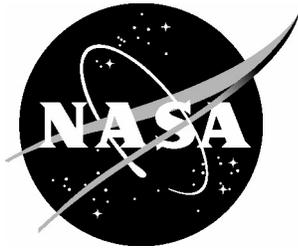


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# Active Tailoring of Lift Distribution to Enhance Cruise Performance

*Neal J. Pfeiffer and Joel G. Christians  
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April 2005

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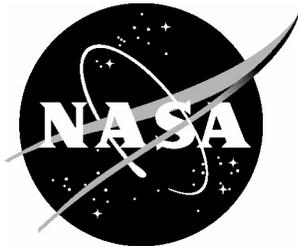
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## Summary

During Phase I of this project, Raytheon Aircraft Company (RAC) has analytically and experimentally evaluated key components of a system that could be implemented for active tailoring of wing lift distribution using low-drag, trailing-edge modifications. Simple systems such as those studied by RAC could be used to enhance the cruise performance of a business jet configuration over a range of typical flight conditions. The trailing-edge modifications focus on simple, deployable mechanisms comprised of extendable small flap panels over portions of the span that could be used to subtly but positively optimize the lift and drag characteristics. Of key importance is that the proposed system implements the basic elements of “morphing” in a practical, first-order application to an existing aircraft configuration.

This research is funded by the NASA Langley Research Center under NRA 03-LaRC-02, “Maturation of Advanced Aerodynamic and Structures Technologies for Subsonic Transport Air Vehicles.” The project directly addresses the reduced-emissions objectives of the NASA Twenty-First Century Technology Program (TCAT) through reduced cruise drag.

Under contract NNL04AA34C, Raytheon Aircraft Company (RAC) completed the necessary analytical and experimental evaluation to demonstrate a technology readiness level (TRL) of 3 for a trailing-edge device to improve cruise characteristics by completing the following tasks:

- 1) Complete a literature review. Many reports from academia, industry and government agencies were reviewed during the process of generating design concepts.
- 2) Develop initial concepts. 4 concepts were identified for study based on the literature review as well as RAC experience.
- 3) Complete a first-order analytical study aimed at targeting an initial, optimal lift-distribution schedule. A preliminary analysis of several concepts was completed using computational fluid dynamics (CFD).
- 4) Down-Select concepts. Prior to wind tunnel testing, four concepts were selected for low speed aerodynamic testing. One configuration, the cruise tab, was later selected based on wind tunnel data and CFD analysis.
- 5) Develop a mechanization scheme. Concepts for mechanizing the trailing edge devices were created to determine the feasibility of each design under consideration.
- 6) Develop a set of trailing-edge lofts. Solid models of seven different configurations (4 concepts with multiple deflections and sizes) were generated.
- 7) Modify an existing wind-tunnel model of the Premier I and conduct a basic low-speed test. A low-speed model was modified and a successful test completed collecting data from 4 configurations with deflections.
- 8) Prepare a final report and briefing. This document serves as the final report for Phase I of this study and compliments the oral presentation given at NASA Langley Research Center in August of 2004.

Several concepts such as the trailing-edge wedge and distributed wedges were eliminated from the study based on wind tunnel data. A slotted wing concept may be viable, possibly warranting further investigation beyond what the scope of this study allowed. The cruise tab concept yielded reduced aircraft drag and could be practically integrated in a marketable aircraft. Given the positive indications in aerodynamic performance of the cruise tab, technology benefits have been assessed for the cruise tab and are presented in this report.

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## List of Nomenclature

<u>SYMBOL</u>	<u>DESCRIPTION</u>	<u>UNITS</u>
$\alpha$ , AOA	Angle of attack	degree
$C_D$	Drag coefficient	~
$C_{D_0}$	Zero lift drag coefficient	~
$C_{D_i}$	Lift induced drag coefficient	~
$C_L$	Lift coefficient	~
e	Oswald efficiency factor	~
L/D	Lift-to-drag ratio	~
K	Lift induced drag coefficient	~
M	Mach number	~

## List of Acronyms

AIAA	American Institute of Aeronautics and Astronautics
AVST	Aerospace Vehicle Systems Technology
B&CA	Business & Commercial Aviation Magazine
CFD	Computational Fluid Dynamics
DTE	Divergent Trailing Edge
IFR	Instrument Flight Rules
MSES	A coupled viscous/inviscid Euler method for CFD analysis
NASA	National Aeronautics and Space Administration
NBAA	National Business Aircraft Association
VFR	Visual Flight Rules
RAC	Raytheon Aircraft Company
RTM	Resin Transfer Mold
SLA	Stereo-Lithography Apparatus
TCAT	Twenty-First Century Technology Program
TE	Trailing Edge
TRANAIR	Full-potential/boundary-layer coupled code for CFD analysis
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UWAL	University of Washington Aeronautical Laboratory
WSU	Wichita State University

## **1. Introduction**

The Advanced Aerodynamics Technologies topic of the NASA Twenty-First Century Technology (TCAT) Program is directed at achieving “reductions in cruise drag or overall vehicle weight or increases in high lift capability ... of transport/tanker aircraft.” Inherent in this is a goal to reduce overall fuel burn, which feeds directly into the reduced-emissions objective for the NASA Office of Aerospace Technology Enterprise. These goals are to be achieved through manipulation of the flow-field about the aircraft through either passive or active means.

The goal of this specific study was to investigate aircraft drag-reduction concepts that could be readily implemented. This implies that in addition to providing a performance benefit, the concept must result in a product that is manufacturable, certifiable, and maintainable in the field at a cost that customers are willing to accept. In addition, any given concept should be compatible with both transonic transports and business airplanes.

The elements that make up parasite drag are one place to start. Laminar flow is a phenomenon that is proven to reduce skin friction and provide a sizable performance benefit, but it is difficult and costly to achieve on swept-wing, production airplanes in a normal service environment. Flow separations that increase parasite drag are normally eliminated during the development phase of an aircraft. Excrescence drag is dependent in part on the surface finish that is a result of the manufacturing technique. It also depends on the number, shape, and size of all the protuberances required by a modern aircraft.

Most of the common, parasite-drag sources are resolved during an aircraft development program. The remaining major source of drag is the lift-dependent component, which is a combination of the vortex drag due to the trailing wakes and the form-drag component that varies with lift.

Modification of the wing span-load is the fundamental method utilized to alter the lift-dependent drag. A number of trailing-edge modifications have been proposed in the literature to modify this lift-dependent component. Some of these modifications could be utilized on an airplane without major alteration of the airframe design. Others are more complicated and require extensive airframe modification and sophisticated, actuation systems to control their shapes.

## 2. Literature Review

A literature search was conducted to identify potential concepts for active tailoring of lift distribution to improve cruise performance. The following criteria were considered while reviewing the published papers:

- What concepts have been analyzed and/or experimentally tested?
- What concepts have proven successful?
- Which concepts could have a direct application to production aircraft?
- Are there variations to the documented concepts that could be modified for use?
- Which concepts could be practically designed and tested on an existing low-speed wind tunnel model?
- Which concepts could be designed and tested on an existing aircraft test bed in Phase II?

The highest priority was placed on the ability to modify or generate a variation of the concept that could be applied to a general aviation aircraft or subsonic transports. This requirement, coupled with TRL requirements of Phase I and II, assisted in focusing on concepts that could be designed, fabricated, and wind tunnel tested in a six month period and flight tested in 3 years. An additional criterion that had an impact on the down-select was how the concept would be installed on current production aircraft or could be envisioned on new aircraft in the near future.

Approximately sixty-five papers related to controlling lift distribution through active or passive flow control were reviewed. The concepts ranged from simple “low-tech” Gurney flaps (Reference 1) to complex “high-tech” wing morphing using smart technology. Several reports out of NASA Langley were reviewed concerning “morphing” technology. The most helpful was the “AVST Morphing Project Research Summaries in Fiscal Year 2001” (Reference 2) with an entire collection of reports encompassing several different morphing technologies. Several other NASA papers were reviewed and most were found to be on the “high-tech” end of the spectrum very similar in nature to the various reports in the reference mentioned previously.

Papers published by the American Institute of Aeronautics and Astronautics (AIAA) proved to be an excellent source of research covering the full spectrum from low to high technology concepts. Several papers concerning trailing edge devices were reviewed and provided concepts that met several of the above mentioned criteria.

Following the literature review, 4 trailing edge devices with potential to improve aerodynamic characteristics were selected for technical analysis and wind tunnel testing:

- Cruise Tab
- Trailing Edge Wedge
- Distributed Lower-Surface Wedges
- Slotted Flaps

### 3. Concept Study and Down-Select

The purpose of this section is to describe the trailing edge concepts chosen for analysis and testing.

#### 3.1 Cruise Tab

Trailing-edge devices have been utilized by racing sailplanes to achieve the best lift-to-drag ratio for a wide range of flight conditions. They have small-chord flaps across the entire span of the wing that can be deflected slightly trailing edge down for thermaling flight or slightly up for high-speed dash to cover distance on course. This flap motion allows the sailplane to obtain the best combination of lift and drag for a wide range of flight conditions. It can be envisioned that each deflection of the flaps could be considered a separate configuration that produces a distinct drag polar with the minimum drag occurring at varying lift coefficients (see Figure 1).

Sailplanes operate at flight conditions where compressible effects are small; therefore, the drag of the sailplane can be minimized by choosing the appropriate deflection angle to match the indicated airspeed of the glider. This could be done continuously, but typically the sailplane pilot will choose a few flap settings and match a range of airspeed to each.

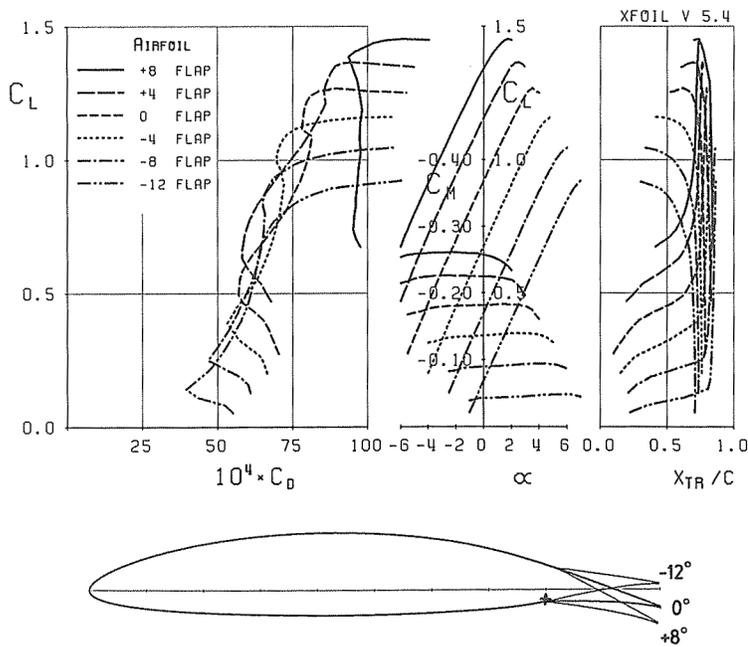


Figure 1 Example of Sailplane Cruise Flap Aerodynamics (Reference 3)

In Reference 4, the authors discuss improvements as much as a 7% increase in range through the use of automated cruise flaps. This improvement is acknowledged with some reservation in that the calculations were done with a natural-laminar-flow airfoil on a low speed UAV.

Business aircraft and jet transports operate at higher wing loadings than sailplanes and are carefully designed to utilize flaps during takeoff and landing to minimize runway requirements. The cruise flap concept can be adapted to a jet aircraft by replacing the aft end of the flap with a movable tab. This tab could be rotated on a simple axis either slightly trailing-edge up or down

again dependent on airspeed. Since the Mach range is higher for a jet, the deflection angle really becomes a function of the aircraft lift coefficient and Mach number. So while there is a single polar for the sailplane case, each tab deflection for a jet would require multiple drag polars or drag-rise modeling to cover the Mach number range. It should also be noted that the conditions for climb should be studied, since improvements in climb would also impact the overall mission performance.

Sailplanes for over forty years have utilized surfaces that can maintain significant amounts of laminar flow. This produces a laminar ‘bucket’ in the drag polars for different cruise-flap deflections. It is very important to optimize the flap deflection so that the drag stays within the ‘bucket’ for nearly all airspeeds. While the effect of laminar flow amplifies the benefit of a cruise tab, the effect is still present for turbulent airfoils.

Modern transonic airfoils can be designed with a ‘flat-rooftop,’ pressure distribution that is favorable for laminar flow. In addition, the use of a small-chord, cruise tab can be used to tailor the location and strength of the shock at transonic conditions. This can allow a wing to have lower wave drag for a wider range of lift coefficient and Mach number.

### **3.2 Trailing-Edge Wedge**

In 1978, Robert Liebeck (Reference 5) introduced the idea of installing a small (1 to 2% of the chord) flat plate perpendicular to the underside of the wing along the trailing edge. Since then, Gurney flaps have been noted widely in the literature as a means to reduce drag. The trapped vortex ahead of the small flat projection provides a flow similar to what would be observed with a small wedge on the lower surface, and a wedge is likely to produce less drag. It should be possible to articulate either a Gurney flap or a trailing edge wedge to optimize its position during flight.

One of the advantages of a trailing wedge, commonly referred to as a divergent trailing edge (DTE), is the possible improvements found over the simple Gurney flap. As reported by Richter and Rosemann (Reference 6), a DTE generates less drag than a Gurney flap of the same height and that at a constant  $C_L$ , the DTE produces a better lift to drag performance. The authors also discuss the importance of sizing the DTE, stating that the device height controls the change in lift and the chord-wise length is used to minimize drag. This study was of special interest because the analysis was done at Mach 0.755, near the high speed cruise of the Premier I.

These results were in agreement with those stated by the authors of Reference 7. They found that generally, when sized properly, several different sizes and shapes of trailing edge wedges and Gurney flaps showed improved L/D in comparison to the baseline airfoil.

The trailing-edge wedge, as proposed in this study, would retract when not needed and deflect in one direction only: upward or downward.

### **3.3 Distributed, Lower-Surface Wedges**

A variation on the Gurney flap is a “serrated” trailing edge device. Work found in the literature proposes the use of a serrated trailing-edge shape can be more efficient than the solid plate Gurney flap.

As reported by Vijgen (Reference 8), an 8% increase was witnessed in  $L/D_{\max}$  when comparing a serrated Gurney flap to a baseline configuration. He believed this was caused by a reduced pressure drag due to “nearly streamwise (axial) vortices immediately downstream of the serrated edges is believed to favorably affect the boundary-layer flow approaching the trailing edge by inducing higher-momentum flow into the flow near the surface and in the wake immediately behind the wing.”

As reported in Reference 9 by Neuhart and Pendergraft, observations from water tunnel tests suggest that additional small vortices are formed by the serrations that when combined by the larger vortices induced by the trailing edge, allow for the boundary layer to remain attached for a longer period.

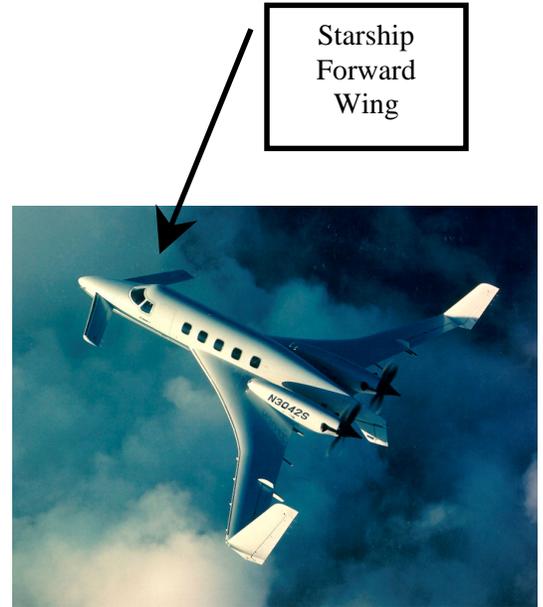
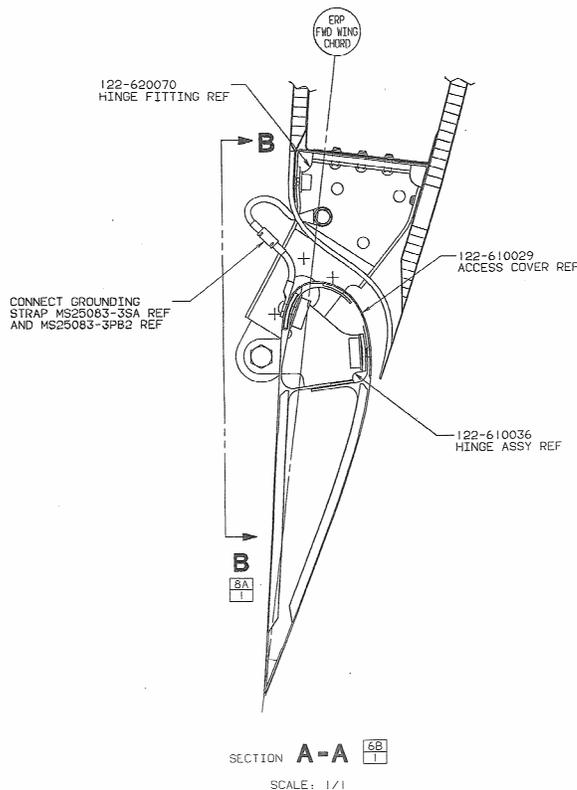
### **3.4 Slotted Flap**

A wing with a slot between the main wing and a flap during cruise was proposed by Richard Whitcomb at NASA in 1970's. His work was very experimentally oriented and this limited the progress that he could make. The CFD methods that are now available allow an optimized, slotted-flap wing to be designed. An optimized wing of this type would have the potential for large runs of laminar flow and decreased shock strength and greater thickness for a given design Mach number or a higher cruise Mach number for a given thickness.

To fully take advantage of this concept requires that a wing be designed with it in mind from the outset.

The advantages of the slotted flap are discussed by Steinbuch and Shepshelovich in Reference 10. Using CFD codes including MSES V2.6, the authors found that small deflections in the flap in high altitude, high-speed cruise conditions could improve maximum lift. It was also determined that the maximum  $L/D$  was found at higher  $C_L$ 's, therefore allowing for better climbing and loitering performance.

The slotted flap has already been demonstrated to a TRL of 10 through its integration into the design of an operational general aviation aircraft. The Beech Model 2000 Starship, designed and produced by Raytheon legacy Beech Aircraft Company, has a slotted elevator on the forward wing. Figure 2 shows the Starship forward wing and a production drawing of the slotted elevator.



**Figure 2 Slotted Elevator on Beech Starship Forward Wing**

## 4. Low Speed Wind Tunnel Test

### 4.1 Test Facilities & Model

A low speed wind tunnel test was completed from June 14<sup>th</sup> through June 18<sup>th</sup>, 2004 at the F. K. Kirsten Wind Tunnel at the University of Washington Aeronautical Laboratory (UWAL). The purpose of the test was to both collect quantitative data and to provide correlation to the CFD analysis.

The model used for this test was the final developmental low-speed wind tunnel model for the Beechcraft Premier I Model 390. The model is a 1/8 scale model originally designed for installation in either the Walter H. Beech Memorial 7 x 10 Foot Low Speed Wind Tunnel at Wichita State University (WSU) or the F. K. Kirsten Wind Tunnel at the University of Washington Aeronautical Laboratories. The model was manufactured by the Raytheon in-house fabrication facilities known as Blue Streak. It includes movable control surfaces and removable flap surfaces with brackets to locate them on the model.

## 4.2 Definition of Test Articles

The 4 concepts discussed in Section 3 were tested on the Premier I model using different deflections or sizes to comprise 7 configurations. The scope of this research project as well as schedule limited the number of variations that could be manufactured and tested. Table 1 describes the configurations tested.

**Table 1 Configurations Tested in Low-Speed Wind Tunnel**

Configuration #	Description	Figure
1	2% Distributed Lower Surface Trailing Edge Wedges	Figure 3
2	2% Lower Surface Trailing Edge Wedge	Figure 4
3	1% Lower Surface Trailing Edge Wedge	Figure 5
4	Thin Lower Surface Trailing Edge Wedge	Figure 6
5	Cruise Tab Down 5 degrees	Figure 7
6	Cruise Tab Up 5 degrees	Figure 8
7	Slotted Flap	Figure 9

The lofts for Configurations 1 through 6 were designed in a similar manner in that only the aft 30% of the flap chord was altered.

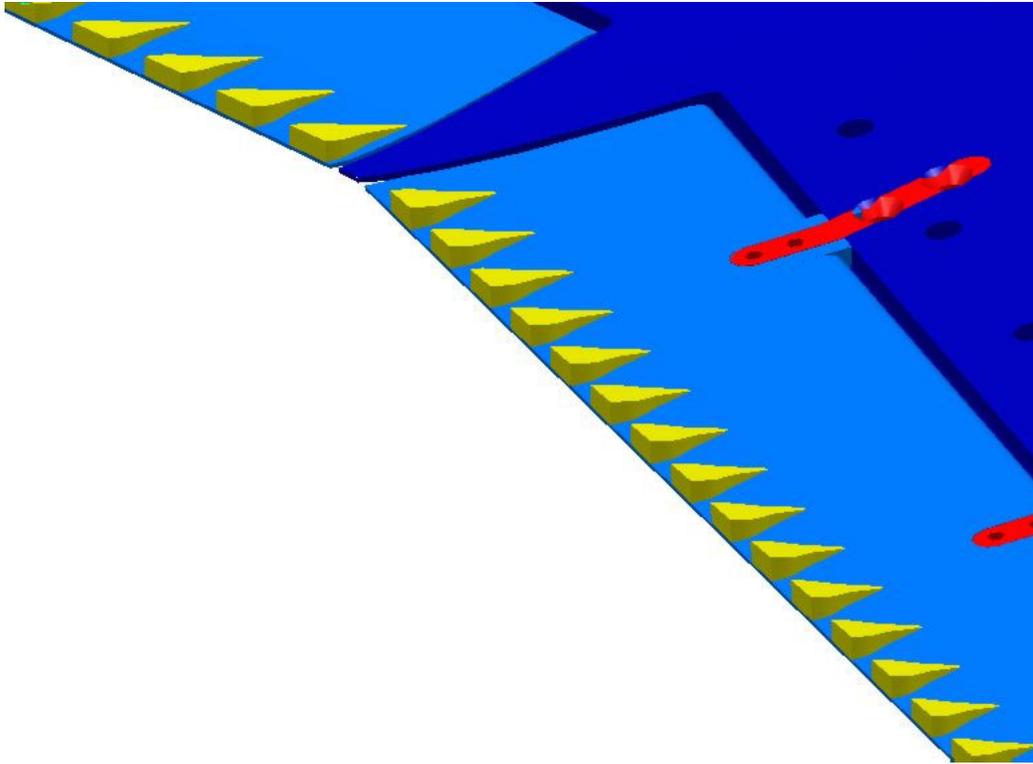
Configuration 1 was created with a trailing edge thickness equal to the 2% trailing edge wedge. The distributed wedges were modeled from NACA scoops with the length equal to 30% flap chord. The wedges (shaped as NACA scoops) protrude into the airflow, as opposed to being recessed into the wing. The spacing between the wedges is set equal to the width of each wedge, as shown in Figure 3.

Configurations 2 and 3 were generated by rotating the lower surface contour about a point at 70% flap chord until the trailing edge thickness was 2% and 1% that of the wing chord, respectively. The upper loft remained unchanged.

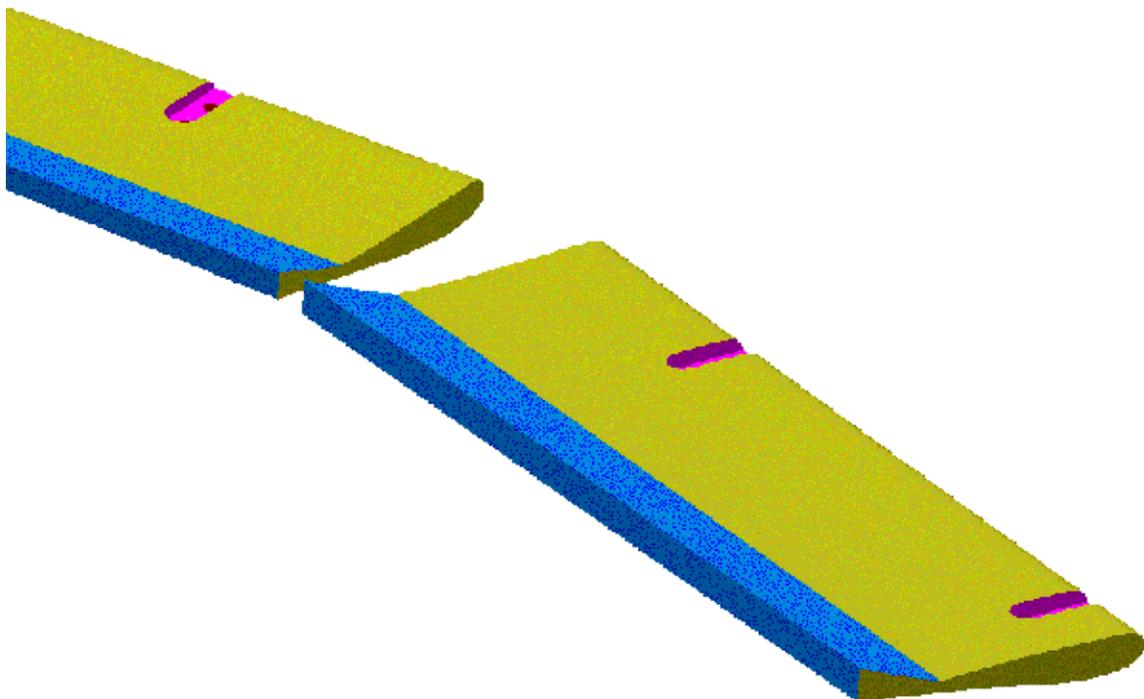
Configuration 4 was defined by maintaining the upper surface of the airfoil to the original loft and setting the lower surface equal to the “Cruise Tab Down” lower surface. This was done to determine, assuming an improvement existed, what part of the contribution was due to the thicker blunt trailing edge (Configuration 4) and what part of the improvement is generated by the new lower surface contour (Configuration 5).

The cruise tab (Configurations 5 and 6) was defined by simply rotating the current loft at the 70% flap chord point by 5 degrees in each direction. There were no additional changes made to the loft shape.

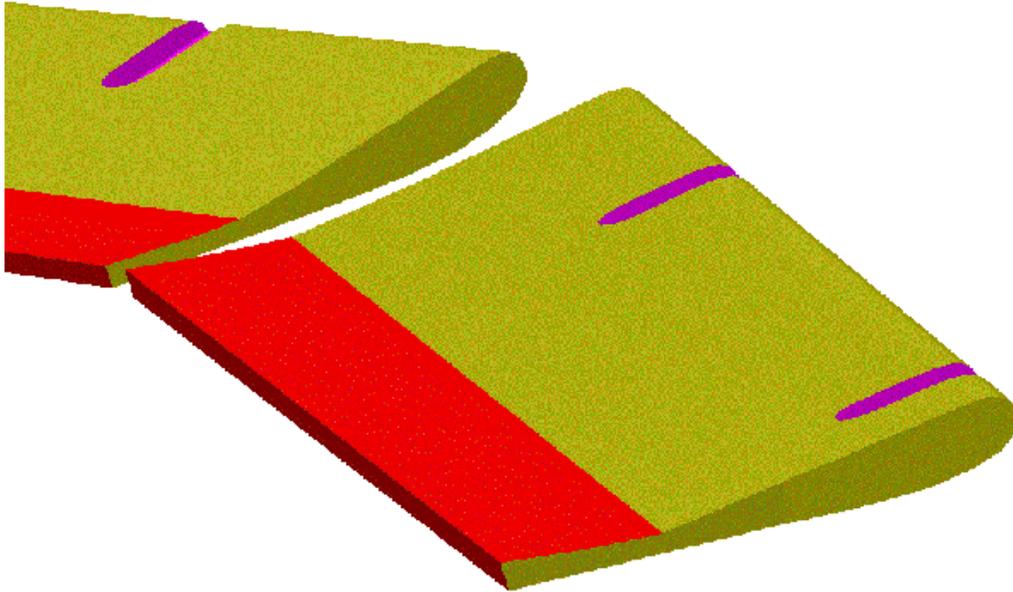
Configuration 7 incorporates a slot between the wing and flap. Given the limitation that the main wing of the wind tunnel model could not be modified, only the cove and flap region were altered. The creation of the slot required that the modified flap chord be shorter than the baseline flap chord. This, in turn, required an entire airfoil change to the flap. An optimized flap and cove shape were defined using CFD.



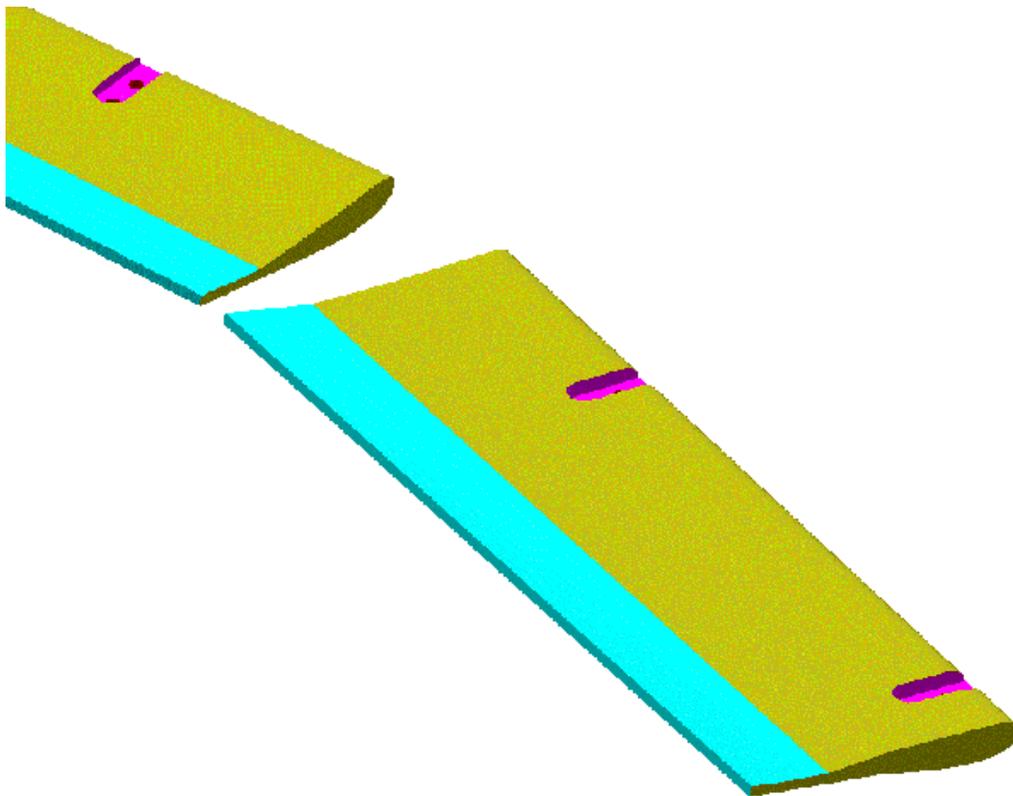
**Figure 3 Configuration #1, Distributed, Lower Surface Trailing Edge Wedges (view of lower surface)**



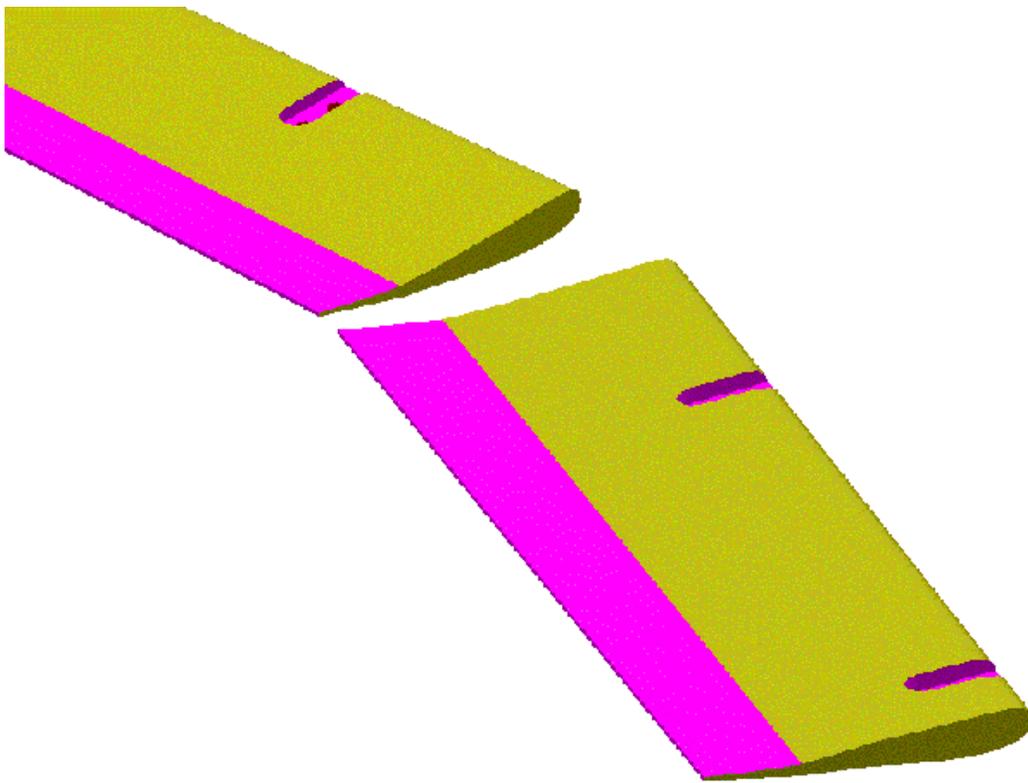
**Figure 4 Configuration #2, 2% Lower Surface Trailing Edge Wedge (view of lower surface)**



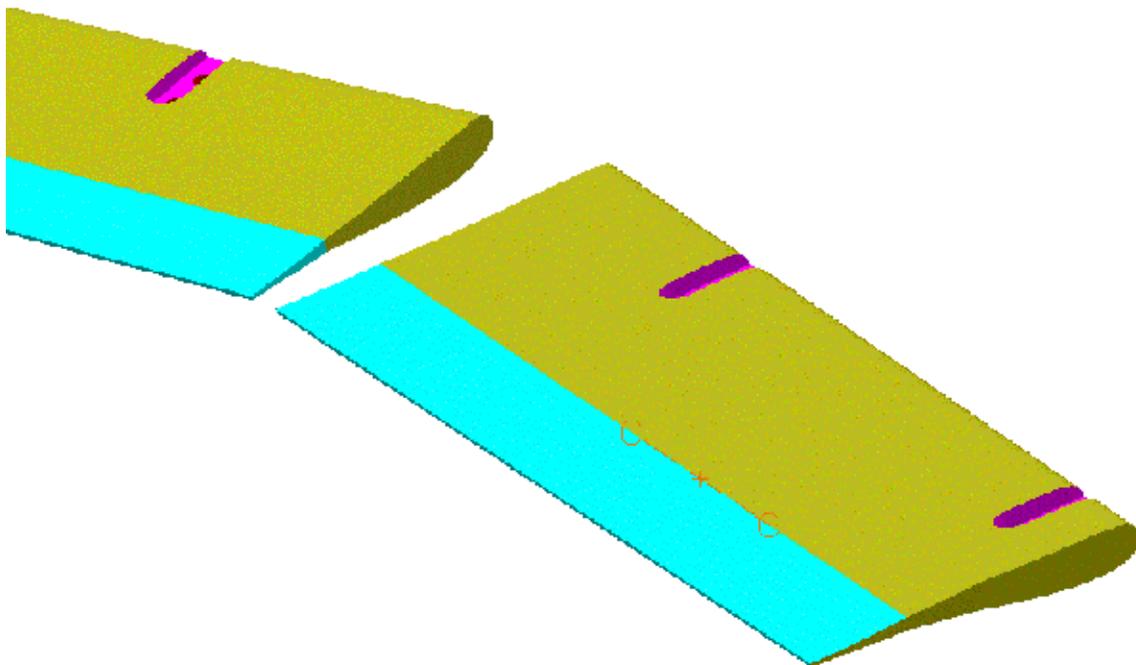
**Figure 5 Configuration #3, 1% Lower Surface Trailing Edge Wedge (view of lower surface)**



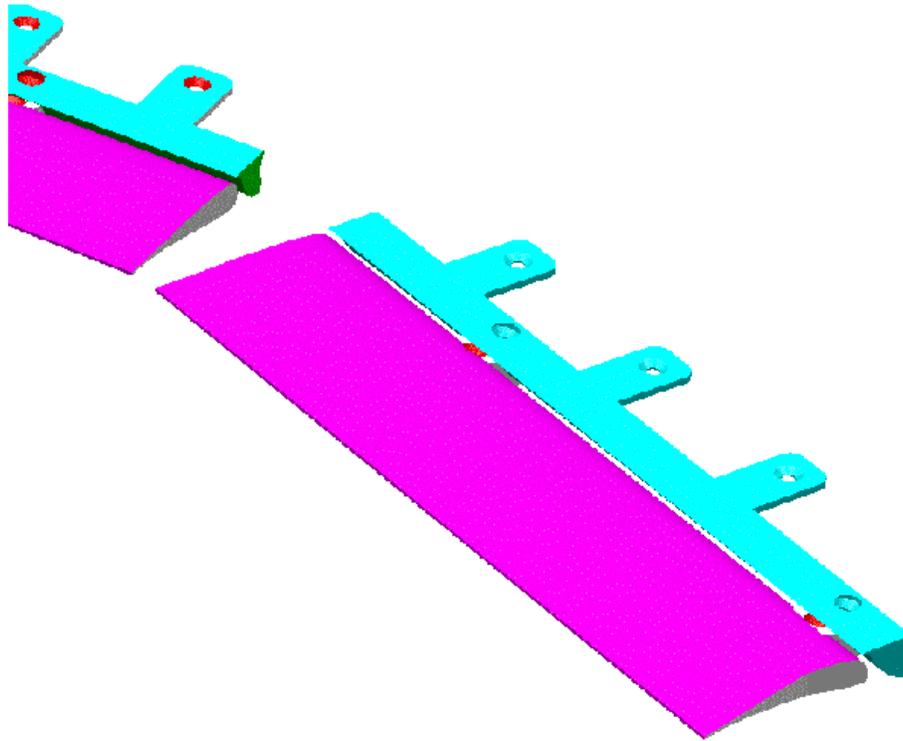
**Figure 6 Configuration #4, Thin Lower Surface Trailing Edge Wedge (view of lower surface)**



**Figure 7 Configuration #5, Cruise Tab Down (view of lower surface)**



**Figure 8 Configuration #6, Cruise Tab Up (view of lower surface)**



**Figure 9 Configuration #7 Slotted Flap (view from top)**

### **4.3 Manufacture of Test Articles**

The test article flaps were manufactured using a stereo-lithography apparatus (SLA) and the original baseline flaps are machined aluminum. Using the SLA manufacturing method gave the advantage of rapidly and inexpensively prototyping many different configurations. All of the test articles were constructed by the Raytheon fabrication facilities known as Blue Streak.

Given the small scale of the trailing edge devices, it was determined that producing “add-on” parts that attached to the baseline flap would be time consuming to install and would carry the high risk of breaking during the installation or removal of the part. An entire new set of flaps was produced to minimize the risk of damage and to reduce model change time for each configuration; therefore a total of 28 new flaps were constructed (7 configurations X 4 flaps) as shown in Figure 10.



**Figure 10 Final SLA Test Articles**

#### **4.4 Summary of Test Activities**

The test was completed from June 14<sup>th</sup> through June 18<sup>th</sup>, 2004. A total of 137 runs were completed (including weight and strut tares). Table 2 summarizes the breakdown of the test runs. The model installed relatively easily with few problems and is pictured in Figure 11. Reference 11 documents the test procedures and data obtained.

**Table 2 Summary of Wind Tunnel Test Runs**

<b># of Runs</b>	<b>Description</b>
106	Force Runs (82 pitch runs and 24 yaw runs)
5	Flow Visualization Runs (Sublimation)
11	Weight Tares
15	Fork Tares (12 force runs and 3 weight tares)



**Figure 11 Installation of the Beechcraft Premier I Model 390 at UWAL**

All seven configurations were tested using fixed transition. Following each model change a series of three pitch runs were executed. The first run tested the entire angle of attack ( $\alpha$ ) range of the aircraft from  $-6$  to  $+20$  degrees. The second run was a refined pitch run over the  $\alpha$  range that would be experienced in a high speed cruise condition. These runs were completed from  $-1$  to  $+4$  degrees by increments of  $0.25$  degrees. The third run was a repeat of the second run. It was expected that some of the trailing edges would have a very small effect (as compared to the baseline) and therefore the repeat run was used to determine differences due to repeatability versus differences due to small configuration changes. After testing all of the configurations, it was determined that the effect of each device was very pronounced in comparison to the baseline and that the difference in repeat runs was very small and therefore the third run was replaced with a beta sweep throughout the remainder of the test.

In order to obtain the best tunnel corrections, a run with a change in horizontal tail incidence and a run with no horizontal tail were required. This gave the needed information to determine the wall-corrections using the classical method.

A series of runs were completed with the slot of Configuration 7 taped closed to investigate the impact of the slot (Figure 12).



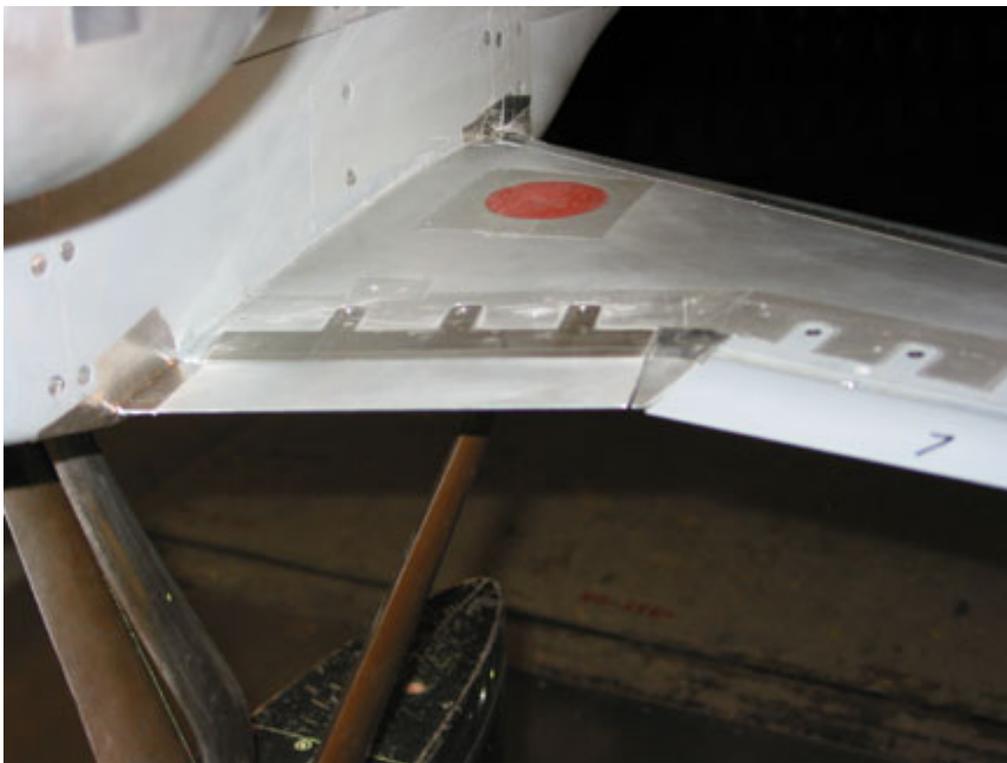
**Figure 12 Configuration #7 with slot taped**

Small stall strips, located on the inboard wing were removed along with the wing trip strips to investigate any effect of fixed versus free transition (see Figure 13). Five configurations (baseline, 4, 5, 6 and 7) were then tested with free-transition on the wings.

Three series of “combination flaps” were tested with the baseline flaps installed in the outboard position only. The inboard flap position was installed with Configurations 6, 5 and 7 respectively. These runs were completed to determine how much of the contribution was from the inboard flap only in comparison to both the inboard and outboard together. An additional series with Configuration #7 in the outboard and the baseline flaps in the inboard position was completed as shown in Figure 14.



**Figure 13 Configuration #7 with Stall Strip and Wing Trip Strips removed.**



**Figure 14 Combination Configuration - Inboard Baseline flap with Slotted Outboard flap**

## 5. Discussion of CFD and Wind Tunnel Results

The wind tunnel testing provides useful information for the incompressible, low-speed flight conditions; however, the conditions of primary interest in this study are in the transonic cruise region. The effects of compressibility are fundamentally important for intermediate and high-speed cruise. The scope of this Phase I study precluded the use of a transonic wind tunnel test, so computational fluid dynamics data provided compressible aerodynamic information.

A series of TRANAIR runs were made for all concepts studied at a range of Mach numbers. The results of the TRANAIR analysis are presented in conjunction with the wind tunnel data for a holistic view of the aerodynamic characteristics.

### 5.1 Trailing-Edge Wedge

The wind tunnel results for trailing-edge wedges (Configurations 2, 3, and 4) are shown in Figure 15. While the wedges increase the lift of the aircraft for a constant angle of attack, the configurations all produced more drag than the baseline at low-speed conditions.

While the trailing-edge wedge is a simple design, the concept is limited to downward deflections only. If the wedge were installed on the upper surface, the wedge could deflect upward, but still in only one direction. This serves to limit the effectiveness of the trailing edge wedge.

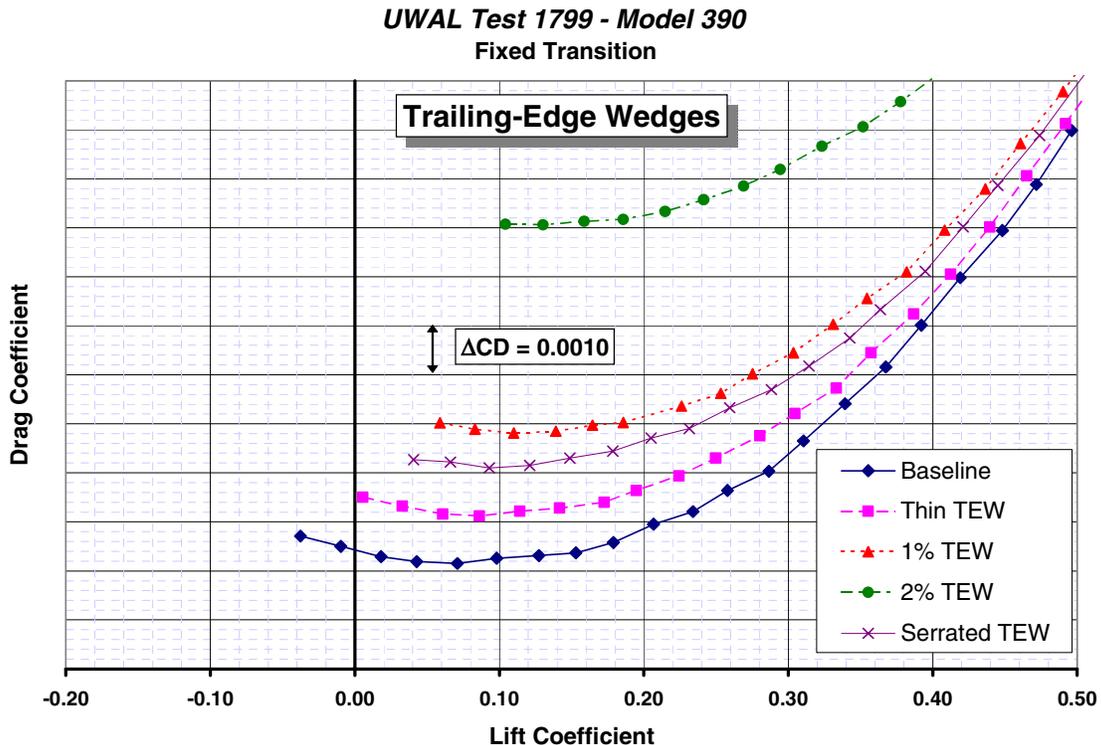


Figure 15 Trailing-Edge Wedge Results for Low-Speed Wind Tunnel Test

## 5.2 Distributed, Lower-Surface Wedges

The distributed, lower surface wedges (Configuration 1), increased the lift of the aircraft for a constant angle of attack. As shown in Figure 15, the drag of the distributed wedges is higher than the baseline at all lift coefficients.

Each wedge installed on the lower surface in this configuration has approximately the same height of the wedge used in the full-span, 2% trailing edge wedge (Configuration 2). The distributed wedges, however, have only half the span-wise coverage as the full-span configuration. This results in approximately the same cross-sectional area as the 1% trailing-edge wedges (Configuration 3). Wind tunnel results indicate that the distributed wedge configuration has very similar aerodynamic characteristics (see Figure 15) as the 1% trailing edge wedge. This indicates that the cross-sectional area is more of a contributor than the shape of the wedges. Also, there seems to be no other benefits through improved mixing with the wake or other physical processes.

The distributed wedges are considerably more complicated than the simple full-span wedges in terms of parts count and installation. Given that the added complexity does not result in aerodynamic benefits, the distributed wedges are only of academic interest.

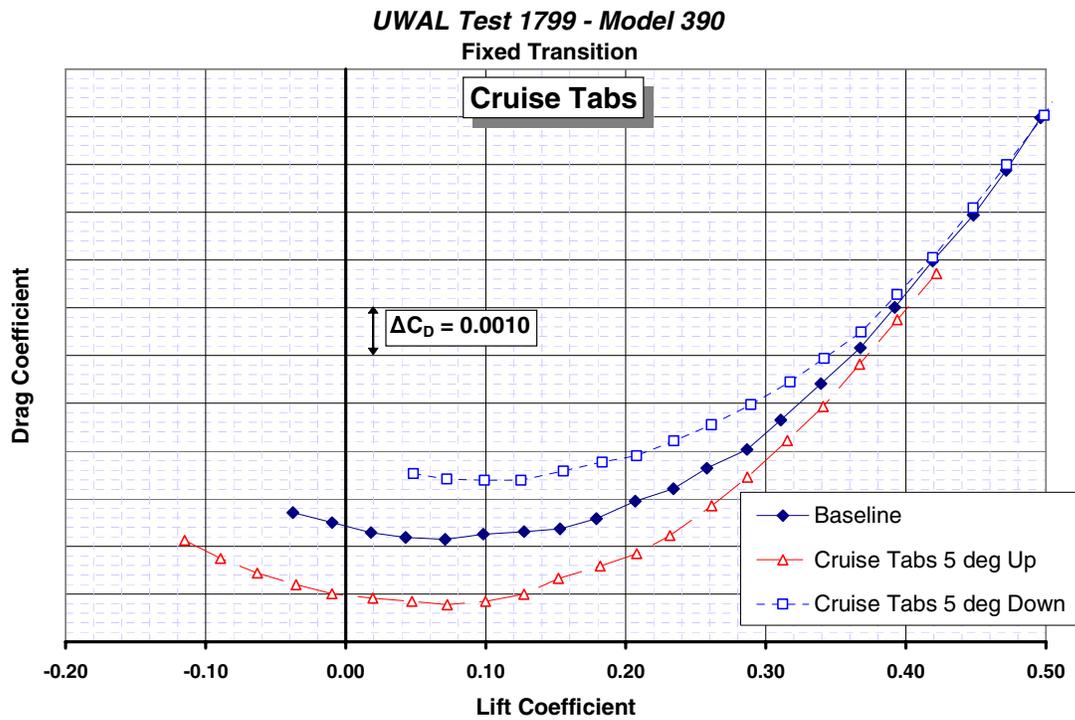
## 5.3 Cruise tab

Wind tunnel test results for the cruise tab (Configurations 5 and 6) are shown in Figure 16. It can be seen that the upward trailing edge tab deflections were the most effective in lowering the drag of the aircraft. It should be noted that the drag polars for upward and downward tab deflections do not cross, indicating that the tab-up configuration would be the optimum configuration throughout the lift coefficient range.

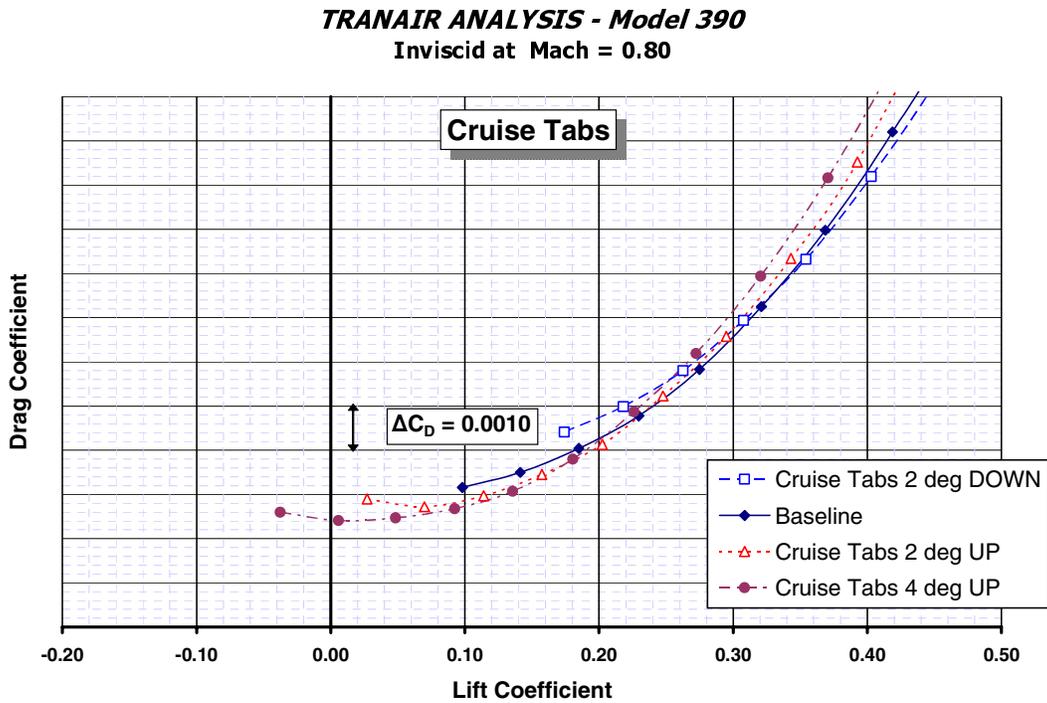
As the low speed wind tunnel data for the cruise tab show positive results, it is appropriate to examine the high speed characteristics using computational fluid dynamics.

A series of inviscid TRANAIR runs were made at Mach numbers of 0.64, 0.70, 0.75, and 0.80 for each tab configuration. Full drag-polar shapes were developed for all but the Mach = 0.75 case, where a limited number of cases were run to provide limited results in the early, drag-rise region. The results for Mach = 0.64 and 0.70 were very similar, so only those for Mach = 0.70 are presented here.

Similar to the sailplane case, these polars show that there are preferred cruise-flap deflections for each  $C_L$ , but also in combination with Mach number. Figure 17 shows that at Mach 0.80 the polars cross over demonstrating that changing the configuration as the aircraft changes flight  $C_L$  (typically running between .2 and .4 at this speed for the Premier I), would improve cruise performance. Figure 18 shows that when operating at Mach 0.7, the polar for the 4-degree, tab-up configuration is best for  $C_L$ 's below 0.30. As  $C_L$  is increased, the optimum transitions through the 2-degree, tab-up position to the zero configuration at a  $C_L$  of 0.45.

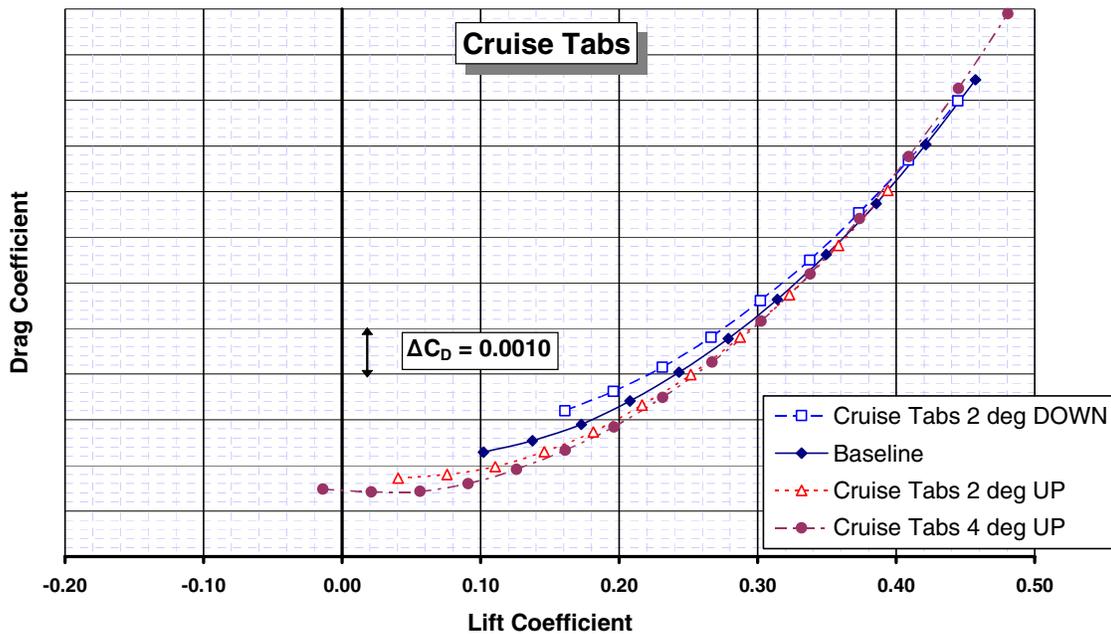


**Figure 16 Cruise Tab Results from Low-speed Wind Tunnel Test**



**Figure 17 TRANAIR Run of Cruise Tabs at Mach 0.80**

**TRANAIR ANALYSIS - Model 390**  
**Inviscid at Mach = 0.70**



**Figure 18 Run of Cruise Tabs at Mach 0.70**

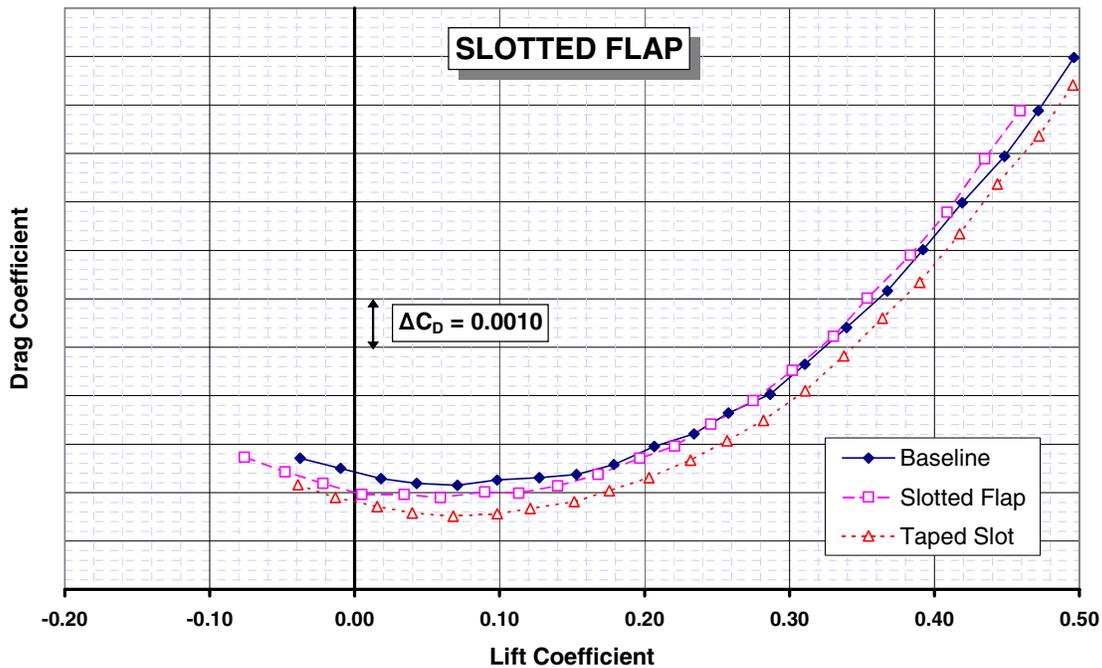
On a production aircraft with this cruise-tab concept, a control system would manage the tab deflections up or down depending on the flight condition to obtain the best aerodynamic performance. This would be represented by a composite drag polar through the lowest drag points to generate an optimum curve for each Mach number. These new curves would be used to define the best possible drag improvement.

### 5.4 Slotted Flap

Wind tunnel test results for the slotted flap (Configuration 7) are shown in Figure 19. Given the scope of the research, modifications to the basic wing structure were not feasible. The design of the slotted flap was limited to the constraints of the existing Premier wing on the wind tunnel model; therefore, the airfoil shape could not be redesigned or optimized to take advantage of the slot in the flap. Simple airfoil studies using MSES were done to define the shape of the flap and cove at transonic speeds. This resulted in a flap airfoil that was shorter in chord than the existing one and with a slightly different camber and thickness distribution. To determine the impact of camber change for the slotted design, the slots were sealed with tape and wind tunnel tested.

The drag from the wind tunnel was relatively good for this configuration, even though the main airfoil remained unchanged. It was also interesting that when the slot was sealed with tape on both the upper and lower surfaces, the drag dropped further. This should not be unexpected since the baseline Premier configuration utilizes slot-lip spoilers and these are present with a back-facing step on the wind-tunnel model. There is no step for the slotted flap and taping the gap closed should provide less parasite drag than for the baseline.

**UWAL Test 1799 - Model 390**  
Fixed Transition

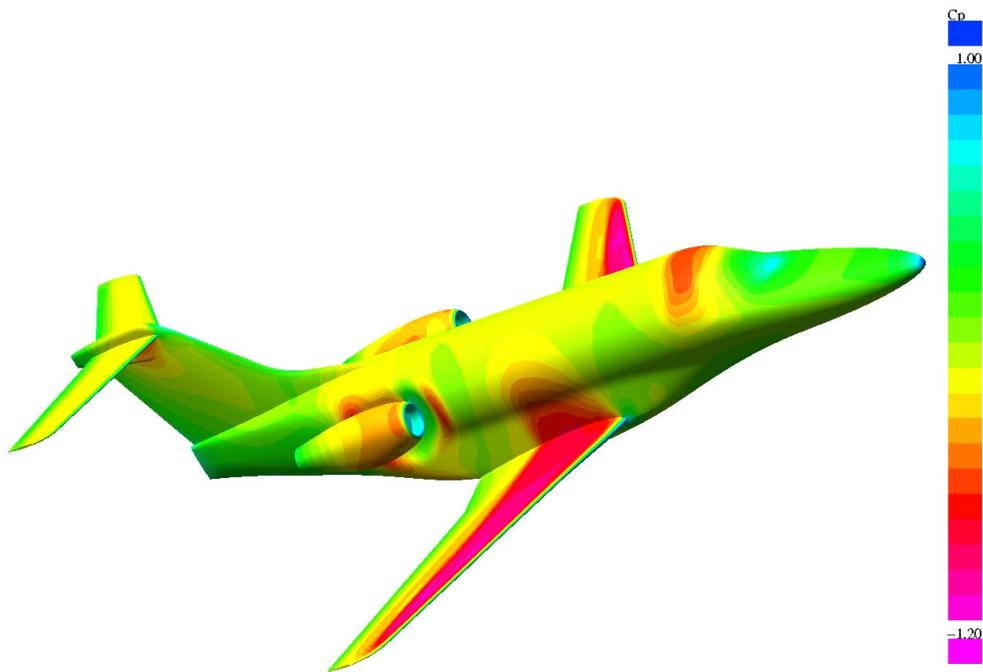


**Figure 19 Flap Results from Low-speed Wind Tunnel Test**

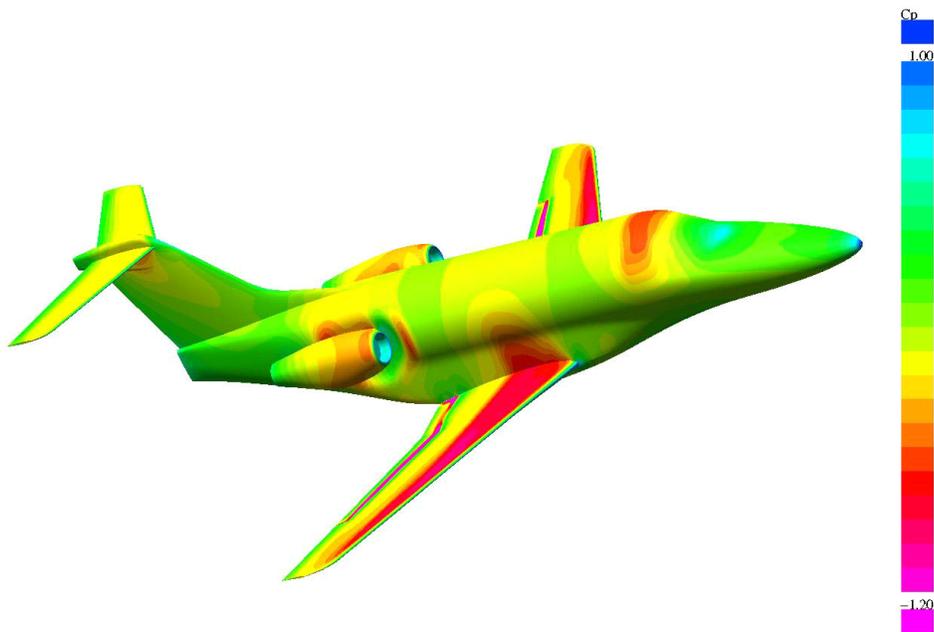
The performance at  $M = 0.80$  was investigated with TRANAIR for a nominal case of the slotted flap with no flap deflection. This produced a strong shock along the slot and leading edge of the flap with a considerable, wave-drag increment. (See Figure 20 and Figure 21).

The fact that having the slot did not produce a significant drag increment in the tunnel means that it should be possible to carefully design for transonic flow with two elements. A comprehensive effort incorporating the slotted flap during the wing design process could show more benefit. The scope of this research does not allow for additional study of the transonic characteristics of the slotted flap; however, the concept may warrant further examination.

Following the wind tunnel testing and aerodynamic analysis, the cruise-tab emerged as the most viable concept for improving cruise performance. The improvement in aircraft performance is presented in Section 7.0, Technology Benefits Assessment.



**Figure 20 Premier I Baseline Configuration Pressure Coefficients**



**Figure 21 Premier I – Slotted Flap Configuration Pressure Coefficients**

## 6. Mechanization

A primary focus of this study has been to identify concepts for improving aircraft performance using a device that can be integrated into an operational aircraft. A concept that provides significant aerodynamic improvement while adding additional weight or complexity may not be attractive in terms of overall design synergy. Design studies were conducted for all 4 concepts discussed in this research to determine if acceptable means of manufacturing are possible. It was found that all of the concepts presented could be integrated into an operational aircraft with varying degrees of complexity. This report will focus on the mechanization concepts for the cruise tab.

Although the cruise tab concept has potential applicability to many types of aircraft, the Premier I business jet was used as a “baseline” for this design study. This provides a very conservative view of design options as the Premier wing and flap are exceptionally thin, providing very little volume for additional systems. Figure 22 shows the thin flap section for the Premier I. Larger transport aircraft may have more flexibility in integrating this type of system into a flap.

In addition to the limited space, other challenges specific to the Premier include:

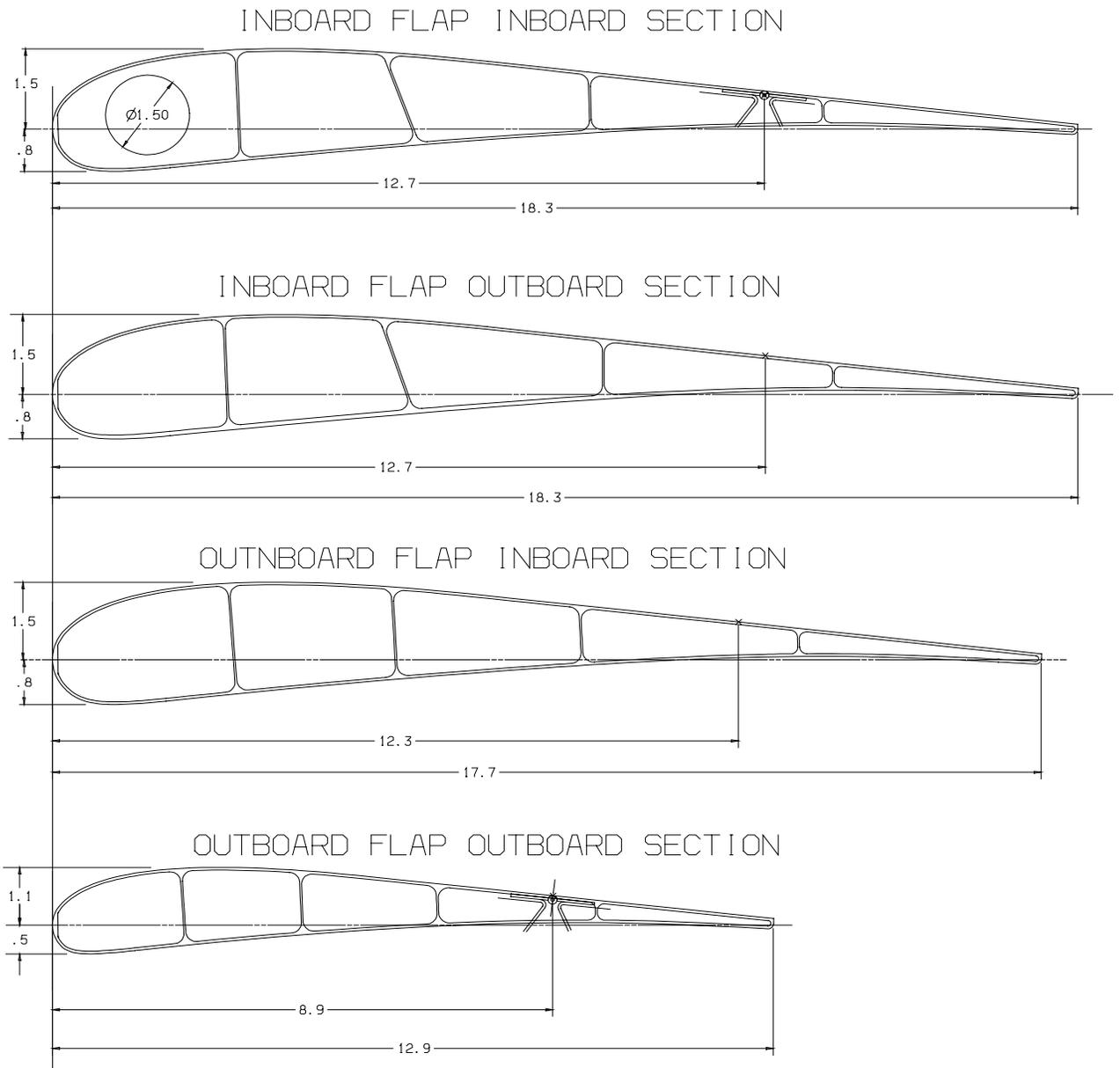
- The flaps are constructed using Resin Transfer Molding (RTM) processes and therefore the skins, spars and webs are constructed of one piece with no access panels or holes.
- The ends of the flaps are closed out using plugs that are bonded into the RTM piece.
- The outboard flap, unlike the inboard flap, has taper that complicates installing, maintaining and operation of the flap tab.
- Since the whole flap tab assembly must traverse as the main flap changes deflections through takeoff, cruise, approach and landing configurations, the tab must have a flexible attachment to the power source and rigging installation and still maintain its position through the flap changes.

The integration of a cruise tab into a flap requires consideration of the following sub-systems:

- Actuation (electric or hydraulic)
- Drive Mechanism
- Hinge Design

### 6.1 Actuation

The requirement for flexibility as the flap traverses precluded any purely mechanical actuation through the use of control cables or torque tubes. Also, hydraulic actuators were ruled out because of space requirements and the potential necessity to reroute already existing hydraulic systems (spoiler and landing gear/brakes).



**Figure 22 Flap Sections for Premier I**

The obvious requirement was for the flap tab system to be able to deflect and lock into place once it is at the desired location, regardless of the location of the main flap assembly. This could be done through the use of electronic actuators. Raytheon Aircraft has years of experience with this type of design not only in the current Premier flap system but also in the Bonanza, Baron, and King Air product lines. Since the main flaps are already electrical, it would seem that an electronic cruise tab control system would be the most effective type of installation for this application. This option would also allow for easy integration into the autopilot control and the benefit of a gearing system that would lock the tab position. This design would lock the tab at the last commanded position in the event of a power failure.

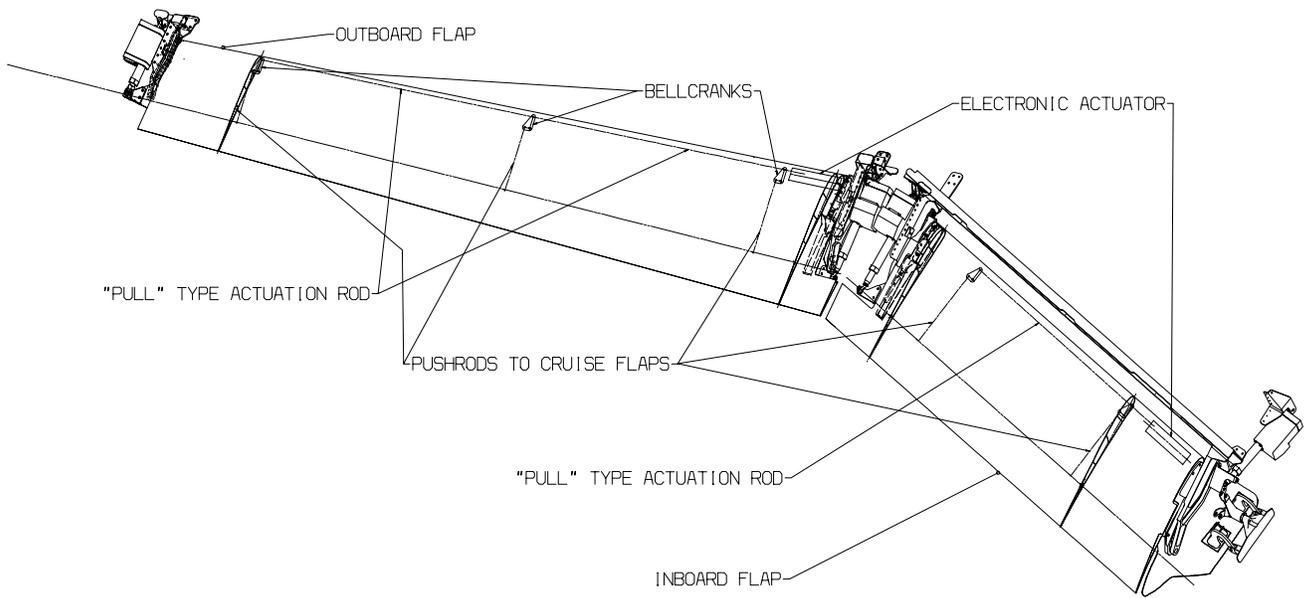
The current Premier flaps are driven by very small and effective (400 pounds of force) actuators. This fact, as well as vendor research, makes it very encouraging that an actuator meeting the size and load requirements of the flap tab could be located.

## **6.2 Drive Mechanism**

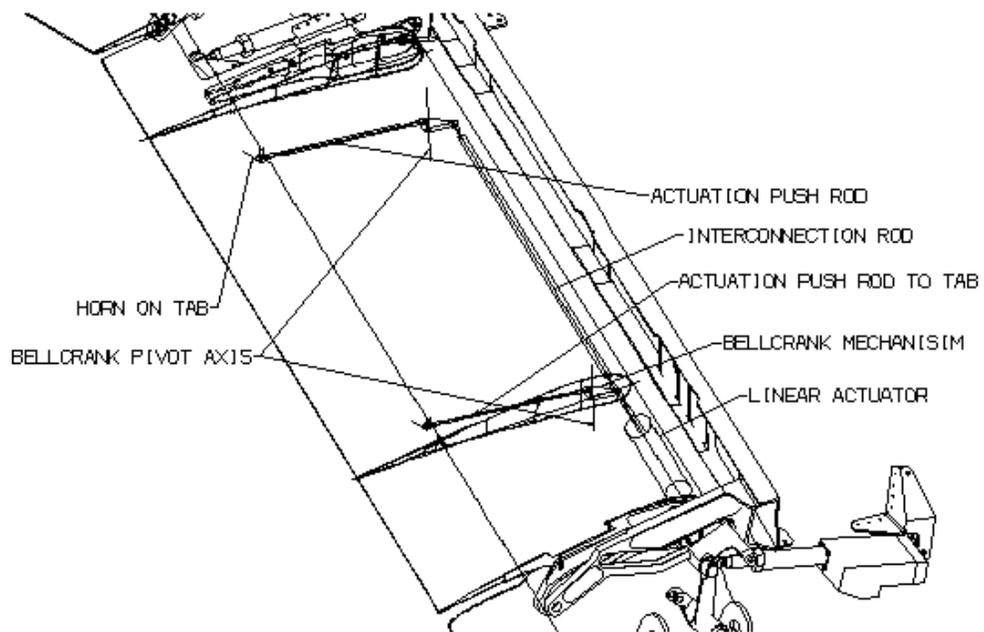
One possibility for the design of the drive mechanism is to install a series of pushrods along the span of the flap. The actuator would be placed in the forward portion of the flap where the airfoil thickness is the greatest. The first section of the RTM assembly would have an access panel installed for easy removal and servicing of the unit.

The most practical design for the mechanism is a simple pushrod from the actuator to a small horn on the cruise tab. This concept is acceptable for the inboard flap with a constant chord; however, the outboard flap with taper requires a more complex system. One approach would be to install several bell cranks along the flap with varying arm ratios driven by a single interconnected rod. Figure 23 and Figure 24 show this arrangement.

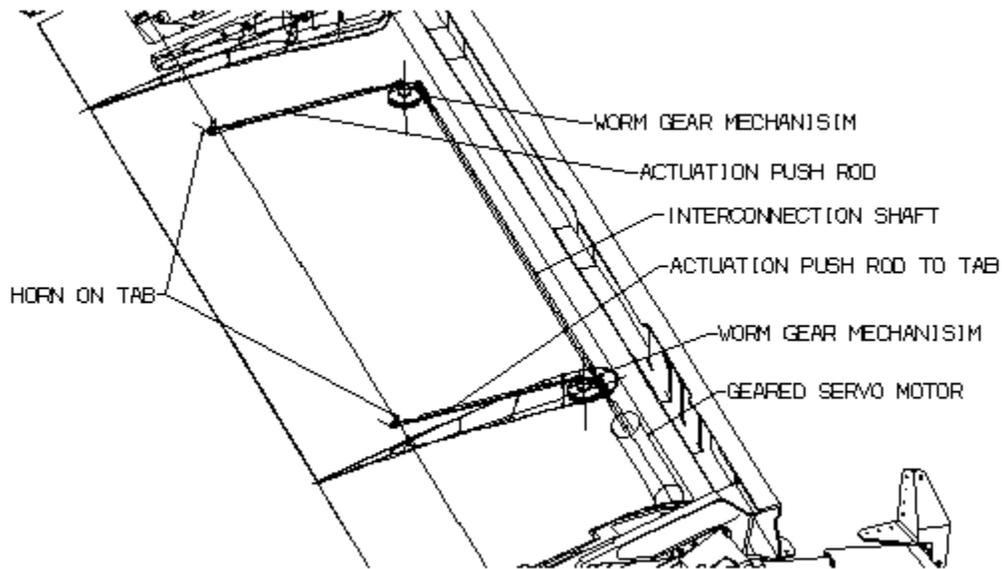
Another option for the actuation of the cruise tab is to drive the pushrods through the installation of a set of worm gear type angle drives (see Figure 25). The gear boxes would be connected together through the use of a single long drive shaft. This is a common design used in the industry. This option is similar to the bell cranks except that worm gear boxes would replace the bell cranks and the “pull” type actuation rod would be replaced with a torsion type drive shaft connecting all the gear drives together. The elements, when timed properly, would be rigidly linked together and the electronic actuator would simply become a drive motor for the drive shaft.



**Figure 23 Bell cranks and Push Rods for the Cruise Tab**



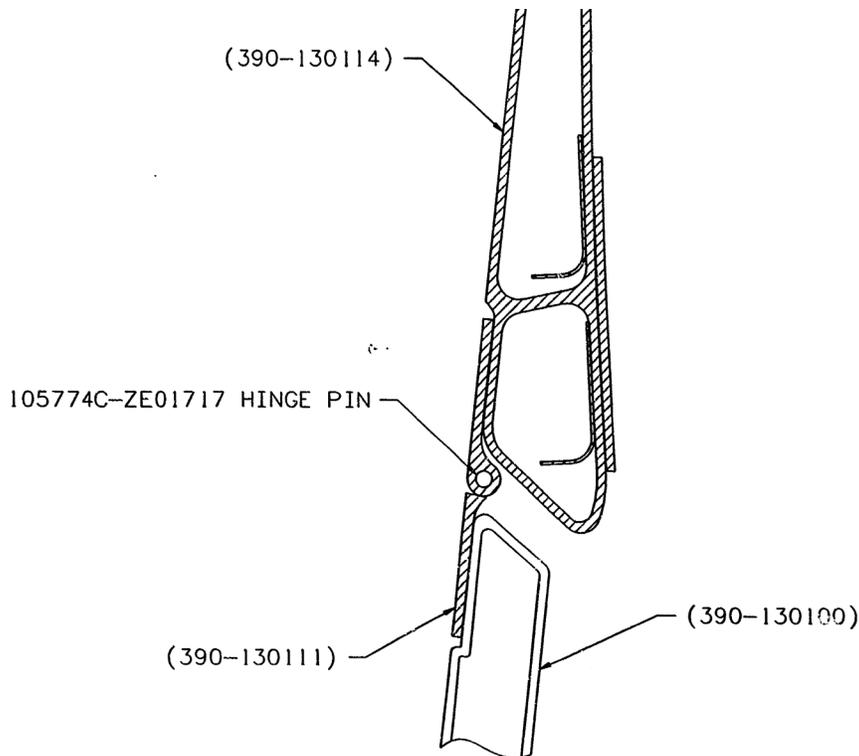
**Figure 24 Detail of single Bell crank Location**



**Figure 25 Sketch of Worm Gear Actuation Unit with Linking Drive Shaft**

### **6.3 Hinge Design**

The attachment of the cruise tab could be done with the installation of a continuous piano wire type hinge along the full span of the tab. The actual hinge would have to be of a material such as titanium, stainless steel, or graphite composite for galvanic corrosion reasons. The standard aluminum hinge, similar to the aileron tab on the Premier, could be used if special precautions to insulate it from the graphite are provided as shown in Figure 26. The advantage of this type of hinge is that it provides a high level of redundancy while requiring very limited area (one of the requirements of this installation).



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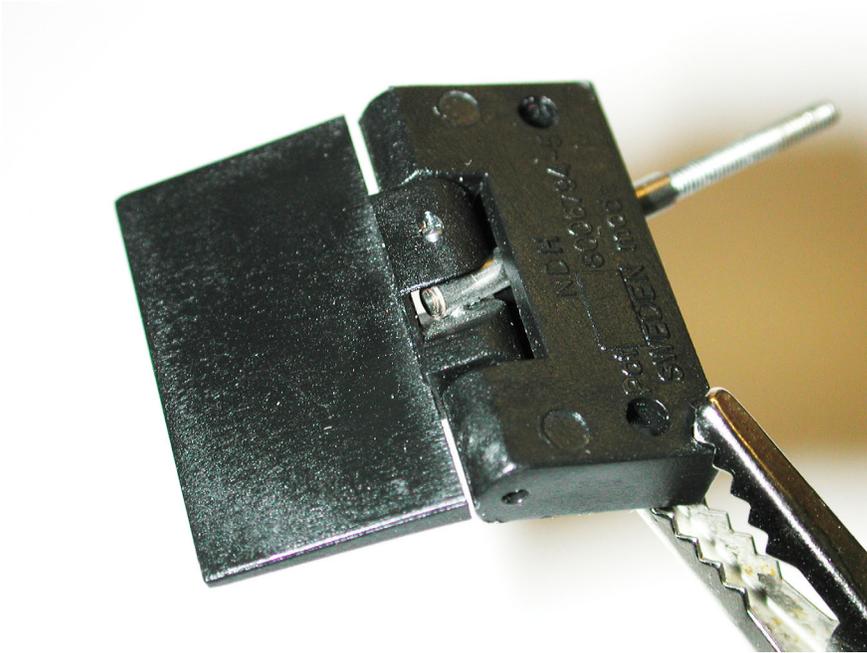
  
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**Figure 26 Premier Aileron Trim Tab Hinge**

A second option for attaching the cruise tab is the installation of an oblique angle hinge. While not commonly used, the oblique angle hinge is used occasionally in the industry and was used at Raytheon Aircraft for years on the aileron for the 1900 commuter airline. The oblique angle hinge has both advantages and disadvantages over the piano hinge. Both hinges are compact but the oblique has a lower profile and can be centered between the upper and lower surface and not fixed to a surface as the piano hinge is. One disadvantage is that the parts are highly leveraged and over time can develop free-play requiring re-rigging.

Figure 27 and Figure 28 show an example of the oblique angle hinge used in a model aircraft application. The flattened paddle was inserted into the control surface and the body with the two holes was mounted in the rear spar cove area with the threaded actuator rod free to move from side to side, deflecting the tab.

This study of actuation devices, drive mechanisms, and hinge connectors indicates that a cruise tab could be installed on a flap such as that on the Premier with relatively low design risk. Additional trade studies to identify total system weight, reliability, maintainability, and certification issues should be conducted in a proposed Phase II of this study.



**Figure 27 Oblique Hinge Control Surface Actuator in the Down Position**

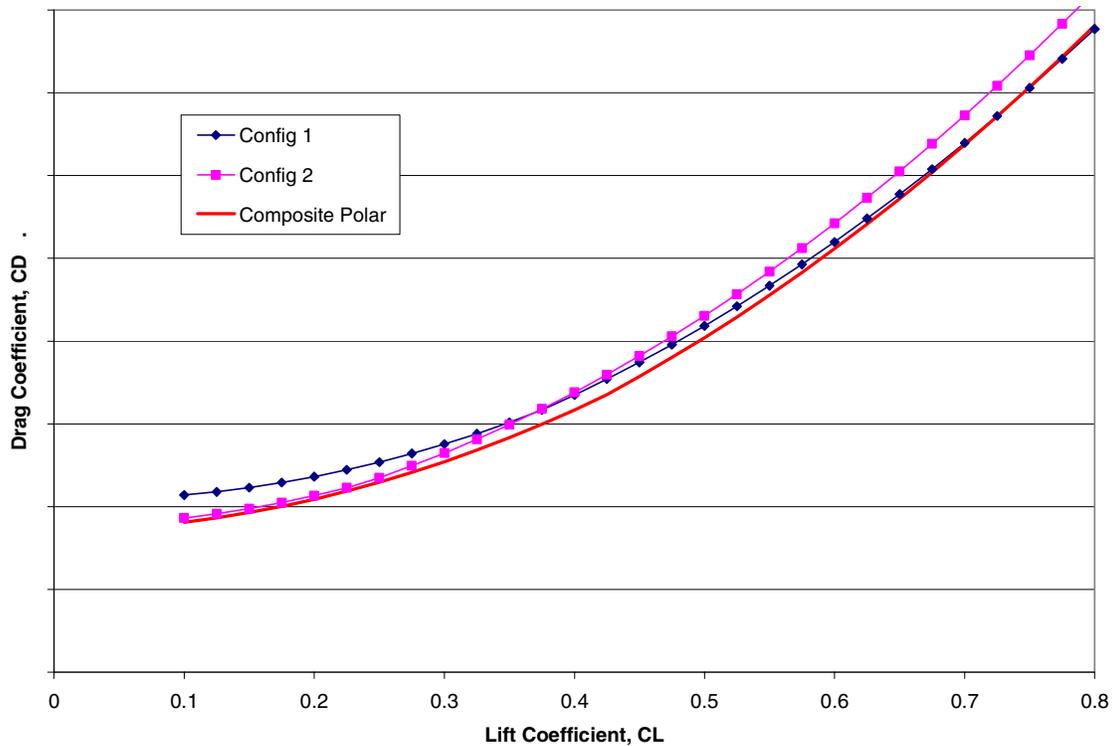


**Figure 28 Oblique Hinge Control Surface Actuator in the Up Position**

## 7. Technology Benefits Assessment

### 7.1 Aircraft Performance

Following the completion of the wind tunnel and CFD analysis, the current Premier I drag polar was modified to include the effects of the cruise tab. A composite drag polar was then created to envelope the lower bounds of the polars for the baseline, 5 degree trailing edge up (-5), and the 5 degree trailing edge down (+5) configurations. Figure 29 shows an exaggerated example of creating a composite polar from 2 drag polars representing different tab deflections.



**Figure 29 Generic Demonstration of Composite Drag Polar Determination**

The Premier I polar is represented using a series of equations to describe the subsonic drag polar and associated compressible drag rise (Reference 12). For modifications to the subsonic polar, the wind tunnel results were used to adjust values for the minimum parasite drag coefficient ( $C_{D0}$ ), the lift-dependent drag coefficient ( $K$ ), and the  $C_L$  for minimum  $C_D$  ( $C_{Loffset}$ ). For the compressible drag rise, and the drag divergence Mach number (Mach number defining the beginning of steep drag rise) was altered based on the results from TRANAIR.

In completing this analysis many issues and assumptions should be summarized to better understand the results:

- The cruise-tab drag polar was generated from the envelope of polars for each deflection analyzed.
- Climb, cruise, and descent segments within the mission analysis utilized the same drag definition (subsonic polar and drag rise.)

- The drag definition for the deflected-cruise-tab configuration was generated as a perturbation to the certification drag definition for the Premier 1 airplane.
  - The wind-tunnel results provided the justification for the increment to parasite drag, a multiplier for the lift-dependent drag, and a delta for the  $C_{L\text{offset}}$ .
  - The TRANAIR results provided the justification for the increment in the drag rise. The shape of the drag rise from the certification report for the airplane was retained.
- Both fixed and free transition on the wing was measured in the wind tunnel. The results for fixed transition were used to define the drag changes.
- No penalty for increased weight of the cruise tab system was included in the mission analysis.

The new polars were input into the RAC in-house mission analysis program. All missions for this study include the NBAA mission profile and reserves (Reference 13) as defined in Figure 30. It should be noted that Premier I has sufficient performance to direct climb to 41,000 feet and does not generally incorporate step climbs.

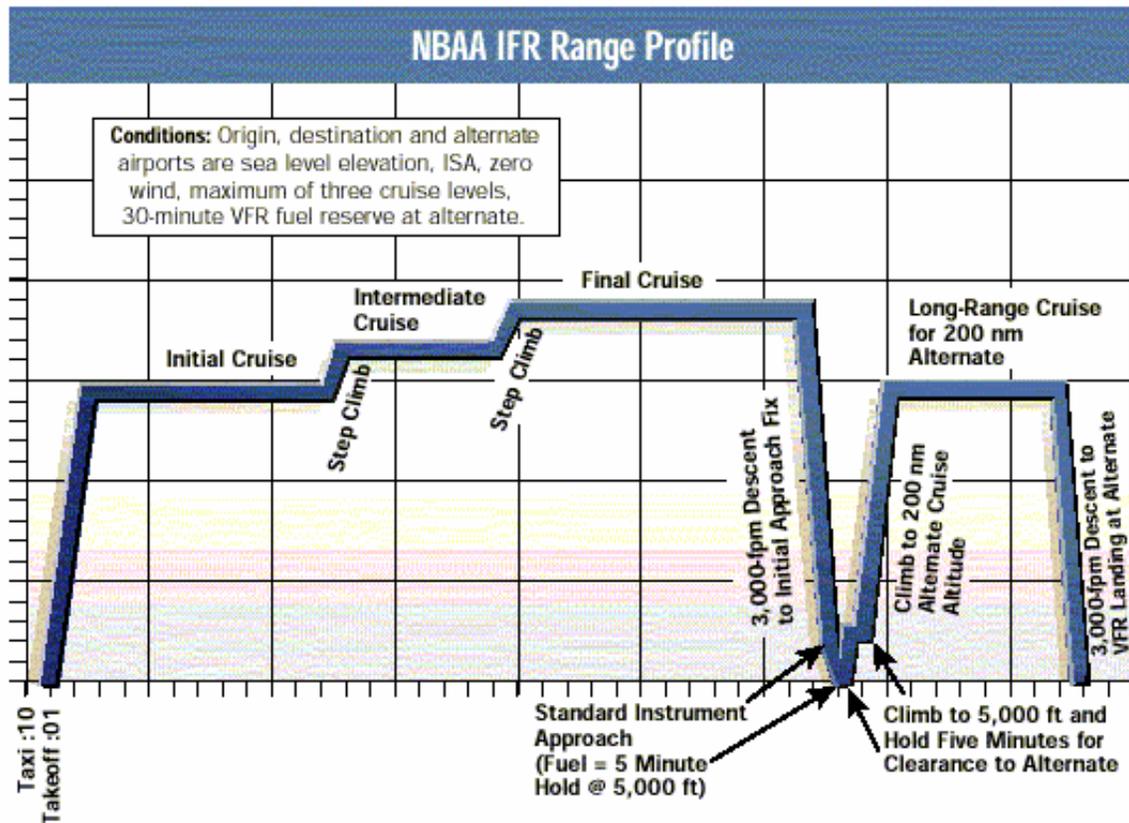
Business jet performance is often evaluated for the following types of missions:

- Long Range Cruise (99% max specific-range)
- High Speed Cruise
- Constant Speed Cruise

Performance in the long range cruise mission with the cruise tab enhancement has been compared to the baseline Premier as shown in Figure 31. The chart shows that for any mission length, the addition of the cruise tab reduces the fuel required for the entire mission by 1 to 1.5%. It should also be noted that the aircraft flies a given set distance mission at speeds approximately 2 to 4 knots faster than the baseline mission. The cruise tab, therefore, enhances value to the customer by saving fuel and increasing long-range speed for a given distance traveled.

For a maximum take-off weight with 4 passengers, long-range cruise mission, the cruise tab enhanced aircraft is capable of flying an additional 2.2% of total range. In determining this value, the reserve portion of the mission was optimized with the new polar and the speeds were set equal to those of the baseline mission.

Company research indicates that operators tend to fly aircraft such as the Premier at maximum speeds over short distances for the majority of all missions flown. Figure 31 shows the benefits of the cruise tab in this high-speed, short distance mission. Again, the cruise tab has increased the maximum speed of the aircraft while saving approximately 1.5% of the total fuel.

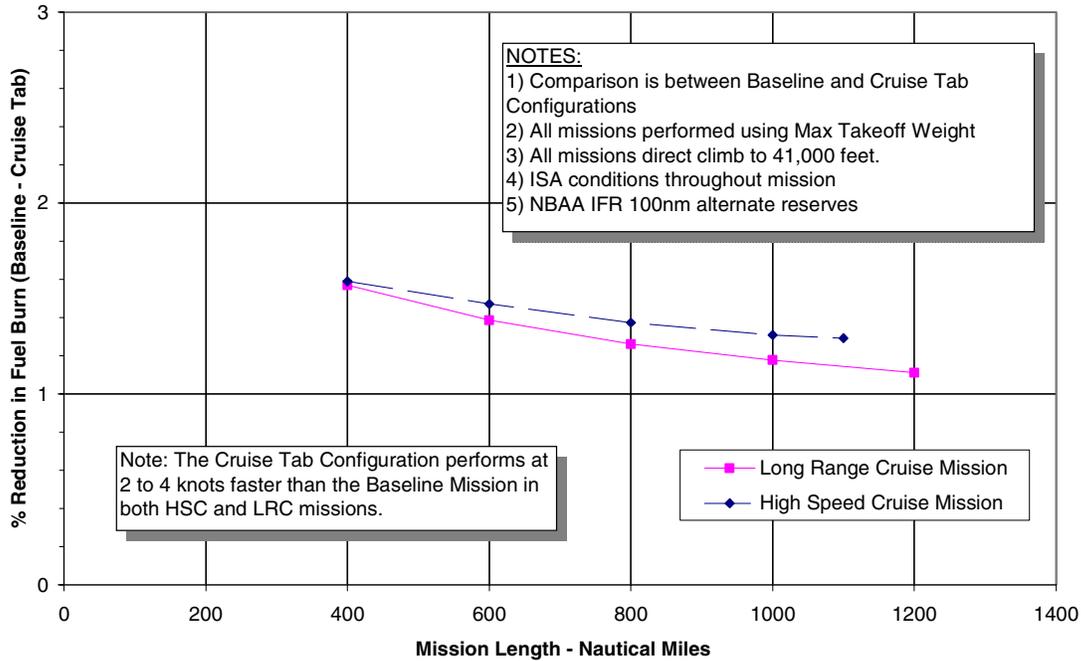


**Figure 30 NBAA IFR Mission Definition (Reference 13)**

Figure 32 shows the savings in fuel for constant speed, set distance missions as this represents how many aircraft are actually operated. For this design of the cruise-tab, it can be seen that higher cruise speeds (lower lift coefficients) provide more fuel savings. This is expected as the drag savings for the cruise tab are more pronounced at lower lift coefficients.

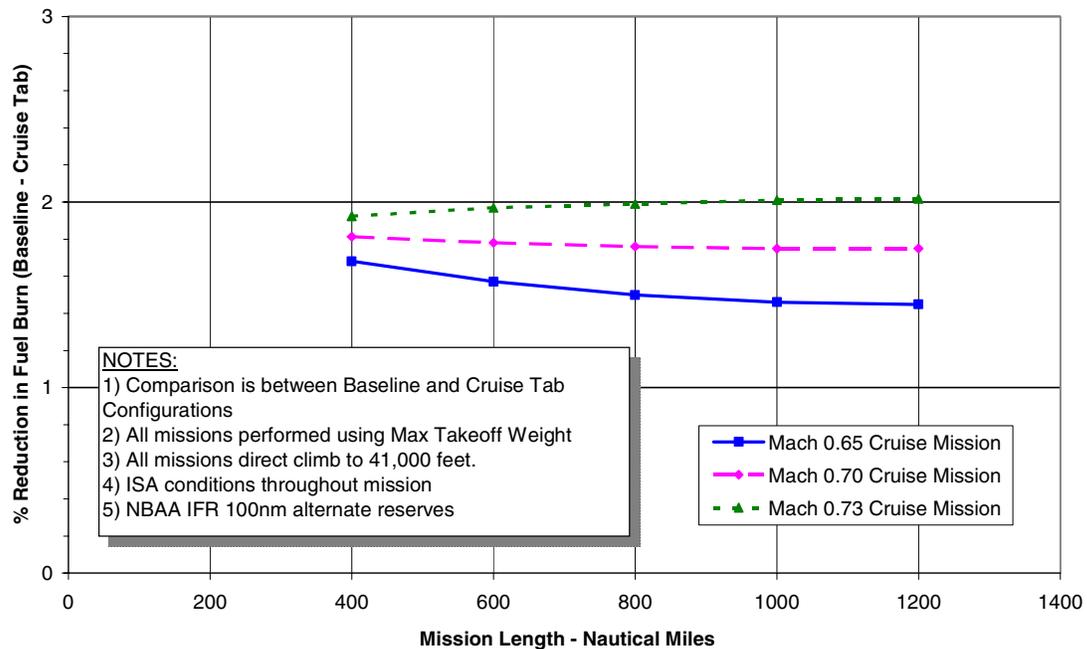
Considered over the lifetime of an aircraft, the savings in fuel burn resulting from the cruise tab configuration is not trivial. The device also serves to increase maximum speed and extend range of the aircraft, adding value for the customer.

**Active Tailoring of Lift Distribution  
NASA Contract NNL04AA34C  
Model 390- Performance Analysis**



**Figure 31 Reduction in Fuel Required for High Speed and Long Range Missions**

**Active Tailoring of Lift Distribution  
NASA Contract NNL04AA34C  
Model 390- Performance Analysis**



**Figure 32 Reduction in Fuel Required for Constant Speed Missions**

## 7.2 Overall Assessment of Technology

The wing on the Premier I was highly optimized during the design efforts. The initial airfoils from mid-span outward were designed using the MSES-LINDOP system that allowed for a multipoint optimization over six different flight conditions. These covered the typical cruise altitudes from 30,000 to 41,000 feet at light and heavy weights and speeds from  $M = 0.70$  to  $0.82$ . The final design then utilized the pressure distributions from the 2-D work to specify target pressures for a 3-D adjoint method, SYN87.

The net result is that based on the TRANAIR results for the  $C_L$ 's between 0.23 and 0.35, the existing wing is optimum at  $M = 0.80$  and only a drag count or two worse than the best option over  $C_L$ 's down to 0.20 or up to 0.40. At  $Mach = 0.70$ , the existing configuration is best for  $C_L$ 's above 0.35. At  $C_L = 0.20$ , the configuration with the cruise tab deflected 4 degrees upward is about 5 counts better.

Lift coefficients below 0.20 are of no practical interest in terms of airplane performance. The speed for 99% of maximum specific range is typically used to determine a value long-range-cruise segments. For the Premier 1, this speed would be about  $Mach = 0.68$  at start of cruise with it dropping as fuel is burned off and ending closer to  $Mach = 0.62$  at the start of descent. Rarely does the aircraft operate at these speeds. Instead, they operate very close to the maximum speed range for the airplane, which is in the  $M = 0.76$  to  $M = 0.80$  range, depending on weight, altitude, and temperature.

In conclusion, the use of a simple trailing edge tab has been demonstrated as effective in changing the camber of the wing. These camber changes enable modifications to the aircraft drag polar in flight, impacting parasite drag, the lift coefficient at which drag is a minimum, the induced drag, and the drag rise at transonic speeds. For each flight condition, the proper tab deflection can be chosen to achieve optimum camber in terms of the lowest drag.

A study of mechanization concepts has shown that the cruise tab can be practically integrated into a flap system such as that of the Premier I. The system is simple and can be actuated without the need for exotic hardware.

Analytic mission studies show that the cruise tab device improves aircraft performance as follows:

- Total fuel burn reduced by up to 1.5%
- Mission range extended by 2.2% (long range cruise speeds)
- Maximum speed increased by 2 to 4 knots

The results from Phase I indicate that this technology, the simple cruise tab, warrants further investigation.

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14. ABSTRACT During Phase I of this project, Raytheon Aircraft Company (RAC) has analytically and experimentally evaluated key components of a system that could be implemented for active tailoring of wing lift distribution using low-drag, trailing-edge modifications. Simple systems such as those studied by RAC could be used to enhance the cruise performance of a business jet configuration over a range of typical flight conditions. The trailing-edge modifications focus on simple, deployable mechanisms comprised of extendable small flap panels over portions of the span that could be used to subtly but positively optimize the lift and drag characteristics. The report includes results from low speed wind tunnel testing of the trailing-edge devices, descriptions of potential mechanisms for automation, and an assessment of the technology.					
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