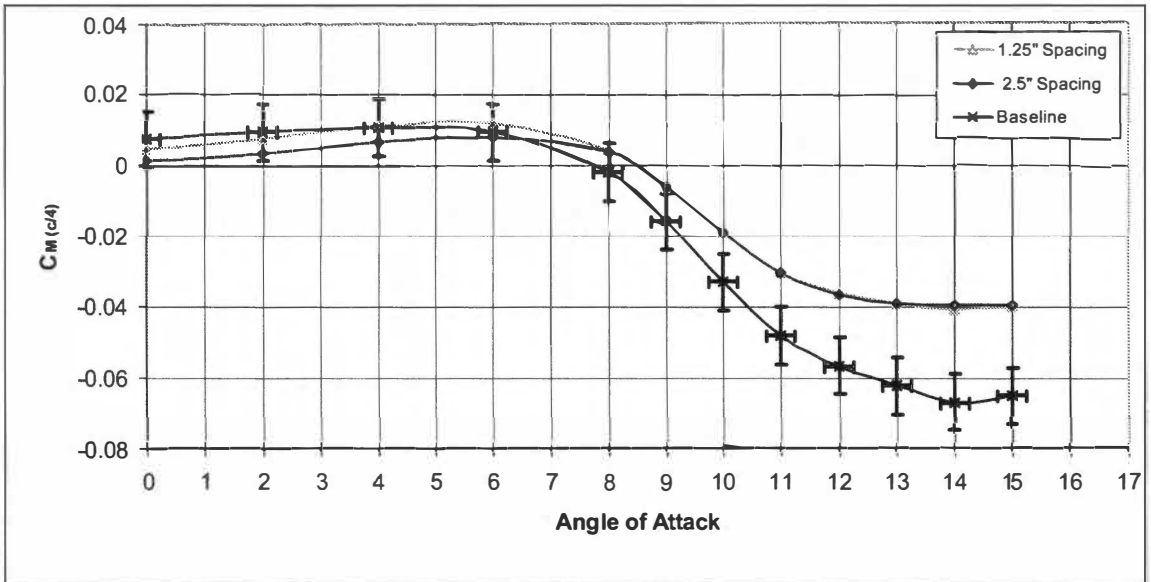


Figure 5.3.4: Size Comparison of 1/4" Flap Mounted VGs, α dependent Moment Coefficient, $\delta = 0^\circ$

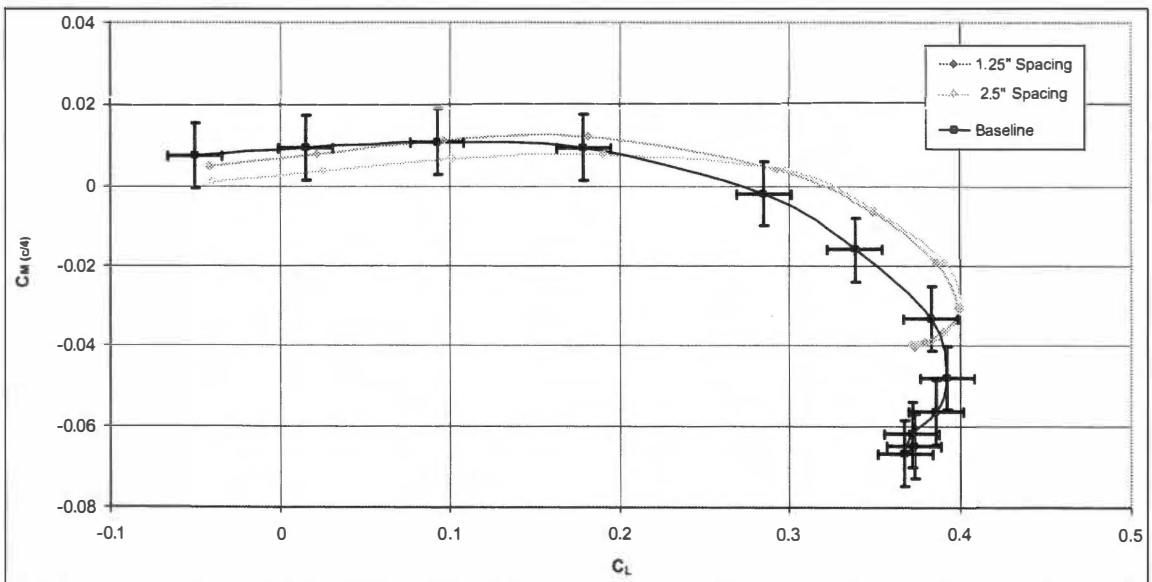


Figure 5.3.5: Size Comparison of 1/4" Flap Mounted VGs, α dependent C_L / C_M Coefficient, $\delta = 0^\circ$

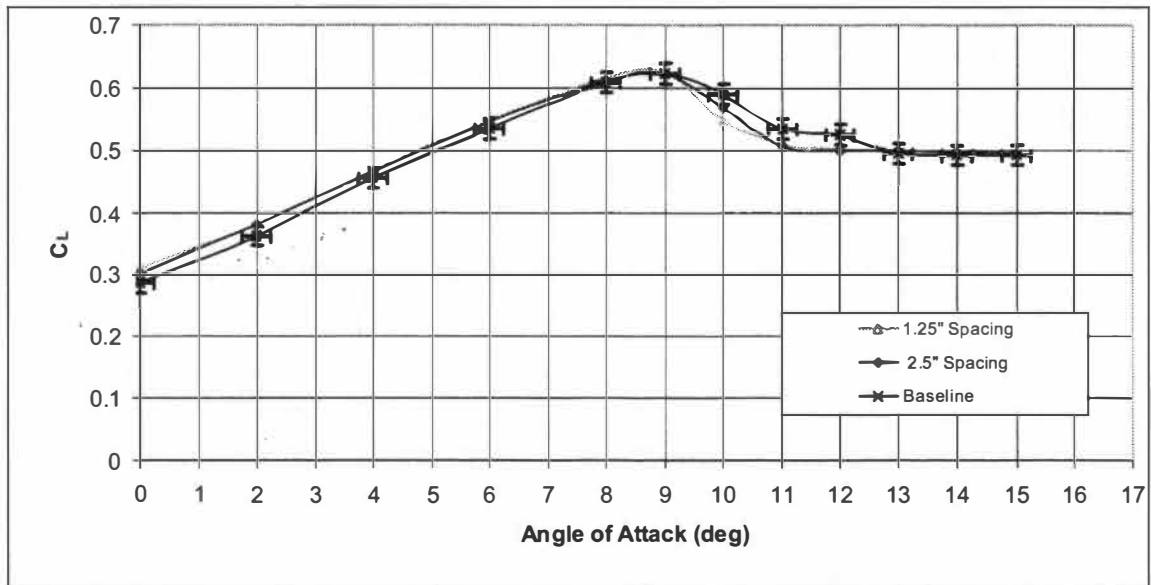


Figure 5.3.6: Size Comparison of 1/4\" Flap Mounted VGs, α dependent Lift Coefficient, $\delta = 10^\circ$

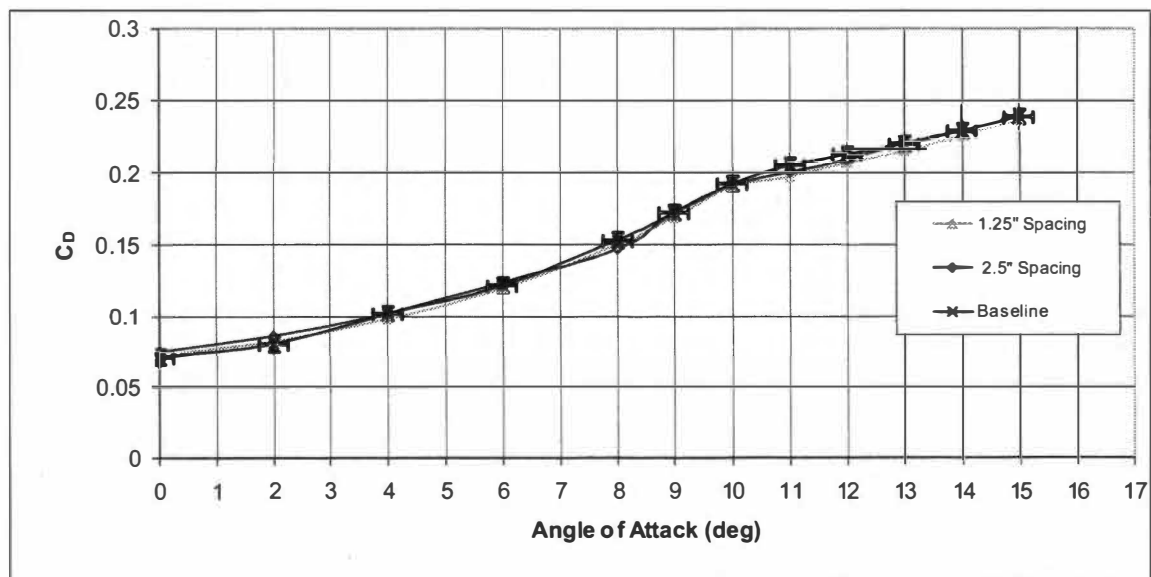


Figure 5.3.7: Size Comparison of 1/4\" Flap Mounted VGs, α dependent Drag Coefficient, $\delta = 10^\circ$

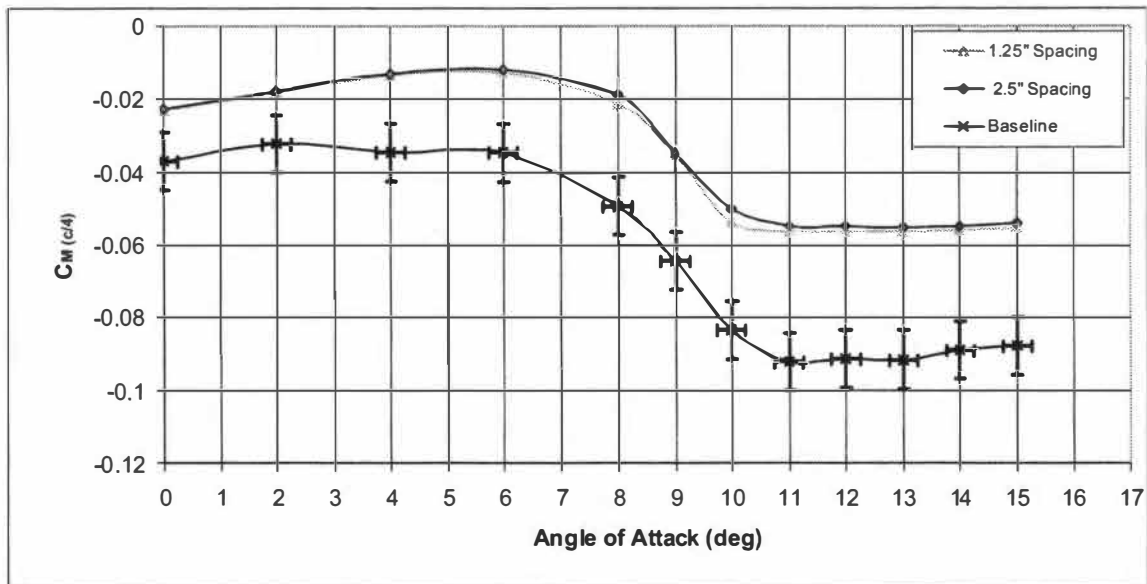


Figure 5.3.8: Size Comparison of 1/4" Flap Mounted VGs, α dependent Moment Coefficient, $\delta = 10^\circ$

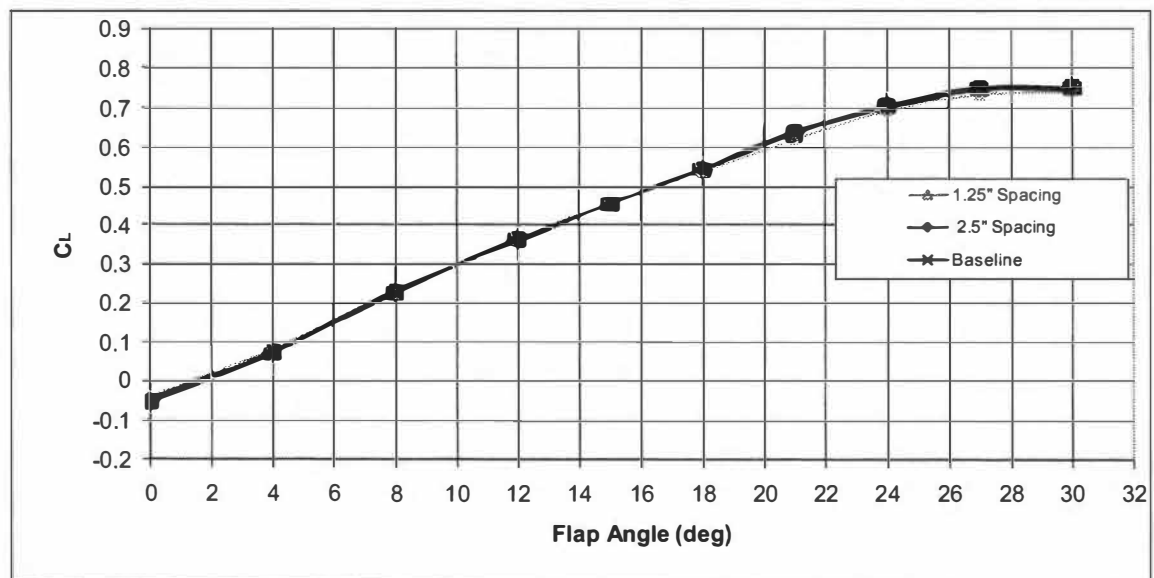


Figure 5.3.9: Size Comparison of 1/4" Flap Mounted VGs, δ dependent Lift Coefficient, $\alpha = 0^\circ$

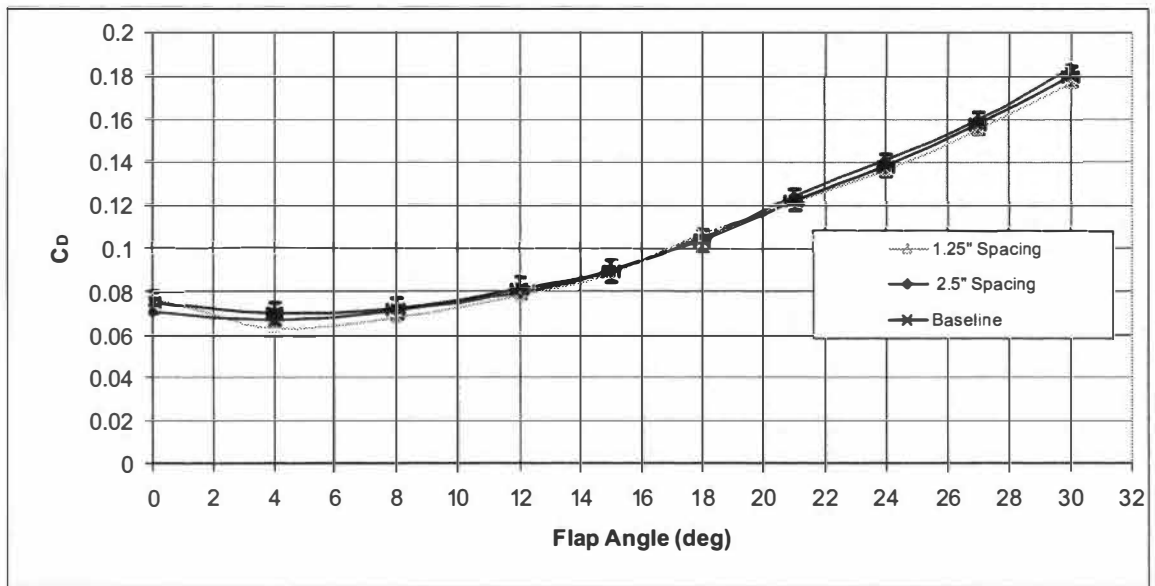


Figure 5.3.10: Size Comparison of 1/4" Flap Mounted VGs, δ dependent Drag Coefficient, $\alpha = 0^\circ$

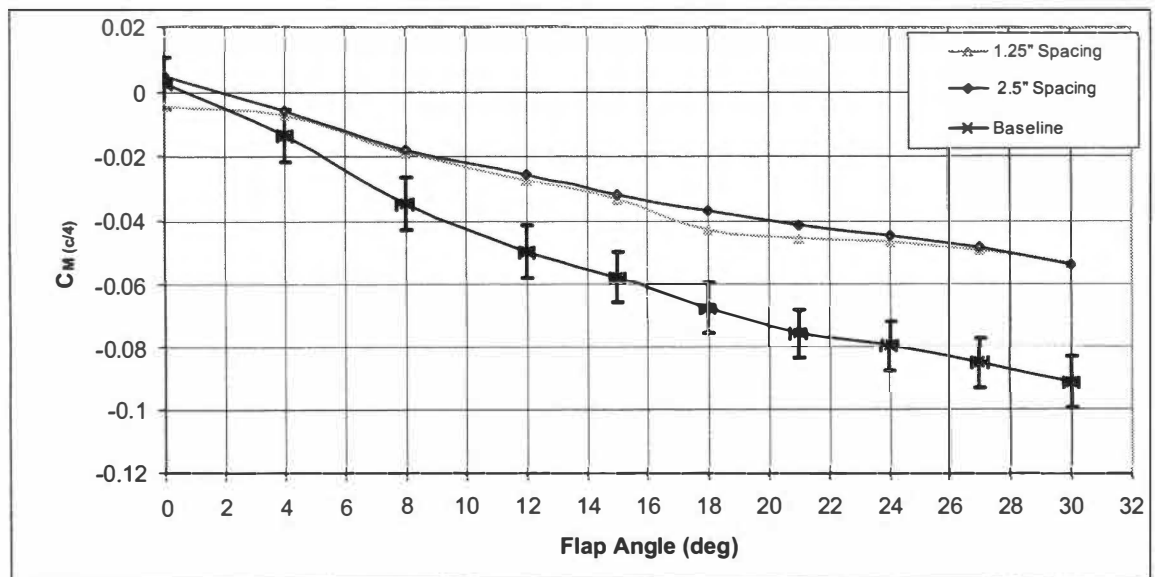


Figure 5.3.11: Size Comparison of 1/4" Flap Mounted VGs, δ dependent Moment Coefficient, $\alpha = 0^\circ$

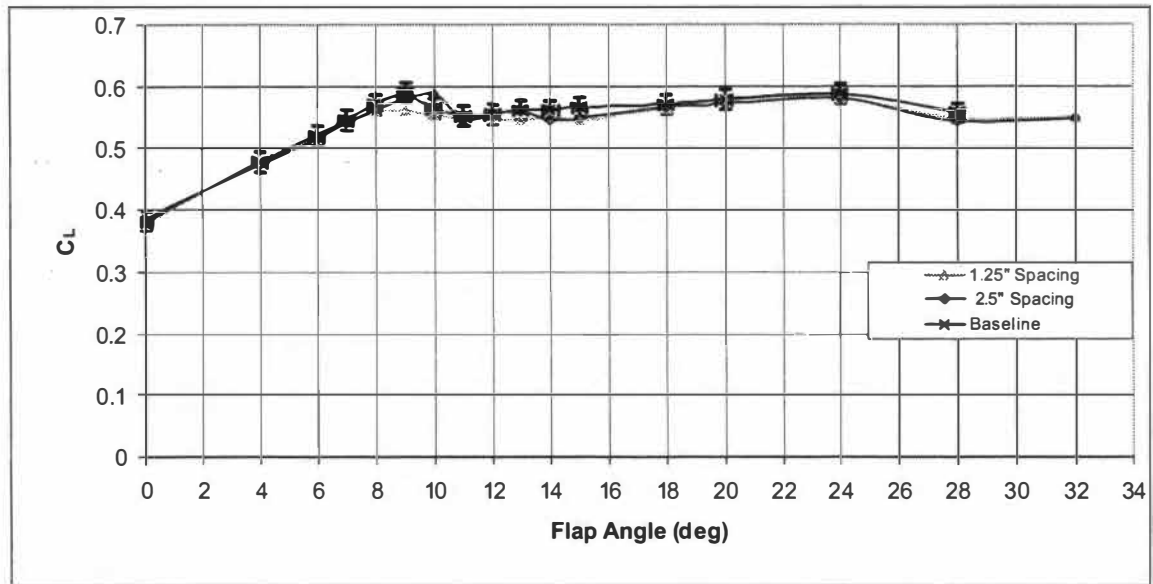


Figure 5.3.12: Size Comparison of 1/4" Flap Mounted VGs, δ dependent Lift Coefficient, $\alpha = 10^\circ$

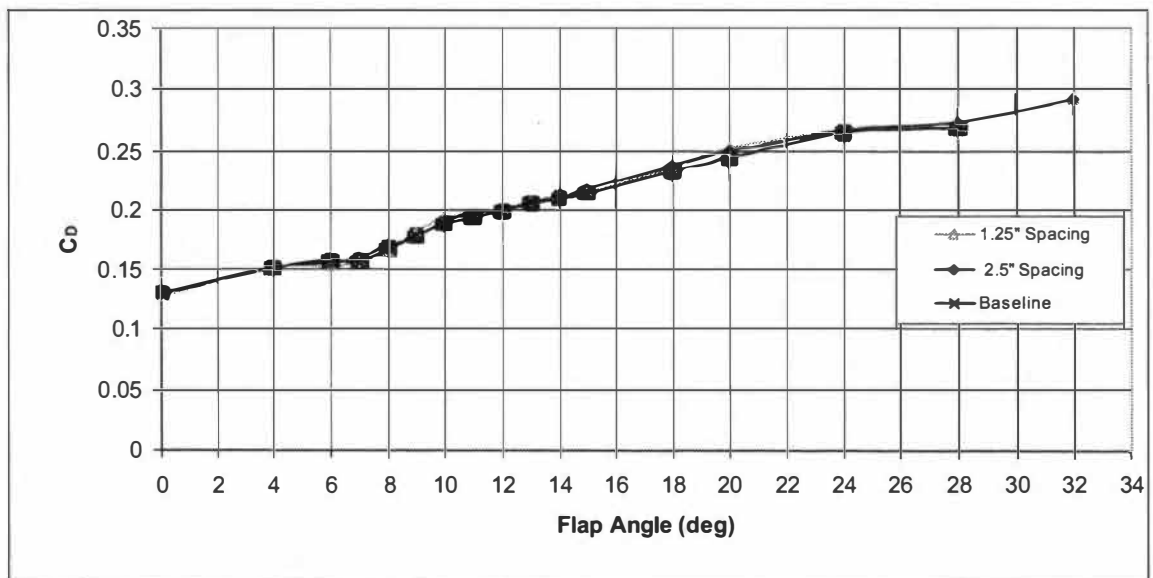


Figure 5.3.13: Size Comparison of 1/4" Flap Mounted VGs, δ dependent Drag Coefficient, $\alpha = 10^\circ$

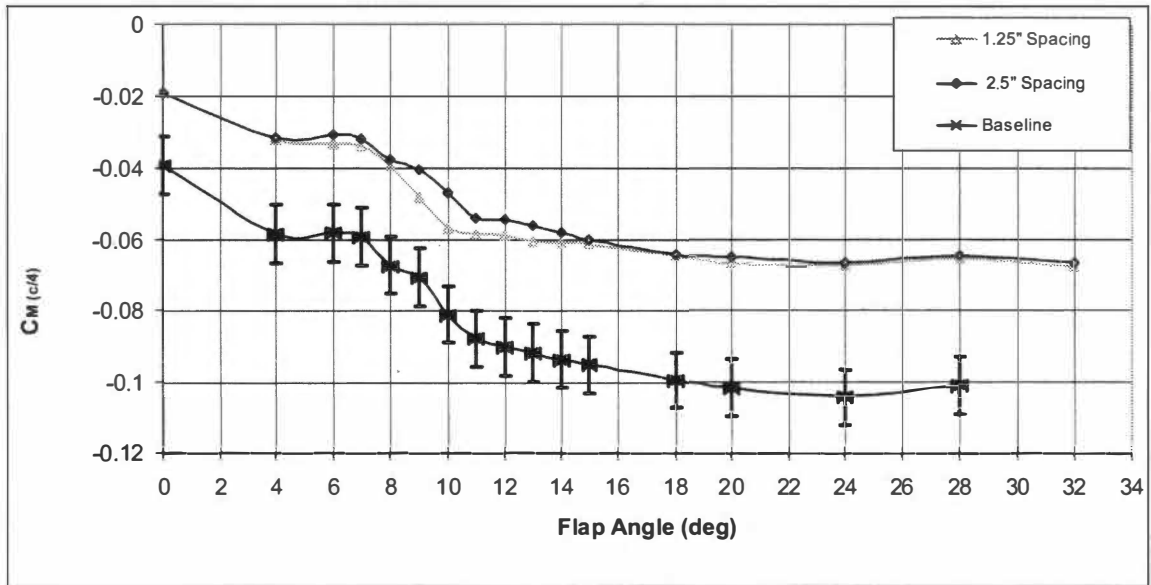


Figure 5.3.14: Size Comparison of 1/4" Flap Mounted VGs, δ dependent Moment Coefficient, $\alpha = 10^\circ$

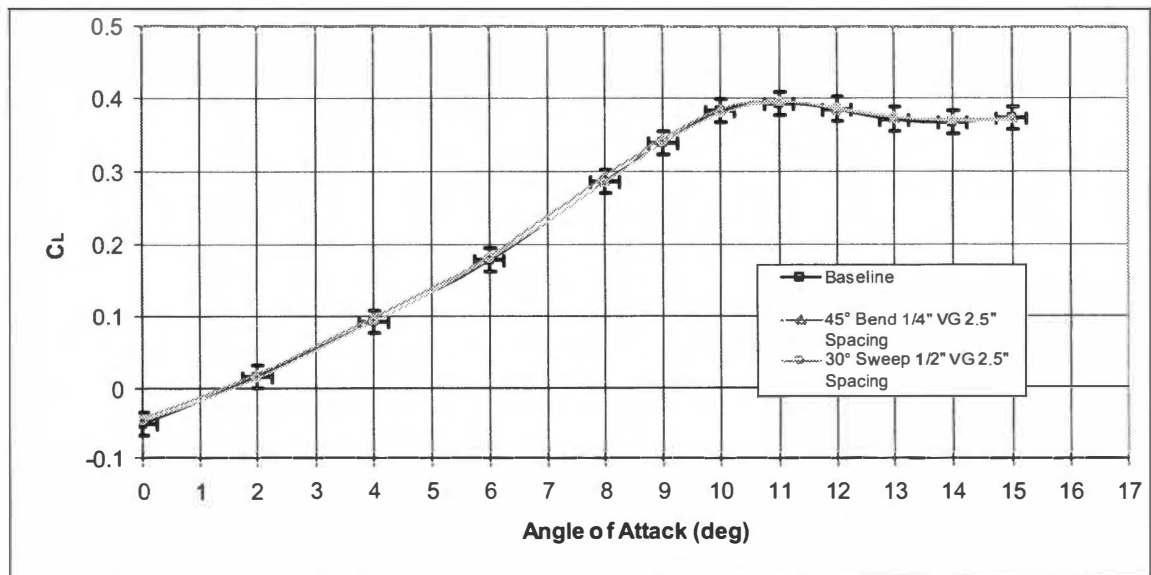


Figure 5.4.1: Size Comparison of Flap Mounted VGs, α dependent Lift Coefficient, $\delta = 0^\circ$

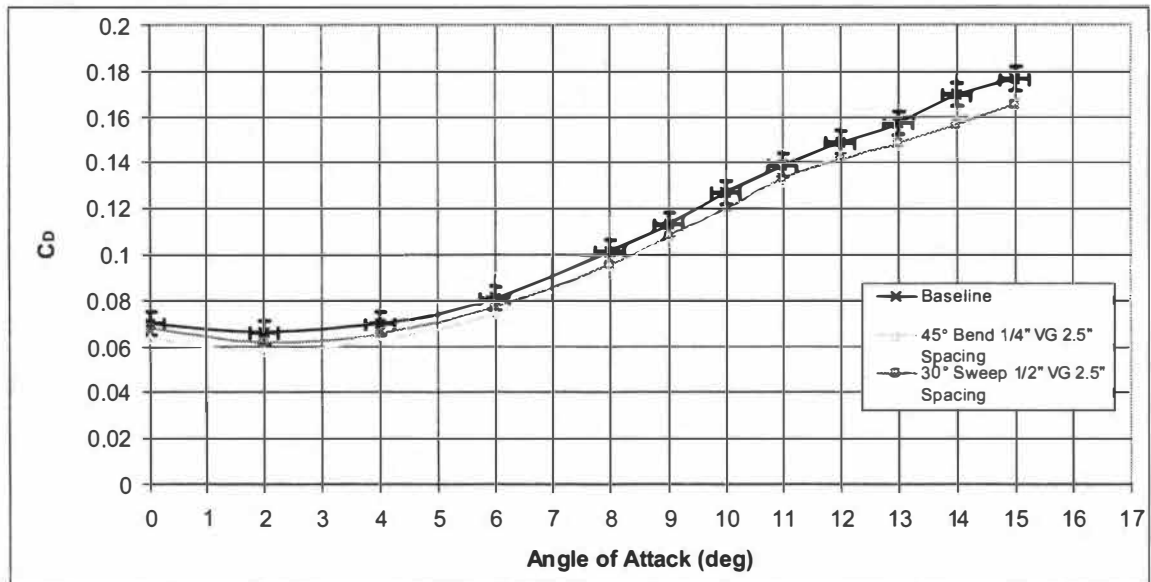


Figure 5.4.2: Size Comparison of Flap Mounted VGs, α dependent Drag Coefficient, $\delta = 0^\circ$

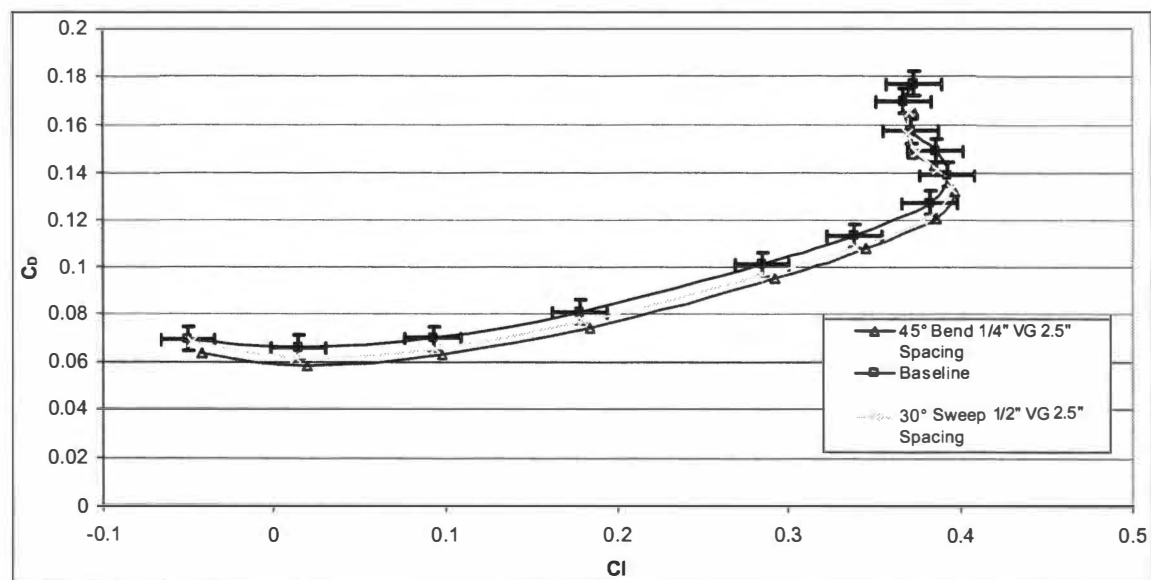


Figure 5.4.3: Size Comparison of Flap Mounted VGs, α dependent Drag Polar $\delta = 0^\circ$

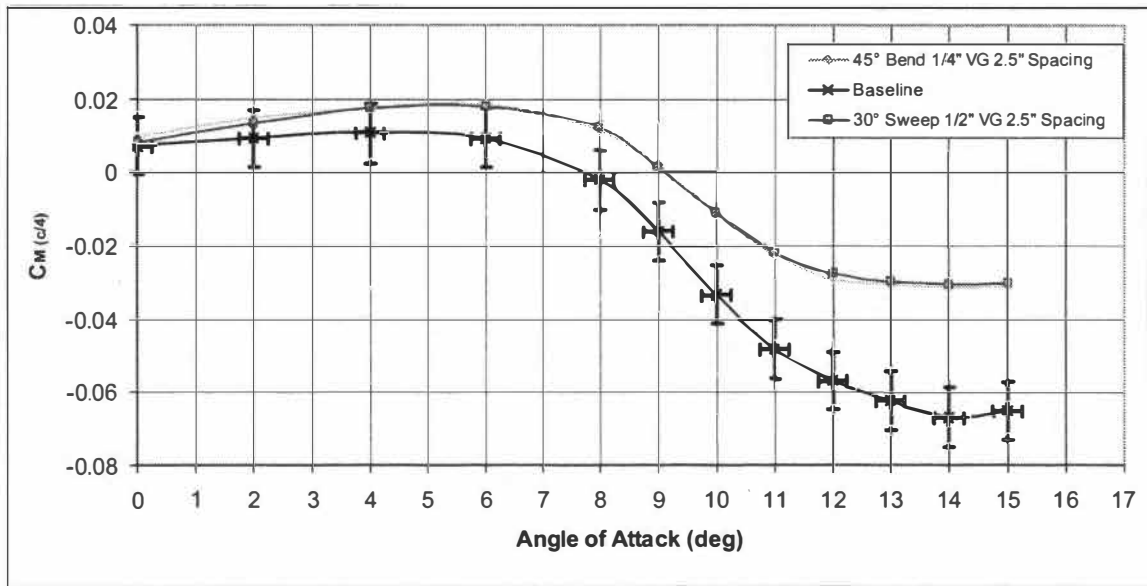


Figure 5.4.4: Size Comparison of Flap Mounted VGs, α dependent Moment Coefficient, $\delta = 0^\circ$

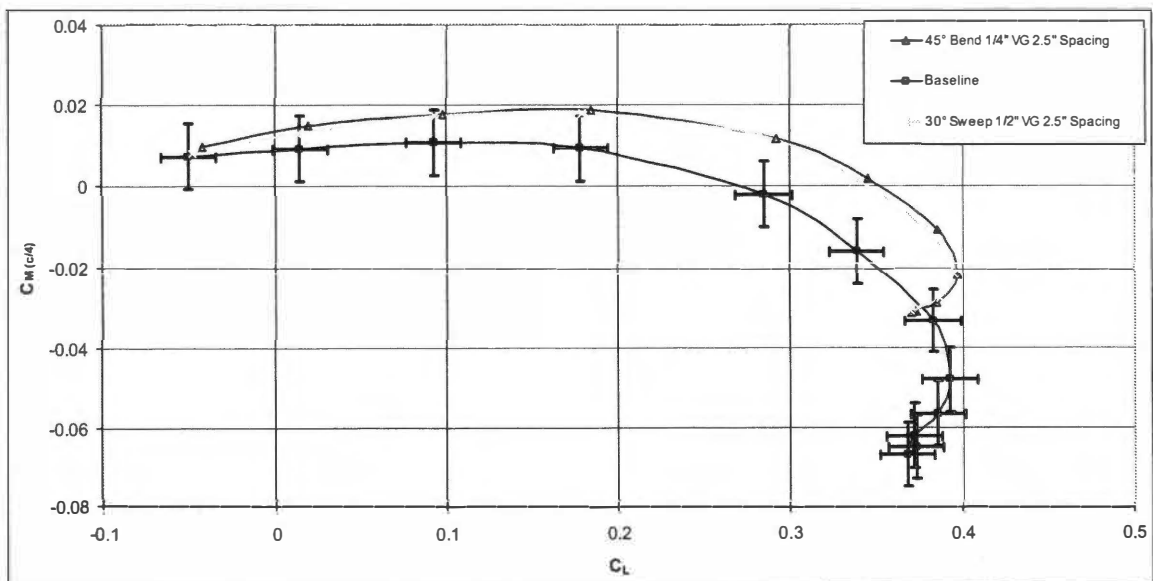


Figure 5.4.5: Size Comparison of Flap Mounted VGs, α dependent Lift / Moment Coefficient, $\delta = 0^\circ$

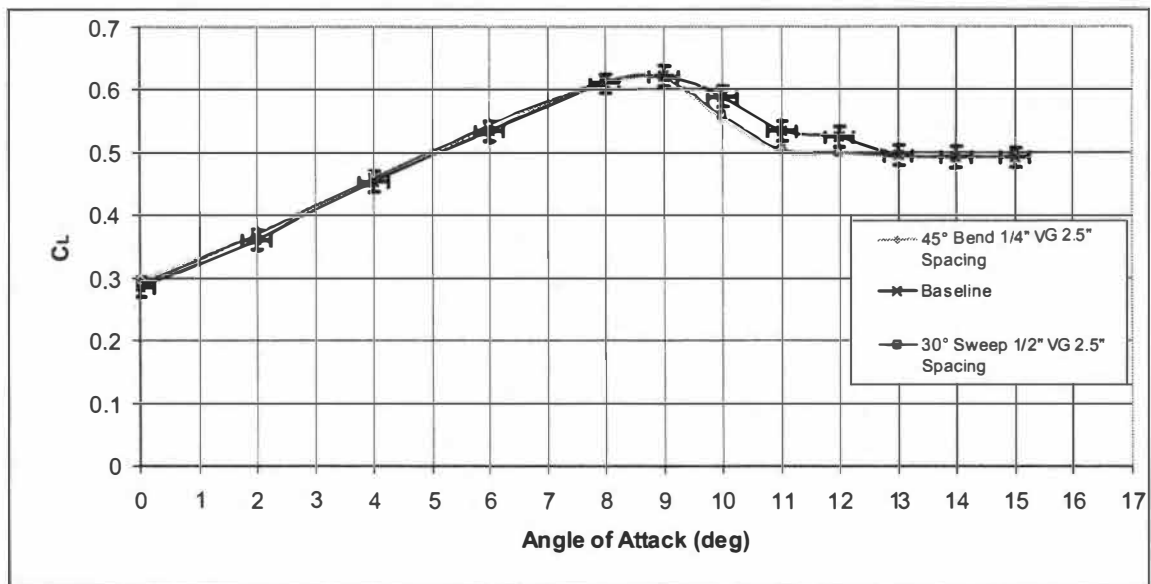


Figure 5.4.6: Size Comparison of Flap Mounted VGs, α dependent Lift Coefficient, $\delta = 10^\circ$

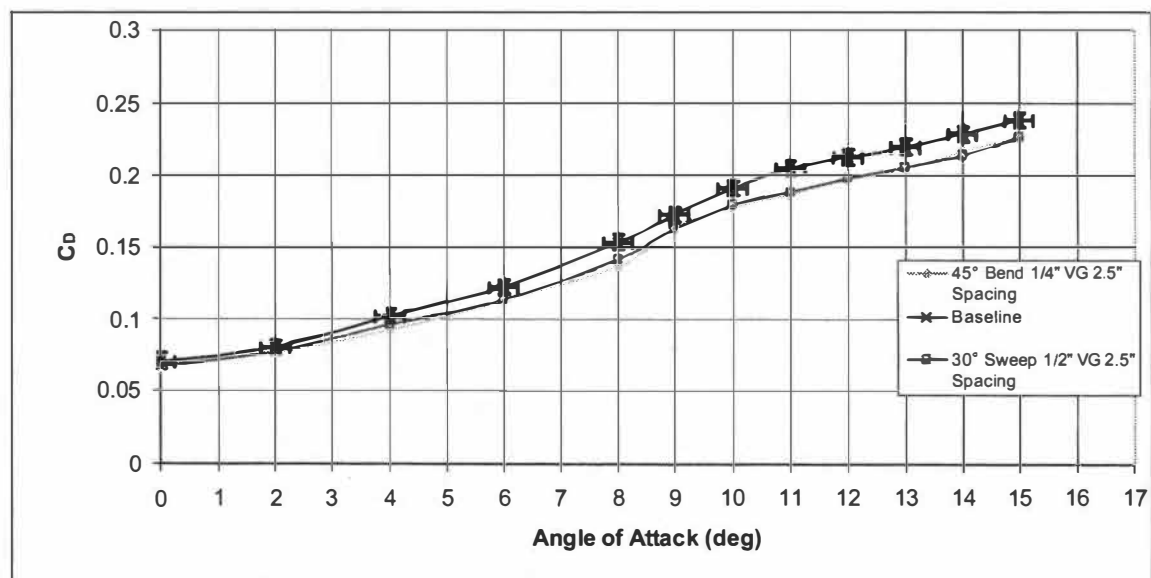


Figure 5.4.7: Size Comparison of Flap Mounted VGs, α dependent Drag Coefficient, $\delta = 10^\circ$

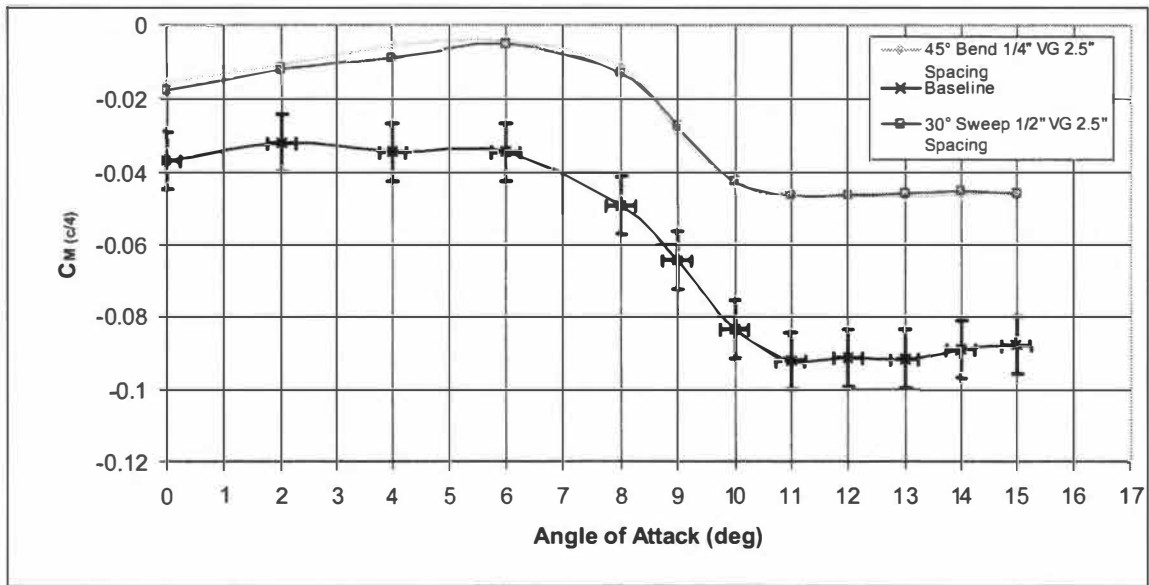


Figure 5.4.8: Size Comparison of Flap Mounted VGs, α dependent Moment Coefficient, $\delta = 10^\circ$

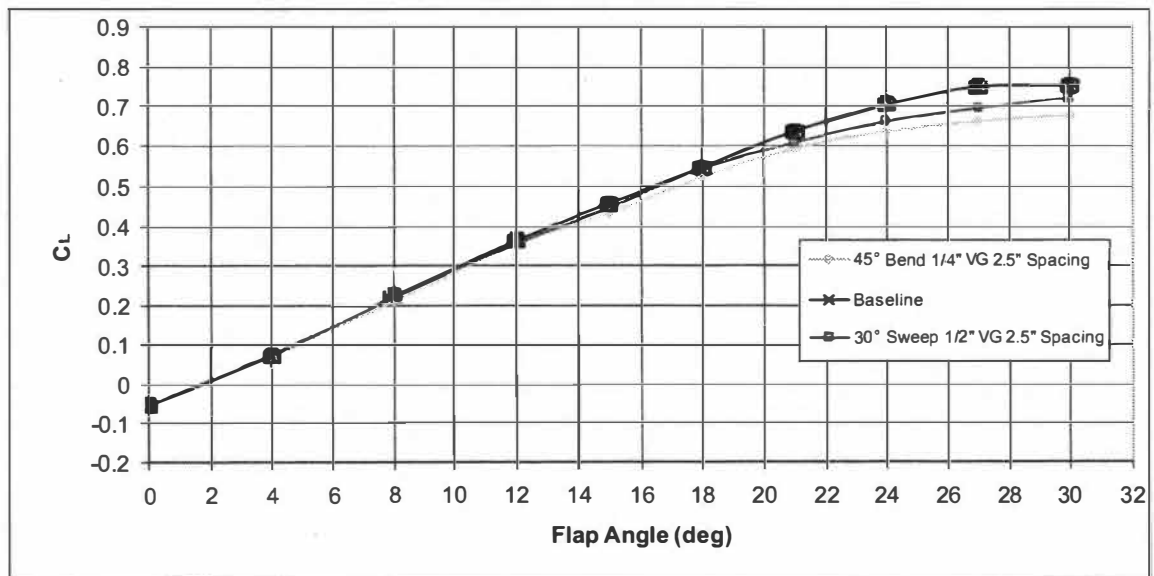


Figure 5.4.9: Size Comparison of Flap Mounted VGs, δ dependent Lift Coefficient, $\alpha = 0^\circ$

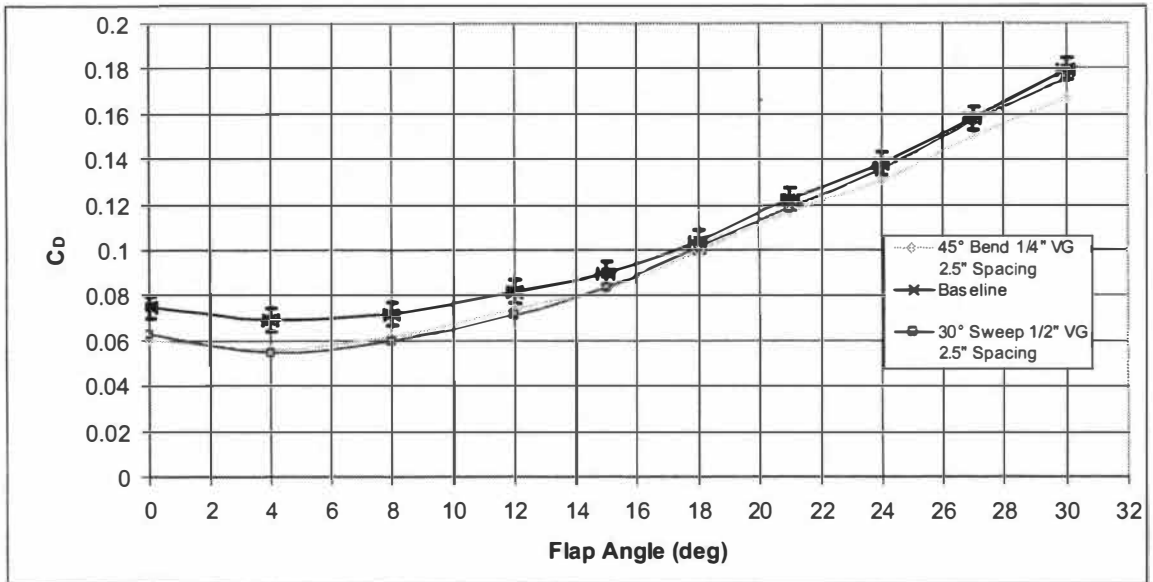


Figure 5.4.10: Size Comparison of Flap Mounted VGs, δ dependent Drag Coefficient, $\alpha = 0^\circ$

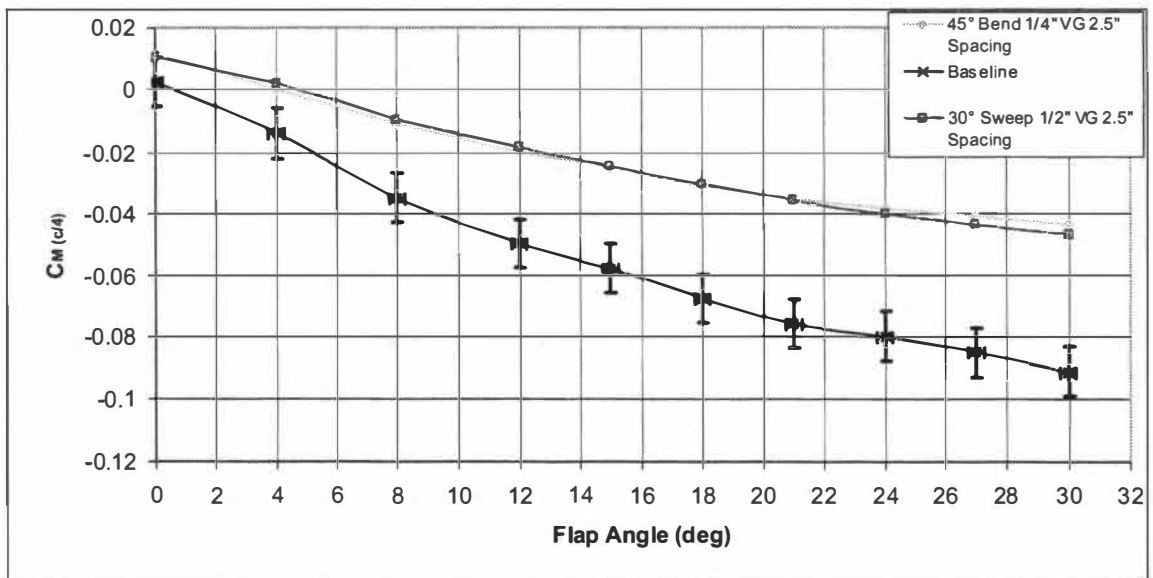


Figure 5.4.11: Size Comparison of Flap Mounted VGs, δ dependent Moment Coefficient, $\alpha = 0^\circ$

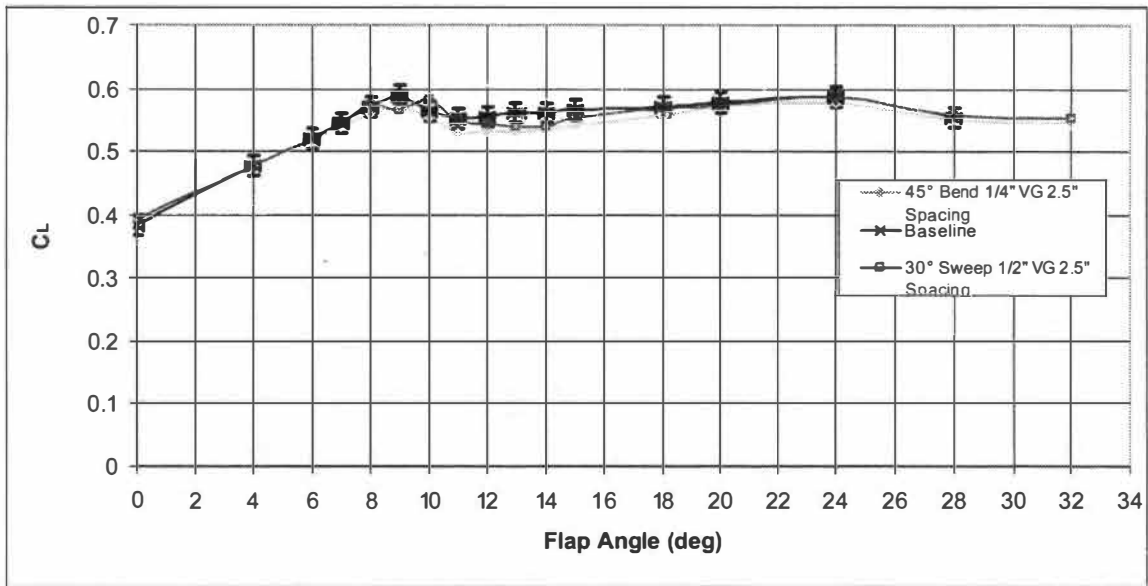


Figure 5.4.12: Size Comparison of Flap Mounted VGs, δ dependent Lift Coefficient, $\alpha = 10^\circ$

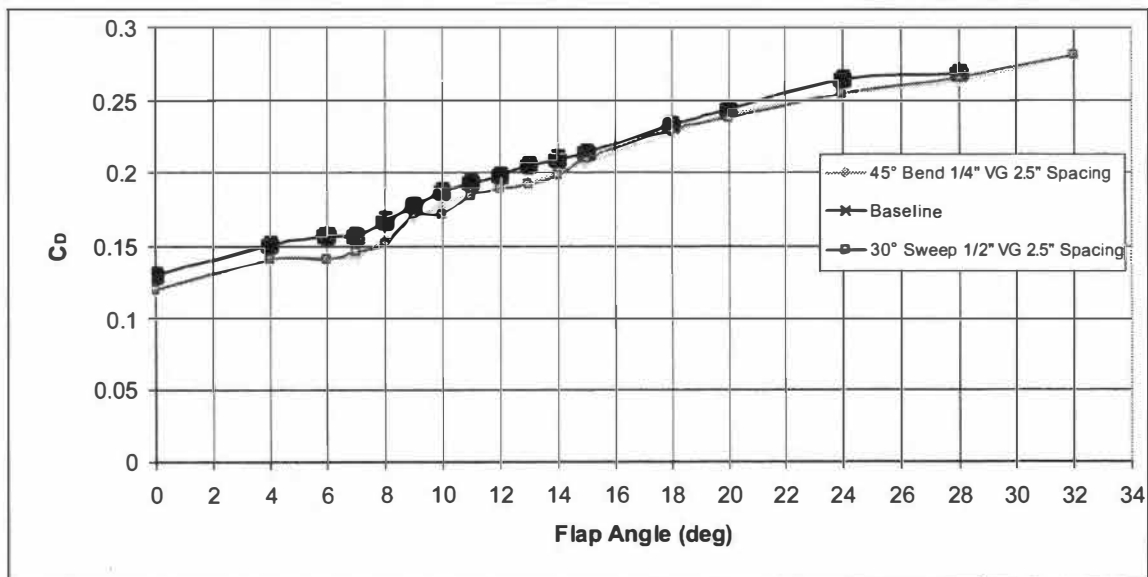


Figure 5.4.13: Size Comparison of Flap Mounted VGs, δ dependent Drag Coefficient, $\alpha = 10^\circ$

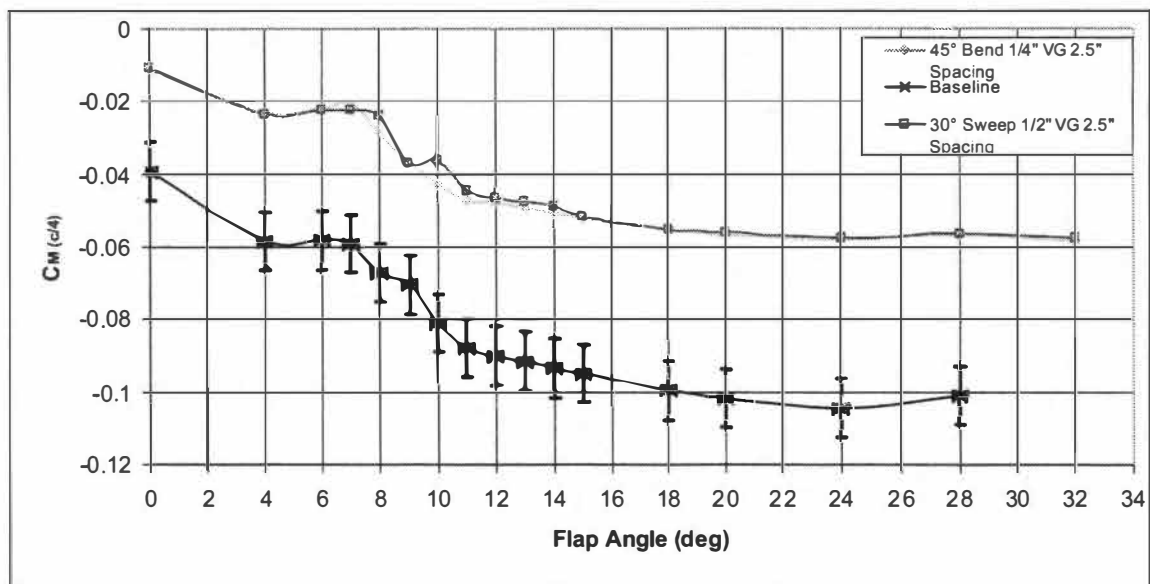


Figure 5.4.14: Size Comparison of Flap Mounted VGs, δ dependent Moment Coefficient, $\alpha = 10^\circ$

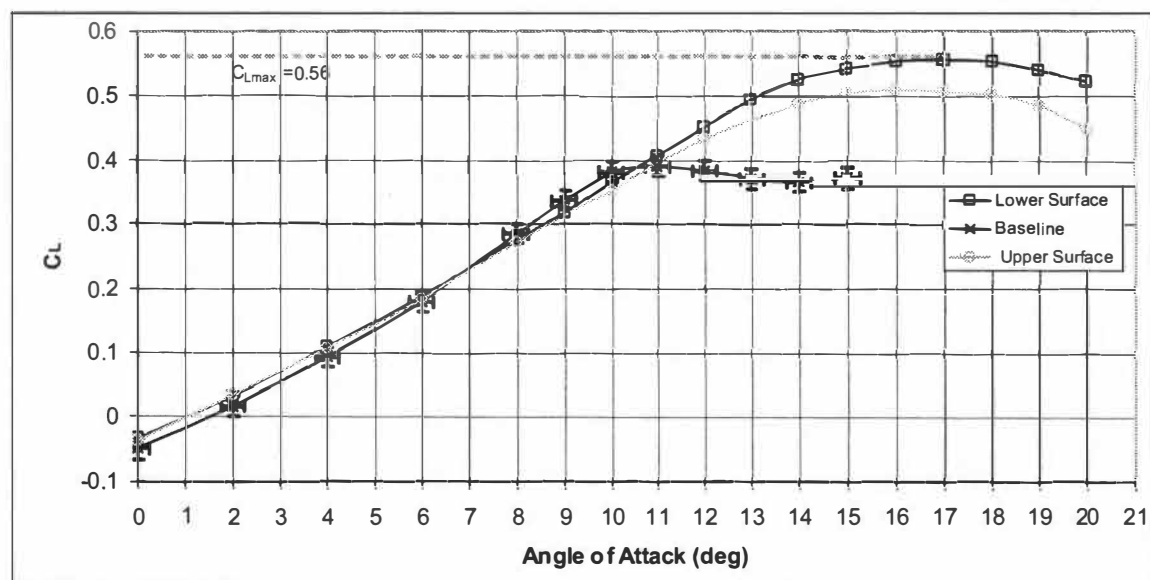


Figure 5.5.1: Leading Edge Surface Comparison 2.0" Spacing, $\frac{1}{2}$ " VGs, α -dependent Lift Coefficient, $\delta = 0^\circ$

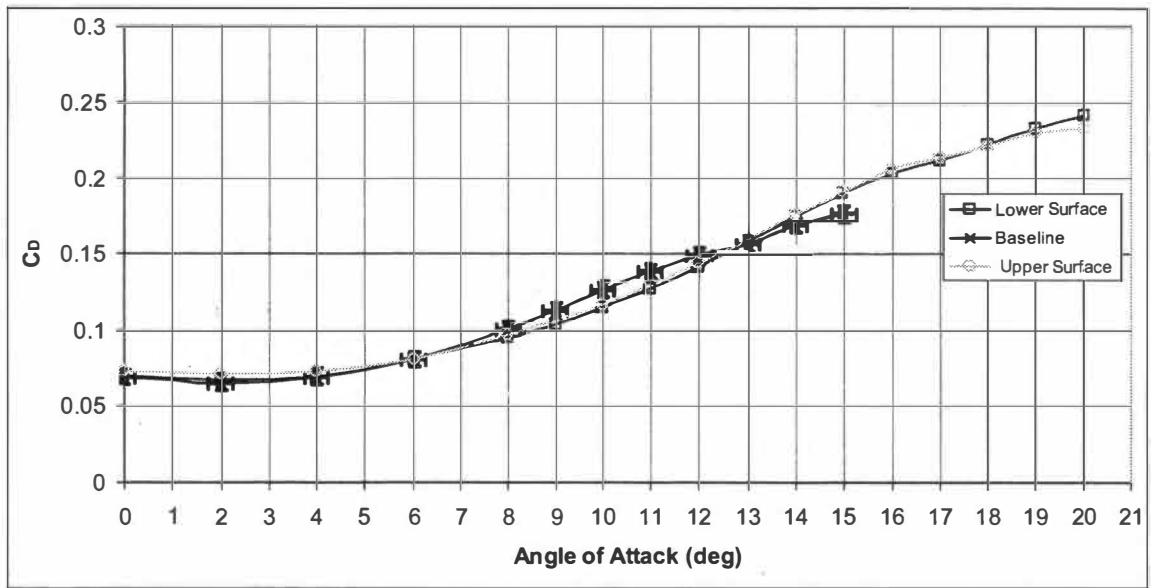


Figure 5.5.2: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, α -dependent Drag Coefficient $\delta = 0^\circ$

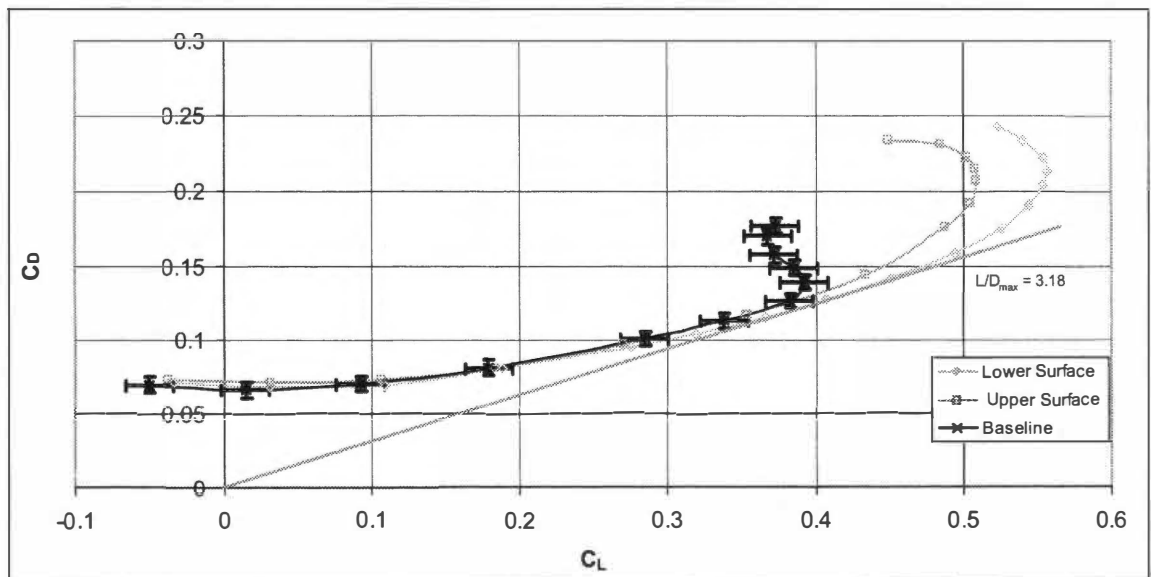


Figure 5.5.3: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, α -dependent Drag Polar, $\delta = 0^\circ$

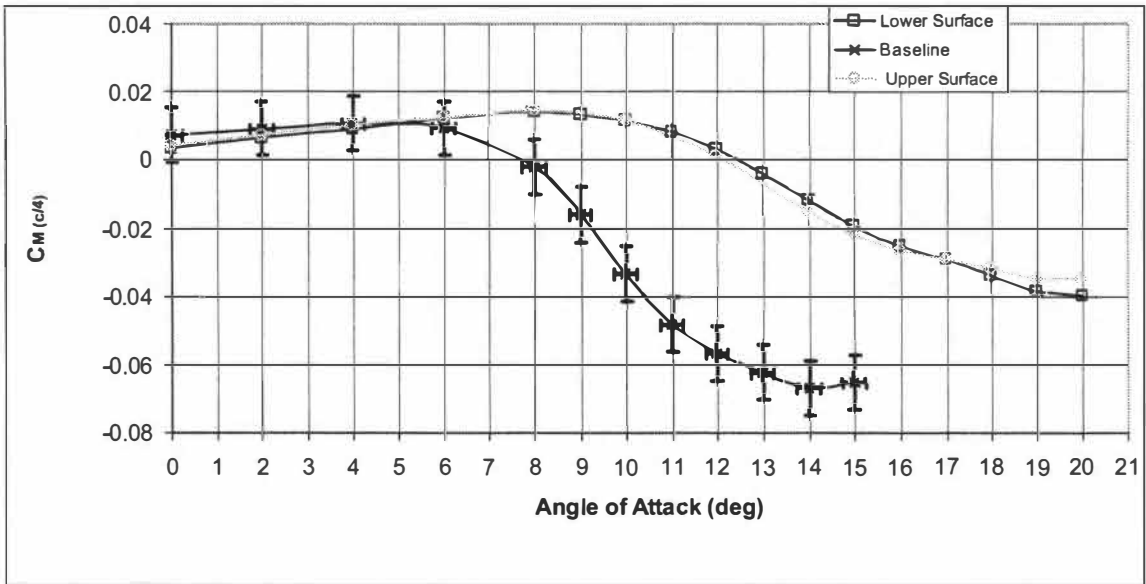


Figure 5.5.4: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, α -dependent Moment Coefficient $\delta = 0^\circ$

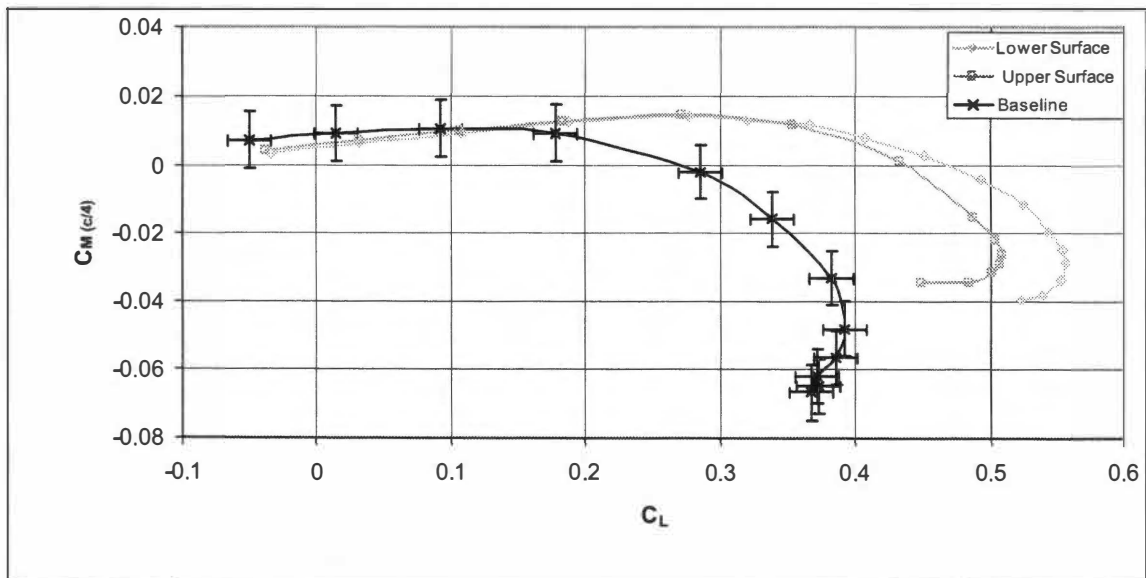


Figure 5.5.5: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, α -dependent Lift / Moment Coefficient, $\delta = 0^\circ$

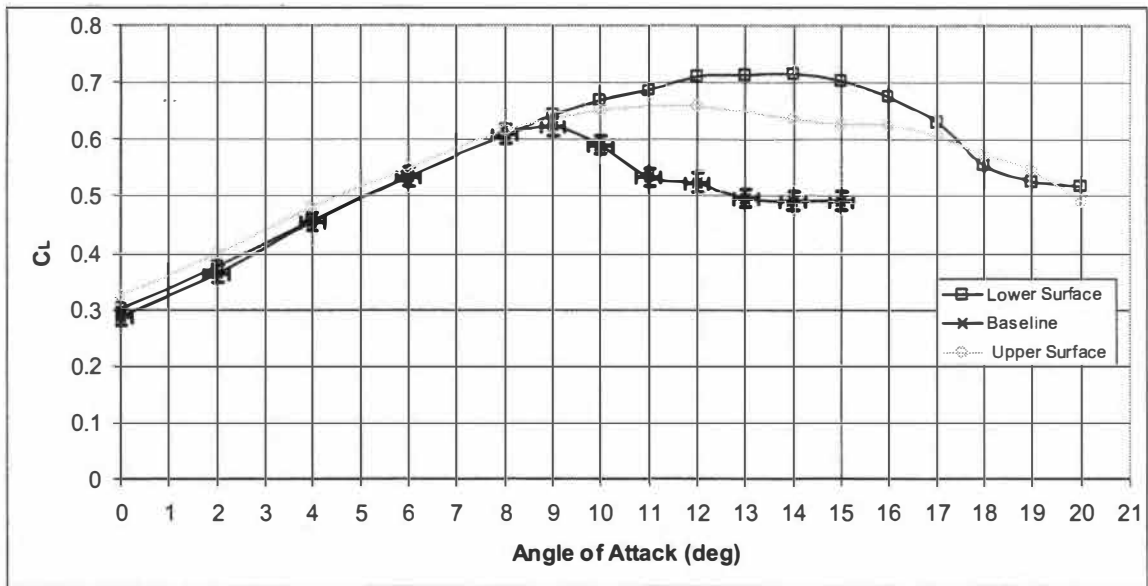


Figure 5.5.6: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, α -dependent Lift Coefficient $\delta = 10^\circ$

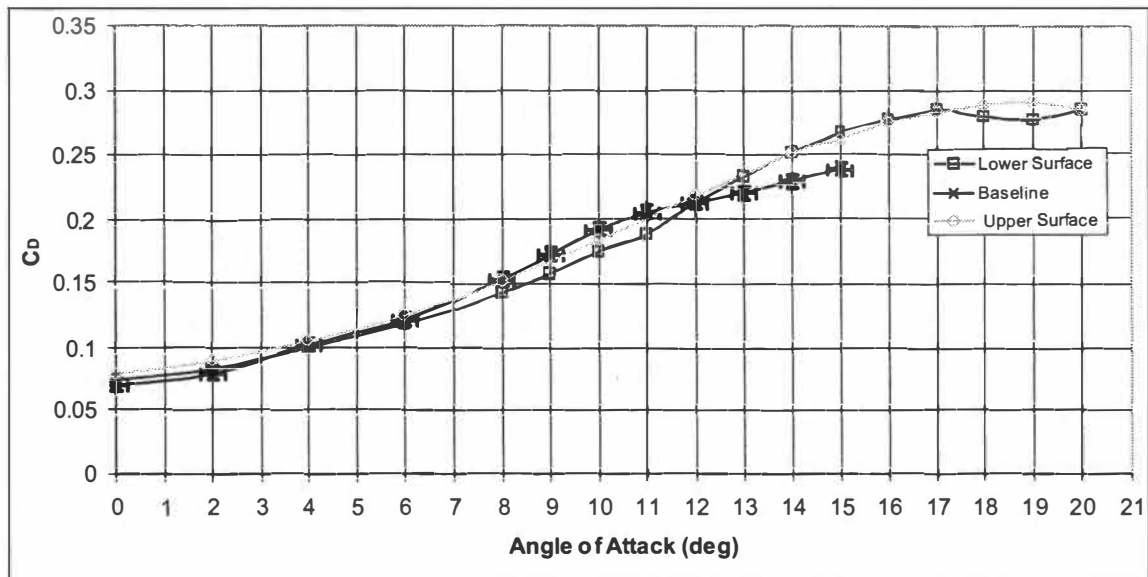


Figure 5.5.7: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, α -dependent Drag Coefficient $\delta = 10^\circ$

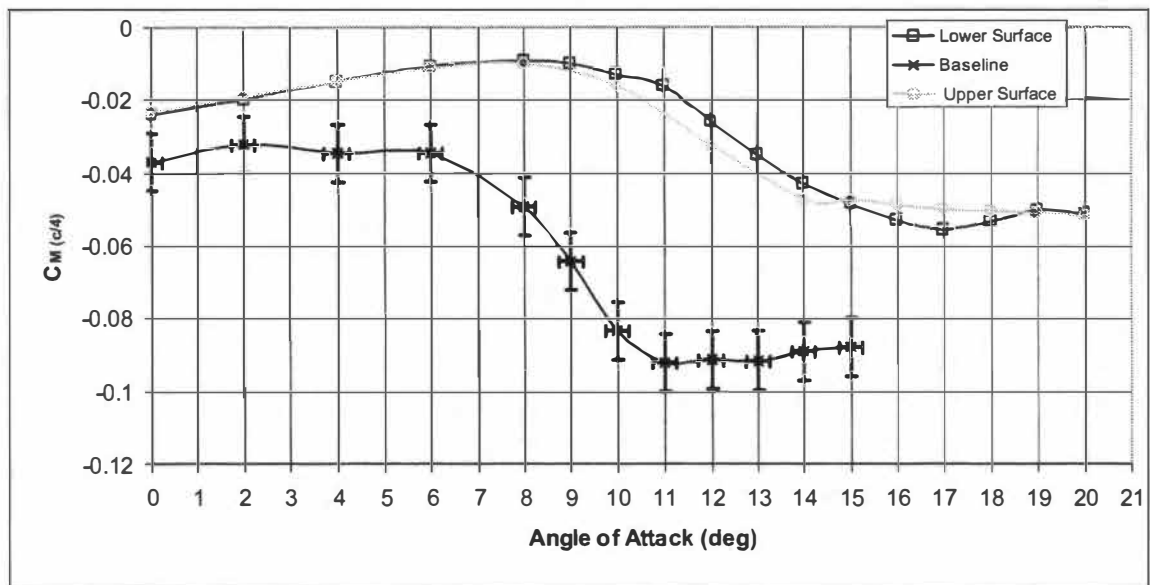


Figure 5.5.8: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, α -dependent Moment Coefficient $\delta = 10^\circ$

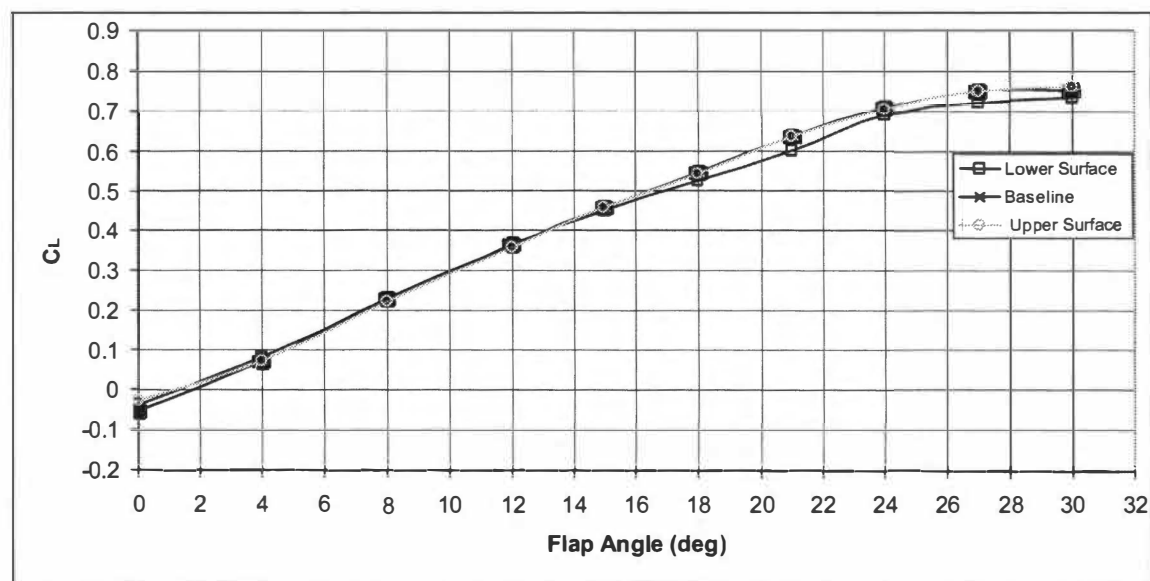


Figure 5.5.9: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, δ -dependent Lift Coefficient $\alpha = 0^\circ$

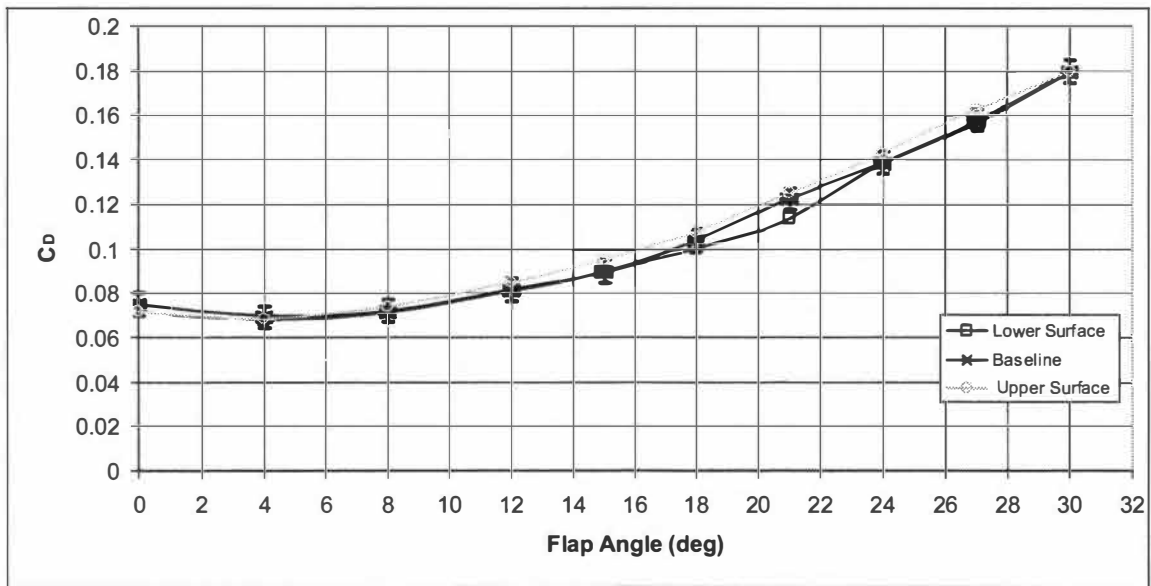


Figure 5.5.10: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, δ -dependent Drag Coefficient $\alpha = 0^\circ$

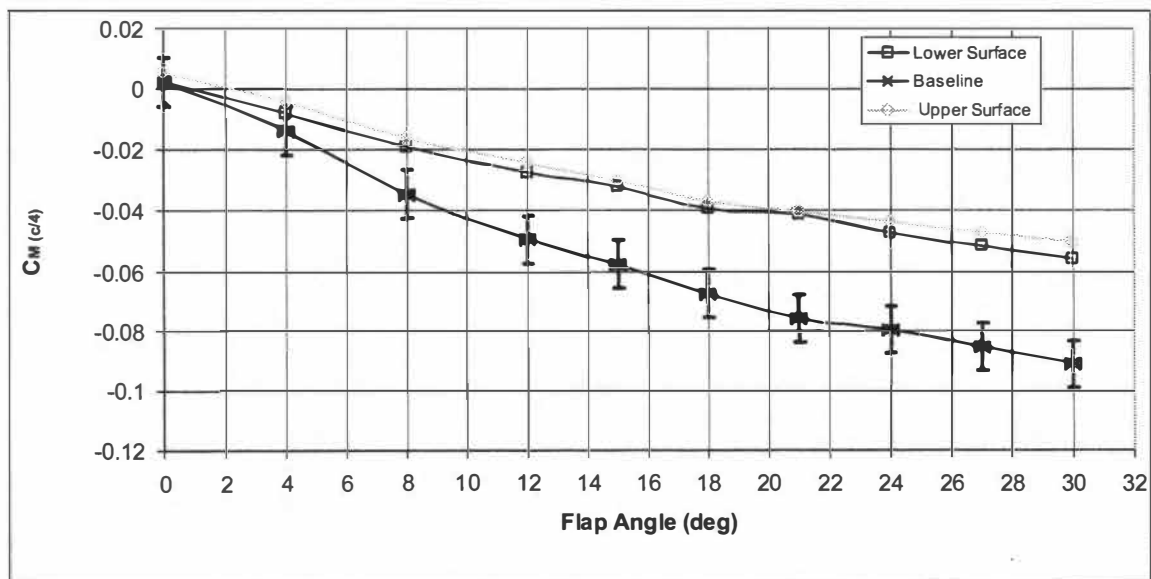


Figure 5.5.11: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, δ -dependent Moment Coefficient $\alpha = 0^\circ$

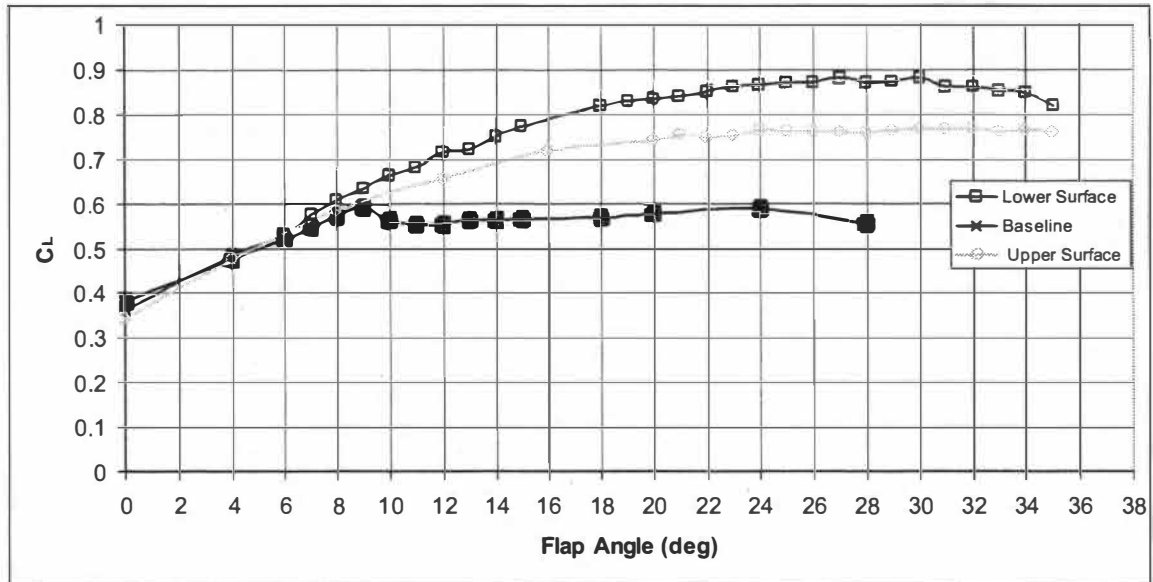


Figure 5.5.12: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, δ -dependent Lift Coefficient $\alpha = 10^\circ$

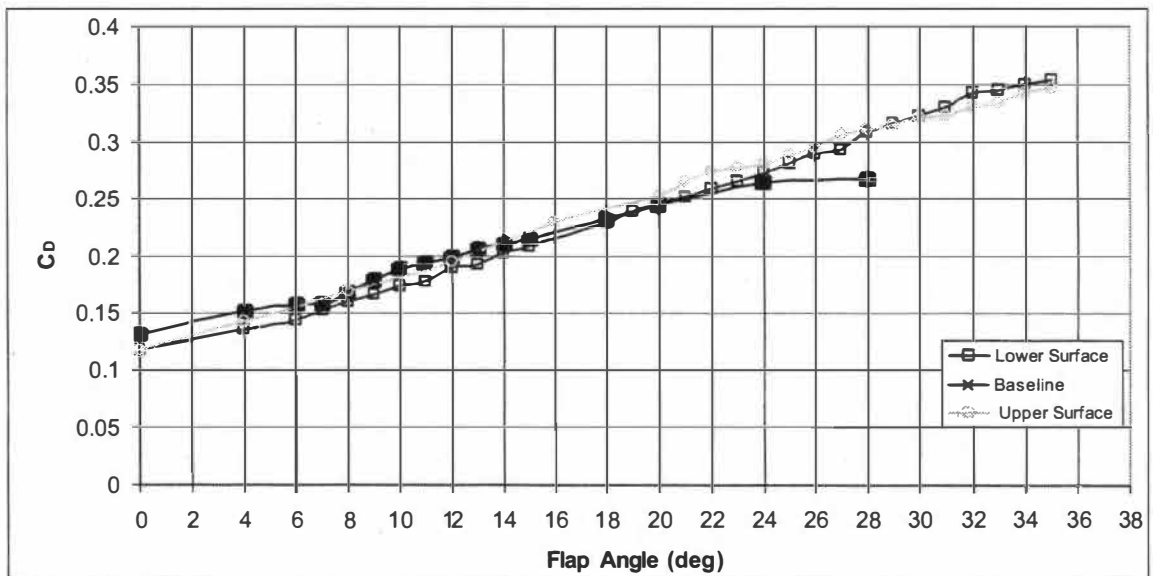


Figure 5.5.13: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, δ -dependent Drag Coefficient $\alpha = 10^\circ$

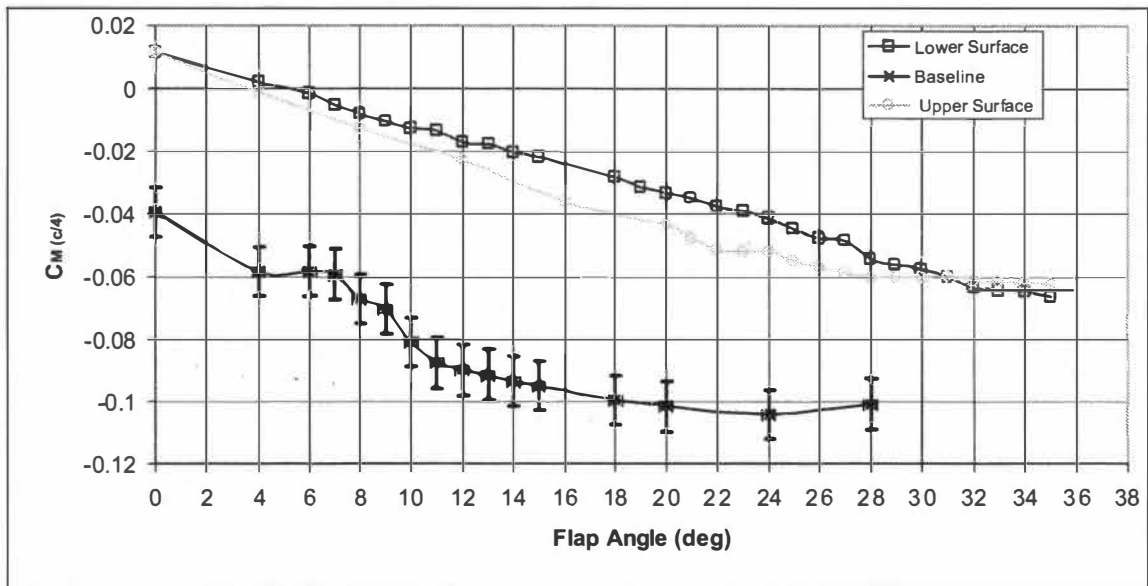


Figure 5.5.14: Leading Edge Surface Comparison 2.0" Spacing, 1/2" VGs, δ -dependent Moment Coefficient $\alpha = 10^\circ$

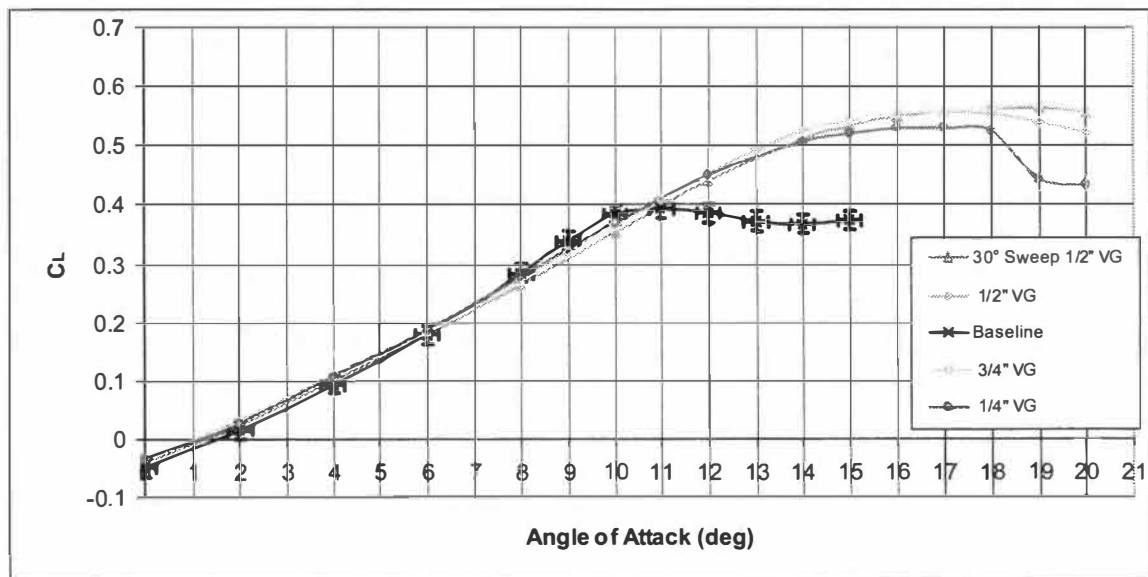


Figure 5.6.1: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Lift Coefficient, $\delta = 0^\circ$

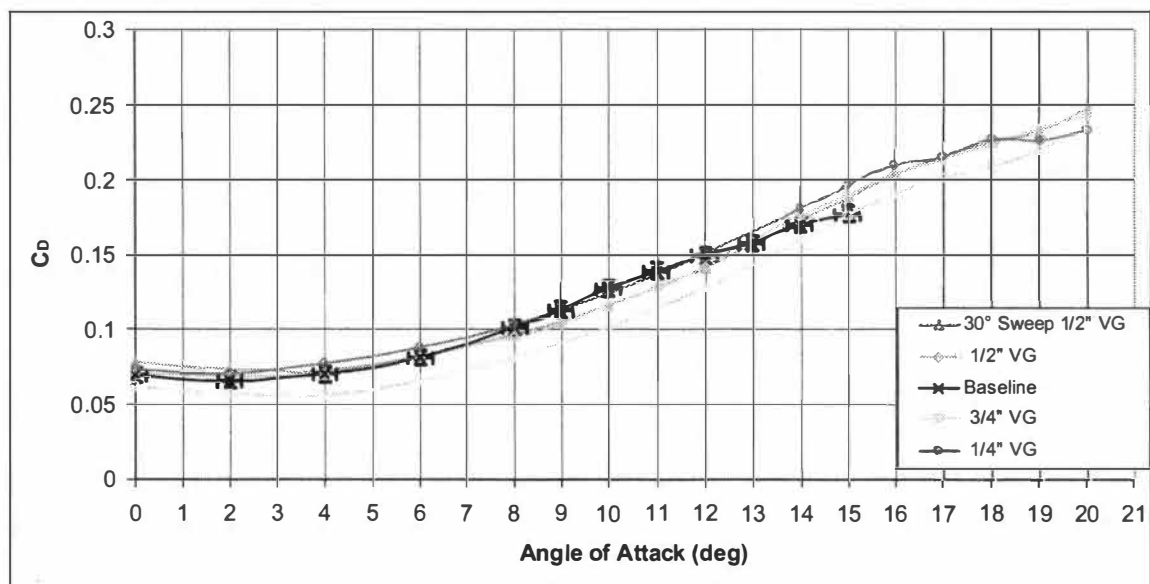


Figure 5.6.2: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Drag Coefficient, $\delta = 0^\circ$

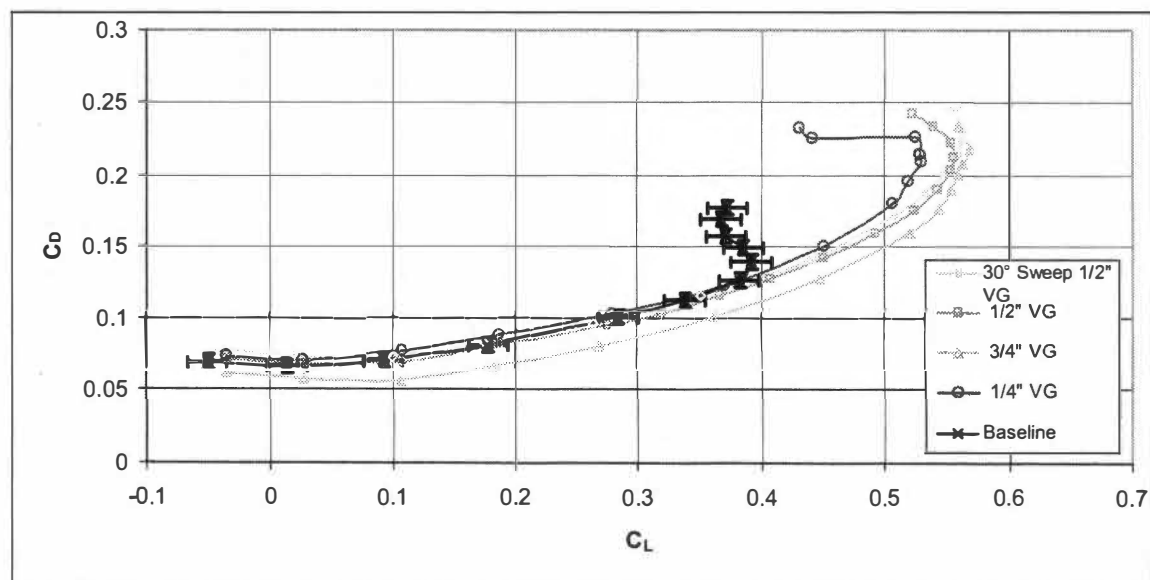


Figure 5.6.3: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Drag Polar, $\delta = 0^\circ$

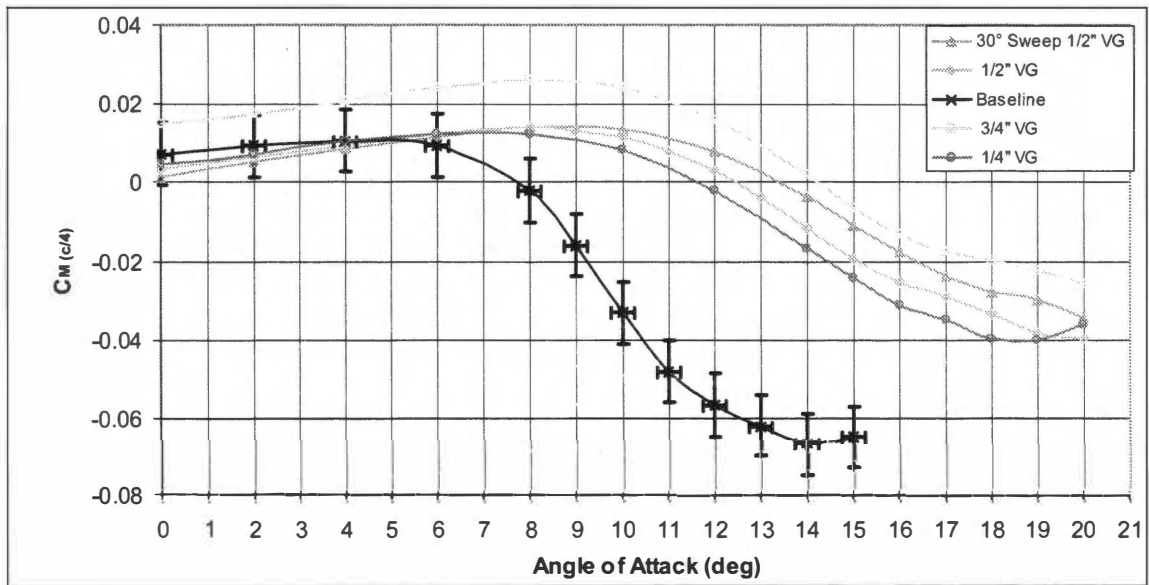


Figure 5.6.4: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Moment Coefficient, $\delta = 0^\circ$

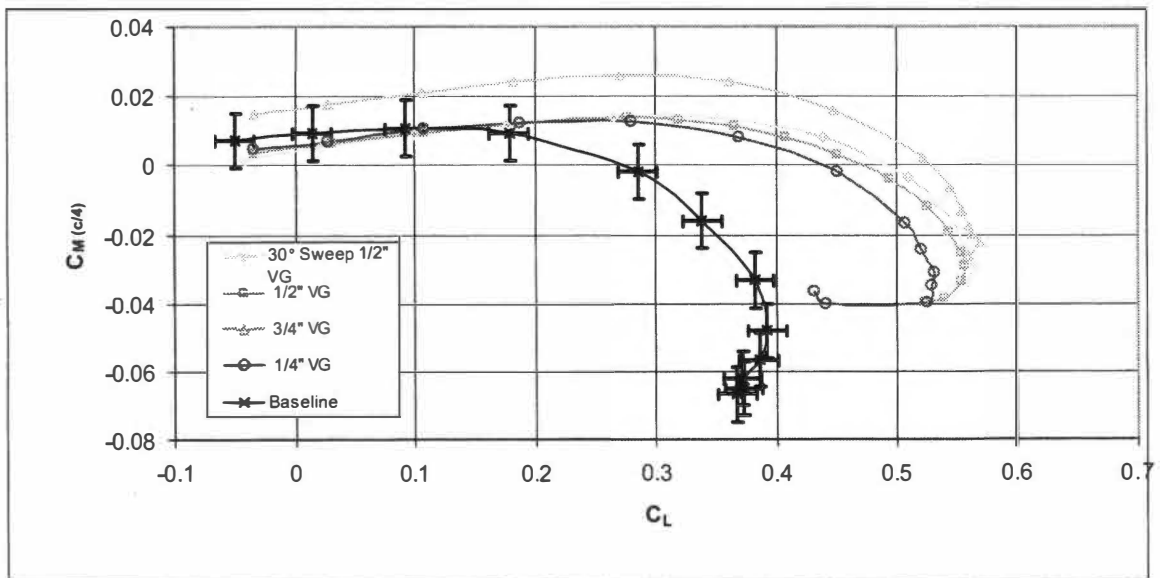


Figure 5.6.5: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Lift / Moment Coefficient, $\delta = 0^\circ$

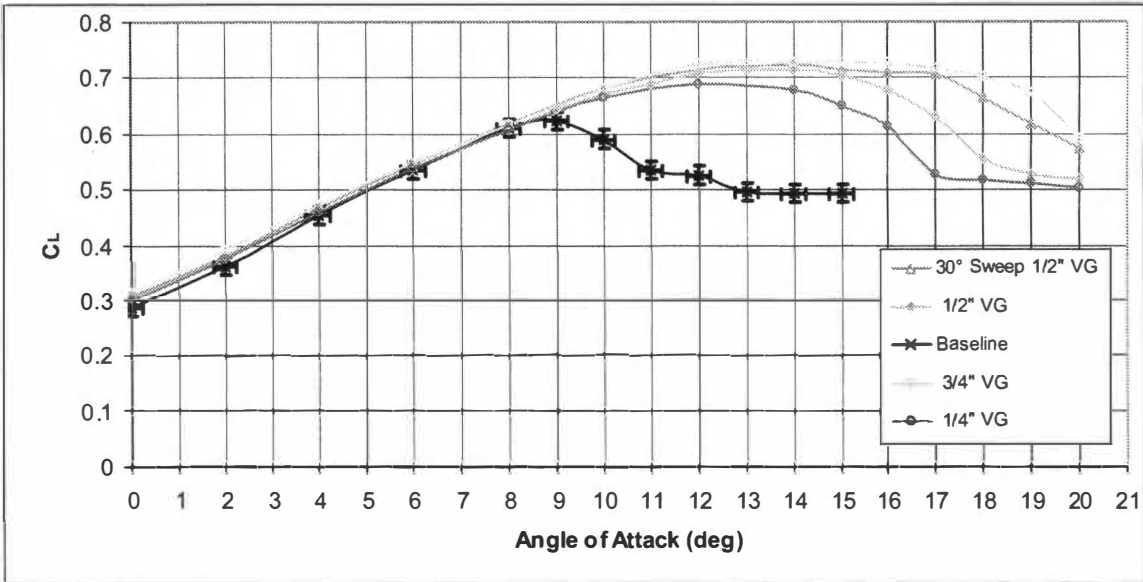


Figure 5.6.6: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Lift Coefficient, $\delta = 10^\circ$

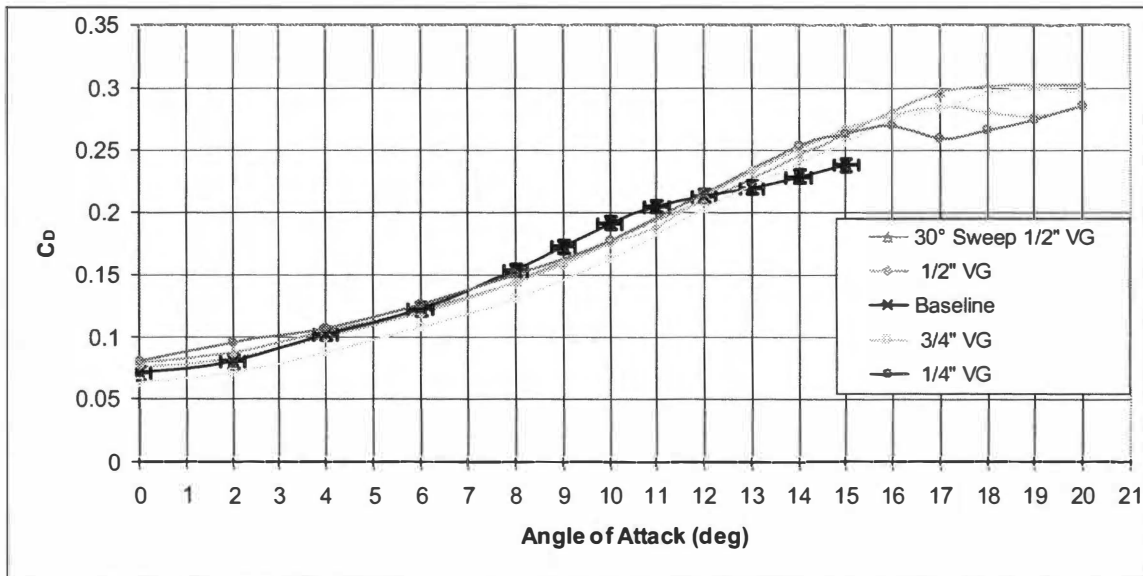


Figure 5.6.7: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Drag Coefficient, $\delta = 10^\circ$

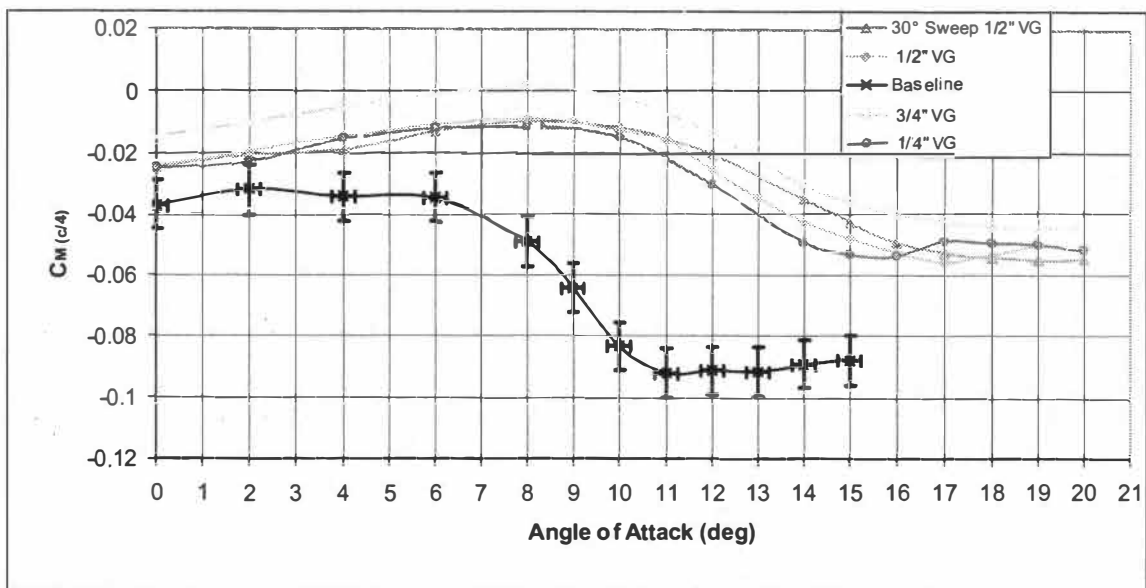


Figure 5.6.8: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Moment Coefficient, $\delta = 10^\circ$

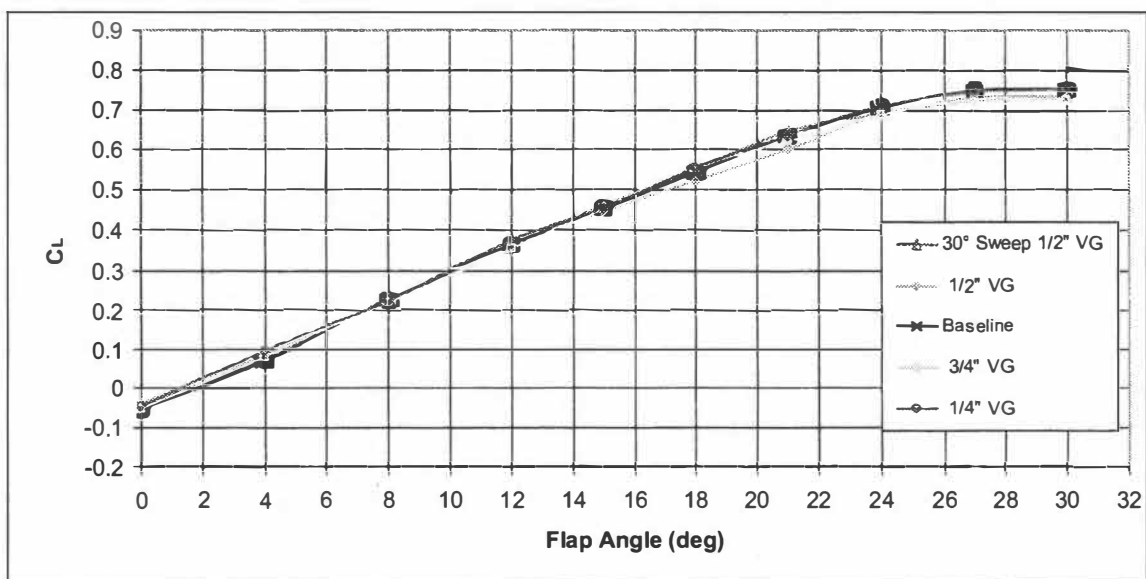


Figure 5.6.9: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, δ -dependent Lift Coefficient, $\alpha = 0^\circ$

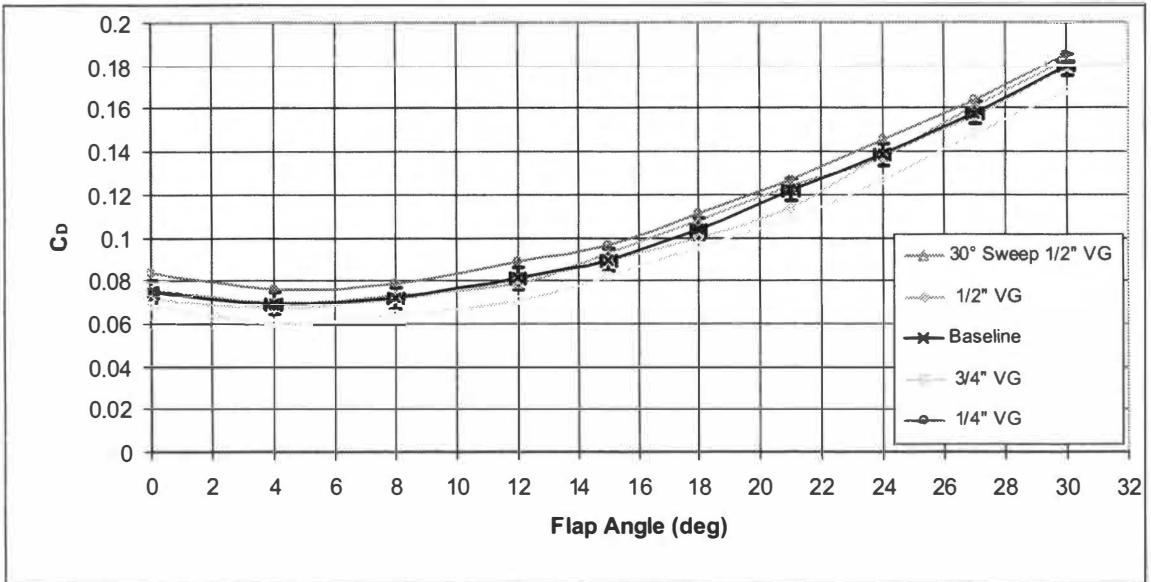


Figure 5.6.10: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, δ -dependent Drag Coefficient, $\alpha = 0^\circ$

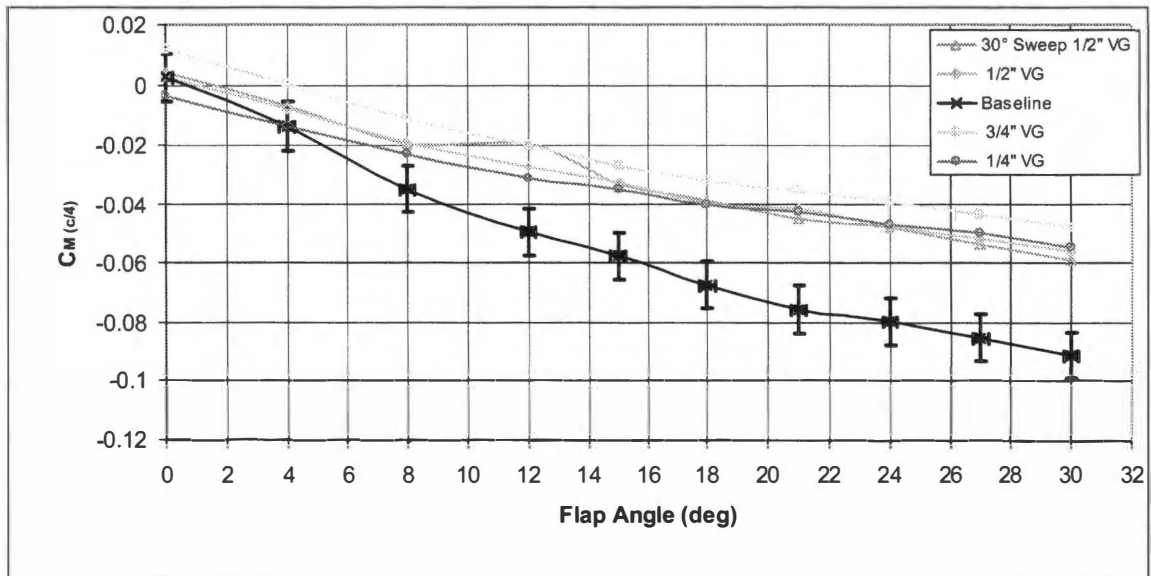


Figure 5.6.11: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, δ -dependent Moment Coefficient, $\alpha = 0^\circ$

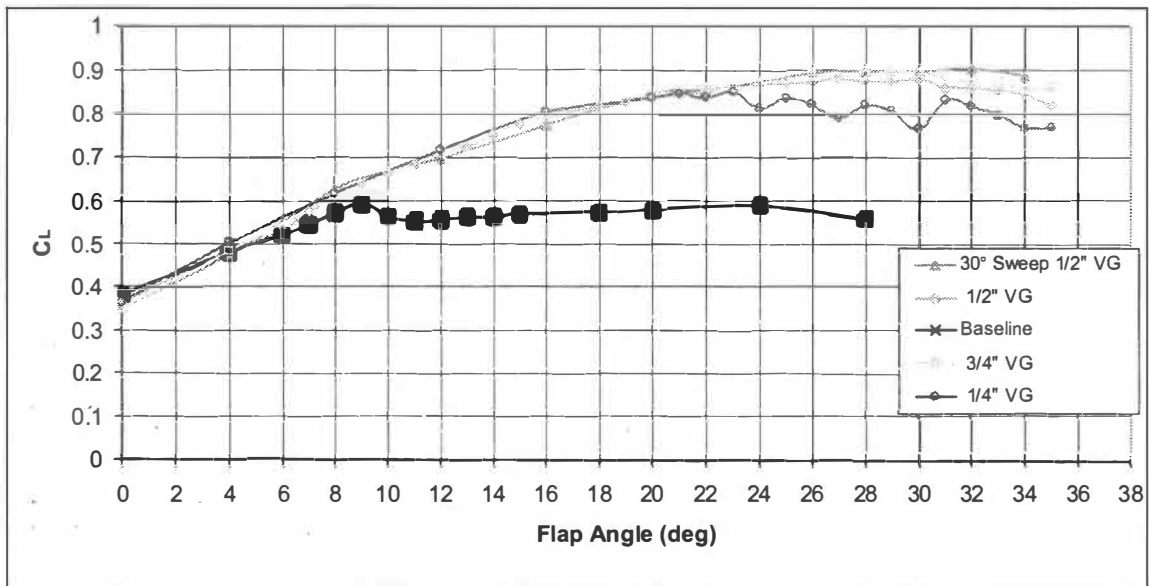


Figure 5.6.12: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, δ -dependent Lift Coefficient, $\alpha = 10^\circ$

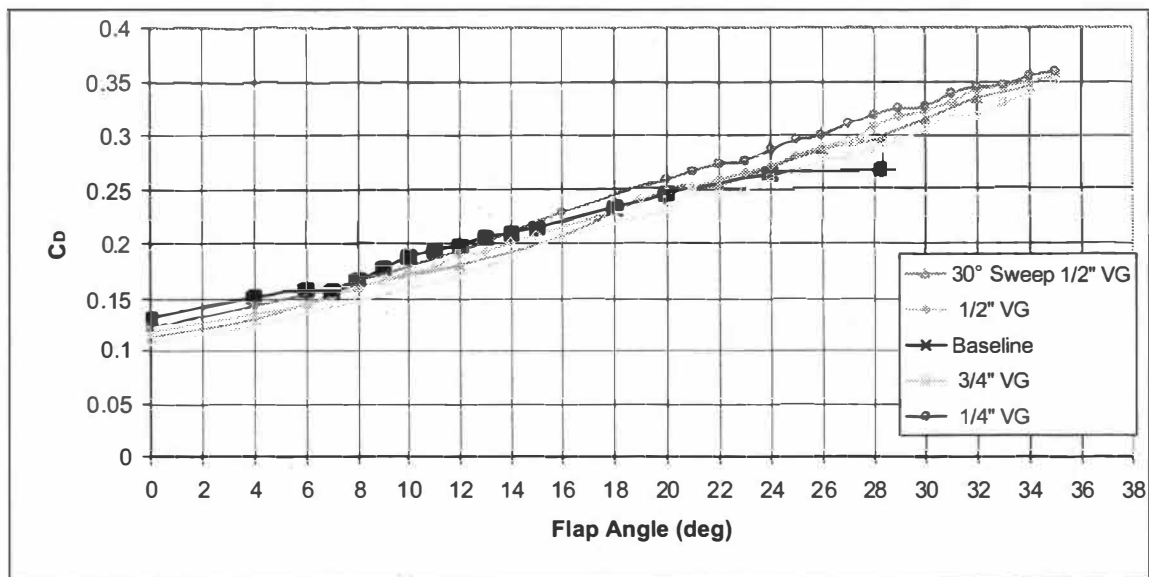


Figure 5.6.13: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, δ -dependent Drag Coefficient, $\alpha = 10^\circ$

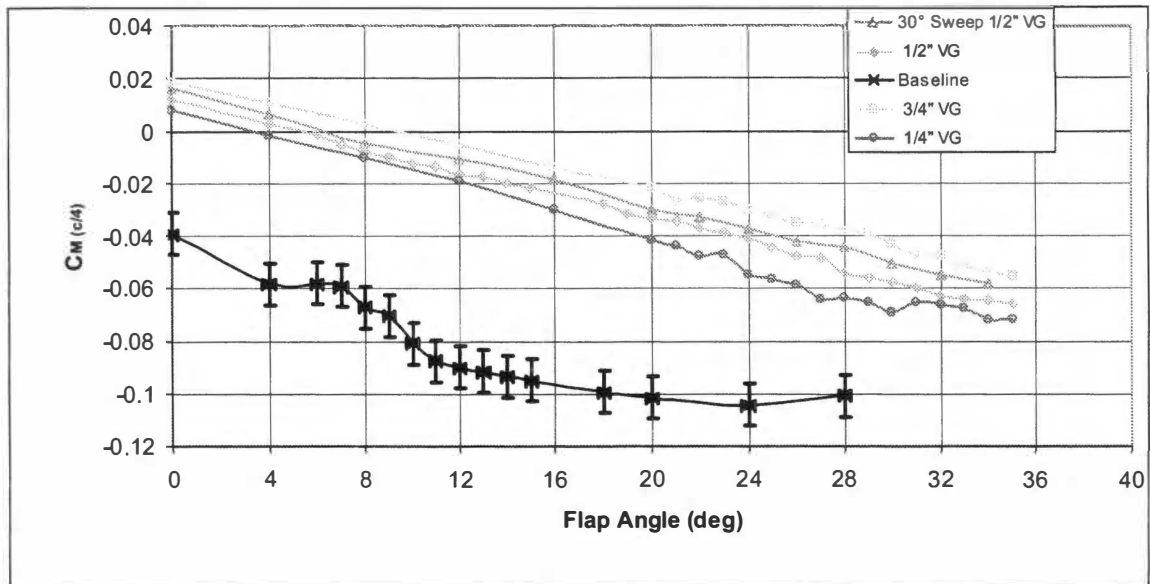


Figure 5.6.14: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, δ -dependent Moment Coefficient, $\alpha = 10^\circ$

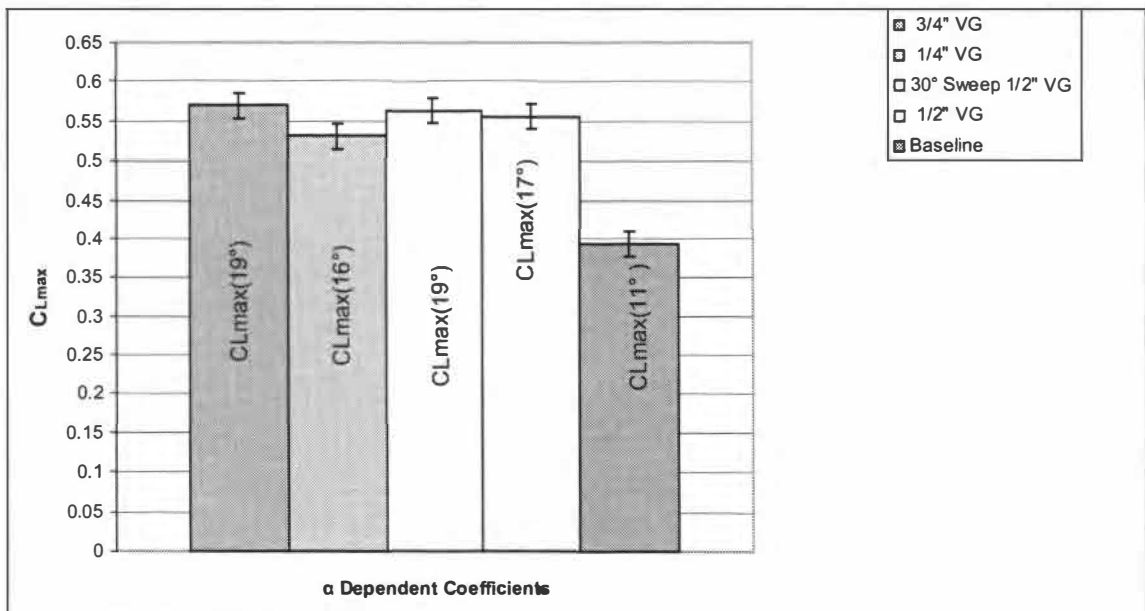


Figure 5.6.15: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent C_{Lmax} , $\delta = 0^\circ$

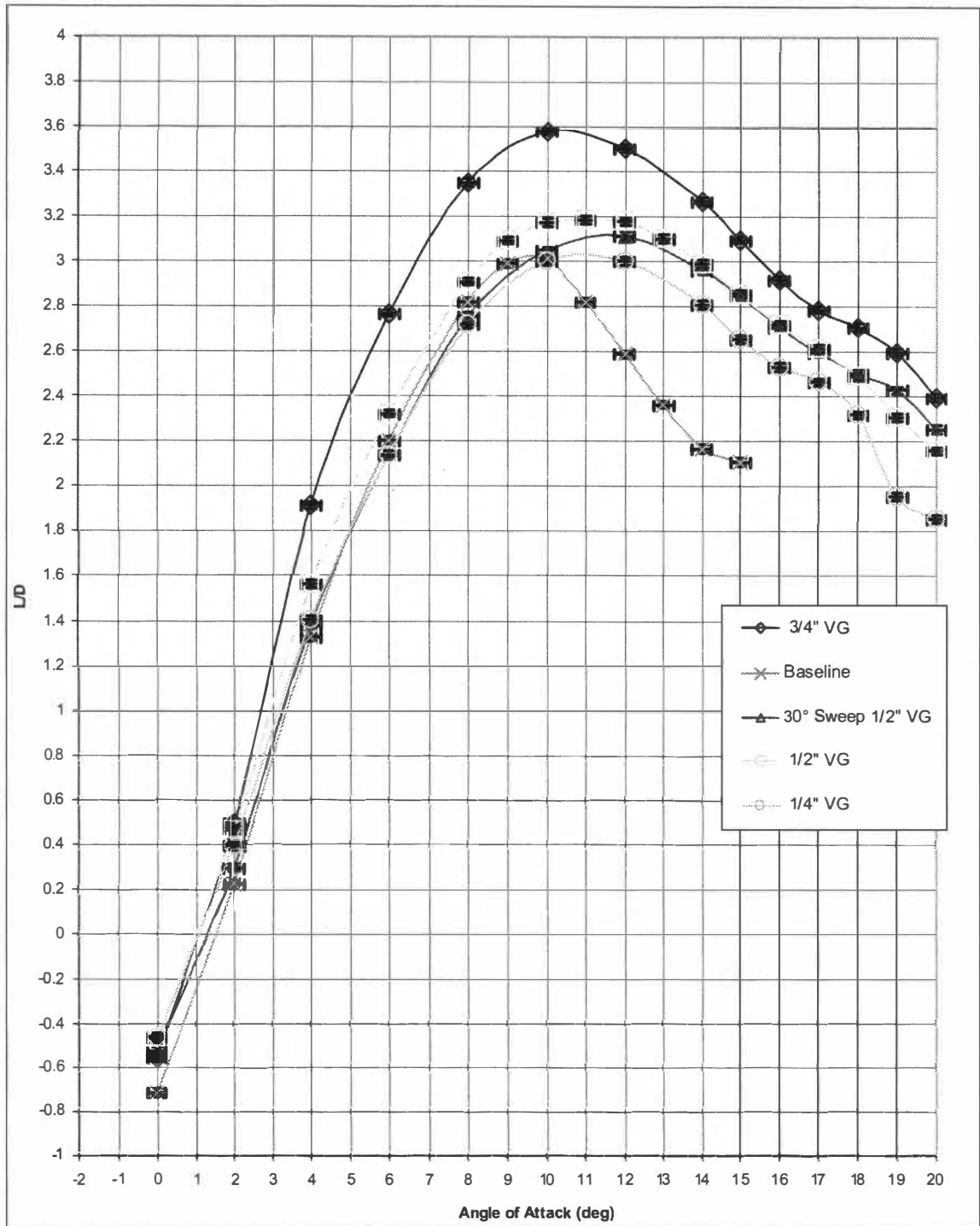


Figure 5.6.16: Leading Edge Lower Surface VGs, 2.0" Spacing, Size Comparison, α -dependent Lift to Drag Ratio, $\delta = 0^\circ$

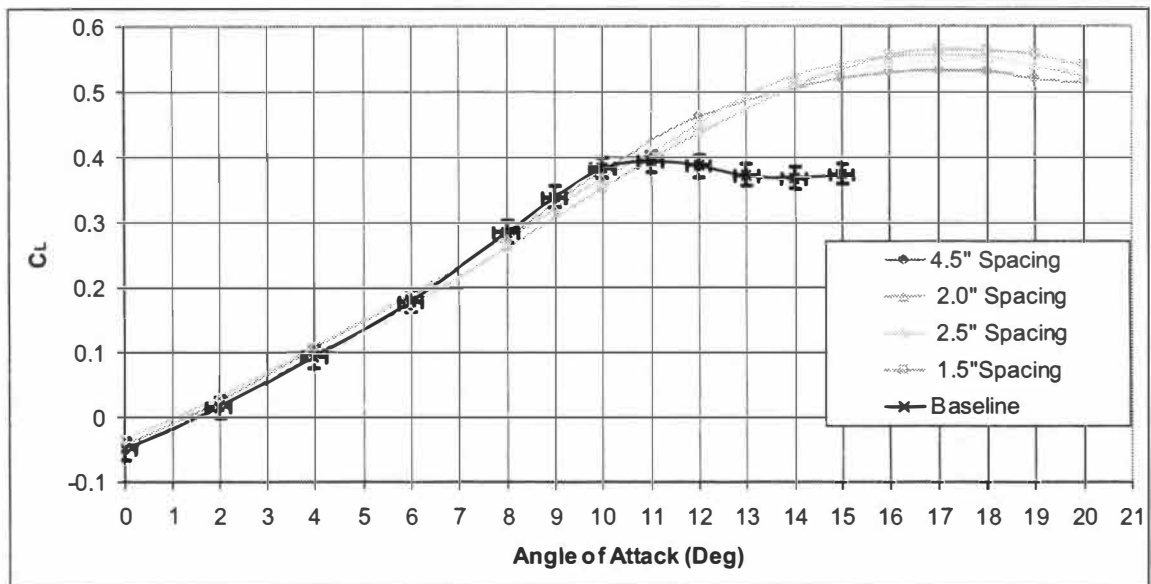


Figure 5.7.1: Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Lift Coefficient, $\delta = 0^\circ$

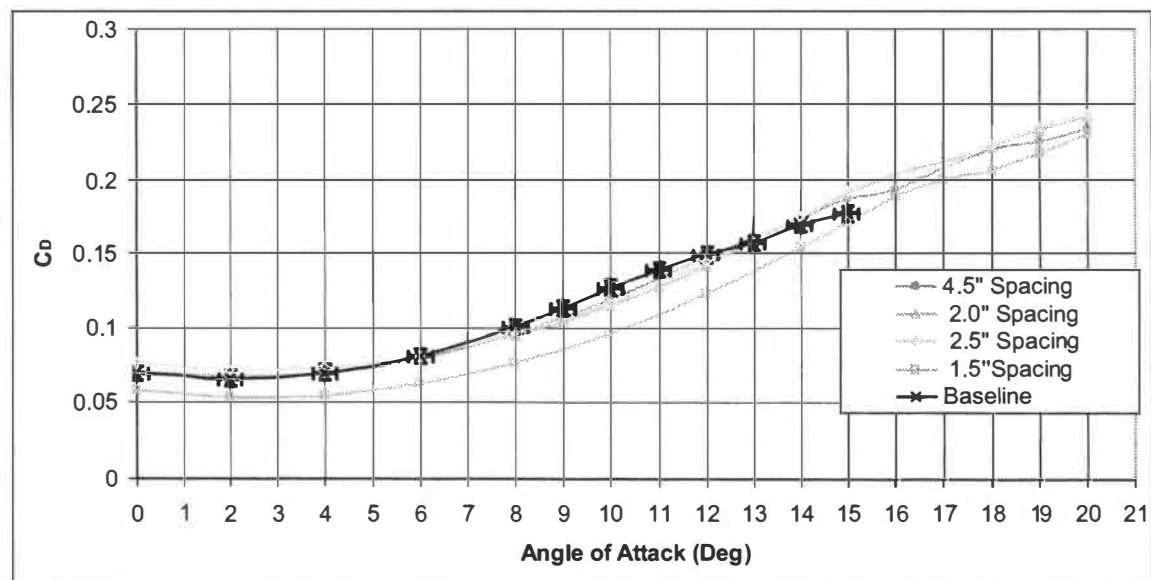


Figure 5.7.2: Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Drag Coefficient, $\delta = 0^\circ$

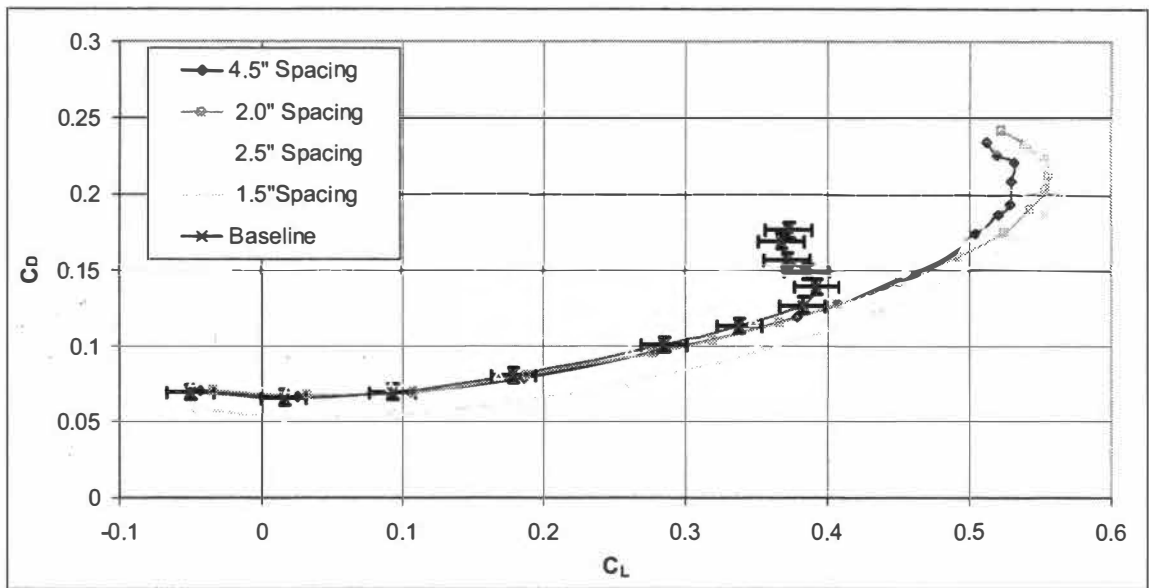


Figure 5.7.3: Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Drag Polar, $\delta = 0^\circ$

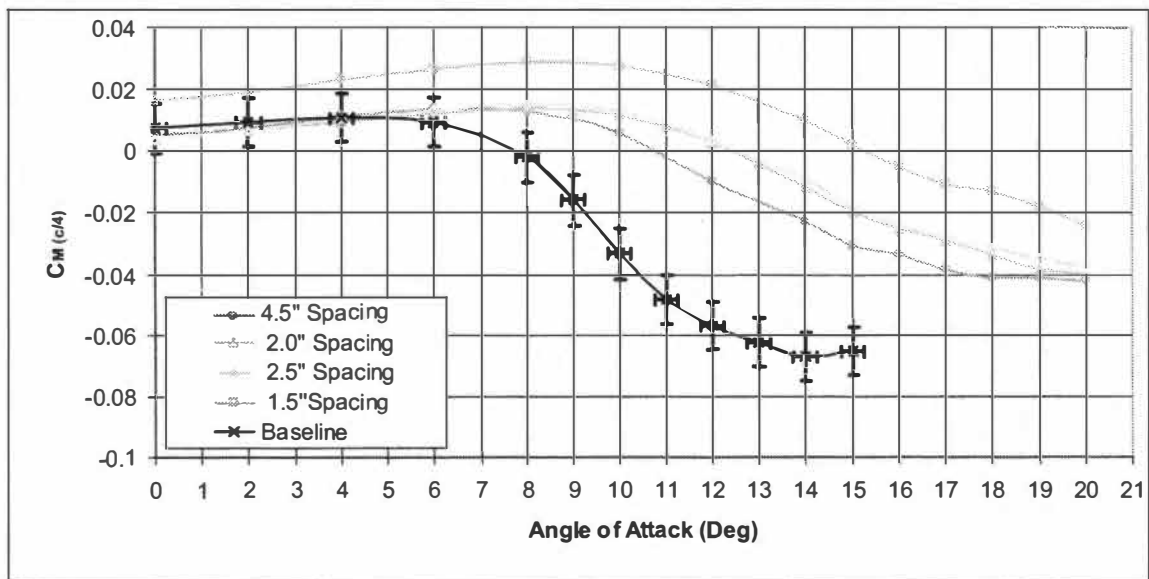


Figure 5.7.4: Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Moment Coefficient, $\delta = 0^\circ$

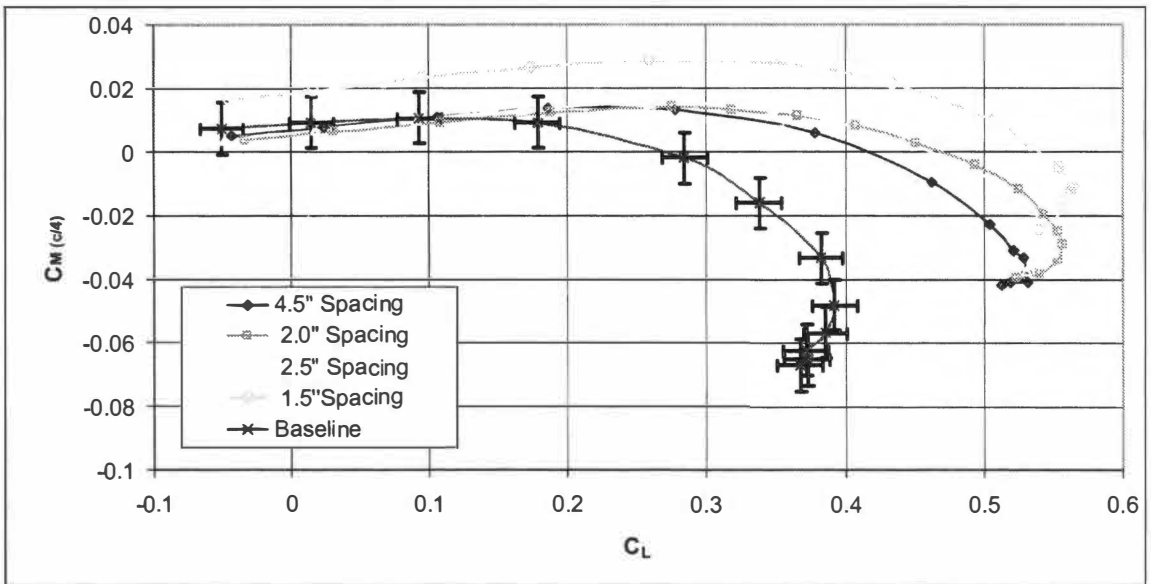


Figure 5.7.5: Lower Surface, Leading Edge, 1/2" VG Space Comparison, α -dependent Moment Coefficient vs Lift Coefficient, $\delta = 0^\circ$

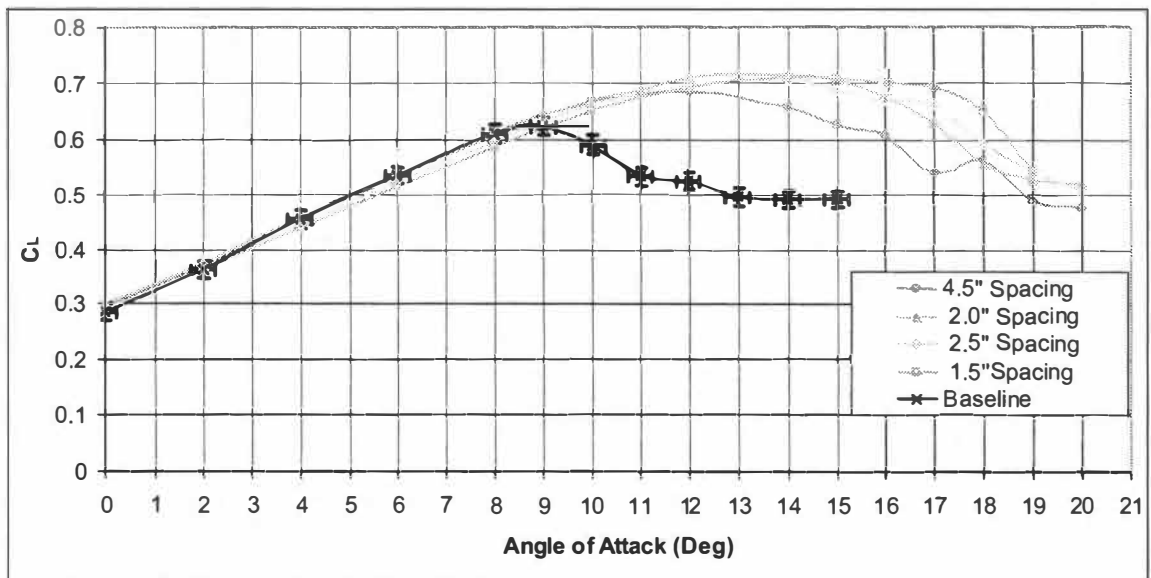


Figure 5.7.6: Lower Surface, Leading Edge, 1/2" VG Space Comparison, α -dependent Lift Coefficient, $\delta = 10^\circ$

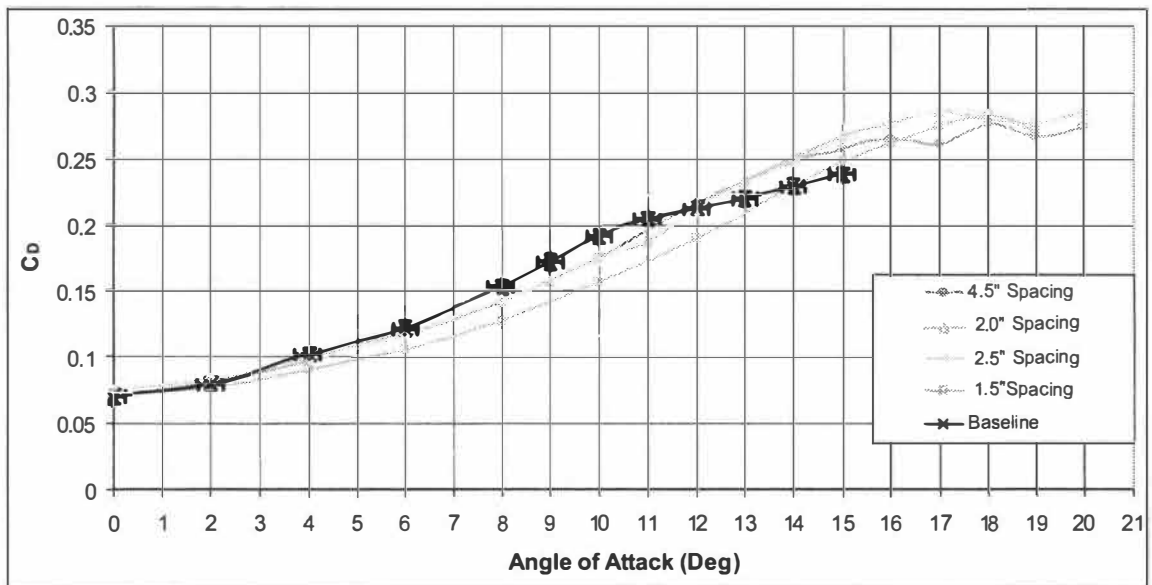


Figure 5.7.7: Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Drag Coefficient, $\delta = 10^\circ$

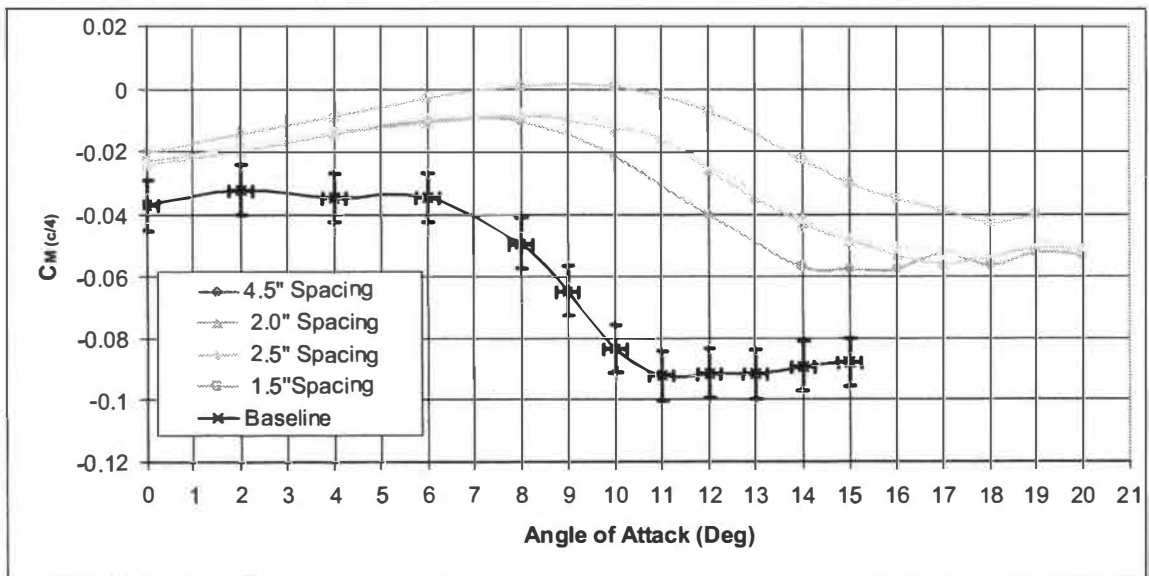


Figure 5.7.8: Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, α -dependent Moment Coefficient, $\delta = 10^\circ$

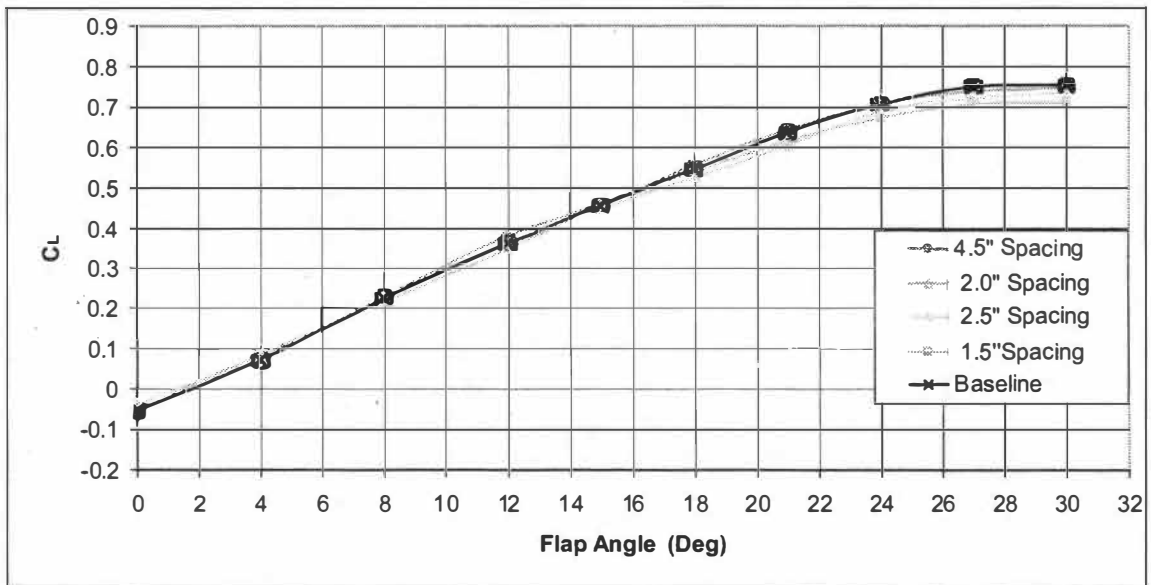


Figure 5.7.9: Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, δ -dependent Lift Coefficient, $\alpha = 0^\circ$

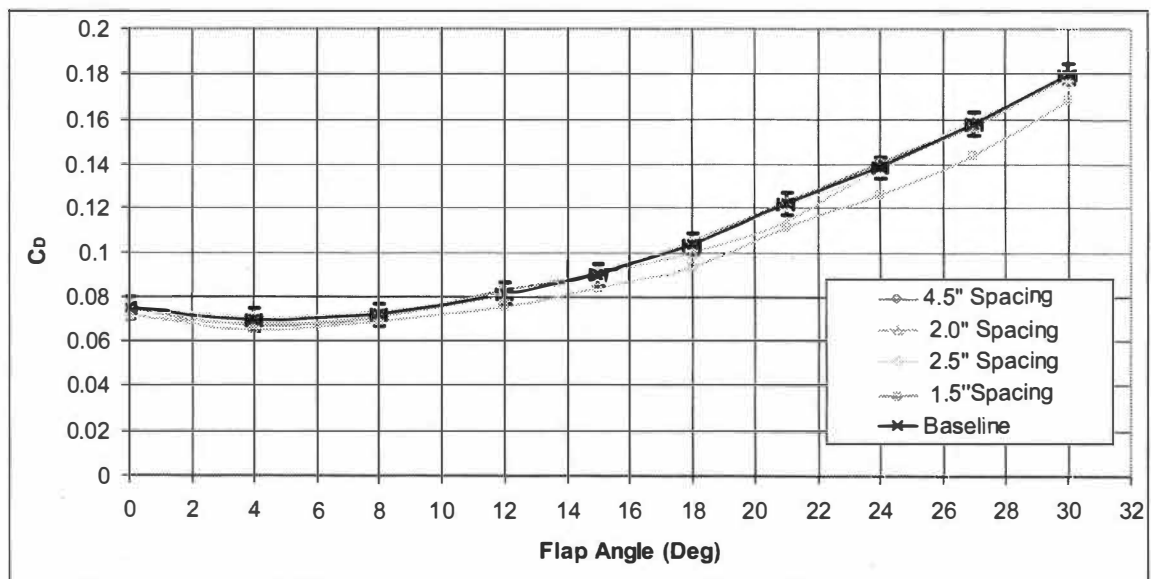


Figure 5.7.10: Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, δ -dependent Drag Coefficient, $\alpha = 0^\circ$

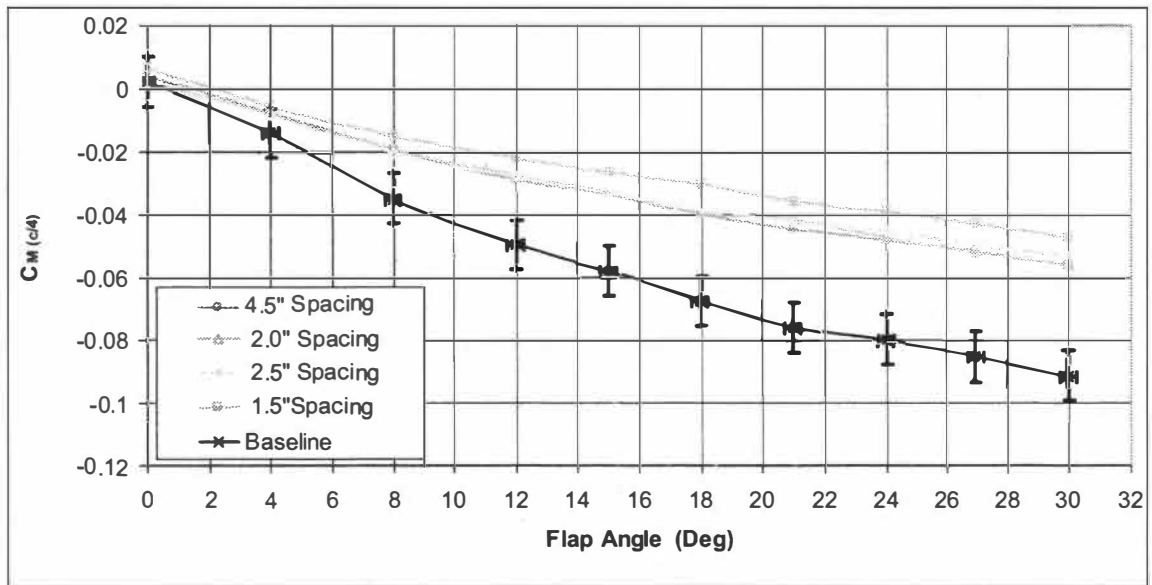


Figure 5.7.11: Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, δ -dependent Moment Coefficient, $\alpha = 0^\circ$

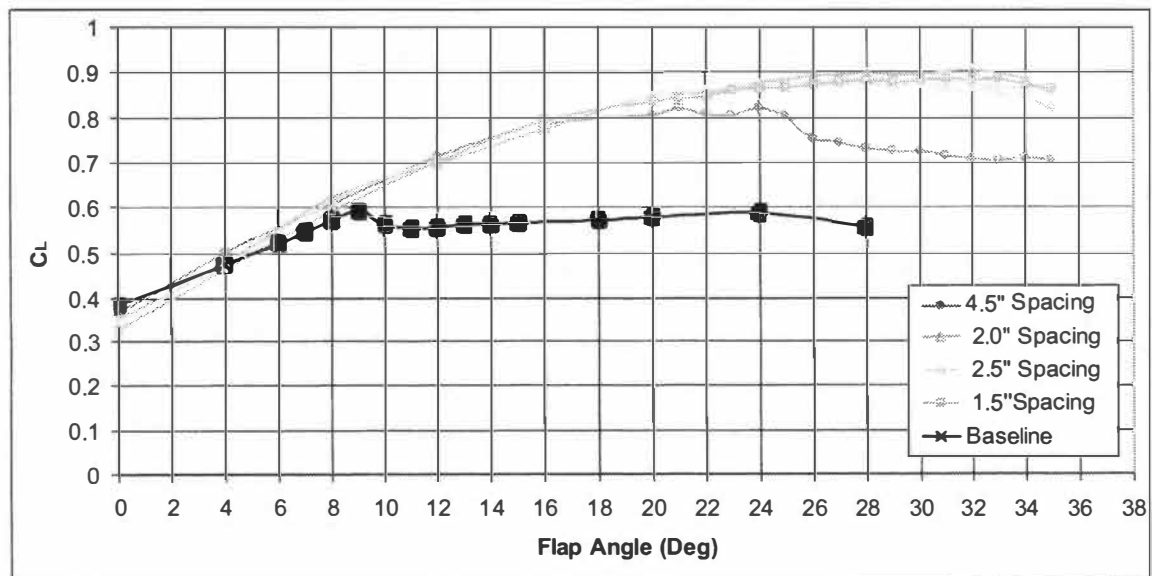


Figure 5.7.12: Lower Surface, Leading Edge, $\frac{1}{2}$ " VG Space Comparison, δ -dependent Lift Coefficient, $\alpha = 10^\circ$

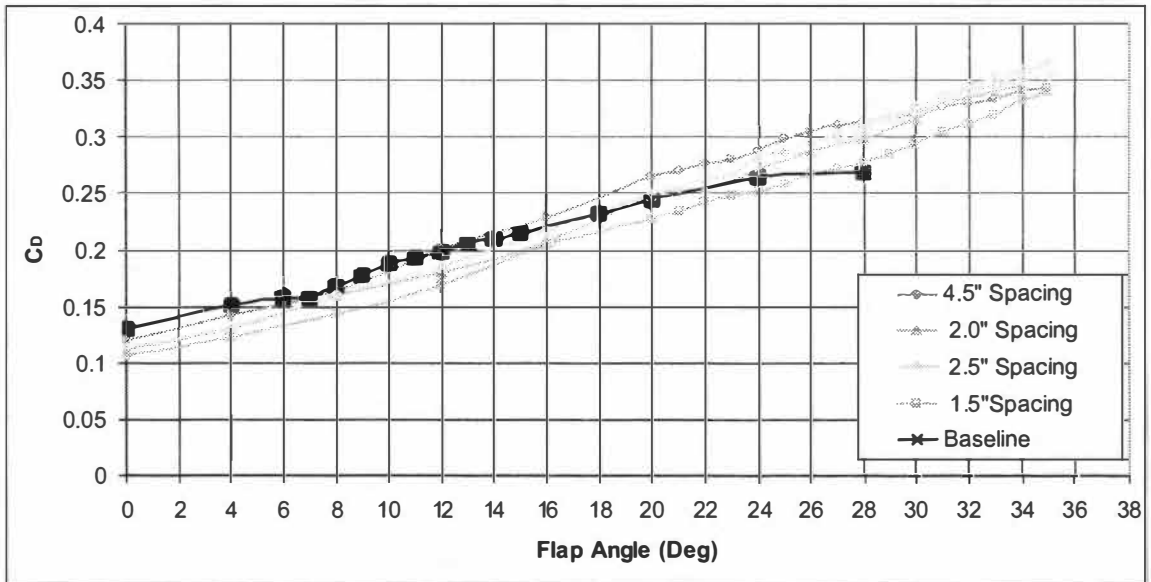


Figure 5.7.13: Lower Surface, Leading Edge, 1/2" VG Space Comparison, δ -dependent Drag Coefficient, $\alpha = 10^\circ$

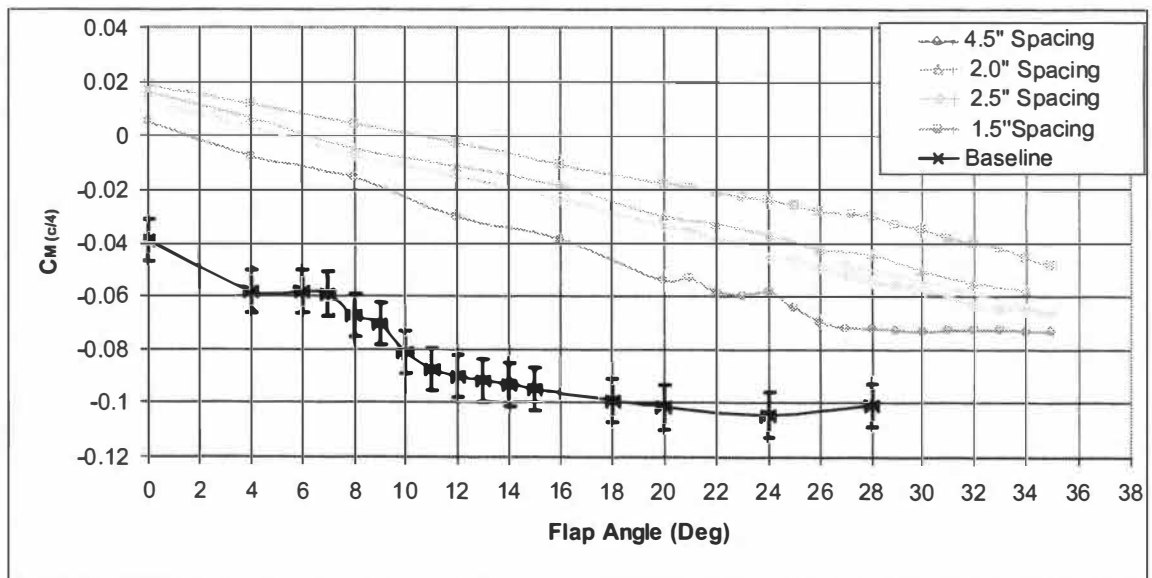


Figure 5.7.14: Lower Surface, Leading Edge, 1/2" VG Space Comparison, δ -dependent Moment Coefficient, $\alpha = 10^\circ$

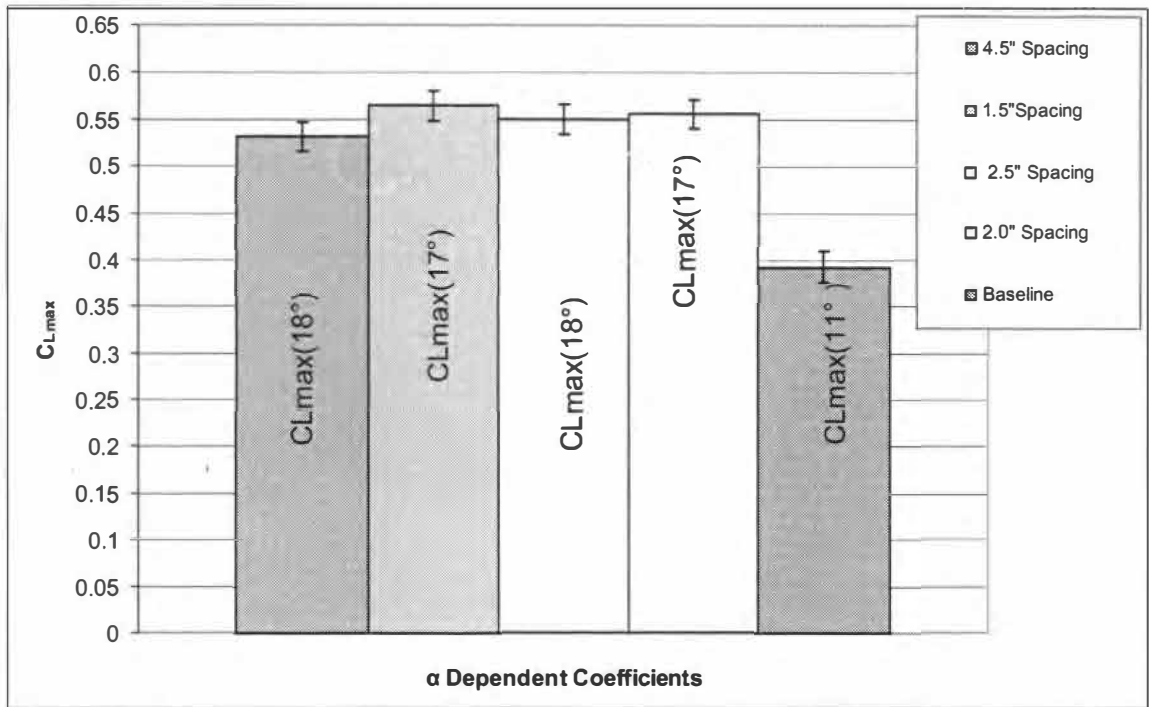


Figure 5.7.15: Lower Surface, Leading Edge, 1/2" VG Space Comparison, α -dependent C_{Lmax} , $\delta = 0^\circ$

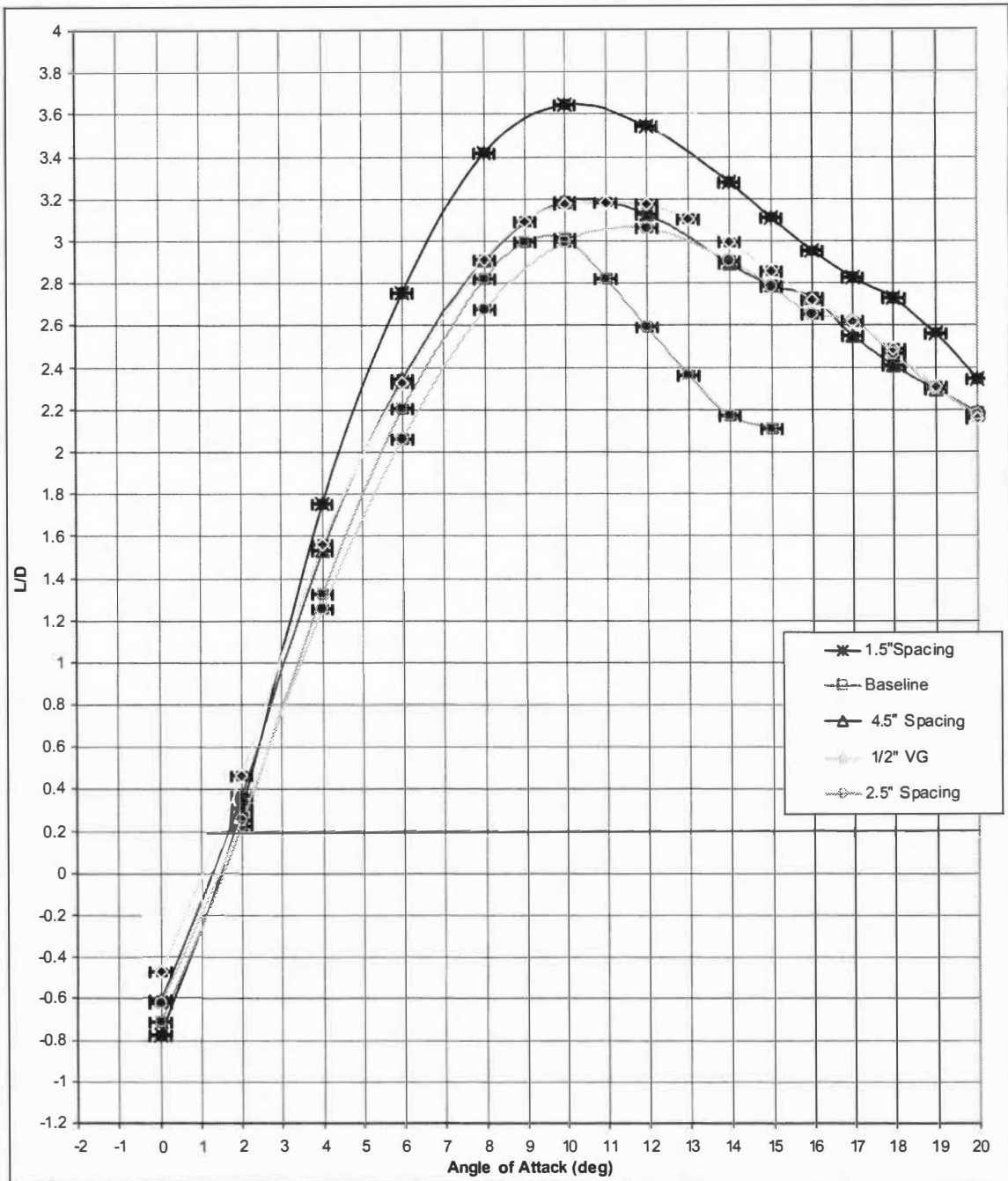


Figure 5.7.16: Lower Surface, Leading Edge, 1/2" VG Space Comparison, α -dependent Lift to Drag Ratio, $\delta = 0^\circ$

VITA

Charles McConnell was born and raised in Nashville Tennessee and graduated from Hume-Fogg Academic High School in 1992. He was awarded a Bachelor of Science degree in Aerospace Technology with minors in Mathematics and Industrial Technology from Middle Tennessee State University in Murfreesboro Tennessee in May of 2002. In December 2005 he will graduate from The University of Tennessee, Knoxville having fulfilled the requirements for a Master of Science degree in Aerospace Engineering with a concentration in Aerodynamics and Thermal Analysis.

7695 2036 69
03/08/06 MAR