UNCONVENTIONAL AIRCRAFT CONCEPTS

Editors: F.J. Sterk
E. Torenbeek

Papers presented at a symposium organized by the Netherlands Association of Aeronautical Engineers (NVvL) and the Students Society "Leonardo da Vinci" on April 24 1987, at the Delft University of Technology

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FOREWORD

The selection of a general arrangement for new fixed-wing aircraft is one of the most challenging and crucial phases of conceptual design. Superficially it seems that designers have an overwhelming freedom of choice between configurations with, for example,

- o propeller or jet (turbofan) propulsion systems, and in the near future: high-speed propellers, unducted fans, or ultrahigh bypass engines;
- o various wing dispositions relative to the fuselage, both in the vertical and longitudinal sense;
- o in the case of propellers: tractor or pusher;
- o horizontal stabilizers at the aft fuselage or vertical tailplane, foreplanes (canards), or both (three-surface aircraft), or even tandem wings;
- o a single fuselage, with two or even without any fuselage (all-wing aircraft).

However, the history of aircraft development has shown that each era of technological state-of-the-art produced in fact a small range of generally favoured combinations, for example:

- o single engine, tractor-type propeller aircraft for low-speed general aviation;
- o low-to-medium subsonic propeller-driven transport aircraft with cantilever monoplane wings and wing-mounted tractor engines;
- o high-subsonic jet transports with wing- or aft-fuselage mounted podded turbojet and, later, turbofan engines;
- o supersonic tailless delta wing fighters (e.g. Mirage) or fighters with thin, moderately swept, low-aspect ratio wings and aft tails (e.g. F-16)'

It is also clear that the development of these categories has always been rather evolutionary in civil aviation, but less so in military aircraft design, where the degree of freedom seems to be higher.

It is unlikely that the design trends are set merely by conservatism, for example a desire to continue a proven concept in order to avoid the large financial risks of totally new development programmes. The sharp competition always sets incentives to new and innovative concepts since new designs must be considerably improved to be competitive to (derivatives of) already established and proven types. The outcome of a conceptual design study contains a careful balance of pros and cons, with interfaces between

- o desired operational characteristics,
- o new technological developments,
- o the economic environment (e.g. fuel prices),
- o continuity in the design philosphy and production facilities,
- o the objectives of reliability and maintainability.

Exceptional aircraft concepts have emerged from time to time and often faded away after the appearance of unexpected and unsurmountable engineering problems and/or non-existence of appropriate airworthiness criteria (e.g. Learfan). Such has been the fate of the tail-first concept until the late sixties. The designers of the SAAB Viggen in Sweden and Burt Rutan in the U.S. have to be given credit for the fresh approach to aircraft design, capitalizing on their potential promise and carefully tailoring the shape of their aircraft to the peculiar aspects of canards. The outcome of this has stimulated the development of new breeds of highly manoeuvrable transonic fighters and efficient general aviation aircraft.

The main driving factor behind the evolution of aircraft shapes has always been the engine development. This will remain to be the situation with the newly emerging high-speed turboprop or unducted fan engines. But there are several other interesting lines of thought, for example:

a) Sweeping a high-speed wing forward instead of backwards has the potential of improving L/D and roll control at high angles of attack. It shows promises for application in fighter design, provided measures have been taken to avoid aeroelastic divergence and flutter. The experimental X-29 aircraft uses an aeroelastically tailored composite wing, in combination with other new technologies (variable camber, active controls, post-stall manoeuverability). Application to high-aspect ratio wings, e.g. on transport aircraft, deserves attention.
b) The all-wing configuration has challenged many designers in the past (Horten, Northrop, Lee). The inherently high L/D and low structural weight (due to lateral distribution of the load) could result in large gains in range and economy. The bottleneck appeared to be poor dynamic longitudinal stability and gust sensitivity, which became fatal to the Northrop XB-35 and YF-49B. Recently, however, the all-wing configuration has been reanimated since new developments in Active Control Technology could suppress its dynamic problems. Stealth Technology has given new impetus to the development of shapes with little reflection of radar waves, resulting in configurations with blended wings and bodies.
c) Tail-first aircraft have the potential of weight and drag reduction since both lifting surfaces have positive lift, as opposed to the usually downloaded aft-tail. However, their balancing is more complicated and the canard requires a very careful design. The requirements of low induced drag and high lift are counteracting, except in the case of artificially stabilized aircraft. The potential gains appear to be realized on highly manoeuvrable close-coupled canards (Gripen, Rafale, Lavi, EFA, EAP). The appearance of several new G.A. aircraft (Avanti, Starship, Avtek 400) seems to indicate that secondary effects of their general arrangements (high power pusher propellers, low cabin noise level) are at least as important as the presence of the foreplane.
d) Recently, configurations with two fuselages have been studied by staff of NASA Langley and others. Reduced wing bending moments and less parasite drag per passenger have been quoted as their main features. In some cases it was proposed to compose one large capacity aircraft from two existing fuselages and wing halves, to which a new centersection with some extra engines and a new tailplane were added. Even if certain problems of lateral controlability and passenger comfort can be solved, it is not likely that airlines will favour these aircraft for passenger transport, but further study should be done, e.g. application to dedicated freighters.
e) A most intrigueing and innovative concept is the joined wing, an invention of J. Wolkovitch, one of the lecturers of the symposium. It combines some of the merits of the old bracing principle with aeroelastic tailoring, forward and aft sweep, as well as a modest gain in induced drag.

These and several other concepts form the main subject of the present one-day symposium, organized by the NVvL and "Leonardo da Vinci". The organizing committee has considered but also rejected the inclusion of new V/STOL-type concepts, due to their special character. Propfan propulsion may have a certain influence on future design trends, but this subject is covered during several occasions elsewhere.

Hopefully the lecturers will show convincingly that unconventional concepts, some of which have been proposed in the past, have grown to maturity these days. But most interesting of all will be the situation where several of these concepts could be combined, resulting in a favourable synergistic effect. It is not unlikely that elements of the symposium will show the Netherlands aeronautical society new directions for research and development. Sooner or later aircraft will be designed, manufactured or operated in this country, which contain elements of the presently unconventional concepts. Let us therefore pay attention to them before they have become common place.

March 1987
F.J. Sterk
E. Torenbeek

SURVEY OF UNCONVENTIONAL AIRCRAFT DESIGN CONCEPTS

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Lockheed-Georgia Company

ABSTRACT

The need for improved aircraft performance and efficiency has provided the motivation for consideration of unconventional design concepts for aircraft envisioned for operation in the 1990-2000 time period. Advances in technology permit continuing improvements in aircraft performance and economics but unconventional design concepts show the potential for larger incremental improvements in aircraft efficiency. The paper reviews preliminary design system studies of unconventional aircraft including span-distributed loading, multi-body, wing-in-ground effect, flying wing, oblique wing, transonic biplane and future needs in design concepts. The data include a comparison of the performance and economics of each concept to that for conventional designs. All of the design concepts reviewed incorporate appropriate advanced technologies. The aircraft design parameters include Mach numbers from 0.30 to 0.95, design payloads over one million pounds, and design ranges up to 5,500 nautical miles.

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Fellow, American Institute of Aeronautics and Astronautics

I. INTRODUCTION

Aeronautical engineers are motivated to consider unconventional aircraft design concepts in order to achieve a particular performance or operational improvement such as drag reduction, increased useful load, short airfield capability and/or combinations thereof. External influences such as the fuel crisis of the early 1970's provided the impetus for a number of approaches toward the achievement of aircraft fuel efficiency including Very Large Aircraft, VLA, air cargo concepts and variable and fixed geometry designs for normal 200 to 400 passenger-sized aircraft. The fuel crisis also provided the motivation for a concerted effort within NASA, the Air Force, and industry on the application of advanced technologies for the improvement in aircraft fuel efficiency. This effort includes the NASA Aircraft Energy Efficiency (ACEE) Program (References 1 -4). Advanced technologies including super-critical wing, advanced composite materials, advanced turbofan and propfan propulsion and laminar flow control have been identified in these programs as those that show the most significant potential benefits and which merit acceleration toward technology readiness (References 5-8). As will be discussed later, the selected application of these advanced technologies enhances the performance of unconventional aircraft design concepts as well.

There have been two AIAA Very Large Vehicle Conferences: the first in Arlington, Virginia in April 1979 (References 9 - 11) and the second in May 1982 in Washington, D. C. (References 12 - 14). These conferences covered a very broad range of vehicles including lighter-than-airships, surface effects ships, marine systems, nuclear-powered aircraft, hydrogen-fueled aircraft, and other air vehicles (Reference 9). Review papers covering design concepts and advanced technologies for large cargo aircraft have been presented at several conferences of the International Forum for Air Cargo (References 15 - 16).

This paper presents the results of preliminary design system studies of Very Large Aircraft, VLA, and for the more normal 200 to 400 passenger-sized aircraft. Design concepts reviewed include span distributed loading, multi-body wing-in-ground effect, flying wing, oblique wing, transonic biplane, and a review of future needs. The data include a comparison of the performance and economics of each concept to that for an equivalent conventional design. All design concepts incorporate appropriate advanced technologies. The aircraft design parameters include Mach numbers from 0.30 to 0.95, design payloads over 1 million pounds, and ranges up to 5,500 nautical miles.

This paper is intended as a brief summary of some unconventional design concepts, and only highlights of the study results and technical issues are presented. The reader is provided with references to more detailed reports on the design studies of the concepts. This paper is an extension of a similar paper by the author given at the 15th Congress of the International Council of the Aeronautical Sciences held in London, England, on September 7-12, 1986 (Reference 17.)

II. SYSTEMS TECHNICAL APPROACH

The results presented in this paper cover a wide range of unconventional design concepts with different mission parameters and advanced technology assumptions employed in the preliminary design system studies. Inherent in the technical approach to each study is a procedure in which the particular unconventional aircraft design is compared to a reference aircraft design without use of the unconventional design feature. In each case the unconventional design aircraft and the reference aircraft are sized to provide identical performance capabilities of design cruise Mach number, payload, range, and airfield performance. It should be noted, however, that in the case of the wing-in-ground effects (WIG) aircraft where the tactical requirement to fly at extremely low altitude combined with the proposed power augmented ram lift system makes for a comparison with a high altitude cruise reference aircraft less meaningful, although such comparison data are available in Reference 18.

In order to provide a consistent data base from which the several design concepts can be compared, use is made in the Lockheed studies of the Generalized Aircraft Sizing and Performance (GASP) computer program. This program accounts for the interaction of the design constraints and technical disciplines involved in the aircraft design process such as mission requirements, geometric characteristics, engine data, and aerodynamic parameters. The GASP program is designed to calculate drag coefficients and weight on a component basis, integrate the results into complete aircraft drag and weight, select the propulsion system size by matching cruise thrust or takeoff distance requirements, determine the aircraft sized for the mission, and iterate the process until the defined mission parameters are satisfied. The GASP program has sufficient flexibility to permit the use of adjusting factors representing changes in the level of technology for various technology areas such as airfoil and materials technology. GASP has been used in a number of previous studies (References 8, 12, 15, and 18) to synthesize aircraft for design variables, such as wing loading, aspect ratio, cruise power setting, Mach number, range, payload, and field performance.

III. RESULTS OF SYSTEM STUDIES

Very Large Aircraft

One of the more interesting designs in the evolution of Very Large Aircraft concepts is the span distributed loading design in which the cargo is carried in the wing. By distributing the payload along the wing span, the structural weight of the wing is reduced as a result of the compensating effects of aerodynamic lift and inertia of the wing. Pioneering work by Lockheed in 1979 resulted in the spanloader configuration shown in Figure 1. The lockheed configuration has a gross weight of 1,200,000 pounds, a payload capability of 660,000 pounds for a range of 3,300 nautical miles and a cruise speed of M - 0.75. The supercritical wing is swept back 40° for the 20 percent wing thickness to provide the volume for two rows of 8x8 foot cargo containers and also achieve the M = 0.75 design cruise speed. The effective aspect ratio of the wing is 6 including end plate effects. Advanced technologies utilized include graphite epoxy composite materials in primary and secondary structure, lift augmentation for improved airport performance, and an air cushion landing gear. More details of the design are contained in Reference 19. A relative size comparison of the spanloader design and the Lockheed C-5 transport is shown in Figure 2 and illustrates a disadvantage of the spanloader concept. The disadvantage results from the need to support the payload throughout the wing span to the tips. This aircraft, therefore, requires very wide runways and taxiways which are not available at current airports. To alleviate this disadvantage and to provide airfield flexibility, the Lockheed concept has air cushion landing systems located at each wing tip and at the centerbody.

Benefits due to the Lockheed spanloader design concept as compared to that for a conventional design aircraft are summarized in Figure 3 and show: 12 percent lower direct operating costs, 8 percent lower fuel consumption, and 10 percent lower gross weight.

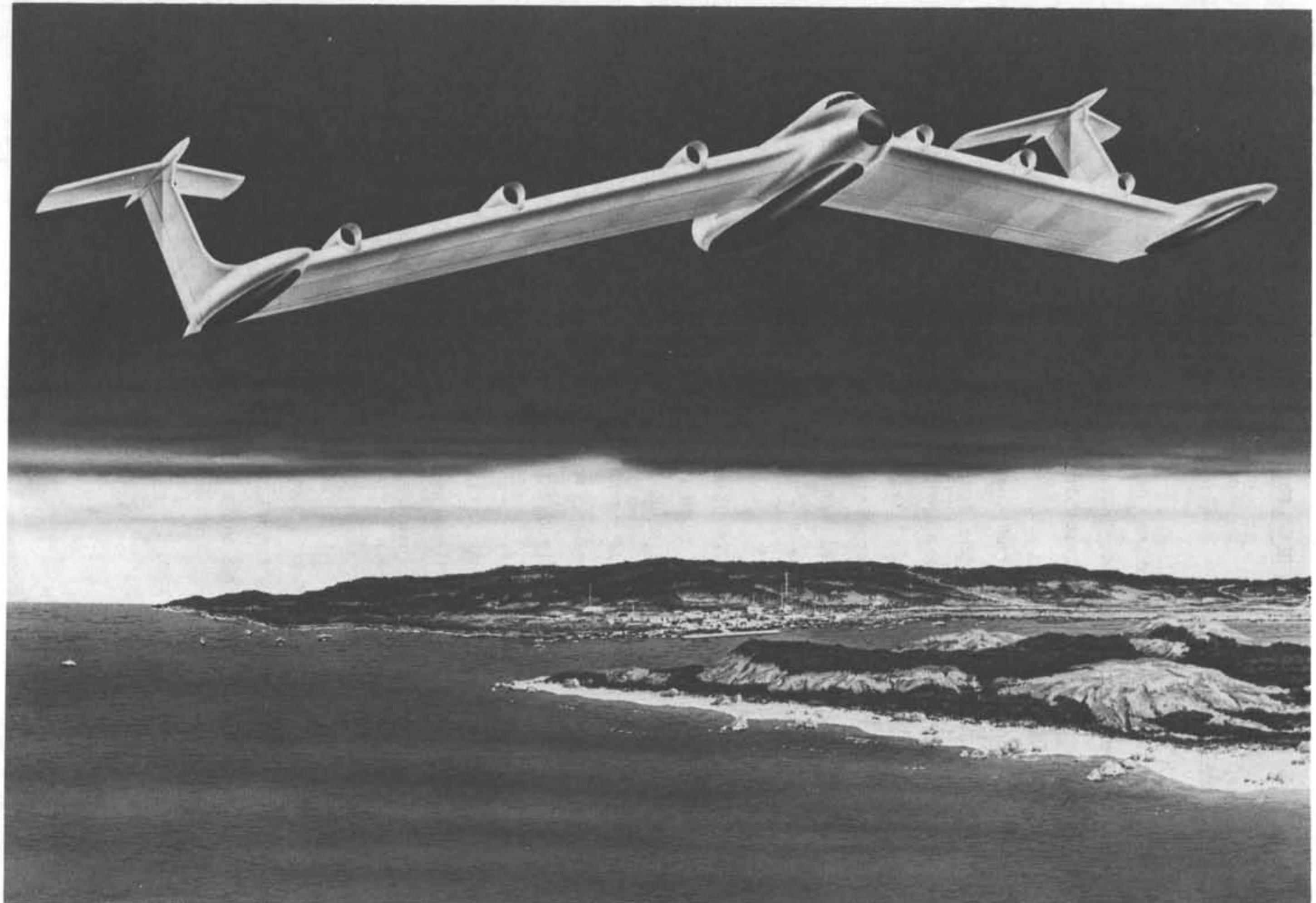


Figure 1 - Lockheed spanloader concept

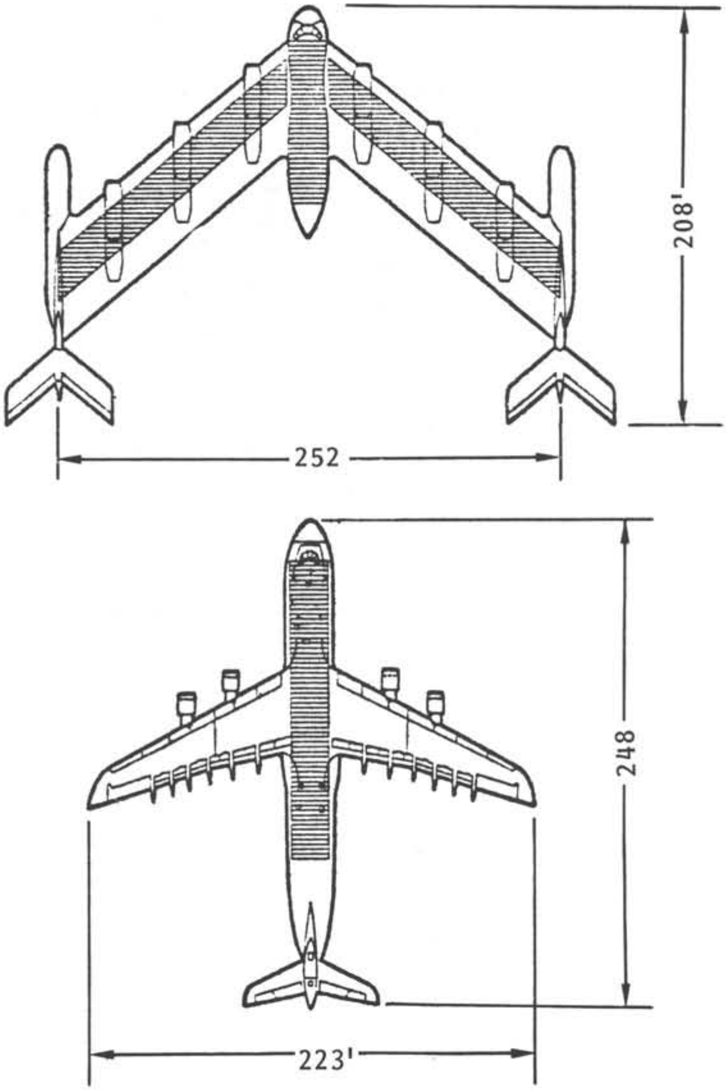


Figure 2. Comparison of Spanloader and C-5

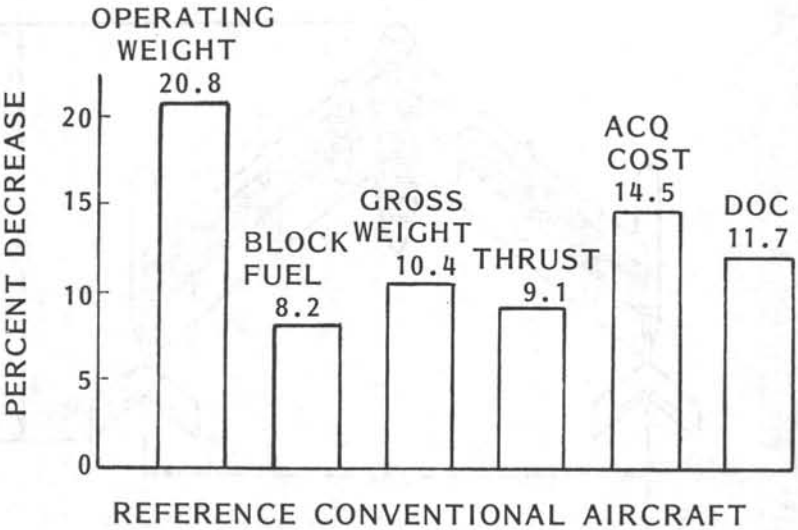


Figure 3. Benefits of the Spanloader Concept

Interest in the span distributed loading concept by the NASA Langley Research Center (Reference 20) resulted in NASA/industry system studies by Boeing, Douglas, and Lockheed reported in References 21 - 24. Design studies by Boeing covered payloads over 1 million pounds as shown in Figures 4 and 5 for a span-distributed load freighter with a gross weight of 2,354,000 pounds, payload of 1,047,000 pounds, a range of 3,600 nautical miles, and a cruise Mach number of 0.78. The effective aspect ratio of the wing is 7.73 including the end plate effects of the tip fins. This configuration resulted in a 50 percent reduction in direct operating costs, DOC, as compared to a conventional equivalent freighter aircraft.

Figure 6 shows relative direct operating costs as a function of aircraft gross weight for several existing freighter aircraft and projected future aircraft. The shaded line depicts the large reduction in operating cost per ton-mile as aircraft size increases from the L-100/727 through the 707/DC-8 to the 747. The slope of the line is also a result of the improvement in technology which has occurred simultaneously with the progressive increases in size. Also shown on this line is a projected conventional aircraft with 1990 technology representing a further significant increase in aircraft size. The points below the shaded line represent the unconventional spanloader aircraft concept that shows potential for highly-efficient cargo operations with even greater reductions in DOC.

An interesting alternative to the spanloader design concept is the multibody concept wherein the payload is carried in separate bodies located on the wing as illustrated in Figure 7 for a two-body arrangement. The basic advantage of the multibody concept is the reduction in wing root bending moments and the synergistic effects of the resulting reduction in wing weight on the performance of the aircraft. It is also expected that faster loading and unloading of the two fuselages is possible as compared to the larger fuselage required of the comparable payload conventional airplane.

Preliminary Lockheed studies were made for a 441,000-pound payload, 4,000-nautical-mile range, M = 0.80 cruise speed transport (Reference 25). More detailed study and optimization were accomplished in a NASA-funded study of

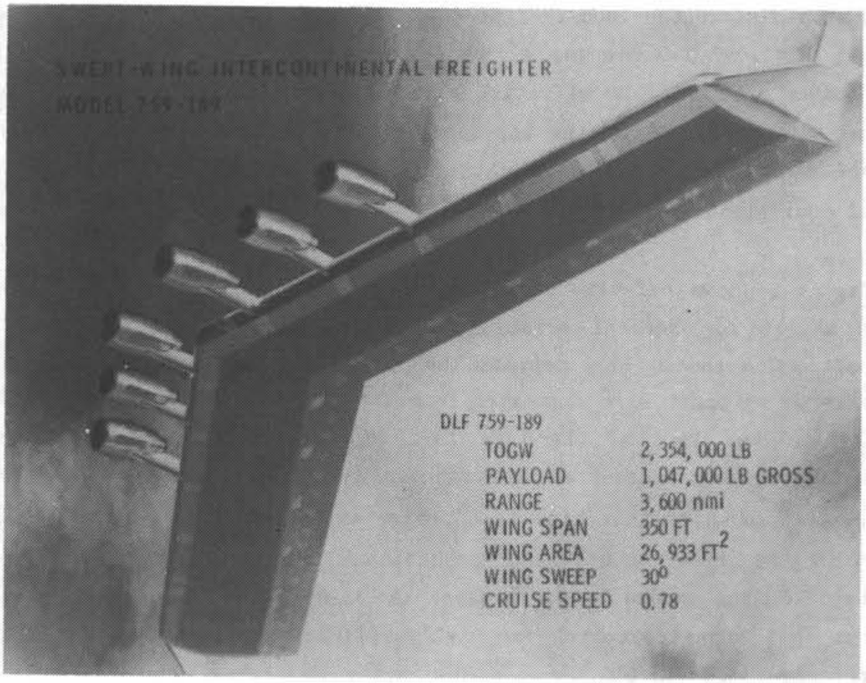
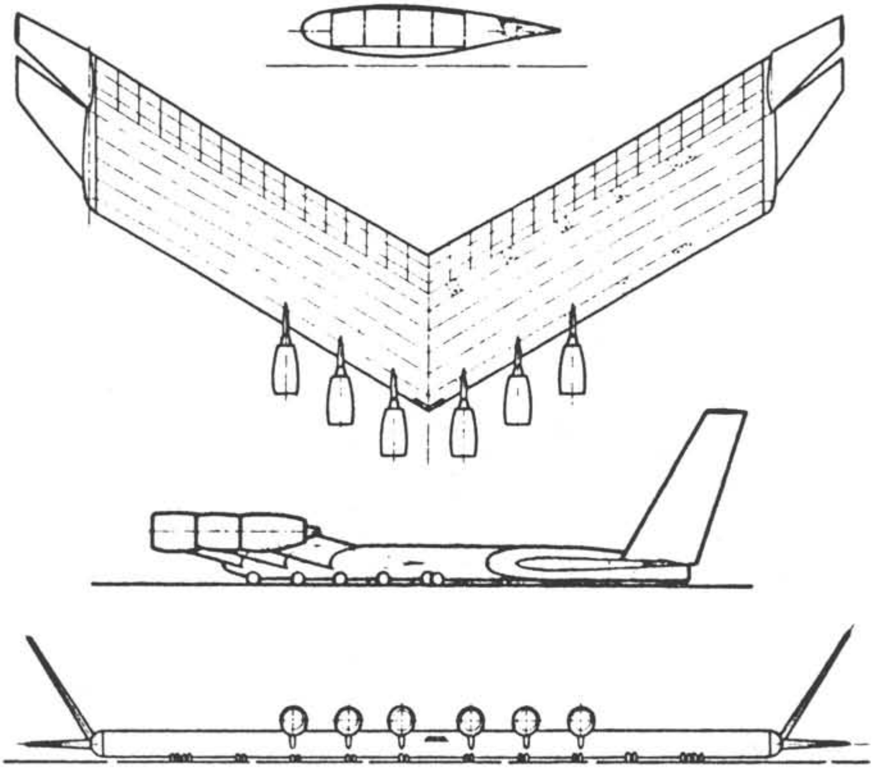


Figure 4 - Boeing distributed load freighter



TOGW		2,354,000 LB
OEW		687,936 LB
WING AREA		26,933 FT^2
ASPECT RATIO (EFF)		7.73
SWEEP		30°
t/c		0.19
CRUISE MACH		0.78
ENGINES	BPR	9.5
	SLST	93,000 LB

Figure 5. General Arrangement, Boeing Distributed Load Freighter

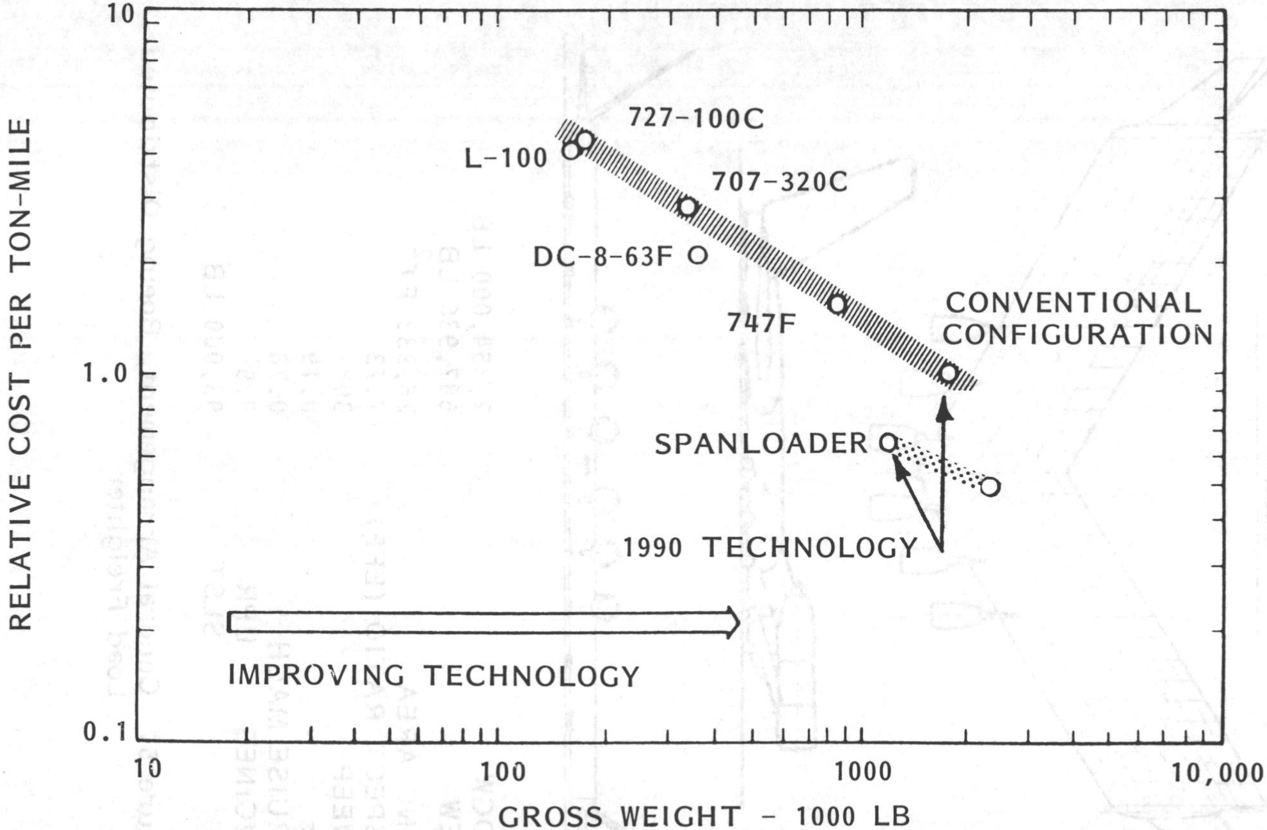


Figure 6. Operating Cost Trend

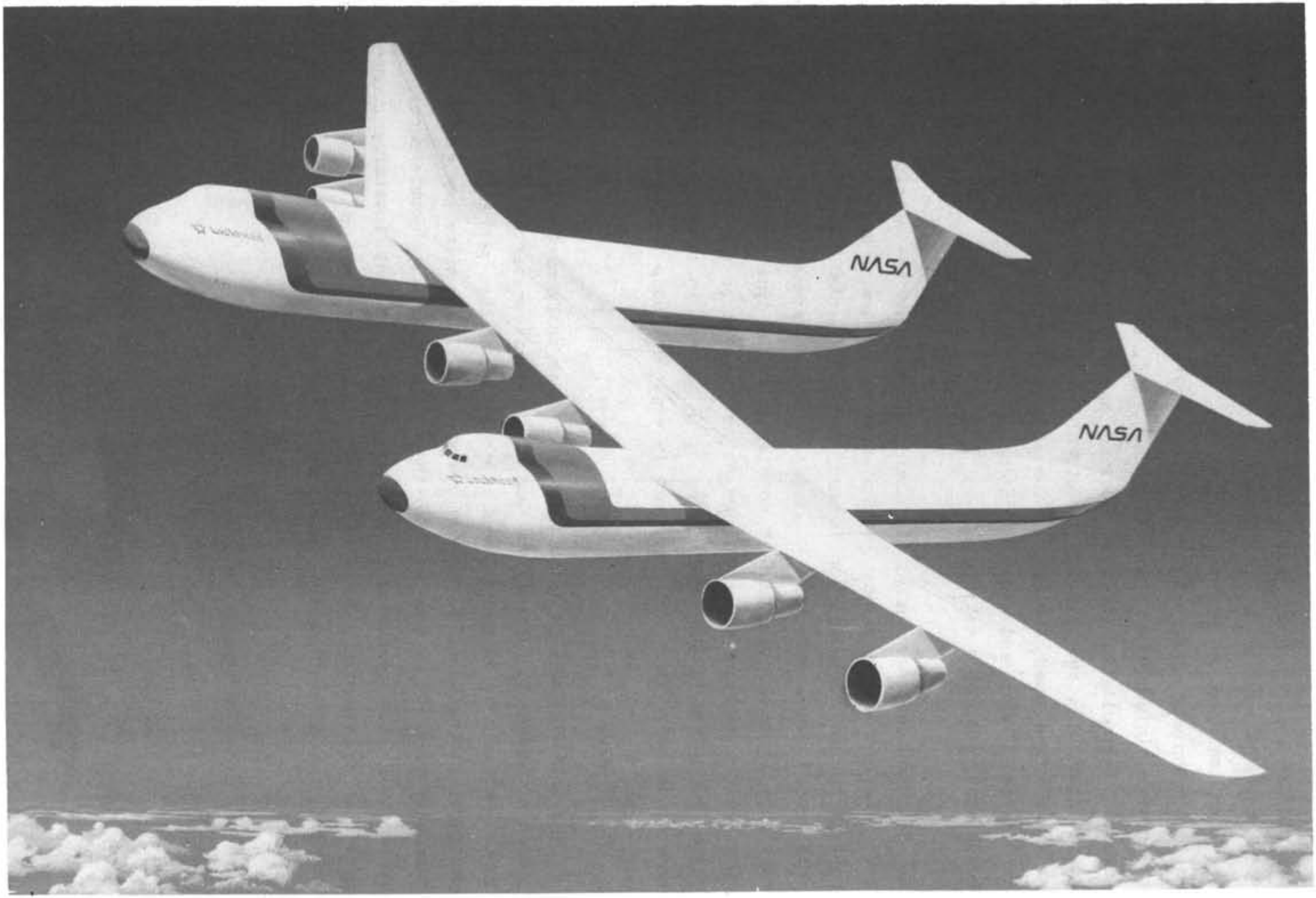
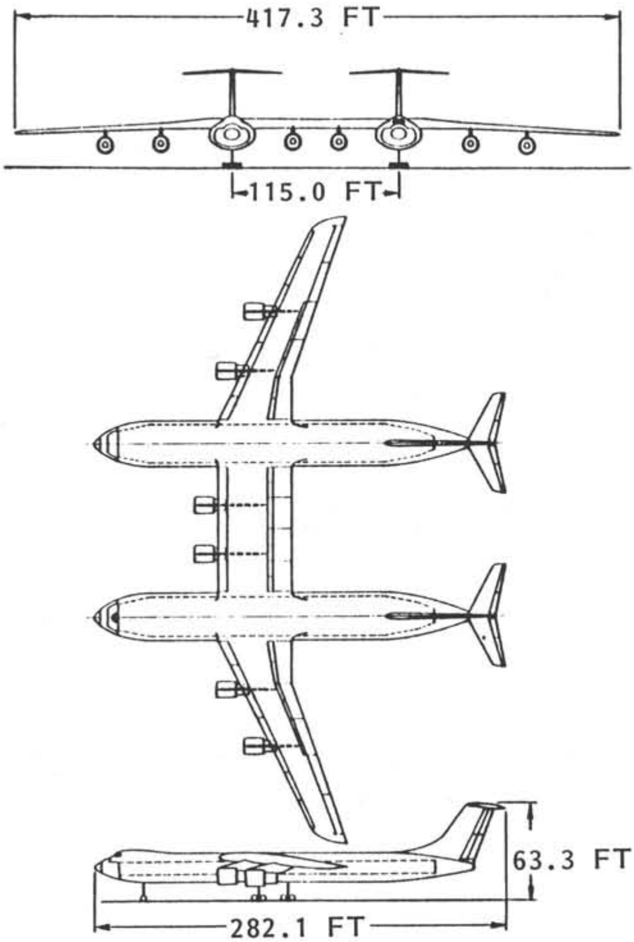


Figure 7 - Multibody cargo transport concept

the multibody concept by Lockheed as reported in References 26-27. In the NASA study the payload was 772,000 pounds for a range of 3,500 nautical miles and a cruise speed of M = 0.80. A general arrangement drawing of this large payload multibody configuration is given in Figure 8. The aircraft were sized to achieve minimum direct operating cost, DOC, for the mission requirements. Advanced technologies employed include supercritical aerodynamics, relaxed static stability, and advanced structural materials. Graphite epoxy composite materials are used for all secondary structure and empennage primary structures. Wing and fuselage structures are selectively reinforced with boron epoxy composite materials.

As discussed previously, the basic advantage of the multibody concept is the reduction in wing-root bending moments as compared with a singlebody configuration. The variation of wing bending moments from root to tip given in Figure 9 show a reduction in wing-root bending moment of 51 percent for the multibody at the cruise flight condition. The synergistic effects of the reduction in multibody aircraft weight as compared to the singlebody aircraft given in Figure 10 show reductions of 8 percent in operating weight, 13.5 percent in block fuel, 11.7 percent in engine thrust, 10 percent in aircraft unit cost, and 11 percent in DOC.

The multibody design concept has also been analyzed for civil 150 and 250 passenger commercial transports and the results presented in Reference 28. These studies show 26 percent reduction in seat miles per gallon for the 150 passenger aircraft and 38 percent reduction in seat miles per gallon for 250 passenger aircraft as comparedd to their single fuselage counterparts. These aircraft utilize technologies associated with current inservice commercial passenger transports. In effect the study represents a way of achieving improvements in performance and economics without relying on new technology advances.



SPEED	0.80 MACH
PAYLOAD	771,618 LB
RANGE	3,500 NM
OPERATING WT	763,000 LB
GROSS WT	1,980,100 LB
BLOCK FUEL	372,200 LB
ASPECT RATION	10.74

Figure 8. Multibody General Arrangement

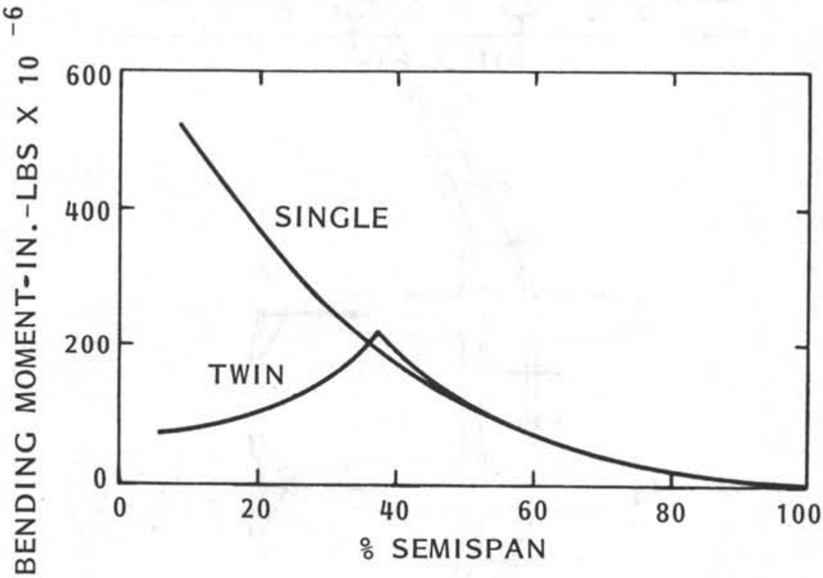


Figure 9. Comparison of Wing Bending Moments for Single and Twin Fuselage Configurations

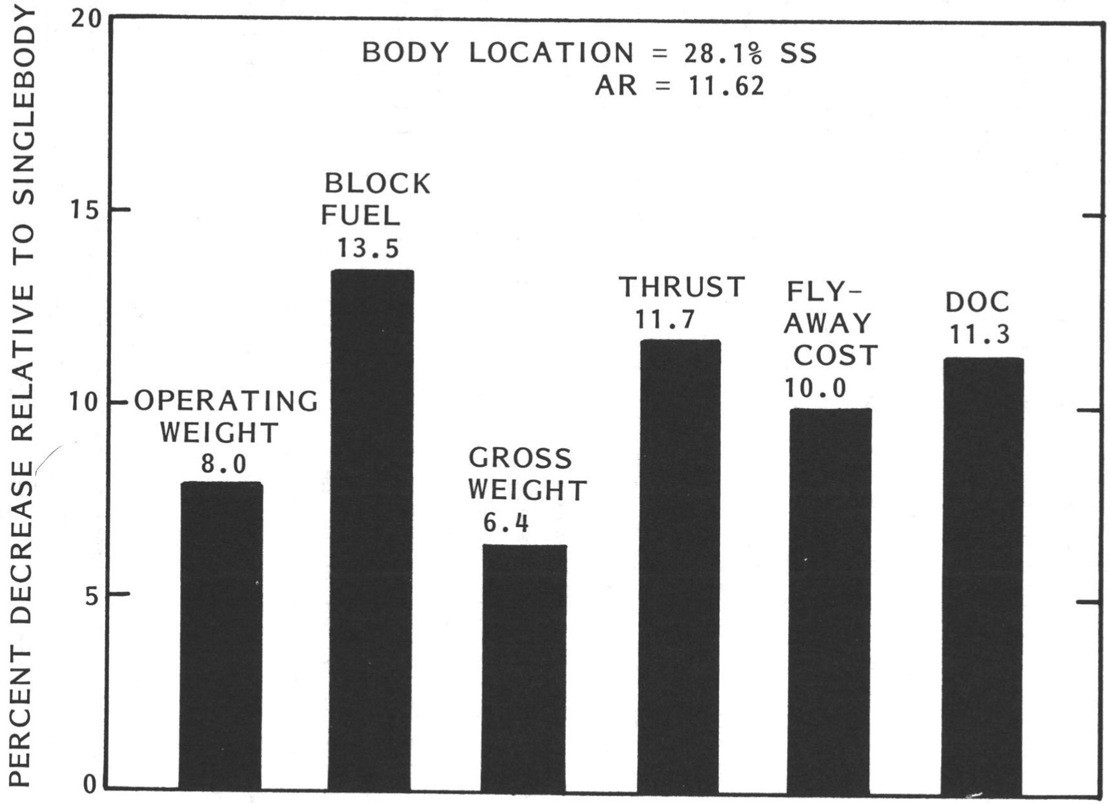


Figure 10. Benefits of the Multibody Concept

Wing-in-Ground Effect Aircraft

The transport aircraft shown by the artist's sketch in Figure 11 utilizes a power augmented ram system for lift augmentation during takeoff and landing and cruises in close proximity to the ocean surface where drag is reduced in accordance with wing-in-ground effect theory. The logistics mission requires the aircraft to takeoff from the sea surface, transport 441,000 pounds of payload, 4,000 nautical miles, over sea state 3 conditions at a cruise speed of 0.40 Mach and then land on the sea surface. Part of the study results were generated under continuing preliminary design and system studies by the Lockheed-Georgia Company and part of the results were sponsored by the Naval Air Development Center under the Advanced Naval Vehicles Concepts Evaluation Project (References 29 and 30).

The cruise altitude is determined as a compromise between the ideal altitude specified by the classical ground effect theory shown in Figure 12 (Reference 31) and the operational requirement for sea state 3 with a structural design limit for sea state 4. Flight in ground effect inhibits the downwash induced by the wing lift, thus suppressing the induced drag. This reduction can be expressed as an increase in effective wing aspect ratio. This relationship is shown on Figure 12, where the ratio of effective aspect ratio (A_E) to geometric aspect ratio (A_{GEOM}) is given as a function of the height of the lowest extension of the wing surface, including endplates (h), above the water surface divided by the wing chord (c). The solid line represents Wieselsberger's theory and the dashed line is extracted from Lockheed wind tunnel tests.

Basic to the design of the wing-in-ground effect aircraft discussed here is the application of power-augmented ram (PAR) lift based upon the pioneering investigations of the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) on water based ground effect vehicles (References 32-34). These investigations showed that the PAR system can be used to provide lift enhancement during take-off and landing so that the wing loading of the WIG can then be optimized for cruise performance conditions. Furthermore, by means of PAR lift during takeoff and landing the contact speed between the

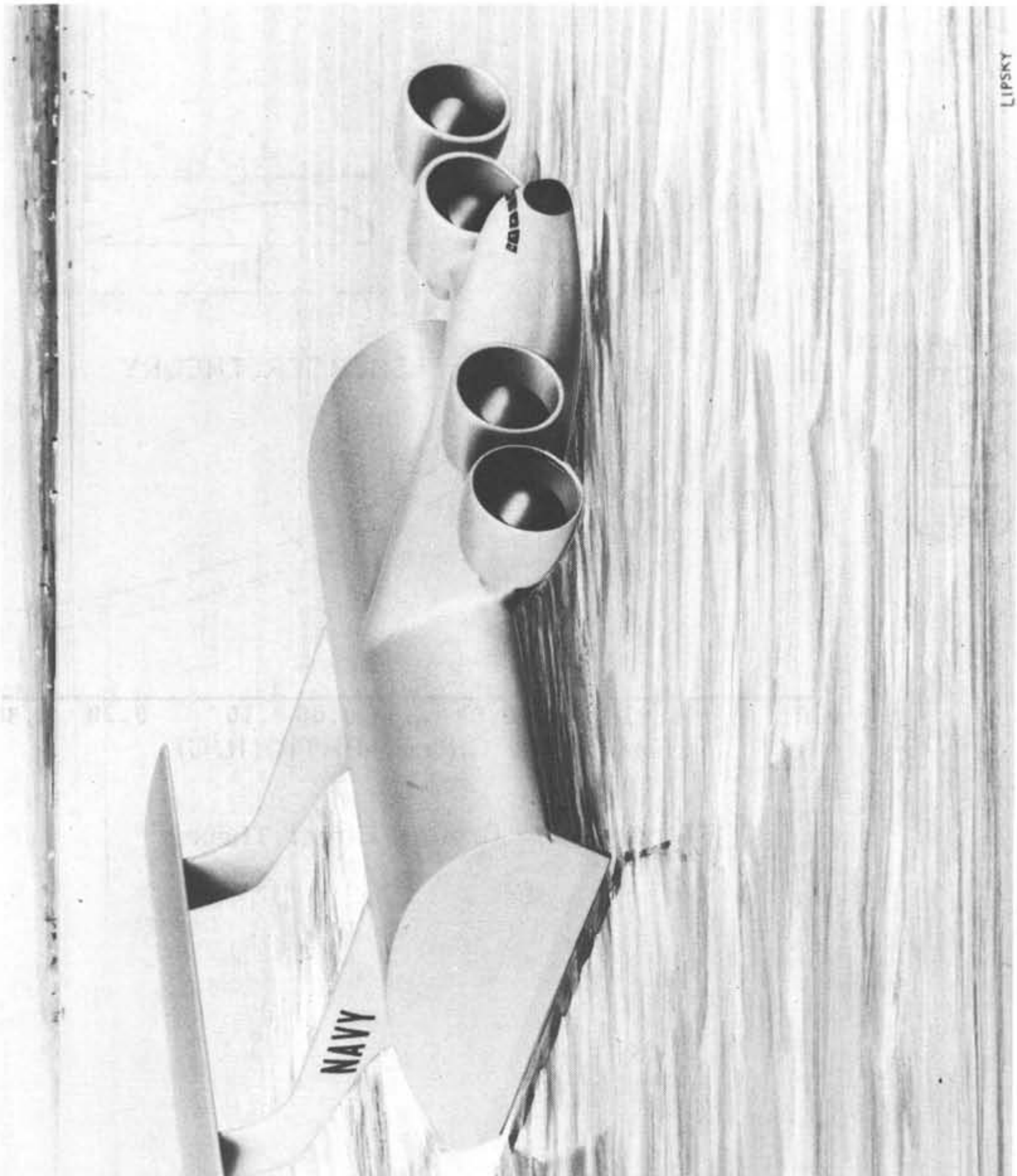


Figure 11 - Wing-in-ground effect transport

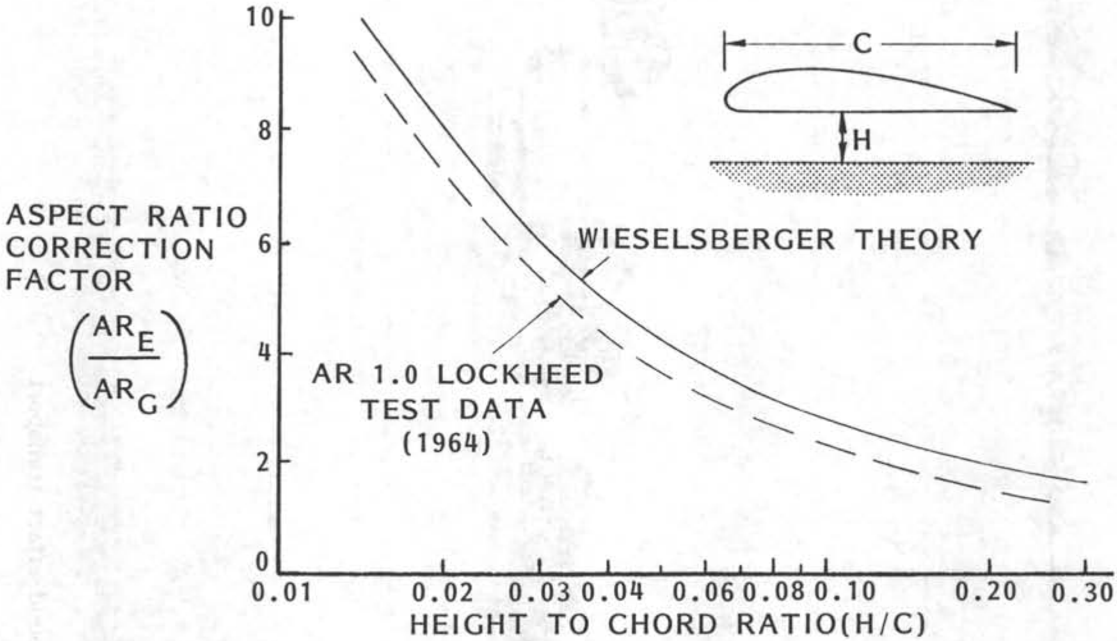


Figure 12. Ground Effect Theory

water and primary structure is reduced by about 60 percent; hence, there is no need for a hulled surface and the structural weight of the aircraft is reduced.

Par lift augmentation during takeoff and landing is illustrated in Figure 13 for the spanloader PAR/WIG configuration. The engines are rotated so that the primary propulsion efflux is directed toward the cavity under the wing formed by the wing lower surface, wing end plates, wing trailing-edge flaps, and the water surface. In this manner lift up to six times the installed thrust can be obtained while still recovering 70 percent of the thrust for acceleration. A complete description of the theory and experiments on PAR is given in Reference 32.

The general arrangement of the spanloader PAR/WIG aircraft shown in Figure 14 is the result of the unusual characteristics of the system. These characteristics include PAR lift augmentation for takeoff and landing, cruise flight only in ground effect, payload contained in the wing, and all operations accomplished on or above the ocean surface. An additional constraint imposed in the ANVCE study was the span limitation of 108 feet to allow use of facilities sized for the majority of contemporary naval vessels. The resulting transport configuration has a very low aspect ratio wing, rotatable engines mounted forward on the fuselage, a wing area of 9,828 square feet, a takeoff gross weight of 1,362,000 pounds for a payload of 441,000 pounds, and four engines with sea level static thrust of 95,600 pounds each. Twin vertical tails and an all movable horizontal tail provide aerodynamic control. This aircraft has a relatively low operating weight empty as compared with its takeoff gross weight.

The alternate fuselage-loader PAR/WIG design development includes differences from the spanloader design in that the payload is contained in the fuselage, the restriction on wing span is removed, and the number of engines is increased from 4 to 6. The resulting design of the fuselage loader with a payload of 441,000 pounds is shown in Figure 15. The aircraft has an effective aspect ratio of 11.02, a takeoff gross weight of 1,196,200 pounds, and 6 engines with a sea level static thrust of 50,400 pounds each. The data

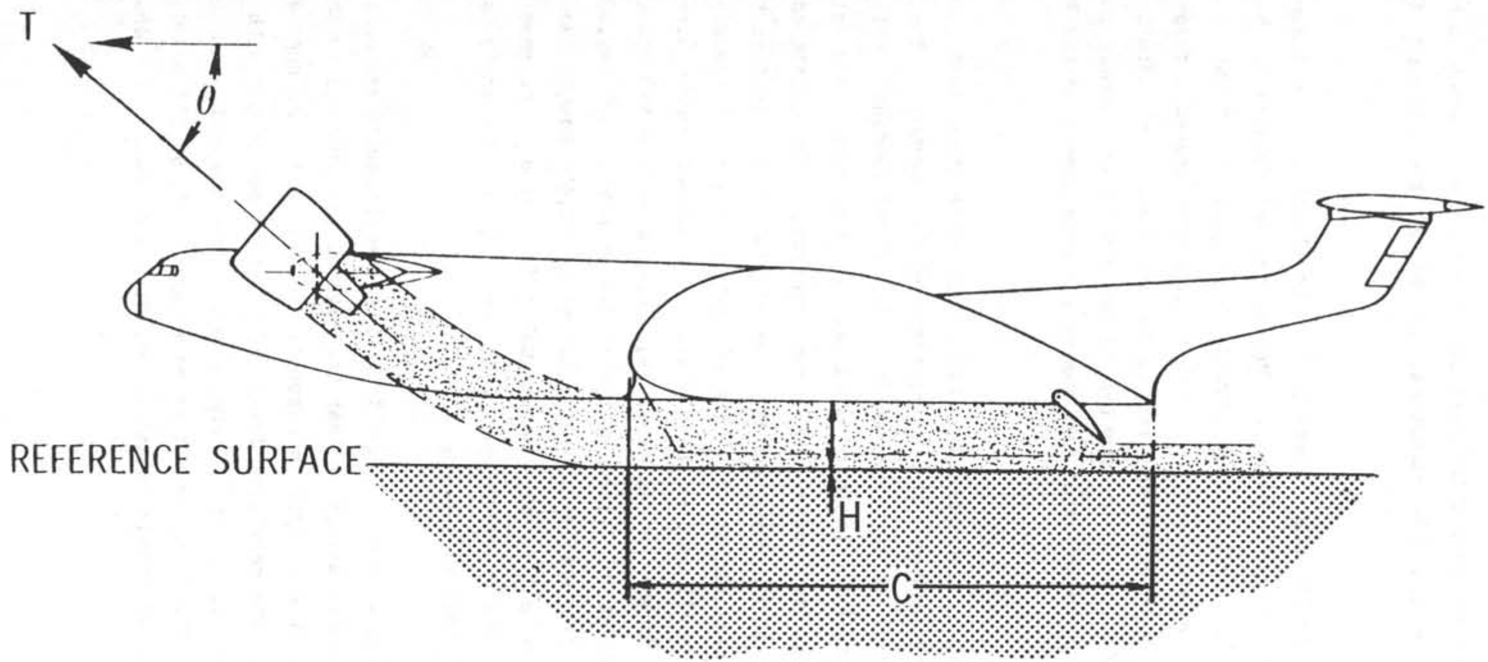
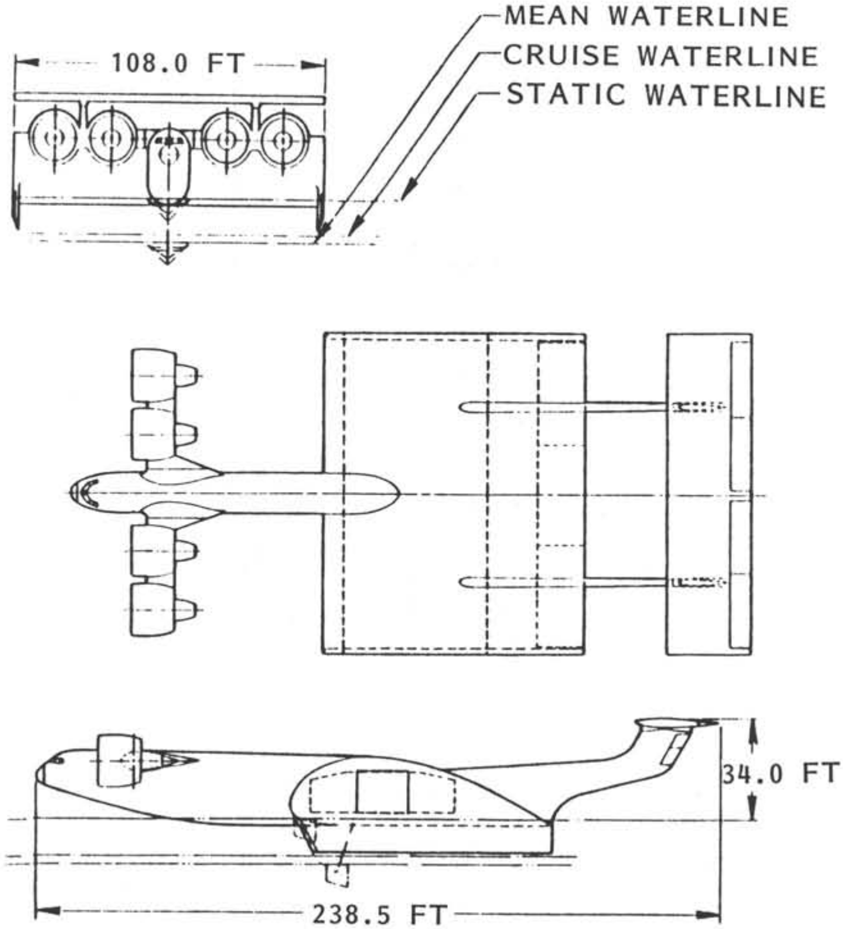
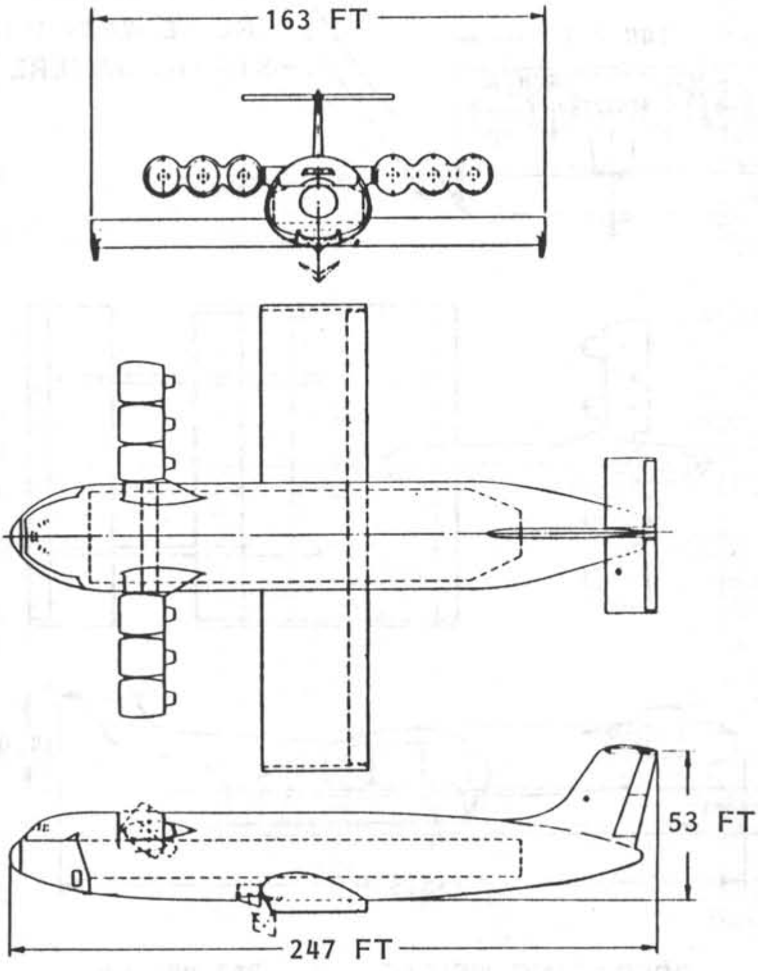


Figure 13 - PAR lift augmentation



OPERATING WEIGHT	357,900 LB
FUEL	563,100 LB
GROSS WEIGHT	1,362,000 LB
WING AREA	9,828 SQ. FT.
ASPECT RATIO (G)	1.19
ASPECT RATIO (E)	5.70
WING LOADING	139 LB/SQ. FT.
THRUST/WEIGHT	0.2808
THRUST/ENGINE	95,600 LB

Figure 14. PAR/WIG Spanloader Configuration



OPERATING WEIGHT	329,800 LB
FUEL	425,400 LB
GROSS WEIGHT	1,196,200 LB
WING AREA	6,743
ASPECT RATIO (G)	3.94
ASPECT RATIO (E)	11.02
WING LOADING	177 LB/SQ. FT.
THRUST/WEIGHT	0.2526
THRUST/ENGINE	50,000 LB

Figure 15. PAR/WIG Fuselage Configuration

for the spanloader and fuselage loader design characteristics presented in Figure 16 show that as compared to the fuselage loader the spanloader is 9 percent heavier in operating weight, 14 percent heavier in gross weight, uses 33 percent more fuel, and has 25 percent lower cruise efficiency. Part of this deficiency in performance of the spanloader design is attributed to the restriction of wing span to 108 feet and the attendant effect on the reduced wing aspect ratio.

The Oblique Wing Concept

The oblique wing concept originated by R.T. Jones of NASA Ames Research Center has the capability to configure the aircraft for efficient performance for a wide range of flight conditions. (Reference 35). At supersonic speeds the concept has indicated the ability to achieve significant reductions in wave drag and the sonic boom associated with supersonic transports. Boeing has completed studies for NASA on supersonic transport aircraft operating at M = 1.2 (Reference 36). These studies showed the oblique wing to be lighter, quieter, and more fuel efficient than symmetrical swept wing configurations designed for the same mission.

Lockheed has performed a design study for NASA to assess the performance and economic potential of oblique wing transports operating at subsonic speeds. Both commercial and military missions were investigated in this study for a transport to be introduced into service in 1985. (Reference 37). An initial baseline configuration shown in Figure 17 is designed to transport a 200 passenger payload for a distance of 3000 nautical miles at a cruise speed of M = 0.95. This design concept features an aspect ratio (4 wing pivoted to a sweep of 45° for the cruise flight condition. The wing is pivoted to the unswept position for takeoff and landing. The design includes supercritical airfoil sections, graphite epoxy composite structures, and reduced static stability for sizing the tail surfaces. As shown in Figure 17 the aircraft has a takeoff gross weight of 290,760 pounds.

PAYLOAD = 441,000 LB. RANGE = 4000 NM SPEED = 0.4 CRUISE ALT = SL			
	SPANLOADER	FUSELAGE LOADER	Δ %
GEOMETRIC ASPECT RATIO	1.19	3.94	-70
EFFECTIVE ASPECT RATIO	5.70	11.02	-48
CRUISE L/D	15.59	19.79	-21
NUMBER ENGINES	4	6	-33
THRUST/WEIGHT RATIO	0.2808	0.2526	+11
CRUISE POWER SETTING	0.65	0.57	+14
OPERATING WEIGHT - LB	357,900	329,800	+9
BLOCK FUEL - LB	524,600	394,700	+33
GROSS WEIGHT - LB	1,361,900	1,196,200	+14
PAYLOAD/GROSS WT.	0.324	0.369	-12
TON-MILE/LB. FUEL	1.68	2.23	-25

Figure 16 - Comparison of spanloader and fuselage loader designs

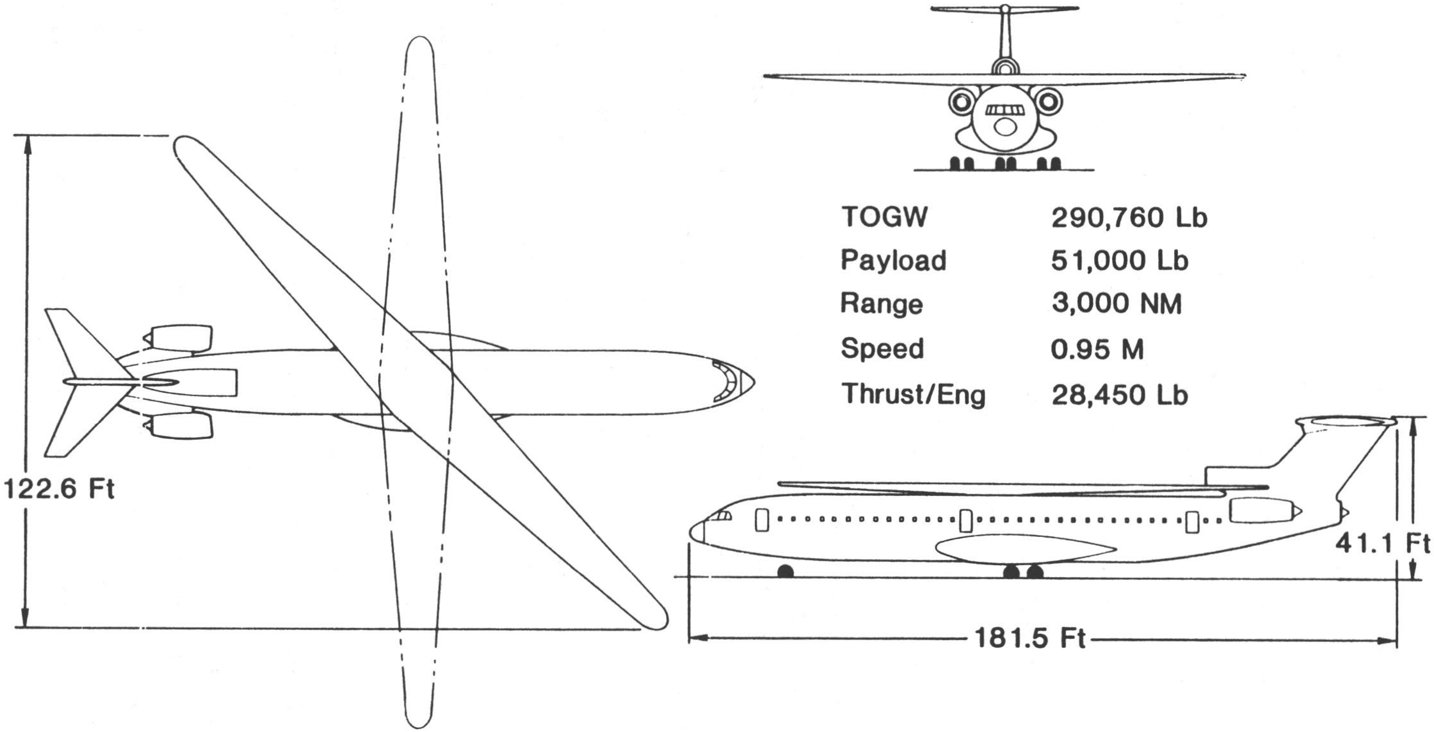


Figure 17 - Oblique wing design concept

The advantages of the oblique wing design concept as compared with that for its fixed swept wing counterpart are given in Figure 18. The oblique wing advantages include reductions of 7 percent in takeoff gross weight, 5 percent in direct operating costs, and 7 percent in block fuel. The capability to unsweep the wing for takeoff and landing results in a significant reduction of 55 percent in community noise footprint area. Additional oblique wing aircraft advantages include efficient operation for multi-mode military operations such as high speed dash combined with low speed reconnaissance.

The next step in NASA oblique wing development is the experimental flight program of an F-8 aircraft equipped with a variable sweep oblique wing.

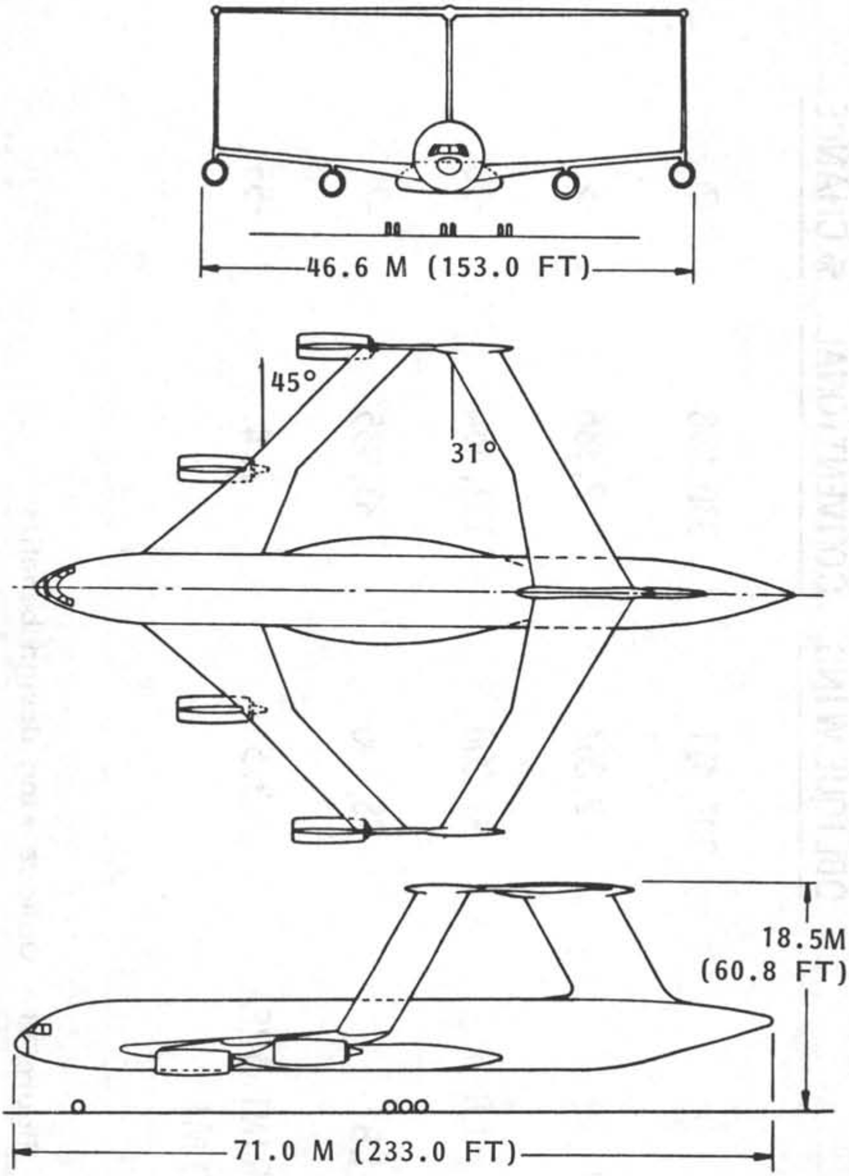
Transonic Biplane Concept

Another method of improving aircraft performance and efficiency is by use of a biplane design. The aerodynamic foundation was established as early as 1934 when it was shown that a closed rectangular lifting system (a biplane with fins connecting the wing tips) would produce the smallest possible induced drag for a given span and height (Reference 38). Drag reductions of as much as 50 percent of the monoplane induced drag are predicted in Reference 38 for a vertical separation between the wings equal to the semispan. As an extension of the NASA/Industry Advanced Transport Technology, ATT, program completed in 1972, reconsideration was given to the concept of a transonic biplane as proposed by the Lockheed-Georgia Company. In the transonic biplane concept shown in Figure 19 the two primary lifting surfaces are a swept-back wing attached to the lower part of the forward fuselage and a swept-forward wing attached to the top of the vertical tail at the rear of the fuselage. The cruise Mach number, payload and range are the same as that for the NASA/Lockheed ATT 400 passenger monoplane transport described in Reference 39.

Whereas the biplane theory of Prandtl in Reference 38 gave no consideration of wing sweep, the stagger theory for biplanes by Munk in Reference 40 would indicate that sweep has no effect on the reduction in induced drag expected. Low speed wind tunnel tests at the Lockheed-California Company in 1972 confirmed these analytical results by showing induced drag

	OBLIQUE WING	CONVENTIONAL	% CHANGE
TOGW - LB	307,411	330,238	-7
DOC - ¢/ST MI	2.267	2.386	-5
THRUST / ENG - LB	91,206	101,464	-10
BLOCK FUEL - LB	78,196	83,935	-7
NOISE FOOTPRINT AREA, 90 EPNdB - SQ MI	3.5	7.4	-55

Figure 18 - Oblique wing design benefits



SPEED	0.95
PAYLOAD	84,800 LB
RANGE	5500 NM
OPERATING WT	281,392 LB
GROSS WT	664,896 LB

Figure 19 - Transonic Biplane Concept

values consistent with the theory of Reference 38 for a swept biplane similar to that shown in Figure 19 (Reference 41). High subsonic and low supersonic speed wind tunnel test of a similar biplane configuration were conducted by NACA in 1953, but the vertical separation between the wing was very small, and as expected, little drag reduction was obtained (Reference 42). For the subject transonic biplane concept the vertical separation between the wings selected corresponds to a height to span ratio of 0.30. As shown in Figure 20 the theory of Reference 38 for a closed biplane system predicts a value of induced drag of 60 percent of that for an equivalent monoplane of the same aspect ratio at a height to span ratio of 0.30.

Parametric preliminary design system studies conducted on the transonic biplane design concept of Figure 19 are reported in Reference 43. In the parametric design study, the configuration variables evaluated were aspect ratio, cruise lift coefficient (or wing loading) and small variations in wing sweep. The principal results of the study are shown in the weight summary comparison of Figure 21. The data in Figure 21 show that the weight and fuel required for the biplane concept are approximately the same as those for the monoplane design of the NASA/Lockheed ATT study for the same mission requirements. Furthermore, the biplane concept incurred flutter instabilities at speeds well below those required for transport aircraft cruising at M = 0.95. The flutter motions are extremely complex and no single feature of the configuration was isolated as the source of the instabilities. The low frequencies shown by the flutter results would make the biplane amenable to flutter suppression by means of active control systems, but this was beyond the scope of the investigation.

A brief investigation of the alternate configurations to provide for passive flutter elimination did not provide a satisfactory resolution of the problem. The alternate configurations included reduced wing tip spacing and a rear wing with a gull-like inboard section. Whereas the biplane configuration results in substantial reductions in drag due to lift, the parametric studies show that minimum airplane gross weights occur at aspect ratios lower than those for an equivalent monoplane. The cruise lift-to-drag ratios for the optimum biplane (at aspect ratio of 4.4) are approximately the same as those for the monoplane.

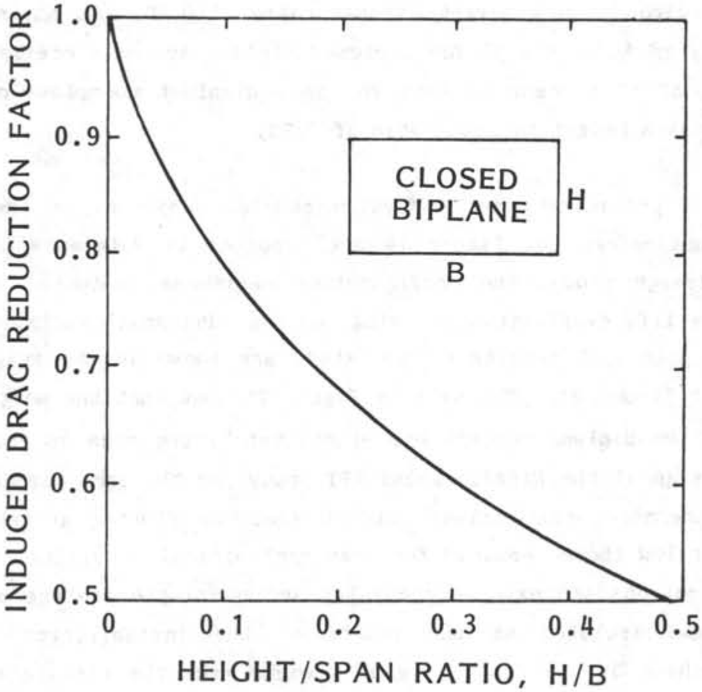


Figure 20 - Closed Biplane Drag Reduction

ITEM	BIPLANE LB	MONOPLANE LB
FORWARD WING	13,060	48,284
AFT WING	13,570	-
TIP FINS	9,033	-
HORIZONTAL TAIL	-	4,105
VERTICAL TAIL	14,079	3,212
FUSELAGE	58,970	54,125
OPERATING WEIGHT	281,392	282,377
PASSENGER PAYLOAD	84,800	84,800
MISSION FUEL	298,704	299,248
RAMP GROSS WEIGHT	664,896	666,425

Figure 21 – Weight Summary Comparison

A recent AIAA survey paper on the joined wing concept contains information on related configurations such as the subject biplane concept (Reference 44). The joined wing is defined as a design concept that incorporates tandem wings arranged in such a manner as to form diamond shapes in both the plan view and the front view. As noted previously one of the alternate configurations considered for the subject biplane had wing tip spacing reduced to one half that of the reference biplane design. The reduced wing tip spacing showed a flutter speed increase of 25 percent over that for the reference biplane but also showed a large drag increase and was, therefore, eliminated from further consideration. Interesting work on the development of the joined wing concept will be presented by Dr. Wolkovitch at this conference.

IV. FUTURE NEEDS

It is expected that needs for future air transport systems will emerge from two important activities - the U.S. Office of Science and Technology Policy which emphasizes civil aeronautics and the Air Force Project Forecast II which emphasizes military aeronautics. Whereas these two activities are discussed separately, it should be noted that the associated advanced technology development programs are generally applicable to both civil and military aeronautical systems.

National Aeronautical R & D Goals

An Aeronautical Policy Review Committee was established by the Director, White House Office of Science and Technology Policy, to assess the state of aeronautics research and the role of the Federal Government in supporting that research. This assessment resulted in a directive published in March 1985 establishing National Aeronautical R & D Goals. As shown in Figure 22, three goals are identified for subsonic, supersonic, and transatmospheric aircraft. The subsonic goal envisions the technology for a new generation of affordable, fuel-efficient aircraft operating in an updated National Airspace System. The supersonics goal is to attain efficient long-range supersonic cruise capability. This capability is essential to U.S. trade in the Pacific Rim which today is 32 percent of our two-way trade worldwide as compared to 23 percent for Western Europe. The farthest point in the Pacific could be reached in four to five hours. The transatmospherics goal is to develop the technology for a vehicle that can routinely cruise and maneuver into and out of the atmosphere with take off and landing from conventional runways. This goal will progressively build on advancements in subsonic, supersonic, and hypersonic aeronautics technology and will provide options in both aeronautics and space systems. This program will have significant impact on military and civil leadership in the 21st century.

Project Forecast II Initiatives

The Air Force Project Forecast II team was established in 1985 by the Commander, Air Force Systems Command for the purpose of identifying key technologies and systems that will provide technological leverage 10 to 20 years in the future. Over 2000 ideas were considered and screened down to a total of 70 which was divided into 31 in systems and 39 in technologies. A number of the system concepts of Air Force Project Forecast II are presented in Figure 23. The Forecast II systems have been listed in three major areas of subsonic aircraft, ssupersonic/hypersonic aircraft, and special purpose systems. The Intratheater VSTOL Transport identified as the advanced tactical transport must operate in a hostile environment and is no longer a peacetime flying truck with military features. The Multirole Global Range Aircraft provides global force projection and requires exceptional aerodynamic and propulsive efficency. One application of the High Altitude, Long Endurance, Unmanned Aircraft is for the airborne optical platform of the Strategic Defense Initiatives Program. This aircraft operates at altitudes of 65,000 to 90,000 feet and with its sensors can locate, track, and identify incoming reentry systems from an ICBM in the terminal phase of the trajectory. It can alert interceptor systems to destroy the incoming weapons.

The supersonic VSTOL Tactical Aircraft is an outgrowth of the Air Force Supercruise tactical system. The Air Force is considering a Mach 4 interceptor that will have 50 percent lower fuel consumption that is currently possible. Other hypersonic vehicles will be highly survivable and be able to reach any place on earth from orbit in 45 minutes. The National Aerospace Plane is the system described previously that can routinely cruise and maneuver into and out of the atmosphere and capable of takeoff and landing from conventional runways. Special operations systems include airborne surveillance, theater air warfare command, control, communications, and intelligence systems, AWACS, airborne command post, and others.

In the sections that follow several aircraft concepts will be reviewed including preliminary mission requirements, key technologies, and design concepts. It should be noted that all of the design concepts are in the early

NOTE: EXECUTIVE OFFICE OF THE PRESIDENT, OFFICE OF SCIENCE AND TECHNOLOGY POLICY, MARCH 1985

Figure 22 - National Aeronautical Goals

INTRATHEATER VSTOL TRANSPORT AIRCRAFT
MULTIROLE GLOBAL RANGE AIRCRAFT
HIGH ALTITUDE, LONG ENDURANCE, UNMANNED AIRCRAFT

SUPERSONIC VSTOL TACTICAL AIRCRAFT
HYPERSONIC INTERCEPTOR AIRCRAFT
LONG RANGE BOOST-GLIDE VEHICLE
AEROSPACE PLANE

AIRBORNE SURVEILLANCE SYSTEM
SPECIAL OPERATIONS AIRCRAFT

THEATER AIR WARFARE C^3I
SUPER COCKPIT

Figure 23 - Air Force Project Forecast II Systems

stages of formulation and, therefore, can be changed by international events, national priorities in development funding, and environmental issues.

Intratheater VSTOL Transport

Conceptual design and system studies of advanced tactical VSTOL transport concepts have been under study for over 20 years. The advanced tactical transport will require outstanding reliability and repairability to cope with the need to operate behind the enemy lines in a hostile environment.

In order to obtain VSTOL field lengths with desired payloads and cruise speeds the aircraft must utilize powered lift systems, advanced composite materials to reduce weight, and advanced propfan or turbofans propulsion for low fuel consumption and desired thrust-to-weight ratios. Satisfactory flying qualities will require active controls and a flight management system tied into and advanced flight station utilizing artificial intelligence. For assault landings an advanced landing gear capable of sustaining sink rates up to 16 feet per second will be required.

A few of the tactical transport design concepts that have been investigated by Lockheed are shown in Figure 24. The STOL concepts feature an upper surface blown flap powered lift system shown in the upper part of the figure. On the lower right, a General Electric propfan system or unducted fan (UDF) obtains STOL from the high propulsive effectiveness at take off and landing speeds. This UDF concept also obtains some lift increases from the external flow of the propfans over the deflected flaps. The VTOL concept utilizes direct lift engines located in the rectangular doors areas in the center of the wing for take off and landing. After vertical take off at a suitable altitude the propfans at the rear of the aircraft provide thrust for transition to forward flight and for cruise and the doors for the direct lift engines are closed. Thrust vectoring and active controls provide for satisfactory flying qualities during the critical transition flight regime. The low lift curve slope of the delta wing planform improves the ride quality for low altitude, high speed flight conditions.

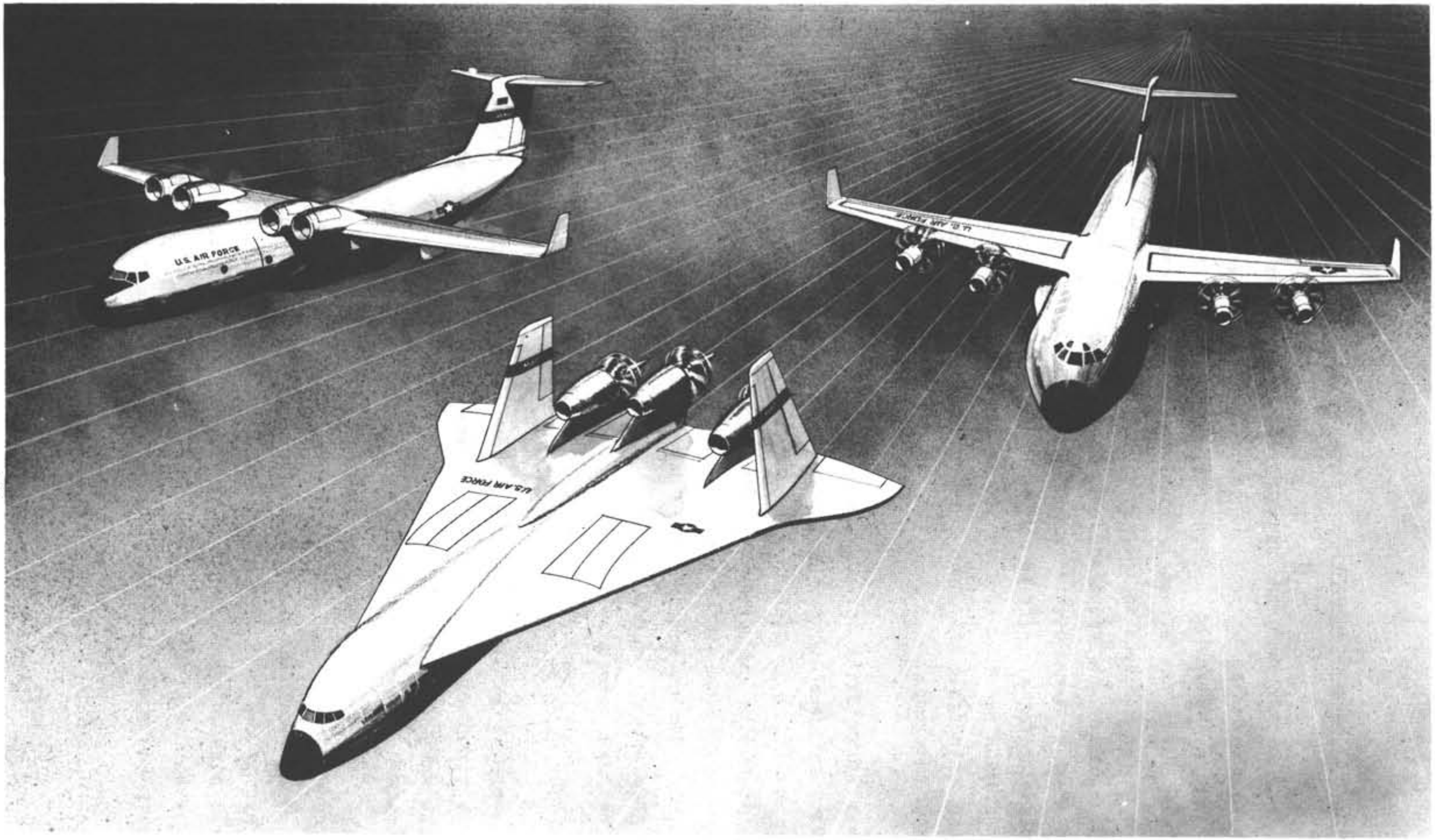


Figure 24 - Tactical transport concepts

Multirole Global Range Transport

As discussed previously the notable feature of the multirole global range transport is the desire to carry large payloads for long ranges, say, 10,000 nautical miles, unrefueled. The achievement of this exceptional range capability requires the effecttive integration of advanced technologies and innovative design concepts in the system definition. Outstanding reliability and maintainability are required for the long times of flight involved and operation from austere destination bases. There is renewed interest in defense planning for aircraft to carry heavy payloads for long distances or to remain on station for long periods of time with such payloads. This interest has brought forth again the concept of a single airframe capable of performing a variety of missions.

The key technologies include the use of advanced composite materials in both primary and secondary structures in order to achieve a weight saving of about 20 percent as predicted in previous Lockheed design system studies. Very high propulsive and aerodynamic efficiences at M = 0.80 cruise conditions can be obtained by use of advanced propfans and natural and hybrid laminar flow control. Design studies show that laminar flow control aircraft tend toward higher aspect ratio wings which also provide a reduction in induced drag. The high aspect ratio wings require active controls for gust and maneuver load alleviation and flutter suppression.

An example of an innovative design concept for a multrirole long range aircraft is given in Figure 25. The flying wing concept is capable of Mach 0.80 cruise speed and has counter rotation pusher propfans and a center body to accommodate a variety of payloads associated with the multi-purpose capability. Mission capability includes airlift, laser weapon carrier, airborne command post, and ICBM missile carrier/launcher. The system studies indicate significant acquisition cost savings of about 20 percent can be obtained by the use of a single multi-purpose aircraft capable of satisfying the several mission requirements. The application of active controls and a fully integrated digital flight control system will be required to provide satisfactory flying qualities for this configuration.

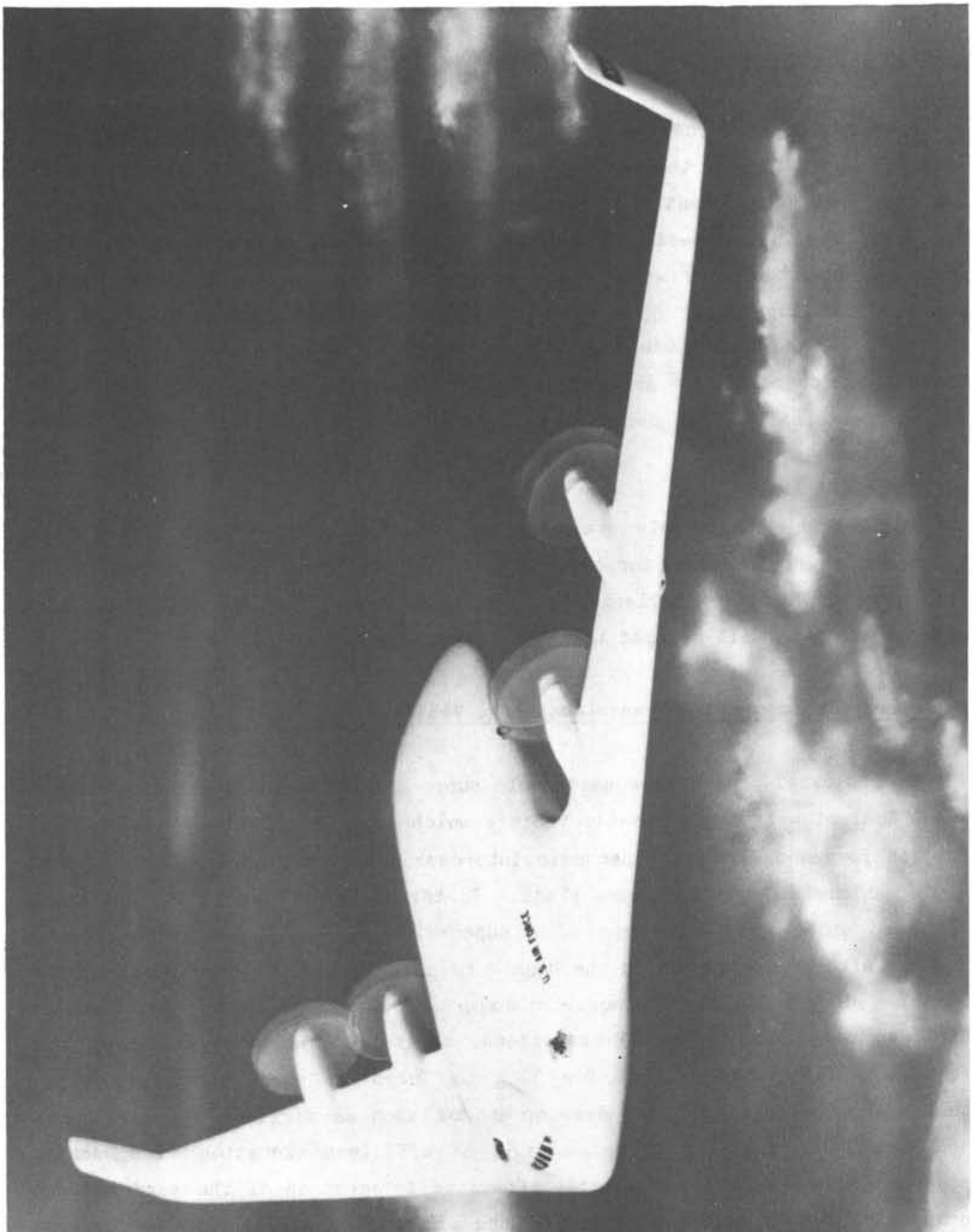


Figure 25 - Global range aircraft concept

Supersonic Transport

Advances in aerodynamics, advanced structural materials, propulsion, and avionics systems since the cancellation of the SST program by Congress in 1971 indicate that development of a viable new supersonic transport could begin by the early 1990's. A design concept for an SST is shown in Figure 26. NASA work indicates that the use of supersonic laminar flow control could reduce the fuel consumption by 35 percent. The reduction in gross weight and the increase in cruise altitude resulting from the use of supersonic laminar flow control could reduce the sonic boom levels to permit operation at supersonic speeds over land. This capability would expand the aircraft operation and improve its economics.

Studies at Aerospatiale are underway for a second-generation supersonic transport to replace the Concorde. They want to retain their leadership in this area. Thus the challenge is established and it is up to the U.S. to determine how it will respond to this challenge.

Hypersonic Transport and Transatmospheric Vehicle

As discussed, there is considerable support for the National Aeronautical R & D Goal of a transatmospheric vehicle which is identified by the Air Force Project Forecast II as a hypersonic interceptor aircraft, a long range boost glide vehicle and the aerospace plane. In the commercial airlines, interest has been shown in the concept of a super fast airline known as the Orient Express with cruise speeds in the Mach 4 to 6 range. A Lockheed version of a Mach 6 hydrogen-fueled hypersonic transport is shown in Figure 27. Such an airliner could carry 250-300 passengers, cruise at altitudes above 100,000 feet, and fly non-stop from New York to Tokyo in about two hours. The technical challenges for the development of such an airliner are formidable and include: propulsion system capable of efficient operation at subsonic, supersonic, and hypersonic speeds; effective integration of the airframe and propulsion system since the shape of the airframe determines the performance of the engine; high temperature and low weight materials; and advanced avionics systems. An additional challenge for commercial operation is finding

SUPERSONIC TRANSPORT CONCEPT

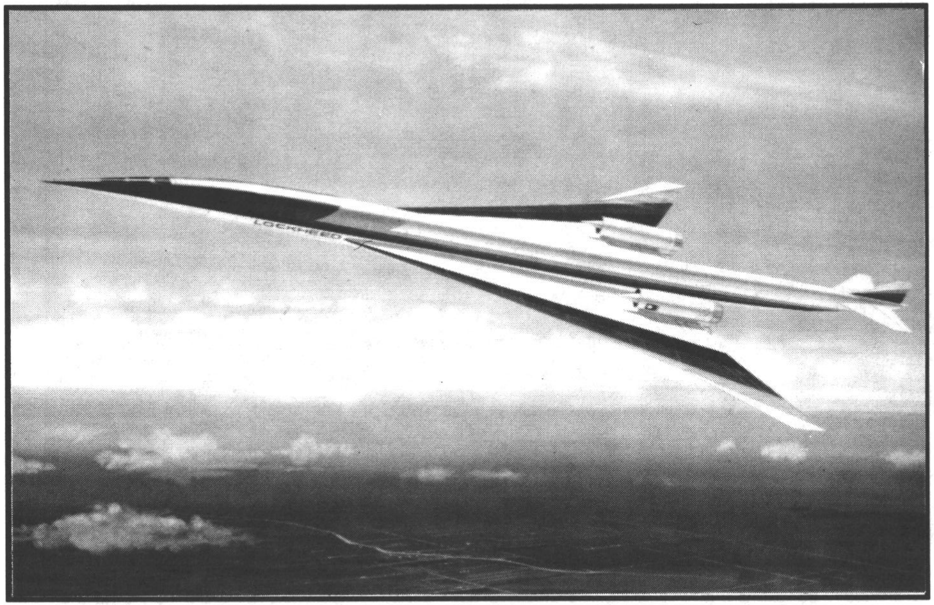


Figure 26 - Supersonic transport concept

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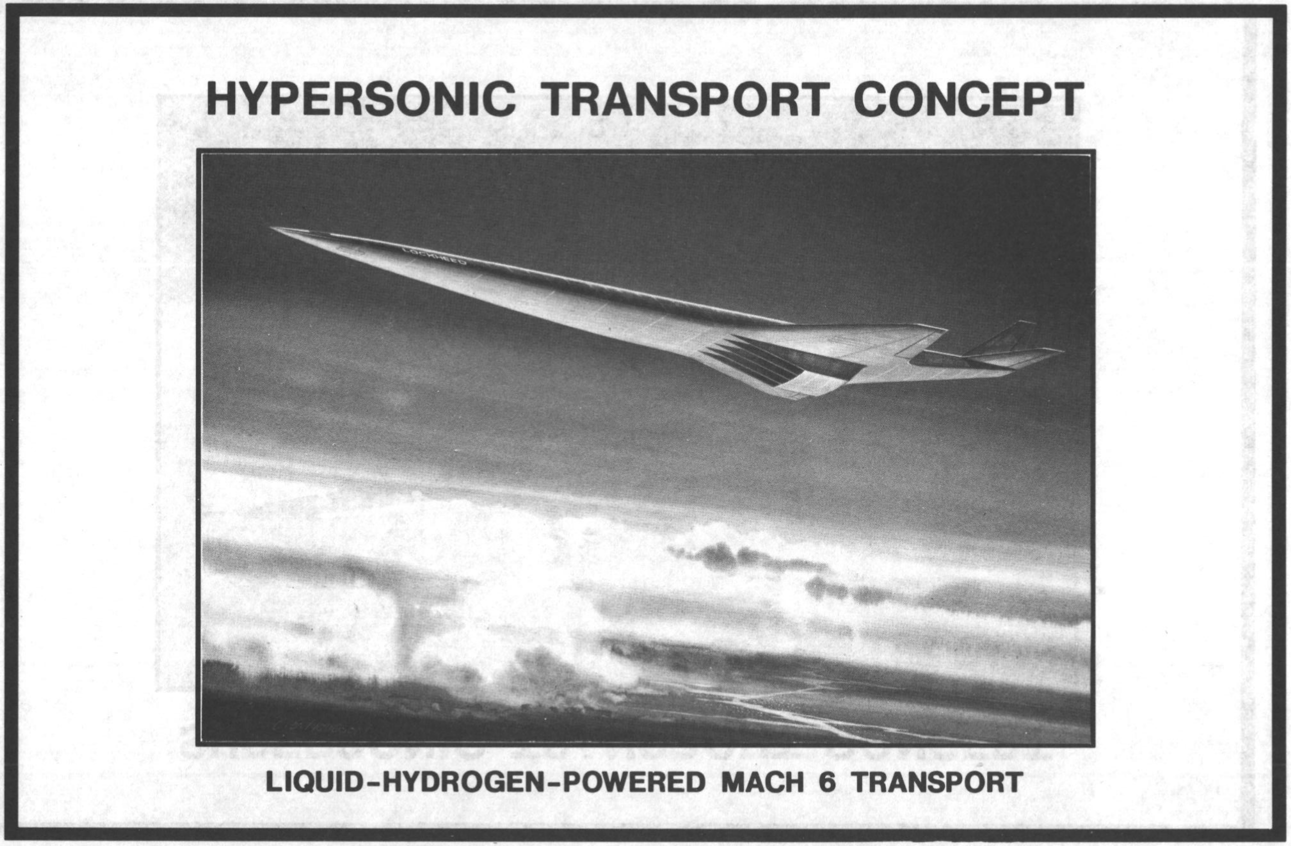

Figure 27 - Hypersonic transport concept

economic ways to construct the elaborate, new airport fuel storage and handling facilities required for liquid hydrogen. This hypersonic transport might be termed the first step in the development of the ultimate transatmospheric vehicle.

The transatmospheric vehicle, TAV, is a single-stage-to-orbit aircraft that can maneuver into and out of the atmosphere and take off and land horizontally from standard airfields. An artist's concept of a Lockheed TAV is shown in Figure 28. One of the advantages of the TAV is that it can reduce the flight time between the U.S. and the Pacific Rim countries to two hours. Another advantage is that this single-stage-to-orbit vehicle could reduce the cost for putting a pound of payload into orbit by a factor of 20 or more as compared to that for the Space Shuttle.

The technology challenges are essentially the same as those discussed earlier for the hypersonic transport except for the more stringent re-entry requirements. Development of the TAV will require a national commitment of resources and technology development. It is estimated that a full scale development program for a flight demonstrator aircraft would cost about two billion dollars or more.

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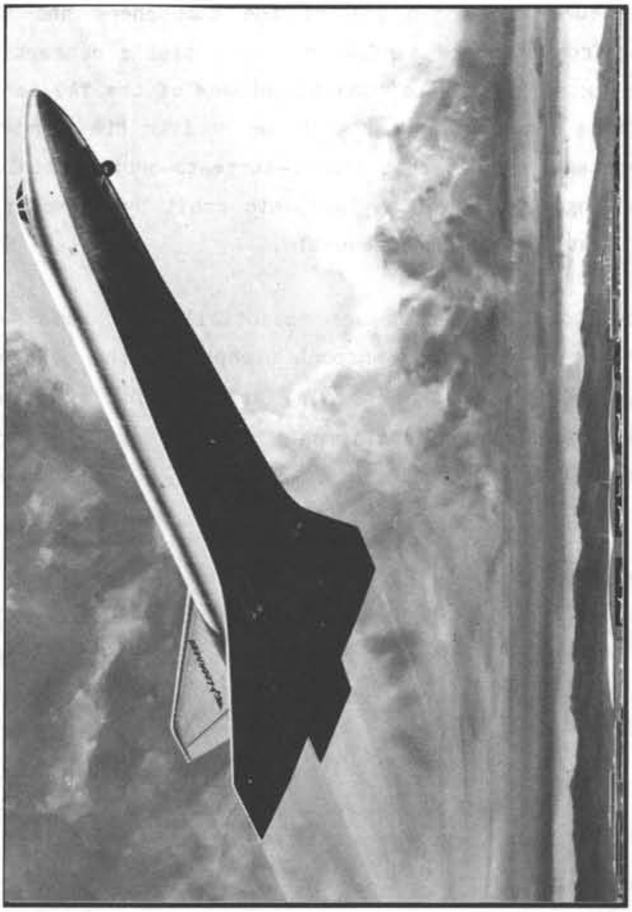

Figure 28 - Transatmospheric vehicle concept

V. CONCLUDING REMARKS

Unconventional design concepts based upon the potential benefits to be derived from the singular effect of an aerodynamic or structural principle must be subjected to the preliminary design system study process that incorporates aerodynamic, structural, propulsion and other system elements. In this manner it can be determined if the potential benefit still remains when the aircraft design is optimized to a figure of merit such as minimum weight or direct operating costs, DOC. Whereas the best available methods are used to determine the weight and performance of these unconventional design concepts, generally there is a lack of statistical and experimental data to validate the performance estimates. As shown by the results in the present paper some of the unconventional concepts such as span-distributed loading, multibody, and wing-in-ground effect show potential for significant benefits in performance as compared with conventional designs. The expected benefits for the transonic biplane concept are not borne out in the results of the design system study. This result, even though a negative one, is still of value to the aircraft design community by enhancing the data base for unconventional aircraft concepts.

The predictions of the White House National Aeronautical R & D Goals and the Air Force Project Forecast II Initiatives point to opportunities for progress in aeronautics more dramatic than any made during the past twenty-five years. How the U.S. will respond to these opportunities will depend upon the resources applied to the accelerated development of key technologies. the priorities established for the achievement of national goals, and the assessment of the environmental impact of the systems within these national goals. Today the aviation industry is at the threshold of opportunities and challenges where as Lockheed's former chairman, Robert E. Gross, stated ... "the horizons are absolutely unlimited."

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ADVANCED TECHNOLOGY AND UNCONVENTIONAL AIRCRAFT CONCEPTS

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ABSTRACT

The National Aeronautics and Space Administration (NASA) continuously undertakes a small study effort in aircraft conceptual/preliminary design often referred to as aircraft systems studies. The purpose of the studies is to investigate the complex interrelationships among technologies in order to provide an understanding of the overall behavior of the system. The result of system research enable the identification of high payoff technologies as well as fosters the coordination of focused research to specific aeronautical systems. NASA, as an independent agency, is free to examine the integration of technologies into an aircraft system without the bias associated with a product line or customer pressures. The results are such that sometimes an airplane study concept sometimes takes an unusual or unconventional form to enhance the application of a particular technology set. The intent of the studies is not to create an unconventional concept, but rather maximize the payoffs associated with emerging technologies. This paper traces a common thought process through the conceptualization of multibody subsonic and supersonic transports to a short takeoff and landing twin-boom fighter and to a vertical-attitude takeoff and landing fighter.

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1. INTRODUCTION

The National Aeronautics and Space Administration (NASA) continuously undertakes a small study effort in aircraft conceptual/preliminary design often referred to as aircraft systems studies. The purpose of the studies is to investigate the complex interrelationships among technologies in order to provide an understanding of the overall behavior of the system. The results of system research enable the identification of high payoff technologies as well as fosters the coordination of focused research to specific aeronautical systems. NASA, as an independent agency, is free to examine the integration of technologies into an aircraft system without the bias associated with a product line or customer pressures. The results are such that sometimes an airplane study concept sometimes takes an unusual or unconventional form to enhance the application of a particular technology set. The intent of the studies is not to create an unconventional concept, but rather maximize the payoffs associated with emerging technologies. This paper traces a common thought process through the conceptualization of multibody subsonic and supersonic transports to a short takeoff and landing twin-boom fighter and to a vertical-attitude takeoff and landing fighter.

2. SUBSONIC TWIN-FUSELAGE AIRCRAFT

An excellent article on subsonic twin-fuselage aircraft by Dr. John Houbolt of the NASA Langley Research Center was published in the April 1982 issue of Astronautics and Aeronautics. The section of this paper on subsonic aircraft is a synopsis of his work.

The concept of twin-fuselage aircraft is not new. Twin-fuselage seaplanes were built in Italy during the late twenties and early thirties. Figure 1 is a photograph of the twin-fuselage P-51 (P-82) Mustang. The North American Aircraft Company built 272 of these during World War II. The P-82 had almost double the range, greatly increased payload, and better takeoff performance than its single-fuselage forebearers. It held a long-distance nonstop flight record for a propeller-driven aircraft of over 5,000 nautical-miles. Of course, this record is now held by another unconventional multi-fuselage aircraft--the Voyager, which flew around the world nonstop and without refueling.

Fig. 1. North American F-82 "Twin Mustang."

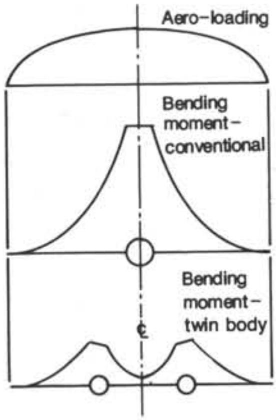

Fig. 2. Wing bending moment alleviation in twin-fuselage aircraft.

The most commonly recognized benefit of twin-fuselage aircraft is reduced wing weight due to wing-bending-moment relief. Figure 2 illustrates alleviation of wing-bending loads by separation of a large central mass into two outboard-positioned masses. Load alleviation allows a lighter wing structure since the wing weight per unit length for a constant thickness wing is proportional to the bending moment. Wing weight control by increasing thickness conflicts with the thinness desired to reduce aerodynamic drag and, thus, is a limited compromise. Separating a single fuselage into outboard twin fuselages powerfully reduces wing bending moment and the associated wing weight.

A simple-wing weight reduction is, however, only a small piece of the synergism at work. The bending-moment alleviation allows the use of considerably higher-aspect-ratio wings on twin-fuselage aircraft than on single-fuselage aircraft. Since L/D is proportional to $AR^{1/2}$, better aerodynamic performance is realized by higher-aspect-ratio wings. Figure 3 shows the typical variation of seat-miles per gallon with aspect ratio for single- and twin-fuselage 282-passenger 1982 technology transports. Problems of growing wing weight, fuel volume, gear storage, and aeroelasticity preclude the use of aspect-ratio values higher than about 10 for conventional transports; in fact, historically, the upper practical limit has been around 8. A twin-fuselage concept removes these limitations. The practical upper limit for twin-fuselage aircraft is judged to be on the order of 14 to 16. The figure shows an over 40-percent gain in seat-miles per gallon in going from an AR = 8 single-fuselage to an AR = 14 twin-fuselage transport with both carrying 282 passengers. Also included in these curves is the effect of fuselage wetted area and weight.

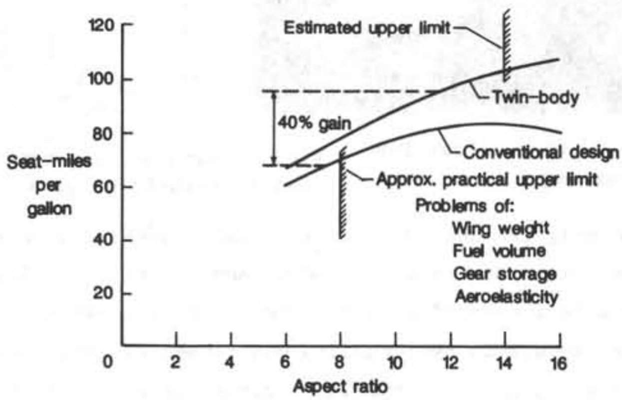

Fig. 3. Aspect ratio effects.

Increased fuselage wetted area and fuselage weight are drawbacks usually stated by those skeptical of twin-fuselage transports. But is that true? Figure 4 gives an insight to the fuselage-wetted-area picture. The curves show wetted surface areas as a function of passengers carried for various numbers of abreast seating. The numbers for all the curves were determined by using armrest spacing and aisle widths of 20 inches, seat pitch was 36 inches, and allowances consistent with present practice were made for cockpit space, galleys, lavatories, closets, and tail-cone volume. The lower left-hand point on each curve corresponds to a fuselage fineness ratio of 7 and the upper right to a value of 12. For number abreast seating of 6 and below, a single aisle is used; for 7 and greater, two aisles are used. The short horizontal lines indicate where some existing aircraft are. The left side of these lines apply to configurations with low-density seating while the right side indicates high-density seating versions. The fact that the curves of Fig. 4 pass through the middle of lines for existing aircraft tends to lend creditability to them.

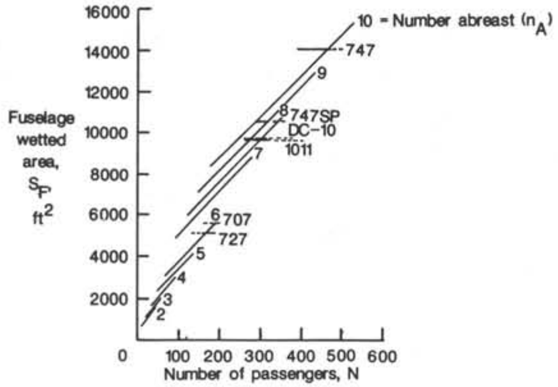

Fig. 4. Fuselage wetted area.

To illustrate the use of these curves, consider the example of 250 passengers. The lowest wetted area solution for a single fuselage is seven-abreast seating and has a wetted area of 8,225 ft^2. For two fuselages, each with 125 passengers, the five-abreast curve is used. The associated wetted area is 3,933 ft^2 which, when doubled, gives a total of 7,866 ft^2, less than that obtained for the single-fuselage design. Obviously, the key is the number of aisles. Fuselage diameter behaves as an integer of seat spacing and aisle width. The curves, thus, behave in a discontinuous, quantum-jump fashion. Put simply, the wetted area outcome depends on whether the number of passengers is smaller or larger than 190 or so passengers. If the number of passengers is in the range of 200 to 400, it appears that the use of a twin-fuselage will always yield a smaller wetted surface area. Note, also, these results have not yet considered the elimination of the second cockpit and using that space for passengers.

With respect to fuselage weight, twin-fuselage design also appears to have the advantage. Studies indicate the effect of cabin pressurization on fuselage weight favor narrow bodies over wide bodies to the extent that, almost invariably, two fuselages weigh less than a single fuselage with the same total passenger capacity.

Fuselage spacing is a trade between the desire for large separation to aid in load alleviation and several other factors. Four considerations call for less separation: adverse yaw due to engine out (assuming fuselage-mounted engines), landing gear spacing, keeping the rolling moment of inertia to a minimum, and preventing excessive dynamic behavior of one fuselage relative to the other. Consideration of all these effects indicate that a fuselage separation

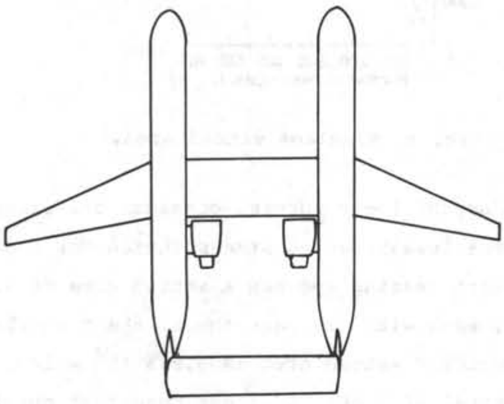

Fig. 5. General layout of twin-fuselage transport.

distance, centerline to centerline, of about 35 percent of the wing span is a good practical choice. Figure 5 illustrates a general layout of such a configuration. Such a design yields spans from 140 to 190 feet and gear spacing in the range of 50 to 65 feet. These should be compatible with existing gates and runways.

TABLE 1 - DESIGN PARAMETERS FOR A TRANSCONTINENTAL, TWO-ENGINE AIRCRAFT

- 250-PASSENGER AIRCRAFT -

Parameter	Single Fuselage	Twin Fuselage	% Change
Weights (lbs.)			
Wing	31,004	24,998	
Tail	6,481	5,377	
Fuselage	33,278	27,288	
Engine and Nacelles	26,397	22,432	
Equipment*	56,157	47,160	
Payload	65,000	65,000	
Fuel	77,244	55,952	
Gross	295,561	248,207	-16
Wing Area (Sq. Ft.)	2,758	2,288	
Fuselage Area (Sq. Ft.)	8,225	7,866	
Max. Total Thrust (lbs.)	79,191	67,298	-15
Wing Span (Ft.)	143.8	162.2	
Aspect Ratio	7.5	11.5	
Zero-Lift Drag Coefficient	.0189	.0203	
Lift-Drag Ratio	16.6	19.9	
Fuselage Length (Ft.)	179	125	
Fuselage Diameter (Ft.)	16	11	
Number Abreast Seating	7	5	
Wing Loading (psf)	107	108	
Seat Miles/Gallon	68	94	+38

* Landing gear, surface controls, auxiliary power, instruments, hydraulics, electrical and electronic components, furnishings, air conditioning, and miscellaneous which typically account for about 19% of the aircraft gross weight.

Table 1 gives characteristic numbers for 250-passenger single- and twin-fuselage designs. Both have transcontinental range with reserves for a 200-mile alternate and a 45-minute hold. Both cruise at Mach 0.75 and take off in 10,000 feet with one engine out. The twin-fuselage version yields an impressive 38-percent increase in seat-miles per gallon over the reference conventional design, a 16-percent decrease in gross weight, and a 15-percent decrease in maximum thrust required. No new technology is incorporated in these numbers. Advanced technology would yield benefits for both single and twin fuselage, but would not be expected to change the balance between the two concepts.

3. TWIN FUSELAGE SUPERSONIC TRANSPORTS

Supersonic twin-fuselage concepts, such as the computer generated drawings shown in Fig. 6, have the potential to increase the passenger capacity of SST's to the level of widebody subsonic transports without incurring significant aerodynamic, weight, or noise penalties. During the later phases (1981) of the Supersonic Cruise Research Program in the United States, greater attention was being placed on studying SST concepts that had large passenger capacity in order to obtain seat-miles per gallon that compared favorably with wide-body subsonic transports. Multilobe fuselage and multibody concepts were examined. The multilobe concept keeps fuselage cross-section to a minimum by reducing the number of aisles while greatly increasing passenger capacity. Because the fuselage fineness ratio decreases, the multilode approach does incur a wave-drag increase

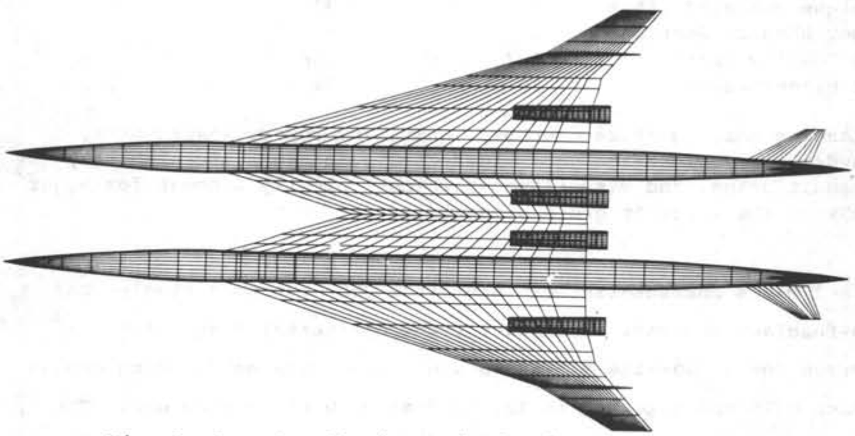

Fig. 6. Computer drawing twin-fuselage supersonic transport concept.

(this disavantage is somewhat offset by a span increase for side-by-side lobes).

Twin-fuselage supersonic transports have all of the advantages associated with their subsonic counterparts plus another that is unique to the supersonic speed range. At supersonic speeds, bodies can be located with respect to each other so that the drag of the combined flow field is less than that of the two separated bodies. This beneficial interference is best illustrated by the classical Busemann biplane as shown in Fig. 7 (Ashby and Landall, 1965).

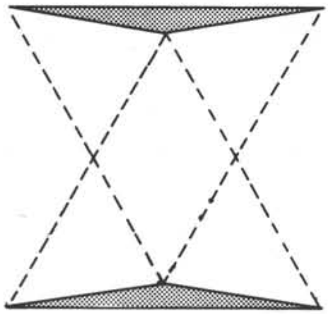

Fig. 7. Busemann biplane.

Busemann's biplane is a two-dimensional example of shaping and placing airfoils so that there is mutual cancellation of waves between the two planes. At zero lift, the expansion wave at the shoulder cancels the compression wave from the leading edge of the opposite airfoil resulting in zero wave drag. This is indeed a very nice situation, but how well does it transfer to three-dimensional fuselages with wings? Jeffrey Bantle (1985) showed that the favorable interference (through both experiment and theory) between two Sears-Haack bodies with fineness ratios typical of SST fuselages could lead to a 56-percent reduction in wave drag and a 15-percent reduction in the total drag with respect to a single large equivalent volume body. Bantle's work was not configuration oriented so it did not account for the space associated with an extra aisle in the single large body. The work also showed that simple linear far-field wave-drag predictive methods can accurately calculate the interference effects between bodies.

A Mach 2.7 equivalent area curve for a single large body and a twin-body supersonic transport is shown in Fig. 8. The wave drag relates to these equivalent bodies which are calculated from the normal component of the cross-sectional area as intersected by Mach planes inclined to the freestream at the Mach angle. The effect of separating fuselages laterally is to lengthen the Mach projections of the fuselage cross-sectional area, thus the wave-drag equivalent body appears to be longer and have a higher fineness ratio for the twin-fuselage concepts. Although this explanation is simplified, it explains why twin-fuselage supersonic concepts are attractive from a far-field wave-drag point of view. Again, in this figure, the single

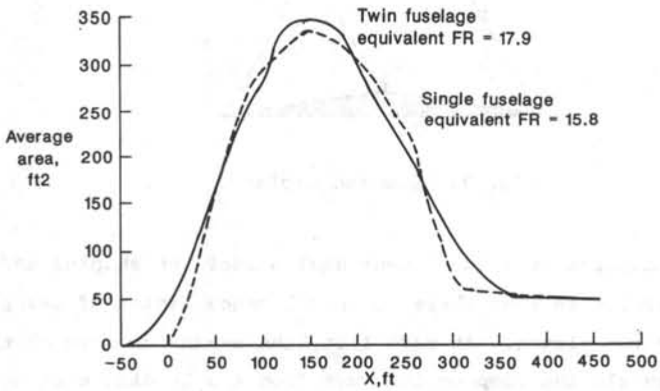

Fig. 8. Equivalent area distribution comparison.

fuselage is simply twice the volume of each of the separated twin fuselages and, thus, does not account for the extra aisle space that would be necessary.

Wave drag, drag-due-to-lift at 0.1 lift coefficient, and skin friction at Mach 2.7 for a systematic series of fuselage separations are shown in Fig. 9. The left side ($\Delta y/b) = 0$) represents a single large-fuselage configuration and the right ($\Delta y/b = 1.0$) represents two aircraft joined at the wing tips. The sketches at the top depict configurations associated with three of the points. As depicted, actual wing area was allowed to vary, but reference area was held constant. The wave drag for the complete twin-fuselage concepts

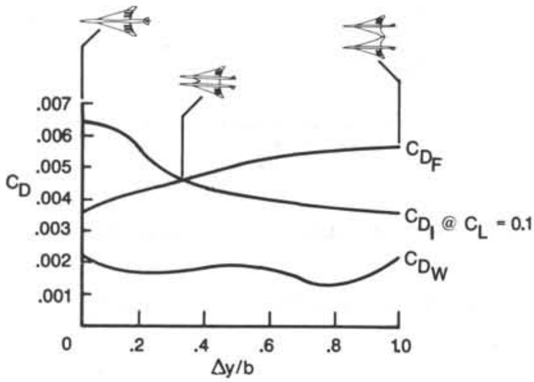

Fig. 9. Component drag versus fuselage spacing.

tends to bottom out with a fuselage separation of .8 of the original wing span--rather far apart from a practical view. However, the drag-due-to-lift shows a quick decrease and then a gradual fall-off with separation as the aspect ratio and wing area increase. Skin friction increases with fuselage separation since the wetted area increases with the increasing wing area (again the single large fuselage is double the volume and the extra aisle is not accounted for, so the single-fuselage numbers are low). Figure 10 brings the drag components together and shows L/D_{max} versus fuselage separation. The maximum L/D occurs at the separation distance where wave drag is a minimum--about .8 wing of the original wing span. As just mentioned, this is rather far apart from a practical point of view; however, examination on the curve indicates that most of the increase in L/D_{max} is achieved at about half that separation. Coincidentally, this roughly corresponds to the fuselage separation distance as a

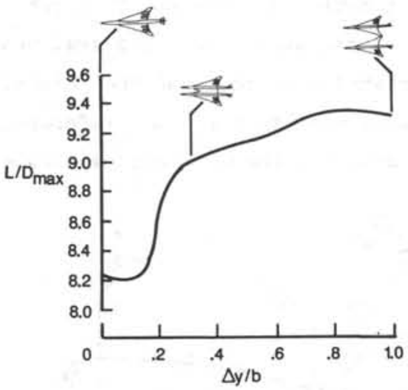

Fig. 10. Lift-drag ratio versus fuselage spacing.

fraction of wing span that Dr. Houbolt chose to focus on for subsonic twin-fuselage studies.

An artist's concept of a twin-fuselage supersonic concept from a 1982 Astronautics and Aeronautics article by Maglieri and Dollyhigh is shown in Fig. 11. The fuselage separation is 0.40 of the original single-fuselage wing span. In this arrangement, the fuselages are

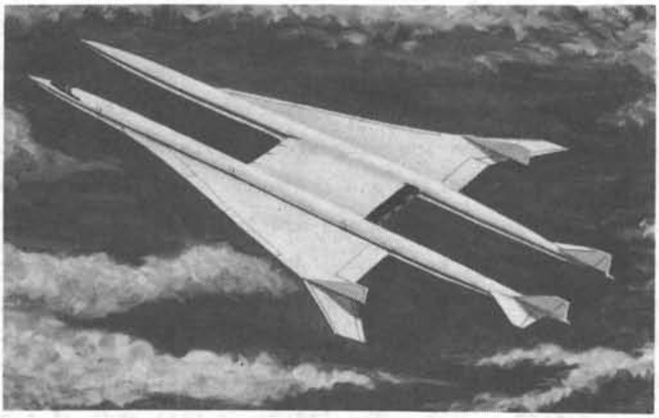

Fig. 11. Twin-fuselage supersonic transport.

connected by an engine package which makes a good connector because it is structurally thick, aerodynamically thin, locates the engines on the vehicle centerline, and frees the wing for additional flap area. The cruise aerodynamic performance (M L/D_{max}) equals or exceeds that of a single-centerline fuselage configuration having only half of the passenger capacity.

Variations of this concept may be of interest to help solve the sonic boom problem associated with supersonic flight. A longitudinal skewing of the fuselages, as illustrated in Fig. 12a, would stretch the volume and lift further and reduce the overall boom level. Another variation would be to tailor the fuselages by introducing a lateral camber, as illustrated in Fig. 12b. This would enhance the beneficial interference effects much as the Busemann biplane does. More study is needed to determine if the aerodynamic effects are more beneficial than any weight increase associated with the increased complexity of fuselage shaping.

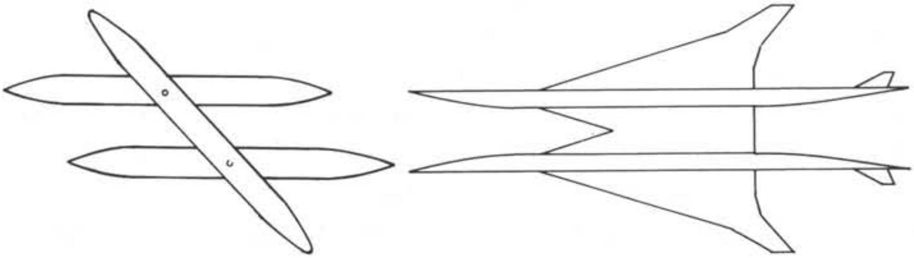

Fig. 12. Additional twin-fuselage concepts. Part (a): Longitudinal skewing to reduce sonic boom; part (b): Lateral camber to reduce wave drag.

Figure 13 shows the payoff in productivity of large-payload twin-fuselage advanced supersonic transport (AST). A single-body advanced supersonic transport can more than double the productivity available with wide-body subsonic jets of similar size. The twin-body SST would bring about another doubling and would introduce an economy of scale that allows competitive supersonic transportation.

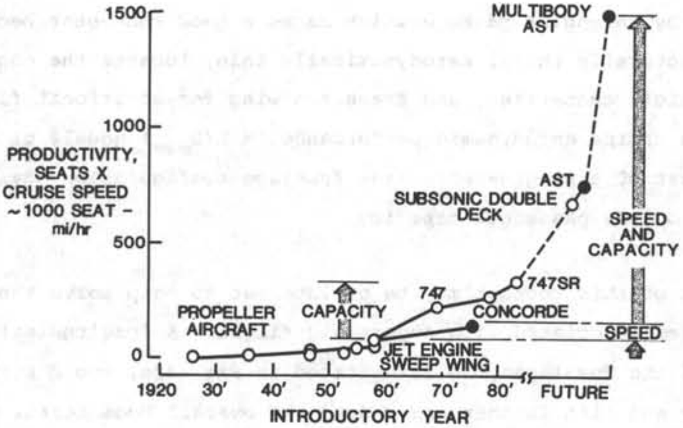

Fig. 13. Productivity of long-range transports.

4. SUPERSONIC TWIN-BOOM FIGHTER

Almost invariably aircraft designers will attempt to apply promising concepts to other classes of aircraft. Supersonic fighter aircraft have limitations for which the twin-fuselage concept appears to be a natural solution. Supersonic fighters are generally severely limited in available internal volume. Fuselages have relatively low fineness ratios and the addition of more cross-sectional area would lead to large wave-drag penalties. This situation, more often than not, results in external weapons carriage while internal weapon carriage would be more desirable. In an attempt to increase available fuselage volume, some preliminary studies examined several twin-body supersonic fighter concepts. Although drags were lower than a single large-volume fuselage, the configurations still simply had too much volume in too short of a length and drag levels were unacceptable; however, all was not lost in these studies.

A twin-boom concept as shown in Fig. 14 was a spinoff of the twin-fuselage studies. The twin-boom concept as reported by Dollyhigh, et al (1984) was a highly blended configuration featuring a centrally

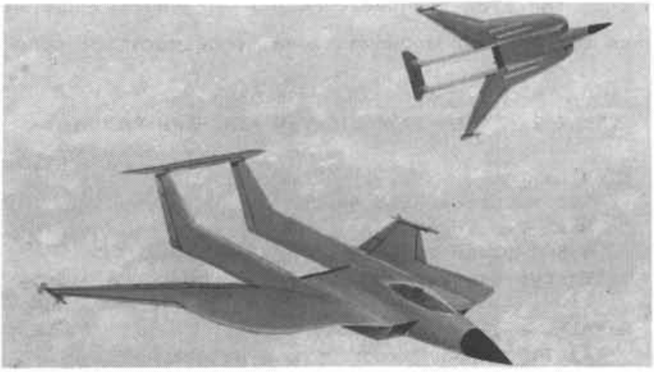

Fig. 14. Twin-boom fighter concept.

located engine package similar to that illustrated for the supersonic transport. The configuration was carefully tailored so that the center of gravity, aerodynamic center, and nozzle were all located very close together. Another key feature was a two-dimensional vectoring/reversing nozzle to provide STOL performance. The near collocation of center of gravity and nozzle hinge line allowed large thrust vector angles, thus providing large values of direct lift while minimizing the moments to be trimmed. The name of the configuration is derived from the long twin booms (but not distinct twin fuselages) extending aft of the engine to the twin vertical tails which have a single horizontal tail mounted atop and between them.

A summary of the performance characteristics of the twin-boom concept on an all supersonic ($M = 2.0$) 500-nautical-mile radius mission is shown in Table 2. A 1985 level of technology is assumed for the engine, materials and structures, controls/avionics/displays, and subsystems. In short, the results indicate that for an aircraft weighing less than 43,000 pounds, large gains in takeoff and landing performance, maneuver, acceleration, and supersonic cruise can be achieved. It should be noted that the 1,000-foot landing roll was the constraint that sized the aircraft to a takeoff gross weight larger than needed to meet the remaining requirements. The situation seems to be true for STOL fighter concepts in general. It also sets up the impetus for another unconventional configuration concept.

TABLE 2 - TWIN-BOOM FIGHTER AIRCRAFT RESULTS

Mission
- 500 Nautical Mile Radius
- Mach 2.0 Cruise
- 4,560 Pound Payload
- Energy-Maneuverability Requirements

Results - 1985 Technology
- 42,750 Pound Takeoff Gross Weight
- 430 Foot Takeoff Roll
- 1,000 Foot Landing Roll
- 0.7/Minute Acceleration M = .7 to 1.8/35,000 Feet

Sustained Load Factors
- 7.0 g's at M = 0.9/30,000 Feet
- 6.8 g's at M = 2.0/45,000 Feet

5. SUPERSONIC CRUISE TAIL-SITTER

Keep in mind the idea that once the aircraft designer establishes a trend of thought, he tends to push on. In this case, the key point was the pursuit of directing the thrust through the aircraft's center of gravity which led to the examination of vertical-attitude takeoff and landing concepts. This is certainly not a new concept. History has several examples of successful vertical-attitude takeoff and landing experimental aircraft. The most notable U.S. example is the Ryan XV-13 wire hanger which underwent successful flight testing in 1953. Accepting that vertical-attitude aircraft are feasible, an examination of an important technology trend also indicates that practical vertical-attitude aircraft may now be possible.

Historical and projected trends are shown in Fig. 15 for engine thrust-to-weight ratio, engine weight fraction, and the resulting aircraft thrust loading. These data are from a paper by Dollyhigh and Foss (1985) that examined the impact of advanced technology on fighter aircraft requirements. The ratio of maximum thrust-to-engine

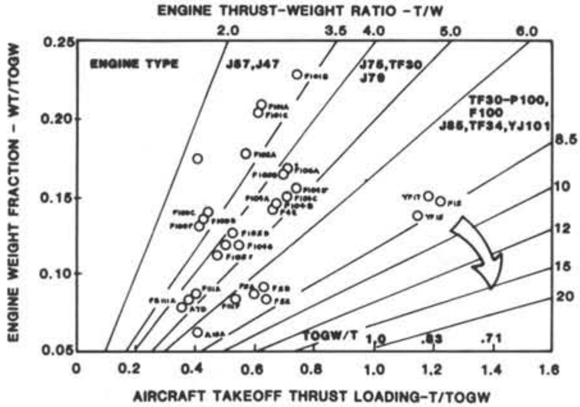

Fig. 15. Fighter aircraft engine sizing trends.

weight has increased from 3 to 8.5 over the history of jet fighter aircraft. Current engine technology supports a thrust-to-weight ratio in excess of 10. Engine manufacturers are projecting thrust-to-weight ratios in excess of 15 by the year 2000. Some are even predicting that it will be 20 at the end of the first decade of the 21st century. For past high-performance fighters, higher thrust-weight ratios in engines have generally been used to increase vehicle thrust-weight ratio instead of reducing the engine weight fraction. With vehicle thrust-weight ratios already in excess of 1.0, future high-performance engines are expected to yield substantial reductions (greater than 40 percent) in engine weight fraction while allowing for even further aircraft thrust-weight-ratio increases. The arrow in the figure shows the expected trend.

The implication of the trend in higher thrust-weight engines on overall vehicle sizing are shown in Fig. 16. Aircraft takeoff gross weight is shown versus aircraft thrust-weight ratio with various levels of engine technology. The curves are for a conventional aluminum airplane sized for the mission of 500-nautical-miles radius at Mach 2.0 cruise. Advancing engine technology will reduce TOGW considerably, but just as important are the changes in sizing trends

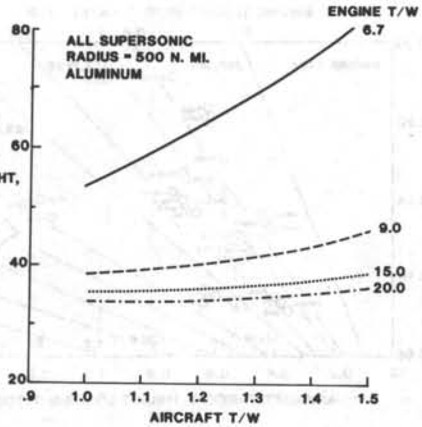

Fig. 16. Aircraft sizing trends.

with increased aircraft thrust weight. Increasing fighter thrust-weight ratio from 1.0 to 1.4 using existing engines penalizes vehicle takeoff gross weight by about 40 percent. Introducing a current technology, advanced engine drops this penalty to approximately 13 percent. Near-future engine technology will allow the penalty to drop to approximately 8 percent, even before considering other technologies that will reduce the sensitivity even further. The result of advanced engines will be small, extremely maneuverable fighter aircraft that have thrust-to-weight ratios of 1.4 and greater.

An airplane such as that illustrated by the artist's concept in Fig. 17 would take advantage of high thrust to weight acting through the center of gravity to achieve vertical takeoff and landing. A cursory study of the concept referred to as a "supersonic tail-sitter" was performed by Robins, et al in 1985. Anhedral in the wings and the large vertical tail form a tripod on which the aircraft sits. Inflatable rubber doughnut-shaped devices which fold into the pods upon retraction provide high footprint area. The engine is located as far forward as feasible to minimize ground erosion. The wing extends almost to the nose of the aircraft so that aerodynamic center is located in the region of the center of gravity. Trim and

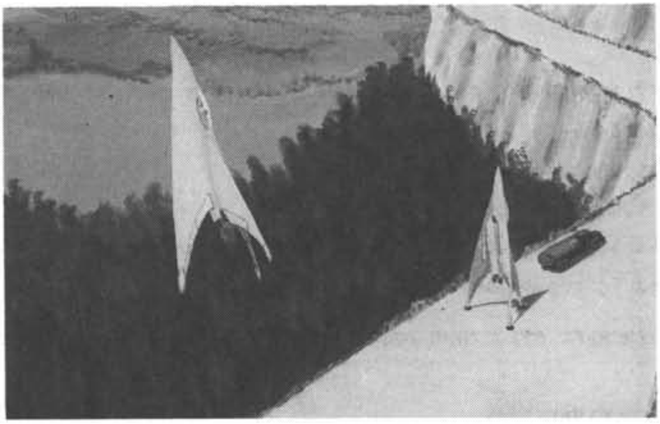

Fig. 17. "Tail Sitter" supersonic fighter.

control of the vehicle in the standard operating mode would be through vectoring engine gross thrust. The assumption was made that the landing mode could be fully automated with the pilot retaining only abort or continue options.

A summary of the results of the preliminary study based on a 1985 level of technology is presented in Table 3. At a takeoff gross weight of only 25,200 pounds, including a 1,840-pound payload, the mission capability was calculated to be 600-nautical-miles radius at Mach 2.0 sustained cruise. Sustained turn capability was 5 g's at both Mach 0.9, 25,000-foot altitude and at Mach 2.0, 50,000-foot altitude. A much higher maximum sustained turn performance was estimated, but concern over the novelty of the concept caused the designers to use a maneuvering limit load factor of 5 g's in determining the structural weight. Hindsight indicates that this concern was unnecessary; nevertheless, the study did indicate that very high levels of performance can be achieved by this type of aircraft using a current level of technology readiness. Further advances in engines, materials, and control system should lead to more serious consideration of such concepts.

TABLE 3 - SUPERSONIC TAIL SITTER - PERFORMANCE SUMMARY
1985 TECHNOLOGY

- Sustained supersonic mission capability ($M = 2.0$) to 600 nautical miles radius
- TOGW = 25,200 pounds
- Payload 1,840 pounds
- Sustained 5g capability at $M = .9$, 25,000 feet*
- Sustained 5g capability at $M = 2.0$, 50,000 feet*

* NOTE: AIRCRAFT STRUCTURE DESIGNED TO 5.0g LIMIT LOAD AT TOGW

6. CONCLUDING REMARKS

An overview of some NASA-Langley-directed systems studies that resulted in several unconventional aircraft concepts has been presented. The unconventional concepts were the result of the synergistic integration of advanced technologies in aerodynamics, structures and materials, and flight systems. The intent of the studies was not to create an unconventional concept but rather to maximize the payoffs associated with a particular feature or technology. A variety of apparently unrelated unconventional aircraft concepts were discussed; however, these aircraft concepts were not totally unrelated. There was a chain of events or a thought process at work that led to each aircraft concept being a spinoff from an earlier unconventional concept. This thought process was presented through the conceptualization of twin-body subsonic transports to twin-body supersonic transports to a short takeoff and landing twin-boom fighter and to a vertical altitude takeoff and landing fighter. One feature clearly shared by all of the aircraft concepts presented is that consideration of such unconventional configurations can hold the promise of a quantum leap in performance.

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FORWARD SWEPT WINGS & APPLICATION IN HIGH ASPECT RATIO AIRCRAFT CONFIGURATIONS

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ABSTRACT

Aviation history notes a host of aerodynamic design concepts: some exploited at a great length, whilst the others explored initially and found "lacking" in some major related technology at the time e.g. in propulsion or materials for adequate structural strength. The latter type of concept has then to await the "natural" progress of the related technology before a possible realisation. The Forward Swept Wing (FSW) concept corresponds aptly with the description of the latter type. World War II research led to a FSW on the Junkers JU-287 bomber which first flew in 1944. The FSW permitted a large bomb-bay so that stores could be suspended at the aircraft CG. The FSW appeared again in 1964 on the HFB 320 HANSA business jet. Forward sweep allowed the wing main spar to be located behind the cabin. Both aircraft above were designed with relatively low sweep to prevent the structural aero-elastic divergence problem of the FSW.

Technology advances in composites, active controls, and improved understanding of the aerodynamic interferences (e.g. canard inclusion) have paved the way towards re-consideration of the FSW concepts. The Grumman X-29A currently undergoing flight trials represents the most recent FSW realisation which has been "integrated" with several emerging technologies.

This paper addresses the objectives: (i) indicating the scope of FSW applications with emphasis on the high aspect ratio types, (ii) discussing briefly the design requirements and evaluation criteria for a new project to enter service, (iii) highlighting some the features of FSW that render it attractive for incorporation in civil, business or transport type aircraft, and (iv) proposing areas for future work.

LIST OF SYMBOLS

c	Wing chord
C_D	Drag coefficient
C_{D0}	Profile Drag coefficient (Friction and Parasite parts)
C_{Di}	Lift Induced Drag coefficient
CG	Centre of Gravity
C_L	Lift coefficient
C_{Lmax}	Maximum Lift Coefficient
$C_{l\beta}$	Rolling Moment Coefficient due to sideslip
C_m	Pitching Moment Coefficient
C_{m0}	Pitching Moment Coefficient at zero lift
$C_{n\beta}$	Yawing Moment Coefficient due to sideslip

D	Drag
i_W	Wing root incidence
L	Lift
LE	Leading Edge
M	Mach No.
s	Wing semi-span
sfc	specific fuel consumption
TE	Trailing Edge
V	Velocity
V_L	Equivalent airspeed
W	Weight
x,y,z	Cartesian Co-ordinate system (x streamwise)
x_{ac}	location of aerodynamic centre or neutral point
α	Angle of attack
β	Angle of sideslip
δ_C	Canard incidence
δ_T	Tailplane Deflection
θ	Wing Twist
λ	Wing Taper ratio
Λ	Wing Sweep angle
2-D	Two-Dimensions
3-D	Three-Dimensions

1. INTRODUCTION

Some of the benefits of using Forward Swept Wings (FSW) on aircraft, eg. reduced lift-induced-drag, improved high angle of attack performance and a better "useful-volume-integrated" and more compact layout, have been appreciated for the past four decades. The lack of adequate material and structural technology in the past, to cope with the FSW aero-elastic divergence problem prevented any serious exploitation of these benefits. With advances in composites material structures, active controls, and improving knowledge of the favourable aerodynamic interferences (e.g. canard effects), the FSW concept is being explored on military and civil/transport aircraft.

The advent of gas-turbine and rocket propulsion in the 1940's overcame the "speed-cubed" law of power required and enabled level flight at transonic speeds. With faster speeds came the attendant problems such as drag rise, trim and handling changes and buffetting. Such problems had been hitherto experienced only in steep dives by propellor-driven aeroplanes. For given lift, wing sweep whether aft or forward, postpones and alleviates the shock effects in transonic/supersonic flight. The properties of the wing in normal flight below stall are largely dictated by the inviscid phenomena. This implies consideration (Fig.1) of airflow conditions prevailing normal to the local sweep lines (strictly the sweep of the isobars). The airflow component parallel to the sweep line causes relatively small effects except when viscid effects dominate (eg. at high α or low Reynolds number). The swept wing effectively behaves as if it were flying in a slower airstream.

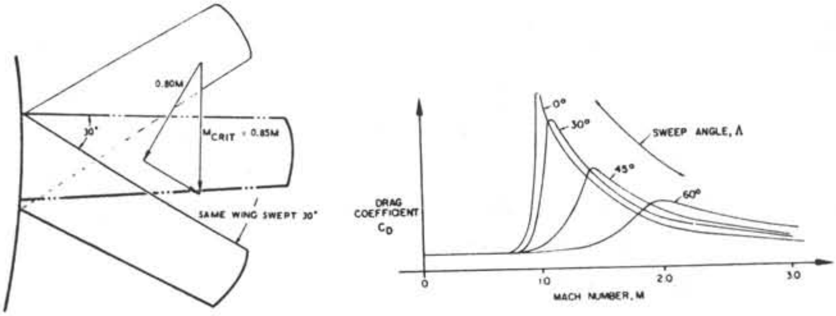


Fig.1. Wing Sweep Effects.

To overcome the FSW aero-elastic divergence (Fig.2), the designer using conventional isotropic materials required a stiffer and heavier wing structure and incurred design penalties. The penalties grew with increasing forward sweep. This design obstacle for the FSW channeled the major efforts in technology towards Aft Swept Wing (ASW) aircraft.

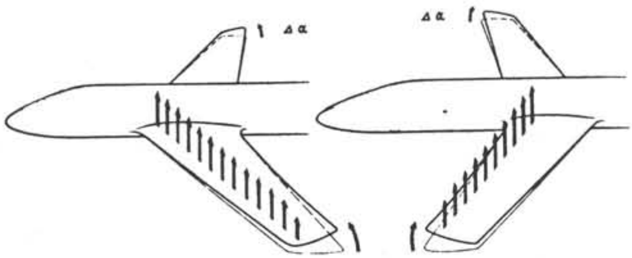


Fig.2. Aero-elastic Deformation of ASW & FSW.

Flying FSW Types: JU-287 and HANSA

World War II studies led to a FSW on the Junkers JU-287 bomber which first flew in 1944 (Fig.3). The FSW permitted a large bomb-bay so that stores could be suspended at the aircraft CG. The JU-287 flew about 16 times before the end of the War. The design featured four jet engines including two mounted in an unusual location at the nose of the aircraft. The FSW appeared again in 1964 on the HFB 320 "HANSA" business jet (Fig.4). Forward sweep in this case allowed the wing main spar to be located behind the passenger cabin (Wocke, Ref.1). Neither of these two aircraft however exploited the full advantages of forward sweep. The actual sweep angle (near 15°) was kept low to avoid the inherent FSW structural aero-elastic divergence problem without undue weight penalties using the conventionally available metallic isotropic materials. Both aircraft used tail stabilisers. During the design phase of the HANSA, the disadvantages of a high tail location and its link with wing "deep-stall" were not fully appreciated. In fact, a HANSA prototype was lost during high incidence trials, signifying the problem for the future.

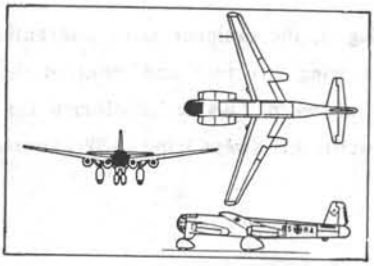


Fig.3. JU-287.

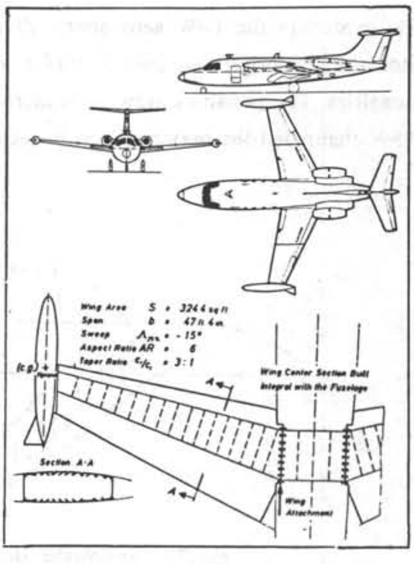


Fig.4. HFB-320 Hansa.

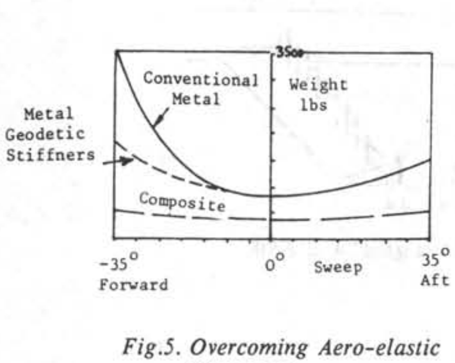


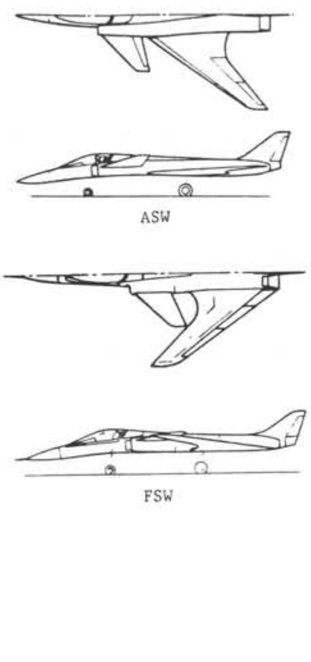
Fig.5. Overcoming Aero-elastic Divergence.

The configuration optimisation programme of the Hansa included consideration of several design variables (Ref.2 and 3) such as engine location, V - Tails, translating-cum-pivoting LE and TE controls (reducing hinge-line sweep with increasing deflection) and inclusion of wing-fences. Surprisingly, canards were not considered.

In the aviation literature, there are several other FSW projects which did not proceed beyond being exercises on paper.

Revival of Interest in FSW

Krone revived the interest in FSW in 1970's (see Ref.4 to 8). He demonstrated that the major problem of aero-elastic divergence for higher angles of forward sweep can be overcome with an aero-elastically tailored wing using composites. Such a wing is stiff in torsion and does not incurr undue weight penalties (Fig.5). Incidently, geodetic structures although costly to produce can also be given similar attributes. These realisations coupled with the advances in related technology e.g. the use of favourable aerodynamic interference with a foreplane, active controls and propulsion, emphasised examination of FSW for several aircraft types. The Defence Advanced Research Projects Agency (DARPA) in USA initiated studies and a design competition in 1976 for a FSW combat aircraft manned demonstrator. This competition realised three designs. The General Dynamics project (Ref.7) based on the F-16 had a conventional empennage and implied replacing the F-16 ASW by an aspect ratio 4 FSW (LE sweep -23°).



		FSW	ASW
TOGW	lb.	16,115	19,397
Fuel Weight	lb.	5,446	4,740
Wing Area	sq. ft.	281	161
Size of 2 Turbofans	P&W 77-07	30.3%	49%

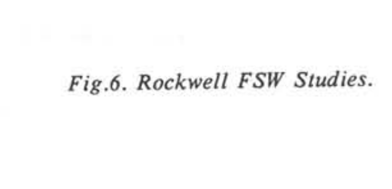


Fig.6. Rockwell FSW Studies.

The Rockwell project (Robinson and Robinson, Ref.9) featured a canard-FSW (LE sweep -45°) layout and was based on the HIMAT research vehicle. The FSW design emphasised high performance throughout the flight envelope from low speeds near the ground through to transonic manoeuvre and to Mach 1.8. The Rockwell comparative studies led to a FSW layout with twin-engine thrust vectoring nozzles to attain short field performance (Fig.6). Eventually, the Grumman design emerged successfully from the competition. This aircraft (Fig.7) denoted as the X-29, features a low aspect ratio canard and an aspect ratio 4 FSW (LE at -30°). The thickness/chord of the aerofoil section of the wing is about 5%. The aircraft embodies a Northrop F-5 forebody and components from several other current aircraft. The aircraft first flew in Dec. 1984. Several recent papers (Refs.10-17) have highlighted the features of Research and Development (R&D) on the X-29 and the current status of the flight envelope exploration. This programme has inspired several general review papers on the impact of FSW technology (Ref.18-22).

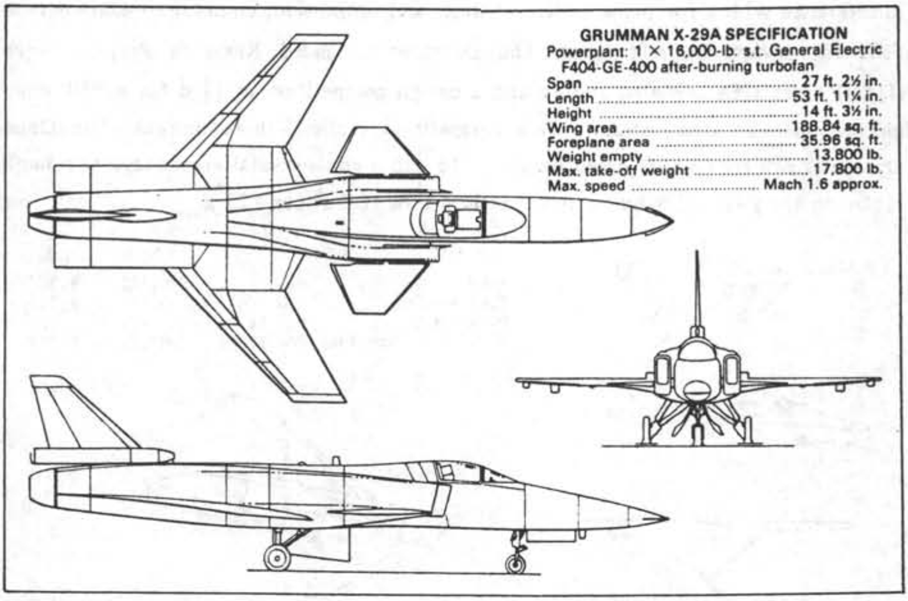


Fig.7. Grumman X-29A.

Objectives of This Paper

The objectives of this paper are essentially fourfold: (i) to give an idea of the scope of FSW applications with emphasis on the high aspect ratio types, (ii) to discuss briefly the design requirements and evaluation criteria for a new project to enter service, (iii) to highlight some of the the features of FSW (with theoretical and experimental evidence) that render it attractive for incorporation in civil, business or transport type aircraft, and (iv) to propose areas for future work.

2. AN INDICATION THE SCOPE OF FSW APPLICATIONS & STUDIES

Encouraged by the X-29 programme, the scope of possible FSW applications has been continually widened to embrace several types of aircraft. Kalemaris (Ref.23) has studied V/STOL concepts illustrated in Fig.8. His preliminary estimates revealed that no significant penalties arise due to FSW. In-flight performance was superior for the FSW designs. The FSW frees a single lift/cruise engine V/STOL from the constraints of the Pegasus type engine cycle. This has significant implications for other classes of V/STOL as the engine cycle can be optimised for in-flight performance. Project evaluations indicate the possibility of a single lift/cruise engine V/STOL with excellent supersonic performance.

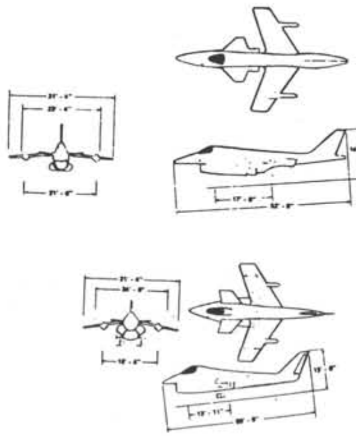


Fig.8. V/STOL Concepts (Kalemaris).

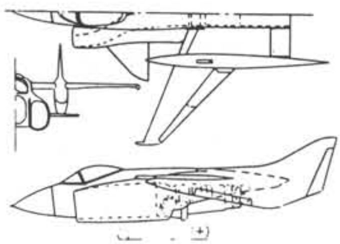


Fig.9. V/STOL Concept (Howe).

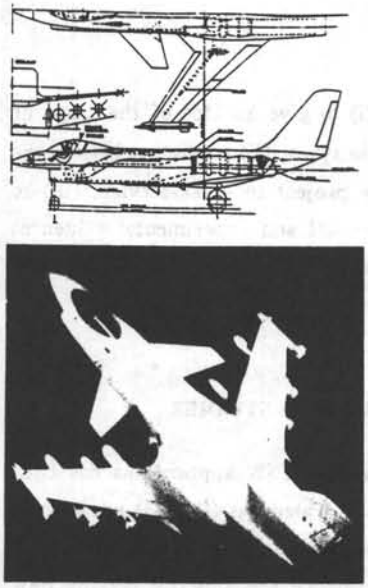


Fig.10. V/STOL Concept
(Fielding).

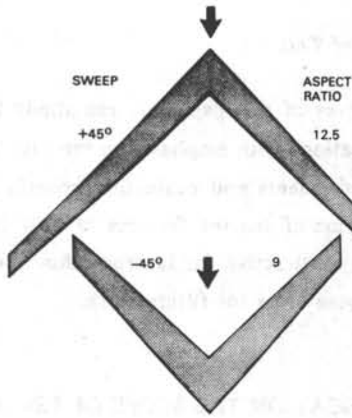


Fig.11. Equivalent ASW & FSW
(Truckenbrodt).

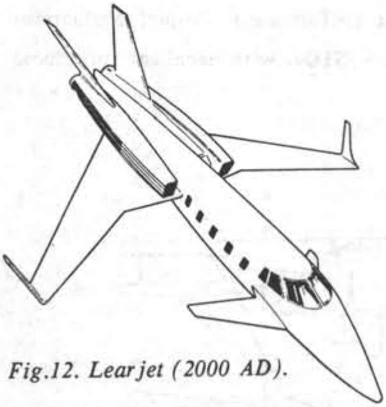


Fig.12. Learjet (2000 AD).

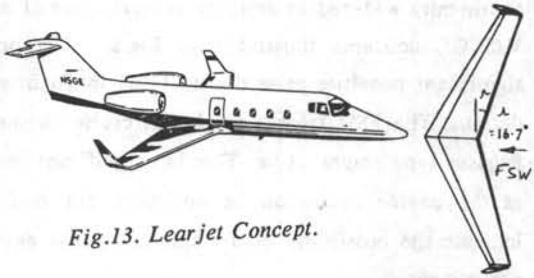


Fig.13. Learjet Concept.

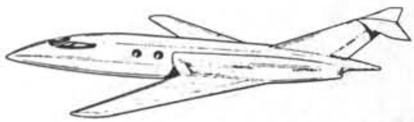


Fig.14. Beechcraft Concept.

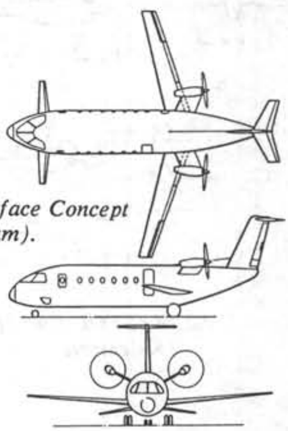


Fig.15. 3-Surface Concept
(Roskam).

Fig.16. Rutan's Concept.

Howe(Ref.24) and Fielding(Ref.25) consider FSW in V/STOL aircraft. They discuss the possibility of compact layouts (Figs.9 and 10).

At the 1980 Munich ICAS, Truckenbrodt (Ref.26) reviewed his earlier work on the JU-287 and HANSA in the light of the advancing FSW technology and proposed high aspect ratio transonic FSW designs. The constraints in his study on FSW and ASW with mid-chord sweep at 45° were twofold: (i) that twist is optimised to ensure elliptic spanwise load distribution at $C_L = 0.45$ and (ii) that the onset of flow separation is inboard at $C_L = 1.0$. He showed (Fig.11) that a FSW of aspect ratio of 9 compares with an ASW of aspect ratio 12.5 in satisfying constraint (i), but constraint (ii) is satisfied by the FSW only, thus surmising its superiority. A case was made for comparisons at lower wing sweep angles.

The resurgence of interest in FSW led to the Bristol Conference in 1982 (Ref.27) at which some 31 papers were presented. Papers included R&D studies on several aircraft with low and high aspect ratio FSW. The impetus has been maintained at a higher level in the USA rather than in Europe.

Figure 12 depicts the Learjet LRXX proposal (Ref.28) of an "Executive" canard-FSW design for the year 2000 AD with Mach 1.8 cruise capability. However on a shorter time-scale Cook and Abla (Ref.29) refer to a study on adapting a FSW on the Learjet model 55 (Fig.13) by reversing the 20° quarter-chord sweep. A comparable Beech FSW high-tail supersonic design (Ref.30) is depicted in Fig.14.

Roskam (Ref.31) has proposed a 3-surface "Commuter" aircraft (Fig.15) which offers an optimum arrangement of the aircraft major components including the undercarriage. Trim drag can be minimised at all flight attitudes. In a similar vein, Rutan (Ref.32) also released details of the Model-72, a canard-FSW design (Fig.16).

Taking next the high-wing designs, these are symbolised by the Lockheed canard-FSW "transport" (Fig.17). Smith and Srokowski (Ref.33) have compared an ASW and several "equivalent" cranked FSW planforms. They indicated that a FSW with a cranked TE can be designed without any undue transonic penalties. A canard has a favourable influence.

Nangia (Ref.34) presented some theoretical comparisons and discussed "pros and cons" for high aspect ratio FSW and ASW aircraft. In Ref.35, Nangia described an experimental programme on high aspect ratio FSW and ASW "Transport" and "Executive"

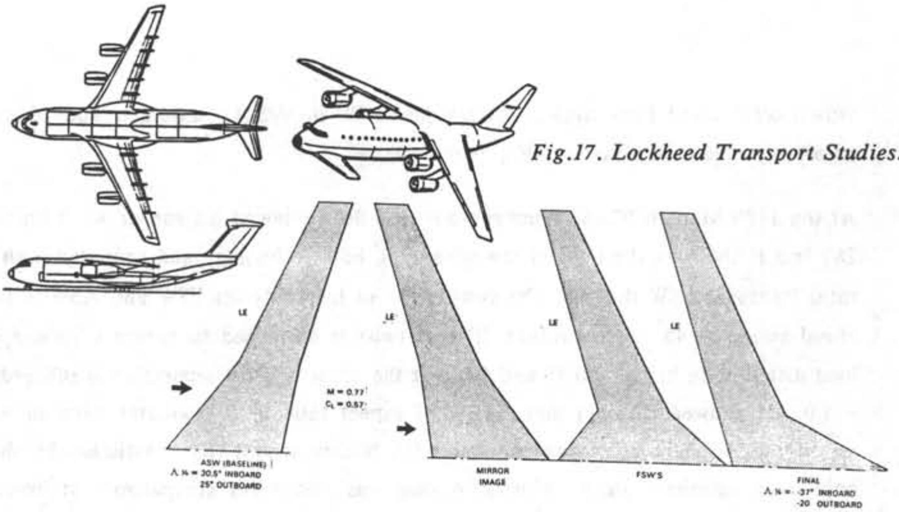


Fig.17. Lockheed Transport Studies.

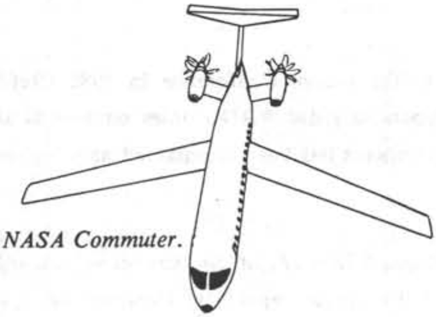


Fig.18. NASA Commuter.

Fig.19. NASA Light Aviation.

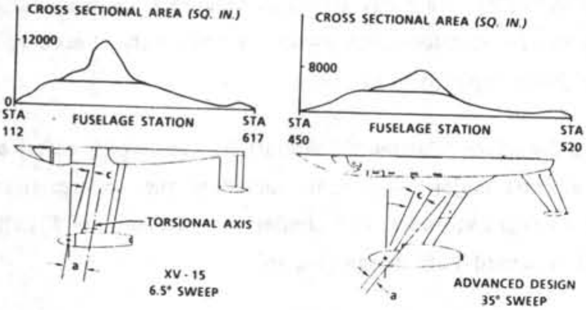


Fig.20. FSW in "hybrids".

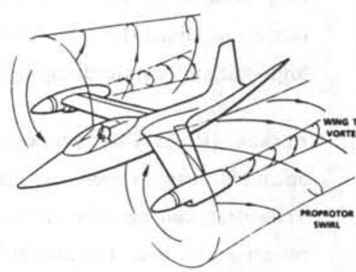


Fig.21. Prop-rotor swirl.

Fig.22. Buisness tilt-rotor.

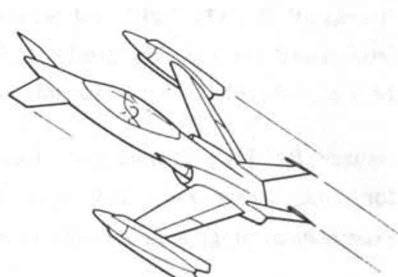


Fig.23. Transonic tilt-fold rotorcraft.

types. The subsonic longitudinal tests, albeit at low Reynolds number highlighted several general notions. Some of these are related in Section 7.

NASA Langley's interest in integrating high aspect ratio FSW has been inferred from two designs proposed for the 1990's (Ref.36). Figure 18 shows a commuter transport with an aspect ratio 12 natural laminar flow wing with supercritical characteristics. Forward sweep of 15°-22° is necessary in order to maintain balance with the two counter-rotating prop-fan powerplants mounted on struts at the rear of the fuselage. The general avaition design (Fig.19) features a supercritical 12° FSW with natural laminar flow, a pusher turbo-prop engine and fly-by-wire controls. A gross weight of 4,430 lb is expected with a six seats. The range is 1,300 naut. mi, cruising at 346 kt.

Recently, FSW incorporation has spread into the "hybrid" aircraft types which combine rotor and fixed wing flight (Drees, Ref.37). Figure 20 illustrates how the concept takes advantage of wing root being located behind the cabin. The FSW allows a smoother variation of cross-sectional area as well as reducing the rotor "overhang" and increasing the flapping clearance. Figure 21 shows that prop-rotor swirl opposes the wing-tip vortex flow field thus reducing the induced wing downwash and induced power. Figure 22 illustrates a possible tilt-rotor passenger concept that can realise speeds of near 450 knots in level flight. The wing is of relatively high thickness/chord ratio (15 - 18%) to integrate the prop-rotor drives. Thicker wing sections facilitate FSW torsional rigidity. Looking far into the future, a tilt-fold rotor concept with separate jets to achieve transonic forward flight is shown in Fig.23.

An idea for future is applying circulation control (CC) to FSW. At the Bristol FSW conference (Ref.38), Nicholls explained that CC on the FSW provided extra lift without significantly altering the location of the centre of pressure. The trim penalties (e.g. increased trimming surface area) could be avoided (Fig.24).

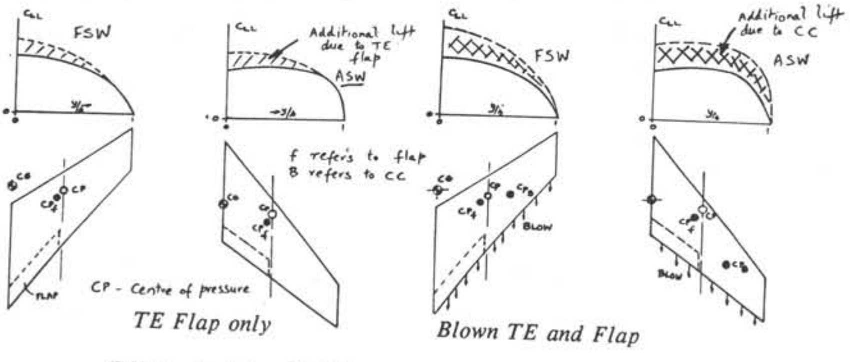


Fig.24. Applying TE Flap and Circulation Control.

3. DESIGN REQUIREMENTS & EVALUATION CRITERIA

For a new product line to transpire and be viable, a rational commercial viewpoint demands the evaluation of the benefits and improvements to be achieved against the resources utilised. Black and Stern (Ref.39) mention that "value is related to the amount one would be prepared to pay for the usefulness supplied, in the circumstances....". In the context of aircraft as being the product, the value of an improvement differs greatly between combat and transport circumstances.

The transport value is related by Bore in Refs.40 and 41 to the payload shuttling performance of the fleet, over a given set of airfields. The set of airfields available depends on the aircraft in terms of airfield performance, need for approach guidance and other factors. The main factors that determine the value of the transport capacity can be related to the general range (R) equation applied to constant $M - C_L$ cruise segments at all altitudes.

$$R = \frac{a_0.(M.L/D).\ln(W_1/W_2)}{(1+\epsilon).(s/\sqrt{\theta})}$$

where

ϵ is a small factor much less than 1.0
a_0 is the Velocity of sound at sea-level
M is the flight Mach number
L/D is the lift/drag ratio at constant $M - C_L$ cruise
W_1 is the landing weight including reserve fuel
W_2 is the take-off weight with fuel
$(s/\sqrt{\theta})$ is the jet engine specific fuel consumption (sfc) corrected for the atmospheric relative temperature θ.

Taking the payload shuttling capacity as being proportional to (PAYLOAD x SPEED), a quantity C - the payload shuttling capacity per unit of fuel consumption can be related to the payload weight W_P as:

$$C \propto (W_P/W_2).\frac{(M.L/D)}{(s/\sqrt{\theta})}$$

This equation neatly groups the terms which affect the transport efficiency. The ratio (W_P/W_2) embraces the various weight terms, the (M.L/D) term embraces the aerodynamics. The fuel consumption $(s/\sqrt{\theta})$ term includes the engine efficiency as a function of M. Each of these terms occurs as a factor to the specific payload capacity so that a 10% change in any factor would lead to a 10% change in the value of C.

There are of course, gross simplifications implicit in the foregoing derivation, since it represents only the cruise portion of flight. Smith and Stephenson (Ref.42) mention that a "feeder" airliner operating over a typical 300nm stage flight would consume only 25% of block fuel during cruise, with the whole flight achieving around 70% of the cruise efficiency. Half of the excess fuel represents engine starting, taxi-out, take-off, approach, landing and taxi-in. The remainder of the excess fuel is used during climb and descent when the conditions for optimum sfc and best L/D are not compatible. However, consideration of cruise efficiency and payload shuttling capacity does enable an appreciation of the relationships between weight, drag, speed and sfc.

For overall efficiency therefore, additional parameters relating to the field performance are introduced. As an example, to minimise the landing/take-off runway lengths, high C_{Lmax} is demanded from the wing LE/TE devices. In aerodynamic terms, the overall efficiency and mission/role requirements are interpreted with flight envelope.

Figure 25 illustrates the flight envelope of a large high aspect ratio aircraft (C-5A from Ref.43). The envelope specifies a high L/D at cruise Mach number near 0.85.

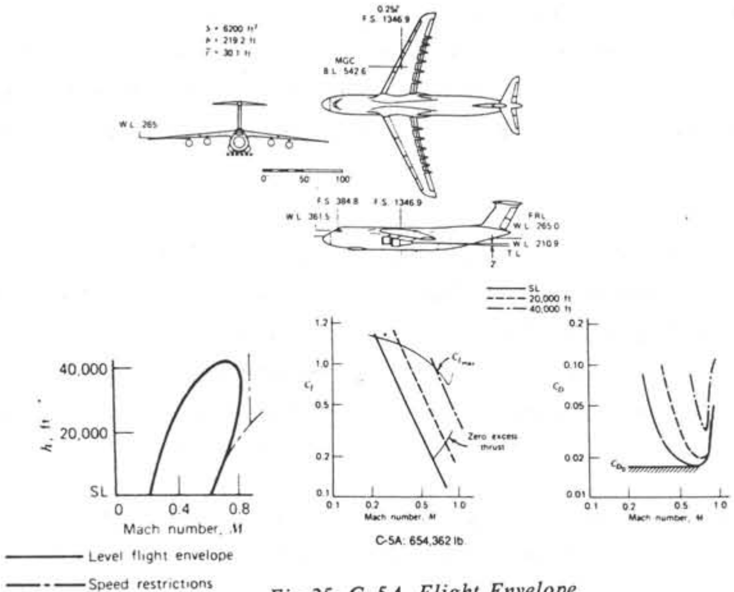


Fig.25. C-5A, Flight Envelope.

At low speeds, the critical requirements are landing and take-off with short runs to enable not only compliance with stringent noise regulations, but also to reduce the airport runway size and the associated maintenance costs. The short runway philosophy is consistent with a greater frequency of aircraft movements. The designer therefore has to offer low speed at high lift without excessive drag. The stall pattern is encouraged to be well behaved so that handling and response are satisfactory.

At high speed cruise, the L/D is affected by the lift dependent drag (C_{Di}) and various friction and parasitic drag terms (comprising the C_{D0} term). C_{Di} depends on wing aspect ratio, shape of span loading, LE sweep and aerofoil properties. In general, an increase in aspect ratio or a reduction in sweep both lead to reduction of C_{Di}. Aerofoils with larger nose radii delay LE "bubble type" flow separations and allow increased "capture" of LE suction at high speeds.

A component of drag arises due to trim of the aircraft throughout the flight envelope. It is important to keep this as low as possible. Application of ideas e.g. using 3-surfaces, improved flight control and "mild" relaxed stability allow scope for reducing this component.

Compromises between low and high speed flight therefore require variable geometry on the wing. The accepted procedure is to design the wing with camber and twist for transonic cruise, allowing extensive regions of supercritical flow terminated by a transonic shock lying near the TE on the wing upper surface. LE and TE devices are then deployed to meet the low speed requirements. It is worth noting that a tapered FSW offers an appreciably high TE sweep and this aspect is considered in Sections 4 and 5.

Costs

It is of utmost importance to appreciate the cost leverage of the aircraft fleet. The fleet provides the whole of total useful capability, but implies only a fraction of the costs. In view of the long useful life cycles of the modern transports, the attention is devoted to Direct Operating Costs (DOC). Black and Stern (Ref.39) stipulate that a reduction in DOC of 20 - 30% may justify the entry of a totally new aircraft into service. Only about half that improvement in DOC is necessary for a derivative aircraft.

In general terms, the most important parameters affecting the aircraft unit cost are installed power and the number produced. In terms of the investment profile for the builder, it is vital to reduce the design and manufacture cycle time for the aircraft and its propulsion system, and to reduce the manufacturing investment and unit costs especially at the stage of peak investment.

4. "SWEEP EQUIVALENCE" BETWEEN FSW & ASW PLANFORMS

Several ways of measuring "equivalence" of FSW and ASW may be postulated. The choice is dictated largely by the mission/role of the aircraft. For example, subsonic design and high lift capability would lead to relating the wing sweep at 25% chord line. Structural considerations based on the maximum wing thickness/chord or wing-box sweep line suggest a comparison at 35-40% chord line. A more practical criteria follows from considering efficient transonic cruise and the location of transonic shock terminating the supercritical flow and lying well aft near 70-80% wing chord. The shock wave-compressibility drag is minimised by ensuring as much sweep as allowable. The shock sweep then becomes a measure of "effective aerodynamic sweep". On the fuselage side, the shock will always lie normal to the line of flight. At the wing-tip, 3-D effects will modify the idealised behaviour.

The following example demonstrates the transonic equivalence principle by comparing the sweep angles of various chord lines of an ASW and a FSW of aspect ratio 8, taper ratio 1/3 and shock sweep of 30° at 75% chord line.

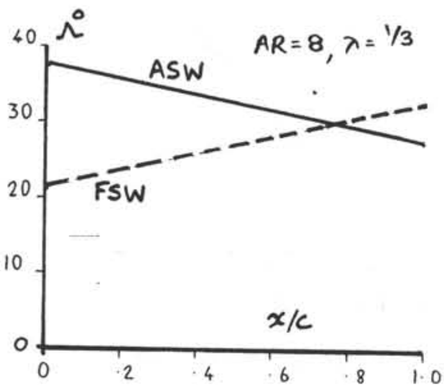


Fig.26. Sweep - chord line.

chord-line	ASW	FSW	Difference
LE 0%	37.4°	-21.3°	-16.1°
25%	35.1°	-24.3°	-10.7°
50%	32.6°	-27.2°	-5.4°
75%	30°	-30°	0°
TE 100%	27.3°	-32.6°	+5.4°

	ASW	FSW	Ratio
length/span	0.4449	0.3824	0.8595

Figure 26 shows the sweep angle plotted against the chord line. The FSW offers a reduction of LE sweep by about 16° which is nearly half the shock sweep angle. The ratio length/span for the FSW is nearly 15% less.

Smith and Srokowski (Ref.33) refer to FSW and ASW of aspect ratio 10.5 and taper ratio 0.4. For equal shock sweep at 70% chord-line, a reduction of 12° in LE sweep has been noted (Fig.27). The LE sweep/shock-sweep advantage for the FSW increases as the wing taper ratio or aspect ratio reduces.

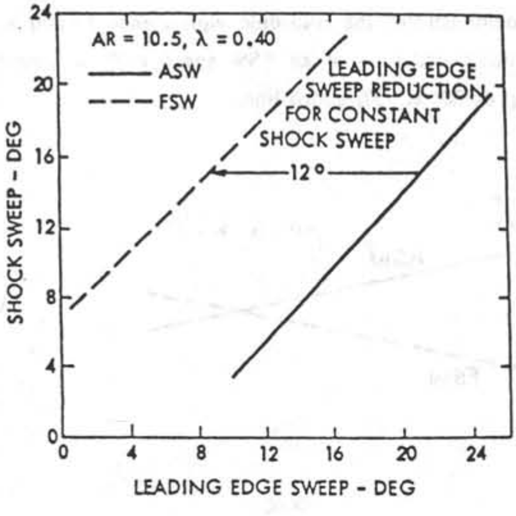


Fig.27. LE Sweep - Shock Sweep.

5. EXPLOITING LE SWEEP/SHOCK-SWEEP ADVANTAGE OF THE FSW

The options for exploiting the LE sweep/shock sweep advantage lie in integrated design.

(i) *Higher drag divergence Mach number.* Increasing the LE sweep and hence the shock sweep would increase the fuel efficiency for high transonic speed operation thus leading to lower operating costs.

(ii) *Higher lift curve slope for tapered FSW.* This arises by virtue of lower LE sweep.

(iii) *Reduced Wing-root Bending Moment.* The root region of the FSW carries a higher loading moving the spanwise centre of load inboard and reducing the bending moment at the root. As a result, a lighter wing or a higher aspect ratio wing may be schemed for a given bending strength.

(iv) *Possibility of lower Lift induced Drag.* Combining the aspect ratio increase with lower wing LE sweep allows a reduction in lift induced drag. Lower wing LE sweep permits higher LE suctions to be attained on the inner wing where the aerofoil sections are thicker and the radii higher. This is particularly significant at high C_L.

(v) *Reduction in Wing Twist.* On a swept wing, the component of velocity parallel to the LE causes the airflow to drift in that direction. The greater the sweep, the more pronounced is the drift. On account of lower sweep, the FSW requires less twist to counteract the drift towards the wing tip. The reduction in twist on the FSW produces a wing with improved transonic capability.

(vi) *Increased Wing thickness/chord coupled with increased sweep.* Structural sweep increase allows fuel-volume increase as well as wing weight reduction. In turn this can lead to lower acquisition costs.

Smith and Srokowski (Ref.33) suggest lengthening of the root chord to attenuate wing-body interference by encouraging the transonic shock to move aft.

(vii) *More Effective LE Controls.* By virtue of lower LE sweep, LE controls: flaps or slats are expected to be more effective. Further, the wing tip area is less prone to stalling and the size of devices can be reduced.

(viii) *Reduced Pitch-up tendency.* **By virtue of lower LE or 25% chord line sweep, the pitch-up tendency reduces.**

(ix) *Increased Natural Wing laminarisation.* **Lower LE sweep allows natural flow direction away from the wing tip and offers a suitable environment to encourage and maintain laminar boundary layer. The fuselage effects are confined to the inboard wing.**

6. REDUCTION OF OVERALL DRAG USING FSW - AN EXAMPLE

Defining the drag components as:

$$C_D = C_{Dmin} + C_{DL} \quad \text{and} \quad C_{DL} = C_{DLP} + C_{Di}$$

where

C_{Dmin} is the minimum drag coefficient
C_{DL} is the lift dependent drag coefficient
C_{DLP} is the viscous profile drag coefficient due to lift
C_{Di} is the lift induced drag coefficient

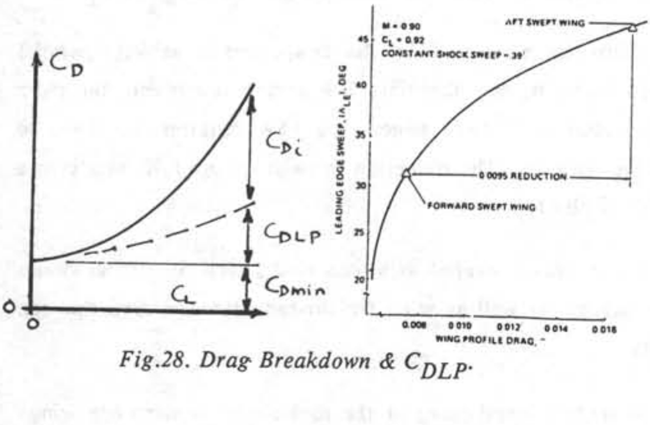


Fig.28. Drag Breakdown & C_{DLP}.

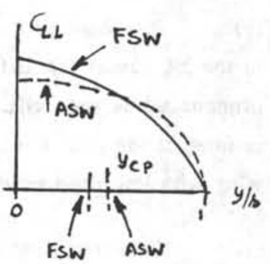


Fig.29. Load Distributions.

The advantage of the FSW over an equivalent ASW is due to reductions in the components C_{DLP} and C_{Di}. Figure 28 shows the variation of C_{DLP} with LE sweep angle. This graph is based on experimental investigations carried out by Grumman on a series of thin "K - series" aerofoil super-critical wings operating at Mach 0.9 and C_L = 0.9. If the conditions of identical shock sweep, shock location and planform parameters (aspect ratio, taper ratio) are applied, the resulting FSW LE sweep is less than that of the ASW. Taking the example (Section 4) of shock sweep 30°, The FSW indicates nearly 0.0035 reduction in C_{DLP}.

The lift induced drag component varies with wing planform parameters: aspect ratio, taper ratio and LE sweep. In general, the lower sweep of the FSW gives a lower C_{Di} at low C_L. At high C_L, Mach and Reynolds numbers effects determine the LE suction attained and hence the drag.

Under conditions of equal lift and identical spanload, the centre of pressure of the FSW is more inboard along the swept structural span than on the ASW (Fig.29). Consequently, the bending moment about a pivot point on the fuselage can be considerably less. If the span of the FSW is then allowed to increase while maintaining the wing area, until pivot bending moments are equal, the accompanying increase in aspect ratio produces a reduction of lift induced drag.

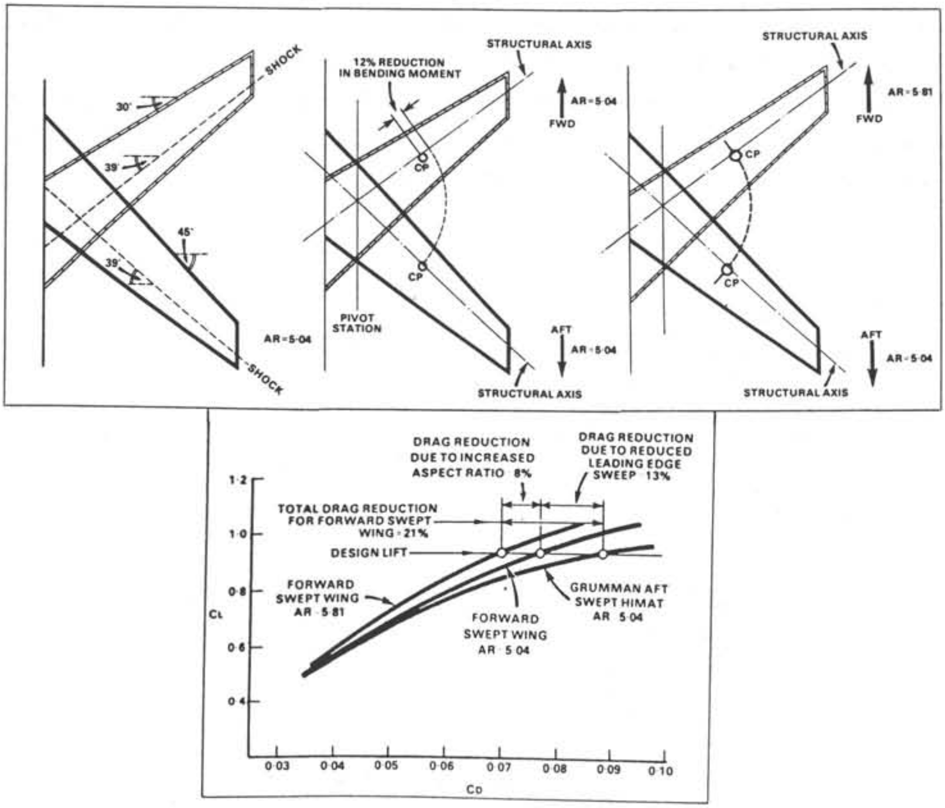


Fig.30. Exploiting FSW LE Sweep/Shock Sweep Advantage.

Spacht (see Ref.20) illustrates the whole process with a starting aspect ratio of 5.04 for the FSW and ASW (Fig.30). The emerging "equivalent" FSW has an aspect ratio 5.81 and it offers a total drag reduction of 21% (C_{DLP} 13% and C_{Di} 8%) at Mach 0.9 and C_L = 0.9.

7. FSW FEATURES, DISADVANTAGES & ADVANTAGES

We now look at general flow features that have a bearing on an aircraft design with a FSW. The emphasis is on longitudinal characteristics. It is to be stressed that experimental database is sparse in many areas of FSW technology and is open therefore for ample expansion.

a. Stall Progression and Vortex System Development

Because of higher tip loading, an ASW is prone to flow separations that move gradually inwards as the angle of attack increases (Fig.31). In contrast, the root region of the FSW is highly loaded and as the angle of attack increases, the stall spreads from the root outwards (Ref.44). Presence of simply shaped or parallel-sided bodies does not alleviate the stall behaviour. The overall stall pattern is a combination of 2-D type stall at the root and 3-D behaviour spreading from the wing tip.

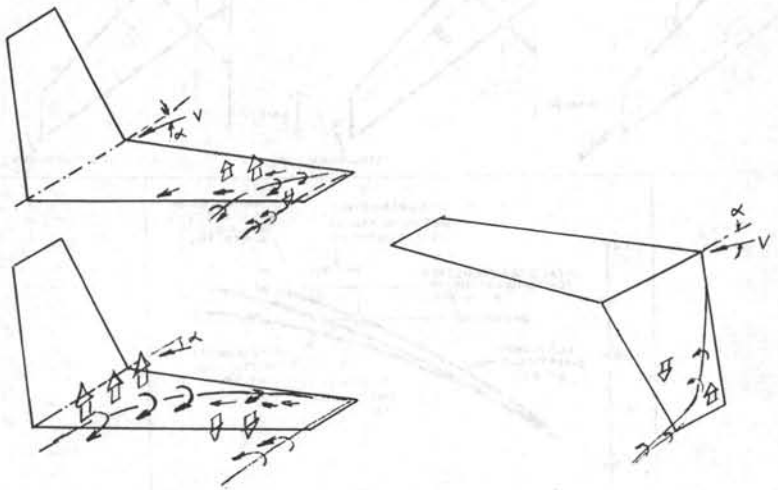


Fig.31. Stall Progression on FSW & ASW.

At high α, the wing-tip of a FSW behaves like a "yawed-delta" and two vortices can be observed: a tip vortex trailing downstream and a LE vortex in the opposite sense which remains over the wing prior to either being absorbed in the wing root flow or bursting near the wing TE in the mid-semi-span region. The LE vortex, although lying at a much lower effective sweep, gives rise to non-linear lift in the wing-tip region. It also induces upwash on the inner wing and therefore encourages the initiation and existence of the root stall. In addition, a spanwise flow drift into the wing root is also observed. The consequence of the interaction of the two phenomena is that the stall behaviour, with respect to α is gentle on the FSW but the overall lifting and low drag potential is hampered by the existence of LE vortex. The phenomenon is particularly severe on thin wings.

Possible ways of abating the LE vortex (Fig.32) are (Refs.45,46,47):–

(i) by improving the aerofoil section properties to enable attached flow being maintained on the outer wing e.g. by increasing LE radius or using LE droop. The use of LE droop only in the wing root area may prevent high LE suctions there and delay the 2-D type stall but may not affect the 3-D behaviour initiated from the wing-tip.

(ii) by using wing-fences to reduce the spanwise flow drift. The fence height needs to be adequate so as not to become submerged in the boundary layer at high α.

(iii) by boundary layer control (suction) to delay flow separations (Ref.47)

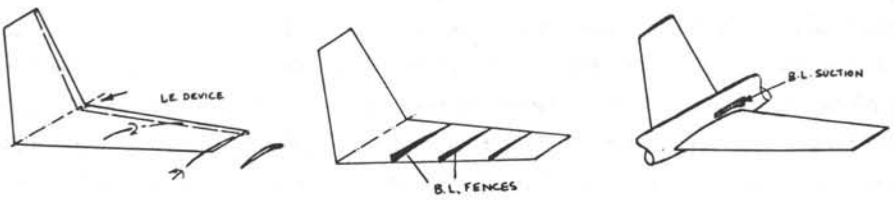


Fig.32. Abating FSW LE Vortex & Separation.

b. Centre Section - Compressibility & M_{crit} Effects

In symmetric flight, there can be no cross-flow at the centre-section of a swept wing. On the FSW, this causes very high velocities compared with those on the wing panels. Hoerner (Chap.15, Ref.48) provides the following measured data for non-lifting and lifting cases:

Non-lifting case, $C_L \simeq 0$, Aerofoil t/c =12%.

C_{pmin}	x/c	
-0.25	0.37	centre, 45° ASW
-0.27	0.25	average in wing panels
-0.60	0.03	centre, 45° FSW

Lifting case, $C_L \simeq 0.35$, Yawed Wing Tests at Mach 0.6 (aspect ratio 9 to 7.5, Aerofoil NACA 65-210)

C_{pmin}	M_{crit}	Near the LE
-0.3	0.8	centre, ASW 30°
-0.6	0.7	average Wing Panels
-1.2	0.6	centre, FSW 30°

The main point here is that the centre-section of the FSW needs extremely careful design to prevent the occurrence of super-critical velocities there and hence preclude the achievement of the full potential of the rest of the wing.

c. The Need for a Canard

An obvious means to influence the centre-section of the FSW is to add a swept-back "fillet" at the the wing-root (Fig.33). The upshot is that the root problem of the wing transforms into two problems at separate spanwise locations and although an amelioration on the inner wing flow may be evident, the essential difficulties still persist. The upwash on the outer wing may in fact be increased. An additional drag penalty may be incurred.

A more elegant solution is to place a canard so that its induced downwash reduces the effective angle of attack on the wing root area at the expense of an upwash increase over the outer wing (Fig.34). The canard also induces favourable outflow (sidewash) which opposes the natural wing inflow. This enables control over the wing root stall so that full potential of the wing is more likely to be achieved. By judicious choice of the

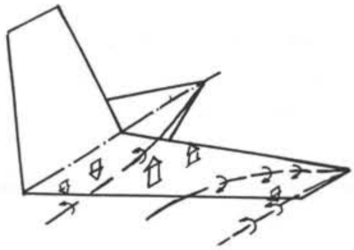


Fig.33. Wing Root-fillet.

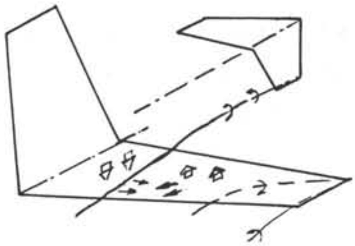
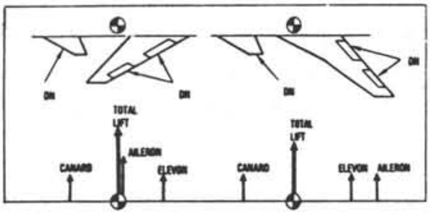


Fig.34. Canard Effects.



- AFT SWEPT WING HAS LONG MOMENT ARMS TO TRIM
- CANARD TRIMS PITCHING MOMENTS IN BOTH CASES USING ITS MAXIMUM LIFTING POTENTIAL
- AFT SWEPT WING HIGH LIFT DEVICES LIMITED BY CANARD TRIMMING CAPABILITY

Fig.35. Close-Coupled Canard.

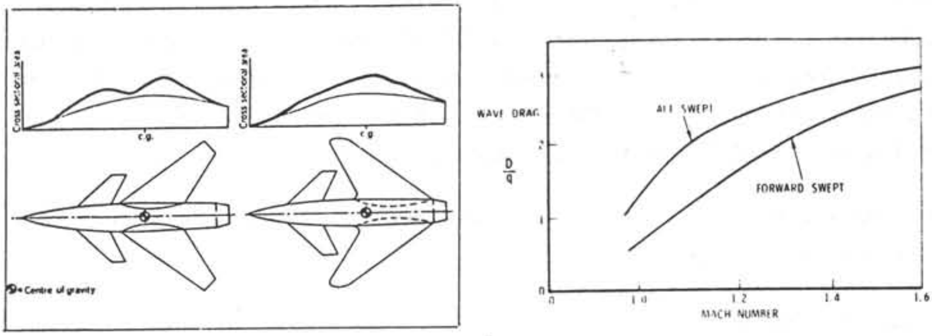


Fig.36. Area Ruling & Wave Drag.

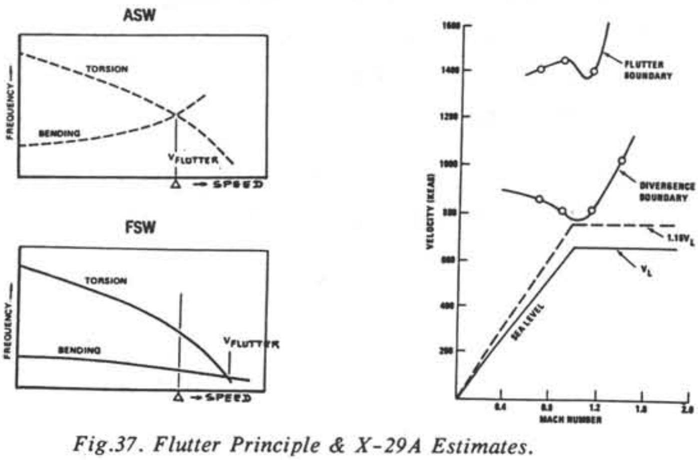


Fig.37. Flutter Principle & X-29A Estimates.

canard span relative to the wing span, the stall on the wing can be arranged to initiate immediately aft of the canard tip and to spread inboard and outboard simultaneously. The stall is therefore well behaved and the wing tips remain effective to α to 40° or 50°.

A close-coupled canard allows an extremely compact layout. The short moment arm produced by sweeping the wing TE forward avoids any undue limits on the use of high lift TE devices being imposed by the canard trimming power available (Fig.35 from Ref.49).

Introduction of longitudinal instability allows the canard to carry increased loading thus requiring less lift in the root region of the FSW. This corresponds with significant reductions in wing lift induced drag C_{Di}. A corollary that arises is the need for a "tolerant" canard design.

d. Area Ruling

Efficient transonic (and indeed supersonic flight) requires smooth cross-sectional area distribution of the whole aircraft to keep the wave drag low. Comparative studies undertaken at Rockwell suggested that the FSW fills the cross-section "gap" behind the canard without resorting to a "coke-bottle" type narrow-waisted fuselage. Total wave drag may therefore be reduced. The FSW therefore allows increasing useful volume near the CG and more of the weight can be located there (Fig.36).

A thicker fuselage helps in reducing the wing bending moment and contributes to a lighter or smaller aircraft.

e. Wing Mounting On Fuselage

The FSW generally requires a wash-in twist to attain elliptic load distribution at cruise. Cruise lift and cabin floor requirement imply that the local incidence of the wing with respect to the fuselage axis is near zero. For an ASW, the requirement of wash-out twist implies a 3° to 5° wing incidence on the body.

A low root setting angle of the FSW also renders it more favourable for high location on the fuselage. The high wing location also helps in improving the FSW dihedral stability.

f. Winglets (Tip-fins)

Winglets (or Tip-fins) are often employed on ASW configurations not only for stylistic reasons but also to improve the flight efficiency. For example, winglets have been "retro-fitted" on "span-limited" designs. The experience is that properly designed winglets show benefits such as higher C_{Lmax} and lift-curve slope and improved cruise L/D. Winglets enable flight at lower α with a reduction of overall wing twist requirement. Potential gains from winglets have to be offset against an increase in total profile drag and a possible increase in weight because of rise in wing bending moment. Longitudinal, directional and lateral stability of the FSW must also be considered.

The tip of the FSW is lightly loaded with respect to the root. The winglet can therefore aid in re-distributing the spanwise loading throughout the the complete α range so that a higher usable C_L is realised for a given local C_{Lmax} at the wing root.

An up-turned winglet can partly compensate for the reduced $C_{l\beta}$ because of forward sweep. For high angles of forward sweep, the winglet, if upstream of the CG, may cause reductions in $C_{n\beta}$ and also longitudinal stability. In a typical canard-FSW configuration however, the winglet is likely to be in line with the CG.

g. Flutter

The FSW is less prone to the wing flutter problem (Fig.37). For the Grumman X-29A, the flutter boundary is at more than twice the maximum design speed of the aircraft. The critical boundary is of course the wing divergence which has been set at $1.2(V_L)$ (EAS).

It is interesting to reflect that for an ASW aircraft one of the essential design criteria is adequate wing flutter margin. Aileron operation can further errode into this margin. Structural divergence is not usually described as a major problem for an ASW.

It has been shown that low-frequency body freedom flutter phenomenon may become severe on certain designs with high forward sweep. Wykes et al (Ref.50) and Niblett (Ref.51) have discussed the implications. Niblett notes that an aircraft is liable to flutter if it has a FSW and a positive "tail-off" CG margin or an ASW and a "negative" CG margin but a simple cure for the flutter does not appear to exist. Active Control is a possible solution.

8. EXPERIMENTS ON HIGH ASPECT RATIO CONFIGURATIONS

As mentioned in Section 2, a series of comparative model experiments on high aspect ratio FSW and ASW configurations ("Transport" and "Executive" types) were undertaken by the author (Ref.35). The subsonic longitudinal stability tests although conducted at low Reynolds number highlighted several general notions.

Figure 38 illustrates the series of models representing the high wing "Transport" types (TFSW and TASW series). The FSW and the ASW (aspect ratio 8, taper ratio 0.4, uncambered aerofoil NACA-0015) were of "equivalent" quarter chord sweep of 25°. Canard and tail arrangements could be configured. The FSW (+5° wash-in twist) was attached to the fuselage at setting $i_w = 0°$. The ASW (-5° wash-out twist) was mounted at $i_w = +5°$.

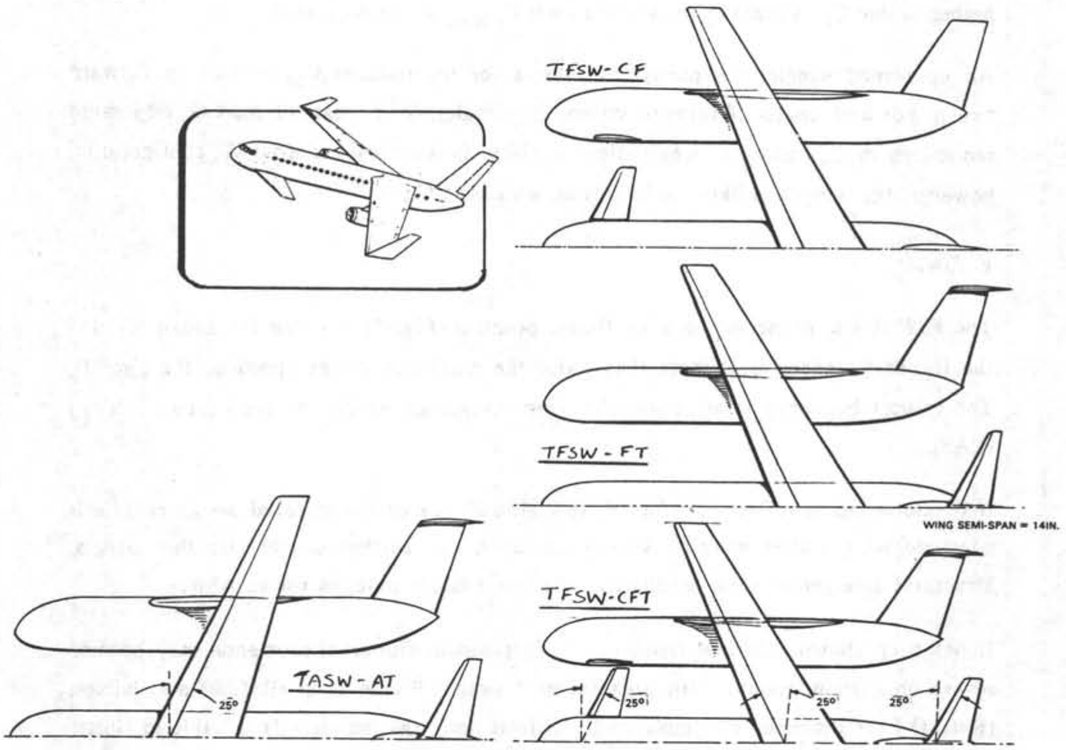
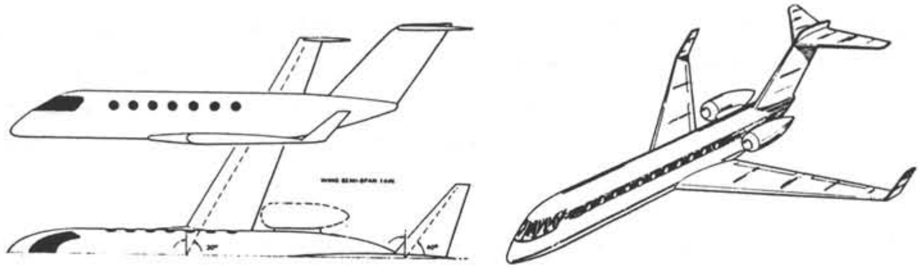
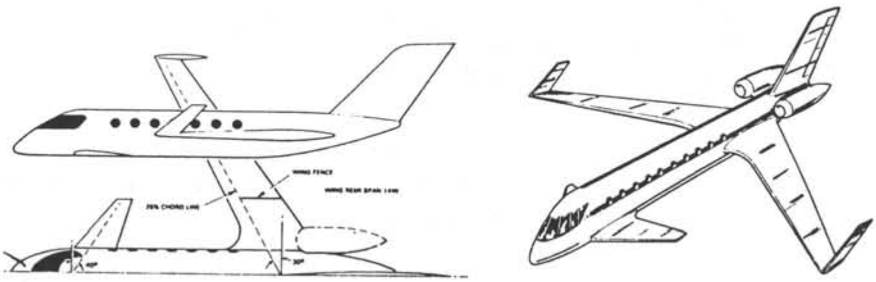


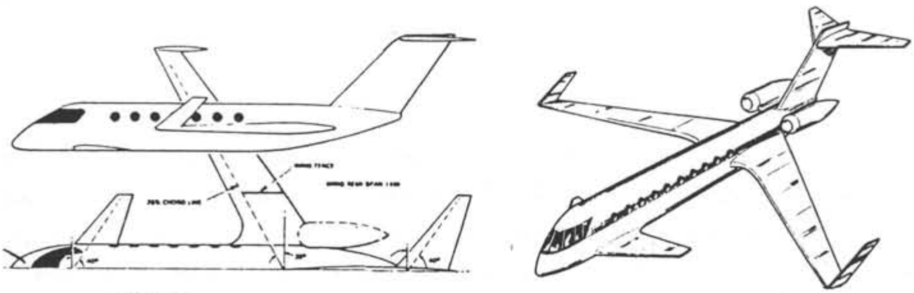
Fig.38. "Transport" Series of Models.



EASW–AT



EFSW–CF



EFSW–CFT

Fig.39. "Executive" Series of Models.

Based on experience with tests on the "Transport" series of models, a series of models (Fig.39) to represent the "Executive" types (EFSW and EASW series) were designed. The FSW and the ASW (aspect ratio 8.75, taper ratio 0.4, aerofoil NACA 2415 at the centre-line and NACA 2410 at the wing tip) were of "equivalent" quarter chord sweep of 30°. The cambered aerofoil section was more tolerant for low Reynolds no. tests. Canard and tail arrangements could be configured. The FSW ($+3^{\circ}$ wash-in twist) was attached at mid-fuselage at $i_w = 0^{\circ}$. The ASW (-3° wash-out twist) was mounted at $i_w = +3^{\circ}$ low on the fuselage.

Both series of models were tested in the Bristol University 3.5 ft open-jet wind tunnel (speed: 110 ft/sec, Reynolds number: 0.2×10^6 based on wing geometric mean chord). In each series, the combinations were:-

F: FSW & Body (Wing with wash-in twist)
CF: Canard (low) + FSW & Body
FT: FSW & Body + Tailplane (high :above the Fin)
CFT: Canard (low) + FSW & Body + Tailplane (high) in a 3-suface concept
A: ASW & Body (wing with wash-out twist)
AT: ASW & Body + Tailplane (high: above the Fin)

Simple LE and TE devices were installed on a few combinations. Winglets (Tip-fins) were also tested. Due to geometry considerations: wing twist and wing root incidence, the effective LE sweepback of the winglets (measured from the fuselage axis) was up to 11° higher on the FSW than on the ASW configurations. The effects due to wing-fences were also assessed on F and CF combinations.

The experimental results mentioned here mainly focus on the "Executive" Series of models and lend support to the ideas discussed so far.

a. F, CF, FT, CFT combinations (EFSW Series)

Figure 40 illustrates the longitudinal characteristics on the EFSW series of models. The canard and the tailplane are both set at 0° incidence. The results are not trimmed and are based on gross wing area. The basic wing-body (F) shows the onset of non-linearity and hence flow separation, and increase in C_D at C_L above about 0.65. This is accompanied by pitch-up tendency; C_L however continues to increase through the α range.

Addition of the canard (CF) leads to an increase in C_L, forward shift of neutral point and a gentler "pitch-up". This suggests that the canard helps in relieving the FSW root separation.

The FT combination C_L curve essentially follows the wing-body (F) curve with the added contribution of the tailplane operating in the wing downwash flowfield. The neutral point moves aft.

The CFT combination C_L curve follows the CF curve. The tailplane in the CFT combination is in the downwash of both the canard and the wing. Thus the measured incremental lift coefficient ΔC_L due to canard and tail together is slightly less than the sum of the individual ΔC_L of the canard and the tailplane.

The exposed area of the canard is only about 52% that of the tailplane but the lift gain is greater for the canard for α above 15°.

Because of small-scale Reynolds number, it is appropriate to look at L/D and C_m for C_L up to about 0.7 prior to the onset of flow separation and non-linearities.

	C_L	Max L/D	Δ(L/D)	C_{m0}	x_{ac}	ΔC_{m0}	Δx_{ac}
F	0.52	20	0	-.015	.208c	0	0
CF	0.56	18.2	-9.9%	-.093	-.320c	-.078	-.527
FT	0.63	18.4	-8.0%	.220	.856c	+.235	+.648
CFT	0.58	17.0	-15.0%	.155	.281c	+.170	+.073

The canard and the tailplane, when used individually, cause 8 to 10% reduction in L/D but in combination together they cause only a 15% reduction. This preliminary look suggests detailed estimates of trimmed L/D with equivalent trimming volume ratios as well as achieving balanced trimming surface areas with respect to the C_{m0} of the combination.

The effect of canard deflection δ_C (-5°, 0°, +5°) is illustrated for the CF combination in Fig.41. As δ_C increases, the canard stall approaches at lower C_L. The pitch control power of the canard with $+\delta_C$ reduces with increasing C_L for the same reason. On the other hand, $-\delta_C$ control power remains essentially constant for C_L up to 0.8. As may be anticipated, placing a canard on a wing-body implies a penalty on L/D at low C_L below

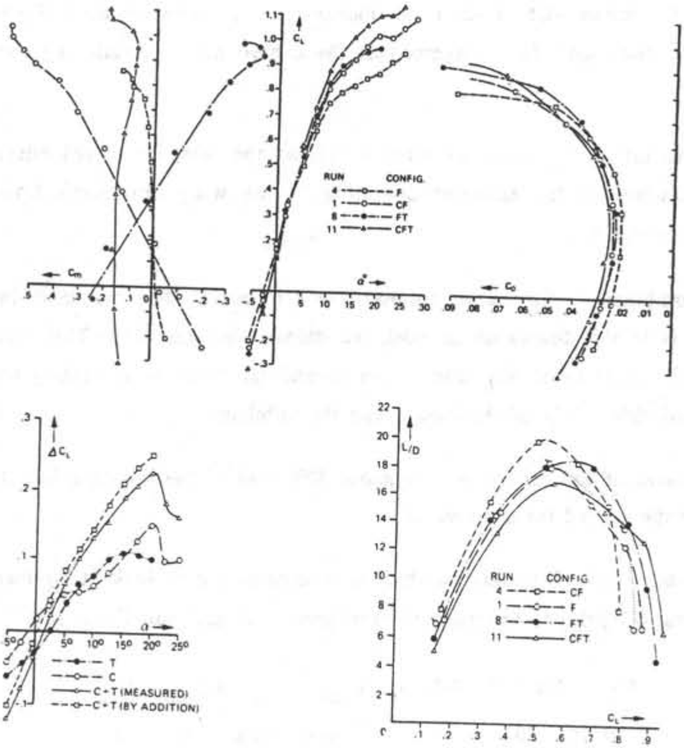


Fig.40. EFSW - F, CF, FT & CFT Combinations.

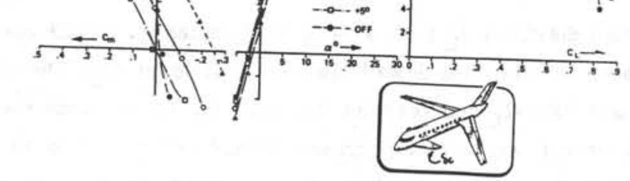


Fig.41. EFSW - CF, Canard Deflection.

about 0.7. At higher C_L, the L/D penalty disappears and there is a net gain. Negative δ_C improves L/D for C_L between 0.6 and 0.8.

Figure 42 shows the longitudinal data for a few values of δ_C and δ_T. Wing-body only (F) curves are also illustrated. All the C_m curves are nearly parrallel to the C_L axis up to C_L = 0.7. This implies that the balance point of the model coincides with the neutral point of the CFT combination. The canard control power is roughly half that of the tailplane. This corresponds with the effective trimming volume ratios. An assessment of δ_C and δ_T required for trimmed flight follows:

Lower C_L	δ_T	δ_C	Higher C_L	δ_T	δ_C
	0°	-5°		-4.5°	+5°
	+2°	0°		+5°	+6°

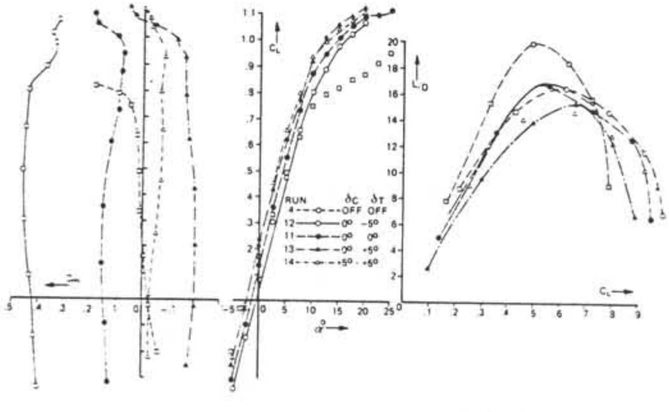


Fig.42. EFSW - CFT. δ_C & δ_T deflections.

Obviously many combinations are possible. The idea here is to optimise L/D without causing an adverse effect on the wing root flow. At cruise type C_L therefore a negative or small δ_C may provide a better L/D. At higher C_L the favourable effect of the canard on the wing root flow is needed and $+\delta_C$ will be accompanied by $+\delta_T$.

b. LE & TE Devices on CF

Figure 43 shows results of an "ad-hoc" approach to extend the C_L - α characteristics of the CF combination with simple extended chord LE and TE flaps. The flap deflections are not optimised for this exercise. The effect of the LE flap on the C_L and C_m characteristics is particularly significant and the linear part is maintained to C_L near 1.1. As expected, the flap incurrs a drag increase for low C_L below 0.8, but L/D is considerably improved at higher C_L. The TE flap gave an improvement of 0.53 to raise the C_{Lmax} to 1.62. The envelope of L/D curves can therefore be extended beyond a C_L of 0.92 obtained with the LE flap.

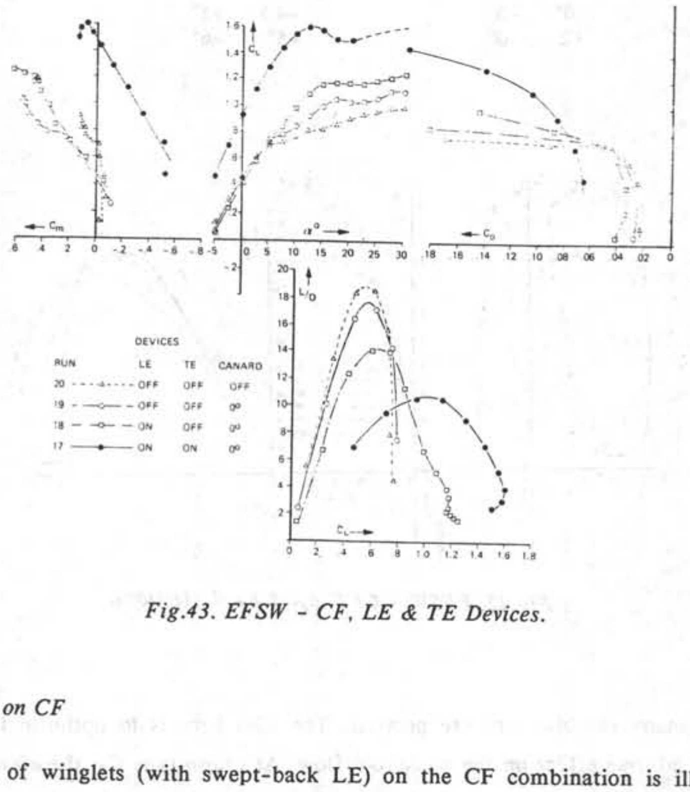


Fig.43. EFSW - CF, LE & TE Devices.

c. Winglets on CF

The effect of winglets (with swept-back LE) on the CF combination is illustrated in Fig.44. The main effects are: (i) to increase the peak L/D from 18 to 19.3, (ii) to increase the lift-curve slope because of increased wing-tip loading, and (iii) to move the neutral point aft (3%) with a slight increase in $-C_{m0}$ (from -0.20 to -0.22).

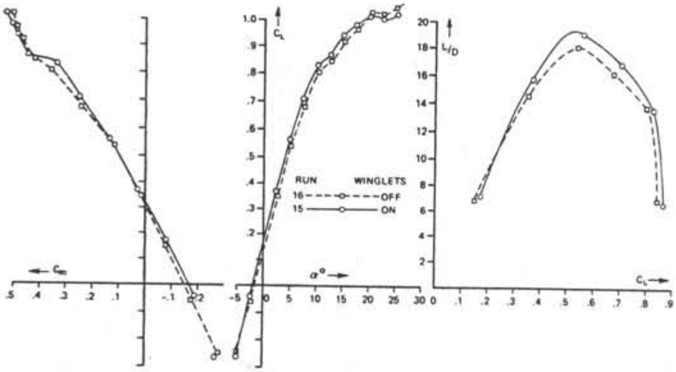


Fig.44. EFSW - CF, Winglets.

d. Wing Fences on F and CF

Figures 45 and 46 illustrate the effect of boundary layer wing fences located at y/s = 0.35 on two combinations F and CF. Percentage improvement in L/D for both combinations is shown in Fig.47. The beneficial effect due to the fences arises at higher C_L for the CF combination. The gains measured of the order of 8% in L/D are significant. To enable an effective control of the spanwise drift of the flow on the FSW, the height of the fence should be sufficient to cope with boundary layer thickness at high α. The design is therefore largely configuration and Reynolds number dependent.

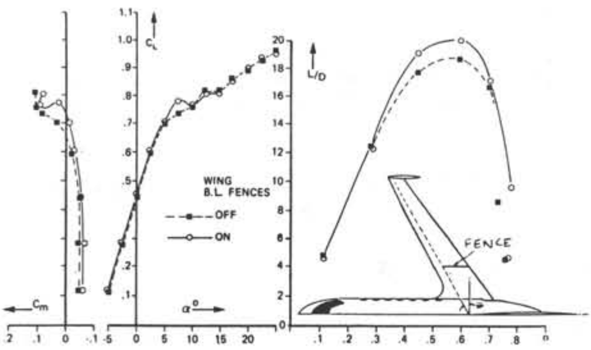


Fig.45. EFSW - F, Wing Fences.

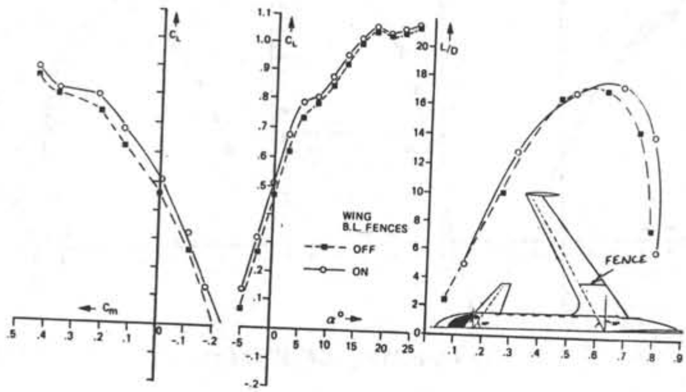


Fig.46. EFSW - CF, Wing Fences.

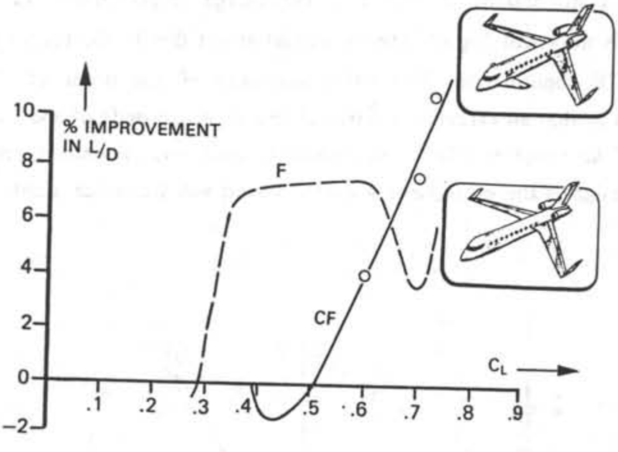


Fig.47. EFSW - F & CF, L/D improvement due to Wing Fences.

e. A and AT Combinations (EASW Series)

The effect of tailplane and its deflection δ_T (-5°, 0°, +5°) is depicted in Fig.48. C_L and C_m "breaks" from linearity occur near $C_L = 0.75$. C_{Lmax} occurs near $\alpha = 16°$ and this is followed by a sharp stall. Maximum L/D of 17.5 for the wing-body occurs at $C_L = 0.57$. With the tailplane, the maximum value of L/D depends on δ_T but it occurs near $C_L = 0.62$.

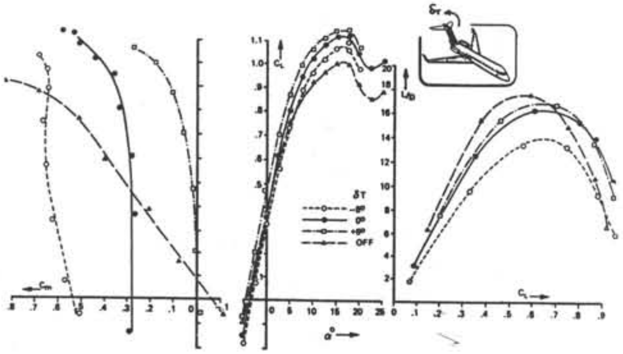


Fig.48. *EASW - AT, δ_T deflection.*

f. Winglets on AT

The effect of winglets (with swept-back LE) on the AT combination is shown in Fig.49. At low C_L the winglets produce a penalty in L/D. At higher α, a small improvement in lift leads to about 3% gain in L/D. The stalling α is earlier with the winglets on. For high C_L there is a penalty again as the winglets may encourage tip stall.

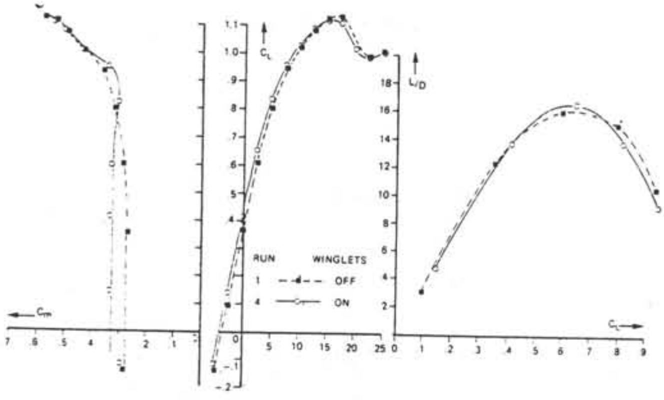


Fig.49. EASW - AT, Winglets.

g. Comparisons of CF and AT (Executive types)

The inclusion of winglets plays an important role in these comparisons. Figure 50 shows the effect on L/D. The FSW configuration offers substantial gains beyond C_L = 0.25, whilst the ASW configuration offers gains beyond C_L = 0.5. As mentioned earlier, due to geometry considerations, the effective LE sweepback of on the winglet on the FSW is higher by about 11°.

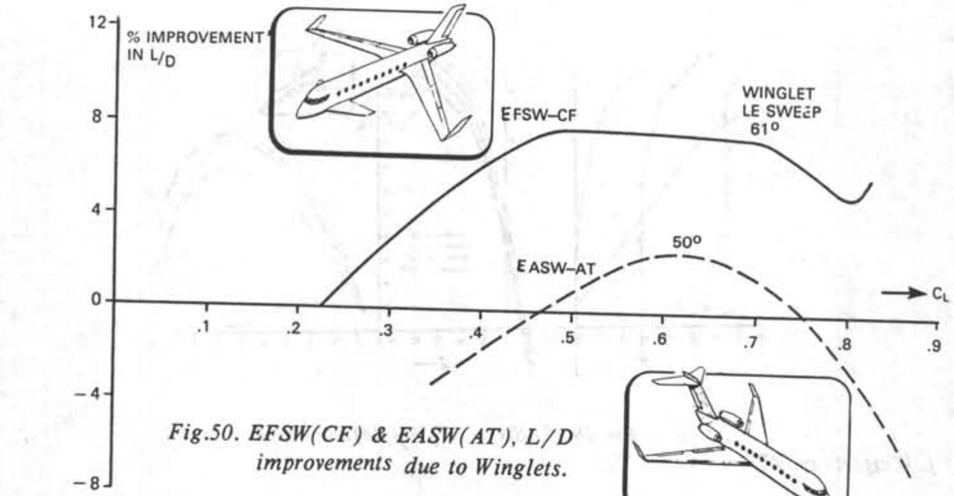
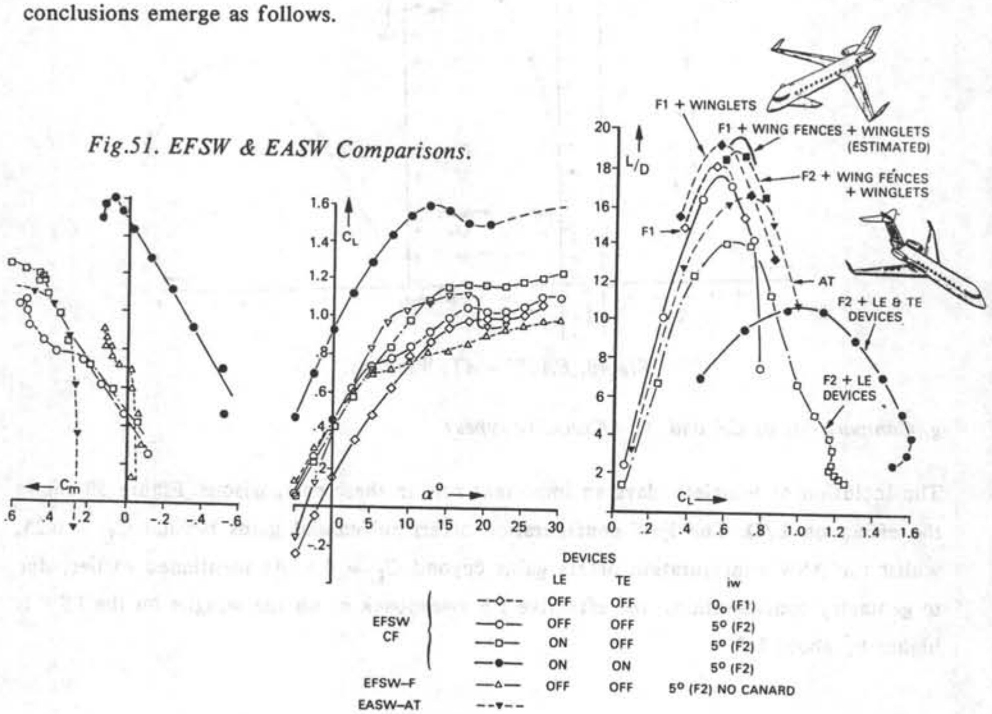


Fig.50. EFSW(CF) & EASW(AT). L/D improvements due to Winglets.

Fig.51 shows the longitudinal relationships. One AT combination is shown. The CF combinations include two variations of wing-root incidence: F1 refers to $i_W = 0°$ and F2 refers to $i_W = +5°$. F1 produces slightly higher peak L/D (by 2.8%) than F2. F2 produces larger lift at $\alpha = 0°$. Bearing in mind the reservations about the Reynolds no. and flow separation effects that become increasingly dominant above $C_L = 0.7$, significant conclusions emerge as follows.

Fig.51. EFSW & EASW Comparisons.



Compared with the F1 and F2 combinations, the AT combination has a higher lift curve slope. The Reynolds no. effects are possibly less severe on the AT than on the F1 and F2 combinations. The non-linearity on the AT C_L - α curve begins at about C_L of 0.9, whilst on the FSW it is nearer C_L of 0.7. The stall is sharper on the AT.

With a mid-semi-span LE flap, the non-linearity of the F2 can be delayed to about C_L = 1.1. Thereafter the behaviour is gentle up to C_L of 1.25. Further increases with an improved LE flap are feasible.

The following table list the peak values of L/D obtained.

	EASW (AT) $i_W = +3^\circ$		EFSW (CF) $i_W = 0^\circ$			$i_W = +5^\circ$		
	C_L	L/D	C_L	L/D	%L/D	C_L	L/D	%L/D
Basic	.65	16.3	.55	18.2	11.6	.56	17.7	8.6
Basic+Winglets	.65	16.3	.57	19.3	14.9	.58	18.7	11.3
Basic+Wing Fence			.60	18.5	13.4	.61	17.9	9.8
Basic+Wing Fence +Winglets			.66	19.5	19.6	.67	18.9	15.9

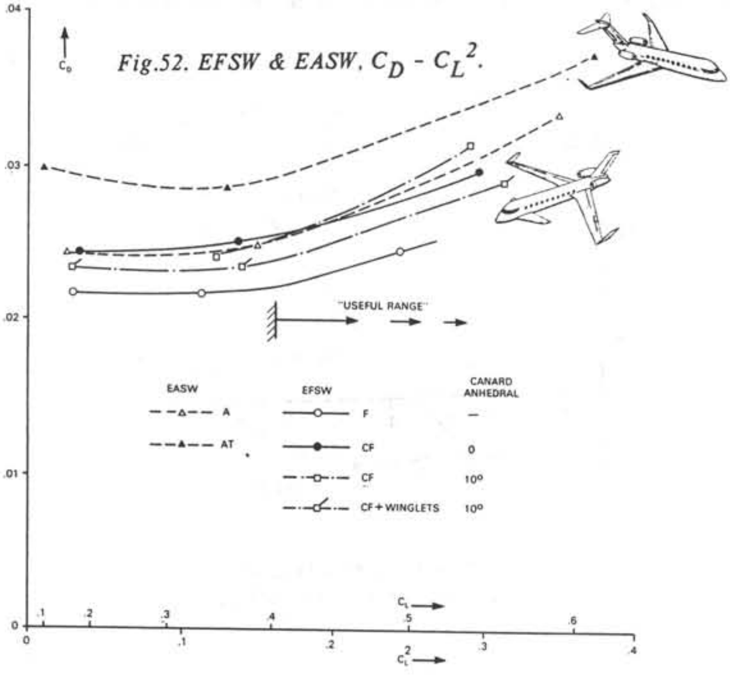


Fig.52. EFSW & EASW. C_D - C_L^2.

The basic CF combination offers about 11% improvement in L/D over the AT combination. The winglets on the F1 combination improve this figure to about 15%. Optimised winglets (lower sweep) hold promise of additional 5-10% improvement. The root stall on the FSW may be ameliorated with wing fences and up to 19% improvement in L/D has been measured.

The inferences for L/D may be supported by the C_D - $C_L{}^2$ relationships (Fig.52). The FSW designs produce smaller C_{D0} and also smaller slope and hence lower lift-induced drag. Winglets also reduce the slope. It must be stressed that more accuracy will be required in any future work as the drag polars are not symmetrical.

h. Comparisons of CF and AT (Transport types)

As in the "Executive" series, the inclusion of winglets is very significant in these comparisons. Figure 53 shows the effect on L/D. The FSW configuration offers substantial gains beyond C_L = 0.3, whilst the ASW configuration offers gains beyond C_L = 0.73. Due to geometry considerations, the effective LE sweepback of the winglet on the FSW is higher by about 10°. Figure 54 correlates the improvement in L/D against winglet LE sweepback for the FSW and ASW configurations of the "Transport" and "Executive" series. Reduction of LE sweepback of the winglet is beneficial.

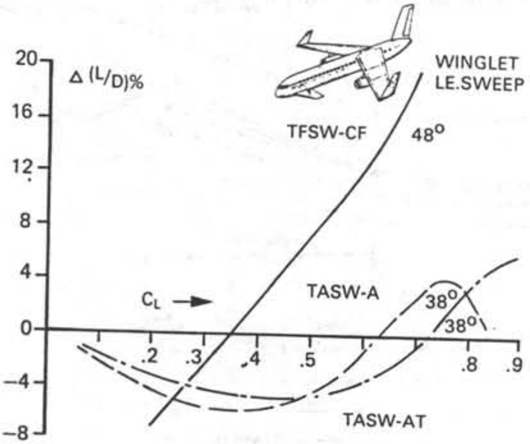


Fig.53. TFSW(CF) & TASW(A, AT), L/D improvements due to Winglets.

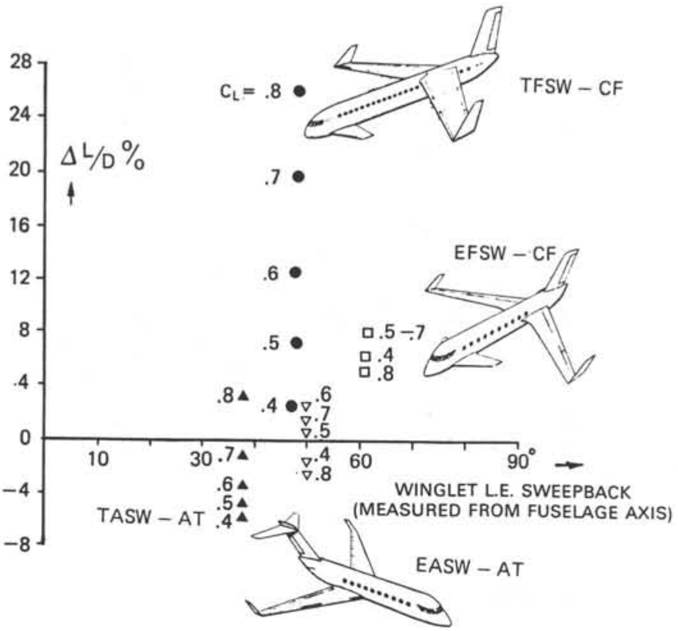


Fig.54. L/D improvement and Winglet LE Sweepback.

Figure 55 shows the longitudinal relationships. One AT combination is shown. The CF combination includes two variations: F1 with and F2 without wing-root fillets. The fillets lead to slight increase in lift but penalise the peak L/D. As indicated earlier, the Reynolds no. and flow separation effects become increasingly dominant above C_L = 0.7. Nevertheless significant inferences emerge as follows.

Compared with the F1 and F2 combinations, the AT combination has a higher lift curve slope. The Reynolds no. effects with regard to stall onset are possibly less severe on the AT than on the F1 and F2 combinations. Flow separation on the AT appears at the wing tip where the chord is smaller than that on the wing root. On the FSW, the stall generally begins in the wing root area. The non-linearity on the AT C_L - α curve begins at C_L of 0.8, whilst on the FSW it is nearer C_L of 0.65. The stall is sharper on the AT.

With a mid-semi-span LE flap, the non-linearity of the F1 can be delayed to about C_L = 0.8. Thereafter the behaviour is gentle up to C_L of 1.1. Further increases with an improved LE flap design are feasible.

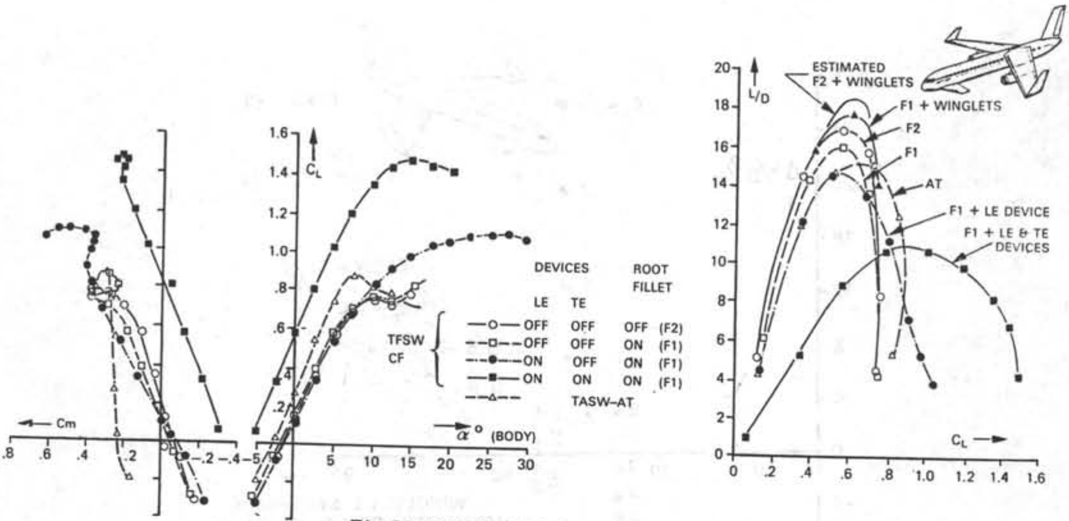


Fig.55. TFSW & TASW Comparisons.

The following table lists the peak values of L/D obtained.

Wing Root Fillets	TASW (AT) off		TFSW(CF) off			on		
	C_L	L/D	C_L	L/D	%L/D	C_L	L/D	%L/D
Basic	.68	15.1	.58	16.8	11.3	.58	15.9	5.2
Basic+Winglets	.69	15.1	.62	18.4	21.8	.62	17.5	15.9

The basic CF combination without wing-root fillets offers about 11% improvement in L/D over the AT combination. The winglets on the F1 combination lead to an extra 10% bringing the total improvement to 21%. The wing-root fillets on the CF give a penalty of 5% in L/D, indicating that an accurate design of wing-root junction is mandatory.

i. Further Work

Taking the two series of tests and plotting Δ(L/D) against wing sweep (25% chord-line, in this paper), a rather optimistic picture for FSW indicating upto 20% improvement in peak L/D emerges as shown in Fig.56. The results of Spacht for aspect ratios near 5 and work undertaken at BAe (Ref.21) for aspect ratio 4 support the trend. Obviously there are many oppurtunities for ringing the changes in these overall comparisons. The tests have made a strong case for work on FSW aircraft at higher subsonic/transonic speeds at realistic Reynolds numbers. Directional and lateral stability tests have been indicated. FSW may be optimised with several means e.g. by exploiting the reduced wing-root bending moment, LE flaps, ensuring extensive natural laminar boundary layer, winglets and 3-surface layouts.

Figure 57 (from Ref.52) depicts the principle of adapting high aspect ratio FSW in multi-body fuel-efficient aircraft concepts.

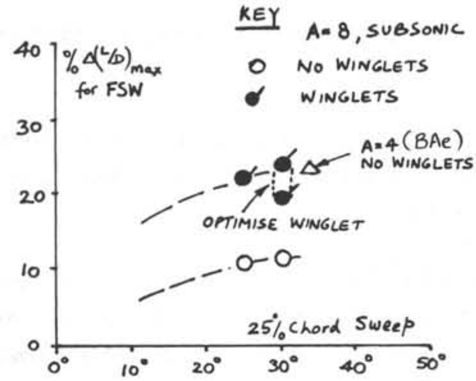


Fig.56. FSW L/D improvement vs Sweep.

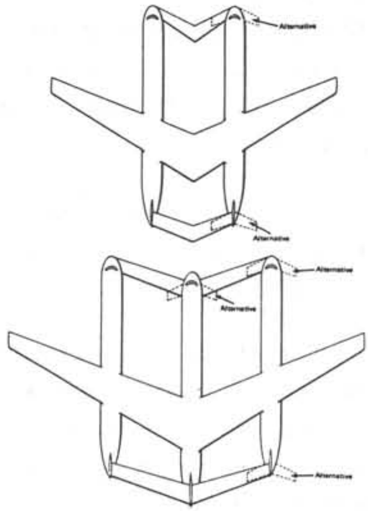


Fig.57. Multi-Fuselage Concepts.

9. CONCLUDING REMARKS

Some of the benefits of using FSW on aircraft, eg. reduced lift-induced-drag, improved high angle of attack performance and better "useful-volume-integrated" and compact layout, have been appreciated for the past four decades. The lack of adequate structural technology in the past, to cope with the FSW aero-elastic divergence problem prevented any serious exploitation of these benefits. Advances in composite material structures, active controls, and improved knowledge of the favourable aerodynamic interferences (e.g. canard inclusion) have paved the way towards re-consideration of the FSW concepts. The Grumman X-29A currently undergoing flight trials represents the most recent practical realisation of a FSW which has been "integrated" with several emerging technologies. The FSW concept is now being explored on military and civil/transport aircraft.

This paper has attempted:

(i) to give an idea of the scope of FSW designs that range from combat types to transport types and hybrid tilt rotor concepts. The emphasis is on high aspect ratio.

(ii) to discuss briefly the design requirements and evaluation criteria for a new project to enter service. A formula given relates the payload shuttling capacity of an aircraft directly to the aerodynamic term (M.L/D) and specific fuel consumption terms. It is mentioned that a reduction in DOC of some 20 - 30% is required to justify entry of a totally new aircraft. Only half that DOC improvement is necessary to introduce a derivative.

(iii) to highlight some of the features of FSW that render it attractive for possible incorporation in civil, business or transport type aircraft. Canards and Winglets provide favourable effects that may be exploited by FSW.

(iv) to review comparative FSW and ASW experimental investigations undertaken by the author on two series of high aspect ratio configurations representing the high wing "Transport" and "Executive" types. Bearing in mind the reservations about low Reynolds number of the tests, the FSW configurations indicated up to 15 - 20% advantages in L/D over the ASW configurations (exact value depended on the presence of winglets, wing-fences etc.). Winglets appeared to be 3 - 4 times more effective on FSW than on ASW (in lift and L/D terms). LE flaps on the FSW were very effective in delaying the FSW root flow separation.

(v) to propose areas for future work on FSW configurations at higher subsonic/transonic speeds at realistic Reynolds numbers. Directional and lateral stability tests have been indicated. FSW optimisation may be attempted by several means e.g. by exploiting the reduced wing-root bending moment, LE flaps, ensuring extensive natural laminar boundary layer, winglets and 3-surface layouts. Multi-fuselage fuel-efficient concepts may also be projected.

ACKNOWLEDGEMENTS

The author considers himself fortunate to have participated in the FSW research over the past few years. It is noted with pleasure that the comparative nature of the FSW studies

has meant more than a "cursory glance" or an excursion into understanding the "conventional" ASW technology. In particular, the comparative wing studies have offered the author an opportunity and a reason to delve into the past and current literature in some detail. This has helped him considerably in widening his horizons on topics such as: development of LE suction, lift and drag distributions and vortex flows. Amongst many persons consulted, the author wishes to thank Prof. Lewis Crabtree (University of Bristol) and Mr. Clifford Bore (British Aerospace, Kingston) for their helpful, stimulating, timely advice and suggestions. Any opinions expressed are author's own.

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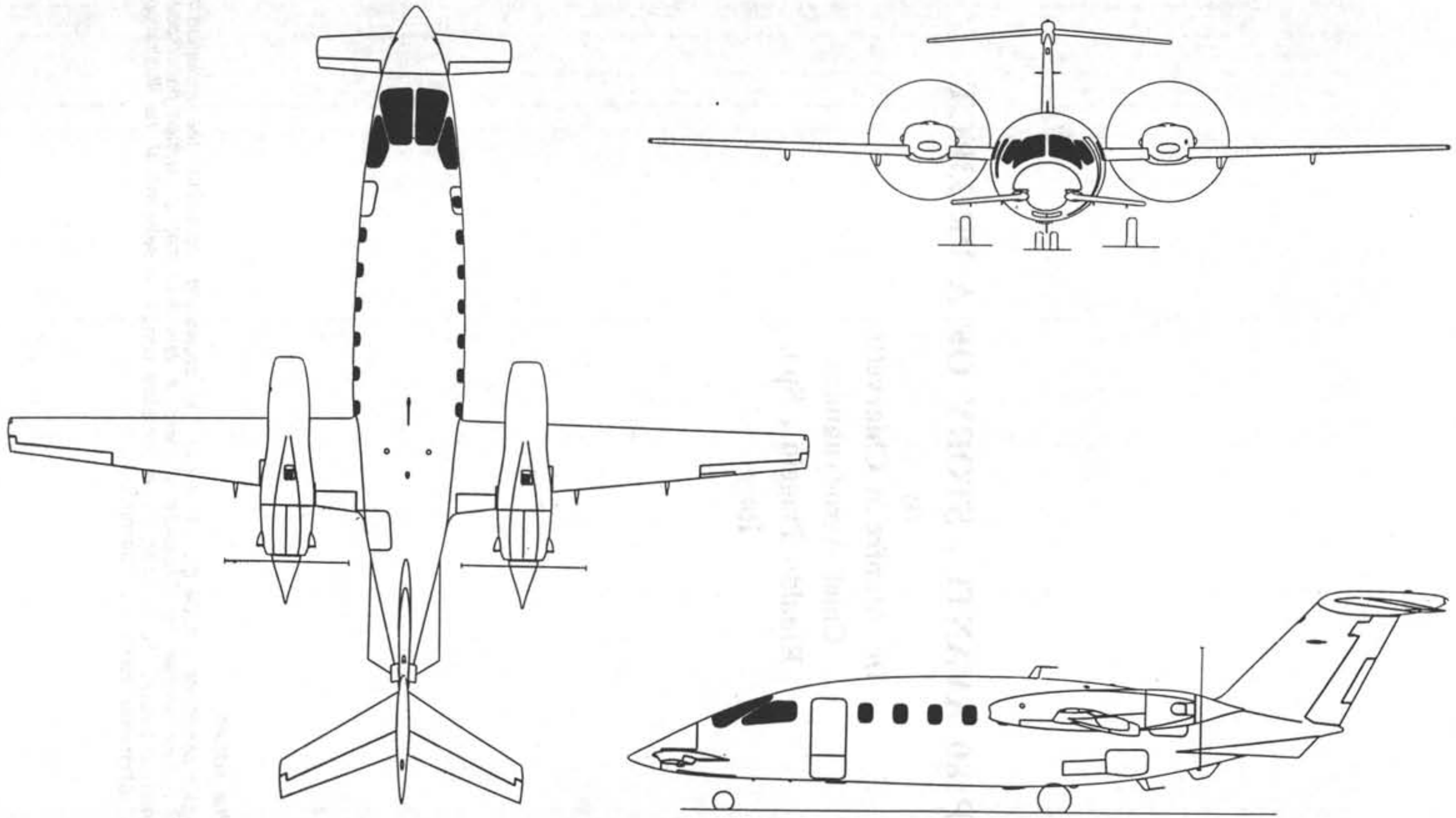
P180 AVANTI , STORY OF A PROJECT

by

Dr. Manfredo Chiarvetto
Chief Aerodynamics
Rinaldo Piaggio , Spa.
Italy

Note from the editors .

Due to certain conditions outside the control of the organizing committee the invitation to present this lecture reached mr. Chiarvetto at such a late date that a written paper could not be handed in timely. The following pages therefore contain a selection of the illustrations used by mr. Chiarvetto during his presentation .



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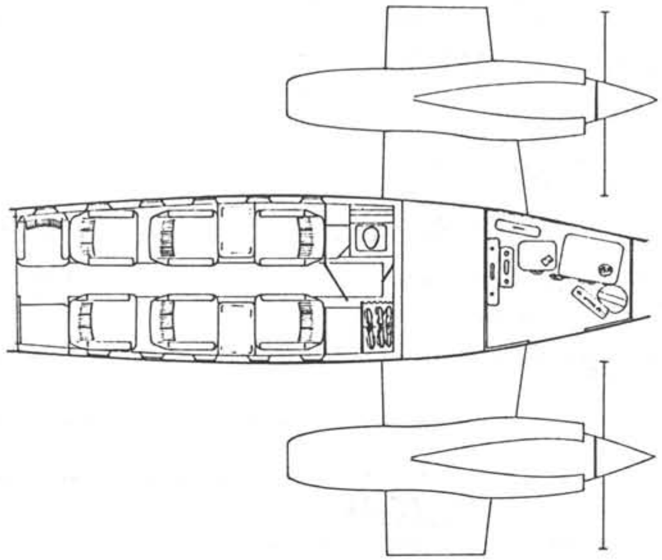
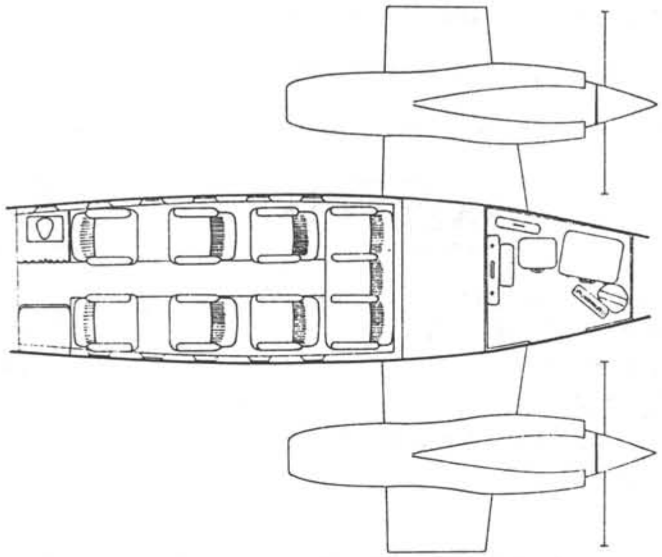


EXECUTIVE LAYOUT



PASSENGER LAYOUT

SPECIFICATIONS

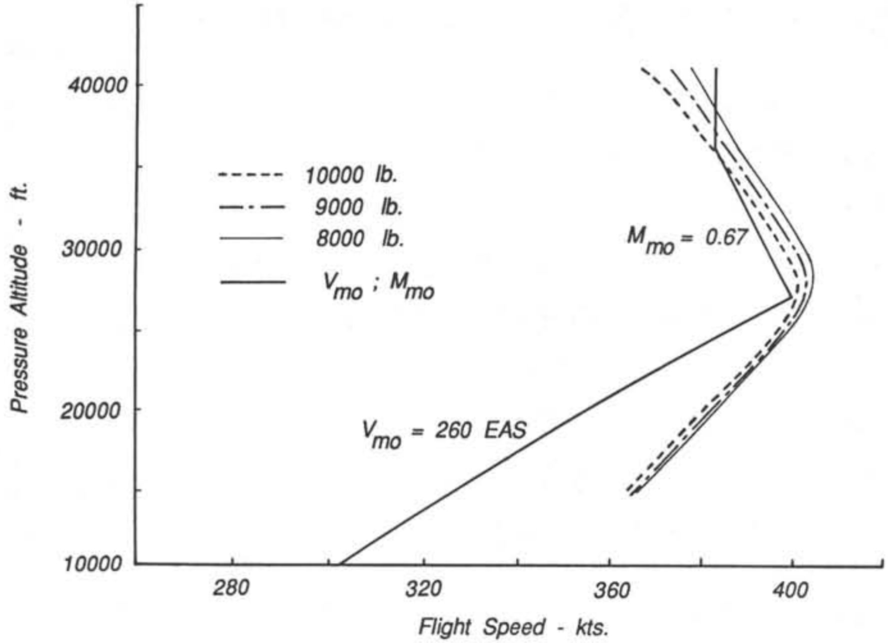
* 6 TO 9 PASSENGERS + 2 PILOTS	
* MAXIMUM SPEED	400 kts.
* FUEL CONSUMPTION	1 lb./n.m.
* MAXIMUM CRUISE ALTITUDE	41000 ft.
* IFR RANGE AT 400 kts. (2 PILOTS + 4 PASS.)	1000 n.m.
* PRESSURIZATION	9 psi.

WEIGHTS

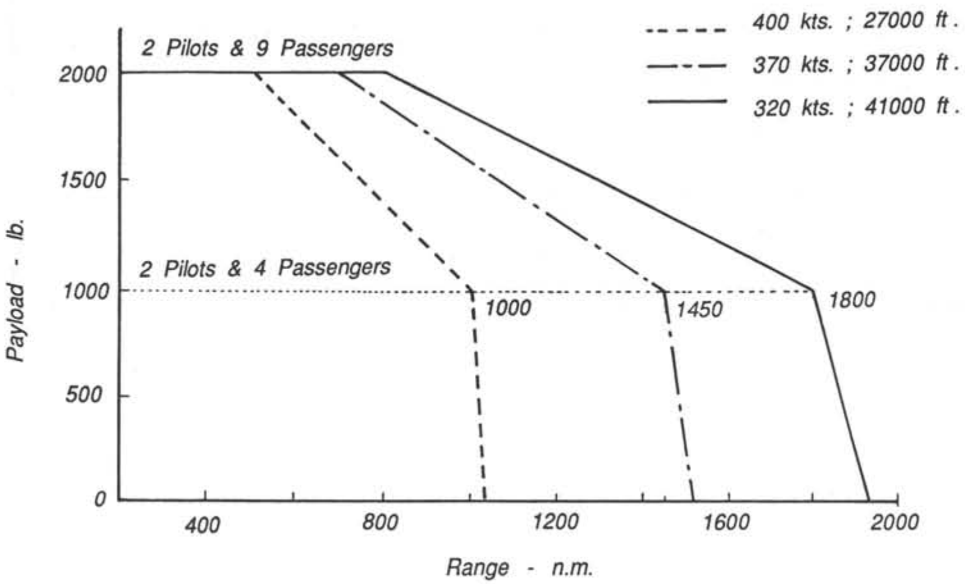
* OPERATIONAL EMPTY WEIGHT	6900 lb.
* MAXIMUM USABLE FUEL	2700 lb.
* MAXIMUM PAYLOAD	2000 lb.
* PAYLOAD WITH MAXIMUM FUEL	1000 lb.
* MAXIMUM TAKE-OFF WEIGHT	10510 lb.
* MAXIMUM LANDING WEIGHT	9985 lb.

POWERPLANT

* TWIN TURBOPROP	P&W PT6A-66
- MAXIMUM POWER	1600 shp.
- FLAT RATED AT	800 shp.
* PROPELLERS	
- FIVE BLADE COUNTER-ROTATING	
- FEATHER	
- REVERSE	



MAXIMUM SPEED CRUISE



IFR RANGE / PAYLOAD

RESEARCH AND DEVELOPMENT

* *FIRST CONFIGURATION STUDY*	*1979*
* *FIRST WIND TUNNEL TEST*	*1979*
* *WING SECTION TEST*	*1980 - 1981*
* *TRANSONIC WIND TUNNEL TEST*	*1982 - 1984*
* *COMPLETE FINITE ELEMENT MODEL*	*1982*
* *WIND TUNNEL FLUTTER TEST*	*1983*
* *DEVELOPMENT GO AHEAD*	*1983*
* *STRUCTURAL TESTING*	*1982 - 1986*
* *COMPOSITE DESIGN AND DEVELOPMENT*	*1983 - 1986*
* *FIRST FLIGHT*	*20 AUGUSTUS 1986*

TECHNOLOGY

- *THREE LIFTING SURFACE CONFIGURATION*
- *ADVANCED AERODYNAMICS*
- *TURBOPROPS*
- *PUSHER PROPELLERS*
- *ADVANCED COMPOSITES*

WHY THREE LIFTING SURFACES ?

* *CANARD + WING CONFIGURATION IS POTENTIALLY MORE EFFICIENT THAN WING + TAIL CONFIGURATION*

* *THE CANARD + WING CONFIGURATION HAS ITS LIMITATIONS*
  - *STABILITY AND CONTROL REQUIREMENTS REDUCE THE EFFECTIVENESS OF HIGH-LIFT DEVICES ON THE WING*
  - *A LARGER WING AREA IS REQUIRED FOR THE DESIGN STALL SPEED*
  - *THE EFFICIENCY OF THE CONFIGURATION IS REDUCED*

* *CANARD + WING CAN HAVE AN EFFICIENCY IMPROVEMENT*
  - *AN ARTIFICIAL STABILITY AUGMENTOR SYSTEM*

  OR

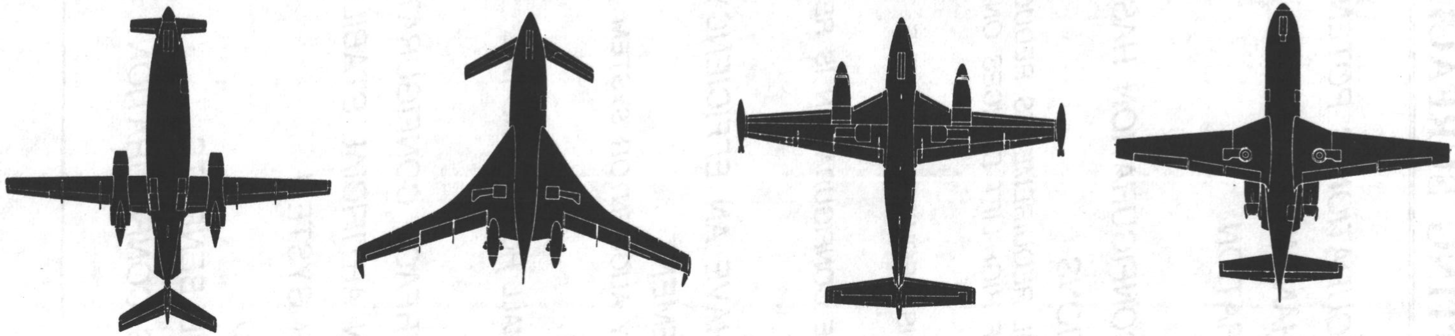
  - *THE ADDITION OF A SMALL HORIZONTAL TAIL*

* *THE THREE LIFTING SURFACE CONFIGURATION DOES NOT REQUIRE AN ARTIFICIAL STABILITY AUGMENTOR SYSTEM*

  AND

  MAINTAINS THE BENEFITS OF CANARD + WING CONFIGURATION

DIFFERENT CONFIGURATIONS COMPARISON



AVANTI | STARSHIP | CHEYENNE IV | CITATION SII

	TOTAL AREA sq.ft.	STALL SPEED kts.	MAX. SPEED kts.	POWER
CHEYENNE IV	*355*	*89*	*348*	*2 * 1000 shp.*
STARSHIP	*345*	*79*	*352*	*2 * 1000 shp.*
AVANTI	*226*	*82*	*400*	*2 * 800 shp.*
CITATION SII	*412*	*81*	*402*	*2 * 2500 lb.*

AERODYNAMIC DESIGN

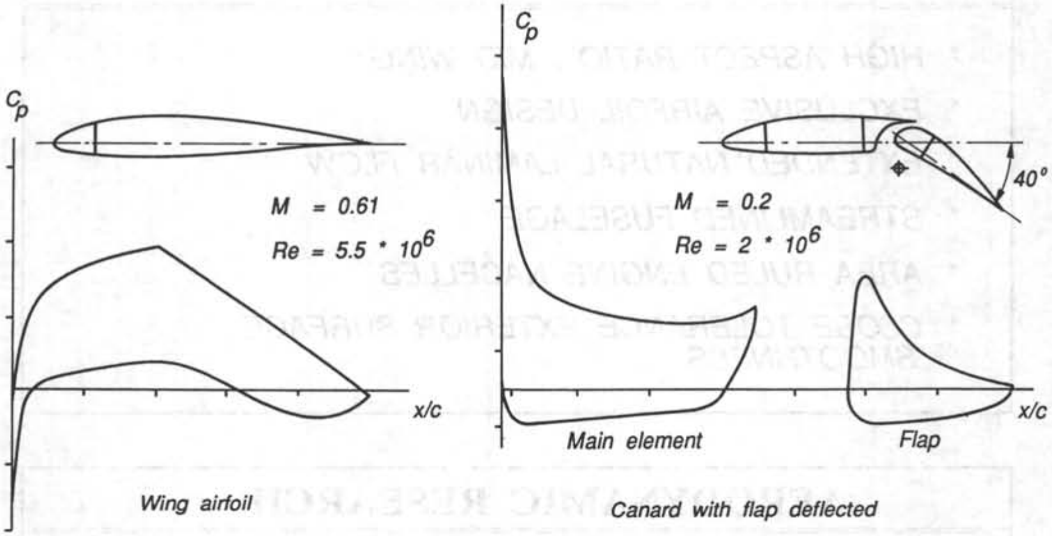
* *HIGH ASPECT RATIO , MID WING*
* *EXCLUSIVE AIRFOIL DESIGN*
* *EXTENDED NATURAL LAMINAR FLOW*
* *STREAMLINED FUSELAGE*
* *AREA RULED ENGINE NACELLES*
* *CLOSE TOLERANCE EXTERIOR SURFACE SMOOTHNESS*

AERODYNAMIC RESEARCH

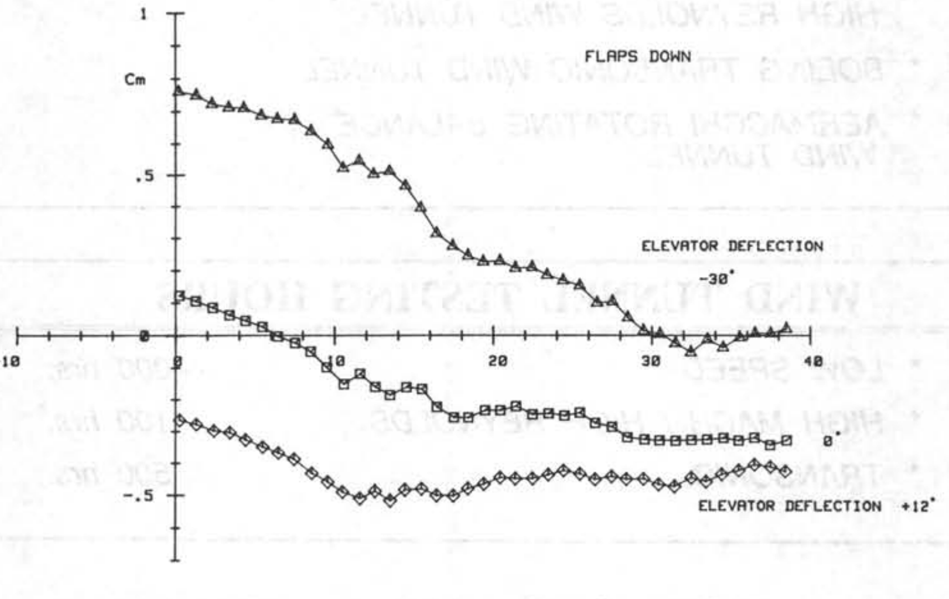
* *COMPUTATIONAL AERODYNAMICS*
* *PIAGGIO LOW SPEED WIND TUNNEL*
* *WICHITA STATE UNIVERSITY (WSU) LOW SPEED WIND TUNNEL*
* *OHIO STATE UNIVERSITY (OSU) HIGH REYNOLDS WIND TUNNEL*
* *BOEING TRANSONIC WIND TUNNEL*
* *AERMACCHI ROTATING BALANCE WIND TUNNEL*

WIND TUNNEL TESTING HOURS

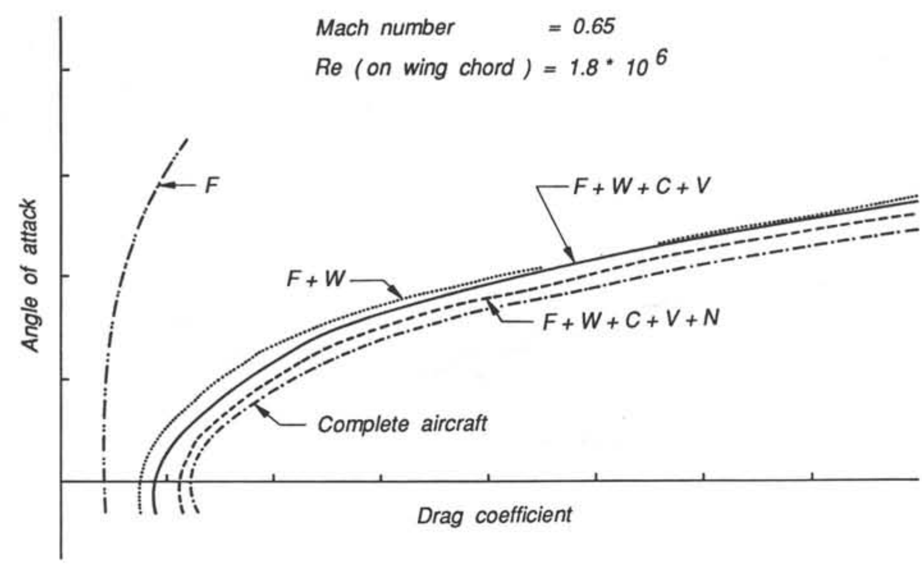
* *LOW SPEED*	*4000 hrs.*
* *HIGH MACH / HIGH REYNOLDS*	*100 hrs.*
* *TRANSONIC*	*500 hrs.*



TYPICAL PRESSURE DISTRIBUTION

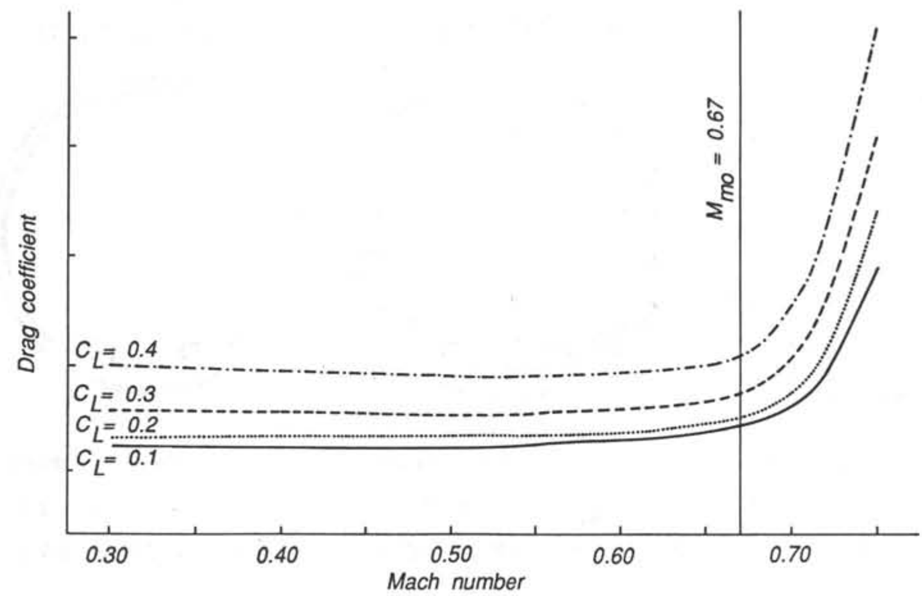


DEEP STALL INVESTIGATION



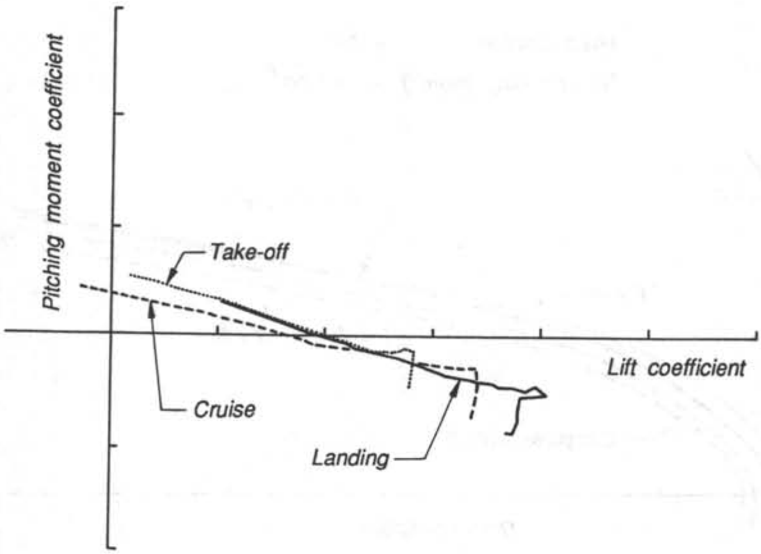
BTWT MODEL DRAG BUILD-UP

DATA ELABORATED FROM BOEING TRANSONIC WIND TUNNEL TEST (BTWT)



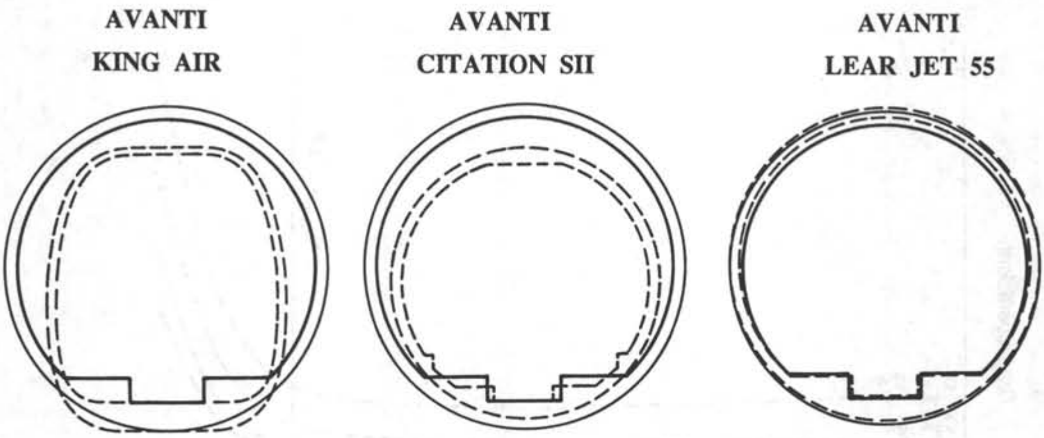
MACH DRAG RISE

DATA ELABORATED FROM BOEING TRANSONIC WIND TUNNEL TEST (BTWT)



EFFECT OF FLAP DEPLOYMENT ON TRIM

DATA ELABORATED FROM BOEING TRANSONIC WIND TUNNEL TEST (BTWT)



	Height	*Width*		*Height*	*Width*		*Height*	*Width*
AVANTI	*5.74 ft.*	*5.9 ft.*	*AVANTI*	*5.74 ft.*	*5.9 ft.*	*AVANTI*	*5.74 ft.*	*5.9 ft.*
KING AIR	*4.80 ft.*	*4.5 ft.*	*CITATION SII*	*4.80 ft.*	*4.9 ft.*	*LEARJET 55*	*5.74 ft.*	*5.9 ft.*

COMPARISON

STRUCTURAL RESEARCH

* *FINITE ELEMENT MODELS*
* *COMPONENT CYCLING TESTS*
* *FLUTTER MODEL 1 : 5 SCALE*
* *FLUTTER WIND TUNNEL TESTS*

STRUCTURAL TESTS

* *FULL SCALE LIMIT LOAD TESTS*
  - *SUCCESSFULLY COMPLETED*
* *COMPOSITE COMPONENTS ULTIMATE LOAD TESTS*
  - *SUCCESSFULLY COMPLETED*

GROUND VIBRATION TEST

* *TESTS COMPLETED ON PROTO 1*
* *PROTOTYPES CLEARED FOR FULL EXPANSION OF FLIGHT ENVELOPE*

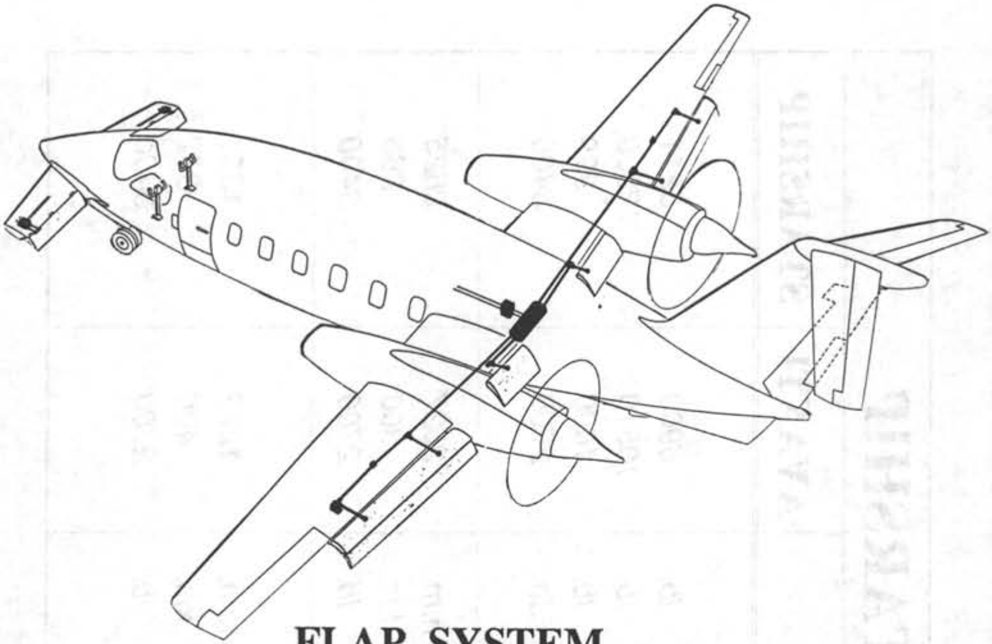
COMPARISON

		①	②	③	④	⑤	⑥
MAXIMUM TAKE-OFF WEIGHT	lb.	10510	12050	14000	15100	15780	22000
CABIN PRESSURIZATION	psi.	9	7.5	6.5	8.8	9.1	9.7
WING LOADING	lb/sq.ft.	61	41.1	46.2	44.1	65.4	70.5
MAXIMUM CRUISE SPEED	kts.	400	348	316	402	447	465
SPECIFIC RANGE	n.m./lb.	0.5	0.41	0.4	0.34	0.37	0.34
LONG RANGE CRUISE SPEED	kts.	300	298	300	322	388	415
SPECIFIC RANGE	n.m./lb.	0.92	0.63	0.49	0.48	0.47	0.42
VFR RANGE (FULL TANKS)	n.m.	2200	1447	1806	2308	1920	2557
SPECIFIC RANGE	n.m./lb.	0.9	0.58	0.54	0.44	0.42	0.37
IFR RANGE	n.m.	1800	1263	1573	1862	1560	2089
SPECIFIC RANGE	n.m./lb.	0.83	0.58	0.53	0.42	0.4	0.36
FLIGHT TIME							
IFR 300 n.m. MISSION	hrs.	0.85	0.97	1.08	0.88	0.75	0.73
IFR 600 n.m. MISSION	hrs.	1.68	1.90	2.08	1.65	1.42	1.38
IFR 1000 n.m. MISSION	hrs.	2.73	3.15	3.42	2.75	2.33	2.30

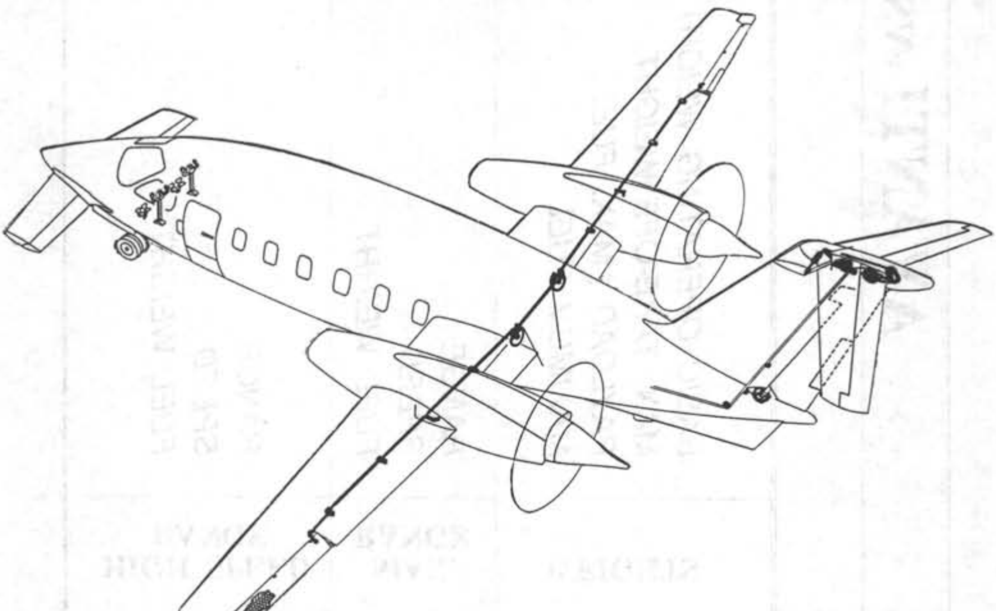
① : AVANTI
② : CHEYENNE IV
③ : SUPER KING AIR 300
④ : CITATION SII
⑤ : BEECHJET
⑥ : CITATION III

AVANTI vs. STARSHIP

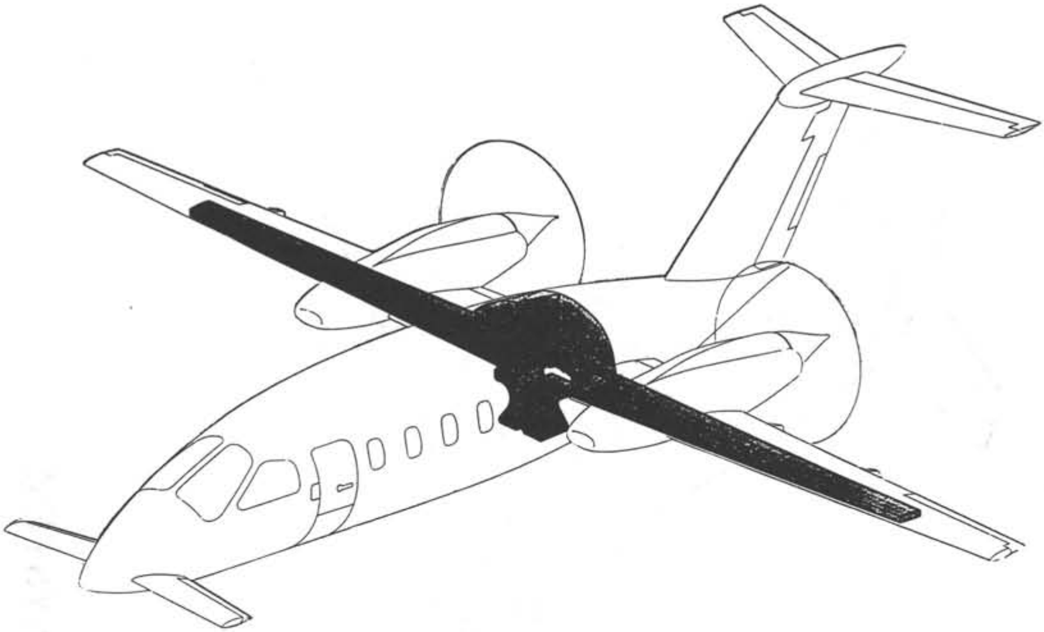
			AVANTI	STARSHIP
WEIGHTS	BASIC OPERATING WEIGHT	lb.	6900	8211
	MAX. TAKE-OFF WEIGHT	lb.	10510	12500
	PAYLOAD (MAX. FUEL)	lb.	1000	999
	MAXIMUM FUEL	lb.	2700	3400
MAX. RANGE	RANGE	n.m.	2527	2625
	SPEED	kts.	300	266
	FUEL WEIGHT	lb.	2700	3400
HIGH SPEED RANGE	RANGE	n.m.	1279	1361
	SPEED	kts.	400	352
	FUEL WEIGHT	lb.	2700	3400



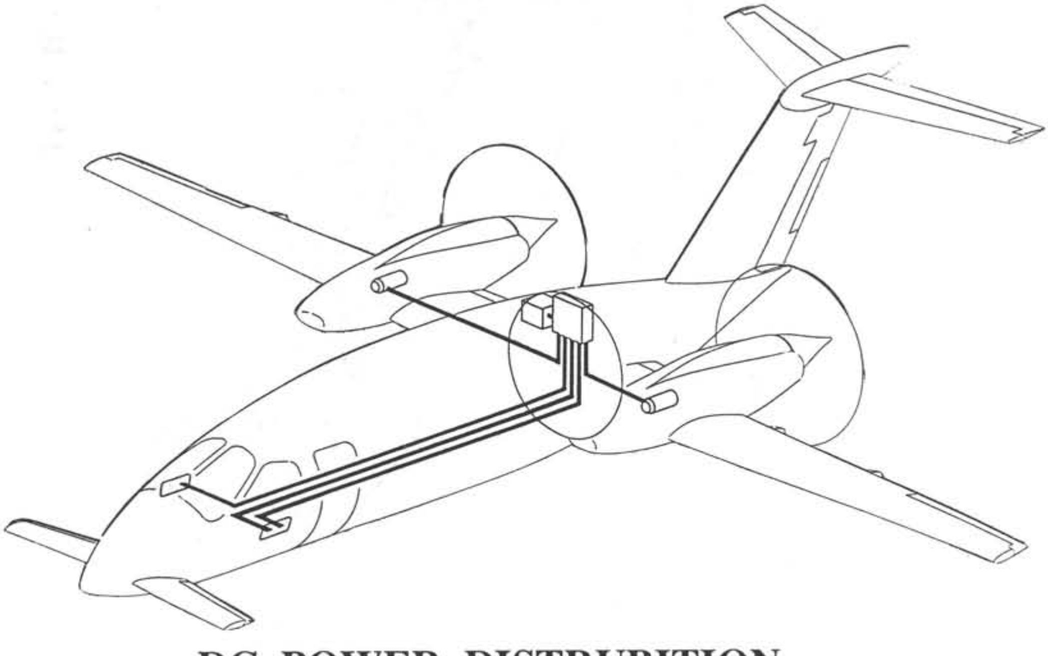
FLAP SYSTEM



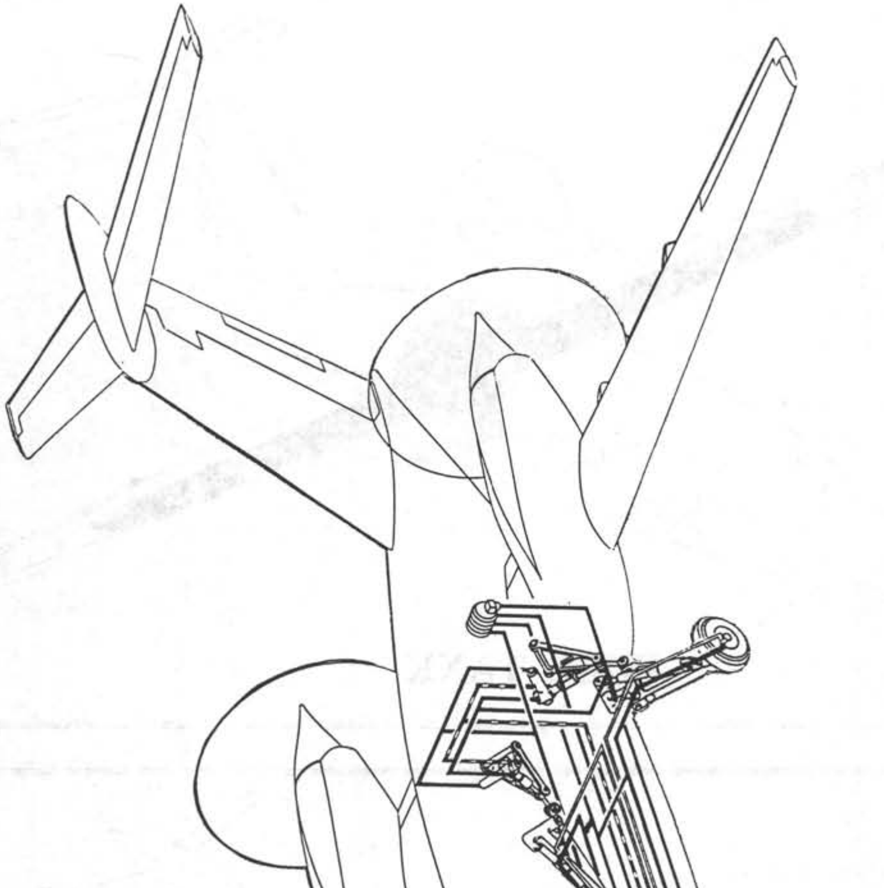
CONTROL SYSTEMS



FUEL TANK



DC POWER DISTRUBITION



HYDRAULIC SYSTEM

A SECOND LOOK AT THE JOINED WING

Julian Wolkovitch
Roland Montalbo

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Torrance, California 90505

ABSTRACT

The joined wing is a new aircraft configuration which employs tandem wings arranged to form diamond shapes in both plan view and front view. Previous papers have shown that the joined wing provides large weight savings plus aerodynamic advantages. The present paper describes further work on the concept, including new structural analysis methods, wind tunnel tests at high angles of attack, and analyses of lateral stability and control.

The test data show good stall characteristics for all the wind tunnel model configurations tested. These include an agricultural airplane, a research airplane, and a remotely piloted vehicle. Lateral stability and control characteristics are normal provided the fin area is adequate. Wave drag at Mach numbers between 1.0 and 2.0 is lower for joined wing than for conventional or canard configurations.

1. INTRODUCTION

An overview of the joined wing has been given by Wolkovitch (1985), who defines the joined wing as an arrangement of wings that form diamond shapes in both plan and front views, as in Figs. 1 and 2. Advantages claimed for the joined wing include light weight, high stiffness, low induced drag, good transonic area distribution, high trimmed maximum lift coefficient, reduced wetted area and parasite drag, direct lift and sideforce control capability, and good stability and control. The purpose of the present paper is to present new results on the joined wing

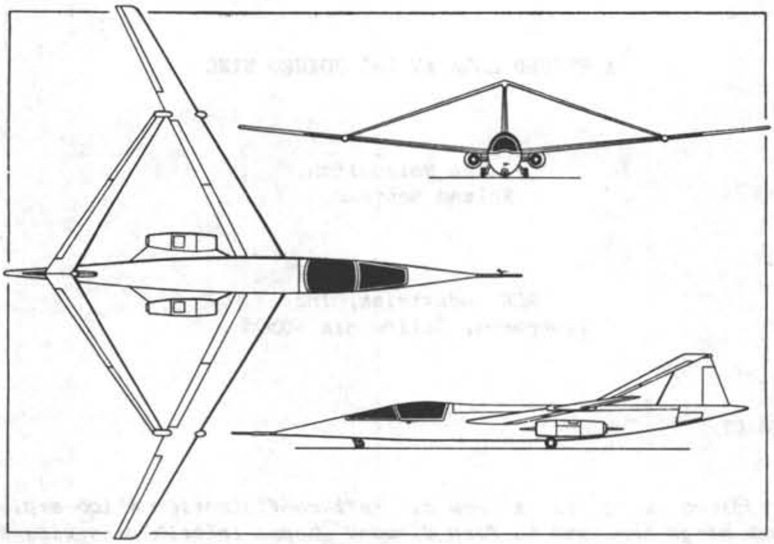


Fig. 1. ACA Industries JW-1 Research Airplane.

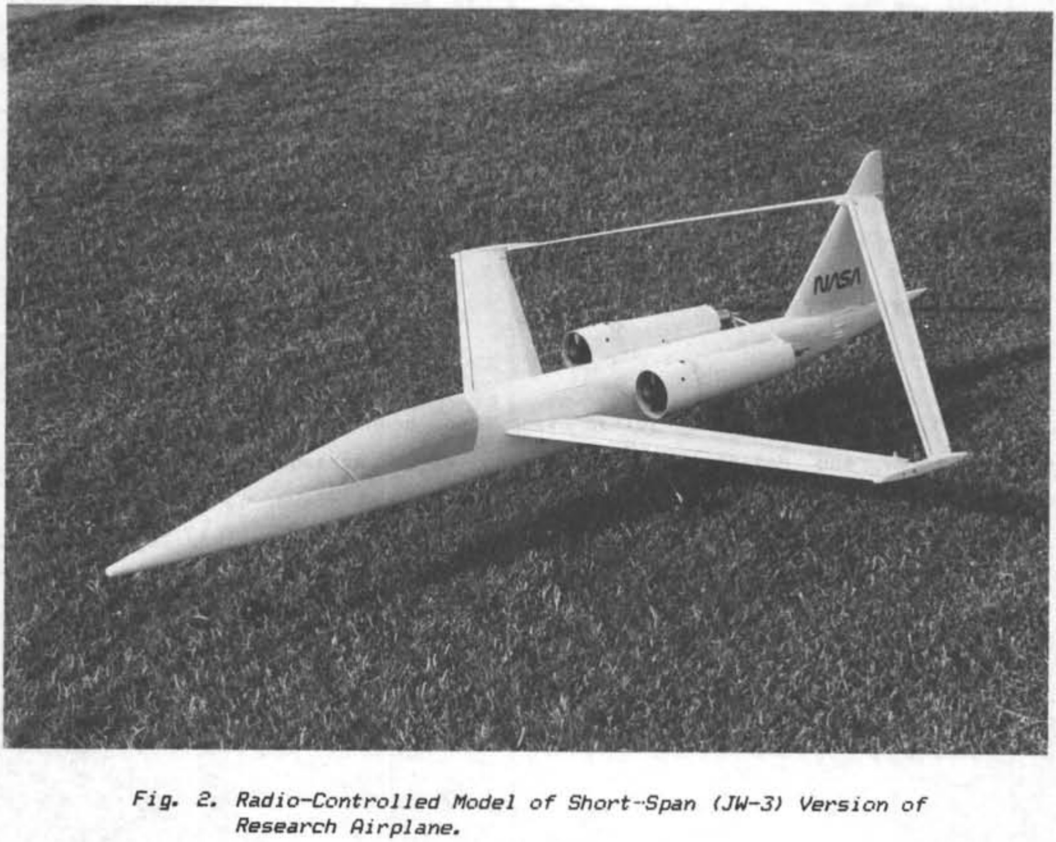


Fig. 2. Radio-Controlled Model of Short-Span (JW-3) Version of Research Airplane.

concept, plus some fresh perspectives on previous results. It is presumed that the reader is familiar with the overview paper cited above; hence only a brief summary will be given of previous work before presenting the new data.

The weight savings predicted for the joined wing are large, as shown by Figs. 3 and 4, which show the results of finite-element calculations made at NASA Ames Research Center by Miura and Shyu (1985). These Figures compare the weights of joined wings versus aerodynamically equivalent wing-plus-tail systems. Both systems have the same gross projected area (GPA), equal taper ratios, equal magnitudes of sweep angles (sweepback or sweepforward) and equal ratios of front to rear lifting surface areas. The total design airloads and the properties of the structural material (aluminum) were equal, and identical optimization techniques were employed to determine the minimum-weight structures. A streamwise thickness/chord ratio of 12% was employed for all lifting surfaces. The rear/front surface span ratio, B, and the overall aspect ratio, A (span squared/GPA) were as noted in Figs. 3 and 4.

For joined wings having the best taper ratio, sweep and dihedral, the weight savings predicted by Miura and Shyu equal 30% to 42% of the weight of the comparable wing-plus- tail system. The resulting performance gains are substantial. As shown by Wolkovitch (1985), for a 155- passenger propfan transport replacing 40% of the wing-plus- tail weight by additional fuel increases the range by 39.6%.

The prospect of performance gains of this magnitude has caused the joined wing to become a prime topic of aeronautical research. This has generated new results presented here, plus a second look at some of the earlier results, as described below.

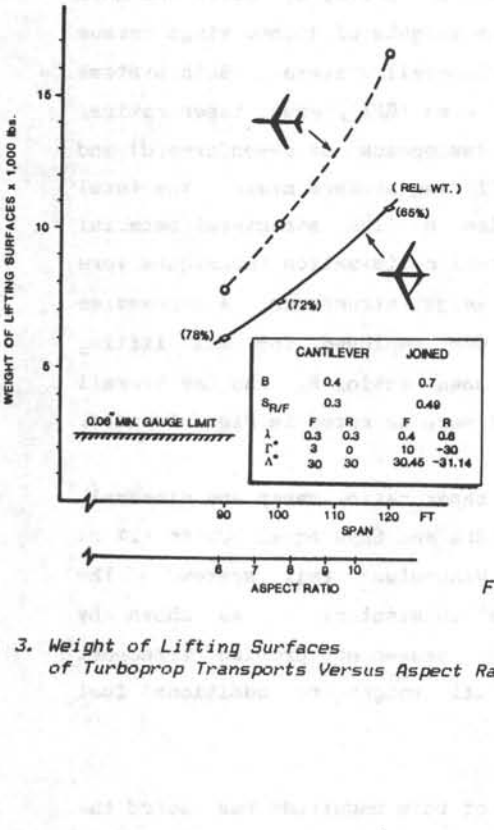


Fig. 3. Weight of Lifting Surfaces of Turboprop Transports Versus Aspect Ratio.

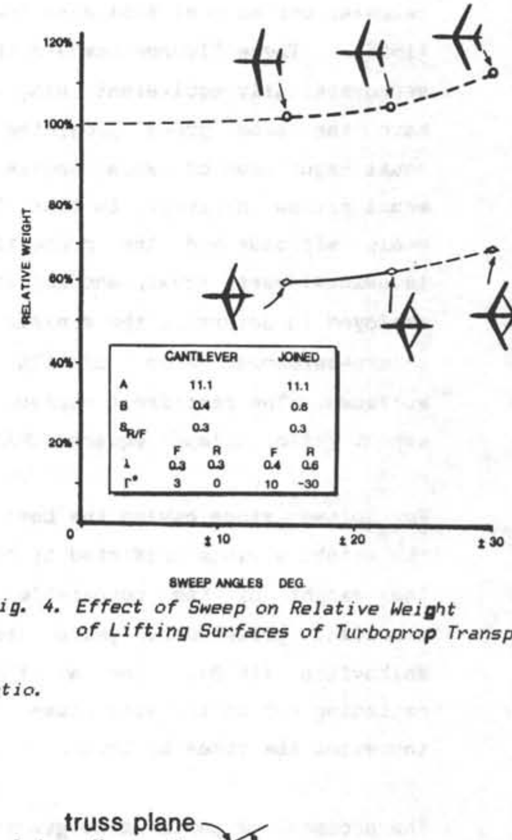


Fig. 4. Effect of Sweep on Relative Weight of Lifting Surfaces of Turboprop Transports.

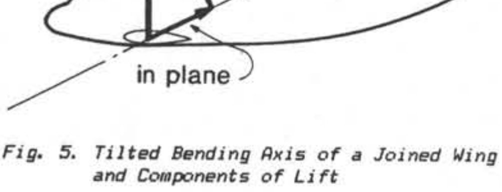


Fig. 5. Tilted Bending Axis of a Joined Wing and Components of Lift

2. EFFECT OF SPAN RATIO ON STRUCTURE WEIGHT

It has been shown in the references cited above that the greatest weight savings are obtained when the rear wing has 60% to 80% of the span of the front wing. Miura and Shyu (1985), and Samuels (1982) indicate that if the front and rear wings have equal spans (the "tip-jointed" configuration) the weight saving is not so large, perhaps less than 20%. This places the tip-jointed configuration at a disadvantage compared to the inboard-jointed configuration. However the tip-jointed configuration has some aerodynamic advantages over the inboard-jointed arrangement (such as higher span-efficiency factor and the capability to generate larger pitch control moments), so it is worth considering whether this disadvantage could be removed or reduced.

To approach this question it may be helpful to consider the structural rationale for the joined wing from a different viewpoint than the tilted-truss theory of Wolkovitch (1985). That theory regards the joined wing as a tilted truss structure as shown in Fig. 5. An alternative viewpoint (Miura and Shyu, 1985) explains the characteristics of minimum-weight joined wings by considering the spanwise variation of bending moments about untilted x and z axes, as shown in Fig. 6. This figure shows a typical bending moment versus span variation for a tip-jointed configuration (Miura and Shyu, 1985). The reversal in bending moment Mx (positive for positive lift) is due to the interaction between the rear wing and front wing. Positive moment on the front wing induces a compressive force on the rear wing, which in turn causes a reactive force from the rear wing, acting downward and forward. This effectively reduces Mx, causing it to reverse sign as shown in Fig. 6.

Figure 7 shows component and resultant moments at three spanwise stations. Near the wing root Mx is high and positive in sign; near the one-half span location Mx is zero; and near the joint Mx

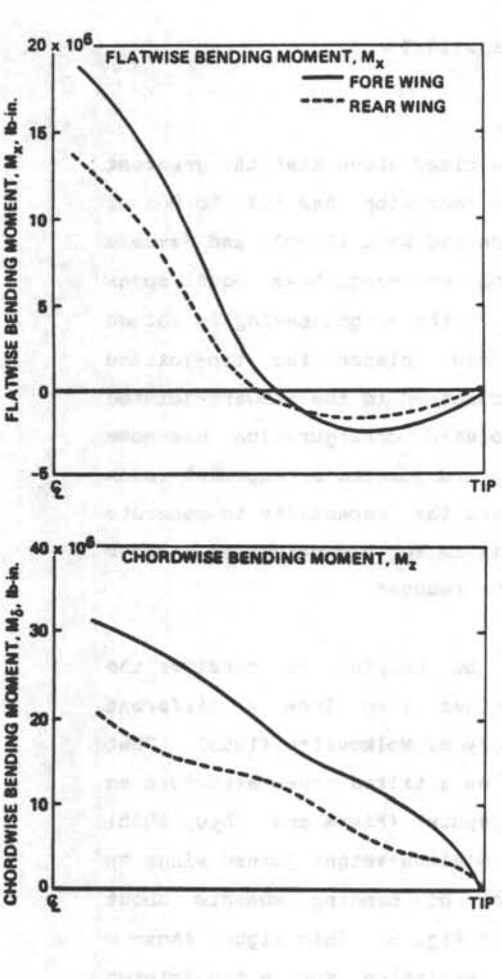


Fig. 6. Bending Moments Acting on a Tip-Jointed Joined Wing.

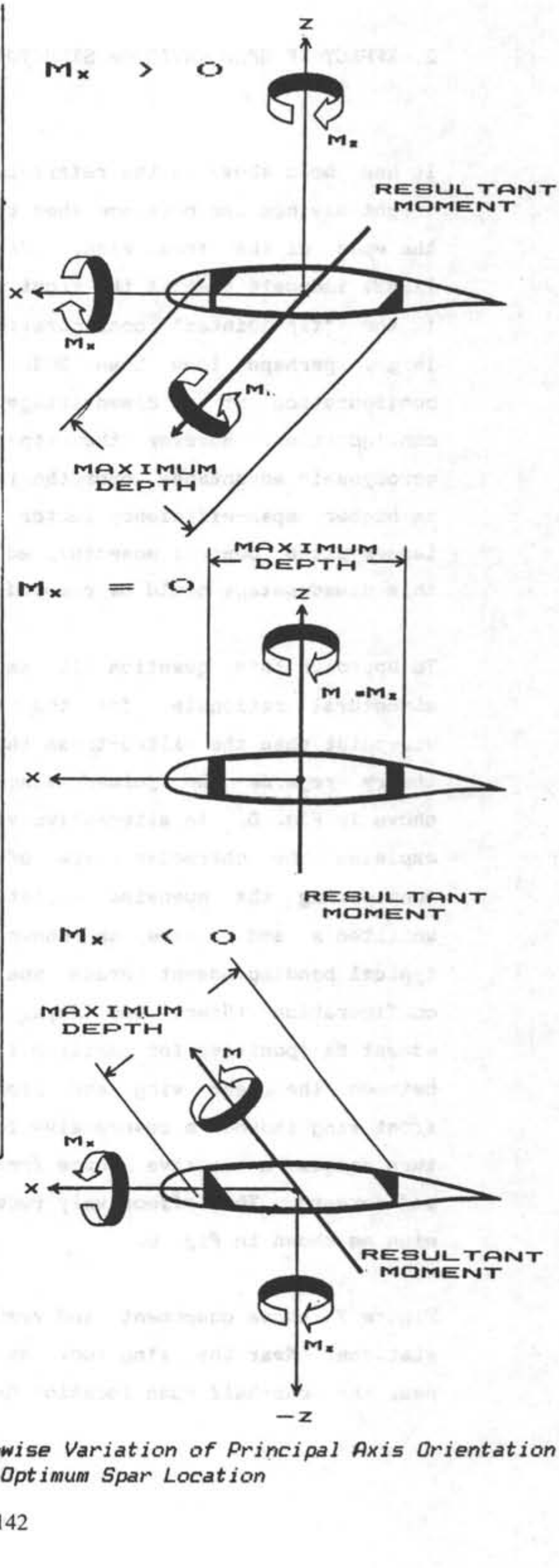


Fig. 7. Spanwise Variation of Principal Axis Orientation and Optimum Spar Location

becomes negative. The bending moment about the vertical axis, Mz, remains positive, i.e. at all spanwise stations the forward force from the rear wing bends the front wing forward. The resultant moment M is thus oriented as shown in Fig. 7. Figure 7 also shows the optimum locations for structural material, such that the specified locations provide maximum box-beam depth to best resist the resultant bending moments.

Figure 8 shows that the reversal in bending moment about the longitudinal axis seen in tip-jointed configurations is generally not exhibited by inboard-jointed designs. This is because of the lift on the outboard wing panel. Its resulting bending moment adds directly to that induced by the lift of the inboard panels, causing an upward shift in Mx. This keeps the total Mx positive at any spanwise station. As shown in Fig. 8, Mx is still much smaller than it would be if the wings were not joined.

Figure 7 shows that even in the outboard wing sections where the Mx bending moment is reversed the optimum distribution of structural material provides effective beam depth greater than the airfoil thickness. Nevertheless, minimum weight wings display high mass concentrations in these regions (Miura and Shyu, 1985; Samuels, 1982). This indicates that, regardless of sign, the magnitudes of the local bending moments are undesirably high. These bending moments might be reduced by modifying the geometry of the tip joint, or by changing the taper ratio of the rear wing independently of the front wing. If such geometric changes can reduce the bending moments in the outboard panels without increasing the inboard bending moments, the aerodynamically superior tip-jointed configuration might match the large weight savings provided by inboard-jointed configurations. This appears to be a rewarding area for research.

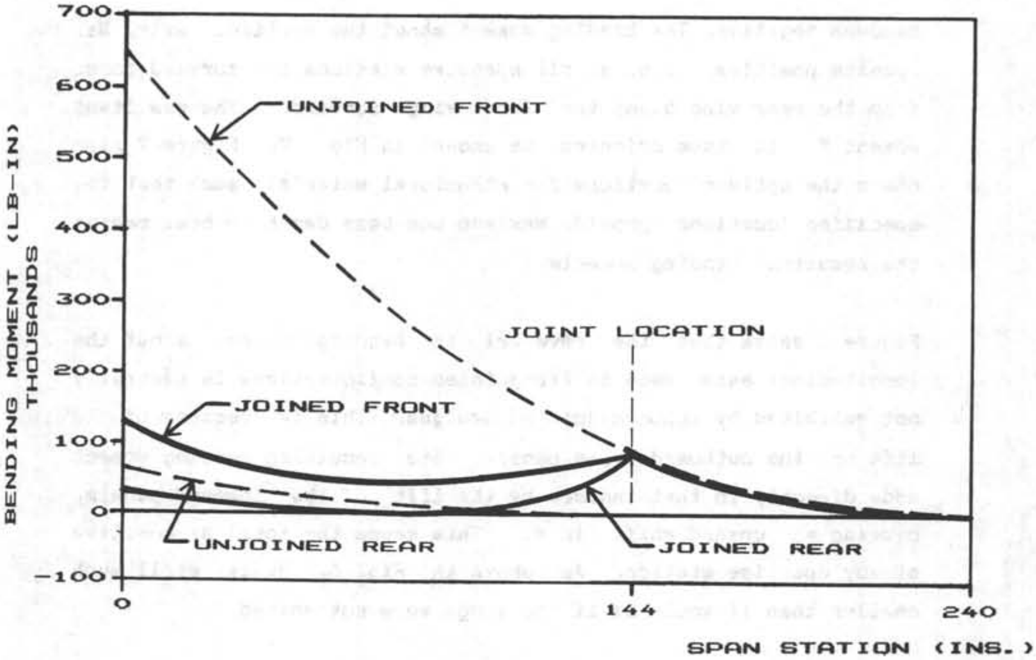


Fig. 8. Bending Moments acting on an Inboard-Jointed Joined Wing.

3. PRELIMINARY STRUCTURAL DESIGN OF JOINED WINGS

Standard finite-element programs, such as NASTRAN, can analyze a wide variety of structures. This versatility is gained at the cost of program complexity and lengthy inputs. For preliminary design of joined wings one would like to have a program that gives approximate answers but requires only a few numbers to be inputted. Steps in this direction have been taken by Hajela and Chen (1986) and Hollmann (1986).

Hollmann's model is shown in Fig. 9. The front wing is divided into 60 panels inboard of the joint. These panels extend from the leading edge to 80% chord. The rear wing is similarly divided, and the outer portion of the front wing, (which may be dihedralled to model a winglet), has 40 panels. Each spanwise station traverses 5 chordwise panels. This paneling is maintained for all joined-wing geometries, regardless of sweep, dihedral, or taper ratio.

The utility of this standardized model resides in the fact that by specifying only a few parameters, such as sweep, dihedral, and taper ratio, a structural model of the wing is rapidly constructed. The elements of this model are simple beams, one per panel. Appropriate boundary conditions link the beam-elements to provide a first-order approximation to the bending and torsional behavior of the wings.

Such a simplified model is clearly limited. For example, it does not model individual panel buckling, although it does provide a first iteration to the beam-column bending of the complete rear wing, (which is in compression for positive "g" loads). The torsional-flexural interactions between the front and rear wings are modeled, but it is assumed that the torsional axis is always at 40% of the chord. Another limitation of the Hollmann model is that the control surface chord is assumed to equal 20% of the

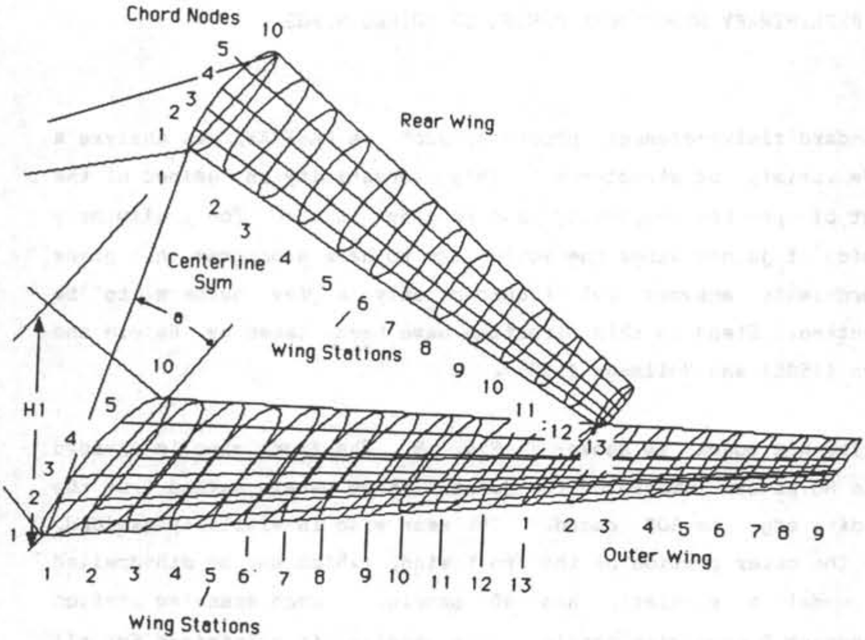


Fig. 9. Hollmann Structural Model.

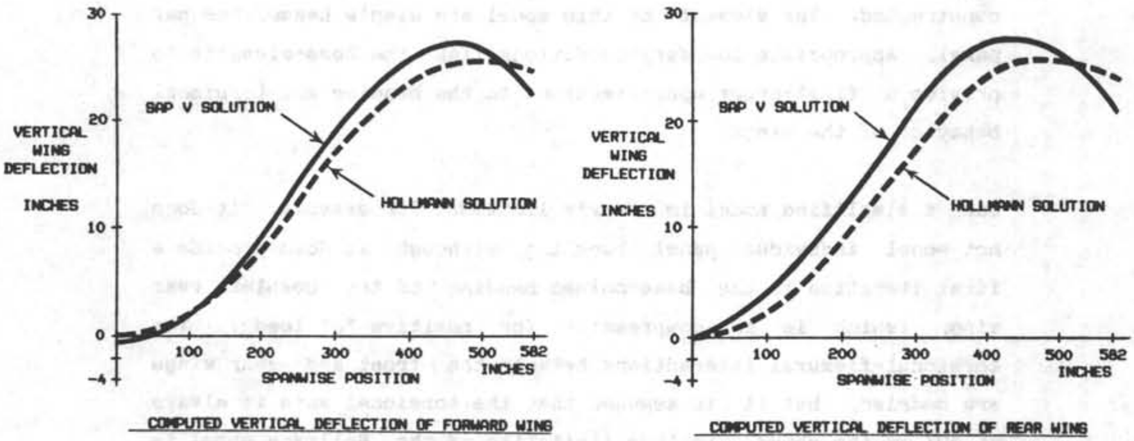


Fig. 10. Comparison of Results from Hollmann and SAP V Programs.

local wing chord. Despite these limitations, the Hollmann program has proved to be valuable for preliminary structural design of joined wings. Its results can set the stage for more sophisticated analyses using standard finite-element programs, by reducing the number of geometric variables that need to be investigated.

Figure 10 shows typical results of the Hollmann program, comparing its predictions with those of Samuels (1982) for a tip-jointed transport wing. The flexural deflections of the Hollmann program are in fair agreement with the deflections computed by the SAP V finite-element model employed by Samuels.

Hajela and Chen (1986) have used an even simpler model to study general trends of joined-wing structural behavior. Hajela's model represents the chordwise variation in skin thickness by four different thicknesses of material, two on the wing upper surface and two on the lower surface, each extending over half the chord at any given spanwise station.

The simplicity of the above models enables some generalized studies of joined wings to be performed without tedious computation, and further attempts in this direction should be encouraged, provided the results are calibrated against those of more sophisticated models.

4. DESIGN OF JOINED WINGS FOR LOW INDUCED DRAG

For inboard-jointed configurations the sum of the front and rear wing chords decreases abruptly at the spanwise location of the joint. Previous references (Wolkovitch, 1984, 1986) suggested that the front wing incidence should display a correspondingly abrupt increase in incidence at the joint to preserve the smooth span-loading required for minimum induced drag. A disadvantage of doing this is that at least one of the spars of the front wing must have a "step" at the joint location. However, as described below, recent wind-tunnel tests indicate that this incidence jump can be eliminated with little drag penalty.

NASA Ames Research Center have tested a 1/6-scale wind-tunnel model of the joined-wing research aircraft shown in Fig. 1. This aircraft employs the fuselage and landing gear of the existing AD-1 aircraft. The landing gear is short. Hence, to avoid tail bumping, the wings are set at high incidence angles. The front wing incidence is 7.5 degrees at the root, 5.5 degrees at the joint, and 2.1 degrees at the tip. The rear wing root incidence is 2.0 degrees, rising to 4.0 degrees at the tip. Linear variations are employed between these values, with no discontinuity in incidence at the joint. The test results (Smith, 1987) do not show any significant increases in drag due to this simplification of the model. The test data also show that the stall commences inboard of the joint, and that the ailerons remain effective through the stall. This suggests that it would be acceptable to droop the ailerons slightly (2 or 3 degrees) to obtain the minimum possible induced drag.

An alternative approach is exemplified by the long-endurance RPV shown in Fig. 11. A half-scale model of this configuration was tested as part of a U.S. Navy research program into low Reynolds Number vehicles (Foch, 1986), and a full-scale version is now under construction by ACA Industries, Inc., under U.S. Navy sponsorship. Here the decrease in total chord at the joint was minimized by adding elevons to the outer wing panels. The elevons comprised flat plates hinged to the slightly thickened trailing edge of the FX-63-137 front wing airfoil.

The configuration of Fig. 11 has the appearance of a strut-braced tailless aircraft, but achieves a higher span-efficiency factor and maximum lift coefficient than typical swept-back tailless aircraft, which download their wingtips for trim and positive Cmo

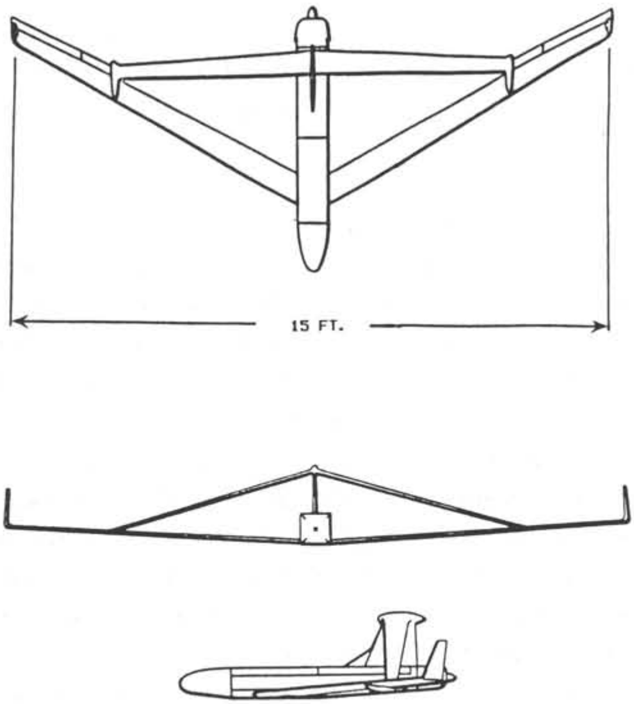


Fig. 11. ACA Industries "LAURA" Long Endurance Remotely Piloted Vehicle.

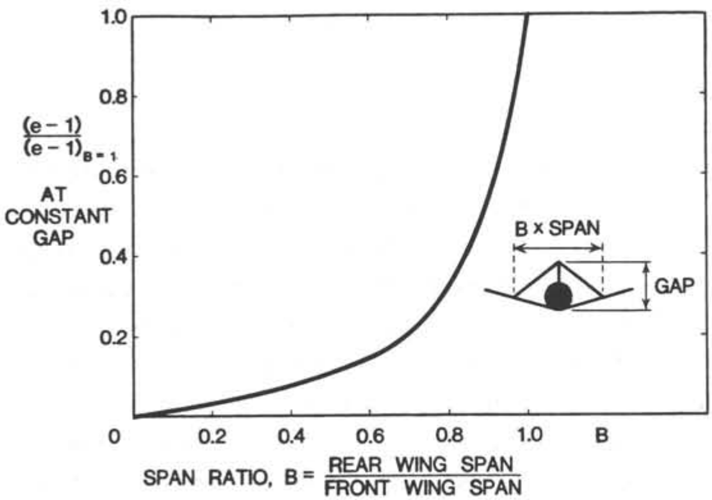


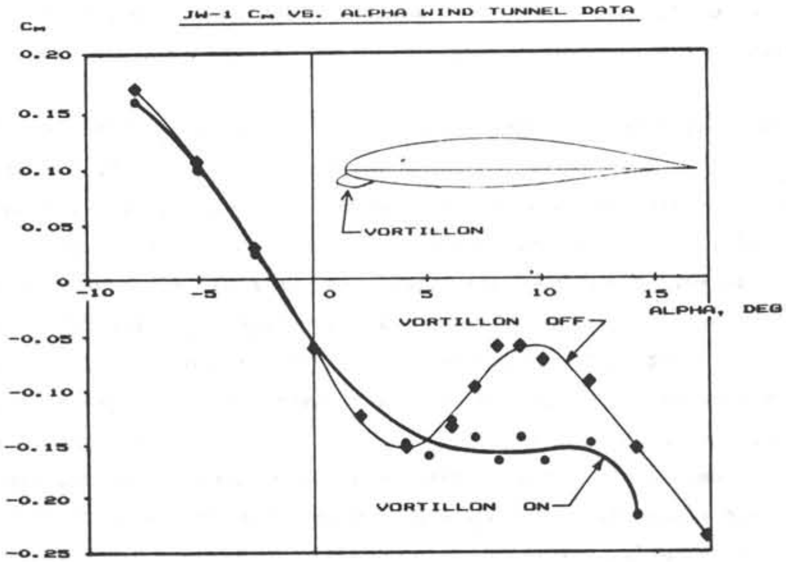
Fig. 12. Effect of Span Ratio on Span-Efficiency Factor.

(pitching moment at zero lift). This is because positive Cmo was obtained via rear wing incidence; the elevons maintained positive lift, thus ensuring a smooth span-loading of the total front plus rear wing lift.

For any given Trefftz-plane configuration an "ideal" span-efficiency factor can be computed which corresponds to optimally loaded lifting surfaces. Such optimal loading may not be attained due to practical trim considerations, but the ideal span-efficiency factor is still of interest as a Figure of Merit for the induced drag characteristics of alternative configurations. Letcher (1972) computed the ideal span-efficiency factors of diamond-shaped Trefftz-plane configurations; these apply to tip-jointed joined wings. Wolkovitch (1986) has extended these calculations to tip-jointed joined wings with winglets. Ideal span-efficiency factors for inboard-jointed wings have not been published previously, and are given in Figure 12. This Figure shows that the ideal span-efficiency factor decreases rapidly if the joint is moved inboard, although it is always higher than that of a planar wing.

5. LONGITUDINAL STABILITY

The JW-1 wind-tunnel model and its shorter-span variants all displayed linear variations of pitching moment with angle of attack below the stall. (Note that stall occurs at approximately 6 degrees angle of attack because of the high wing incidence necessitated by the short landing gear). Figure 13 shows typical lift and pitching moment variations with angle of attack (Smith, 1987). The Reynolds Number was approximately 900,000 based on the mean geometric chord of the gross front wing area, which was the reference area for coefficients. (The reference length was front wing mean aerodynamic chord). Small vortillons on the front wing



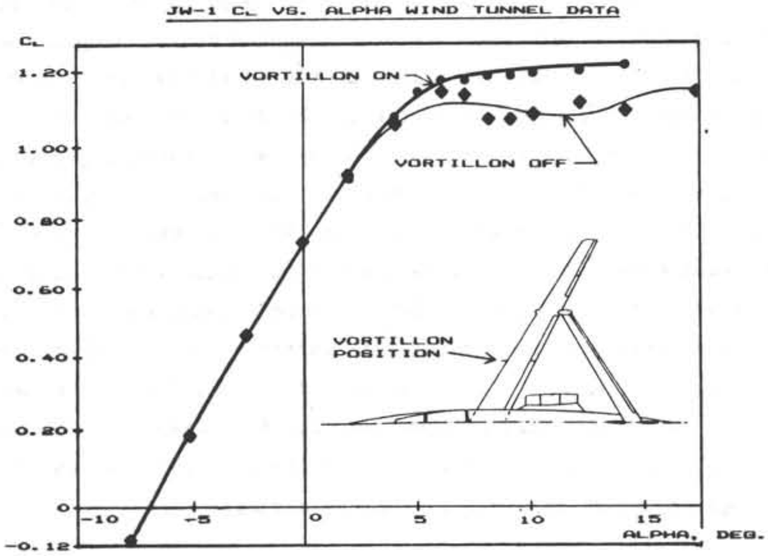


Fig. 13. Lift and Pitching Moment Coefficients for a 1/6-Scale Wind-Tunnel Model of the JW-1 Airplane.

smoothed out the pitching moment break at the stall, with no measurable extra cruise drag.

Vortillons were also beneficial for the RPV configuration of Fig. 11. The full-scale design flight condition for this vehicle involves very low speed cruise, such that the rear wing chord Reynolds Number is only approximately 130,000. Wind tunnel tests at this Reynolds Number indicated that the rear wing was stalling before the front wing. The resulting pitching moment break was cured by fitting 6 vortillons to each side of the rear wing. Each vortillon was dihedralled to point inward at 45 degrees to the chord plane, but had no yaw angle. Each vortillon chord was approximately 10% of the local rear wing chord. The addition of the vortillons did not induce any measurable increase in drag at any lift coefficient.

Figure 14 shows the effect of high angles of attack on the pitching moments of a joined-wing agricultural airplane model (White, 1987). These tests were performed at low Reynolds Number (approximately 150,000 based on mean chord of the gross front wing area). For comparison, Fig. 14 also shows corresponding data on a canard aircraft (Yip, 1983) tested at full-scale Reynolds Numbers (approximately 1.9 million based on the mean chord of the gross rear wing area). For the free transition conditions tested, both configurations show a pitch-down characteristic below the stall, with generally similar post-stall variation of pitching moment with angle of attack. The maximum lift coefficients attained are similar for both configurations, so it is reasonable to assume that the joined wing maximum lift coefficient would be superior if it were tested at full-scale Reynolds Numbers.

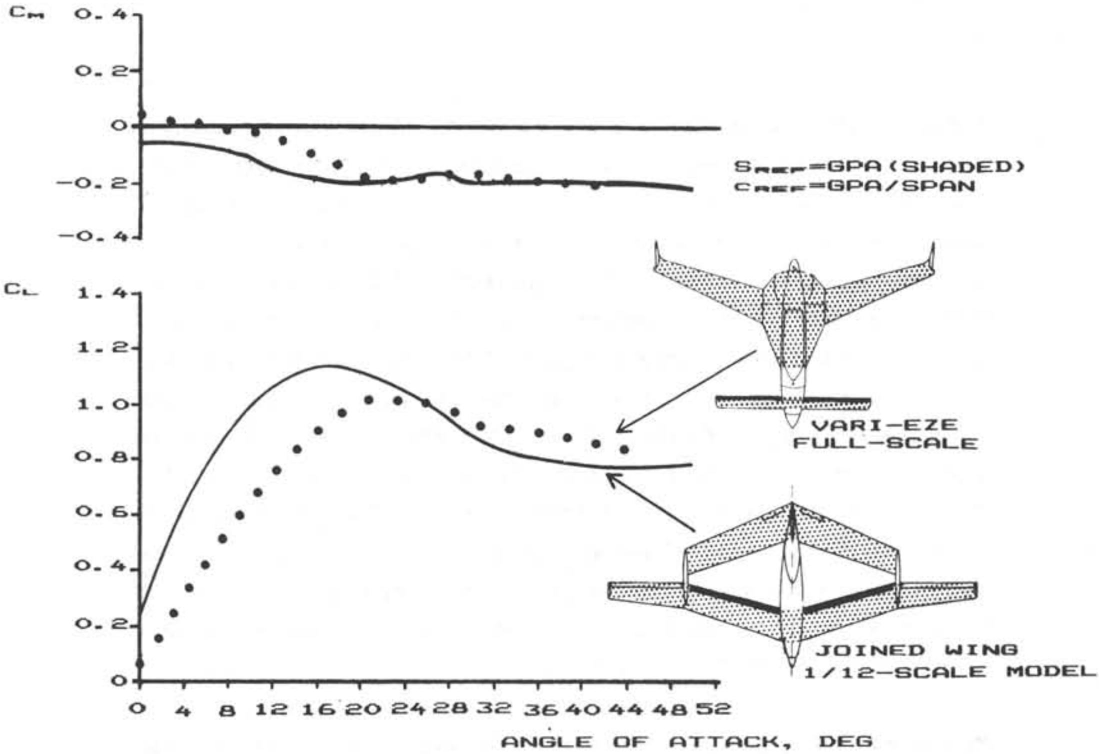


Fig. 14. Lift and Pitching Moment for a 1/12-Scale Model of a Joined-Wing Agricultural Airplane and for a Full-Scale Canard Airplane.

6. LATERAL STABILITY

Figure 15 shows wind-tunnel measurements of directional stability and dihedral effect on the JW-1 (Smith, 1987). The levels are comparable with standard lightplanes. Since joined-wing aircraft have a nose-down inclination of the principal inertia axis, some concern has been expressed about possible degradation of Dutch Roll mode damping. This concern appears to be unfounded, as shown by the computed time vector polygons of Fig. 16. Each term in the lateral equations of motion is represented by a side of the appropriate polygon (McRuer, 1972). The damping effect of the yaw damping derivative Cnr is opposed by the product of inertia term Jxz, but the magnitude of this term is not sufficient to cause a substantial loss of damping ratio. The damping ratio is approximately 0.1 and the undamped natural frequency of the Dutch Roll mode is 2.2 radians per second at the assumed flight condition of 100 KTAS at 10,000 ft.

Vortex-lattice computer programs are widely employed for the calculation of longitudinal characteristics. Most of these programs are constrained to model symmetric configurations. Figure 17 illustrates an artifice devised by Barnaby Wainfan of ACA Industries, Inc. for using symmetric vortex-lattice models to represent asymmetric flight conditions on joined-wing and conventional aircraft. Each half of this Figure shows the front view of a joined wing rolled through 90 degrees. The halves are widely séparated, so that the aerodynamic interference between the left and right vehicles is minimal. Angle-of-attack variations of the vortex-lattice program correspond to sideslip variations of the vehicle that is being modeled.

The use of this model has shown that the rear wing acts like an endplate on the fin, increasing its effectiveness. However, the fin reduces the local sidewash at the rear wing so the rear wing provides less directional stability than it would in isolation.

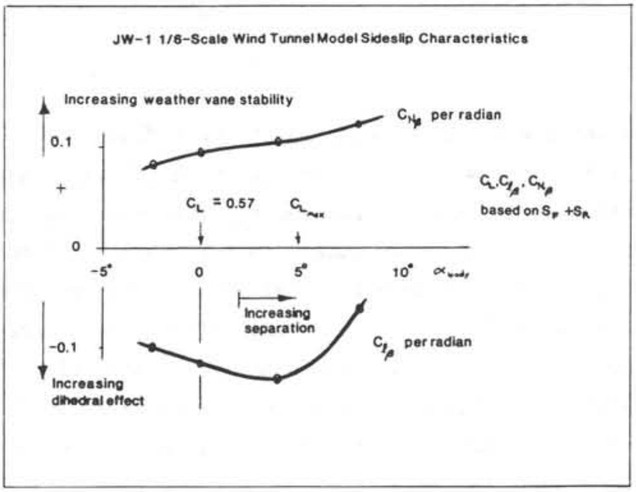


Fig. 15. Directional Stability and Dihedral Effect of a 1/6-Scale Wind-Tunnel Model of the JW-1 Airplane.

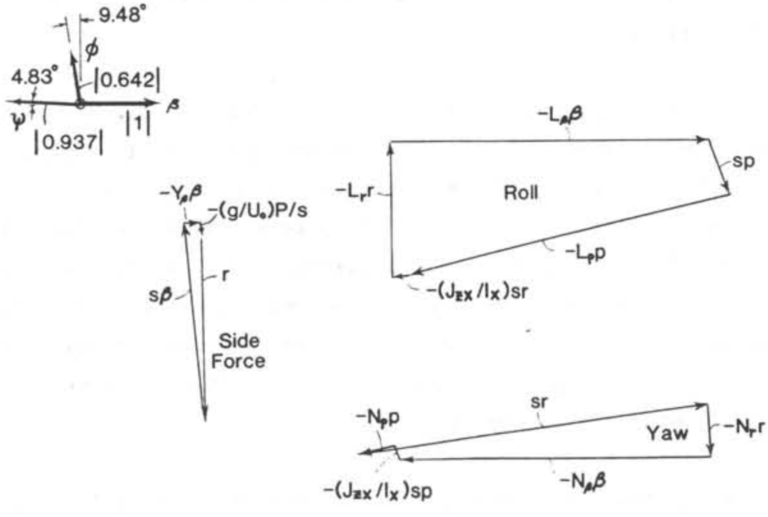


Fig. 16. Time Vector Polygons for the JW-1.

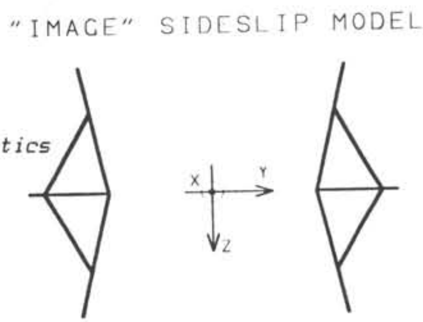


Fig. 17. Model for Computing Sideslip Characteristics of Joined Wings Using a Symmetric Vortex-Lattice Model.

7. WAVE DRAG

Figure 18 shows some new results on the wave drag of joined wings at zero lift. These results are the work of Finley (1986), who computed the wave drag for three configurations having equal gross projected areas, thickness/chord ratios (5%), and equal taper ratios (0.3). Leading edge sweep angles of 40 degrees (positive or negative) were employed. The configurations were representative of fighter designs. One had a conventional wing plus tail, the second employed a canard, and the third was a joined-wing configuration. Realistic fuselage shaping and volume constraints were applied, and the wave drag of the joint fairings was taken into account. Finley showed that at low supersonic Mach Numbers the joined wing configuration has considerably less wave drag than its competitors.

The joined wing is well suited for thin airfoils. Miura and Shyu (1986) have shown that the weight penalty for reducing thickness-chord ratio is less for a joined wing than for a cantilever wing-plus-tail. This offers large benefits for supersonic flight, as shown by the lowest graph on Fig. 18. The graph represents a modification to the previous joined-wing design in which the thickness/chord ratio is reduced to 3%. The zero-lift wave drag is typically less than 50% of the wave drag of the conventional configuration.

A promising area for further study is the wave drag at finite lift. This should be reduced by the joined wing, since the lift is carried over a large fraction of the total vehicle length.

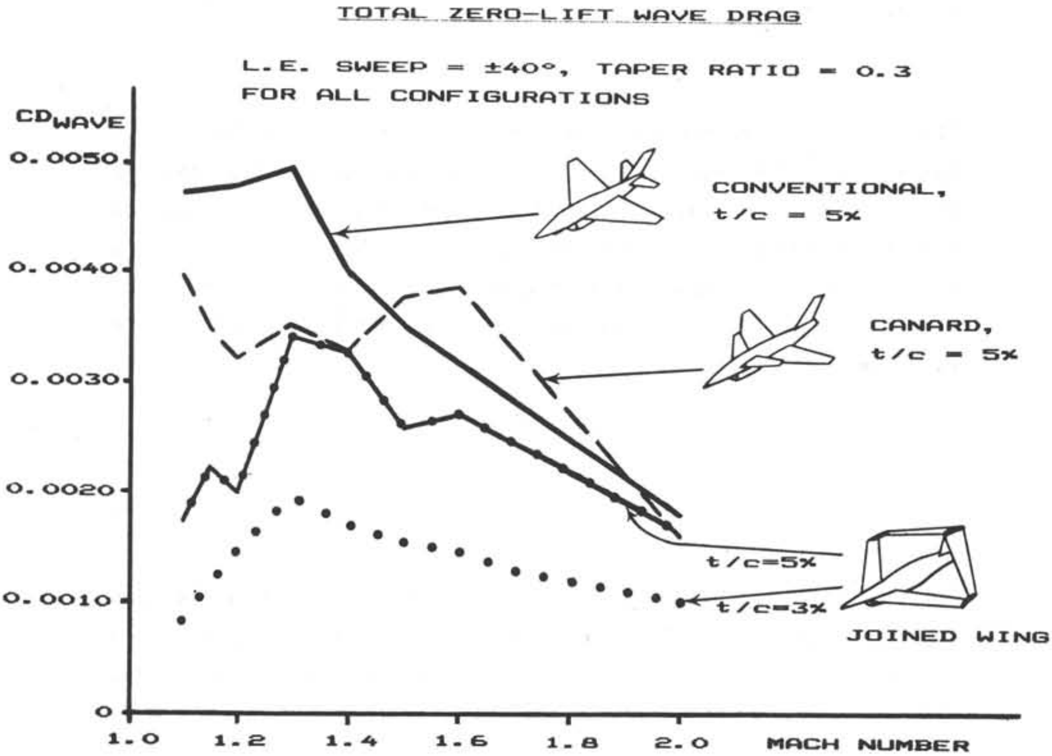


Fig. 18. Wave Drag at Zero Lift for Conventional, Canard, and Joined-Wing Aircraft.

8. CONCLUSIONS

The results of recent research on joined wings have been summarized. The research topics include structural optimization, stability and control, induced drag, wave drag, and high angle-of -attack behavior. No adverse characteristics have been found, and wind tunnel tests and analytic studies indicate that the joined wing can provide substantial performance benefits for subsonic and supersonic aircraft.

9. FINAL REMARKS

The space available for this paper has not permitted any discussion of many refinements and subtle points of joined-wing design. Therefore, the reader who wishes to evaluate the joined wing for any specific application should contact the authors to obtain the most up-to-date information.

ACKNOWLEDGEMENTS

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The selection of a general arrangement for new fixed-wing aircraft is one of the most challenging and crucial phases of conceptual aircraft design. Superficially it seems that designers have an overwhelming freedom of choice between various configurations, but the history of aviation has shown that each era of technological state-of-the-art produced but a small range of generally favoured configurations.

New technological developments, such as high-speed propellers and composite material applications, have stimulated research into the possibilities of unconventional configurations. The symposium organized by the Netherlands Association of Aeronautical Engineers and the Students Society "Leonardo da Vinci" is intended to make an assessment of some of these configurations.

This book contains the proceedings of the symposium, dealing with tail-first (canard) and three-surface aircraft, forward sweep technology, multi-fuselage aircraft and the joined wing. All of the authors have been intimately involved in research and development associated with these new shapes.

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