Optimization of a Vortex Generator Configuration for a 1/4-Scale Piper Cherokee Wing

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OPTIMIZATION OF A VORTEX GENERATOR CONFIGURATION

FOR A 1/4-SCALE PIPER CHEROKEE WING

by

Kerri A. Raykowski

A thesis submitted to the Aerospace Engineering Department
in partial fulfillment of the requirements for the degree of
Master of Science in Aerospace Engineering

Embry-Riddle Aeronautical University
Daytona Beach, Florida

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This thesis was prepared under the direction of the candidate's thesis committee advisor, Professor Charles N. Eastlake, P.E., Department of Aerospace Engineering, and has been approved by the members of her thesis committee. It was submitted to the Office of Graduate Studies and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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ABSTRACT

Author         Kerri A Raykowski
Title           Optimization of a Vortex Generator Configuration for a 1/4-Scale Piper Cherokee Wing
Institution     Embry-Riddle Aeronautical University
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Several sets of wind tunnel tests were performed to determine an optimum vortex generator configuration for a 1/4-scale model of the Piper Cherokee wing. Several variables were incorporated into this experiment in an effort to determine their influence on vortex generator performance enhancement (or degradation). Vane type vortex generators were used with 3 different leading edge sweeps: zero (rectangular planform), 20, and 45 degrees. Three different vortex generator heights were tested (0.05", 0.1", and 0.2") to find the optimal vortex generator height relative to the local boundary layer thickness. The vortex generator angle of incidence relative to the freestream was varied from 10 to 30 degrees in increments of 5 degrees. Other variables included were spanwise row density, chordwise row location as well as number of rows, co- vs. counter-rotating vortex generator placement, and the influence of stagger and opposing rotation in successive rows. Some vortex generator configurations were found to both enhance lift and decrease cruise drag (by up to 10.7% and 4%, respectively). Other configurations were found to be beneficial in either lift (by up to 10.7%) or drag (by up to 14.5%).
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1. INTRODUCTION

1.1 Explanation of need

Aircraft, like any vehicle, are subjects of compromise. The first choice for landing gear configuration may not have been economically practical. A laminar flow airfoil may have been sacrificed for one that might offer more consistent performance in a greater number of flight conditions. There are very few aspects of a production aircraft that have been around since the preliminary design phase.

It is common knowledge why aircraft have designated take-off and landing speeds--to retain the highest amount of lift possible without stalling the wing or overshooting the runway. This, in itself, is a compromise an aircraft must make. The faster air is flowing over a wing, the more lift is being generated. But at landing, velocity must be low in order to touch down and have the ability to stop short of the end of the runway. The way an aircraft can still attain high lift at such low velocities is by increasing the wing's angle of attack. Unfortunately, the wing has an upper limit on this increase in lift. This is the phenomenon known as stall. A pilot must make adjustments to allow his aircraft to walk the fine line between enough lift to keep his aircraft aloft and a sudden loss of lift that could result in a less-than-desirable landing.
12 Previous Research

The concept of using vortex generators to enhance performance is certainly not a new one. As early as the 1940’s, most aircraft companies began testing to determine the benefits of VG’s.

Vortex generators have, throughout their evolution, been used in numerous applications. These include delay of flow separation on numerous surfaces, increasing efficiency of fan, propeller, or compressor blades, and assisting with heat transfer. Initially, VG’s were not intended for aircraft surfaces. United Aircraft Corporation (UAC) employed VG’s to eliminate flow separation in their 8-ft wind tunnel diffuser (a common problem when the divergence angle is too great). This late 1940’s experiment praises the counter-rotating VG set-ups for their superior mixing capability. Tapered vane-type VG’s (shown in Fig 1 la, below) performed best when there was no sweep of the 1/4-chord line and no twist. The suspended airfoil type VG (shown in Fig 1 lb, below) proved to be an inefficient means of mixing. Reference 15 cautions, however, the use of multiple rows of VG’s. A staggered arrangement is best in this case, but the interference of successive vortices is a concern.

![Figure 11](image)

Figure 11 VG’s tested by UAC

A few decades later, Senoo and Nishi (of the Research Institute of Industrial Science at Kyushu University and the Kyushu Institute of Technology, Japan) continued work on VG applications in conical diffusers. The VG’s tested here were in excess of the local...
BL thickness with a VG chord of roughly 0.75". The VG angle of incidence was determined to be optimal at 14°, with anything greater producing essentially identical results. It was found that the proper use of VG’s can allow a 16° diffuser to achieve as high a pressure recovery coefficient as an 8° diffuser, greatly reducing the necessary diffuser length. Co-rotating VG configurations were found to work best. A higher pressure recovery coefficient was obtained when the VG’s were moved further upstream.

Reference 2 tested various VG types and configurations on a NACA 4415 airfoil at the University of Kansas to determine optimum spanwise spacing and chordwise location of both stationary and retractable VG’s. It was also determined that ramp VG’s (shown in Fig.1.2, below) produced vortices with the longest distance at breakdown, which were then used in the optimization process. Using the optimal configuration, \( C_{L,max} \) was increased by 14% in addition to an increase in \( \alpha_{stall} \) of up to 3°. Maximum lift was achieved when the VG’s were placed between 8% and 15% chord. Optimal VG spacing for the VG’s tested was determined to be 0.7-1.1". Little or no effect was seen when the VG’s were located aft of the 40%c line. Stationary VG configurations were found to increase cruise (L/D) by up to 300%. Multiple row of VG’s did not enhance performance appreciably. Another benefit of pop-up VG configurations is their ability to

Figure 1.2: Pneumatically deployed ramp VG²
be selectively deployed, enhancing maneuverability. By raising VG’s on one wing, for example, an increase in roll rate to the opposite side results.

Research done at Ohio State University in the mid-1980’s focused on VG placement on the laminar flow canard airfoil of the Voyager aircraft. Pilots of this and other laminar flow canard aircraft reported a nose-down pitch moment (leading to a change in pitch trim) when passing through rain showers. This effect is caused by the early transition (leading to a loss of lift and increase in drag) induced by rain droplets on the surface of the canard. The airfoil model tested was full-scale with a tape strip (to induce transition) placed at 5%c. The 3 VG types tested were manufactured as counter-rotating pairs. All VG’s were the flat plate vane type. Two of the sets had rectangular planforms, standing 0.15” and 0.25” high. The final set had a delta planform, incorporating both LE and TE sweep (although not equal). The VG angle of incidence was held constant at 20° relative to the freestream, although not specified why. Spacing between VG pairs was also held constant at 3”. The reason for choosing this spacing was also unspecified. Two (x/c)-locations were tested for the first VG planform--0.17 and 0.45. The remaining VG planforms were only tested at the 0.45 (x/c)-location. Although not discussed, it is assumed this was done to avoid testing too tall a VG at a location where the BL was much smaller. (Considering the tripped case, the turbulent BL thicknesses at 17°c and 45°c are calculated to be 0.09” and 0.24”, respectively. This leads to the following ratios between height of the VG and local BL thickness 1.67 and 0.63 for the 0.15” VG’s at (x/c) = 0.17 and 0.45, respectively, 1.04 for the 0.25” VG’s, and 1.67 for the 0.4” VG’s.) It was found that the 0.15” VG performed slightly better in lift when it extended.
beyond the edge of the BL. This was exactly the opposite for cruise drag with the same VG--The lowest cruise drag from this VG was realized when it was submerged within the BL. The two taller VG's increased lift by about the same amount. The 0.4” VG’s did, however, cause somewhat more cruise drag. All VG’s tested reduced the cruise drag of the tripped model by around 60°. This dramatic effect was a result of the reattachment of the flow caused by the VG’s. The special nature of laminar flow airfoils must be considered, however, when discussing results such as these. Such drastic changes in cruise drag were not observed by other researchers testing standard airfoils. Compared to a clean (non-tripped) airfoil, however, the VG’s tested offered no increase in lift. The cruise drag of the VG’s ranged from 13-100% greater than that of the clean wing. Overall, the optimal VG configuration tested was the row of 0.4-inch, delta-wing VG’s at 45%. It increased $C_{L_{\text{max}}}$ of the tripped airfoil by 18% and reduced $C_{D_{\text{cruise}}}$ of the tripped airfoil by 75%. The cruise drag penalty on the clean wing of this VG configuration was also the lowest of those tested. Reference 4 mentions that this optimum configuration was successfully implemented on the Voyager during a rainstorm--pitch performance was greatly enhanced.

When testing wedge VG’s near the TE of a NACA 4412, it was found that the maximum lift coefficient was increased by up to 23°. Unfortunately, the VG’s resulted in a severe drag penalty at cruise. All VG’s tested were submerged within the BL.

Reference 7 discusses the benefits of vane type VG’s versus less conventional types (i.e., wishbone). It has been shown that vane type VG’s work best when the VG height is approximately that of the local BL thickness. Wishbone VG’s (and other low profile’
types) are typically on the order of 10-30% the height of the BL. This is due to the fact that these types of VG's meet or exceed the performance of conventional types. One problem was noted with the counter-rotating vortex pairs produced by VG types such as wishbones and wedged--They lift off of the surface rather quickly. This is most likely due to the enhanced effects of the central region of vortex upflow induced by the superposition of the 2 vortices (see Fig. 1.3, below).

![Figure 1.3: Vortices shed from a single wedge type VG.](image)

Tests performed at NASA Langley Research Center utilized VG’s on a TE flap. Both co- and counter-rotating configurations were tested. It was found that co-rotating configurations were superior when placed at the 19% flap chord location. The counter-rotating configurations performed best at the 25% flap chord location. Reference 10 speculates that this is due to the greater chordwise persistence of co-rotating vortices in a turbulent BL. A reduction in wake size (due to a greater amount of attached flow resulting from the VG’s) was also noted.
1.3 Current Research

Previous research on vortex generators has been quite extensive. Unfortunately, no comprehensive source of generalized design data for aircraft applications could be found. If this sort of data has already been gathered, it must be proprietary. To obtain a viable VG set-up for an aircraft, an owner must research companies offering modification kits for his aircraft. And although the use of VG's is not new, there is still a relatively small list of aircraft for which VG kits are available. Even if a kit is found for a particular aircraft, it is difficult to say whether the VG configuration is really the best it could be for that application.

This experiment's focus was to gather VG design data for use on a Piper Cherokee wing (although much of what is learned can undoubtedly benefit designers seeking to implement VG's on other aircraft). This wing was chosen for several reasons. Primarily, the relatively high thickness-to-chord ratio (t/c) of the Cherokee's NACA 652-415 airfoil cross-section makes it a good candidate for VG's. Although thick (t/c > 14%) airfoils generally offer gentle stall characteristics, their separation regions become extensive and troublesome sooner than somewhat thinner airfoils (See Fig 1.4, below.) Because of this increase in separation resulting from the greater changes in geometry/curvature, the drag of these airfoils is increased. By keeping the BL from separating with proper VG placement, the maximum lift (and possibly the stall angle of attack) can be increased. This would prove extremely useful at landing, where a greater \( C_{L_{\text{max}}} \) would translate to a slower landing speed. The secondary reason behind selecting the Cherokee wing for
these tests was the potential for a full-scale test/confirmation of the experimentally
optimized VG configuration. The author’s thesis advisor was the owner of a 1969 Piper
Cherokee 140 and offered to test the optimum VG configuration on his aircraft. This
would help correlate the 1/4-scale results with those when the same VG set-up is placed
on the full-scale aircraft, validating or invalidating the optimum VG design for the actual
aircraft. Unfortunately, the Cherokee was sold prior to completion of this experiment
and was not available for the full-scale test. Therefore, all results will be for the 1/4-
scale wing only.

Although desirable, the Reynold’s numbers of the full-scale wing could not be
duplicated for this experiment. The test velocity was approximately 85 ft/sec, which
translates into a chord Re of $7.2 \times 10^5$ for the 1/4-scale model. The landing speed of the
full-scale Cherokee is approximately 100 ft/sec, translating to a Re of $2.8 \times 10^6$ (roughly 4
times that of the model). The test velocity was kept at 85 ft/sec to avoid over-stressing
the force balance with the 35-50+ pounds of lift generated by this relatively large model.
The scale of the model was also dictated by the capacity of the test facility. Reference 12
specifies that a wind tunnel model should be no greater than 80% of the tunnel test
section width (to avoid interference with the tunnel walls' BL, etc.) This limited the size
of the model to slightly larger than 1/4-scale, but to keep the numbers neat, the model
was made 1/4-scale

The VG’s selected for this experiment were the flat plate vane type (shown in Fig 1.5,
below) This selection was based on the manufacturability of the VG’s All VG’s were to
be produced by the author, so repeatability in size/shape of the flat plate vane type VG’s
was the most likely of all potential VG shapes (wedges, wishbones, etc.) Each VG had a
chord of 1/4”, a value roughly 1/4 of those VG’s used on full-scale aircraft They were
constructed of aluminum sheet, ranging in height from 0.05” to 0.2” The smallest of
these was also limited by manufacturability This range of VG heights would give a good
range of \( (h_{v_c}/\delta) \)-values to help determine how tall—relative to the local boundary layer
thickness (\( \delta \))—a VG should be Three planforms (see Fig 1.6, below) were also tested to
determine if taper has a noticeable effect on VG performance Non-geometric factors
were also varied to determine their influence on VG performance. These included VG angle of incidence relative to the freestream, spanwise row density, chordwise row location, quantity, and interaction, and placement of VG's in a co-rotating or counter-rotating manner.

The test schedule was set up in a manner that could potentially eliminate some of the variables early-on. The basic test procedure is shown in Fig 17, below.

Prior to testing the various VG configurations, a baseline set of curves for the ‘clean’ (standard roughness applied) wing was established from the average of 2 runs. The lift and drag curves (which prove most useful in this study) are presented in Figures 18 and 19 below. These were used for comparison with all VG tests to determine if improvements were made with each VG configuration.
Lift Coefficient vs. Angle of Attack
'Clean Wing' (Standard Roughness Applied)

Drag Coefficient vs. Angle of Attack
'Clean Wing' (Standard Roughness Applied)

Figure 18: ‘Clean’ wing CL vs. α

Figure 19: ‘Clean’ wing CD vs. α
2. BACKGROUND THEORY

2.1 Separation and Its Progression Toward Stall

The phenomenon of stall has been studied since the dawn of flight, so the concept behind it is no mystery. When a wing’s overall lift force is no longer great enough to support the wing (and the body it is attached to), gravity wins out and an aircraft descends—stall. Delaying stall is a topic of concern and experiment, and for good reason. A pilot would much prefer that his aircraft be able to achieve as much lift as possible.

In order to understand stall, one must be familiar with boundary layers and their formation/progression on a surface. Air, like every real fluid, has a finite viscosity. Due to this viscosity, there is a frictional (shear) force generated as it flows over a surface. Because of this shear force, the velocity near the surface is reduced. This region of slowed flow is known as a boundary layer. The velocity profile within the boundary layer increases from zero at the surface (where the shearing forces are greatest) to freestream velocity at the edge of the boundary layer, as can be seen in Figure 2.1, below.

Figure 2.1 A typical velocity profile within a boundary layer
The height above the surface where the velocity reaches that of the freestream denotes the boundary layer thickness, $\delta$.

The thickness of the boundary layer depends on two things: the Reynold’s number ($Re$) and the nature of the boundary layer. The characteristic length used to calculate $Re$ is the distance from the point where the BL began to grow to some point in question. Therefore, the farther back on a surface, the thicker the BL. Boundary layers can be classified in 3 ways: laminar, turbulent, or in transition. How thick a BL is depends on its classification (nature)

As the name suggests, the streamlines within a laminar BL are stacked upon each other as lamina (lines). The orderly flow within this type of BL, however, does not allow for substantial mixing of the high-velocity flow at the edge of the BL with the low-velocity flow near the surface. Mixing between layers within laminar BL’s is mostly on a microscopic eddy level. This low-momentum flow near the surface is not very capable of remaining attached to the surface of a body once the pressure gradient changes from favorable to adverse. For a given characteristic length and Reynold’s number, laminar BL’s are the thinnest. Reference 12 gives the theoretical calculation for laminar BL thickness:

$$\delta_{(\text{lam})}=(5.2)(x)/((Re)^{0.5})$$

Due to their thinness and relatively low drag, laminar boundary layers are preferable.

Turbulent boundary layers, although not as thin as their laminar counterparts for a given Re and producing more skin friction drag (due to the higher velocity gradient at the surface), do have their benefits. Eddies present in this type of BL allow for better mixing
between layers within the BL, adding energy to the flow near the surface. Because of this re-energized surface flow, a turbulent BL tends to remain attached to the surface better in adverse pressure gradient regions. Allowing the flow to remain attached reduces the size of a body’s separated wake, thereby reducing the body’s pressure drag. A turbulent BL’s theoretical thickness is also given by Reference 12:

$$\delta_{\text{urb}} = (0.37)(x)/((Re)^{0.2})$$

Notice that for a given x-distance along a surface at a given Re, a turbulent BL is substantially thicker.

When a boundary layer is no longer laminar but not yet fully turbulent, it is referred to as in transition. Because this type of BL occurs between the two above-mentioned BL’s, it exhibits characteristics of both laminar and turbulent BL’s. The extent of a transition region on a surface is dependent on many factors (i.e., pressure gradient, suction, Mach number, and heat transfer). It is much preferred to keep the BL thickness as small as possible to keep its drag penalty (which is caused by 2 things: a loss of the flow’s momentum due to the resistive forces at the surface, and the fact that the boundary layer “thickens” the body it is attached to, essentially making it appear more blunt to the flow) to a minimum.
Separation of a BL occurs when the low energy flow at the surface cannot overcome the resistive shear forces. Technically, it is where the shear stress at the wall is equal to zero:

$$\tau(y=0) = (\mu)\left(\frac{\partial u}{\partial y}\right)_{y=0} = 0$$

At the separation point, so much of the flow within the BL has been slowed to the point where the velocity gradient near the wall becomes zero (leading to a shear stress of zero), and any further slowing would actually reverse the flow near the wall. The streamlines in the freestream flow can no longer follow the shape of the body because the BL has ceased to follow the body. The flow continues to move aft, but since separation has occurred, it is not able to rejoin the flow passing under the airfoil. This large loss of flow momentum is commonly referred to as a separated wake.

When a boundary layer encounters a favorable pressure gradient ($p_x$ decreasing) such as that on the fore portion of an airfoil, there is essentially no concern for separation. This is due to the acceleration of the main body of the flow, which in turn adds energy to the slower moving air within the BL. This higher energy will help an otherwise low
energy laminar BL persist along the chord. The additional energy is greatly reduced within the adverse pressure gradient region (p\textsubscript{s} increasing), where the flow is decelerating. A laminar BL encountering such conditions will not be capable of remaining attached for any significant distance. Therefore, assuring that the BL is turbulent before it encounters an adverse pressure gradient is certainly beneficial in an effort to prevent or delay separation.

On most airfoils, the boundary layer remains laminar for a relatively short distance relative to the chord length. Most types of surface roughness (such as insects and other debris) will affect the boundary layer by generating eddies that allow better mixing between layers. This is how a turbulent boundary layer is initiated. At the Reynold’s numbers typically seen by aircraft, the greater portion of attached BL on an airfoil surface is turbulent.

This is generally not true for lower Re-values, such as those seen by scaled wind tunnel models. In order to assure similar flow over a model as is seen by its full-scale counterpart, transition of the BL should occur at the same (x/c)-location. This is done by placing a BL trip at the desired location. Trips will initiate the eddies that will promote a turbulent BL to form. Commonly used methods for inducing transition include jagged tape, thread or wire, and grit.

On relatively thick airfoils (like that employed by the Cherokee wing) at low angles of attack, separation typically occurs near or at the trailing edge. The separation region in such conditions is relatively small and has minimal effect on the performance of a wing, as the majority of lift is generated by the upstream portion of the wing.
noted, however, that once flaps are added to a wing, attention should be paid to assuring
that the flow over the control surfaces is not substantially separated, for obvious reasons.)
As angle of attack increases, the separation region grows and moves toward the leading
edge. Typically, when this separation region has moved to 30-35%c, the wing has
reached its maximum lift production capability. Any further increase in the size of the
separation region will result in a degradation of lift.

Flow visualization is commonly used to inspect the progression of separation on the
surface of a wing. Smoke tunnels give a good idea of the flow patterns over/around a
surface, but separate models are typically needed for smoke tunnel use, as the test section
of most smoke tunnels is significantly smaller than that of a wind tunnel. Attaching yarn
tufts to the surface of a wind tunnel model performs essentially the same function. When
the BL is attached, the yarn tufts can be seen to blow straight back toward the trailing
edge. Very little movement is noticed in the tufts when the flow follows the curvature of
the surface. When separation of the BL is present, the yarn tufts can be seen to “dance,”
moving in every direction, which is quite representative of wake flow. Observing where
this separation region occurs and how it progresses chordwise and spanwise on a wing as
angle of attack changes will suggest areas for improvement on the wing surface.

The 1/4-scale Piper Cherokee wing used for this test was tufted to determine the
location/progression of the separation region. This was done in an effort to determine the
location(s) on the wing where vortex generators would prove most useful, and to avoid
placing them in regions where the flow did not need assistance. It was anticipated that
the root of the wing at the fuselage plate would exhibit a relatively large separation.
region, as is typical of any low- or mid-wing aircraft (where the interference between the wing and the fuselage retards the flow over the inboard portion of the wing). This, however, was not the case. The flow at the endplate used to simulate the fuselage was attached and showed little signs of separation at nearly all tested angles of attack. It is suspected that this was due to the lack of a propeller upstream of the wing/fuselage. The vertical components within the propwash might very well act to increase the effective angle of attack of the wing at the root, adding to the interference problem here. When the propeller is removed, this AOA increase is not present. The interference still plays a part at the fuselage, but the Cherokee wing is fortunate enough to sport an inboard leading edge extension. Such devices generate a vortex motion in the flow, assisting it in remaining attached in adverse conditions. The propeller effects may minimalize the effects of the LEX, but the propeller-less 1/4-scale model is capable of benefiting from the wing modification. A yarn tuft test was performed on a full-scale Cherokee wing, but the tufts were not placed close enough to the fuselage to observe if the flow was separated there or not. A depiction of the progression of the separation region on the full-scale Cherokee wing is shown in Figure 2.4, below.

It was also anticipated that the tuft tests would show a progression of the separation region from the trailing edge to the leading edge. This was observed to be the case (as can be seen in Fig.2.3, below). The stall pattern of the tufted model progressed in a very similar manner as that of the full-scale, validating the quality of the wind tunnel model.
Angle of Attack = 0 degrees

No separation.

Figure 2.3  Separation Progression on the 1/4-Scale Piper Cherokee Wing

Angle of Attack = 6 degrees

Angle of Attack = 7 degrees

Angle of Attack = 8 degrees

Angle of Attack = 9 degrees

Angle of Attack = 10 degrees

Figure 2.4  Separation Progression on the Full-Scale Piper Cherokee Wing

Angle of Attack = 4 degrees

Angle of Attack = 9 degrees

Angle of Attack = 11 degrees
2.2 Standard Roughness--Its Need and Its Placement

One of the standard problems encountered when scaling a wing concerns the location of boundary layer transition from laminar to turbulent. The transition Reynold's number for a flat plate has been determined by theoretical methods and verified by experimentation to be approximately 500,000. Due to an airfoil's small thickness relative to its chord length, convention has been to approximate the airfoil by a flat plate. Therefore, an airfoil's transition Reynold's number is considered to be around 500,000\(^{14}\). This leads to the following relationship:

\[
5 \times 10^5 = \rho V x_{\text{transition}}/\mu
\]

OR

\[
x_{\text{transition}} = (5 \times 10^5) \mu/\rho
\]

Keeping this--along with the definition of Reynold's number--in mind, it is obvious that as freestream velocity decreases, the x-location of transition (\(x_{\text{transition}}\)) must increase. If a wind tunnel cannot match the velocities of a full-scale aircraft, the location will be further aft on the scaled model. Even if a wind tunnel has the capacity to replicate full-scale velocity (which would produce identical values of \(x_{\text{transition}}\) for both the full-scale and reduced-scale wings), the location of transition relative to the chord length would not be the same. This can be seen below.
When considering the full-scale Piper Cherokee under landing conditions, without flaps ($V_{\text{free-stream}} = 55 \text{ kts} = 102 \text{ feet/second}$), its wing would experience transition approximately 9.2 inches from the leading edge (where $(x/c) = 0.15$). The 1/4-scale Cherokee wing at the same velocity, however, will experience transition roughly 10.14 inches from the leading edge, corresponding to a value for $(x/c)$ of 0.64. Any devices (such as vortex generators) placed between these $(x/c)$-locations on both the full-scale and 1/4-scale wings would not encounter the same type of boundary layer flow.

To remedy this, standard roughness is applied to both the upper and lower surfaces of the scaled model to induce transition at the same $(x/c)$-location as naturally occurs on the full-scale wing. Standard roughness is comprised of a narrow band (1/8 to 1/4 inch in width) of grit spanwise near the leading edge. The grit acts as a trip, forcing the boundary layer to transition. Based on the 500,000 conventional transition Reynolds's number, the full-scale Cherokee wing transition locations are calculated to be:

**Take-Off:** $x_t = 9.27 \text{ in}; \ (x_t/c) = 0.154$

**Landing:** $x_t = 9.22 \text{ in}; \ (x_t/c) = 0.146$

(Note: The $x_t$-values are given as distances from the leading edge.)

Using the same relationship, the 1/4-scale values can also be calculated:
Take-Off: \( x_{tr} = 9.27 \text{ in}; (x_{tr}/c) = 0.588 \)

Landing: \( x_{tr} = 9.22 \text{ in}; (x_{tr}/c) = 0.585 \)

Since the boundary layer should transition at the same \((x/c)\)-location for both the full-scale and 1/4-scale wings, grit will be employed to initiate transition sooner on the scaled wing. The grit for this experiment will be placed at approximately 15% of the 1/4-scale chord, as this is a good compromise between the full-scale take-off and landing \((x_{tr}/c)\)-values.

According to NASA and Grumman\(^6\), the maximum grit size is defined by the laminar boundary layer thickness of the scaled model. For the 1/4-scale Cherokee wing with grit at 15% chord, the laminar boundary layer thickness is found using the equation presented in Reference 12:

\[
\delta_{\text{laminar}} = (5.2)(L)/(Re^{0.5})
\]

\[
\delta_{\text{laminar}} = (5.2)(15.75\times0.15)/((1E6)^{0.5})
\]

\[
\delta_{\text{laminar}} = 0.012 \text{ inches}
\]

The minimum grit size is defined by the grit height that yields a Reynolds’s number of 600.

\[
600 = (\rho)(V_{\text{freestream}})(L)/(\mu)
\]

\[
L = (600)(\mu)/(\rho *V_{\text{freestream}})
\]

\[
L = (600)(3.746E-7)/(2 378E-3*94*1.1)
\]

\[
L = 0.01 \text{ inches}
\]

So, to assure transition without incurring a grit drag penalty, the nominal grit size used for the Cherokee model should be between 0.01 in and 0.012 in. Based on Table
21, below, this essentially corresponds with a commercial grit number of 60 (It should be noted that Abbott and von Doenhoff (Reference 1) used #60 grit for the standard roughness on their models tested in Theory of Wing Sections as well) The fact that

### Table 2.1 Commercial Grit Numbers for Various Nominal Grit Sizes

<table>
<thead>
<tr>
<th>Grit Number</th>
<th>Nominal Grit Size (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.0937</td>
</tr>
<tr>
<td>12</td>
<td>0.0787</td>
</tr>
<tr>
<td>14</td>
<td>0.0661</td>
</tr>
<tr>
<td>16</td>
<td>0.0555</td>
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<td>20</td>
<td>0.0469</td>
</tr>
<tr>
<td>24</td>
<td>0.0331</td>
</tr>
<tr>
<td>30</td>
<td>0.0280</td>
</tr>
<tr>
<td>36</td>
<td>0.0232</td>
</tr>
<tr>
<td>46</td>
<td>0.0165</td>
</tr>
<tr>
<td>54</td>
<td>0.0138</td>
</tr>
<tr>
<td>60</td>
<td>0.0117</td>
</tr>
<tr>
<td>70</td>
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</tr>
<tr>
<td>80</td>
<td>0.0083</td>
</tr>
<tr>
<td>90</td>
<td>0.0070</td>
</tr>
<tr>
<td>100</td>
<td>0.0059</td>
</tr>
<tr>
<td>120</td>
<td>0.0049</td>
</tr>
<tr>
<td>150</td>
<td>0.0041</td>
</tr>
<tr>
<td>180</td>
<td>0.0035</td>
</tr>
<tr>
<td>220</td>
<td>0.0029</td>
</tr>
</tbody>
</table>

#60 grit is slightly larger in diameter than the maximum grit size calculated may result in a small amount of grit-induced drag. It is likely, however, that the small difference between ideal and what will be used for this experiment will not affect overall drag in an appreciable manner.

In addition to adding standard roughness to the wind tunnel model, #60 grit was also added to the 2-D and 3-D smoke tunnel models. This was done to replicate the type of boundary layer flow seen by the wind tunnel model in the smoke tunnels.

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3. VORTEX GENERATOR METHODOLOGY AND PREDICTION OF PERFORMANCE

3.1 How VG’s Work

The main purpose of attaching a vortex generator (VG) to a surface is to aid in the mixing process between layers within the boundary layer. By creating a vortex to do so, the low-velocity layers near the surface are given additional momentum to help resist the shear forces predominant there (that work to separate the BL). The delay in separation allows a wing to obtain significantly higher lift coefficients at a given velocity, something especially useful for aircraft at take-off and landing.

A vane-type VG (the type used for this optimization study) acts in a manner not unlike that of a wing. In fact, they visually resemble a wing (see Fig 3.1, below)

![Vortex Generator Diagram]

Figure 3.1 Vane type vortex generators

The cross-section of this type of VG can be a flat plate, a curved flat plate, or a cambered airfoil. Obviously, the cambered airfoil vane-type VG’s will perform best for a given VG incidence angle. However, the flat plate VG’s are much easier (and, therefore, cost-effective) to manufacture, something that often tends to outweigh the small performance increase of the more elaborate types. As the incidence angle of the VG is increased (up to stall), the lift generated by these VG’s will increase. Based on the Kutta-Jukowsky theorem.
as the lift increases, so does the circulation ($\Gamma$). This circulation "spills" off the edge of the VG as a tip vortex. The more lift generated by a VG, the stronger the VG's tip vortex. Therefore, placing VG's at or near their stall angle of attack will generate the strongest vortex. However, drag penalties due to VG placement must be considered. The greater the amount of VG frontal area, the higher its drag. The optimal VG incidence angle would be that which demonstrates the greatest amount of lift added to a body with the lowest drag penalty. Vortex generator incidence angles previously tested for vane-type VG's range from 14 degrees up to 22.5 degrees, with the flat plate VG's dominating the high end of this range (as would be expected).

Other types of VG's act in a slightly different manner. Wedges (also referred to as ramps), wishbones, and other similar shapes force the flow upward, away from the surface of the body. As the flow passes over these VG's, some of it "spills" over the sides, creating a pair of counter-rotating vortices. Location of each vortex in a pair relative to the other is crucial. Improper placement of counter-rotating vortices could result in a cancellation of their lift benefit (leaving only their drag penalty), if not a destruction of flow over the area of the wing surrounding the VG.

When a vortex is generated, the local flow is accelerated. This higher-velocity flow is enabled to remain attached to the surface further along the chord. It is speculated that
this may be due, in part, to the Coanda effect, which explains why a body of higher-velocity flow (a jet) can follow a curvature approaching 90 degrees. This is due to the shear layer between the jet and the ambient body of air acting to entrain flow from outside the jet. When the shear layer is located near a surface, there is little or no ambient air to acquire. The result is a “suction” force acting on the jet, forcing it to follow the curvature of the surface. Since a vortex is a region of accelerated air,
3.2 Vortex Generator Design Criteria

There are many parameters to consider when designing or selecting a VG for a particular application. What type? How large? How many? Where should they be located? Should they generate co- or counter-rotating vortices?

Since all VG's essentially serve the same purpose, it is often the application for which VG's will be used which dictates what style of VG is chosen. If a quick, inexpensive solution is desirable, a vane type VG might be best. If cost and ease of manufacture are not of any real concern, a more elaborate type of VG may be chosen, such as a wishbone. If a small amount of additional drag at cruise is deemed unacceptable, a pneumatically deployed "pop-up" VG is an option, as it can be retracted when the benefits of a VG are unnecessary.

Once the style has been selected, the extent and location of the separation region should be determined (Placing VG’s in a region of attached flow could potentially degrade the original flow quality.) This can be done with yarn tuft or smoke tunnel flow visualization tests. The size of the separation region will help determine the number of VG’s needed. The location of the separation region along the chord will give an idea of how tall a VG is required to be effective. This is a step in the VG configuration design process that should not be ignored. Not knowing where problem areas are will almost always lead to insufficient, ineffective, or inefficient VG placement.

Being familiar with separation progression on a surface will give an idea of the (y/b)- and (x/c)-locations that might benefit from VG’s. The (x/c)-locations can be used to calculate the theoretical BL thickness (δ) where the VG’s will be placed. This gives an
idea of how high the VG's should be. Researchers praise both micro- \( h_{vg} = \text{approx. } (0.5)(\delta) \) and standard \( h_{vg} = \text{approx. } (1+)(\delta) \) VG's. Micro-VG's are significantly submerged within the BL, minimizing their drag penalty. Unfortunately, these short VG's may not generate vortices significant enough to enable ample mixing. This is where the benefit of standard VG's comes in. Since the vortex cores of the vortices generated by these VG's (which are at least as tall as the BL) are at or above the BL edge, significant amounts of high-energy freestream flow are drawn into the surface layers of the BL. These taller VG's do, generally, have higher drag. Again, the cost must be weighed against the benefits in selecting a VG size.

Another factor of concern is the option of generating co- or counter-rotating vortices. Previous testing has shown both to be beneficial. Reference 11, for example, found that counter-rotating VG configurations in a conical diffuser did not perform as well as co-rotating configurations. It was pointed out, however, that the tests performed were not enough to make generalizations about counter- vs. co-rotating VG's. Proper spacing of the counter-rotating configurations has been shown to be much more crucial than for co-rotating set-ups. Those VG's that singly generate a pair of counter-rotating vortices must be properly designed to assure that the vortex spacing issue (both between the 2 vortices generated by a lone VG and between the vortices generated by adjacent VG's) is not a problem. On the other hand, VG's that generate single vortices only require attention be paid to the spacing between VG's.
3.3 Selection of VG’s to Test--An Explanation

Initially, the author wished to perform this optimization study using multiple types of vortex generators. The manufacture of both wedge and wishbone type VG’s prove to be more difficult than anticipated. The size of the VG’s required for the 1/4-scale wing voided the idea of cutting them by hand from stock materials. Paraffin wax molds were also made in hopes that cast epoxy could be used to manufacture the VG’s. Unfortunately, the surfaces of the VG’s came out of the molds lacking smoothness; and hand sanding became far too tedious. One type of VG remained feasible for manufacture by hand--the vane type VG.

The style of vane type VG chosen for this experiment was also a decision based on manufacturability. An extruded airfoil cross-section was not a cost-effective option. The cambered flat plate was considered; but consistency in the amount of curvature added to every VG (including those less than 1/10” high) was a concern. This eliminated the cambered flat plate as an option, leaving only the flat plate. This option, fortunately, would also be the easiest to set at repeatable VG incidence angles, making the entire testing process more convenient.

Since leading edge extensions (when used) create a vortex in addition to that at the tip, this experimenter decided to taper the leading edge of some of the VG’s to observe if this aided in their effectiveness in much the same manner. Three VG planforms were chosen: 1) rectangular (no taper), 2) 30° of leading edge sweep, and 3) 45° of leading edge sweep (see Fig.1.6, p.10). It was observed whether or not the VG performance was enhanced due to this aspect of the design.
The chord of the VG's to be tested here was held constant at 0.25". This allowed the root chord to remain the same for all 3 levels of taper discussed above, whereby eliminating root chord as a potential variable in the optimization process. This VG chord also allowed a greater number of chordwise rows to be tested. Finally, a VG base of this size could be firmly attached with essentially no discontinuity, regardless of the gentle curvature of the wing surface. The incidence angle of the VG's with respect to the freestream was not established initially. Rather, a range of $\alpha_{(\text{VG})}$-values was tested to find the one that proved most effective. Vane type VG tests have mostly been performed using fixed $\alpha_{(\text{VG})}$-values. It was hoped that this experiment would provide information regarding the optimal $\alpha_{(\text{VG})}$ for the flat plate, vane type VG.

The height of a VG is perhaps the single greatest variable in the equation. It was possible to construct vane type VG's as small as 0.05" in height. Shorter VG's posed a construction problem and were excluded from testing. This experiment tested VG heights of 0.05", 0.1", and 0.2" at various $(x/c)$-locations. The optimal VG height relative to the local boundary layer thickness was then determined.

Also a factor in the optimization was the VG spacing, both chordwise and spanwise. Various spanwise and chordwise densities were tested to determine the most effective configuration.

And, finally, the placement of the VG's in both co- and counter-rotating arrangements for this experiment determined if one was better than the other. A test was also run using a pair of VG's as a "single unit" (with their bases touching) to find if close-proximity counter-rotating VG pairs proved more or less effective.
3.4 Prediction of Performance

Based on the previously stated set of test conditions/set-ups, as well as findings from other VG research experiments, the experimenter predicts the following:

1) **VG Taper**: Considering that increasing a wing’s planform area increases its lift produced, a VG with a greater planform will produce more lift and therefore a stronger tip vortex. This, alone, would suggest that the rectangular planform VG should give the best results, followed by the 30° swept VG, and finally the 45° swept LE VG. However, if a vortex is generated around the swept LE, this could enhance the less significant tip vortices of the swept VG’s. Based on this inclination, it is predicted that all 3 VG tapers will perform essentially the same, with the swept VG’s deriving a performance enhancement from their angled LE’s.

2) **VG Angle of Incidence**: As with any airfoil or wing, the VG’s tested in this experiment will have an optimum incidence angle at which lift (and the tip vortex that results from it) is most substantial, an $\alpha_{\text{VG, stall}}$. Reference 16 provides the following $C_L$ vs. $\alpha$ graph for a symmetric airfoil:

![Figure 3.4: Increase in $\alpha_{\text{stall}}$ with change in Re for a NACA 0015 airfoil](image)

Figure 3.4: Increase in $\alpha_{\text{stall}}$ with change in Re for a NACA 0015 airfoil$^{16}$
Since this airfoil is symmetric, this data was used as an analogy for the flat plate (symmetric) VG’s. The lowest Re listed of 42,900 is still significantly greater than that seen by the 0.25” chord VG’s used for this experiment, which have a Re of approximately 1.07x10^4. A relationship between the change in C_{L_{\text{max}}} and change in Re for each set of conditions can be established:

\[
\frac{\%\Delta \text{Re}}{\%\Delta C_{L_{\text{max}}}} \text{from } \text{Re}=3.3 \times 10^4 \text{ to } \text{Re}=4.1 \times 10^4 = \frac{\%\Delta \text{Re}}{\%\Delta C_{L_{\text{max}}}} \text{from } \text{Re}=4.1 \times 10^4 \text{ to } \text{Re}=1.07 \times 10^5
\]

\[
87\% / 15\% = 75\% / \% C_{L_{\text{max}}} \text{ from } \text{Re}=4.1 \times 10^4 \text{ to } \text{Re}=1.07 \times 10^5
\]

\[
\% \Delta C_{L_{\text{max}}} \text{ from } \text{Re}=4.1 \times 10^4 \text{ to } \text{Re}=1.07 \times 10^5 = 12.93\%
\]

And the C_{L_{\text{max}}} for the VG’s can be estimated.

\[
C_{L_{\text{max}}}, \text{Re}=1.07 \times 10^5 = C_{L_{\text{max}}}, \text{Re}=4.1 \times 10^4 \times (0.1293) C_{L_{\text{max}}}, \text{Re}=4.1 \times 10^4
\]

\[
C_{L_{\text{max}}}, \text{Re}=1.07 \times 10^5 = (0.85) - (0.1293)(0.85)
\]

\[
C_{L_{\text{max}}}, \text{Re}=1.07 \times 10^5 = 0.74
\]

Now that the change in Re has been accounted for, so must the change in aspect ratio (AR) from AR = inf. (airfoil) to the low AR-values of each VG, listed below.

\[
\text{AR} = \frac{b^2}{S}
\]

For the rectangular planform VG’s
- For h_{VG} = 0.05”, AR = 0.2
- For h_{VG} = 0.10”, AR = 0.4
- For h_{VG} = 0.20”, AR = 0.8

The relationship used to calculate the lift-curve-slope of a 3-D wing from that of an airfoil is given in Reference 16.

\[
C_{L_{\alpha}} = \frac{C_{L_{\alpha}}(\text{AR})/(\text{AR}+2)}{(0.1 \text{ per degree})(\text{AR})/(\text{AR}+2)}
\]

Using this, the lift-curve-slopes for each VG height can be found.

For h_{VG} = 0.05”, C_{L_{\alpha}} = 0.0091 per degree
For h_{VG} = 0.10”, C_{L_{\alpha}} = 0.0170 per degree
For h_{VG} = 0.20”, C_{L_{\alpha}} = 0.0290 per degree

Using these lift-curve-slopes, the known \alpha_{\text{L}} = 0 for symmetric bodies, and the C_{L_{\text{max}}}, the VG stall angles can be found.
The VG stall angles found will be those at which each VG generates the strongest tip vortex. However, the greater the $\alpha_{\text{VG, stall}}$, the more VG frontal area is exposed to the flow, which leads to greater drag. The $\alpha_{\text{VG, stall}}$ of $81.3^\circ$ for the 0.05” VG’s would be, in essence, similar to putting a perpendicular wall into the flow, which would undoubtedly create immense amounts of drag. It is doubtful that the optimal lift/tip vortex generated by the 0.05” VG’s at this angle of incidence outweighs the large drag penalty. Even the 0.1” VG at $43.5^\circ$ would produce large amounts of drag. It is thought that neither the 0.05” VG nor the 0.1” VG at their respective $\alpha_{\text{VG, stall}}$-values will provide optimal performance with minimal losses. The relatively shallow $\alpha_{\text{VG, stall}}$ of $25.5^\circ$ for the 0.2” VG’s might introduce a small enough amount of frontal area into the flow that the 0.2” VG’s will perform best at or very near their stall angle of incidence. (Although not shown here, the smaller AR of the swept LE VG’s would also lead to an increase in $\alpha_{\text{stall}}$.)

3) VG Height: Since the BL thickness has not yet been measured, this prediction will be based on calculated turbulent BL thicknesses. It is thought that each VG will work best when at least as tall as the local BL is thick. For example, at $(x/c) = 5/15.9 = 0.48$, the BL thickness should be approximately 0.195” high, making the 0.2” VG’s the best option. Predictions for all other $(x/c)$-locations are listed below.
Table 3.1: Optimal VG Height Predictions

<table>
<thead>
<tr>
<th>Inches Aft of Standard Roughness</th>
<th>(x/c)</th>
<th>Calculated Turbulent BL Thickness (in.)</th>
<th>Optimal VG Height Prediction (in )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.23</td>
<td>0.090</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>0.29</td>
<td>0.118</td>
<td>0.1 +</td>
</tr>
<tr>
<td>3</td>
<td>0.35</td>
<td>0.143</td>
<td>0.1 +</td>
</tr>
<tr>
<td>4</td>
<td>0.42</td>
<td>0.169</td>
<td>0.1 +</td>
</tr>
<tr>
<td>5</td>
<td>0.48</td>
<td>0.194</td>
<td>0.2</td>
</tr>
<tr>
<td>6</td>
<td>0.54</td>
<td>0.2205</td>
<td>0.2 +</td>
</tr>
<tr>
<td>7</td>
<td>0.60</td>
<td>0.246</td>
<td>0.2 +</td>
</tr>
</tbody>
</table>

4) VG Spacing  In past experiments, spacing of VG's--both adjacent within a row and in successive rows--has been largely arbitrary. When a configuration worked, not much was done to 'fine-tune' that configuration. This experiment hopes to determine an optimum spacing within a spanwise row and an optimum number of rows and their locations along the chord for the Cherokee wing. Should the generated vortices come too near one another, interference becomes a concern. Only equally-spaced VG configurations will be tested here, as was found to be best in past experiments. It is predicted that optimum spanwise row density will place VG's approximately every 0.88 inches, as demonstrated by Reference 3. Multiple rows may prove beneficial, provided that the succeeding VG's do not interfere with the vortices formed by preceding ones. Therefore, it may be best to stagger the rows, as suggested by Reference 15. It is also hypothesized that placing VG's of the same height in aft rows will prove optimal, as this will reduce the likelihood of vortex interference (since the ratio of the height of the VG to the BL thickness is smaller). The successive VG heights must, however, be tall enough to drawn in ample amounts of higher-energy flow.

5) Co- vs Counter-Rotating VG Arrangement  The difficulty in arranging VG's in a counter-rotating manner was discussed previously. An attempt will be made to find this optimal arrangement by varying the number of VG's within a counter-rotating row. Reference 15 discusses the likelihood of greater mixing with counter-rotating configurations. This would suggest that if this spacing is determined, the counter-rotating set-ups will provide the greatest increase in performance.
4. TEST APPARATUS AND FACILITIES

4.1 Quarter-Scale Wing Model Construction

Decades of wind tunnel research have taught experimenters about the need to replicate Reynold's number as closely as possible. Factors such as \( C_{L,\text{max}} \) and \( C_{D,\text{min}} \) have been shown to vary with increasing \( \text{Re} \)--\( C_{L,\text{max}} \) generally increases, while \( C_{D,\text{min}} \) typically decreases\(^{12}\). Two things, however, prevent many experimenters from testing at full-scale \( \text{Re} \), namely the available wind tunnel test section width and speed capability. To avoid appreciable wall interference and excessive cross-sectional blockage, common practice limits the span of a model to no more than 80% of the width of the test section\(^{12}\). This, in turn, puts a constraint on the maximum scale of the model.

The semi-span model used in this experiment was scaled with this constraint in mind (It was desirable to use the highest scale possible, as data is less translatable the further from full-scale the model is.) The subsonic wind tunnel at ERAU has a test section width of 52 inches. Using the 80% rule-of-thumb, any model should be no more than 41.6” wide. Considering that the Piper Cherokee has a semi-span of 181.8”, both the 1/2-scale and 1/3-scale options were out immediately. A 1/4-scale model of the Cherokee wing, which would have a semi-span of 45 45” (from the aircraft centerline), would be slightly larger than acceptable for the ERAU tunnel. However, the width of the fuselage at the wing (23” for the 1/4-scale aircraft) allowed for the removal of 5.75 additional inches from the span of the model. This was done so that an endplate representing the fuselage could be placed at the inboard end of the wing. This plate would help to eliminate the tip vortex that would be generated at that end of the model, a vortex not
present on the full-scale wing due to placement of the fuselage. The plate is also much more representative of the wing-fuselage junction, which is known to be a trouble spot for BL separation. If this is the case for the full-scale aircraft, it would, in turn, be replicated on the model by using the fuselage plate. Overall, with the 5+ inches removed from the model’s inboard section, the model was 39.625 inches wide, or 76% of the test section width.

Much of the preliminary research done demonstrated the need for both force measurement tests as well as those involving flow visualization. The variation in lift or drag is a crucial factor when analyzing VG performance, for obvious reasons. But flow visualization is just as important, as it provides the experimenter with an idea of how a particular VG, VG pair, or overall VG configuration interacts with the flow field. It also gives a picture of vortex size/tightness, height above a surface, and dissipation characteristics. Desiring both types of information, both quantitative and qualitative, it was decided to construct 2 types of models: 2 to be used for flow visualization and one for qualitative data from a force balance.

One of the flow visualization models was to be mounted in ERAU’s 2-D smoke tunnel. This 1/4-scale model of the outboard section of the Cherokee wing (a NACA 652-415 airfoil) was fixed between the walls of the 2-inch wide test section, making it useful only for single spanwise or multiple chordwise VG tests. The high-quality flow within this tunnel allowed for remarkable photographs of flow-object interaction, which enables both the experimenter and the reader to see what the effects of VG’s are. This model was manufactured from laminated poplar on a Komo VR408P CNC 3-axis milling
machine using tool paths generated from the solid model made in Varimetrix (a parametric, feature-based, solid modeler). This type of wood yielded a superb model, requiring only minimal sanding before priming. Once the model was deemed sufficiently smooth, black paint was applied to assist in the viewing of the white smoke lines. A 3-inch long threaded pipe was connected to one side to facilitate mounting and angle of attack adjustment. Black velveteen was adhered to both sides to assure that the model was in contact with the glass walls of the tunnel without scratching them.

The second flow visualization model (also a 1/4-scale version of the Cherokee outboard wing section) was placed in ERAU’s 3-D smoke tunnel. The 10.5-inch span of this model allowed for the interaction of adjacent VG’s to be observed. This model helped to determine whether co- or counter-rotating vortex pairs interacted more favorably, as contradicting reference information was found regarding this VG set-up. This model was manufactured in the same manner as the first from 2 lb /cu ft polystyrene (often referred to as simply ‘blue foam’). It was also filled until acceptably smooth, after which it, too, was primed and painted. A mount plate was attached to the lower surface so that the model could be attached to a previously built angle of incidence meter.

The third model was used in ERAU’s subsonic wind tunnel. It was mounted to a force balance on the lower wing surface at the mid-point of the span (to optimize available test section width, the model could not be skewed to one side) and at the chordwise CG location. Using the same modeling and manufacturing techniques as the other models, the wind tunnel model was milled from 2 sheets of laminated birch.
plywood. The upper surface was machined, then the lower surface. Both pieces were then hollowed out where feasible, leaving behind a 3/8” shell. This was done in an effort to keep the model weight to a minimum. Once manufactured, both surfaces were sanded and filled. A 4” wide piece of birch ply was shaped and placed between the 2 surfaces at the location of the mounting plate. This spanwise location would house the 6 threaded rods that would bear the loads created by the model, so reinforcement here was certainly a good idea. The upper and lower surfaces were then joined using an extra strength wood glue. Once joined, any gaps in the LE or TE were filled and sanded smooth. This was especially necessary at the TE, where the model became too thin for the milling machine to cut without tearing the wood. The rough spots in the surfaces were also filled and sanded, using a sanding template to assure that the proper contour was being maintained. A balsa wood endcap was attached to the tip, then shaped to match that one the full-scale aircraft. The wind tunnel model was then primed and painted with several thin coats of latex enamel with a gloss finish (resembling that on the real aircraft). Once the wing was finished, a 30”x14”x (3/16)” piece of birch ply was attached to represent the fuselage. This plate could be easily removed, facilitating removal and transportation of the model. Finally, mounting hardware was installed.

The standard roughness was applied to both surfaces (as per Reference 12) once the initial tests with the clean wing were performed to validate the model. The grit was adhered to the surface with extra hold hair spray, as this allows for easy removal and replacement if necessary.

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4.2 VG Construction and Placement

For ease and consistency in manufacture, the VG’s chosen for this experiment were the flat plate vane type (see Fig.1.5, p.9). They were constructed by hand of 0.0115” thick aluminum sheet. The right angle bend between the base and the portion of the VG normal to the surface was made by using a right angle metal template. For those VG’s with planforms consisting of a swept LE, the proper angle was measured, scored, and cut from the VG.

During the optimization tests, each VG was attached to the wing using double-faced tape. This method of VG installation allowed for easy adjustment and removal, yet it held the VG’s firmly enough to resist movement while the tunnel was running.

The VG angle of incidence was set using wooden angle templates. Once the $\alpha_{VG}$ was decided upon, the template was used to transfer this angle to the wing surface with a permanent marker at the appropriate (x/c) line.
4.3 Test Facilities

All tests were performed in the 36”x52” closed test section, closed-circuit, subsonic wind tunnel at ERAU (see Fig 4.1, below) The low-speed test section of the tunnel

Figure 4.1 Subsonic wind tunnel at ERAU

(used for all VG optimization tests performed for this experiment) incorporates 1/2” of wall divergence to account for the horizontal buoyancy effects that result from a growing BL. The wall divergence is appropriate for the velocity used in this experiment, as demonstrated by a measured Glauert factor of zero. The tunnel–powered by an 8-cylinder, 385-HP internal combustion engine driving a fixed-pitch, 6-bladed, 56” diameter wooden propeller--can attain low-speed test section speeds of up to 130 ft/sec. Considering that a turbulence factor (TF) of 1.4 or less classifies a tunnel of this size as ‘good,’ the ERAU tunnel’s TF of 1.3 gives the assurance of ‘good’ data.’

All forces and moments (lift, drag, side force, pitching moment, rolling moment, and yawing moment) are obtained via an Aerolab 6-component, pyramidal, load cell force balance. (The force balance’s load limits and levels of accuracy for the various forces and moments are given in the Appendix.) This information, combined with a velocity
reading (using a Pitot-static probe and a thermistor) is sampled 50 times (as a voltage signal) at a frequency of 60 Hz by a Hewlett Packard 3054C data acquisition system.

Once averaged, the voltage values are converted from analog to digital signals and sent to an IBM PS/2 computer for conversion into force and coefficient values. This is accomplished with the help of a data conversion program entitled “windt.” The test facility can be seen in Fig.4.2, below.
5. TEST PROCEDURE AND RESULTS

Prior to testing, both aerodynamic and weight tares were taken at the test velocity of 85 ft/sec (corresponding to a chord Re of $7.2 \times 10^5$—roughly 1/4 of the $2.8 \times 10^6$ Re of the full-scale wing during a flaps-up landing) and every angle of attack (-5, -3, -1, 1, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16 degrees). Tares were taken to account for any forces or moments not generated by flow over the model. Once this step was completed, the model was fixed to the force balance mounting post and both angle of attack and yaw were zeroed. (It should be noted that zero yaw was maintained throughout this experiment.)

5.1 Flow Visualization on the 1/4-Scale Wind Tunnel Model

Using a grid of approximately 2”x2”, yarn tufts were taped to the upper surface of the wing as well as the fuselage plate. A video camera was used to record the progression of separation on the wind tunnel model, which helped to determine areas that might benefit from VG’s (see Fig.2.3, page 19). The yarn tuft tests were performed at the balance data measurement velocity and incorporated all test angles of attack.

5.2 Wing Alone

The ‘clean’ (standard roughness applied) wing was first run through a series of tests to assure the quality of the model. After determining that the 1/4-scale Cherokee wing was a viable model that produced believable data, 2 runs were made incorporating all test angles of attack. These runs—producing almost identical results—were averaged to produce the baseline curves for the wing (shown in Figs.1.8 and 1.9, p.11).
5.3 VG Angle of Incidence Optimization (Phase 1)

An arbitrary location of 1” aft of the standard roughness as well as an arbitrary number of VG’s (11) was chosen to begin testing. The first phase in the series of VG tests focused on finding the optimum VG angle of attack. Several wooden angle templates were made—ranging from 10° to 30°, in 5° increments—to position the test row of VG’s. The VG’s were evenly spaced at 3” apart, set up in a co-rotating manner. The 0.2-inch high, rectangular planform VG’s were selected for the $\alpha_{\text{VG}}$ optimization, as they were distinctly taller than the local BL, whereby assuring ample mixing between BL sublayers. Each $\alpha_{\text{VG}}$ was tested for wing angles of attack of -5, -3, -1, 1, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16 degrees.

As Fig.5.3.1 shows, the $\alpha_{\text{VG}}$ of 25° yielded the most substantial gain in $C_{L_{\text{max}}}$ when compared to the ‘clean’ (standard roughness applied) wing—roughly 10.7% (consistent with the predicted optimal VG incidence angle). It should also be noted that every VG angle of incidence, except for 15°, enhanced maximum lift somewhat, demonstrating that even a less-than-optimal $\alpha_{\text{VG}}$ can improve lift performance.
When comparing the drag curves of the various $\alpha_{vg}$-values with that of the ‘clean’ wing (as shown in Fig 5.3.2, below), one notices something rather interesting. That is, the VG’s set at 25° actually reduced $C_{D_{crude}} (\alpha=3°)$ by nearly 4%. Although not a substantial decrease, this does contradict most of the ‘standard wisdom’ regarding VG’s—they only increase cruise drag. In the case of the 0.2”, rectangular planform VG’s at 25° incidence, the drag increase due to their obstruction of the flow was outweighed by the capability of their generated vortices to reduce the pressure drag of the wing. This angle
of incidence, proving superior in both lift increase and drag reduction, was carried through the remaining VG optimization tests.

![Drag Coefficient vs. Angle of Attack](image)

**Figure 5.3.2** VG Angle of Incidence Tests—$C_D$ vs $\alpha$

### 5.4 VG Style/Planform Optimization (Phase 2)

Using 11 of the 0.2" VG's (as in Phase 1) set at 25° incidence (the optimal $\alpha_{Vg}$, found in Phase 1), the 3 VG planforms were tested to determine whether or not VG LE sweep
enhances the performance of a VG configuration. Each set of VG’s was tested at 2 \( x \)-locations 1” and 3” aft of the standard roughness strip. Multiple \((x/c)\)-locations were chosen for this phase to find if one planform worked better than the others at one location but was not the optimum choice at another. As seen in Fig 5.4.1, below, the rectangular planform VG’s at 1” provided the greatest lift gain (10.71%). Incidentally, this was the

**Lift Coefficient vs. Angle of Attack**  
**VG Planform Tests**

![Graph showing lift coefficient vs. angle of attack](image)

Figure 5.4.1 VG Planform Tests--\( C_l \) vs \( \alpha \)
same set of VG’s that proved optimal in the first phase of tests. The only VG planform that degraded lift was the rectangular one when located at 3” aft of the standard roughness ($C_{L_{max}}$ was decreased by 3.82%). All other set-ups tested in this phase resulted in a $C_{L_{mix}}$ increase, with the 20° and 45° LE sweep planforms providing gains of 7.3% and 6.4%, respectively, when placed at the 3” location.

The rectangular VG’s also proved superior in $C_{D_{cruise}}$ reduction (3.97%), as shown in Fig 5 4 2, below. However, the 20° and 45° LE sweep VG’s at 3” also demonstrated cruise drag reduction—2.4% and 1.4%, respectively. The remaining 3 VG planform/x-location combinations resulted in 86-91 7% cruise drag increases. The rectangular planform VG’s at 1”, still proving superior, were carried into the next phase of testing.
5.5 VG Height Optimization (Phase 3)

Again, using the same number of VG’s used in Phase 1, tests were performed to determine the most effective VG height relative to the local BL thickness. The optimum planform from Phase 2 (rectangular—no LE sweep) was selected to continue with this series of tests. Each of the 3 VG heights (0.05”, 0.1”, and 0.2”) was located in a single row at the 1”, 3”, 5”, and 7” (aft of the standard roughness) locations for the first set of
tests in this phase. This allowed both the optimum overall VG height and corresponding \((\psi/c)\)-location and the optimum \((h_{\psi}/\delta)\) to be determined. Once the optimum \((\psi/c)\)-location was determined for each VG height, additional tests were performed with the VG’s at rows 1” forward and aft of the original optimum. This was done to fine-tune the optimum \((\psi/c)\)-location for each height.

Based on the \(C_L\) vs \(\alpha\) graph of the 0.05” VG’s (see Fig 5.5.1, below), the optimal \(x\)-location for these VG’s was 2” (aft of the standard roughness). When placed at this location.

![Lift Coefficient vs. Angle of Attack](image)

**Figure 5.5.1** VG Height Tests -- \(C_L\) vs \(\alpha\) for the 0.05” VG’s
location, a 4.2% increase in $C_{L, max}$ was the result. All other $(x/c)$-locations of this $h_{VG}$ proved detrimental to lift.

Figure 5.5.2, below, shows the effects of the 0.05” VG’s on the wing’s drag. All $x$-

![Drag Coefficient vs. Angle of Attack](image)

**Drag Coefficient vs. Angle of Attack**  
VG Height Tests--0.05" VG’s

Figure 5.5.2: VG Height Tests--$C_D$ vs. $\alpha$ for the 0.05” VG’s

locations other than 2” (aft of the standard roughness) demonstrated extreme cruise drag penalties (72.6%-80.7% increases). Unfortunately, even at the 2” location $C_{\text{crmsc}}$ increased by 12.2%. Although much smaller than the other locations, the drag penalty at this location is still significant enough to deter use of VG’s if set up in such a manner.
The 0.1” VG’s yielded somewhat similar results. As can be seen in Fig 5.5.3, below, two x-locations provided additional lift—2” and 4” aft of the standard roughness (increases in $C_{L_{\text{max}}}$ of 5% and 4.7%, respectively). All other $(x/c)$-locations proved detrimental to lift, although, as a whole, not as significantly as the 0.05” VGs. The 2 lift-enhancing locations of the 0.1” VG’s resulted in the smallest cruise drag penalties (13.2% for the 2” location and 10.4% for the 4” location), as shown in Fig 5.5.4, below.
All others resulted in more significant drag penalties, ranging from a minimum at the 1” location of 63.7% to a maximum of 68.1% at the 7” location. Although significant, these drag penalties were less than those induced by the 0.05” VG’s.

The 0.2” VG’s were found to increase $C_{L,max}$ at 5 different x-locations: 1”, 2”, 3”, 4”, and 6” aft of the standard roughness (as shown in Fig 5 5 5, below). The 1” location yielded the greatest lift increase—10.7%. The other lift-enhancing locations resulted in increases of 0.4-6.7%.

Figure 5 5 4. VG Height Tests--$C_L$ vs $\alpha$
for the 0.1” VG’s
Lift Coefficient vs. Angle of Attack
VG Height Tests--0.2" VG's

The 1" (aft of the standard roughness) location, however, was the only one that both increased $C_l_{\text{max}}$ (by 10 71%) and decreased cruise drag (by 4%), as shown in Fig 5 5 6, below. The other lift-enhancing locations for the 0.2" VG's resulted in cruise drag increases of 3-86 9%, with the smallest increase occurring at the 4" location (which also showed the second highest maximum lift increase).
Drag Coefficient vs. Angle of Attack
VG Height Tests--0.2" VG's

Figure 5.6: VG Height Tests--\(C_D\) vs \(\alpha\) for the 0.2" VG's

Figure 5.5 7, below, compares the 8 VG height/location configurations that enhance lift. The 4 greatest maximum lift increases came from the 0.2" VG’s, demonstrating their superiority in lift enhancement. Increasing lift by roughly half that of the optimal condition (0 2", rectangular planform VG’s at 1” aft of the standard roughness) were the 0.1” VG’s at 2” and 4”. The 0 5” VG’s were seen to increase lift only at one x-location 2” aft of the standard roughness.
When comparing the drag curves of the top 8 VG configurations (see Fig 5.5.8, below)—those which either reduce drag or produce the least detrimental increase in drag—it can be seen that only one configuration actually reduces cruise drag—the 0.2", rectangular planform VG’s at the 1” location. Of those VG configurations penalizing in drag, the smallest 2 penalties were also attributed to the 0.2” VG’s. Based on the data presented here, the 0.2” VG’s were the leaders in the drag category as well. Because of their superiority, these VG’s were selected for all successive optimization tests.
5.6 VG Spanwise Row Density Optimization (Phase 4)

Progressing with the optimum configuration found in Phase 3 ($\alpha_{VG} = 25^\circ$, rectangular planform, and $h_{VG} = 0.2")$, testing was done to find the VG spanwise spacing that led to optimal performance. Various numbers of VG’s within a single spanwise row were tested: 15", 7", 4", 3", and 2" (corresponding to 3, 5, 8, 11, and 16 total VG’s in a row, respectively)
The effects of the various spanwise spacings on the wing’s lift are shown in Fig 5.6.1, below. The optimum-performance number of VG’s in a row is quite clearly 11. As it turns out, the number of VG’s chosen for previous phases (11, coincidentally) is the only spanwise density that enhanced lift (by 10.7%). All other VG spacings both greater and less than 3” proved detrimental to \( C_{L_{\text{max}}} \), decreasing it by 4.8% to 8.3%.
The 3” VG spacing also demonstrated its superiority in cruise drag reduction (4%), as seen in Fig 5.6.2, below. All other spanwise VG densities increased drag (from 42.2% to 73.4%). Therefore, the 3” VG spacing proved optimal in both lift and drag.

![Drag Coefficient vs. Angle of Attack](image)

**Figure 5.6.2 VG Row Density Tests -- C_D vs ϑ**

5.7 Co- vs Counter-Rotating VG Placement (Phase 5)

The 5, 8, 11, and 16 total VG configurations (utilizing the optimum a_v, of 25° and h_{VG} of 0.2” from previous phases) were then placed in a counter-rotating manner--every other
VG producing a vortex opposite in rotation of its neighbors on either side. These were compared with the co-rotating results from Phase 4 to determine if counter-rotating configurations really are better than co-rotating if spaced properly.

For all but the 3” spacing, the counter-rotating set-ups decreased lift less than the co-rotating set-ups (as seen in Fig.5.7.1, below). The lift decrease ranged from 1% to 16.9%, with the 5 counter-rotating VG’s (7” spacing) proving the least detrimental. Oddly enough, at the 3” spacing co-rotating is clearly the best option. This could possibly be the spacing at which the interference between adjacent VG’s is least.

By looking at the effects of counter-rotating VG set-ups on drag (as shown in Fig.5.7.2, below), it can be seen that 3 of the set-ups actually reduced cruise drag—the 3” spaced, co-rotating VG’s by 4%, and the 4” and 7” spaced counter-rotating VG’s by 4.4% and 12.6%, respectively. The 7” spacing, counter-rotating set-up was actually seen to surpass the cruise drag reduction of the others threefold, proving it the far superior performer for drag reduction. Although not as beneficial in drag, the extra lift provided by the 11 co-rotating VG set-up (in addition to its drag reduction) made it the choice configuration to continue into the next series of tests.
Lift Coefficient vs. Angle of Attack
VG Co- vs. Counter-Rotating Tests

Figure 5.7.1: VG Co- vs. Counter-Rotating Tests--$C_L$ vs. $\alpha$
Also tested in this series was the 7” spacing, counter-rotating set-up with alternating 0 1” or 0 2” VG heights. It was thought that perhaps by locating the origin of adjacent vortices at different heights from the wing surface there might be more favorable interaction between adjacent vortices and possibly a performance enhancement. Finally, 16 VG’s were placed at the 1” (aft of the standard roughness) location in counter-rotating pairs (see Fig 5 7 3, below). This was done in an attempt to roughly model the VG types that each produce 2 counter-rotating vortices. This was also compared with the other 4” spacing set-ups to determine if the paired VG’s proved more effective.
Figure 5.7.3 Counter-rotating VG pairs

The effects of these configurations on lift and drag relative to their co- and counter-rotating counterparts with the same spacing are shown in Figures 5.7.4 and 5.7.5, below. Both of these additional configurations proved detrimental to both lift and drag. These configurations actually proved more degrading to lift than their co-rotating counterparts (which had greater lift penalties than the counter-rotating set-ups). The drag penalty, however, was reduced from the comparable co-rotating set-ups using these 2 additional VG configurations.
Lift Coefficient vs. Angle of Attack
VG Co- vs. Counter-Rotating Tests--Additional Runs

Figure 5.7.4 VG Co- vs Counter-Rotating Tests--$C_L$ vs $\alpha$
for 2 Additional Configurations
5.8 VG Row Quantity and Location Optimization (Phase 6)

The last step in the optimization process was to determine the optimal spacing of multiple rows of VG’s and whether or not they prove beneficial. The optimal (as determined by the previous phases of testing) 3" spacing, rectangular planform, 0 2" VG’s placed in a row at the 1" (aft of the standard roughness) location. An essentially identical second row of VG’s (using the optimal VG height for the corresponding x-
location, based on the results of Phase 3) was placed at 2", 3", and 4" aft of the standard roughness in successive runs. Unfortunately, all of these configurations caused a small degradation in $C_{L_{\text{max}}}$ (as seen in Fig 5.8.1, below), ranging from 3.7% to 4.8% (with the smallest penalty resulting from the placement of the second row at 2" aft of the standard roughness.

### Lift Coefficient vs. Angle of Attack
VG Row Quantity/Location Tests

![Graph showing Lift Coefficient vs. Angle of Attack](image)

**Figure 5.8.1** VG Row Quantity/Location Tests—CL vs $\alpha$

Not only did the placement of a second row of VG's decrease $C_{L_{\text{max}}}$, but it also increased cruise drag (as seen in Fig 5.8.2, below). The most significant penalty was a result of the second row of VG's being placed at the 2" location.
Two additional tests were run in an attempt to improve the performance of the optimal 2-row VG set-up (deemed to be the second row location of 2” aft of the standard roughness, which had the smallest lift penalty). The first test involved staggering the second row outboard by 1”. Although this configuration proved even more detrimental to lift (see Fig 5.8.1, above), it did demonstrate a reduction in $C_{D_{cru}}$ by 3.3° (see Fig 5.8.2, below). The second of these tests utilized the set-up just discussed, with one small exception—The second row of VG’s was not only staggered but also placed to

**Drag Coefficient vs. Angle of Attack**
**VG Row Quantity/Location Tests**

![Drag Coefficient vs. Angle of Attack](image)

*Figure 5.8.2 VG Row Quantity/Location Tests--$C_D$ vs $\alpha*
generate vortices opposite in rotation as the first row. This set-up increased the lift penalty slightly more than the previously discussed configuration (see Fig 5.8.1, above). However, its cruise drag reduction of 14.5% proved to be the most outstanding of all configurations tested in this experiment (see Fig 5.8.2, above).

It is realized that one of the configurations eliminated early-on in this series of tests may have performed better when changed as in successive phases. However, to complete the series of tests within a reasonable time frame, this experiment could not proceed to new phases with all variables. In general, the optimum VG configuration from an earlier phase was carried into the successive phase for further modification. Doing so, this experiment still tested over 40 VG configurations.

A compilation of all results from this experiment is presented in Table 5.1, below.
**Table 5.1 VG Optimization Test Results**

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<th>VG Row Density</th>
<th>VG Row Location(s)</th>
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<th>Sagger?</th>
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<td>25</td>
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<td>25</td>
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<td>1</td>
<td>25</td>
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<td>DECREASE</td>
<td>14.67</td>
<td>increase</td>
<td>14.54</td>
<td>increase</td>
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6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Lift Enhancement

Through the series of 41 VG configuration tests, several set-ups were found to increase maximum lift. These configurations are presented in Table 6.1, below, ranked in order of greatest lift benefit to the least. It can be seen that the configuration providing the greatest maximum lift increase, Configuration #4 (3” spacing, 0.2”, rectangular, co-rotating VG’s at 25°), also resulted in the greatest reduction in drag of all lift-enhancing configurations. The second greatest CLmax-enhancing configuration follows suit—It shows the second greatest reduction in drag of all lift-enhancing configurations. All but one of the remaining configurations working to increase lift were noted to increase the cruise drag of the wing as well, making them less-than-optimal choices for overall performance enhancement.

The optimal VG height relative to the local BL thickness (hVG/δ) for lift enhancement was determined to be 2.22. However, increases in maximum lift were noted with (hVG/δ)-values of 0.42 to 2.22. The most substantial lift increases occurred with VG’s taller than the BL, with (hVG/δ)-values ranging from 1.18 to 2.22. These findings contradict some of the previous research done in which VG’s taller than half the BL thickness are said to result in loss of lift.

Leading edge sweep was found to neither increase nor reduce the lift enhancement of the 0.2” VG’s. Although the rectangular planform VG’s did yield the highest lift gain, the lift enhancement due to swept LE VG configurations was only about 3-4% less. With
Table 6.1 Lift-Enhancing VG Configurations

<table>
<thead>
<tr>
<th>Configuration Number</th>
<th>Description</th>
<th>% Increase in $C_{L,max}$</th>
<th>% Decrease in $C_{D,unc}$</th>
<th>% Increase in $C_{D,unc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Rect. 0.2&quot;, 11 VG's a Row 1, VG AOA=25, co-rot</td>
<td>10 71</td>
<td>3 97</td>
<td>-----</td>
</tr>
<tr>
<td>8</td>
<td>20deg LE Sweep.0 2&quot;, 11 VG's a Row 3, VG AOA=25, co-rot</td>
<td>7 3</td>
<td>2 44</td>
<td>-----</td>
</tr>
<tr>
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<td>Rect. 0.2&quot;, 11 VG's a Row 4, VG AOA=25, co-rot</td>
<td>6 72</td>
<td>-----</td>
<td>8 3</td>
</tr>
<tr>
<td>22</td>
<td>Rect. 0.2&quot;, 11 VG's a Row 2, VG AOA=25, co-rot</td>
<td>6 63</td>
<td>-----</td>
<td>14 5</td>
</tr>
<tr>
<td>10</td>
<td>45deg LE Sweep.0 2&quot;, 11 VG's a Row 3, VG AOA=25, co-rot</td>
<td>6 44</td>
<td>1 45</td>
<td>-----</td>
</tr>
<tr>
<td>25</td>
<td>Rect. 0.2&quot;, 11 VG's a Row 6, VG AOA=25, co-rot</td>
<td>6 2</td>
<td>-----</td>
<td>13 16</td>
</tr>
<tr>
<td>9</td>
<td>45deg LE Sweep.0 2&quot;, 11 VG's a Row 1, VG AOA=25, co-rot</td>
<td>5 04</td>
<td>-----</td>
<td>8 762</td>
</tr>
<tr>
<td>17</td>
<td>Rect. 0.1&quot;, 11 VG's a Row 2, VG AOA=25, co-rot</td>
<td>4 95</td>
<td>-----</td>
<td>13 16</td>
</tr>
<tr>
<td>19</td>
<td>Rect. 0.1&quot;, 11 VG's a Row 4, VG AOA=25, co-rot</td>
<td>4 66</td>
<td>-----</td>
<td>10 43</td>
</tr>
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<td>4 18</td>
<td>-----</td>
<td>12 15</td>
</tr>
<tr>
<td>7</td>
<td>20deg LE Sweep.0 2&quot;, 11 VG's a Row 1, VG AOA=25, co-rot</td>
<td>2 74</td>
<td>-----</td>
<td>8 60</td>
</tr>
<tr>
<td>5</td>
<td>Rect. 0.2&quot;, 11 VG's a Row 1, VG AOA=30, co-rot</td>
<td>1 25</td>
<td>-----</td>
<td>19 07</td>
</tr>
<tr>
<td>3</td>
<td>Rect. 0.2&quot;, 11 VG's a Row 1, VG AOA=20, co-rot</td>
<td>1 2</td>
<td>-----</td>
<td>28 15</td>
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<td>1</td>
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<td>0 48</td>
<td>-----</td>
<td>34 22</td>
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<td>24</td>
<td>Rect. 0.2&quot;, 11 VG's a Row 5, VG AOA=25, co-rot</td>
<td>0 38</td>
<td>-----</td>
<td>8 688</td>
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</table>
the extensive, yet not all-inclusive tests performed here, it is not apparent that the swept LE VG’s used on many aircraft are really better.

All tested VG incidence angles but one (15°) was found to enhance lift performance, with the most substantial $C_{l,\text{max}}$ increases occurring when the VG’s were set between 20 and 30 degrees. Proving detrimental to lift were all of the counter-rotating and multiple row configurations. The proper counter-rotating configuration eluded this researcher, as it did many previous researchers. Some past experiments have shown counter-rotating configurations to be superior to co-rotating configurations; but based on this experiment’s set of data, this is not the case.

6.1.2 Drag Reduction

This experiment also found that 7 of the tested configurations reduced cruise drag (roughly half the number of set-ups that were shown to be beneficial in lift), as shown in Table 6 2, below. (The configurations are ranked in order from most substantial drag reduction to the least.) The drag-reducing configuration that proves most effective (#41) is also the one that results in the greatest lift penalty. Therefore, even though this VG configuration might be superior in drag-reducing capability, the significant lift penalty that accompanies it may very well be enough to deter aircraft owners from its use.

The least amount of drag penalty--and, sometimes even drag reduction--resulted from VG’s taller than the local BL thickness, with $(h_{VG}/\delta)$-values ranging from 1.18 to 2.22. This was the same range of $(h_{VG}/\delta)$-values that proved optimal in lift performance, suggesting that vane type VG’s should be at least as tall as the BL. Based on these
findings, the use of ‘micro’ vane type VG’s (as recommended by some researchers) would certainly not seem advisable.

Table 6.2: Drag-Reducing VG Configurations

<table>
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<tr>
<th>Configuration Number</th>
<th>Description</th>
<th>% Decrease in $C_D_{ave}$</th>
<th>% Increase in $C_L_{max}$</th>
<th>% Decrease in $C_L_{max}$</th>
</tr>
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<td>41</td>
<td>Rect 0° 2.11 VG’s a Row 1, Rect, 0° 1°, 11 VG’s a Row 3, VG AOA=25, co-rot (see row stagger 1&quot; &amp; opp rot)</td>
<td>14.54</td>
<td>-----</td>
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<td>3.97</td>
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</tr>
<tr>
<td>40</td>
<td>Rect 0° 2°,11 VG’s a Row 1, Rect, 0° 1°, 11 VG’s a Row 3, VG AOA=25, co-rot (see row 1° stagger)</td>
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<td>7.3</td>
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<tr>
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<td>1.45</td>
<td>6.44</td>
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</table>

Two of the swept LE VG configurations (the 20° and 45° LE sweep VG’s at 3° aft of the standard roughness) also worked to reduce drag, but not quite as significantly as the rectangular planform VG configurations. It is possible that since these VG’s enhanced both lift and drag performance, with a few further adjustments in configuration, they could compete with the rectangular planform VG’s.
Only one VG angle of incidence was determined to reduce cruise drag (25°). Every other $a_{VG}$ tested was seen to dramatically increase $C_{D_{cruise}}$, with the smallest drag penalty of 19.1% resulting from the 30° angle of incidence. Two of the counter-rotating configurations were seen to decrease cruise drag by 4-12.6%. Also decreasing cruise drag were the multiple row configurations incorporating the second row of 11 VG's at the 2” aft of standard roughness location staggered outboard 1” (Configuration #40) and opposite in rotation as the first row of VG’s (Configuration #41).

6.2 Comparison of Actual vs. Predicted Results

The optimal VG angle of incidence determined from those tested did prove to be essentially that predicted prior to testing--25 degrees. It should be noted that this $a_{VG}$ was found using the 0.2” rectangular planform VG’s, whose optimal $a_{VG}$ was predicted to be 25°. The shorter VG’s (and also those incorporating a swept LE) were predicted to have higher $\alpha_{stall}$-values. Since those angles were not incorporated into this experiment, the author hesitates to declare the 25° optimum angle of incidence optimal for every set of VG parameters.

As predicted, the swept LE VG’s were found to be essentially equivalent in performance enhancement to the rectangular planform VG’s. Since the swept LE VG’s were eliminated early-on in the optimization process, it would be unwise to conclude that there is no true performance difference seen by sweeping the LE of a VG.

The VG height results were found to be in both compliance with and opposition to the predictions made. At the 1” and 2” aft of standard roughness locations, the 0 1” VG’s
were predicted to demonstrate optimum performance. This, however, was not the case. It was the 0.2” VG that proved to be best at these chordwise locations. The predicted optimal VG height of 0.1” for the 3” location was confirmed through testing. The predicted $h_{VG}$ for best performance at the 4” location was 0.1”; but the optimal performer proved to be the 0.2” VG. And finally, the prediction of the 0.2” tall VG as the optimum at 5”, 6”, and 7” aft of the standard roughness turned out to be correct.

Through the series of tests performed in Phase 4, the optimal VG chordwise spacing was found to be 3” between adjacent VG’s. This was not what was predicted, which was a spacing of 0.88” In fact, the rather dramatic degradation of lift and extreme drag increase when going from 3” to 2” between adjacent VG’s resulted in spacings less than 2” being deleted from the testing process. When placing a second row of VG’s, it was found that by staggering a successive row, performance can be improved (although not without its penalty), as predicted.

And, finally, the counter-rotating configurations proved detrimental to lift. This is in contradiction with the predicted performance of counter-rotating VG’s. However, it is possible that the spacing determined here to be optimal for counter-rotating adjacent VG’s actually is far from that. Only 4 spacings were tested with the VG’s set up like this, making the likelihood of missing the optimal counter-rotating spacing a distinct possibility. It was not predicted that the counter-rotating VG set-ups would prove so beneficial in drag reduction.
6.3 Applications

The experimentally determined optimum VG configuration (a single row of 0.2”, 3” spacing, rectangular planform VG’s with $\alpha_{\text{VG}} = 25^\circ$ set up in a co-rotating manner at 1” aft of the standard roughness) was shown to enhance both lift and drag. This sort of VG set-up would undoubtedly be much appreciated by Piper Cherokee owners, for whom it was designed. Using the $C_{\text{L,\text{max}}}$ of the ‘clean’ 1/4-scale wing (1.041), the flaps-up landing speed is calculated to be approximately 110.11 ft/sec. Once the optimal VG configuration is applied, $C_{\text{L,\text{max}}}$ increases to 1.1525, leading to a reduced landing speed of about 104.65 ft/sec. This 5% landing speed reduction (which should be comparable on the full-scale aircraft) may not seem like much. But this, combined with the 1° reduction in $\alpha_{\text{stall}}$, would certainly make the landing experience less aggravating for Cherokee pilots (and more comfortable for their passengers). The 4% decrease in cruise drag also awarded by this VG configuration would improve the Cherokee’s range and cruise speed as well. The multiple benefits of the optimal VG configuration tested here would make investing in a set of VG’s an easier decision for those speculative aircraft owners.

The owner of an aircraft that had lift performance to spare (so to speak) might be willing to sacrifice 14+% of his maximum lift as a trade-off for the 14+% decrease in his aircraft’s cruise drag (which would significantly increase the range). A more highly-skilled pilot comfortable with higher-speed landings (unavoidable on some aircraft—a fighter jet, for instance) might be willing to land his personal aircraft (with flaps up) at 108 knots (provided, of course, that it is structurally acceptable to do so) instead of the usual flaps-up landing speed of 100 knots in order to get close to an extra hour or so of
flight time between refueling stops. The second greatest reduction in cruise drag (12.55%) was a result of the 7" spacing, 0.2-inch, rectangular VG’s set at an incidence of 25 degrees in a counter-rotating manner. This configuration proved less detrimental (1°) to lift than #41. Considering that the 2% smaller drag reduction is worth the almost undetectable loss in lift, this VG set-up would be an even more likely candidate for use in enhancing range.

Although this experiment only focused on the Piper Cherokee, much of the information found through this series of tests could be applicable to other aircraft, especially those using thicker airfoils for the wing. The optimum VG configuration found for the Cherokee would most likely not be the best for another aircraft, but it is speculated that something very similar might be. Now that information has been determined suggesting the proper height of VG’s relative to the BL thickness, their placement with respect to one another, how many should be used, etc., it will be easier for those wishing to implement a VG configuration on their aircraft to determine certain key parameters with minimal effort.

6.4 Recommendations

This experiment set out to optimize one configuration for the Piper Cherokee wing. Due to the elimination of certain variables early in the experimentation process, it is quite possible that the optimal configuration found here is not truly the best for this wing, but merely one optimum configuration of several. Had certain VG configuration parameters been carried through successive phases of testing, it is speculated that they
could’ve eventually been found to be superior (when set at the proper incidence angle, put in the right chordwise location, etc) In order to determine if the optimum found here is only one of several, it is recommended that more testing be done retaining the variables eliminated early in this experiment. This would certainly require a good deal of additional wind tunnel testing, but since all VG’s and models have been constructed, perhaps this might not be too monumental a task. One parameter of specific interest to the author is the VG leading edge sweep. All of the VG planforms tested proved to be beneficial in lift and drag when placed at the proper location. Although the 2 swept LE planforms did not perform as well as the rectangular one, it is thought that were they set at a more appropriate incidence angle or chordwise location, perhaps their performance would eventually surpass the rectangular planform VG’s.

It is also recommended that more VG heights be tested to determine several things. Would VG’s even taller than those 0.2” high prove even more beneficial in lift enhancement and drag reduction? If so, at what height does the drag penalty of the VG’s become too overwhelming to consider their use? Would VG’s taller than the 0.1” ones but shorter than those measuring 0.2” prove more effective at certain locations? By constructing a few more sets of VG’s at such heights, these questions can be answered.

To better predict the necessary VG height as a variable of the local BL thickness, it is recommended that the BL thickness actually be measured at several locations along the chord and span of the model using either a traversing probe mechanism or BL mouse. This method will yield more accurate δ-values than those calculated theoretically, as the calculations give BL thicknesses for a flat plate. It is true that an airfoil is often modeled
by a flat plate (for simplicity), but in doing so, some accuracy is sacrificed. This reduction in accuracy in calculated BL thickness (not typically substantial, but still present) will carry into the predicted \( (h_{VG}/\delta) \) value, making it less accurate than it could potentially be.

It is suggested that the chordlength of the VG's be a variable in the next stage of optimization tests. Based on the research done prior to experimentation, the VG chordlengths tested previously have, for the most part, been sized in a relatively arbitrary manner. Testing to determine the optimum value of this variable might yield an even more impressive VG configuration.

Testing a finer scale of chordwise locations (not only 1” variations) would also be advisable. This would lead to more accurate predictions of beneficial \( (h_{VG}/d) \)-values.

The spanwise spacings tested could also use some broadening. The spacing of VG's in kits offered by Boundary Layer Research (a company offering performance modifications) is mentioned on the company's web page. Their kits typically place about 90 VG's in a spanwise row on the wing. Taking the width of the fuselage into consideration, this results in an evenly spaced VG configuration of one VG every 3.53 inches. Translating this to 1/4-scale, this would mean placing VG's every 0.88 inches. The trend found in this experiment would lead one to believe that a spacing less than 2' would prove less than beneficial. In an effort to support or denounce the 0.88” spacing, it is advised that a test be performed under these conditions at varying x-locations and VG heights.
And, finally, it is recommended that tests be performed on a flapped wing model. To keep the magnitude of this optimization study under control, only flaps-up tests were performed. This, of course, is not typical of an aircraft at landing. Extending this series of tests to include flap/aileron deflections would determine if VG performance enhancement is affected by the use of control surfaces.
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APPENDIX
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<thead>
<tr>
<th>PARAMETER</th>
<th>LOAD LIMIT</th>
<th>ACCURACY</th>
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