Design Integration of Laminar Flow Control for Transport Aircraft

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Laminar flow control (LFC) promises a significant reduction in aircraft drag, which in turn promises im proved fuel efficiency and lower operating costs This paper discusses Lockheed's progress from 1974 to the present in practical application of LFC to subsonic transport aircraft and includes preliminary design system studies of a $M=0$ 80, 400 passenger LFC aircraft with a range of 6500 n mi Technology challenges in the areas of airfoil development, boundary layer analysis and methods, integrated structural design, the suction system, and the final integrated aircraft configuration are reviewed Experimental investigations covered include wind tunnel tests, low-speed flight tests, and tests of structural specimens As compared with a counterpart turbulent flow advanced technology transport, the system studies indicate reductions of 22% in mission fuel and 8% in takeoff gross weight for the LFC transport.

Introduction

THE pursuit of methods of drag reduction for the im provement of aircraft performance has been an objective of the aeronautical engineer since the advent of the first flight of manned aircraft. Among the many concepts which have received critical analysis, laminar flow control (LFC) has indicated the greatest potential for drag reduction Beginning in 1939 considerable progress has been made in analytical and experimental investigations of the factors affecting the transition from laminar to turbulent boundary layer flow and in the development of methods for the achievement of laminar flow. An excellent review of these early results is contained in a paper by Braslow and Muraca [1] The achievement of laminar flow on an aircraft in flight by means of an active system for laminar flow control by suction is highlighted by results obtained by the British on the Vampire aircraft from 1951 to 1955 and U S Air Force/Northrop tests on the F-94 and X-21 aircraft in the mid 1950's and early 1960's The Air Force/Northrop investigations on the X-21 aircraft shown in flight in Fig 1 did produce extensive regions of laminar flow on the wings of the aircraft under certain flight conditions and at chord Reynolds numbers up to 40 million Furthermore, design criteria were established and validated and crossflow instabilities due to wing sweepback were identified. The X 21 program was terminated, however, before the desired service experience and data base were determined for an operational aircraft Thus the economic and operational feasibility of LFC remains uncertain Ad ditional studies were made on the application of LFC by Lockheed and Northrop in 1962 on the C 141 aircraft and in 1966 on the C 5A The accumulated data base from the above activities formed the background for a special issue of *Astronautics and Aeronautics* (current title: *Aerospace America*) in July 1966 devoted to the theme of Laminar Flow Control Prospects [2 7] Subsequently, little work was done on LFC until the fuel crisis in 1973 With the attendant dramatic rise in fuel costs, attention was directed to the use of advanced technologies for increased fuel efficiency. Laminar flow control was reactivated as one element in the NASA Aircraft Energy Efficiency (ACEE) program in 1976[8 10] and is continuing to the present

This paper reviews progress at the Lockheed Georgia Company from 1974 to the present in the practical application of LFC to subsonic transport aircraft by means of preliminary design system studies Technology challenges in the areas of airfoil development, boundary layer analysis, integrated structural design, the suction system, manufacturing methods, and the final integrated aircraft con figuration are reviewed Experimental investigations include wind tunnel tests, low speed flight tests, and tests of struc tural specimens The benefits of LFC on drag, fuel efficiency, and operating costs are compared with current as well as a counterpart advanced technology turbulent transport The current efforts to test the proposed leading edge cleaning and suction systems on the NASA JetStar flight test aircraft are also discussed

Factors Affecting the Design of Laminar Flow Control Aircraft

Laminar flow control aircraft are distinguished from conventional turbulent flow aircraft by the addition of a suitable surface for removing a portion of the boundary layer, ducting to collect the accumulated flow, and suction units to create the pressure differentials necessary for system operation In the Lockheed concept boundary layer air is sucked through a slotted LFC surface, transferred into chordwise collector ducts, and accumulated in trunk ducts. The trunk ducts carry the air directly to the LFC suction units located in the wing root where it is accelerated to freestream velocity and discharged These characteristics of laminar flow control have significant effects on the development of a practical LFC aircraft, and the quantitative assessment of these effects has been determined or evaluated in several system studies For example, the factors affecting design include important items such as sweepback and airfoil section associated with the wing design and the propulsion system and location to achieve the required performance requirements of payload, range, cruise speed and airport performance The initial feasibility study of LFC transport aircraft is reported by Sturgeon [11 12] The general configuration shown schematically in Fig 2 was selected with a cruise Mach number of 0 80, engines mounted on the rear of the fuselage

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to minimize engine noise propagation into the wing boundary layer, and slots in the wing and empennage surfaces for removal of the boundary layer air

Other important considerations are concerned with manufacturing procedures for fabrication of wing surfaces having very stringent smoothness and waviness requirements and minimum gaps and steps at joints These areas have been addressed primarily in the fabrication of surface structural panels for testing in the structures development program discussed later in this paper A number of procedures have been performed for cutting the surface, including electric-arc discharge, electron beam, and mechanical drilling and sawing It was found that a circular jeweler's saw produced the most desired slot in the titanium outer skin of the wing surface.

From the standpoint of flight operations, a critical factor in achieving and maintaining laminar flow is surface contamination—primarily wing leading-edge contamination from dirt, insects, and other foreign material during takeoff and climbout to cruise altitude The suction during cruise conditions can be affected by corrosion and erosion of the surface and clogging of the suction system at the slots at the outer surface, as well as in the slot ducts Surface maintenance is an in-between-flights activity and includes cleaning of the surface prior to the next flight as well as repairs that may be necessary These operational factors associated with LFC represent severe challenges to the success of the system, and as mentioned earlier, these were not resolved in the X-21 program The emphasis, therefore, has been directed to the successful resolution of these challenges

On April 6-7, 1976 the NASA Langley Research Center conducted a workshop on Laminar Flow Control. The program was arranged as a forum for informal papers and discussions on LFC experience from government and industry Included in the discussions were the effects of advances in technology on the performance and costs of LFC, the outlook for LFC as perceived by government and industry, and critical concerns and possible solutions One result of the workshop was additional contacts by Lockheed with airlines and other aircraft operations relative to LFC transport aircraft A consensus of industry and airline concerns on LFC was obtained. Three major areas of concern include the development of LFC structure and subsystems with acceptable weight and cost, problems with manufacturing the required LFC structure, and operational reliability on a day-by-day basis. The following sections of this paper review the progress which has been made in each of these three areas.

LFC Configuration Characteristics

The general characteristics of the Lockheed LFC aircraft are described in this section The key elements related to operation of the LFC systems shown in Fig 2 include the suction surface, (designed as an integral part of the wing structures), ducting of the boundary-layer flow to a suction unit at each wing root, and cleaning slots located at the wing leading edge to provide for flow of liquid to prevent contamination of the surface during takeoff and climbout The integral wing structure is constructed of bonded graphite/epoxy composites for load carrying members and is covered with a thin titanium face sheet Since titanium was selected for the outer wing surface because of its superior corrosion resistance, the suction slots cut in the titanium should maintain their desired geometry and not degrade with time and operation More details of the wing stucture are provided later The chordwise suction flow is then collected into two main spanwise suction ducts located at the leading edge (shown at the top right of the figure) which connect to the suction unit The liquid used for leading-edge cleaning also serves as an anti-icing medium and consists of a mixture of glycol, water, and a wetting agent LFC suction capability is provided on upper and lower wing surfaces from 0 to 75% chord and on the empennage from 0 to 65% chord

The technology levels applied to the design are consistent with a development schedule providing for initial operation of the aircraft in 1993 The technologies consist of 1) modified supercritical airfoils for the wing, 2) graphite/epoxy composites in primary and secondary structures of the airframe, 3) 1988 engine technology, i e , Pratt and Whitney STF 477 engines, 4) fly-by wire flight control systems, and 5) active controls including relaxed static longitudinal stability

Design Methodology

While the complex and interactive design methodologies used in the development of an LFC aircraft are not discussed in detail here, some of the areas which required special attention from the LFC standpoint are discussed in the following sections

Airfoil and Boundary Layer Analysis

Airfoil development received considerable attention in Lockheed's studies, and the Lockheed and NASA airfoils depicted in Fig 3 show different end results due to different approaches The Lockheed airfoil reflects the result of the baseline aircraft design, which has sufficient wing area and low-speed performance so that leading-edge, high-lift devices are not required Thus, upper and lower surface suction can be utilized in the wing design The NASA airfoil has a reduced

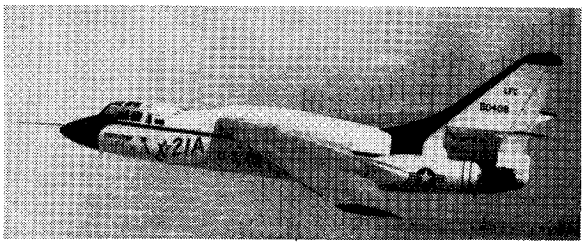

Fig 1 Air Force X 21 LFC aircraft.

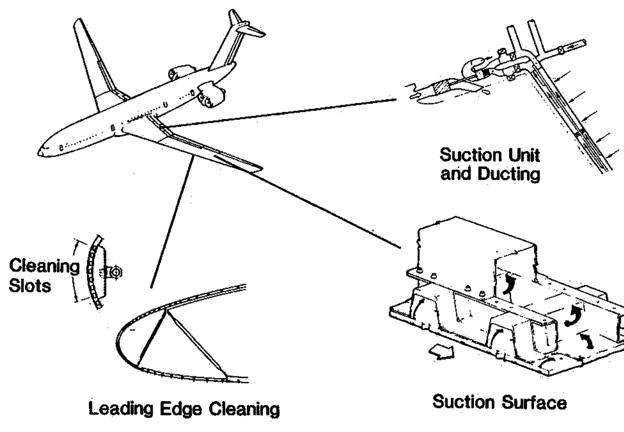

Fig 2 LFC configuration characteristics

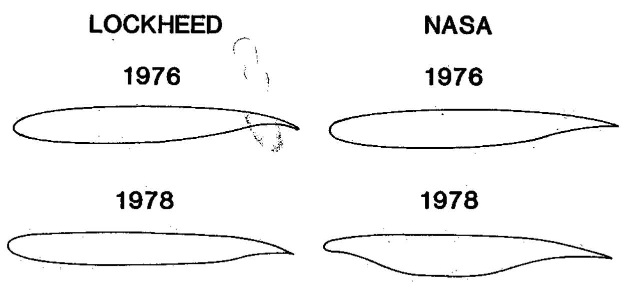

Fig. 3 Lockheed/NASA LFC airfoil designs.

nose radius and the lower surface is undercut near the leading edge, which eliminates the need for suction in this region and permits the use of a leading-edge, high-lift device extending from the lower surface This 1978 NASA airfoil section with suction slots in the surface is currently undergoing tests in the NASA 8 ft Transonic Wind Tunnel In addition, perforations in the surface to provide for suction flow will also be tested in a later series These airfoil sections must also be tailored to minimize the adverse crossflow effects at the leading edge due to wing sweepback in order to achieve the desired $M=0$ 80 cruise speed

Extensive work since 1974 has been done in boundary layer analysis of the laminar boundary layer over the $M=0$ 80 sweptback wing on the Lockheed LFC aircraft This will only be highlighted here because an excellent paper on the Lockheed LFC activity in support of NASA LFC contract activity was presented by Bennett and Brandt [13] The methods utilized by Lockheed include the Nash code from Lockheed[14] and the Cebeci/Kaups code from NASA Langley,[15] which are best suited to calculate the boundary layer over a surface with distributed suction over a porous surface However, in the Lockheed case discussed here, where suction is with discrete slots, the Beasley/Carter code from NASA Langley[16] and the Bennett/Malone code from Lockheed[17] are more useful for boundary-layer calculations Along with the calculation of the characteristics of the laminar boundary layer is the assessment of the stability of the laminar boundary layer Lockheed LFC stability analysis is centered around the Srokowski and Orszag "SALLY" code.[18] This code provides assessment of the leading edge, crossflow instabilities as well as the wing surface Tollmien-Schlichting instabilities

For the estimation of the transonic flowfield characteristics of the complete wing, there has been an evolution of methodology from the Bailey Ballhaus 3 code[19] to a Lockheed version of the FL022 pressure code known as FL022NM [20] Wind tunnel tests at transonic speeds in the Calspan 8-ft wind tunnel on leading-edge glove sections of a JetStar model show very good agreement between the FL022NM estimated pressures and the experimental results [13]

Suction Surface Design Analysis

The application of the boundary layer and stability analyses described in the previous section are input to the design parameters of the suction surfaces of the wing and em pennage The basic design parameters for the suction surface are shown in Fig 4 Important parameters are the slot width, w, slot Reynolds number, R_w, suction pressure coefficient, Cp_S, the height of the sucked boundary layer, z, and slot spacing, ΔC_N.

The difficulty in meeting the requirements for satisfactory slot/suction criteria as established in the X 21 project is illustrated in Fig 5 The data of Fig 5 are presented with slot width and slot spacing as a function of slot Reynolds number The two points shown within the shaded boundaries of Fig 5 satisfy the several criteria for maintaining laminar flow in the boundary layer The boundaries of the shaded area are formed by limit values of parameters obtained from X-21 tests and include $U_z/U_e=0$ 30 for the top, $Cp_S=0$ 02 for the right, and $w/z=1$ 0 for the left boundaries, respectively This graphical method has enhanced the rapidity of the LFC slot design process at Lockheed

Low Speed Tests

Considerable effort has been directed to the very important leading-edge area of the wing in order to provide methods for leading edge cleaning, anti-icing, and suction flow Previous testing has shown that residue at the leading edge region from impact of insects or other foreign objects can cause transition of the boundary layer and thus prevent the attainment of laminar flow Early in the LFC program, Lockheed provided NASA with a special leading edge slat for the JetStar test

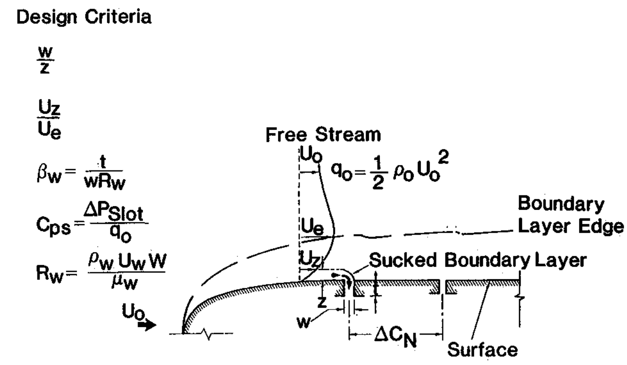

Fig. 4 Surface design parameters

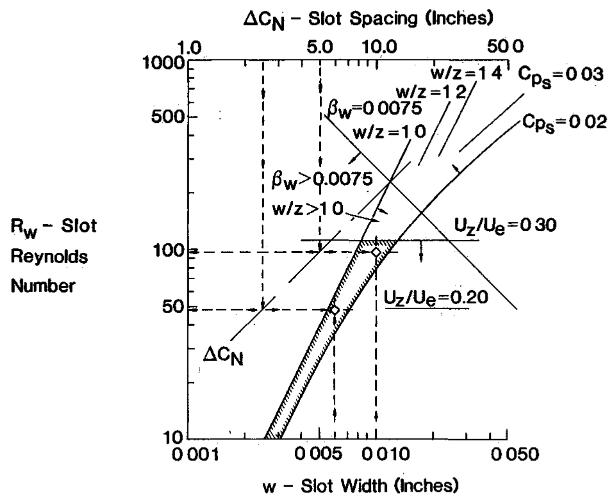

Fig 5 LFC surface design envelope

aircraft which had several smooth surface materials and a set of spray nozzles located on the undersurface near the leading edge. It was determined in the flight tests that spraying liquid over the leading edge was the only effective means of preventing insect residue and contamination of the leading edge during takeoff and climbout to cruise altitude [21] Since the spray nozzle installation was a rather crude means of providing flow at the leading edge, effort was directed to the design of a practical liquid film cleaning system The design featured flow of fluid through dedicated cleaning slots, as previously shown in Fig 2 Validation of the effectiveness of these cleaning slots was obtained in low speed wind tunnel tests of the full scale leading edge test article During simulated takeoff and climbout conditions, blowflies were injected into the airstream ahead of the leading edge at rates considerably greater than that expected, and no accretion of insects was found when the leading edge was covered by a liquid film from the cleaning slots

Other low speed tests were conducted in flight on an LFC glove attached to the wing of a Caproni sailplane, as illustrated in Fig 6 These tests were conducted primarily to develop experience with instrumentation and flowfields associated with laminar flow flight conditions

Wing Structural Design Concepts

As mentioned earlier, the approach to the design of the wing structure must minimize the weight of LFC peculiar items by the integration of these items in the basic wing structure A schematic view of the wing structure concept design given in Fig 7 shows the major features, including the leading edge with its cleaning slots, suction slots, and trunk ducts, as well as the main box area with structural elements such as the hat-section stiffeners and hollow rib caps serving as spanwise and chordwise ducting, respectively, for LFC suction flow The detailed view shows the hat section, wing skin, and outer titanium sheet with suction slots The metering system is also shown integrated into the wing structure. There is a trunk duct divider which separates the lower-pressure air of the upper wing surface from the higher-pressure air of the lower wing surface.

Structural Panel Tests

In order to validate the wing structural design concepts, several structural specimens were fabricated and tested, including small coupon test articles and larger specimens The surface panel selected is based on structural requirements of the upper wing surface midchord region at the 30% semispan location Three surface panels, typical of the main box area with the graphite epoxy skin and hat sections and outer face sheet of titanium, were fabricated and tested The test panels included all LFC elements, such as the suction slot in the titanium outer skin, the slot duct, and metering holes Panel tests included environmental, stuctural component, and fatigue tests Test specimens were cut from the three LFC surface panels The first panel was sectioned to provide test articles for environmental and rib-clip component tests The second panel was used for compression tests, and the third panel was used for fatigue testing Some minor changes in the design concept were required as a result of initial testing Later surface panels incorporated such changes and were subjected to extensive environmental and structural testing, validating the design concepts

One objective in the fabrication of structural components is the identification and development of manufacturing methods and techniques for the LFC-peculiar requirements An example of such a procedure is the cutting of the suction slots in the leading-edge component Slotting was accomplished with 0 003 and 0.005 in slot widths using a high speed steel jeweler's saw The saw is mounted on a boom traverse system and the leading-edge test article is mounted on a rotary table for positioning during slotting

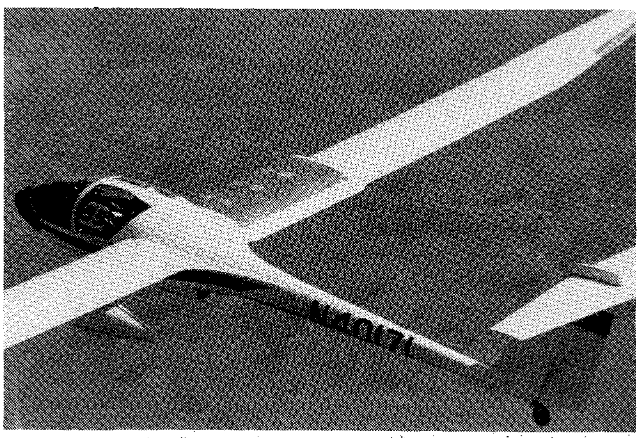

Fig 6 Caproni sailplane with LFC glove.

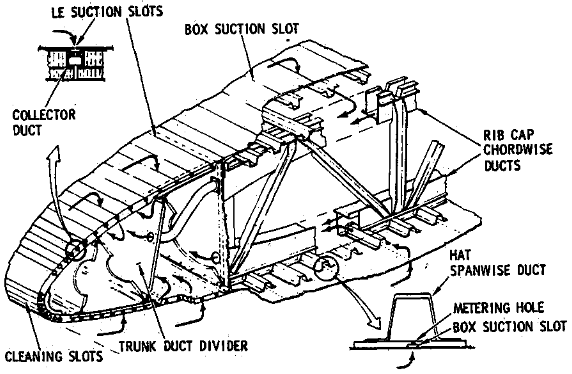

Fig 7 LFC wing structural design concepts

Final LFC Transport Configuration

The final LFC transport configuration shown in Fig 8 represents the integration of all subsystem concepts and design alternatives discussed in the previous sections. The aircraft is a wide-body configuration designed to carry 400 passengers and baggage over an intercontinental range of 6500 n mi at $M=0$ 80 cruise speed with adequate fuel to account for adverse winds, intermittent LFC disruption due to atmospheric conditions at cruise altitude, and international fuel reserves The cargo bays will accommodate 37,000 lb of cargo The total payload of the aircraft, including passengers and baggage, is 84,800 lb

The aircraft is a low-wing T-tail monoplane with four aft-mounted engines An independently driven LFC suction unit is located in a fairing under each wing root Fuel is carried in the wing, including the wing center-section box. The wing has 25 deg sweep at the leading edge, an aspect ratio of 11 6, and a wing loading of 111.8 lb per square foot Full-span flaps, including drooped ailerons, provide the required airport performance for a 10,000 ft runway. Leading-edge, high-lift devices are not required Partial span spoilers are provided Small-chord (10%) secondary flaps incorporated into the main flaps provide an upper surface pressure gradient and shock position control for off-design operation, and serve as active controls to minimize structural requirements The takeoff gross weight of the aircraft is 592,205 lb

A weight breakdown for aircraft LFC-peculiar items is presented in Table 1 The effectiveness of the Lockheed approach in integrating the LFC-peculiar items in the aircraft design is indicated by the relatively low weights (4 4% of the empty weight) incurred for LFC The cleaning fluid required per flight is shown as a separate item and results in 2 6% of the gross weight of the aircraft

To evaluate the benefits in performance and economics of the LFC aircraft, an equivalent turbulent flow aircraft was designed utilizing identical advanced technologies and optimized for fuel efficiency The turbulent-flow aircraft was very similar to the LFC aircraft in that it had the same fuselage with four aft-mounted engines, T-tail, and low-wing monoplane configuration The turbulent aircraft performed the same mission as performed the same mission as the LFC aircraft

A comparison of the weights of the final LFC aircraft and the optimized turbulent flow aircraft is given in Table 2 Whereas the weight empty and operating weight of the LFC aircraft is about 1% greater than that of the turbulent flow aircraft, the takeoff gross weight of the LFC aircraft is 8% lower, due primarily to the 22% reduction in fuel required to accomplish the long-range mission. The reduction in fuel is a result of the reduction in drag of the LFC aircraft Calculations of the aircraft drag indicate a 60% reduction in the wing and empennage drag resulting from the effects of

Table 1 Weight for LFC systems, lb

Surfaces	
Wing	5 152
Horizontal	471
Vertical	595
Suction units	1 318
Ducting	1,436
Installation	1 634
Leading edge cleaning system	716
Subtotal	11 322 (4 4% weight empty)
Cleaning fluid	3 968
Total	15,290 (2 6% gross weight)

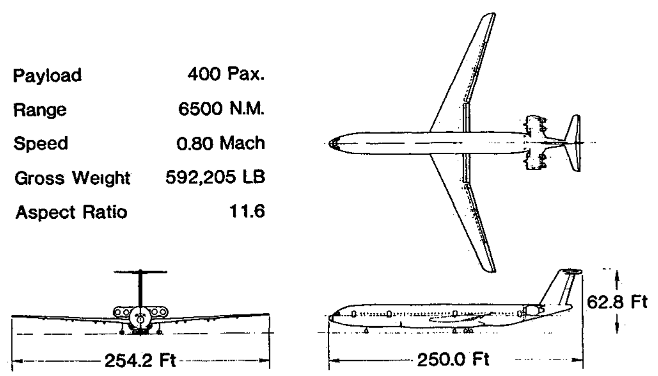

Fig. 8 Final LFC configuration.

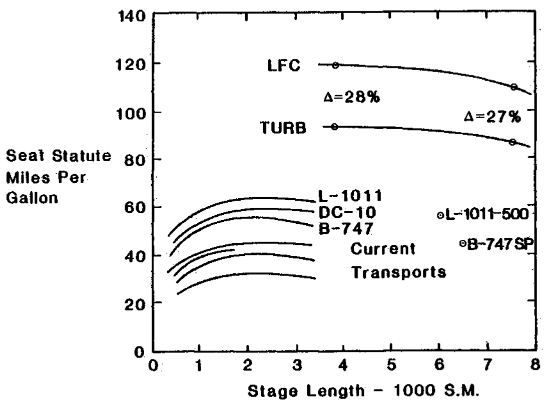

Fig. 9 Benefits of LFC—fuel efficiency.

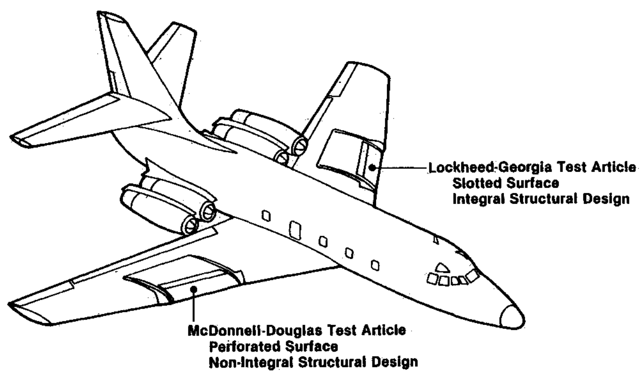

Fig. 10 NASA JetStar LFC test airplane.

LFC in reducing skin friction drag. The corresponding reduction in total aircraft drag due to LFC is 15%.

The benefits of LFC in terms of fuel efficiency are presented in Fig. 9. At the average stage length of 3800 statute miles, the LFC transport shows an advantage in fuel efficiency of 90 and 28%, respectively, as compared to the best of the current fleet of wide-body jets and the advanced-technology turbulent transport. At 6500 statute miles, the fuel efficiency of the LFC transport is further increased to a level greater than that for current transports.

Leading-Edge Systems Flight Test Program

Encouraged by the progress made in the development and validation of leading-edge cleaning, anti-icing, and suction systems so vital to the success of an LFC transport, Lockheed and Lockheed and McDonnell Douglas are currently developing flight test articles to be installed and tested on the NASA Dryden Flight Research Facility JetStar aircraft. The Lockheed activity is reported in Ref. 22. A review of the total NASA program is given by Wagner and Fischer in Ref. 23. In addition to the development of the leading-edge test article, Lockheed has the added responsibility for providing the aircraft structural and support system design and integration.

The schematic diagram in Fig. 10 shows the NASA JetStar flight test airplane with the McDonnell Douglas perforated leading-edge flight test article on one wing and the Lockheed slotted test article on the other wing. Both LFC suction concepts are logical candidates, and the flight tests should determine the effectiveness of these system concepts in leading-edge cleaning, anti-icing, and cruise suction LFC conditions. The test articles are instrumented for measuring boundary-layer conditions, suction flows, and other basic aircraft flight parameters.

After ground and flight checkout and acceptance tests, the aircraft will operate in a simulated airline service phase to accumulate the operational flight data required. The total flight program is reviewed in Ref. 23.

Table 2 Weight comparison of LFC and turbulent aircraft, lb

	LFC	Turb	Δ%
Structure	153,465	150,066	+ 2.2
Propulsion system	34,350	33,243	+ 3.3
Systems and equipment	67,779	69,170	− 2.0
Weight empty	255,594	252,478	+ 1.1
Operating equipment	33,131	33,631	− 1.5
Operating	288,726	286,109	+ 0.9
Pax payload	84,800	84,800	−
Zero Fuel	373,526	370,909	+ 0.7
Fuel	214,711	274,164	−21.7
L. E. fluid	3,968	−	−
Gross	592,205	645,073	− 8.2

Summary of Progress

A summary of progress in laminar flow control has been reviewed in the following areas and includes: 1) the definition of a practical 1993 LFC commercial transport, 2) validation of structural concepts for the wing surface and leading edge, 3) validation of the leading-edge cleaning system concept, and 4) the leading-edge flight test program currently underway.

Although significant progress has been made in LFC, the challenge of developing an LFC transport which is affordable and which has maintainability and reliability characteristics acceptable by the operators still remains.

Acknowledgments

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