Tailless Aircraft Design — Recent Experiences

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ABSTRACT

Several methods for achieving longitudinal trim of tailless aircraft with a desired stability level have been employed over the century of experimentation with such designs. This paper illustrates these approaches in recent applications, focussing on the advantages and problems associated with three very different "flying wing" concepts. Analyses and flight tests have demonstrated that it is often possible to avoid the performance penalties once thought to be inherent in the tailless design.

Example projects include the development of an unswept tailless aircraft for high altitude long endurance missions, a moderately-swept, foot-launched sailplane, and an unstable, oblique all-wing design.

1 INTRODUCTION

It is an honor and a delight to contribute to this symposium in celebration of Bill Sear's eightieth birthday. Although I have met Prof. Sears only a couple of times, I have studied and been inspired by his work in unsteady aerodynamics, supersonic aerodynamics, and tailless airplane design. So I do feel in a very real way one of Bill's students. I have chosen to talk about some experiences with tailless aircraft design, but feel a bit presumptuous giving such a talk to an audience that includes Bill Sears and Irv Ashkenas, some of the true pioneers in this field. So with their indulgence I'll try to describe some of the things that my colleagues and I have done in the last decade in tailless aircraft design.

This lecture will begin with a very short history and overview of some of the issues involved in tailless aircraft design, concentrating, not on the question of whether tailless aircraft are a good idea, but rather on how one designs a good tailless airplane. I will focus on three approaches to one of the fundamental problems of tailless design, that of longitudinal control, and will mention a few additional considerations in their design.

One may be puzzled by the fact that we see so few tailless airplanes. Although the tail of commercial transport aircraft constitutes 25-35% of the wing area and pushes down with as much as 5% of the aircraft weight (~100 passengers with baggage), the horizontal tail has remained a prominent feature of modern aircraft design and despite over thirty years of technological progress, the 707, rolled out in about 1954 and the A340 first flown in 1991, look very similar. This is not simply a reflection of aircraft manufacturers conservatism, but an indication of the fact that horizontal tails are an efficient means of satisfying the requirement for longitudinal trim and control. These are not insignificant constraints. If one optimizes an airplane with respect to about 20 parameters (wing and tail geometry variables, engine size, and operational parameters) to minimize direct operating cost subject to constraints on range, engine-out climb, and field lengths, a design similar to that shown on the left part of figure 1 is produced [1]. With the same analyses, but letting the tail lift coefficient be very large and removing the stability constraint, the tail disappears, and the aircraft gross weight, fuel consumption, and D.O.C. go down by about 10%. Unfortunately, this aircraft cannot rotate on take-off (so the fuel savings is even larger), but these large changes suggest that the approach to aircraft trim and pitch control is a very important element of the design, with the conventional horizontal tail being just one possible solution. The *best* solution depends strongly on additional considerations, but in many applications designs without horizontal tails have met with some success.

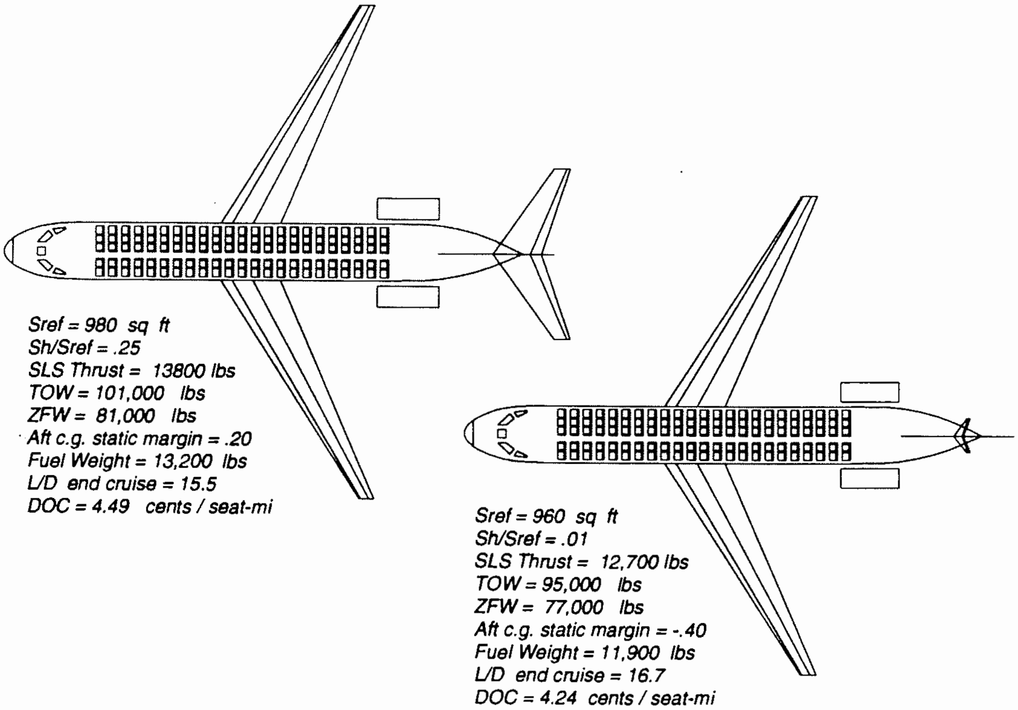


Figure 1. Two Aircraft Optimized for Minimum D.O.C. Right: No Stability or Control Constraints

History

Tailless aircraft have been inspired by a variety of flying seeds and animals. From Zanonia seeds (Fig. 2) to Pterosaurs and modern birds that fly well with little or no tails, Nature seems not to have converged on the 707-like configuration and many airplanes have been based on these models [2].

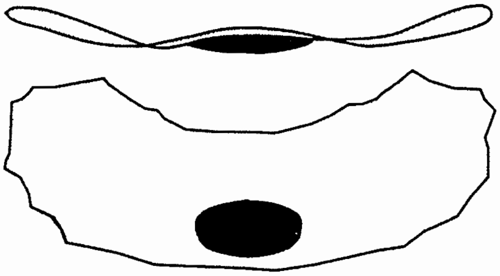


Figure 2. Seed of Zanonia macrocarpa, Span ≈ 6". An Inspiration to Early Aircraft Designers.

Figure 3 illustrates an array of tailless aircraft developed from the early 1900's to the 1950's. The figure suggests a number of approaches to the design of tailless aircraft. In the upper left corner of the figure is one of the early tailless gliders modeled on the Zanonia seed, built by Igo Etrich, and his father, Ignaz. The Etrichs had experimented with one of Otto Lilienthal's gliders which they purchased for 5£ after Lilienthal's death. Aided by Prof. F. Ahlborn, who had investigated the Zanonia seed and written a paper entitled "On the Stability of Aeroplanes" in 1897, the Etrichs constructed what

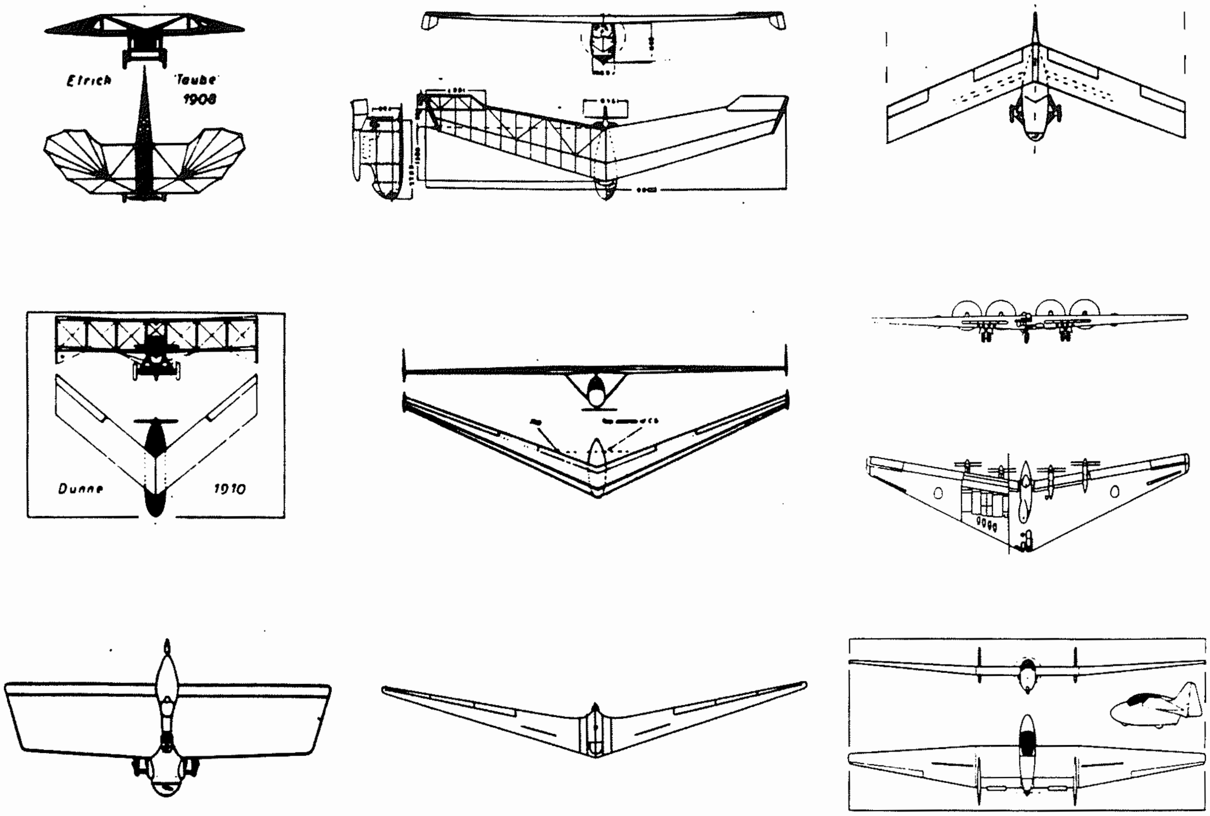


Figure 3. Historical Tailless Aircaft Illustrating Several Design Approaches

was probably the first stable airplane in about 1906. The Taube (Dove) followed several tailless designs by the Etrichs and several hundred were built by a number of companies in Germany and Austria. [2,3]

Below the Etrich airplane is a picture of one of the Dunne tailless biplanes, circa 1910. J.W. Dunne designed several tailless biplanes and monoplanes using a combination of sweep and washout for inherent stability. The stability and controllability of these airplanes led to limited commercial success although the rather high parasite drag and inferior maneuverability discouraged their adoption for military applications, Dunne's original intention.

On the lower left portion of the figure, is one of Rene Arnoux's "flying plank" designs. Arnoux experimented with monoplanes, biplanes, pushers, tractors, low and mid-wing tailless designs all characterized by their use of unswept, nearly rectangular planform wings. From 1909 to 1923 Arnoux demonstrated many successful flights with a variety of airplanes based on this concept. The airplane shown here was an ambitious racer with a 320 h.p. engine that crashed during flight testing.

In the upper center of the figure is the Lippisch "Experiment 64" glider of 1925 incorporating Dunne's concept of sweep and twist for stability, but with more respectable performance. The concept evolved over the next ten years in the Stork series of gliders and many experiments by Alexander Lippisch on a variety of tailless designs. During this same time Professor G.T.R. Hill was developing the Pterodactyl series of tailless airplanes, originally based on the supposed planform shape of a pterosaur, and culminating in a 1934 military fighter, the Pterodactyl Mk V, with a 700 h.p. engine and tractor propeller. Forward sweep was also used for tailless aircraft as evidenced by the 1922 Landwerlin-Berreur racing monoplane of 1922, also powered by a 700 h.p. engine (upper right corner).

Inboard flaps, suggested by Lippisch, are seen in a drawing of the G.M. Buxton high-performance tailless sailplane of 1938 (center). The planform of this glider is similar to that of the Horten brothers, whose enthusiastic development of flying wing sailplanes and powered aircraft began in 1934. Shown below the Buxton glider is the Horten IV sailplane of 1942 with its aspect ratio of 21. The Horten sailplanes were considered to be competitive with conventional sailplanes during 1938-1939 when they were entered in several competitions, flown 180 miles and once climbed 21,000 ft above launch in a thermal. The Hortens continued their work during World War II including an aspect ratio 32 sailplane (Horten VI), a design for a 6-engine 60 passenger transport aircraft (Ho VIII), and the Ho IX jet fighter, all tailless aft-swept designs.

Some of the most famous tailless airplanes are the Northrop flying wings. At the center right of the figure is a drawing of the XB-35, first flown in 1946, following years of experience with tailless aircraft, beginning with the 1940 flight of the Northrop Model 1 Mockup (N-1M). Bill Sears was closely involved in the development of these aircraft, culminating in the YB-49 jet-powered flying wing bomber. Northrop engineers also had plans for flying wing passenger transports [4], but cancellation of the YB-49 program spelled the end of large scale subsonic aircraft programs for many years. Tailless designs continued to be pursued, especially in the sailplane community as indicated by the success of the Fauvel flying wings (lower right of figure 3). Charles Fauvel patented an unswept untwisted tailless design in 1929 and continued working on this configuration for many years. The sailplane shown, the AV. 45 was first flown in 1960 [5].

More recent work on tailless designs is illustrated in figure 4. The SB-13 (upper left) is the result of work at the Akademische Fliegergruppe Braunschweig, begun in 1982 with first full scale flights in 1988. This 15 m span tailless sailplane has demonstrated good performance, but with many difficulties associated with aeroelasticity and handling [6].

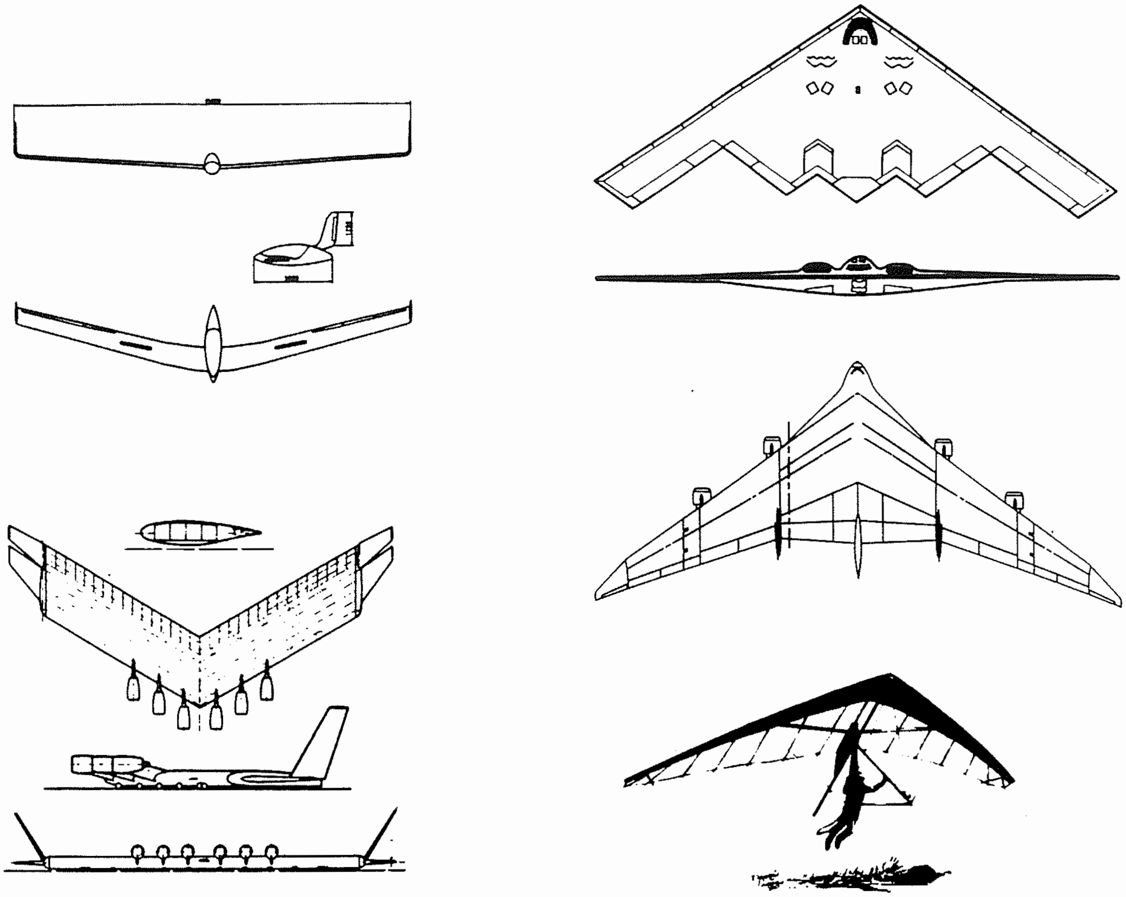


Figure 4. More Recent Actual and Proposed Tailless Designs

In the lower left portion of figure 4 is a span-loaded cargo airplane, studied by Boeing in the 1970's. The far-sighted design was to have a take-off weight in excess of 2 million pounds, 19% thick airfoil sections, six 93,000 lb thrust engines, and a span of over 400 ft. [7]

The Northrop B-2 design (upper right) was motivated by the need for low radar cross section and represents the first large-scale modern tailless program. It is discussed in more detail in Ref. 8. The B-2 has inspired new looks at the tailless design, such as another Boeing concept for a large capacity transport (center right).

Some have said that the flying wing finally found a niche in the world of hang gliding, evolving quickly from the original design by Francis Rogallo to high aspect ratio sailplanes capable of 300 mile flights where oxygen is used routinely. Indeed, despite several attempts to introduce conventional configurations, tailless designs have dominated hang gliding for more than 20 years [9].

So, there actually are a great number of flying wings, but, except perhaps in hang gliding circles, the conventional design still dominates, and it is widely believed that large performance penalties are associated with this design.

> *"A few airplanes ... have been designed without tails in a misguided attempt to save drag. Actually, without a tail, high-lift devices cannot be used on the wing... The tailless high aspect ratio airplane must have a swept wing... All of these effects account for the virtual disappearance of the tailless configuration..." , [10]*

In order to evaluate the performance advantages or disadvantages associated with tailless aircraft, it is necessary to compare a well-designed tailless aircraft with a similarly-designed conventional airplane. One difficulty with this is that it is very easy to design a very bad tailless aircraft while conventional design wisdom leads to a quite good conventional design. In this paper, such a comparison will not be attempted, but rather some of the approaches to achieving a high performance tailless aircraft will be discussed. Many different types of tailless aircraft exist, and may be categorized by the method used to achieve longitudinal stability and trim. We illustrate three approaches with three aircraft developed over the last decade.

2 LONGITUDINAL STABILITY AND TRIM: REQUIREMENTS

One of the basic problems with tailless airplanes involves longitudinal trim.
The requirement is: $C_{m_{cg}} = 0$.

Without a tail: $C_{m_{cg}} = - x_{cg}/c \;\; C_L + C_{m_0} = 0$,
with, x_{cg}/c , the static margin.

For trim, then: $C_{m_0} = sm \;\; C_L$.

If we consider conventional values for static margin, of .1 to .2, the wing must generate values of C_{m_0} that are very large. In fact with just a 5% static margin at an aft c.g., maximum speed condition, many airplanes will fly with a static margin of .35 to .40 at forward c.g. cruise conditions, requiring very large pitching moments about the wing aerodynamic center to trim. The problem is aggravated at higher C_L's as the required C_{m_0} increases linearly with C_L .

There are three approaches to generating these trimming moments without a tail:
1. Use airfoil sections with large, positive values of C_{m_0} (reflexed, self-trimming sections).
2. Rely on three-dimensional effects (sweep and twist) use to make the wing C_{m_0} positive.
3. Employ active controls to make the static margin negative and require conventional negative values of wing C_{m_0} .

The following sections illustrate the use of each of these methods in recent tailless aircraft designs, addressing some of the advantages and problems with each approach.

3 TRIM BASED ON SECTION PROPERTIES

The Zanonia seed employs the first approach. Its airfoil section has an obvious reflexed curvature with a positive C_{m_0}. The seed itself is located near the leading edge of the wing to move the c.g. forward of the a.c.. The design is very stable and simple with a sink rate that surprises even an avid model builder. The Zanonia design problem is particularly simple since it need not accommodate a large c.g. range nor a range of lift coefficients. Thus, although the Reynolds number is very small, it is possible to design an airfoil with relatively good performance subject to these constraints. For aircraft, the section design problem is more difficult.

Section Design Issues

In order to obtain sufficient pitching moment from the section itself, tailless aircraft with typical static margins must use highly reflexed sections. Recall that the C_{m0} needed to trim at a C_L of 1.0 is numerically equal to the static margin, a number of order 0.1. Figure 5 shows a section with a C_{m0} of +0.1. The aft portion of the section is turned upward by a rather absurd amount and we are forced to sacrifice a great deal of lift that could have been carried by the aft part of the airfoil to obtain this pitching moment; the aft portion of the airfoil actually pushes down. With similar rooftop C_p levels and recovery gradients, a conventional section could produce more than twice the C_L. This is the fundamental compromise involved in achieving trim with positive section C_m. This extreme section gives a static margin of only 10% at $C_L = 1.0$.

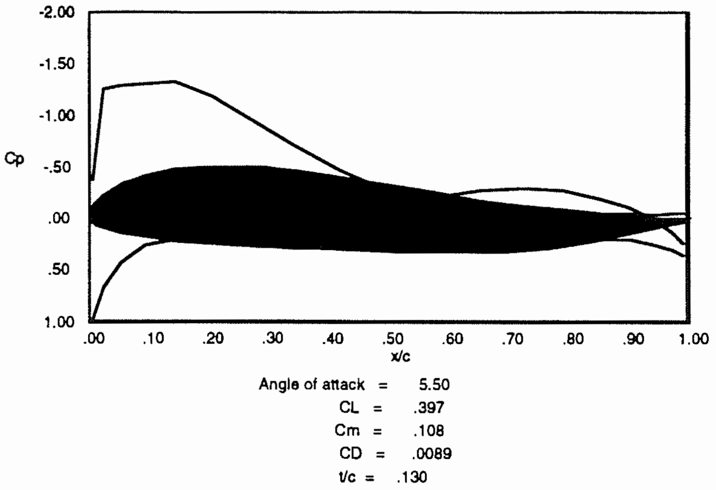


Figure 5. Highly Reflexed Airfoil Section for Trim at C_L =1 with 10% Static Margin.

Although several tailless designs have been flown using conventional sections with negative flap deflections or crude reflex modifications, a more structured approach to positive moment section design can yield considerably better results. By designing a section with a rather conventional upper surface pressure distribution, the less critical lower surface may be used to achieve the required moment with the minimum penalty in section performance. Positive C_p's on the forward lower surface combined with negative C_p's far aft with rather rapid recovery lead to sections with the potential for long runs of natural laminar flow on the lower surface with minimized lift reduction. The section in figure 6 was designed by R. Liebeck [11] and achieves a respectable Clmax of 1.35 measured at a Reynolds number of 250,000, although the C_{m0} is only +0.015. Modern design methods for airfoils are making it possible to use even this first, simple approach to tailless design without as much penalty as might have been required in the past.

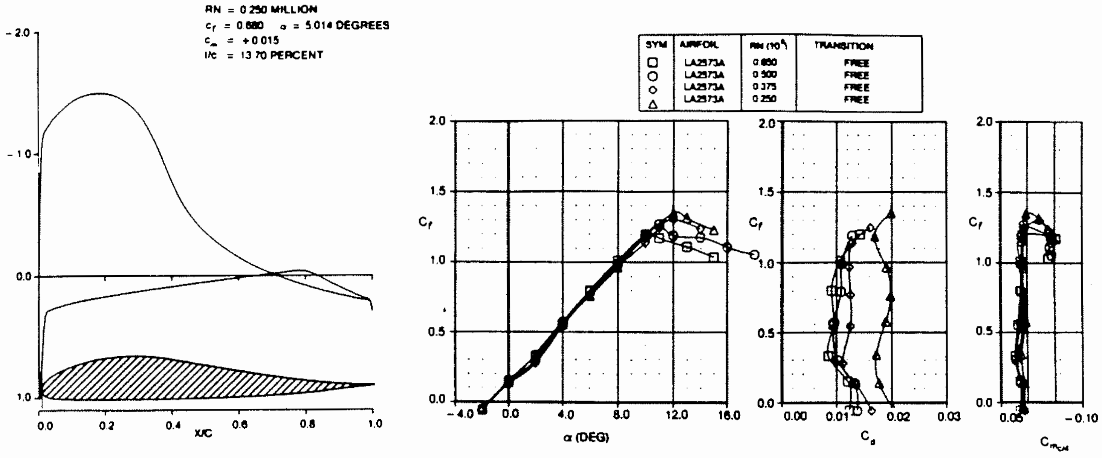


Figure 6. A Carefully-Designed Reflexed Section

Additional Considerations

Even with well-designed airfoil sections, unswept or "plank"-type tailless aircraft often suffer from a variety of other problems. These include: 1. a very small tail arm and corresponding lack of directional stability and control; 2. a non-minimum-phase control response (large direct lift reduction before the aircraft can pitch up and increase lift); 3. generally poor maximum lift coefficients resulting from "negative" flap deflections and inability to employ conventional high lift devices; 4. very low pitch damping often producing poor handling qualities, including the possibility of tumbling [12].

Example: Pathfinder

One example of this design approach is the Pathfinder aircraft, built by AeroVironment about ten years ago, although details have just been released. This prototype of a high altitude long endurance airplane uses an unswept wing with a 100 ft span and 8 ft chord. Its low wing loading of 0.5 lbs/ft^2 leads to a flight speed of about 13 miles per hour (EAS). It is powered by eight electric engines using about 5KW provided by 30 lbs of Silver-Zinc batteries although it carried sample solar cells and aluminum plates to simulate the eventual power source. The airplane was stable in pitch with trailing edge pitch control surfaces and no vertical surfaces. The distributed engines provide yaw control through differential thrust and result in a very lightweight airframe, as the wing is span-loaded to minimize bending loads. The engines are also located so as to minimize torsion loads. This application of a simple tailless design was, like the Zanonia seed, successful because of its restricted design requirements and good design practice. There was no requirement for a high lift system, no c.g. range, a small C_L range, and the engines naturally provided yaw control.

3 TRIM THROUGH SWEEP AND TWIST

Although a positive pitching moment about the wing's aerodynamic center is required for stable, trimmed flight, each section need not produce a positive moment about its a.c.. By sweeping the wing back and including washout, the wing tips lie behind the a.c. and at zero lift, produce a downward force while the inner portion of the wing is lifting, thus producing a positive C_m at zero lift and hence about the a.c.at all C_L 's. This was the idea behind the Horten and Northrop flying wings. The penalties associated with this twist may be large if not done carefully, but they may be negligible if the correct approach to wing design is taken.

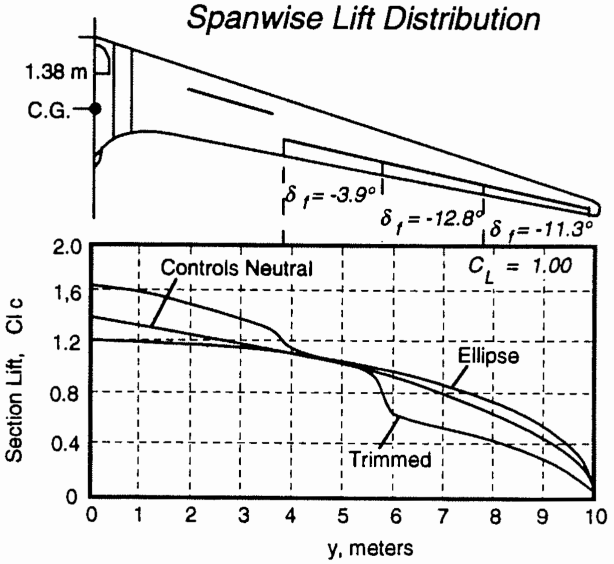
It is reported [13] that the Horten's attempted to achieve a distribution of lift with the centroid of lift located at 33% of the semi-span. Indeed, measured lift distributions on the Horten IV suggest that this was achieved (Fig. 7). The result of this distorted lift distribution is a poor span efficiency, estimated in Ref. 13 based on the shape of the span loading, to be about 0.70 at a C_L of 1.0. This location of the lift centroid is required for trimmed flight with the desired static margins and the highly tapered planform shapes used for these sailplanes. The span loading for minimum induced drag subject to a constraint on centroid position is just the problem of minimum induced drag with fixed root bending moment, solved by R.T. Jones and others [14]. The closed form analytic result is:

$$1/e = 9/2\,\pi^2\,\eta_c{}^2 - 12\,\pi\,\eta_c + 9$$

where η_c is the position of the centroid in units of the semi-span.

e is maximized for $\eta_c = 4/3\pi = 0.4244$, the centroid of the elliptic loading. When η_c is reduced to 33%, the maximum value of e is 0.72. In addition to its poor span efficiency, this sailplane suffered from a rather low $C_{L_{max}}$ of 1.13.

Figure 7. Span load distribution for the Horten IV Sailplane from Ref. 13.



To achieve stable trimmed flight without a penalty in span efficiency it is only necessary to create a wing with its aerodynamic center farther outboard (farther aft) than the 42.4% point. Although it is not obvious, computational studies have shown that this is quite possible for wings with sufficiently high aspect ratio, taper ratio, and sweep.

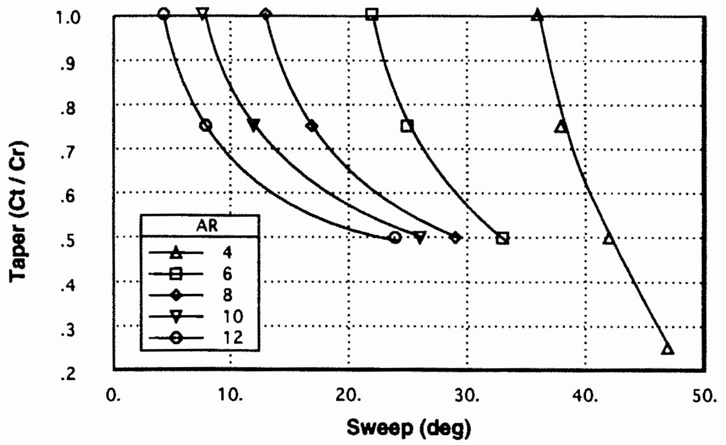


Figure 8. Combinations of Sweep and Taper Required to Move Aerodynamic Center Outboard of 45% Semi-Span. Computations Based on Lifting Suurface Analysis.

This approach may be viewed as illustrated below. The basic lift distribution (at zero lift) has negatively loaded tips to produce the positive C_m needed for trim. This inefficient shape (very non-elliptic) is combined with an additional lift distribution (due to angle of attack) that is also rather non-elliptic because it carries too much lift near the tip. The two distributions combine to form an elliptic distribution. Since the additional loading alone determines the stability, the airplane is stable as well as trimmed with elliptic loading.

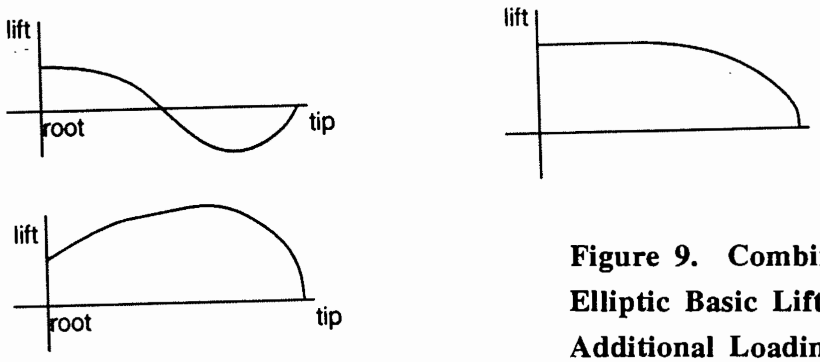


Figure 9. Combining a Very Non-Elliptic Basic Lift Distribution and Additional Loading to Obtain Cmo, Aft a.c., and Elliptic Net Lift.

The aft position of the a.c. also permits the use of rather conventional high-lift devices on this tailless aircraft. Although small inboard flaps were included in early designs by Lippisch and by Buxton in the 1930's, the extent of the surfaces was very limited [2]. The adoption of a planform with outboard a.c. position makes a conventional plain flap of 50% to 60% of the span possible, increasing maximum lift coefficients to values similar to conventional configurations and provides a desirable camber change for reduced drag and increased lift at low speeds.

Flaps of smaller extent may be used in place of elevons. Although the control authority is less substantial, inboard flaps for pitch control, suggested by Lippisch [15] and R.T. Jones [16], among others, have the following advantages. They avoid the non-minimum phase control of elevons (which reduce airplane lift, to produce pitch up, to increase airplane lift). They do not require control mixing and reduced aileron authority. They eliminate possibility of pitch control reversal, and remove the pitch control surfaces from stall-prone tips

Example: SWIFT Development

These ideas studied in the design of a foot-launched sailplane, depicted below [17].

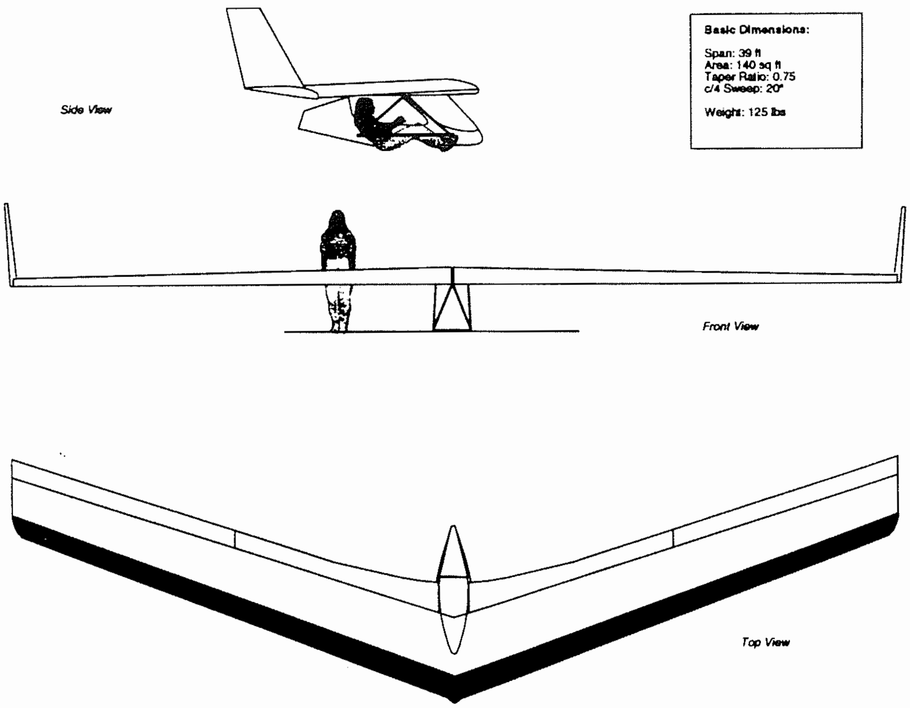


Figure 10. Basic Arrangement of the SWIFT Foot-Launched Sailplane.

Sections with small negative pitching moments were designed with interactive programs and included a great deal of iteration with the structural design. Because the airplane was to have a wing larger than that of a Cessna and yet weight less than 100 lbs, thick sections were required. Pitching moment constraints along with concerns about surface finish lead to a conservative laminar flow design with a designed laminar run of about 30% of the upper surface, tripped before the start of recovery. The section design was complicated by the low Reynolds numbers (700,000 to 3,000,000), large C_l range, and the required inboard flap and elevon deflections.

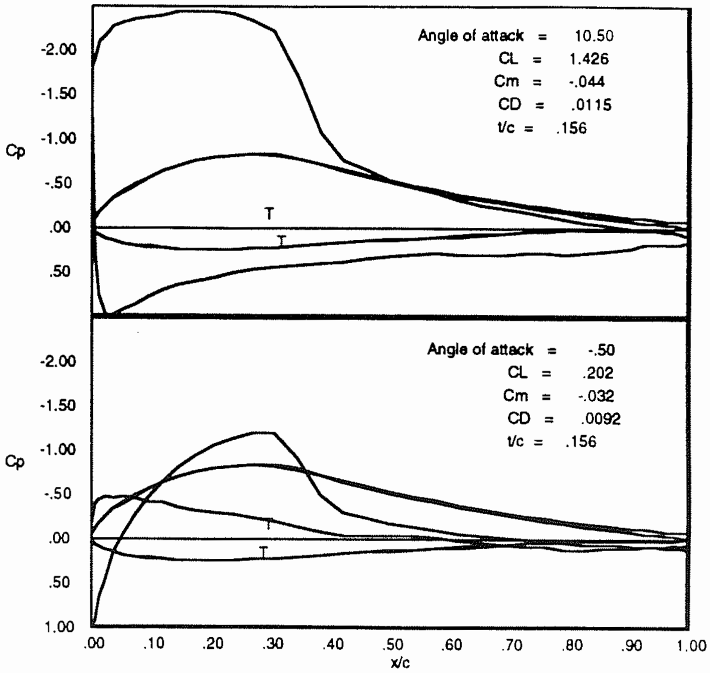


Figure 11. Pressure Distributions on SWIFT Airfoil Sections at Two Angles of Attack. Note small negative moment, conservative laminar design.

The planform itself was designed based on the previously mentioned ideas about span loading. The detailed sizing, control deflections, and twist distributions were determined by numerical optimization of the design based on a simulated cross-country cruising flight. The large tip chords on the resulting planform not only move the a.c. outboard but increase local Reynolds number (a problem with the Horten sailplanes), and lower local C_l's reducing the tendency for tip stall and maintaining roll control to high angles of attack. The design's fixed winglets provide directional stability, increase the effective span, move the a.c. farther outboard, and interfere in a favorable way with the ailerons to improve turning coordination.

At this time about a dozen SWIFT's have been built by Bright Star Gliders of Santa Rosa, California. They have won several U.S. and international competitions with a top speed of 80 mph, a stalling speed of 23 mph, and a maximum L/D of about 25.

Aeroelasticity

The SWIFT's moderate aspect ratio, thick sections, and composite design make it quite stiff and aeroelastic problems have not been observed. However, many higher aspect ratio swept wings are strongly affected by aeroelasticity. Wing bending along the elastic axis increases washout in the streamwise direction and reduces the static margin [18]. The effect is often significant (a 10% reduction in static margin for an aspect ratio 20 wing with taper = .5, t/c = .15, $C_L = .5$ and $\sigma/E = .001$.) Dynamic instabilities involving the same basic aerodynamic phenomena, coupling wing bending modes and airplane short-period modes, have also been observed—in some cases causing major design revisions [6]. For wings with low torsional stiffness elevon reversal is also possible with even more severe implications than conventional aileron reversal. The possibility of using elevon reversal constructively has also been explored in tests of hang gliders in the late 1970's [19]. In fact, hang gliders represent tailless designs incorporating sweep and twist that have been successful largely because of their exploitation of aeroelastic effects. At high angles of attack hang glider wings have (and need) large twist angles. Twist is reduced due to flexibility at low angles of attack where it would cause a performance penalty. Substantial changes in twist and section camber are produced at low angles of attack using the mechanisms shown in figure 12. This results in a C_m curve shown below with an increase in stability at low angles of attack to avoid excess speed and reduce the possibility of tumbling.

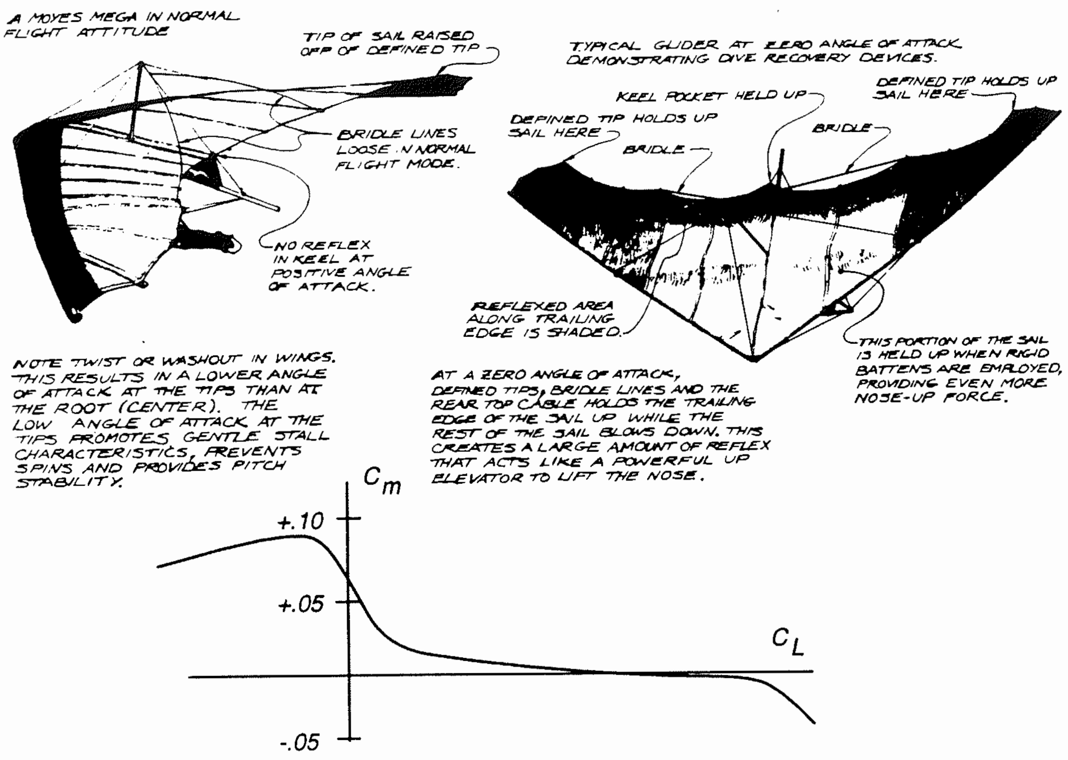


Figure 12. Constructive Use of Aeroeleasticity in Hang Gliders, Drawings by D. Pagen [20]. Below: Typical C_m Curve.

4 UNSTABLE AIRCRAFT AND ACTIVE CONTROL

Basic Approach / Controllability

Some of the difficulties with achieving trim through section design may be eliminated if we discard the requirement for static stability. In this case, as shown in figure 13, a nose down (negative) moment is required about the section aerodynamic center. With conventional section C_m's of about -0.1, this would require a static margin of -10% (c.g. at 35% chord) at a C_L of 1.0. Trim at lower C_L requires a more aft c.g. position, or less camber—a desirable change. If this level of instability can be tolerated (through the use of active controls) many of the objections to the unswept tailless aircraft are answered: conventional sections are acceptable and high lift devices may even be used.

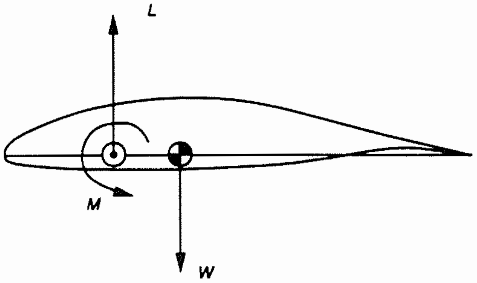


Figure 13. Arrangement of C.G. and A.C. for Unstable Trimmed Section

If the trailing edge of the wing is the only pitch control, however, moving the c.g. aft reduces control effectiveness and at some point (near 20% unstable) the control effectiveness goes to zero as shown in figure 14. The range of c.g. position between 30% and 35% chord is intriguing, however, and this concept is being explored in a number of on-going projects.

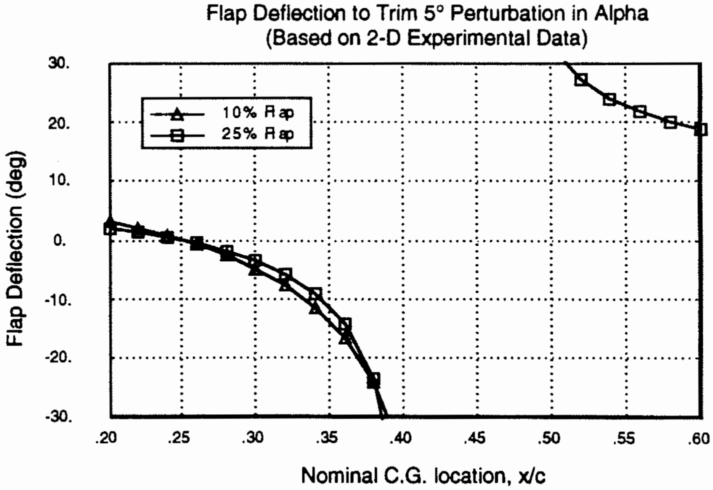


Figure 14. Flap Deflection Required to Trim 5° α Perturbation (based on 2-D experimental data)

To explore the use of active controls in a region in which controllability becomes an issue, Dr. Steve Morris at Stanford constructed an actively-controlled model shown in figure 15. The aircraft weighed about 20 lbs with a 12 ft wing span and incorporated a custom-built 68020-based computer, high-speed servos, an angle of attack sensor and pitch-rate gyro. Many successful flights were performed with levels of instability ranging from 6.5% to 9%.

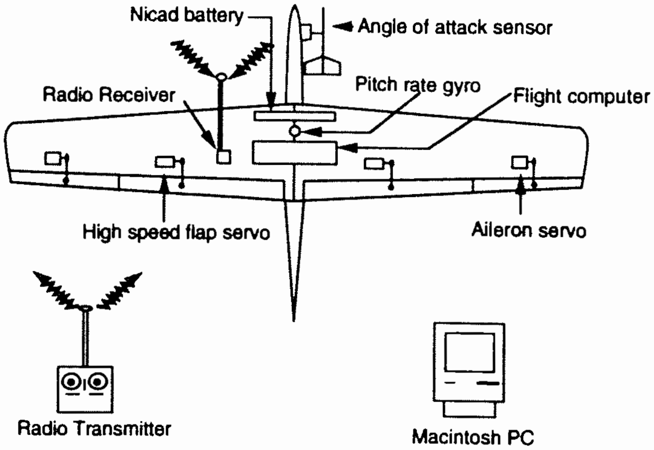


Figure 15. Unstable Flying Wing Model — Hardware Layout.

In-flight data recording (Fig. 16) shows how the closed loop response of the aircraft followed the pilot's commands at the 6.5% stability level. Large variations from the commanded performance, indicative of the reduction in control authority, appear during flights with 9% instability.

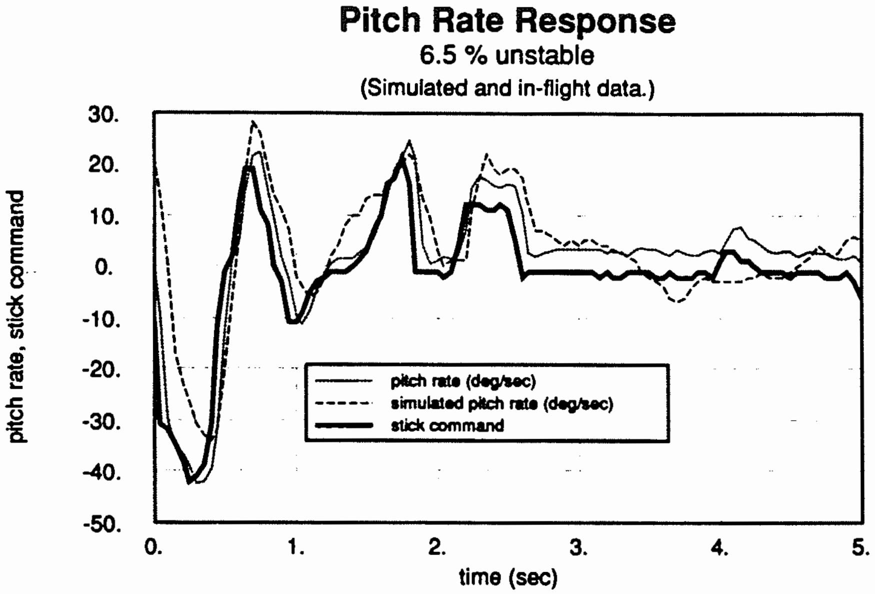


Figure 16. Flight Test Data from Unstable Model Tests

Example: Oblique All-Wing Airplane

A direct application of this approach was suggested by G.H. Lee in 1961 [21]. The oblique flying wing was based on an idea proposed by R.T. Jones to reduce supersonic wave drag [22]. In this concept, passengers were accommodated inside a large obliquely-swept tailless airplane with the potential for large savings in structural weight (due to span loading and thick sections) and drag. In 1961, active control was not practical for a commercial aircraft and subsequent work focussed on oblique wing-body combinations [23]. However, the all-wing version of the oblique wing concept eliminates much of the undesirable wing-body interference, aeroelastic problems, and weight and drag of the wing-body design, leading to a renewed interest in the oblique all-wing configuration in the last few years. Research on the oblique all-wing aircraft at NASA Ames Research Center, Boeing, Douglas, and Stanford is discussed in Refs. 24-26. Current computations suggest lift to drag ratios that are somewhat higher than conventional designs at Mach 1.6, very high subsonic L/D, a potential for large structural weight savings, and a host of problems associated with passenger accommodations, stability and control.

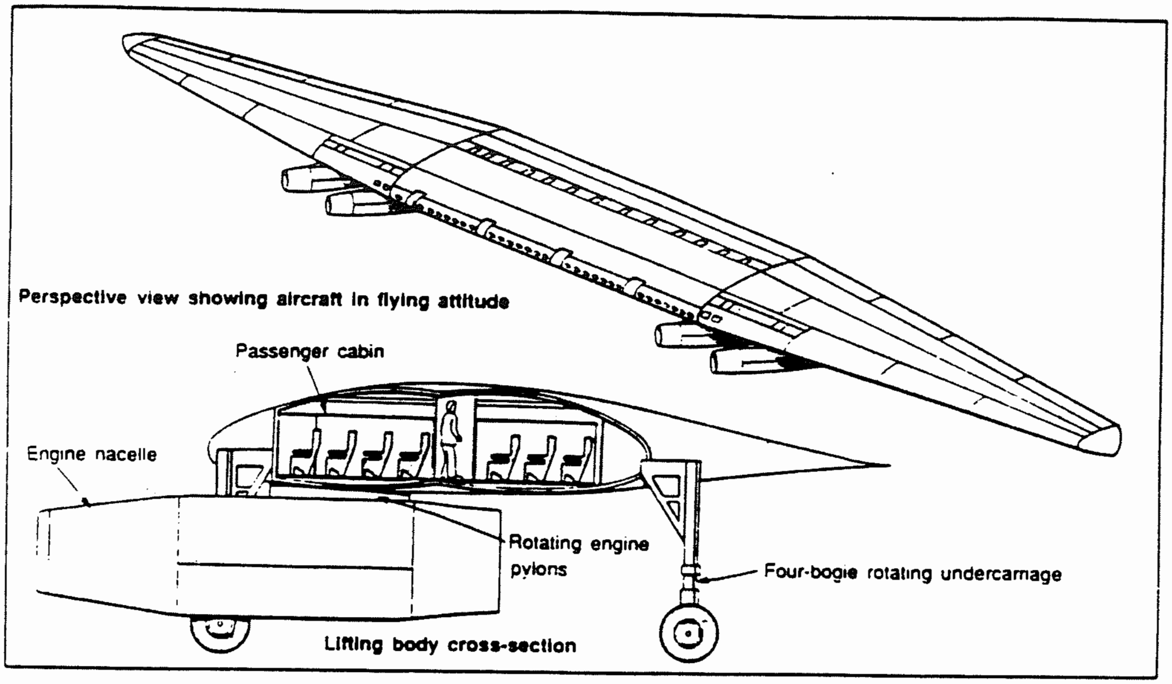
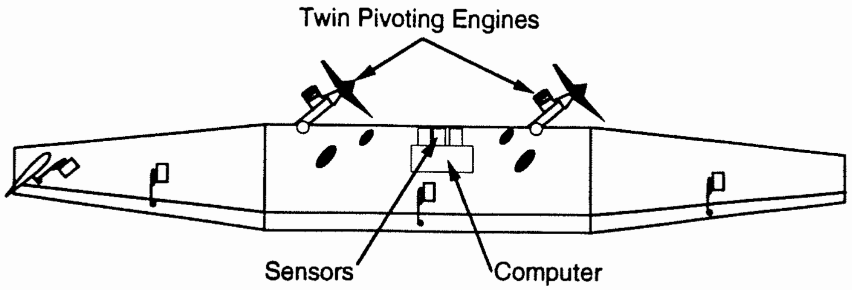


Figure 17. Artist's Concept of an Oblique Flying Wing SST.

Limiting the unswept span to about 400 ft based on airport compatibility considerations leads to an SST design for 450 passengers with an unswept aspect ratio somewhat less than 10, a gross weight of about 900,000 lbs with 4 pivoting engines permitting efficient low speed climb with low seep angles and efficient cruise up to Mach 1.6 with 68° of sweep.



- 20 foot span, 50lb weight
- 7% Statically unstable in pitch
- Onboard computer and sensors for SAS
- Data Recording System

Figure 18. Small-Scale Oblique Wing Flight Research Aircraft

Recent work at Stanford has focussed on the stability and control of the unstable, low control-authority configuration, starting with a 10 ft span, stable, radio-controlled version of the design. Figure 19 shows the characteristic roots of the equations of motions for the unaugmented model as a function of sweep angle. As the sweep is increased, the model becomes very difficult to fly because

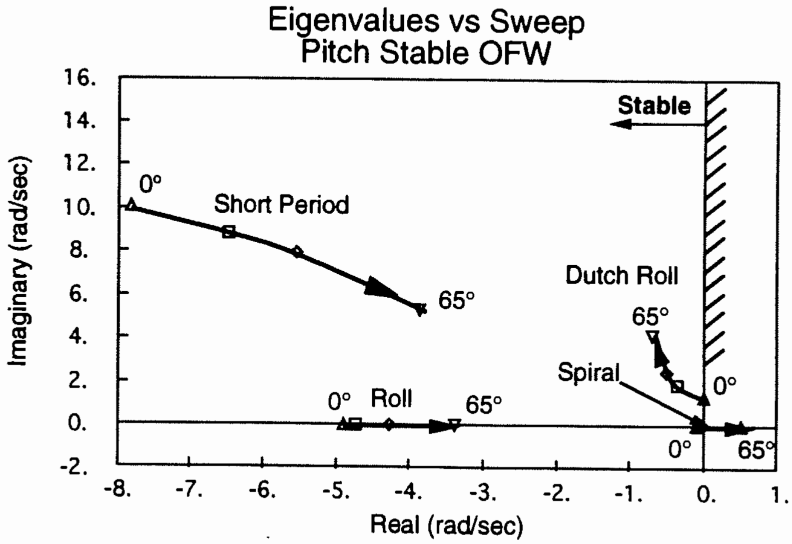


Figure 19. Stability Roots of Oblique Wing Model. Note Unstable "Spiral" Mode.

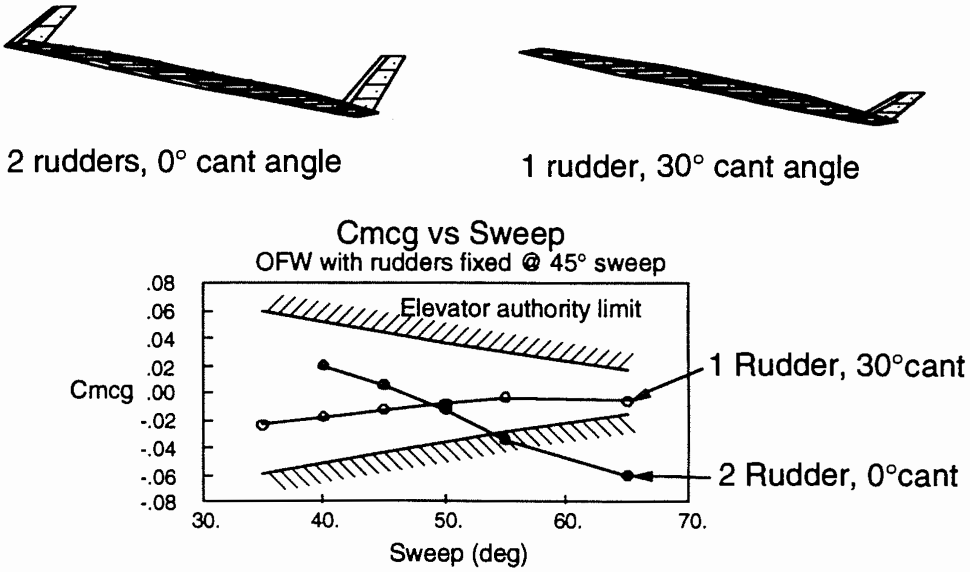


Figure 20. Coupling of Vertical Fins into "Pitch" Motion and Low Control Authority.

of increased coupling and reduced control authority. Figure 20 shows why the original design with two vertical fins became uncontrollable in pitch (motion about the long axis) and crashed spectacularly, while the subsequent single, canted fin design was flown successfully. Figure 21 shows the unusual asymmetric spiral instability that makes turns to the right more difficult than those to the left. Many additional analyses, a wind tunnel test, and flight of a 20 ft span actively-controlled model are planned in the next year.

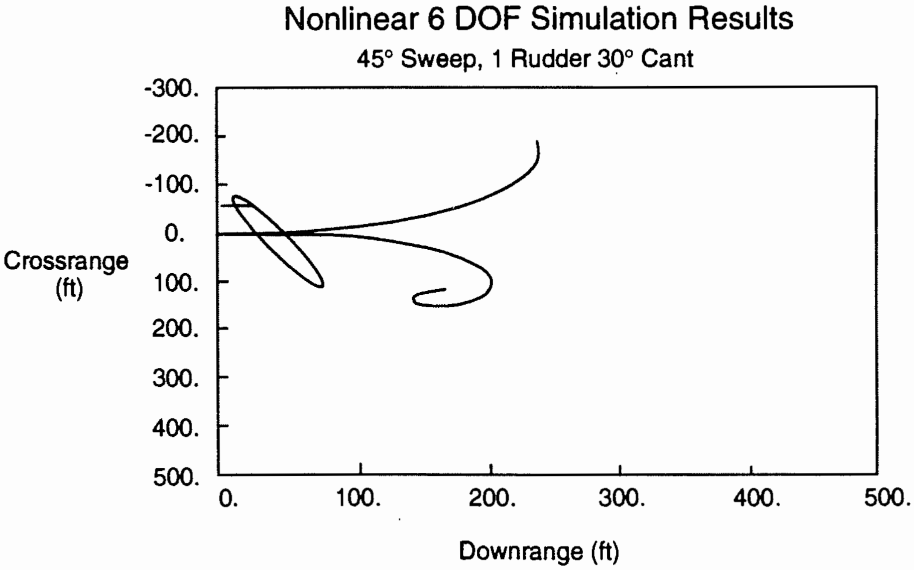


Figure 21. Asymmetric (nonlinear) Spiral Mode Makes Unaugmented Turns Difficult.

One alternative to conventional trailing edge controls that does not suffer from the loss of control effectiveness at aft c.g. positions is that used by birds. Shifting the position of the wing relative to the c.g., either by shifting the pilot weight (hang gliders) or by changing the wing sweep in flight (first suggested by Louis Mouillard in the late 1800's and used by the G.T.R. Hill Pterodactyl, Mk IV [2]) can permit the use of active control without controllability loss. This was the approach taken by AeroVironment in the development of its replica of the largest flying creature, the Quetzelcoatlus northropi. Actively controlled fore and aft motion of the wings combined with a zero-moment section [11] produced successful gliding and powered flights of this model (Fig. 22).

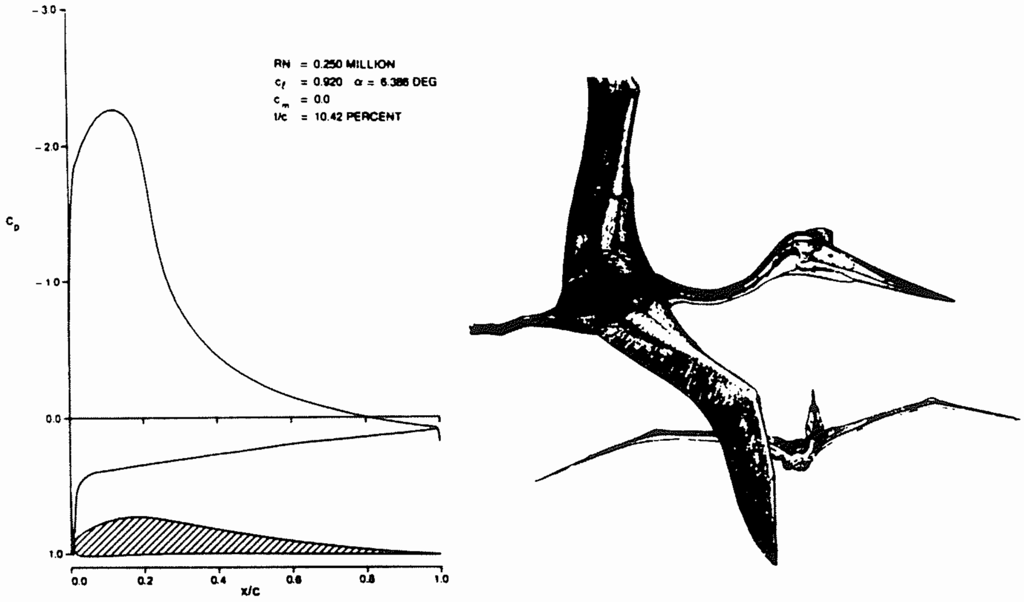


Figure 22. Sections for QN Model Using Active Pitch Control Through Wing Sweep.

Perhaps the most promising compromise for an airplane with active controls involves enhancing the advantages associated with swept tailless aircraft through relaxed stability. This approach, exemplified by the Northrop B-2 and suggested by Prof. Sears [27], provides good controllability in pitch, increased pitch damping, and the potential for good lateral handling qualities [28].

5 CONCLUSIONS

The tailless configuration has been considered by airplane designers for one hundred years and has generally been regarded as inferior to the conventional aft-tail design. However, new roles and requirements, such as the need for low radar cross section or very large aircraft, and the growing acceptance of new technologies, such as active controls, change the rules of the game and may make tailless aircraft attractive alternatives for many new applications.

There is also continued interest in stable tailless aircraft and this paper has briefly described how proper combinations of sweep, taper, and twist can lead to stable, trimmed tailless aircraft without aerodynamic penalties. High aspect ratio, moderately tapered wings can be constructed to have very high span efficiencies over a wide range of C_L's and can accommodate reasonably large trailing edge flaps for good maximum lift performance.

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