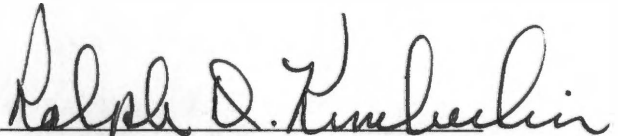
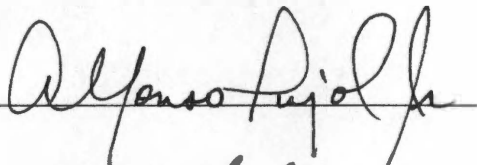


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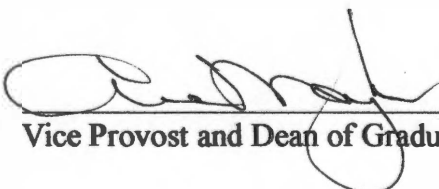
I am submitting herewith a thesis written by Bryan Lloyd Bingham entitled "The Investigation of the Performance Benefits of Half Delta Strakes Mounted On a Piper Navajo". I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.


Dr. Ralph Kimberlin, Major Professor

We have read this thesis and
recommend its acceptance:




Accepted for the Council:


Vice Provost and Dean of Graduate Studies

**THE INVESTIGATION OF THE PERFORMANCE BENEFITS OF
HALF DELTA STRAKES MOUNTED ON A PIPER NAVAJO**

A Thesis

**Presented for the
Masters of Science**

Degree

The University of Tennessee, Knoxville

Bryan Lloyd Bingham

May 2002

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2002
.B56

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Dedicated to My Parents Lloyd and Leslie Bingham

Thank You!

ACKNOWLEDGMENTS

I would like to first thank my parents Lloyd and Leslie Bingham for giving me the opportunities, support, and unequalled encouragement I have needed to make it this far. I would like to thank my father for his engineering expertise throughout my life and my mother for supporting my endeavors every step of the way. It is true that “no one loves you like your parents”. I would also like to thank my sister Joy Bingham for her support along the way. A big thanks is due to Miss Joann Lawson for all of her support and encouragement while I was writing this thesis.

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ABSTRACT

Numerous individuals have performed wind tunnel tests and flight tests employing half delta strakes for performance benefits. For this reason, half delta strakes were designed, fabricated, and mounted on a Piper Navajo; a performance flight test was performed. The results of these tests are compared to the results of identical tests conducted by Mr. Courtney Cumberbatch at the University of Tennessee Space Institute in the year 2000. The test employed six half delta strake prototypes manufactured with advanced composite materials. The six prototypes were tested with a 60 degree strake angle and a 75 degree strake angle. These prototypes were designed to be interference drag reducing devices for the Piper Navajo twin-engine airplane and were flight tested for performance benefits.

Both the 60 and 75-degree strakes tested during this study were mounted with an 18% overlap and 2% gap. These design and mounting measurements were replicated from the Cumberbatch study. The 60-degree strakes provided 2.4% reduction in the minimum power required and a 2.0% reduction in maximum range power required. The 75-degree strakes provided a 5.0% reduction of the minimum power required and a 3.75% reduction in maximum range power required. These reductions are much smaller than the reductions reported in the Cumberbatch study. Cumberbatch reported that the 75-degree strakes used in his test reduced the minimum required horsepower by 16.2% and the maximum range power required by 15.6%. These large differences may have been caused by the use of different data collection consoles and an error in the flight instruments aboard the aircraft during the Cumberbatch flight tests.

The 75-degree strakes provide better drag reduction benefits. Both the 60-degree and 75-degree strakes tested in this study decreased the maximum range speed and required horsepower and the maximum endurance speed and required horsepower of the Navajo. For an average cruise condition of 2200 RPM and 170 Brake Horse Power per engine, the 75-degree strake configuration can provide a 50 mile increase in range and a 20 minute increase in endurance. The data also determined that the strakes did not effect the high speed performance of the Navajo. All data suggests that this strake design is optimum for increasing the maximum range and endurance performance of the Piper Navajo with only a few knots decrease in airspeed and without effecting the cruise performance.

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NOMENCLATURE

AR	aspect ratio
B	wing span
C	wing chord
C_D	drag coefficient
C_{D0}	drag coefficient at zero lift
C_L	lift coefficient
D	drag
dC_D / dC_L^2	slope of C_D vs. C_L^2 plot
e	oswald's efficiency factor
F_R	thrust required
Hg	mercury
H_P	instrument corrected pressure altitude
H_{Po}	instrument corrected pressure altitude
L	lift
lb.	Pounds
L/D	lift to drag ratio
L/D_{max}	maximum lift to drag ratio
P_A	pressure Altitude
P_R	power required
P_{SL}	Pressure at standard sea level conditions
S	wing Area
T_a	corrected ambient air temp at altitude

T_C	instrument corrected ambient temperature
T_o	observed ambient air temperature
T_{SL}	temperature at standard sea level conditions
V_C	calibrated airspeed
V_I	indicated airspeed
V_o	observed airspeed
WS	standard maximum takeoff gross weight
WT	weight at the test point
α	angle of attack
δ	pressure ratio
η_P	propeller efficiency
π	pi
θ	temperature ratio
ρ_o	standard sea level density
σ	density ratio

Abbreviations

BHP _{IW}	brake horse power corrected for all air densities and weights
BHP _T	brake horse power at test point
c.g.	Center of Gravity
FAR	Federal Aviation Regulations
FWD	forward
HP _{TEMP CORR}	brake horse power corrected for all weights and air densities

in.	inches
K	degrees Kelvin
Kts.	Knots
MP	instrument corrected manifold pressure
MP_o	observed manifold pressure
PIW	brake horsepower corrected for all air densities and weights
RPM	revolutions per minute
RPM_o	observer revolutions per minute
VIW	airspeed corrected for all air densities and weight

CHAPTER I

INTRODUCTION

Description of Strake Technology and Theory

Through wind tunnel testing employing smoke, it has been proven by John E. Lamar at the NASA Langley Research Center in Hampton, Virginia in 1978 that delta shaped strakes create vortices in an air flow. For this reason, strake (Flow Energizer) technology has been an area of growing interest. Many studies have been conducted on the benefits of strake configurations for fighter aircraft as well as for general aviation aircraft.

“The benefits of strakes include minimal drag interference at or below the cruise angle of attack, energizing of the upper surface boundary layer, and minimal strake area is needed to produce a significant contribution to the total lift” (1). A strake is a vortex-generating device, placed above the leading edge of a wing to energize the upper surface boundary layer by creating turbulent flow. As air molecules flow over a wing the pressure decreases, reaching a minimum pressure at the maximum wing thickness. The pressure then gradually increases as the molecules progress toward the wings trailing edge. This increase in pressure is referred to as an adverse pressure gradient and is the source of lift induced drag (2). The adverse pressure gradient causes the flow to separate from the aerodynamic surface, which increases the overall drag. Lift induced drag is caused by the air flow separating at the trailing edge of the wing. At low angles of attack the adverse pressure gradient is small and the flow has enough energy to overcome the gradient, so the flow remains attached to the surface for a longer period of time. As the angle of attack increases, the adverse pressure gradient becomes larger and the air

molecules do not have enough energy to overcome the adverse pressure gradient. This increased pressure gradient causes the flow to separate from the wing.

Another form of drag occurs when the air flow travels across adjoining surfaces such as the fuselage-to-wing and wing-to-engine nacelle intersections. Drag caused by adjoining surfaces is referred to as interference drag or separation drag, and it causes the flow to separate from both of the adjoining surfaces. The difference between lift induced drag and interference drag is that the flow separation occurs on two airplane surfaces forming a corner, such as where the wing mounts to the fuselage or where the engine nacelles mount to the wing.

One method of decreasing the interference drag at these intersections is to impart more energy to the air molecules, allowing the air to overcome the adverse pressure gradient and remain attached to the surfaces longer. One method of adding energy to the air molecules is to create vortices in the flow, making the flow more turbulent. Since delta shaped strakes are proven to create vortices in the flow, it has been assumed that strakes could be used to reduce interference drag.

Strakes Used to Decrease Interference Drag

“Interference Drag usually comprises only 2 to 5 percent of the overall drag” (3). Throughout the remainder of this thesis interference drag will be referred to as the drag created from early separation of the air flow at the wing-to-fuselage intersection and the wing-to-engine nacelle intersections only. Since strakes create vortices in the flow, which energize the upper surface boundary layer and reduce early flow separation, all types of strakes have been invented and utilized for several different applications.

A Vortex Generating VG Kit for any Piper Navajo, which include delta strakes, can currently be purchased from Boundary Layer Research Company for approximately \$4,000.00 dollars. Boundary Layer Research Company advertises that this kit will reduce stall speed by 10 knots, decrease minimum controllable speed, and increase gross takeoff weight. These performance improvements are all low speed improvements, which would be expected since the adverse pressure gradient is higher at slower airspeeds.

Studies conducted by Dr. William Wentz revealed that the vortex created by a strake is related to the shape and sweep of the strake. Wentz's studies determined that "angles between 60 to 75 degrees are optimum to create the most effective vortices" (4).

Mr. Thomas Wallis conducted a wind tunnel investigation into the benefits of delta strakes for reduction of interference drag while a student at the Wichita State University. Wallis's study focused on strakes "mounted parallel to the wing on a half model twin-engine airplane at different overlap and gap configurations" (5). Figure 1.1 depicts how overlap, gap, and convergence relate to each other. Overlap is the distance the strake extends past the leading edge of the airfoil and is a key factor in determining the position where the local flow and vortex flow mix. Gap refers to the distance between the strake and the wing surface at a point perpendicular to the chord line. This distance determines how much of the vortex flow interacts with the local airflow over the wing. Convergence is the ratio of the gap height to the distance between the leading edge of the wing and the strake. Wallis's studies conducted with delta strakes at the Wichita State University determined that "a low convergence ratio provided the best drag reduction results". Wallis wind tunnel study also included evaluations of cambered and uncambered strakes. The conclusions of Wallis' study determined that "cambered strakes

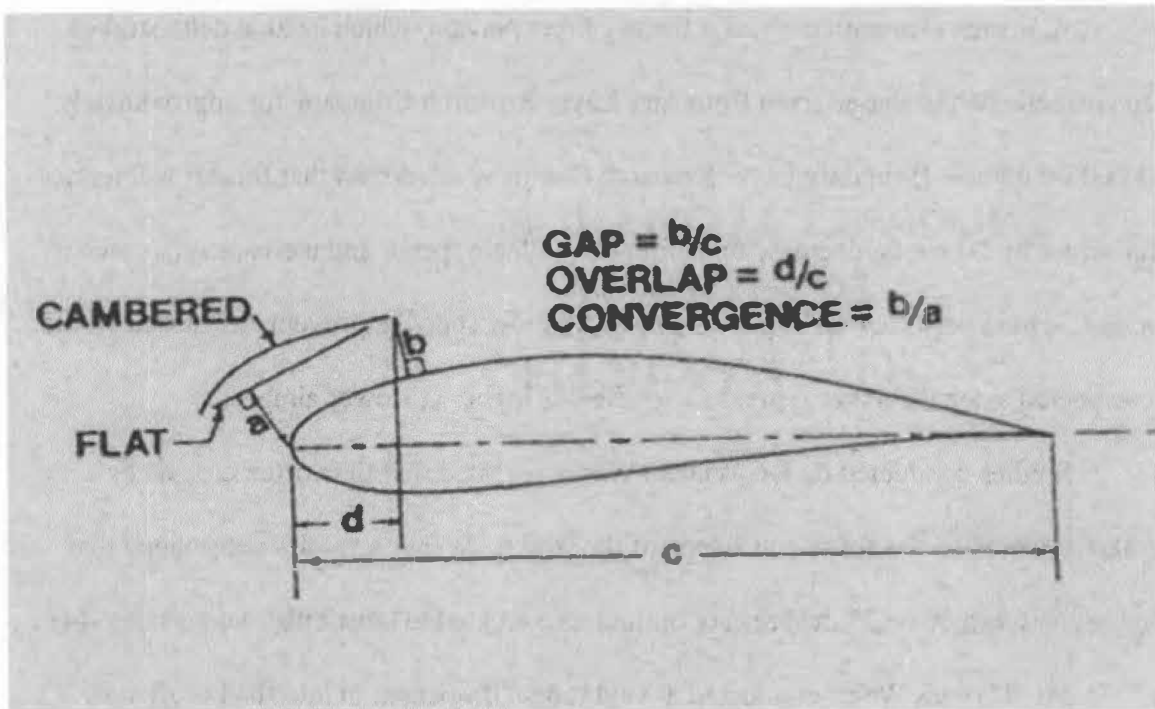


Figure 1.1. Diagram Illustrating Overlap, Gap, and Convergence Ratio (5)

mounted at an 18% overlap and 2% gap provided the best interference drag reduction benefits” (6).

In the year 2000, Courtney Cumberbatch (7) while a student at the University of Tennessee Space Institute, fabricated metal strakes and conducted a performance flight test experiment on a Piper Navajo, N11UT. The strakes were mounted at the wing to engine nacelle and the wing to nacelle intersections in hopes that the strakes would reduce the airplanes interference drag by creating vortices in the flow in order to keep the flow attached to the wing and fuselage surfaces for a longer period of time. Figure 1.2 shows how the strakes are used as flow energizers. Mr. Cumberbatch’s experiment employed 75-degree half delta strakes mounted at the wing-to-fuselage intersections and

the wing-to-nacelle intersections on a general aviation twin-engine Piper Navajo airplane in hopes of improving aircraft performance.

Cumberbatch reported performance enhancements of 15.6%, the drag coefficient was reduced by 18.84%, the lift to drag ratio was increased by 10.16%, and that the overall performance of the aircraft was improved by 26.69% (7).

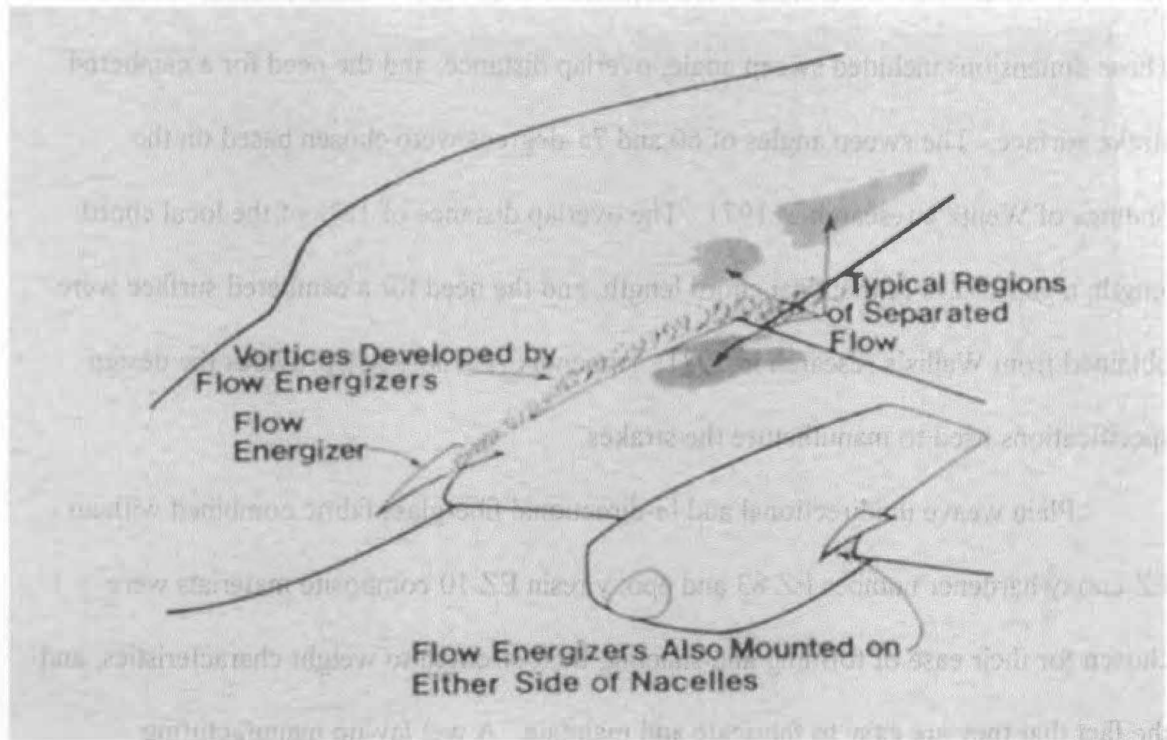


Figure 1.2. Diagram of Strakes Energizing the Flow with Vortices and Extending Flow Separation (7)

CHAPTER II

DESIGN, FABRICATION, AND MOUNTING OF THE HALF DELTA STRAKES

Strake Design

The strake design and mounting dimensions were obtained from the information provided by the Cumberbatch study. The Wentz and Wallis studies were used to verify that the Cumberbatch dimensions were consistent with other available research studies.

These dimensions included sweep angle, overlap distance, and the need for a cambered strake surface. The sweep angles of 60 and 75-degrees were chosen based on the findings of Wentz's research in 1971. The overlap distance of 18% of the local chord length, a gap of 2% of the local chord length, and the need for a cambered surface were obtained from Wallis's research in 1981. Appendix A, Table A.1 provides the design specifications used to manufacture the strakes.

Plain weave unidirectional and bi-directional fiberglass fabric combined with an EZ epoxy hardener number EZ 83 and epoxy resin EZ 10 composite materials were chosen for their ease of forming and shaping, their strength to weight characteristics, and the fact that they are easy to fabricate and maintain. A wet lay-up manufacturing technique was used to fabricate the strakes.

Fabrication of the Strakes

Six strakes were produced for this flight test. Strakes were placed at both the wing to fuselage intersections, and one on each side of the engine nacelles. It was determined that a three-step lay-up procedure was needed. The first lay-up was the delta strake itself. In order to match the wing camber, the upper surface of the Navajo wing was chosen as the mold. Figure 2.1 depicts the Navajo wing being used as a mold to lay-

up the inboard and outboard engine nacelle strakes. This allowed both the wing and the strake to have the same camber. Once the first lay-up was cured, the strakes were trimmed with a 12 inch band saw to an angle of 60 degrees. After the 60-degree flight test was accomplished the strakes were removed from the aircraft and trimmed to 75 degrees. The composite material allowed for only one strake to be manufactured for both the 60 and 75-degree strakes.

The second lay-up was the strake-mounting flange. The strake mounting flanges for the engine Nacelles consisted of a flat lay-up molded from a tabletop and can be seen in Figure 2.2. Once the flange lay-up cured, it was cut to the correct shape and fitted for the particular mounting location. The flanges were then trimmed using a 12" band saw and all the mounting holes were drilled with a .25-inch drill bit. The third lay-up bonded the strake to the flange.

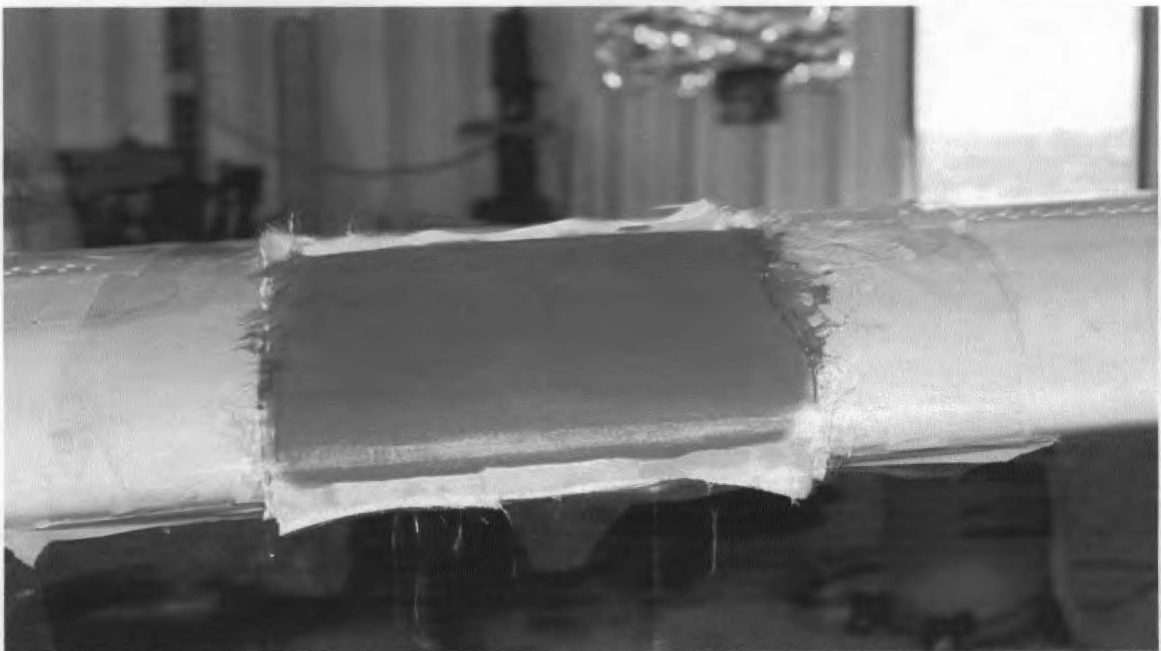


Figure 2.1 First Strake Lay-Up Procedure Using the Navajo Wing as the Mold

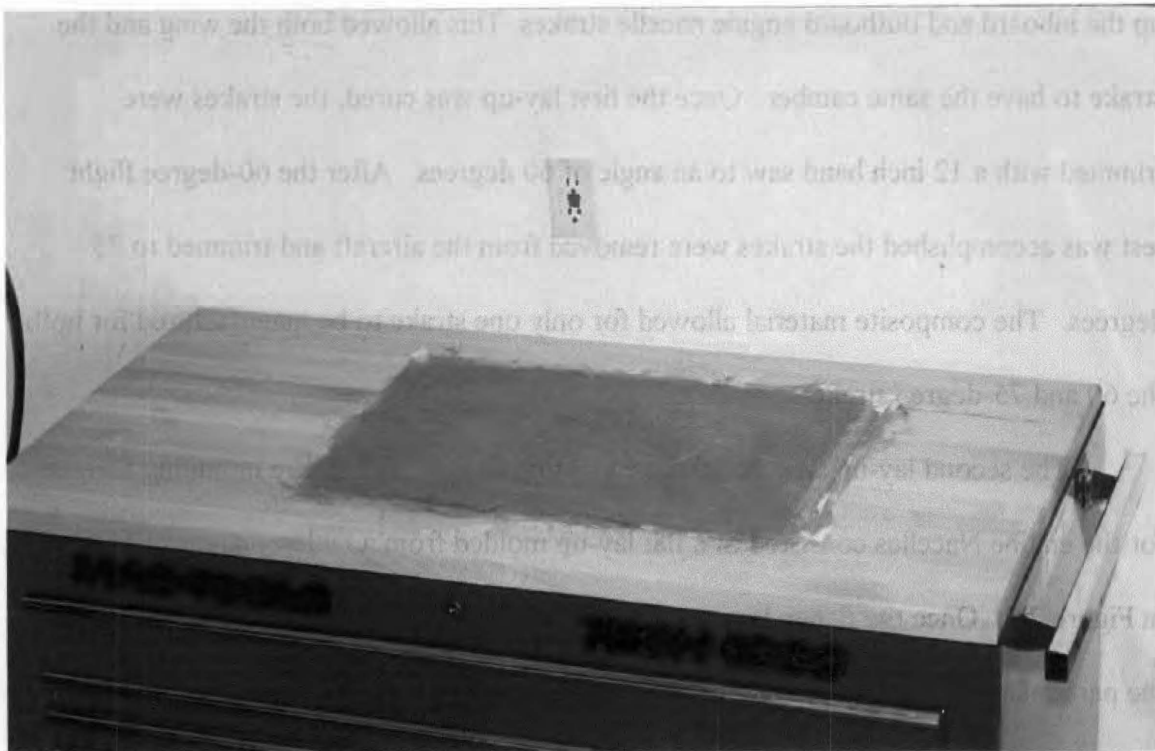


Figure 2.2. Engine Nacelle Flange Lay-Up



Figure 2.3. Strake to Flange Lay-Up

This was accomplished by securing the strake in the appropriate position on the flange and then laying-up 2 inch fabric strips between the flange and the strake. This lay-up procedure is depicted in Figure 2.3. Since the flange was laid up separately, the drilling and shaping of the flanges were easier to accomplish. Once the strakes were fabricated they were sanded, primed, and painted. The dimensions for all six flanges can be found in Appendix A, Table A.1 and A.2.

Mounting the Strakes

The strakes were mounted between the skin of the aircraft and the existing fiberglass fairings. The strakes were designed and fabricated in order to take advantage of the pre-existing mounting holes used to attach these fairings to the airframe. This allowed the strakes to be mounted as a direct add on to the aircraft with no changes needed to the airframe. Pictures of the mounted 75-degree strakes can be found in Appendix C.

CHAPTER III

TEST EQUIPMENT

Test Aircraft

The aircraft used to flight test the strakes was UTSI's PA31-310 Piper Navajo, N11UT and is shown in Figure 3.1. The Navajo is a twin engine, non-pressurized, multi purpose aircraft with retractable landing gear. This aircraft is equipped with two Lycoming TIO-540-A2C turbo-charged, fuel injected, six cylinder, horizontally opposed engines each rated at 310 Horse Power at 2575 RPM and maximum manifold pressure is 46 in. Hg from sea level up to 15,800 feet. The aircraft utilizes a trapezoidal wing planform with a span of 40.67 feet. It has a wing area of 229 square feet. All the specifications for the Piper Navajo were obtained from Dr. Ralph Kimberlin's Performance Lab Notebook (8) and are shown in detail in Appendix C.



Figure 3.1. Picture of the Test Aircraft PA31-310 Piper Navajo

Measurement Instruments

Several flight test parameters needed to be obtained. This task was accomplished through the use of the flight instrumentation already installed on the test aircraft. This installed and calibrated test instrumentation system includes student consoles housing an airspeed indicator, an altimeter, manifold pressure indicator, digital RPM indicators for the left and right engines, a digital ambient air temperature indicator, and a channel selector allowing other aerodynamic parameters to be measured. A picture of the instrumentation console used to collect flight test data is shown in figure 3.2.



Figure 3.2 The Instrumentation Console Aboard the Piper Navajo

1. Airspeed Indicator

The airspeed indicator measures the aircraft's speed in knots. Airspeed indicators are designed to display the difference between the pitot pressure and the static pressure of the aircraft. It is calibrated to sea level conditions. For this reason all observed airspeeds will be corrected for non-standard conditions and errors associated within the instrument will be corrected using calibration charts provided by the electrical engineer Michael Liegh. This calibration data will allow the calibrated airspeed to be calculated from the test data. For reasons of accuracy the same airspeed indicator was used to collect airspeed data for all of the flight tests.

2. Altimeter

The altimeter is a highly accurate barometer, which measures the altitude of the aircraft in feet. Altimeters are equipped with a Kolsman Window, which allows the non-standard pressure offset to be manually changed. For flight test purposes this window is set to 29.92, which is the barometric pressure for a standard atmospheric day. The calibration chart for the altimeter can be found in appendix B.

3. Manifold pressure Indicator

The manifold pressure indicator measures the manifold pressures of each engine and is used for determining the engine horsepower.

4. RPM Indicator

The digital RPM indicator measures the number of rotations of the left and right propeller per minute. This information combined with the manifold pressure are used when determining engine horse power.

5. Ambient Temperature Indicator

The digital ambient temperature indicator provides the temperature outside of the aircraft.

6. Fuel Quantity Indicator

The fuel quantity indicator determines the amount of fuel burned in gallons per hour. This information is used in calculating the weight of the aircraft at each test point.

Special Test

Three performance flight tests were conducted on three different days. The first test was conducted on September 27, 2001 with the following test results. The second test was the baseline test conducted on September 28, 2001 with the following results. The third and final flight test was conducted on November 15, 2001 with the following results. All three performance flight tests were conducted from the Fullerton Regional Airport, Fullerton, California. The maximum altitude of testing was 7,000 feet pressure altitude and the maximum speed achieved was 177 knots.

Method of Test

The flight test methodology used was the same for flight testing the aircraft. This method consists of setting the aircraft at maximum speed. Once the aircraft was stabilized, the engine RPM, manifold pressure, and fuel flow were recorded. The aircraft was then stabilized at a lower power setting and the engine RPM was recorded. The procedure was repeated until the minimum speed was reached.

CHAPTER IV

FLIGHT TESTING THE STRAKES

Purpose

The purpose of this thesis is to evaluate the interference drag reduction benefits of 60 and 75-degree half delta strakes mounted on a Piper Navajo twin engine airplane. The results will then be compared to a similar test conducted by Mr. Courtney Cumberbatch.

Scope of Tests

Three performance flight tests were executed on three different days. The first test was conducted on September 27, 2001 with the 60-degree strakes mounted. The second flight test was the baseline test conducted on September 28, 2001 with no strakes mounted. The third and final flight test was conducted on November 15, 2001 with the 75-degree strakes mounted. All three-performance flight tests were conducted from the Tullahoma Regional Airport, Tullahoma, Tennessee in VMC conditions. The maximum altitude of testing was 7,400 feet pressure altitude and the maximum airspeed achieved was 177 knots.

Method of Test

The Level Flight Performance test method was chosen for flight testing the strakes. This method consists of stabilizing the aircraft at maximum airspeed. Observed airspeed, pressure altitude, temperature, engine RPM, manifold pressure, and fuel quantity were recorded. The aircraft was then stabilized at a lower power setting and the same data was again recorded. This procedure was repeated until the minimum level flight speed was obtained.

This method allows the flight test engineer to statistically normalize the data collected. Once the data is normalized, a power-required curve that is correct for all airplane weights and air densities may be obtained. Lift and drag coefficients for each configuration tested can be mathematically obtained as well.

Baseline Level Flight Performance Evaluation

The baseline performance flight test was conducted on September 28, 2001. This flight test was conducted in order to obtain a power-required curve for the aircraft in its clean configuration without the strakes mounted.

Performance Evaluation With 60-Degree Strakes Mounted

The 60-degree strakes were mounted on the airframe as discussed in chapter II. Once the strakes were mounted a level flight performance test was accomplished on September 27, 2001. This flight test was performed identically to the baseline test procedures described in the paragraph above.

Performance Evaluation With 75-Degree Strakes Mounted

The 75-degree strakes were mounted on the airframe as discussed in chapter II. Once the strakes were mounted a level flight performance test was accomplished on November 15, 2001. This flight test was performed identically as the previous test procedures described in the paragraph above.

CHAPTER V

DATA REDUCTION METHODOLOGY

PIW-VIW Method

The PIW-VIW data reduction method provided in Dr. Ralph Kimberlin's textbook entitled Performance Flight Testing (8) was used to reduce the flight test data. "This method allows the flight test engineer to obtain a power-required curve for the test aircraft that is good for all airplane weights and air densities" (8). Power required curves were derived for the test aircraft in the baseline and strakes mounted configuration. Once this was accomplished, the curves can be compared and evaluated.

"In order to use the PIW-VIW flight test methodology two assumptions are made. The first assumption is that the lift and drag coefficients are constant at a given angle of attack. The second is that propeller efficiency is constant" (8). Once these assumptions are made a power required curve can be obtained by reducing the flight test data to PIW and VIW values using the equations contained in Appendix D. The PIW values are then plotted against the VIW values. In order to normalize the data into a straight line, PIW times VIW is plotted versus VIW^4 and a line is faired through the data points. From these statistically normalized straight line values of PIW and VIW, a power-required curve for the aircraft may be obtained.

Maximum Range Speed

Once the power curve is obtained, the maximum range speed for the test aircraft can be determined. The maximum range speed is the speed that corresponds to the maximum lift to drag ratio. This speed can be determined by drawing a line from the

origin to a point tangent to the normalized PIW-VTW curve. The corresponding VTW speed at this point is the maximum range speed.

Maximum Endurance Speed

The maximum endurance speed for the test aircraft is obtained from the same normalized PIW-VTW curve. The maximum endurance speed corresponds to the minimum power required speed and is found by drawing a line tangent to the bottom portion of the curve. The corresponding speed is the maximum endurance speed.

Lift and Drag Coefficients

The values obtained from the PIW-VTW data reduction are used to calculate the lift and drag coefficients. The equation derivation for the lift and drag coefficients can be found in Appendix B. Once the lift and drag coefficients are obtained, they are used to obtain plots of C_D vs. C_L (drag polars), C_D vs. C_L^2 , and L/D vs. C_L .

is shown in Appendix B.

50-Percent Static Coefficient Test Results

The 50-Percent Static

The 50-Percent Static Coefficient Test Results are shown in Appendix B.

Figure 1 shows the 50-Percent Static Coefficient Test Results for the test aircraft.

The 50-Percent Static Coefficient Test Results are shown in Appendix B.

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The 50-Percent Static

The 50-Percent Static Coefficient Test Results are shown in Appendix B.

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CHAPTER VI

DATA ANALYSIS

Baseline Configuration

1. Power Required Curve

The PIW-VIW plot for the baseline configuration of the Piper Navajo is shown in Appendix B, Figure B.1. This plot shows that the maximum range speed is 120 knots at a horsepower of 240. The plot also shows that the maximum endurance speed is 93 knots at a required horsepower of 215. The minimum horsepower required for this configuration is 215 horsepower.

2. Lift to Drag Ratio

A plot of the lift to drag ratio for the Piper Navajo in the baseline configuration is shown in Appendix B, Figure B.2. This plot shows that the maximum lift to drag ratio of 11 is attained at a lift coefficient of 0.560.

60-degree Strake Configuration Test Results

1. Power Required Curve

The PIW-VIW plot for the 60-degree strake configuration is shown in Appendix B, Figure B.3. This plot shows that in this configuration the Piper Navajo attains a maximum range speed of 118 knots at a horsepower of 235. The plot also shows that the maximum endurance speed is 92 with a required horsepower of 209. The minimum horsepower required for this configuration is 209 horsepower.

2. Lift to Drag Ratio

The plot of the lift to drag ratio vs. lift coefficient is shown in Appendix B, Figure B.4.

This plot shows that the maximum lift to drag ratio of 11.3 is attained at a lift coefficient of 0.559.

75-Degree Strake Configuration Test Results

1. Power Required Curve

The PIW-VIW plot for the 75-degree strake configuration is shown in Appendix B, Figure B.5. This plot shows that in this configuration the Piper Navajo attains a maximum range speed of 117 knots with a required horsepower of 231. The plot also shows that the maximum endurance speed is 90 with a required horsepower of 205. The minimum horsepower required for this configuration is 205 horsepower.

2. Lift to Drag Ratio

The plot of the lift to drag ratio vs. lift coefficient is shown in Appendix B Figure B.6. This plot shows that the maximum lift to drag ratio of 11.558 is attained at a lift coefficient of 0.563.

Data Trends and Benefits Comparisons

Figure 6.1. depicts that the power required curves shift downward and slightly to the right with the application of the strakes. This data supports that the 60-degree and 75-degree strakes did reduce interference drag resulting in a shift of the power-required curve. The power curve plotted in blue represents the 60-degree strake configuration. This configuration increases the range of the aircraft by approximately 25 miles cruising at 10,000 feet pressure altitude with the engines set at 230 brake horse power. The power required curve plotted in yellow represents the 75-degree strake configuration. The 75-degree strakes provided the best increase in range and endurance. At an engine power setting of 2200 RPM and 170 Brake Horse Power per engine, the range of the Piper

COMPARISON OF THE NORMALIZED POWER CURVES IN THE BASELINE AND STRAKE CONFIGURATION

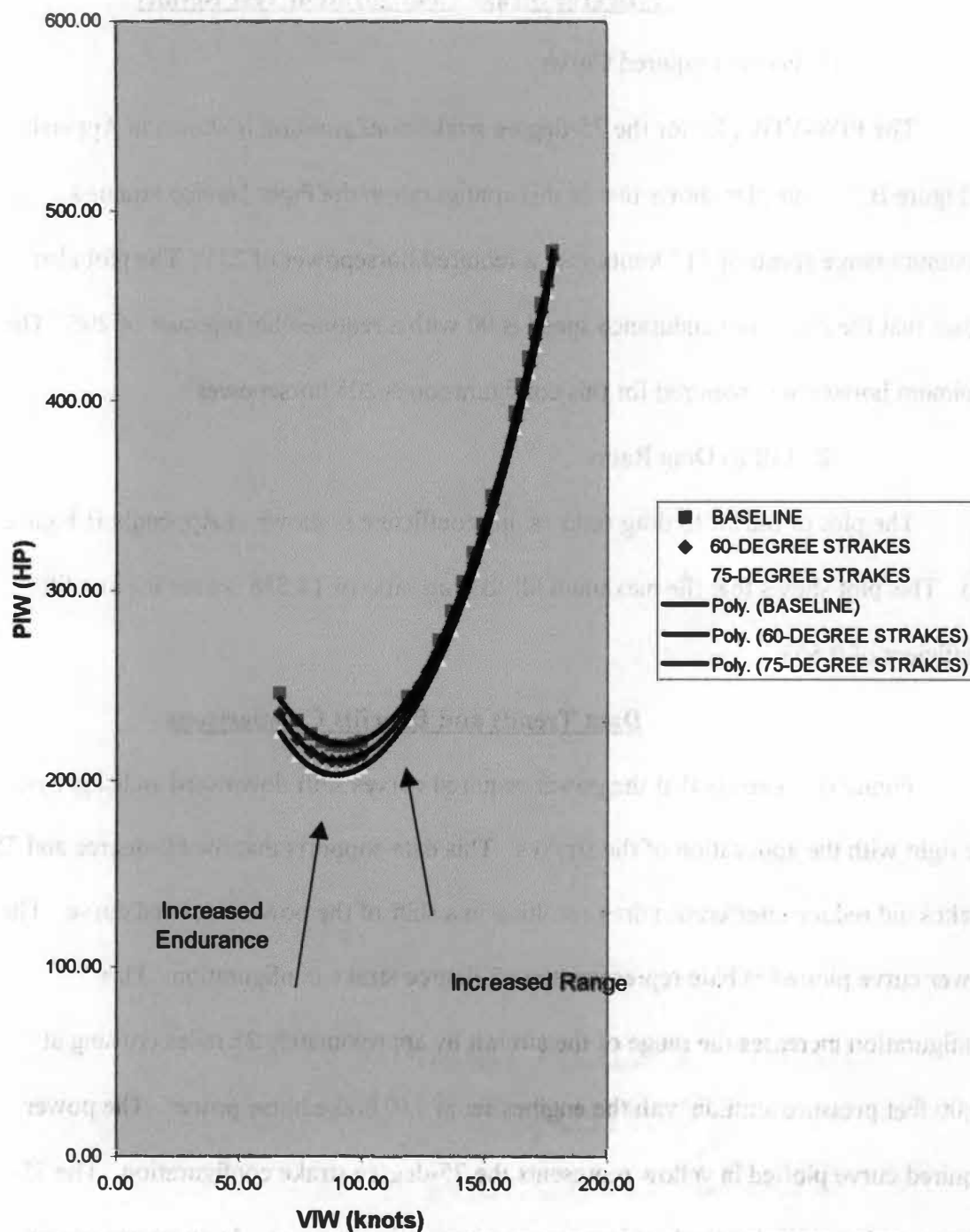


Figure 6.1. The Effects of Strakes on the Power Required Curve

Navajo can be increases increased approximately 50 miles and the endurance increased approximately 20 minutes. The 75-degree strake configuration provided the best drag reduction.

The strakes reduce the minimum power required from 215 hp in the baseline configuration to 209 in the 60-degree strake configuration, and to 205 in the 75-degree strake configuration. This provides a reduction in the minimum power required for the aircraft as shown in Table 6.1. The strakes also shifted the maximum endurance speed of the aircraft from 93 knots to 92 knots with the 60-degree strakes, and then to 90 knots with the 75-degree strakes.

The maximum range speed was changed from 120 in the baseline configuration to 118 knots in the 60-degree configuration, and 117 knots in the 75-degree configuration. The maximum range horsepower was also lowered from 240 horsepower in the baseline configuration to 235 with the 60-degree strakes, and to 231 horsepower in the 75-degree strake configuration.

Table 6.1. Power, Range, and Endurance Benefits of the 60 and 75-Degree Strakes (6)

CONFIGURATION	Minimum Power REQUIRED	REDUCTION IN POWER	POWER REQUIRED FOR MAXIMUM RANGE SPEED	REDUCTION IN MAXIMUM RANGE POWER REQUIRED	MAX V_R
BASELINE	215		235		120
60 DEGREE STRAKES	209	2.4%	235	0%	120
75 DEGREE STRAKES	205	5.0%	235	0%	120

Cumberbatch's figures are more than three times as high for the reduced maximum endurance power benefits, and he reports nearly the same power reduction benefits for maximum endurance power required. Cumberbatch's data for the strake condition correlates with the data in this thesis, but his baseline data is extremely high. This data was most likely incorrect due to the data collection method. Cumberbatch collected the baseline data from the co-pilots instruments, which had not been calibrated, and then collected the strake data from the passenger's instrument console, which had been calibrated. These results are compared to the Cumberbatch studies in Table 6.2. The data Cumberbatch collected from the calibrated instruments correlates to the data presented in this thesis, but the data collected from the uncalibrated instrumentation varies significantly.

Strake Effects On the Drag Polar

The drag polars for the baseline and strake conditions are shown in Figure 6.2. These curves reflect the power required curve in that the drag is reduced at the lift

Table 6.2. Power, Range, and Endurance Benefits reported in the Cumberbatch Study

CONFIGURATION	Minimum Power REQUIRED	Reduction In Minimum Power Required	POWER REQUIRED FOR MAXIMUM RANGE SPEED	REDUCTION IN MAXIMUM RANGE POWER REQUIRED	MAX VR
BASELINE	238.57		282.2		124
75 DEGREE STRAKES	200.04	16.2%	238.15	15.60%	117.5

coefficients (C_L) that corresponds to lower airspeeds. The lift coefficient values corresponding to high airspeeds are unaffected. The zero lift coefficient of the Navajo is .027 for the baseline and both of the strake configurations.

The drag is reduced starting at lift coefficients of .6 and continue through the low end of the power curve. Even though the lift curve slope is not linear in the high lift coefficient and low speed spectrum, the drag polar indicates that this strake design provides low speed performance benefits while at the same time it does not take away from the airplanes high-speed performance.

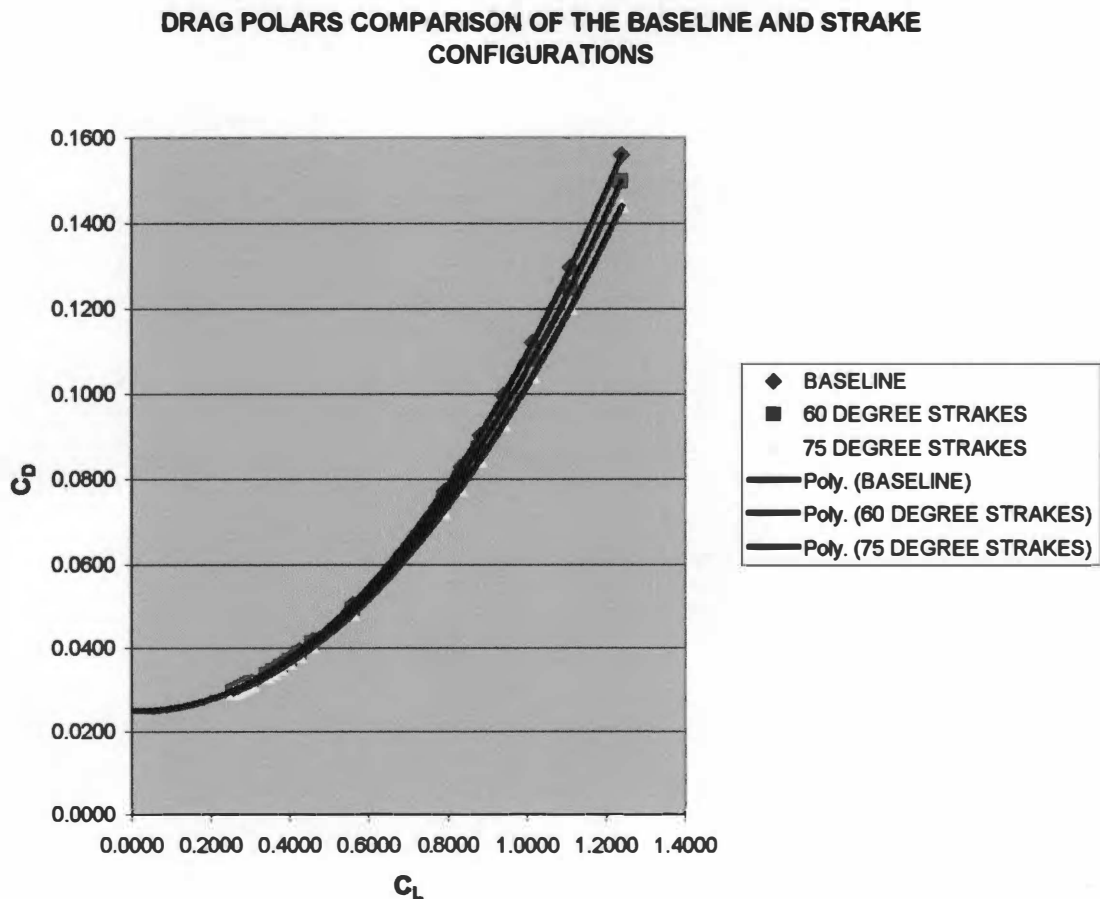


Figure 6.2. The Effects of Strakes on the Drag Polar

Operators of twin engine Piper Navajos could use these strakes to increase their optimum range and endurance speeds. The data also suggests that the drag reduction produced from these strakes would probably increase takeoff and climb performance and lower the minimum takeoff speed of the aircraft. Further testing for takeoff and climb performance would be needed to verify this assumption. However, this flight test determined that the 60 and 75-degree strake design provided low speed performance enhancements without effecting the airplanes cruise performance.

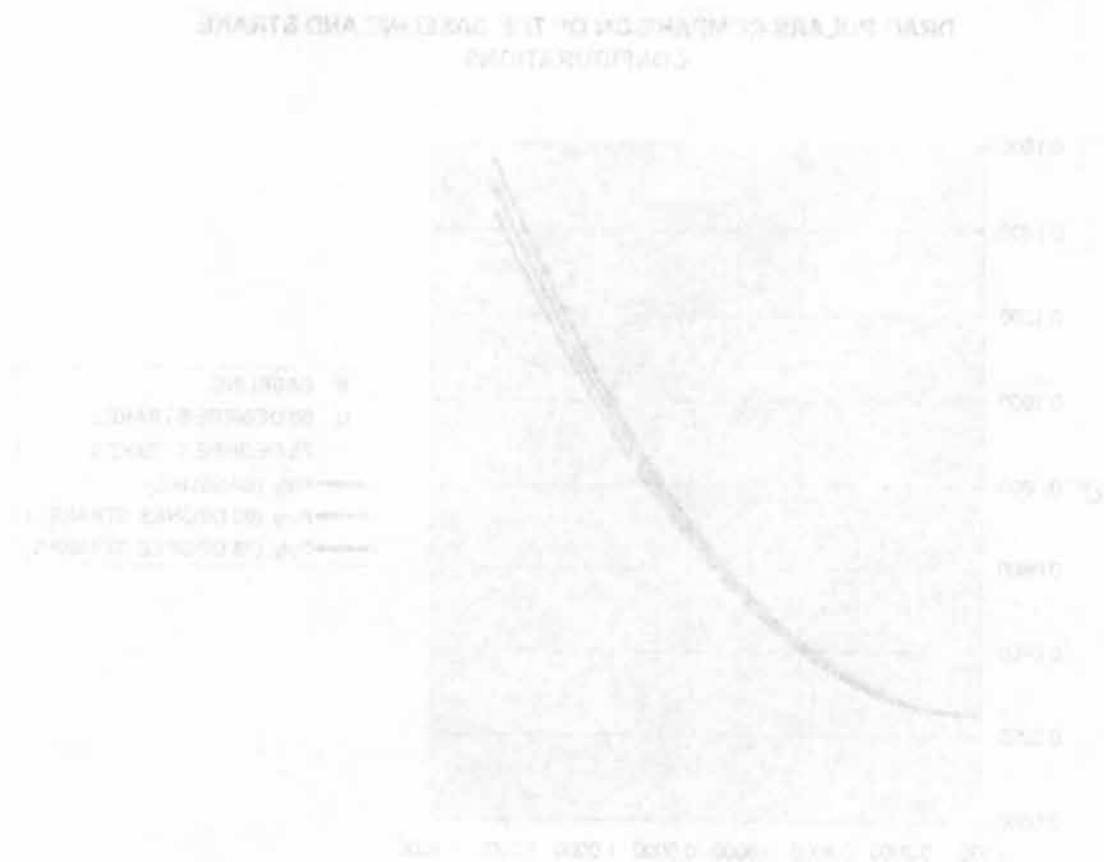


Figure 6.2 The Effects of Strakes on the Drag Coefficient

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Both the 60 and 75-degree strakes tested during this study were mounted with an 18% overlap and 2% gap. These design and mounting measurements were replicated from the Cumberbatch study. The 60-degree strakes provided 2.4% reduction in the minimum power required and a 2.0% reduction in maximum range power required. The 75-degree strakes provided a 5.0% reduction of the minimum power required and a 3.75% reduction in maximum range power required. These reductions are much smaller than the reductions reported in the Cumberbatch study. Cumberbatch reported that the 75-degree strakes used in his test reduced the minimum required horsepower by 16.2% and the maximum range power required by 15.6%. These large differences may have been caused by the use of different data collection consoles and an error in the flight instruments aboard the aircraft during the Cumberbatch flight tests.

The 75-degree strakes provide better drag reduction benefits. Both the 60-degree and 75-degree strakes tested in this study improved the maximum range speed and the maximum endurance speed of the Navajo. For an average cruise condition of 2200 RPM and 170 Brake Horse Power per engine, the 75-degree strake configuration can provide a 50 mile increase in range and a 20 minute increase in endurance. The data also determined that the strakes did not effect the high speed performance of the Navajo. All data suggests that this strake design is optimum for increasing the maximum range and endurance performance of the Piper Navajo with only a few knots decrease in airspeed and no effect on the cruise performance.

Recommendations

The strakes reductions of the Navajos power required curve indicates that this strake design would be able to improve the airplanes rate of climb performance and reduce the stalling speed. The first recommendation is to perform more tests with this strake design. Such tests should include a test to determine the climb performance improvements of the Piper Navajo with theses strakes mounted. Other tests that should be conducted include stall speed reduction tests, minimum takeoff speed tests, and tests to determine the handling qualities of stall recovery with the strakes mounted.

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APPENDICES

Appendix A: Sample Data

Table A.1: Sample Data for Appendix A

Sample ID	Sample Weight (g)	Sample Volume (mL)	Sample Density (g/mL)
1	10.5	1.2	8.75
2	12.3	1.5	8.20
3	15.7	1.8	8.72
4	18.9	2.1	9.00
5	22.1	2.4	9.21

Table A.2: Sample Data for Appendix B

Sample ID	Sample Weight (g)	Sample Volume (mL)	Sample Density (g/mL)
1	10.5	1.2	8.75
2	12.3	1.5	8.20
3	15.7	1.8	8.72
4	18.9	2.1	9.00
5	22.1	2.4	9.21

APPENDIX A

Strake Design Specifications

Table A.1. Overlap, Gap, and Convergence Ratio Dimensions

Location	Local Wing Chord (ft.)	18% Overlap Distance	2% Gap Distance	Convergence Ratio
Root	9.42	1.7	0.188	0.821
Inboard Nacelle	7.17	1.29	0.143	0.572
Outboard Nacelle	6.21	1.12	0.124	0.441

Table A.2. Strake Length and Mounting Dimensions

Location	Local Wing Chord (ft.)	Length of Strake (in)	Mounting Distance Above Wing (in.)
Root	9.42	20.4	2.256
Inboard Nacelle	7.17	15.48	1.716
Outboard Nacelle	6.21	13.44	1.488

APPENDIX B

Flight Test Data Analysis

Aircraft: PA 31-310 N11UT

Date: September 28, 2001

Pilot: Dr. Ralph Kimberlin

FTE's: Bingham, Leigh

Test: Level Flight Performance

Data: Baseline

Configuration: Clean, gear up, weight 6165.74 lbs.

NORMALIZED PIW VS. VW FOR THE BASELINE CONFIGURATION

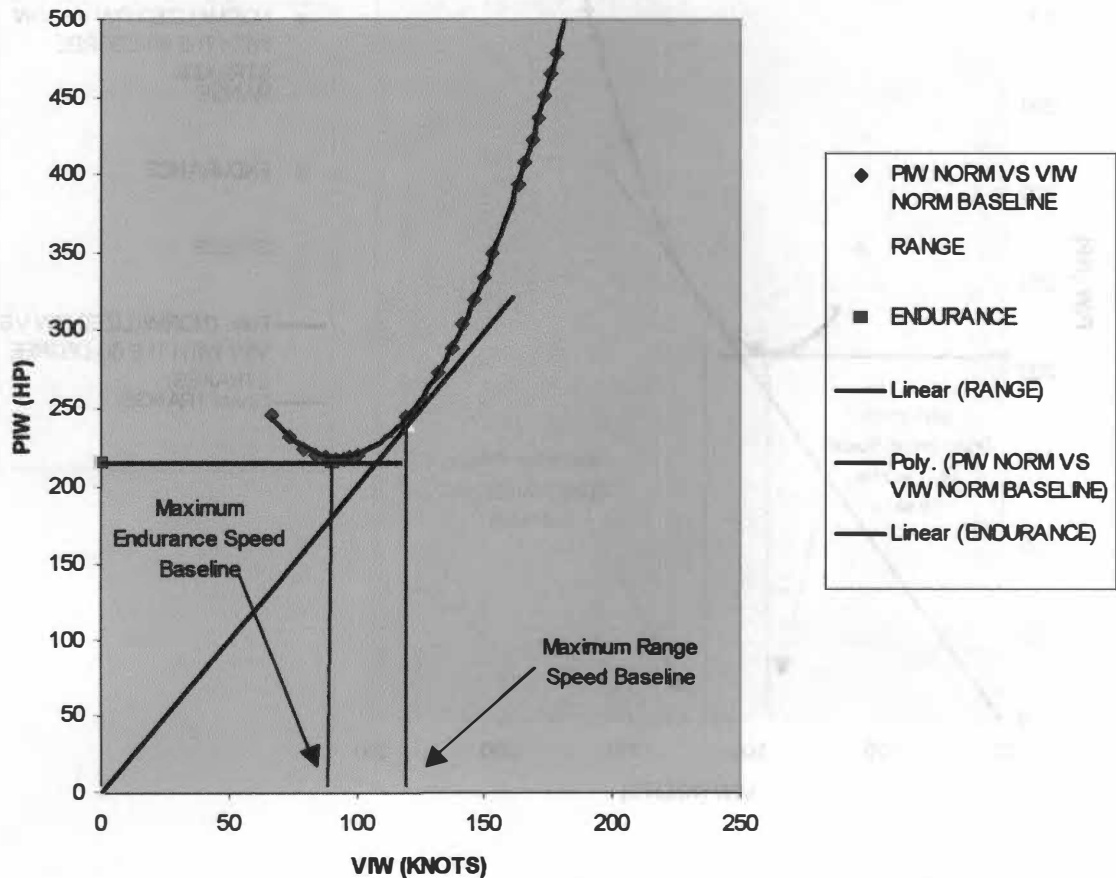


Figure B.1. Normalized Power Curve For the Baseline Configuration

Aircraft: PA 31-310 N11UT **Date:** September 27, 2001

Pilot: Dr. Ralph Kimberlin **FTE's:** Bingham, Leigh

Test: Level Flight Performance **Data:** 60-Degree Strakes

Configuration: Clean, gear up, weight 6165.74 lbs., 60-Degree Strakes Mounted

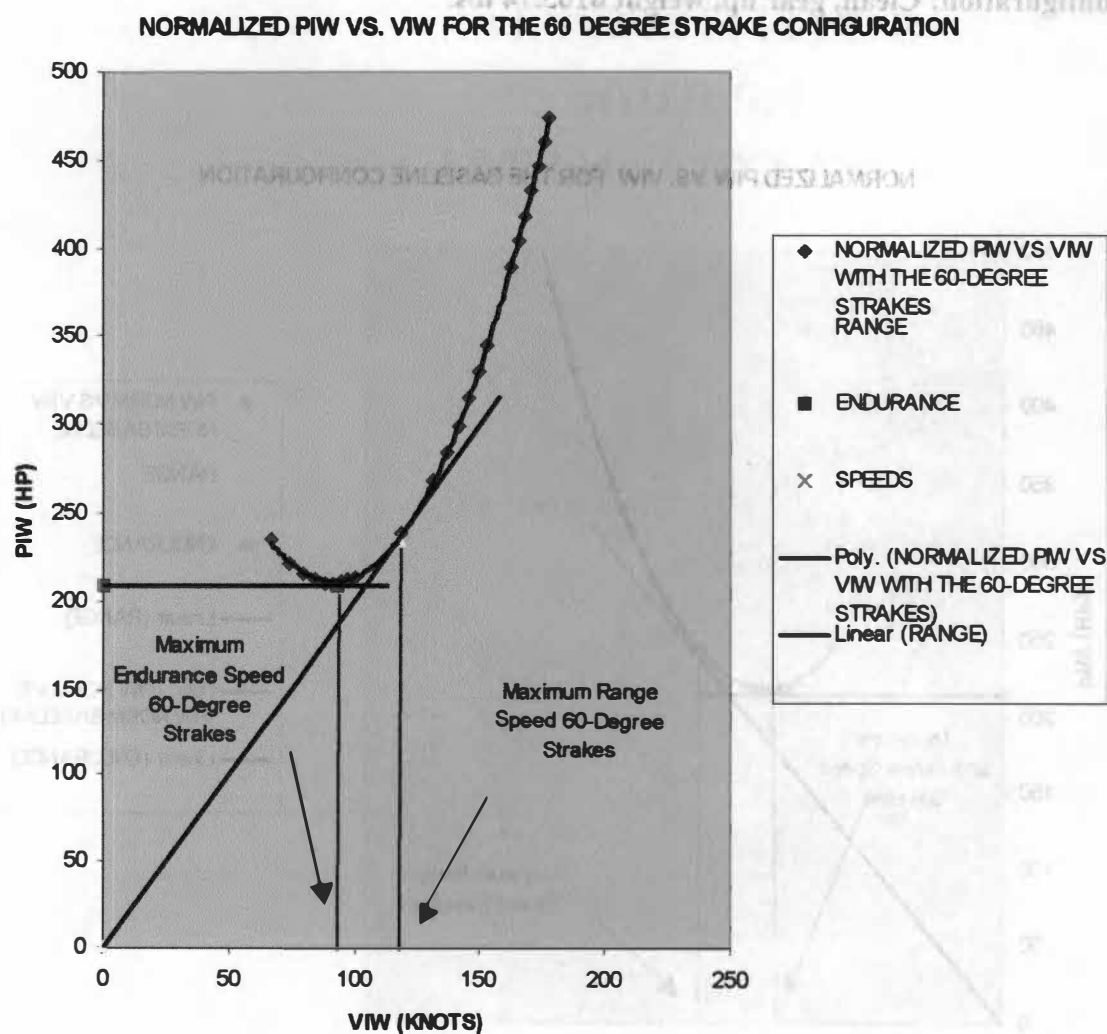


Figure B.2. Normalized Power Curve For the 60-Degree Strake Configuration

Aircraft: PA 31-310 N11UT

Date: November 15, 2001

Pilot: Dr. Ralph Kimberlin

FTE's: Bingham, Leigh

Test: Level Flight Performance

Data: 75-Degree Strakes

Configuration: Clean, gear up, weight 6165.74 lbs., 75-Degree Strakes Mounted

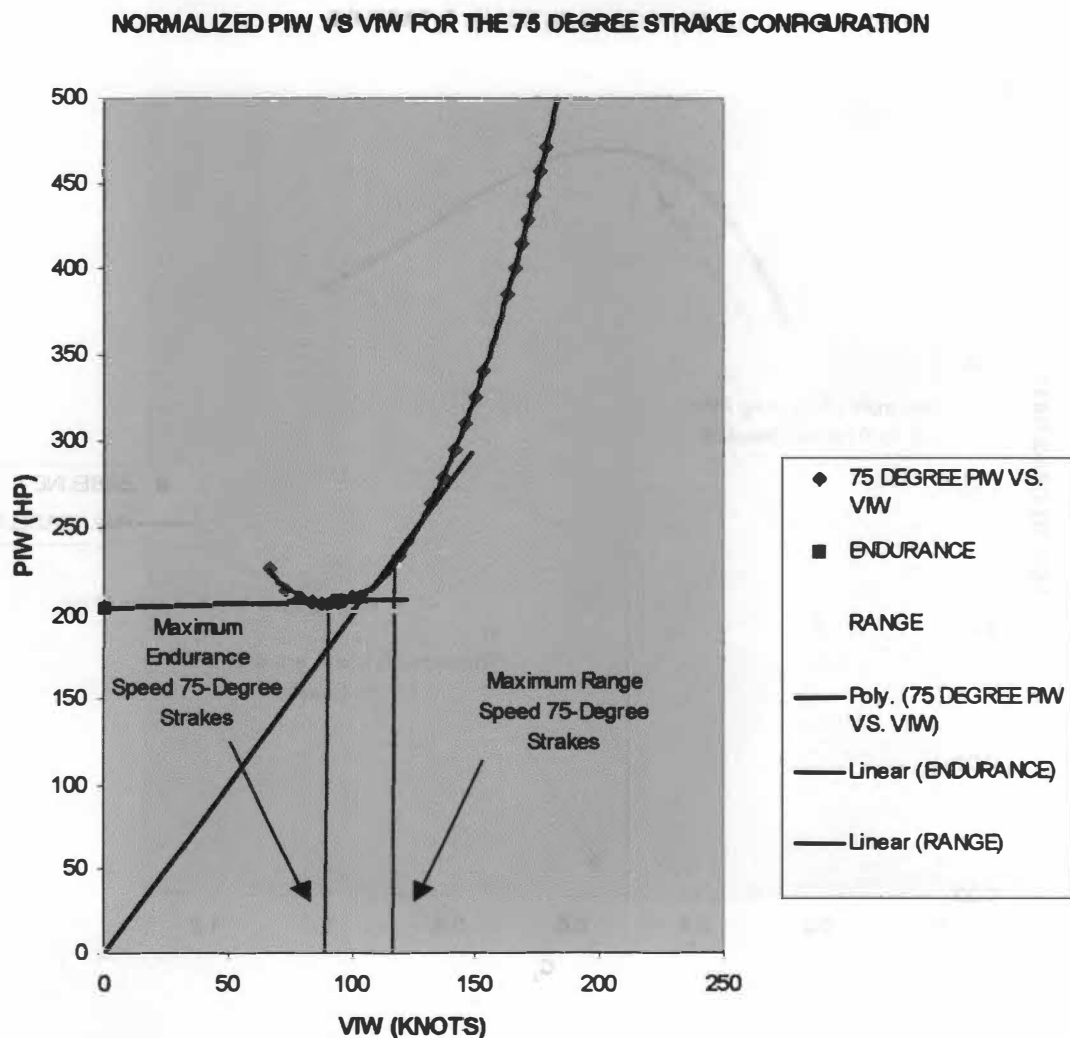


Figure B.3. Normalized Power Curve For the 75-Degree Strake Configuration

Aircraft: PA 31-310 N11UT **Date:** September 28, 2001
Pilot: Dr. Ralph Kimberlin **FTE's:** Bingham, Leigh
Test: Level Flight Performance **Data:** Baseline
Configuration: Clean, gear up, weight 6165.74 lbs.

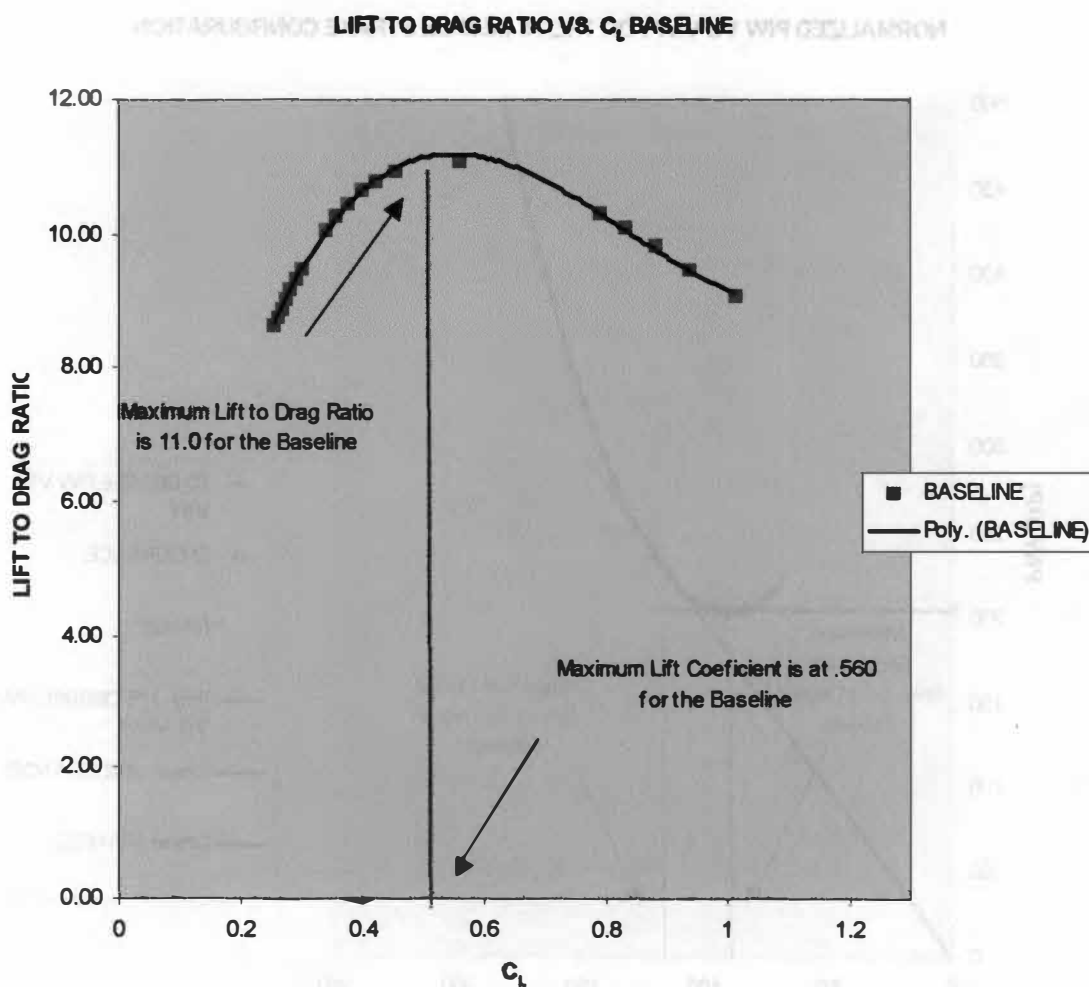


Figure B.4. Lift to Drag Ratio Vs. C_L for the Baseline Configuration

Aircraft: PA 31-310 N11UT

Date: September 27, 2001

Pilot: Dr. Ralph Kimberlin

FTE's: Bingham, Leigh

Test: Level Flight Performance

Data: 60-Degree Strakes

Configuration: Clean, gear up, weight 6165.74 lbs., 60-Degree Strakes Mounted

LIFT TO DRAG VS. C_L WITH THE 60-DEGREE STRAKES MOUNTED

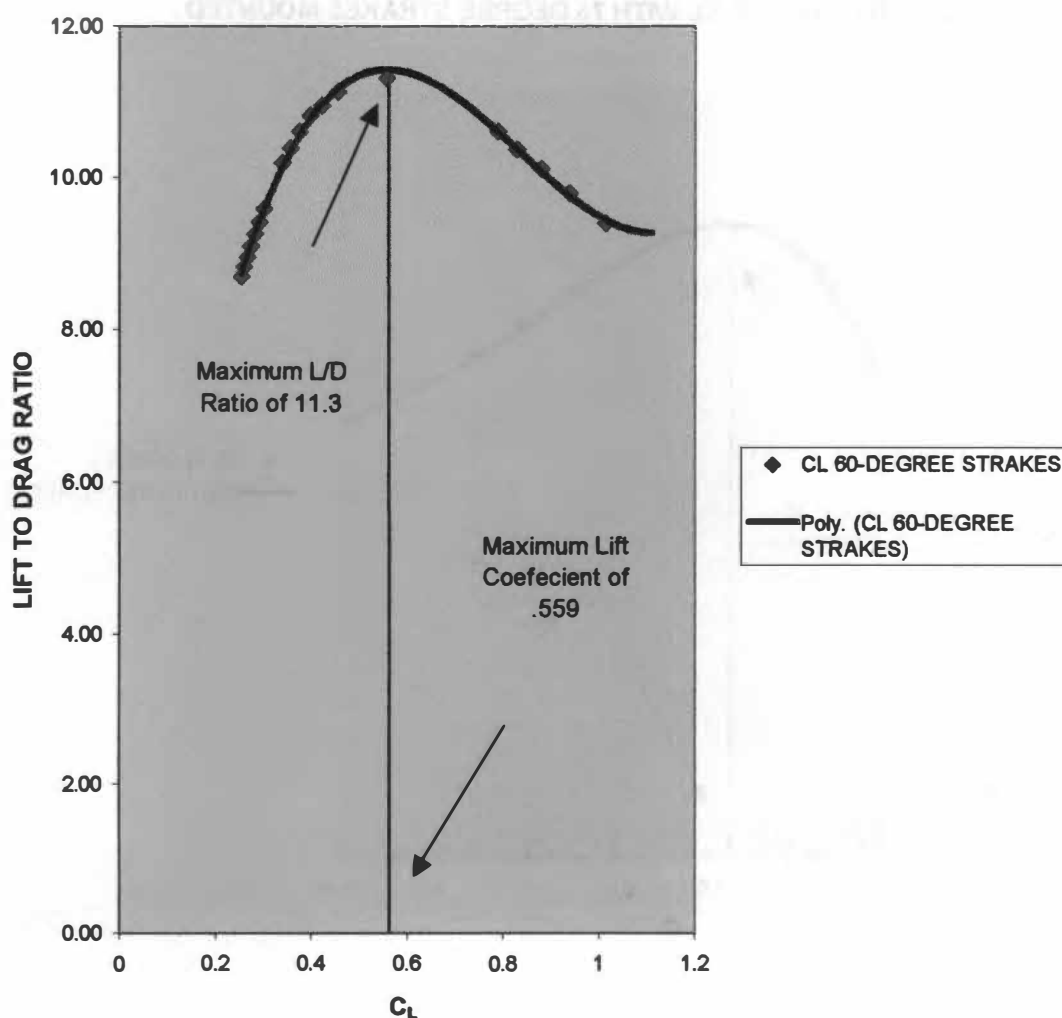


Figure B.5. Lift to Drag Ratio Vs. C_L for the 60-Degree Strake Configuration

Aircraft: PA 31-310 N11UT

Date: November 15, 2001

Pilot: Dr. Ralph Kimberlin

FTE's: Bingham, Leigh

Test: Level Flight Performance

Data: 75-Degree Strakes

Configuration: Clean, gear up, weight 6165.74 lbs., 75-Degree Strakes Mounted

LIFT TO DRAG VS CL WITH 75 DEGREE STRAKES MOUNTED

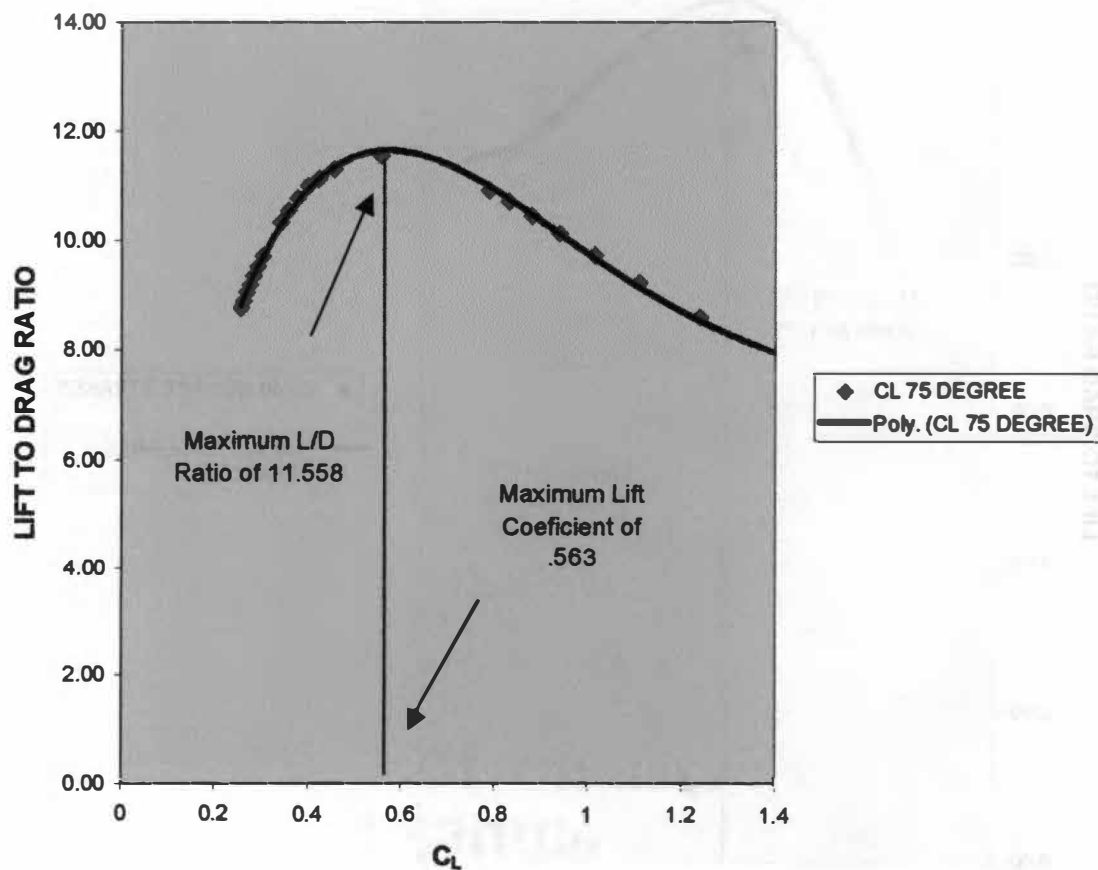


Figure B.6. Lift to Drag Ratio Vs. C_L for the 75-Degree Strake Configuration

APPENDIX C

Pictures of the 75-Degree Strakes Mounted on the Piper Navajo

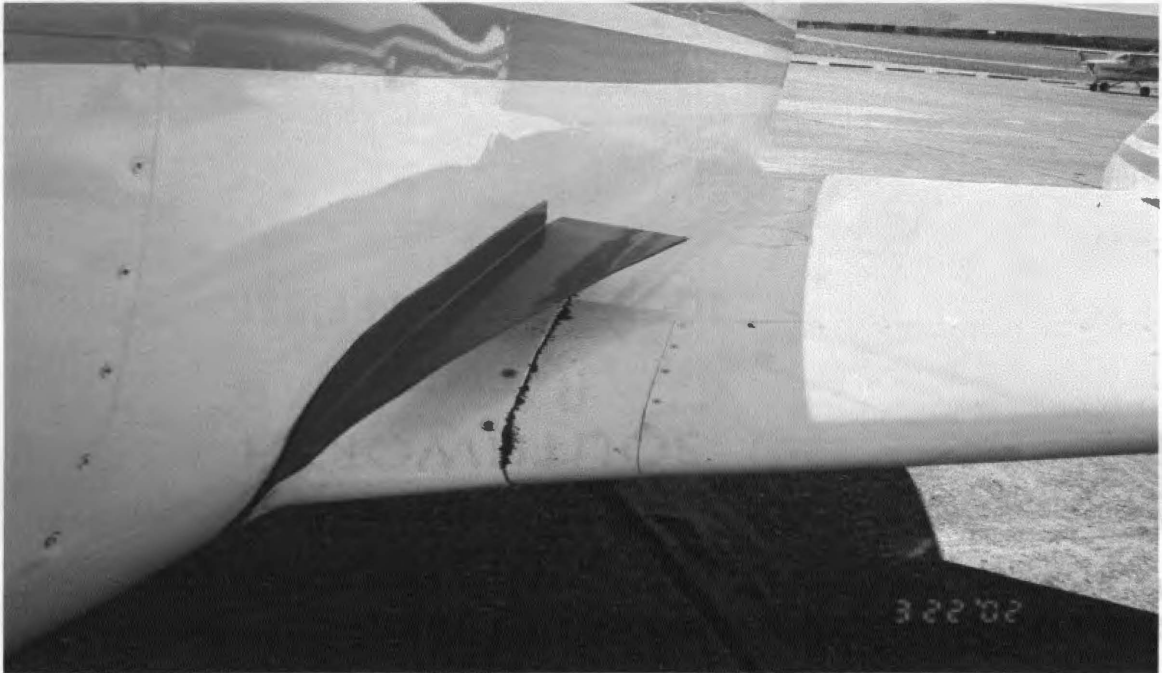


Figure C.1. Picture of the 75-Degree Left Root Strake Mounted to Left Fuselage

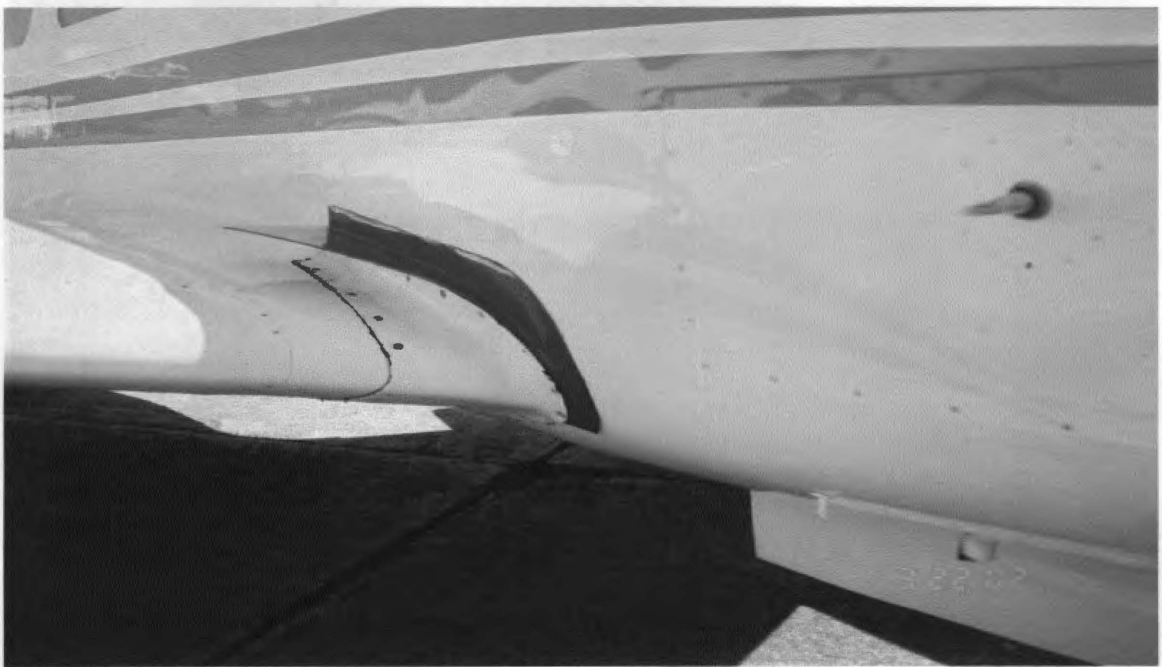


Figure C.2. Picture of the 75-Degree Right Root Strake Mounted to Right Fuselage



Figure C.3. Picture of the 75-Degree Left Inboard Nacelle Strake Mounted to the Left Engine Nacelle



Figure C.4. Picture of the 75-Degree Right Inboard Nacelle Strake Mounted to the Right Engine Nacelle



Figure C.5. Picture of the 75-Degree Left Outboard Nacelle Strake Mounted to the Left Engine Nacelle



Figure C.6. Picture of the 75-Degree Right Outboard Nacelle Strake Mounted to the Right Engine Nacelle

APPENDIX D
Piper Navajo Specifications

Maximum Horsepower	620 HP. (310 HP./Eng.)
Wing Area	229 Sq. Ft.
Wing Span	40.67 Ft.
Root Chord	9.42 Ft.
Tip Chord	7.17 Ft.
Maximum Gross Weight	6500 Lbs.
V _S Full Flaps, Gear Down, Power Off, 6500 Lbs.	63 KCAS
V _{MC}	74 KCAS
V _A	159

APPENDIX E

Data Reduction Equations

PIW-VIW Equations for Level Flight Performance

$$V_c = V_o + \Delta V_{ic} + \Delta V_{pos}$$

V_c = Calibrated Airspeed

V_o = Observed Airspeed

ΔV_{ic} = Airspeed Instrument Correction

ΔV_{pos} = Airspeed Position Correction

$$H_{pc} = H_{po} + \Delta H_{pc} + \Delta H_{pos}$$

H_{pc} = Calibrated Pressure Altitude

H_{po} = Observed Pressure Altitude

ΔH_{pc} = Altimeter Instrument Correction

ΔH_{pos} = Altimeter Position Error

$$T_a = T_o + \Delta T_{ic}$$

T_a = Ambient Temperature

T_o = Observed Temperature

ΔT_{ic} = Temperature Instrument Correction

$$\theta = \frac{T_a}{T_{sl}}$$

θ = Temperature Ratio

T_a = Ambient Temperature

T_{sl} = Standard Sea Level Temperature

The temperature ratio is calculated using the observed outside air temperature in degrees Celsius and the following equation.

$$\theta = \frac{(T_a + 273.15)}{288.15}$$

Where 288.15 is the absolute temperature at standard sea level conditions in degrees Kelvin.

$$\delta = \frac{P_a}{2116.217} = \left[1 - \left(6.875585 \times 10^{-6} \times H_{PC} \right)^{5.255863} \right]$$

δ = Pressure Ratio

P_a = Ambient Pressure

H_{PC} = Calibrated Pressure Altitude

$$\sigma = \frac{\delta}{\theta} = \frac{\rho_a}{\rho_{sl}}$$

σ = Density Ratio

δ = Pressure Ratio

θ = Temperature Ratio

ρ_a = Ambient Air Density

ρ_{sl} = Standard Sea Level Density

$$VIW = \frac{V_C}{\sqrt{\frac{W_T}{W_S}}}$$

V_C = Calibrated Airspeed

W_T = The aircraft weight at the time the test data point was collected

W_S = The standard aircraft gross takeoff weight

$$PIW = BHP_T \frac{BHP_T \sqrt{\sigma_T}}{\left(\frac{W_T}{W_S}\right)^{\frac{3}{2}}}$$

BHP_T = The brake horse power at the test point determined from Engine Charts
supplied by the engine manufacturer

σ_T = The density ratio at the time the test point was recorded

W_S = The standard gross takeoff weight of the test aircraft

W_T = The calculated weight of the aircraft at the test point

Equations for Calculating Lift and Drag Coefficients

$$C_L = \frac{2L}{\rho_o VTW^2 S}$$

S = Wing area

$\rho_o = .002377 \frac{\text{Slugs}}{\text{ft}^3}$ = standard sea level density

VIW is obtained from the VIW-PIW curve

In level unaccelerated flight lift is equal to weight therefore the equation can be written:

$$C_L = \frac{2W_S}{\rho_o VTW^2 S}$$

Where W_S is equal to the standard gross takeoff weight.

In order to determine the drag coefficient C_D it is necessary to calculate the thrust required (F_R). In order to calculate F_R an assumption is made that the propeller efficiency is a constant value of .83. This assumption was determined from Dr. Ralph Kimberlin's textbook entitled Performance Flight Testing. Using the values obtained in the PIW-

VIW normalization curve the following equation can be used to calculate the thrust required.

$$F_R = \frac{550PIW\eta_P}{VIW}$$

Where $\eta_P = .83$

In level unaccelerated flight, thrust is equal to drag, therefore the equation for calculating the drag coefficient is written as:

$$CD = \frac{2D}{\rho_o VIW^2 S} = \frac{2F_R}{\rho_o VIW^2 S}$$

D = Drag

Oswald's Efficiency Factor

Oswalds efficiency factor is calculated using the following equation:

$$e = \frac{1}{\pi AR \frac{dCD}{dC_L^2}}$$

AR = The aspect Ratio of the Wing

$\frac{dCD}{dC_L^2}$ = The slope of the CD versus C_L^2 line

APPENDIX F

Data Reduction Tables

Calculations for the Baseline Configuration Flight Test

Table F.1. Instrument Correction for Airspeed, Altitude, and Temperature Computations Along With Pressure and Density Ratios for Baseline Configuration

RUN#	V _b	V _c	V _C	H _b	H _c	T _b	T _c	T _C	δ	θ	σ
1	1730	1735	1735	3250	3270	158	2890	281.7	0.8873	0.9775	0.9078
2	1700	1705	170	3100	3120	161	2893	2820	0.8923	0.9785	0.9118
3	1650	1655	165	3000	3020	164	2896	2822	0.8955	0.9792	0.9146
4	1570	158	157	3000	3020	165	2897	2822	0.8955	0.9792	0.9146
5	1500	151	149	3000	3020	162	2894	2822	0.8955	0.9792	0.9146
6	1400	141.5	139.5	3000	3020	158	2890	2822	0.8955	0.9792	0.9146
7	1330	135	133	2800	2820	157	2889	2826	0.9022	0.9806	0.9200
8	1200	1223	1203	2800	2820	158	2890	2826	0.9022	0.9806	0.9200
9	1090	111.6	108.6	2800	2820	159	2891	2826	0.9022	0.9806	0.9200
10	950	98	95	2800	2820	158	2890	2826	0.9022	0.9806	0.9200
11	840	87	84	2800	2820	157	2889	2826	0.9022	0.9806	0.9200
1	1740	1745	1745	5500	5530	152	2884	277.2	0.8157	0.9520	0.8479
2	1700	1705	170	5500	5530	15	2882	277.2	0.8157	0.9520	0.8479
3	1650	1655	165	5500	5530	147	2879	277.2	0.8157	0.9520	0.8479
4	1570	158	157	5500	5530	147	2879	277.2	0.8157	0.9520	0.8479
5	1510	152	150	5500	5530	14	2872	277.2	0.8157	0.9520	0.8479
6	1430	144.5	142.5	5500	5530	135	2867	277.2	0.8157	0.9520	0.8479
7	1370	139	137	5400	5430	139	287.1	277.4	0.8187	0.9527	0.8505
8	1220	1243	1223	5200	5230	141	287.3	277.8	0.8249	0.9540	0.8557
9	1170	1196	1176	5200	5230	141	287.3	277.8	0.8249	0.9540	0.8557
10	1020	1035	1005	5200	5230	14	287.2	277.8	0.8249	0.9540	0.8557
11	880	91	88	5200	5230	141	287.3	277.8	0.8249	0.9540	0.8557
12	830	86	83	5200	5230	141	287.3	277.8	0.8249	0.9540	0.8557

Table F.2. Power and Weight calculations for the Baseline Configuration

RRM _L	RRM _R	MP _O	HP _{ALT}	HP _{ALT}	HP _{TEMP CORR}	Fuel	W _{FUEL}	W _f	W _g
2400	2400	32.5	240	480	473.92	189	1134	6274.74	6247.74
2400	2400	30.5	230	460	454.17	187	1122	6262.74	6247.74
2400	2400	28.8	212	424	418.56	185	1110	6250.74	6247.74
2400	2400	27	196	392	386.90	183	1098	6238.74	6247.74
2400	2400	25	180	360	355.50	181	1086	6226.74	6247.74
2400	2400	22.8	175	350	345.87	180	1080	6220.74	6247.74
2400	2400	21.2	150	300	296.72	179	1074	6214.74	6247.74
2400	2400	19	138	276	272.93	178	1068	6208.74	6247.74
2400	2400	17	120	240	237.29	177	1062	6202.74	6247.74
2400	2400	15.5	110	220	217.56	177	1062	6202.74	6247.74
2400	2400	16.5	115	230	227.48	176	1056	6196.74	6247.74
2400	2400	33.5	259	518	507.88	169	1014	6154.74	6247.74
2400	2400	31.5	245	490	480.59	168	1008	6148.74	6247.74
2400	2400	29.7	245	490	480.85	167	1002	6142.74	6247.74
2400	2400	27.7	205	410	402.34	165	990	6130.74	6247.74
2400	2400	25.8	190	380	373.35	164	984	6124.74	6247.74
2400	2400	24	175	350	344.18	162	972	6112.74	6247.74
2400	2400	22	170	340	334.23	159	954	6094.74	6247.74
2400	2400	20.3	145	290	285.18	158	948	6088.74	6247.74
2400	2400	18	128	256	251.75	157	942	6082.74	6247.74
2400	2400	16	115	230	226.22	156	936	6076.74	6247.74
2400	2400	14.7	95	190	186.84	156	936	6076.74	6247.74
2400	2400	17	110	220	216.35	155	930	6070.74	6247.74

Table F.3. PIW and VIW Normalization Calculations for the Baseline Configuration

PIW	VIW	PIW/VIW	VIW ²	VIW ² _{min}	PIW/VIW _{min}	VIW _{min}	PIW _{min}
448.62	173.13	7767.6	89354004.6	10000000	85037	177.83	478.20
432.13	169.80	73374.8	83121398.6	95000000	81537	175.56	464.43
399.99	164.95	65983.1	740489327.4	90000000	78037	173.21	450.55
370.81	157.11	58258.9	609327434.4	85000000	74537	170.75	436.53
341.70	149.25	50999.1	496214563.0	80000000	71037	168.18	422.39
332.92	139.80	46543.0	381995833.8	75000000	67537	165.49	408.11
286.88	133.35	38256.0	316232522.0	70000000	64037	162.66	393.69
264.27	120.68	31890.8	212080851.5	55000000	53537	153.14	349.59
230.09	110.00	25309.1	146393218.2	50000000	50037	149.53	334.62
210.95	95.34	20113.0	82636737.5	45000000	46537	145.65	319.52
220.90	84.34	18631.7	50510017.9	40000000	43037	141.42	304.32
478.31	175.81	84093.0	955450514.3	35000000	39537	136.78	289.06
453.27	171.36	77674.3	862321715.9	30000000	36037	131.61	273.82
454.17	167.41	76034.5	785514082.9	20000000	29037	118.92	244.17
381.14	158.49	60407.2	630984526.0	10000000	22037	100.00	220.37
354.20	151.50	53661.0	526787690.0	90000000	21337	97.40	219.06
327.48	144.06	47179.0	430758152.7	80000000	20637	94.57	218.21
319.92	138.71	44375.1	370184131.2	70000000	19937	91.47	217.96
274.20	123.89	33970.2	235557461.6	60000000	19237	88.01	218.57
242.41	119.18	28892.0	201779330.3	50000000	18537	84.09	220.44
218.15	101.90	22230.9	107837257.2	40000000	17837	79.53	224.29
180.18	89.23	16077.7	63392119.8	30000000	17137	74.01	231.56
208.94	84.20	17593.2	50266077.8	20000000	16437	66.87	245.79

Table F.4. Lift Coefficients, Thrust, Lift to Drag Ratio, Range and Endurance Calculations for the Baseline Configuration

C_L	C_L^2	F_R	C_D	L/D	V_{RANGE}	P_{RANGE}
0.2559	0.0655	727.32	0.0298	8.63	0	0
0.2621	0.0687	715.50	0.0300	8.75	120	240
0.2687	0.0722	703.55	0.0303	8.88		
0.2760	0.0762	691.48	0.0307	9.02	$V_{ENDURANCE}$	$P_{ENDURANCE}$
0.2839	0.0806	679.29	0.0311	9.17	0	215
0.2930	0.0858	667.01	0.0315	9.33	90	215
0.3030	0.0918	654.64	0.0320	9.49		
0.3415	0.1166	617.43	0.0341	10.06	L/D MAX	CL
0.3578	0.1280	605.24	0.0350	10.25	11	0.56
0.3771	0.1422	593.35	0.0362	10.45		
0.3996	0.1597	582.01	0.0376	10.65		
0.4243	0.1800	571.59	0.0395	10.77		
0.4579	0.2096	562.74	0.0420	10.93		
0.5602	0.3139	555.34	0.0508	11.06		
0.7907	0.6253	596.03	0.0771	10.29		
0.8327	0.6934	608.32	0.0830	10.07		
0.8815	0.7770	624.05	0.0903	9.80		
0.9396	0.8828	644.51	0.0997	9.46		
1.0138	1.0279	671.71	0.1122	9.06		
1.1095	1.2310	709.04	0.1297	8.58		
1.2393	1.5368	762.80	0.1560	7.97		
1.4310	2.0477	846.24	0.1999	7.18		
1.7508	3.0655	994.09	0.2876	6.11		

Calculations for the 60-Degree Strake Configuration Flight Test

Table F.5. Instrument Correction for Airspeed, Altitude, and Temperature Computations Along With Pressure and Density Ratios for the 60-Degree Strake Configuration

RUN#	V ₀	V _c	V _C	H ₀	H _{0c}	T ₀	T _a	T _s	δ	θ	σ
1	175.0	175.5	175.5	3000	3020	16.4	289.56	282.177	0.8986	0.9792	0.9146
2	168.0	168.5	168	3000	3020	16.2	289.36	282.177	0.8986	0.9792	0.9146
3	163.0	163.5	163	3000	3020	16.3	289.46	282.177	0.8986	0.9792	0.9146
4	156.0	157	156	3000	3020	16.2	289.36	282.177	0.8986	0.9792	0.9146
5	147.0	148	146	3000	3020	15.8	288.96	282.177	0.8986	0.9792	0.9146
6	139.0	140.5	138.5	3000	3020	15.8	288.96	282.177	0.8986	0.9792	0.9146
7	129.0	131	129	3000	3020	15.5	288.66	282.177	0.8986	0.9792	0.9146
8	121.0	123.3	121.3	3000	3020	15.4	288.56	282.177	0.8986	0.9792	0.9146
9	109.0	111.6	109.6	2800	2820	15.4	288.56	282.573	0.9022	0.9806	0.9200
10	98.0	96	93	2800	2820	15	288.16	282.573	0.9022	0.9806	0.9200
11	86.0	88	86	2800	2820	14.8	287.96	282.573	0.9022	0.9806	0.9200
1	174.0	174.5	174.5	5700	5730	15.8	288.96	276.808	0.8096	0.9606	0.8428
2	170.0	170.5	170	5700	5730	15.3	288.46	276.808	0.8096	0.9606	0.8428
3	166.0	166.5	166	5700	5730	15.2	288.36	276.808	0.8096	0.9606	0.8428
4	159.0	160	159	5700	5730	15	288.16	276.808	0.8096	0.9606	0.8428
5	154.0	155	153	5700	5730	15.1	288.26	276.808	0.8096	0.9606	0.8428
6	147.0	148.5	146.5	5700	5730	15	288.16	276.808	0.8096	0.9606	0.8428
7	136.0	137	136	5700	5730	14.5	287.66	276.808	0.8096	0.9606	0.8428
8	129.0	131.3	129.3	5700	5730	14.6	287.76	276.808	0.8096	0.9606	0.8428
9	121.0	123.6	121.6	5700	5730	14.5	287.66	276.808	0.8096	0.9606	0.8428
10	102.0	103.5	100.5	5700	5730	14.2	287.36	276.808	0.8096	0.9606	0.8428
11	90.0	93	90	5600	5630	14.2	287.36	277.204	0.8157	0.9620	0.8479
12	80.0	83	80	5600	5630	14	287.16	277.204	0.8157	0.9620	0.8479

Table F.6. Power and Weight calculations for the 60-Degree Strake Configuration

RPM _L	RPM _R	MP _O	HP _{ALT}	HP _{ALT}	HP _{TEMP CORR}	Fuel	W _{FUEL}	W _T	W _S
2400	2400	32.5	240	480	473.84	189	1134	6274.74	6274.74
2400	2400	30.5	225	450	444.38	187	1122	6262.74	6274.74
2400	2400	28.7	212	424	418.63	184	1104	6244.74	6274.74
2400	2400	27	195	390	385.13	182	1092	6232.74	6274.74
2400	2400	24.7	175	350	345.87	181	1086	6226.74	6274.74
2400	2400	23	165	330	326.10	179	1074	6214.74	6274.74
2400	2400	21	145	290	286.72	178	1068	6208.74	6274.74
2400	2400	19	132	264	261.06	178	1068	6208.74	6274.74
2400	2400	17	115	230	227.60	176	1056	6196.74	6274.74
2400	2400	15.7	105	210	207.95	176	1056	6196.74	6274.74
2400	2400	17	115	230	227.84	175	1050	6190.74	6274.74
2400	2400	33.5	248	496	485.46	167	1002	6142.74	6274.74
2400	2400	31.4	235	470	460.41	166	996	6136.74	6274.74
2400	2400	29.3	215	430	421.30	164	984	6124.74	6274.74
2400	2400	27.7	198	396	388.12	163	978	6118.74	6274.74
2400	2400	26.1	189	378	370.42	160	960	6100.74	6274.74
2400	2400	23.7	170	340	333.24	159	954	6094.74	6274.74
2400	2400	22	155	310	304.10	158	948	6088.74	6274.74
2400	2400	20.3	140	280	274.62	157	942	6082.74	6274.74
2400	2400	17.7	118	236	231.51	156	936	6076.74	6274.74
2400	2400	16	110	220	215.92	155	930	6070.74	6274.74
2400	2400	14.5	90	180	176.79	155	930	6070.74	6274.74
2400	2400	17	115	230	225.98	155	930	6070.74	6274.74

Table F.7. PIW and VIW Normalization Calculations for the 60-Degree Strake Configuration

PIW	VIW	PIW _{VIW}	VIW ²	VIW _{VIW}	PIW _{VIW} _{norm}	VIW _{norm}	PIW _{norm}
453.15	175.50	79627.6	948655400.1	100000000	84332	177.83	474.23
426.20	168.16	71669.5	799649799.6	95000000	80832	175.56	460.42
403.24	163.39	65885.7	712710513.6	90000000	77332	173.21	446.48
372.04	156.52	58233.4	600249549.1	85000000	73832	170.75	432.40
334.60	146.56	49038.9	461404078.9	80000000	70332	168.18	418.20
316.39	139.17	44031.1	375097902.3	75000000	66832	165.49	403.85
278.59	129.68	36128.3	282841651.5	70000000	63332	162.66	389.36
253.65	121.94	30931.4	221119847.7	55000000	52832	153.14	344.99
222.45	110.29	24533.3	147947332.0	50000000	49332	149.53	329.90
203.25	93.58	19020.5	76700238.6	45000000	45832	145.65	314.68
223.00	85.57	19083.5	53626819.9	40000000	42332	141.42	299.33
460.10	176.36	81146.2	967495443.2	35000000	38832	136.78	283.90
437.00	171.90	75121.3	873195941.6	30000000	35332	131.61	268.47
401.06	167.01	66979.8	777950443.1	20000000	28332	118.92	238.24
370.02	161.01	59578.0	672134160.9	10000000	21332	100.00	213.32
354.70	155.17	55037.7	579685130.0	9000000	20632	97.40	211.83
319.57	148.66	47503.3	488238027.1	8000000	19932	94.57	210.76
292.06	137.05	40025.4	352753787.6	7000000	19232	91.47	210.26
264.14	131.32	34687.8	297431569.6	6000000	18532	88.01	210.56
223.00	123.57	27564.9	233122644.0	5000000	17832	84.09	212.06
208.30	102.17	21282.7	108986436.0	4000000	17132	79.53	215.42
171.07	91.50	15652.6	70093580.0	3000000	16432	74.01	222.03
218.66	81.33	17784.4	43759076.9	2000000	15732	66.87	235.25

Table F.8. Lift Coefficients, Thrust, Lift to Drag Ratio, Range and Endurance Calculations for the 60-Degree Strake Configuration

C_L	C_L^2	F_R	C_D	L/D	V_{RANGE}	P_{RANGE}
0.2559	0.0655	721.29	0.0295	8.70	0	0
0.2621	0.0687	709.32	0.0298	8.83	118	235
0.2685	0.0721	697.20	0.0301	8.96	$V_{ENDURANCE}$	$P_{ENDURANCE}$
0.2757	0.0760	684.94	0.0304	9.10	93	209
0.2840	0.0806	672.55	0.0308	9.26	0	209
0.2927	0.0857	660.04	0.0312	9.42		
0.3027	0.0916	647.43	0.0317	9.59		
0.3415	0.1166	609.30	0.0336	10.19	93	209
0.3575	0.1278	596.71	0.0345	10.38	93	209
0.3768	0.1420	584.36	0.0356	10.60		
0.3993	0.1594	572.48	0.0370	10.81		
0.4235	0.1794	561.40	0.0388	10.94	L/D MAX	C_L
0.4570	0.2089	551.73	0.0412	11.12	11.3	0.559
0.5586	0.3121	541.85	0.0496	11.30		
0.7892	0.6229	576.97	0.0746	10.61		
0.8295	0.6880	588.22	0.0802	10.37		
0.8789	0.7725	602.73	0.0872	10.11		
0.9387	0.8811	621.72	0.0961	9.79		
1.0129	1.0260	647.09	0.1081	9.40		
1.1085	1.2287	682.08	0.1248	8.91		
1.2381	1.5329	732.65	0.1499	8.29		
1.4296	2.0439	811.42	0.1916	7.48		
1.7509	3.0658	951.45	0.2752	6.38		

Calculations for the 75-Degree Strake Configuration Flight Test

Table F.9. Instrument Correction for Airspeed, Altitude, and Temperature Computations Along With Pressure and Density Ratios for the 75-Degree Strake Configuration

RN#	V ₀	V _c	V _C	H ₀	H _c	T ₀	T _a	T _s	δ	θ	σ
1	177.0	177.5	177.5	2750	2770	168	2800	2827	0.9089	0.9810	0.9214
2	1730	1735	173	2800	2820	17	2802	2830	0.9089	0.9820	0.9236
3	1660	1665	166	2850	2870	167	2809	2829	0.9072	0.9816	0.9242
4	1590	160	159	2700	2720	161	2803	2828	0.9065	0.9813	0.9228
5	1550	156	154	2800	2870	161	2803	2829	0.9072	0.9816	0.9242
6	147.0	1485	1465	2800	2870	16	2802	2831	0.9106	0.9823	0.9289
7	1360	138	136	2800	2820	157	2809	2832	0.9122	0.9827	0.9283
8	1250	1273	1253	2800	2820	156	2808	2832	0.9122	0.9827	0.9283
9	1180	1206	1186	2400	2420	156	2808	2834	0.9156	0.9834	0.9311
10	107.0	110	107	2400	2420	152	2804	2834	0.9156	0.9834	0.9311
11	950	98	95	2350	2370	152	2804	2835	0.9173	0.9837	0.9325
12	850	855	855	2400	2430	152	2804	2833	0.9163	0.9833	0.9303
1	1720	1725	1725	7200	7230	15	2802	2738	0.7649	0.9503	0.8049
2	167.0	1675	167	7200	7230	145	2877	2738	0.7649	0.9503	0.8049
3	1600	1605	160	7300	7380	147	2879	2735	0.7606	0.9488	0.8012
4	157.0	158	157	7400	7430	137	2869	2734	0.7591	0.9489	0.8000
5	1510	152	150	7400	7430	135	2867	2734	0.7591	0.9489	0.8000
6	1450	1465	1445	7400	7430	134	2866	2734	0.7591	0.9489	0.8000
7	1360	138	136	7400	7430	132	2864	2734	0.7591	0.9489	0.8000
8	127.0	1293	1273	7300	7330	13	2862	2736	0.7620	0.9486	0.8025
9	1130	1156	1136	7300	7330	129	2861	2736	0.7620	0.9486	0.8025
10	1000	1015	985	7200	7280	125	2857	2737	0.7635	0.9489	0.8037
11	900	98	90	7200	7280	125	2857	2737	0.7635	0.9489	0.8037
12	820	85	82	7200	7230	125	2857	2738	0.7649	0.9503	0.8049

Table F.10. Power and Weight calculations for the 75-Degree Strake Configuration

RPM _L	RPM _R	MP _O	HP _{ALT}	HP _{ALT}	HP _{TEMP CORR}	Fuel	W _{FUEL}	W _L	W _R
2400	2400	35	250	500	493.68	190	1140	6280.74	6247.74
2400	2400	33	230	460	454.26	188	1128	6268.74	6247.74
2400	2400	31	210	420	414.91	187	1122	6262.74	6247.74
2400	2400	29	193	386	381.65	184	1104	6244.74	6247.74
2400	2400	27	175	350	346.11	183	1098	6238.74	6247.74
2400	2400	25	173	346	342.34	182	1092	6232.74	6247.74
2400	2400	23	148	296	293.07	181	1086	6226.74	6247.74
2400	2400	21	135	270	267.37	180	1080	6220.74	6247.74
2400	2400	19	121	242	239.73	179	1074	6214.74	6247.74
2400	2400	17	112	224	222.05	178	1068	6208.74	6247.74
2400	2400	15	100	200	198.30	177	1062	6202.74	6247.74
2400	2400	17.5	114	228	226.01	168	1008	6148.74	6247.74
2400	2400	34	245	490	477.67	166	996	6136.74	6247.74
2400	2400	31.5	240	480	468.32	164	984	6124.74	6247.74
2400	2400	30	238	476	464.01	163	978	6118.74	6247.74
2400	2400	27.5	200	400	390.53	162	972	6112.74	6247.74
2400	2400	25.5	185	370	361.37	161	966	6106.74	6247.74
2400	2400	24	170	340	332.13	160	960	6100.74	6247.74
2400	2400	22	168	336	328.33	159	954	6094.74	6247.74
2400	2400	20	143	286	279.67	158	948	6088.74	6247.74
2400	2400	18	126	252	246.47	157	942	6082.74	6247.74
2400	2400	15.5	112	224	219.28	156	936	6076.74	6247.74
2400	2400	13.5	93	186	182.08	155	930	6070.74	6247.74
2400	2400	16	105	210	205.61	155	930	6070.74	6247.74

Table F.11. PIW and VIW Normalization Calculations for the 75-Degree Strake Configuration

PIW	VIW	PIW ² VIW	VIW ²	VIW ² _{UL}	PIW ² VIW _{ORM}	VIW _{ORM}	PIW _{ORM}
470.15	177.03	83232.7	98240177.7	100000000	83687	177.83	470.61
434.83	172.71	75100.1	88975361.2	98000000	80187	175.56	456.74
397.43	165.80	65894.7	75700107.4	90000000	76687	173.21	442.75
366.88	159.04	58348.3	639743189.1	85000000	73187	170.75	428.63
333.45	154.11	51388.6	54072802.2	80000000	69687	168.18	414.36
330.78	146.68	48517.9	462847981.1	75000000	66187	165.49	399.95
283.80	136.23	38661.6	344413420.3	70000000	62687	162.66	385.39
259.29	125.57	32559.4	248637184.8	55000000	52187	153.14	340.78
233.17	118.91	27726.7	199957972.2	50000000	48687	149.53	325.59
216.29	107.34	23215.1	132731517.6	45000000	45187	145.65	310.25
193.57	95.34	18455.7	82635737.5	40000000	41687	141.42	294.77
223.34	86.19	19248.4	55174460.7	35000000	38187	136.78	279.19
440.23	174.05	76623.5	917755184.6	35000000	38187	136.78	279.19
432.89	168.67	73014.9	809350177.2	30000000	34687	131.61	263.56
428.54	161.68	69285.5	683284907.4	20000000	27687	118.92	232.82
360.93	158.72	57288.7	634706079.3	10000000	20687	100.00	206.87
334.47	151.72	50746.6	529897746.4	9000000	19987	97.40	205.20
307.86	146.23	45018.4	457248459.6	8000000	19287	94.57	203.94
304.79	137.70	41968.9	359433599.6	7000000	18587	91.47	203.21
260.41	128.95	33579.8	276506058.9	6000000	17887	88.01	203.24
229.83	115.13	26460.3	175685530.9	5000000	17187	84.09	204.39
204.93	99.88	20468.0	99506054.9	4000000	16487	79.53	207.31
170.42	91.30	15559.8	69491657.0	3000000	15787	74.01	213.31
192.59	83.19	16021.2	47887045.1	2000000	15087	66.87	225.60

Table F.12. Lift Coefficients, Thrust, Lift to Drag Ratio, Range and Endurance Calculations for the 75-Degree Strake Configuration

C_L	C_L^2	F_R	C_D	L/D	V_{RANGE}	P_{RANGE}
0.2562	0.0656	715.77	0.0293	8.77	0	0
0.2623	0.0688	703.66	0.0295	8.91	117	231
0.2693	0.0725	691.38	0.0298	9.06		
0.2763	0.0763	678.96	0.0301	9.20	$V_{ENDURANCE}$	$P_{ENDURANCE}$
0.2845	0.0809	666.38	0.0305	9.36	0	205
0.2935	0.0862	653.67	0.0309	9.53	95	205
0.3036	0.0921	640.84	0.0313	9.72		
0.3421	0.1170	601.87	0.0332	10.34	L/D MAX	CL
0.3585	0.1285	588.91	0.0341	10.55	11.558	0.56
0.3775	0.1425	576.14	0.0351	10.78		
0.4000	0.1600	563.75	0.0365	11.00		
0.4239	0.1797	552.08	0.0382	11.14		
0.4231	0.1790	552.08	0.0382	11.12		
0.4561	0.2080	541.66	0.0405	11.31		
0.5580	0.3114	529.52	0.0484	11.56		
0.7884	0.6216	559.52	0.0724	10.92		
0.8302	0.6893	569.83	0.0777	10.72		
0.8797	0.7740	583.23	0.0844	10.46		
0.9396	0.8828	600.87	0.0929	10.14		
1.0138	1.0279	624.57	0.1043	9.75		
1.1095	1.2310	657.41	0.1203	9.25		
1.2393	1.5358	705.07	0.1442	8.62		
1.4296	2.0436	779.57	0.1841	7.79		
1.7508	3.0655	912.44	0.2639	6.65		

APPENDIX G

Navajo Weight and Balance Information

Baseline Configuration

Table F.1. Weight and Balance for the Baseline Configuration

Whieght and Balance N11UT				
Piper PA-31, Navajo				
Date:				
Aircraft Tail Number:		N11UT		
pilot:		Dr. Kimberlin		
Configuration:		clean		
CG location:		131.1		
Total Weight:		6165.74		
Position:		center left		
Flight Test		BASELINE		
Item	Weight lbs.	fuel gallons	Arm-Inches	Moment
Basic Aircraft	4570.74		128.0	585237.5496
Pilots Seat	185		119.0	22015
copilots seat			119.0	0
seat 3	155		159.0	24645
sear 4	180		159.0	28620
seat 5			198.0	0
seat 6			198.0	0
seat 7			229.0	0
seat 8			242.0	0
inb fuel	420	70	126.8	53256
out board fuel	630	105	148.0	93240
Fwd Nacelle Baggage	25		43.0	1075
Total Weight	6165.74		131.1	808088.5496

60-Degree Strake Configuration

Table F.2. Weight and Balance for the 60-Degree Starke Configuration

Weight and Balance N11UT				
Piper PA-31, Navajo				
Date:				
Aircraft Tail Number:		N11UT		
pilot:		Dr. Kimberlin		
Configuration:		clean		
CG location:		131.1		
Total Weight:		6165.74		
Position:		center left		
Flight Test		60-DEGREE STRAKES		
Item	Weight lbs.	fuel gallons	Arm-Inches	Moment
Basic Aircraft	4570.74		128.0	585237.5496
Pilots Seat	185		119.0	22015
copilots seat			119.0	0
seat 3	155		159.0	24645
sear 4	180		159.0	28620
seat 5			198.0	0
seat 6			198.0	0
seat 7			229.0	0
seat 8			242.0	0
inb fuel	420	70	126.8	53256
out board fuel	630	105	148.0	93240
Fwd Nacelle Baggage	25		43.0	1075
Total Weight	6165.74		131.1	808088.5496

75-Degree Strake Configuration

Table F.3. Weight and Balance for the 75-Degree Strake Configuration

Weight and Balance N11UT				
Piper PA-31, Navajo				
Date:				
Aircraft Tail Number:		N11UT		
pilot:		Dr. Kimberlin		
Configuration:		clean		
CG location:		131.1		
Total Weight:		6165.74		
Position:		center left		
Flight Test		75-DEGREE STRAKES		
Item	Weight lbs.	fuel gallons	Arm-Inches	Moment
Basic Aircraft	4570.74		128.0	585237.5496
Pilots Seat	185		119.0	22015
copilots seat			119.0	0
seat 3	155		159.0	24645
sear 4	180		159.0	28620
seat 5			198.0	0
seat 6			198.0	0
seat 7			229.0	0
seat 8			242.0	0
inb fuel	420	70	126.8	53256
out board fuel	630	105	148.0	93240
Fwd Nacelle Baggage	25		43.0	1075
Total Weight	6165.74		131.1	808088.5496

VITA

Bryan Lloyd Bingham was born on March 30, 1977 in New Orleans, Louisiana. He is the son of Lloyd and Leslie Bingham of New Orleans, Louisiana. Bryan attended a private school in New Orleans named Country Day from kindergarten to seventh grade. In seventh grade he began attending another private school in New Orleans named Ridgewood Preparatory School. He graduated from the Ridgewood Preparatory School with honors and as a member of Who's Who in America in 1995.

Bryan went on to attend Middle Tennessee State University (MTSU) in Murfreesboro, Tennessee in the fall of 1995. While at MTSU Bryan explored all aspects of aviation receiving a Pilots certificate, an Airframe and Powerplant Technicians Certificate, and a Bachelors of Science degree in Aerospace in the spring of 2000. Throughout his undergraduate education, Bryan worked as an airplane technician predominantly working on General aviation aircraft.

After completing his undergraduate education, Bryan began taking classes at the University of Tennessee Space Institute in Tullahoma, TN in the summer of 2000. He graduated from the University of Tennessee Space Institute in May of 2002 with a Masters of Science Degree in Aviation Systems. Bryan plans to pursue a career in Aerospace as a college professor at Middle Tennessee State University and hopefully go on to receive a PhD.

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