LAMINAR FLOW CONTROL OVERVIEW

Ralph J. Muraca
NASA Langley Research Center

During the past few years there have been a number of significant developments in laminar flow control (LFC) technology. Although some of the technology developments are generic in nature and will benefit other applications, the major thrusts of these activities are for application to future CTOL long-range transport aircraft. The resurgence of interest in LFC stems from the fact that of all the emerging technologies which will lead to more efficient, economically superior, future aircraft, none has the potential for greater benefit than LFC. A recent study indicates that the application of LFC to the wing and tail surfaces of a long-range transport would provide a 28% reduction in fuel consumption and an 8% reduction in direct operating cost (DOC) from those of a comparable advanced technology turbulent-flow transport (fig. 1) at current fuel prices and even greater DOC reductions at higher fuel prices.

The feasibility of achieving laminar flow through surface suction has been demonstrated many times under controlled conditions. The most memorable program, conducted in the mid-1960's, was the U.S. Air Force X-21 Project in which a B-66 aircraft was refitted with an LFC wing (fig. 2). Although problems were encountered early in the program, they were eventually solved and the aircraft was ultimately able to consistently achieve laminar flow over large regions of the wing surface (fig. 3). This program also demonstrated that once a satisfactorily smooth and wave-free surface was obtained, it was possible to maintain and even repair (fig. 4) the wing surface without deteriorating the LFC system performance. Unfortunately, due to pressures on the Department of Defense budgets in this time period, this program was terminated before operational experience in noncontrolled environments was obtained.

Encouraged by the results of the X-21 program and LFC's potentially large benefits, NASA included LFC as one of the technologies to be advanced as part of the Aircraft Energy Efficiency (ACEE) program. The objective of the ACEE/LFC Project is to demonstrate that LFC can be economically applied to long-range transports in the 1990 time period. Technology advances in aerodynamics, materials, manufacturing, propulsion, etc., since the X-21 program as well as those anticipated to be available in this time period will be evaluated as part of this demonstration. An essential ingredient of the technology validation is the development of accurate life cycle cost data and operational experience. Most of the technology to be reported in this group of papers is directly supported by the ACEE/LFC program; consequently, it is focused to help achieve the stated LFC program goals. The LFC program is planned in three phases. Phase I consists of technology development and system studies; Phase II consists of technology demonstration and system development; and Phase III consists of technology validation through systems demonstration. The major elements of the Phase I program are shown in figure 5. They are

Airfoil development and test

Development and improvement of design methods

Evaluation of leading-edge contamination

LFC system definition and concept evaluation

Airfoil Development and Test:

As shown in figure 1 an LFC aircraft can provide significant improvement over a comparable turbulent-flow transport aircraft. This implies that it can take advantage of technology gains in other areas. One of these areas is supercritical airfoil development. Supercritical airfoils offer the promise of large performance improvement over conventional airfoils. For a given drag-divergence Mach number M_{DD}, the advantage appears as either higher section lift coefficient c_l or increased thickness-chord ratio t/c as shown in figure 6. Obviously, it is essential that a supercritical airfoil which lends itself to laminarization be developed. Using newly developed airfoil transonic-flow methods, it is possible to define candidate airfoils having the desired LFC characteristics with a high degree of confidence, thereby minimizing the amount of development testing. The process, which led to the definition of an airfoil shape for the subscale LFC swept airfoil experiment, will be discussed in the paper by Allison and Dagenhart. The primary difference between the pressure distribution on these airfoils and turbulent-flow supercritical airfoils is that at the design condition the upper surface supercritical flow decelerates isentropically without the generation of a shock, thereby avoiding the need to laminarize the boundary layer through the rapid pressure rise associated with a shock.

Development and Improvement of Design Methods:

The methods used during the X-21 program for stability analysis and determination of suction requirements were empirical in nature. During the ensuing years, progress has been made in the development of computing techniques which allow a direct calculation of the growth of disturbances in the boundary layer. These advances provide the opportunity for greater insight into the mechanism of transition and the effect of suction on this mechanism. Furthermore, they will reduce the uncertainty associated with the design of suction systems and allow the determination of optimized suction requirements. This could lead to significant improvements in airplane efficiency by reducing the size of the system components. Minimizing the degree of oversuction has further benefits such as reducing the equivalent suction drag, reducing the laminar skin friction, and reducing the sensitivity to surface roughness. The paper by Srokowski will outline a recently developed method for determining the growth of disturbances in an incompressible boundary layer, assuming the flow is parallel and ignoring nonlinear effects. In addition, he will discuss the effect some of these assumptions will have on disturbance growth and suction rates.

Leading-Edge Contamination:

It has long been known that maintaining the smoothness of the leading-edge region of an airfoil is essential for laminar flow. For flight conditions representative of commercial transport cruise conditions, the allowable height of a roughness particle which can be tolerated is of the order of 1 mm. This height is significantly smaller than insect excrescence found on current aircraft. Consequently, some means of eliminating or reducing insect excrescence must be found if one expects to develop an economically viable LFC transport. The controlling parameter is Reynolds number based upon the roughness dimension and local flow quantities. Previous experiments indicate that for values of roughness Reynolds number less than about 200, a laminar boundary layer can be maintained. This can be achieved by either keeping the roughness particle heights below a given value or by flying at very high altitudes. Since aircraft configurations envisioned for the 1990 time period will not be able to fly most efficiently at these higher altitudes (fig. 7), some methods must be developed for restricting excrescence size to allowable levels. The paper by Peterson and Fisher describes recent efforts to evaluate both passive and active approaches to this problem.

LFC System Definition and Concept Evaluation:

In addition to addressing specific issues, the LFC program has also attempted to identify potential market opportunities and possible configurations for the 1990 time period. The reduction in drag which results from laminarizing the boundary layer on an airplane can be translated into range capability which allows many new city pairs to be economically served. For configurations envisioned for the 1990 time period, design ranges over 5000 n. mi. appear to be achievable providing key technical problems can be resolved. As indicated previously, one of these deals with the emergence of supercritical airfoils. Another requires the efficient integration of structural and airflow requirements to minimize the parasitic weight associated with LFC systems. However, candidate approaches cannot ignore the operational requirements such as inspection, maintenance, and repairs; consequently, many trade-offs are possible. The advent of developments in both metallic and nonmetallic materials must be considered for any future aircraft; however, regardless of which of these approaches appears most attractive, the unique LFC requirements associated with smoothness and waviness almost dictate that new techniques for fabrication of aerodynamic surfaces must be developed. These trade-offs will be discussed in three papers which have resulted from contractual efforts by Boeing Commercial Airplane Company (BCAC), Douglas Aircraft Company (DAC), and Lockheed-Georgia Company (GELAC), along with some interesting approaches to the solution of specific design problems associated with the LFC system. The work breakdown structure for these contracts is as follows:

Evaluation of laminar flow control system concepts for subsonic commercial transport aircraft

Mission definition baseline configuration

Concept evaluation

Aerodynamics

Structures and materials

Suction system

Auxiliary system

Leading-edge cleaning/protection

Configuration selection and assessment

Recommended subsystem development

The baseline configurations selected by the three companies along with the design mission are shown in figure 8. Detailed information on the aircraft configurations will be provided in three papers by Gratzer, Sturgeon, and Pearce. Sturgeon will discuss the results to date of the GELAC efforts to define a practical design for an LFC transport and also the results of environmental and structural testing of a composite wing design in which the suction ducting is an integral part of the load-carrying structure. Gratzer will discuss the results to date of the BCAC efforts. Boeing has also chosen as a baseline approach an integral structural concept using bonded aluminum honeycomb with a slotted aluminum or plastic strip used to remove the boundary-layer air. He will also discuss the results from a series of wind-tunnel tests on a full-scale swept airfoil with suction. Pearce will focus his presentation on the development of porous composite panels which would be used on the Douglas concept. Douglas has chosen as a baseline structural concept a "glove" approach. That is, the outer surface panel is used solely for boundary-layer air removal and does not carry significant structural loads. He will present data from the aerodynamic and structural tests which have been performed to date on the baseline panel concept.

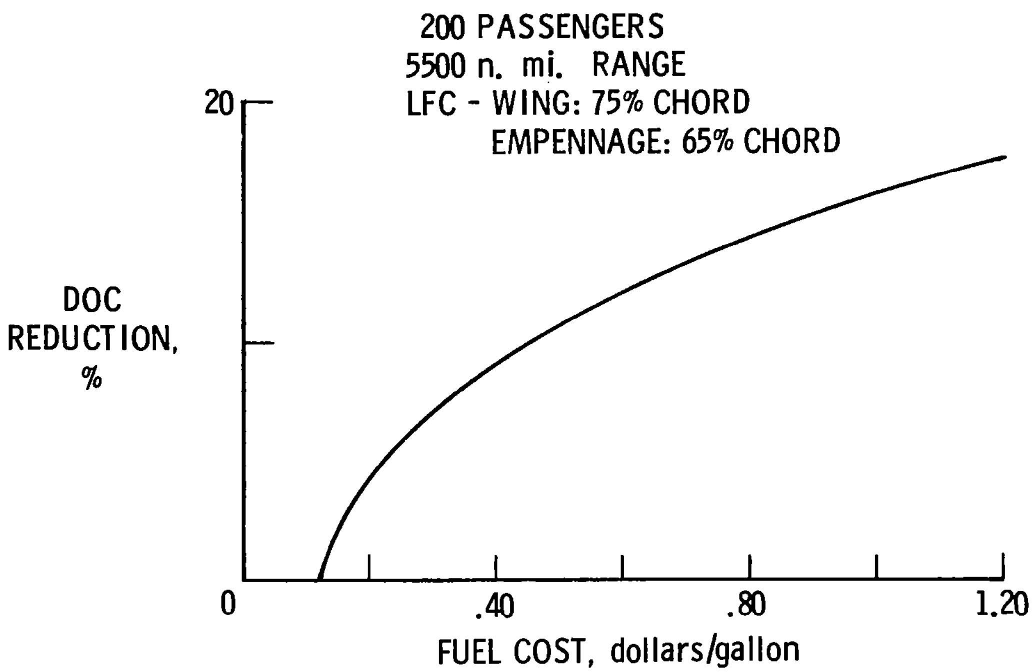

Figure 1.- Economic advantage of an LFC transport over a comparable turbulent-flow transport. (1 gallon = 3.8 liters.)

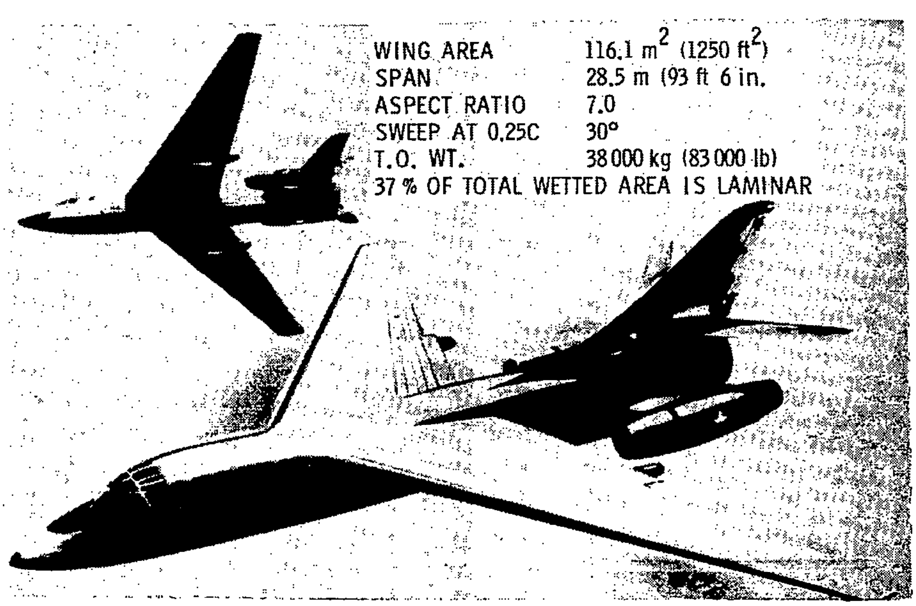

Figure 2.- U.S. Air Force X-21A aircraft.

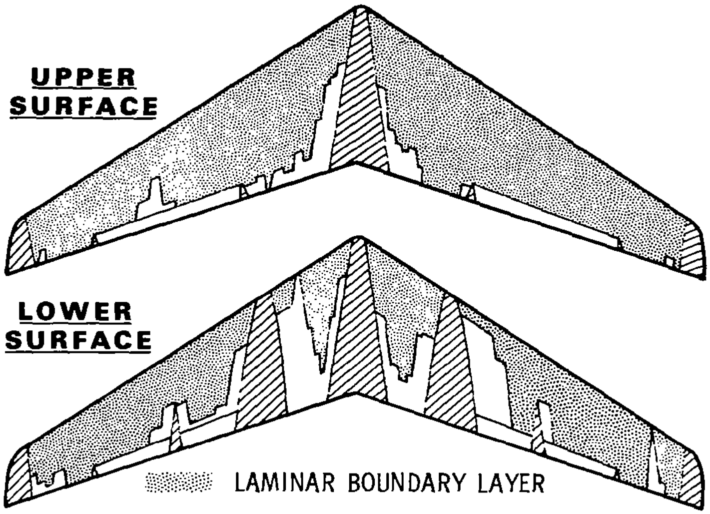

Figure 3.- Typical degree of laminarization achieved on the X-21 wing upper and lower surfaces.

Figure 4.- X-21A wing showing repairability of LFC surface.

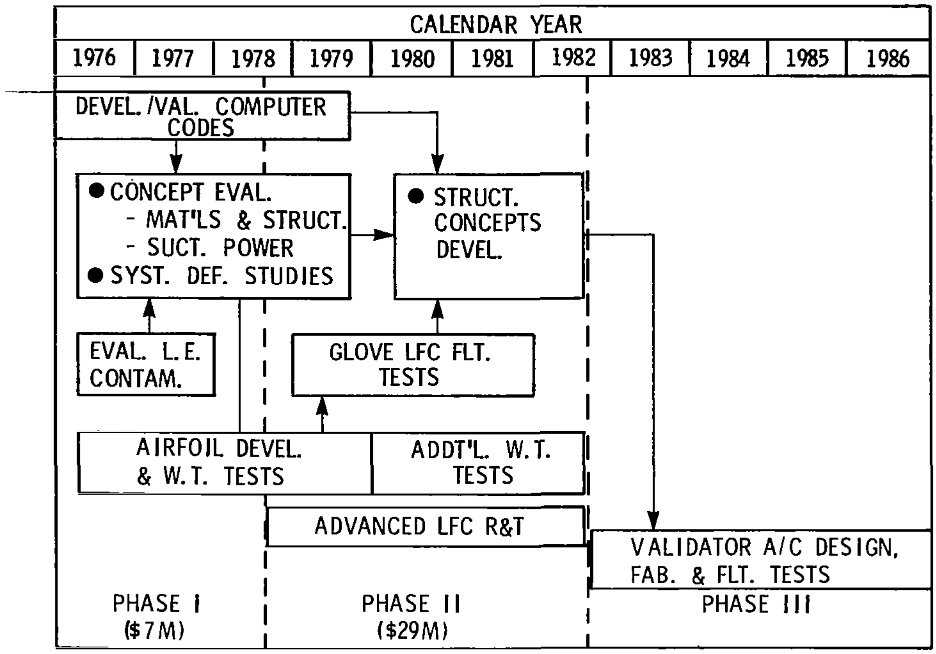

Figure 5.- Laminar flow control program plan.

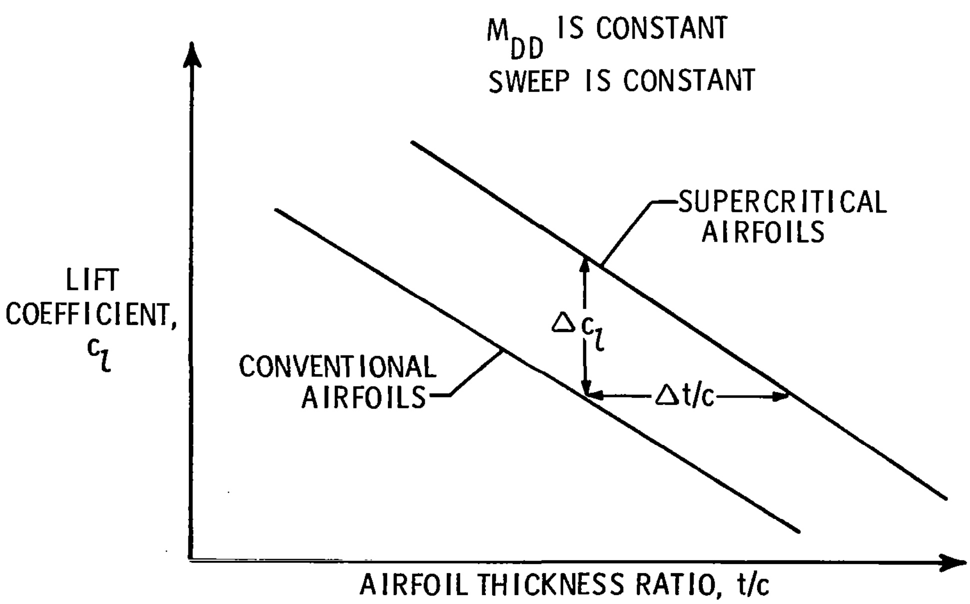

Figure 6.- Performance advantage of current supercritical airfoils.

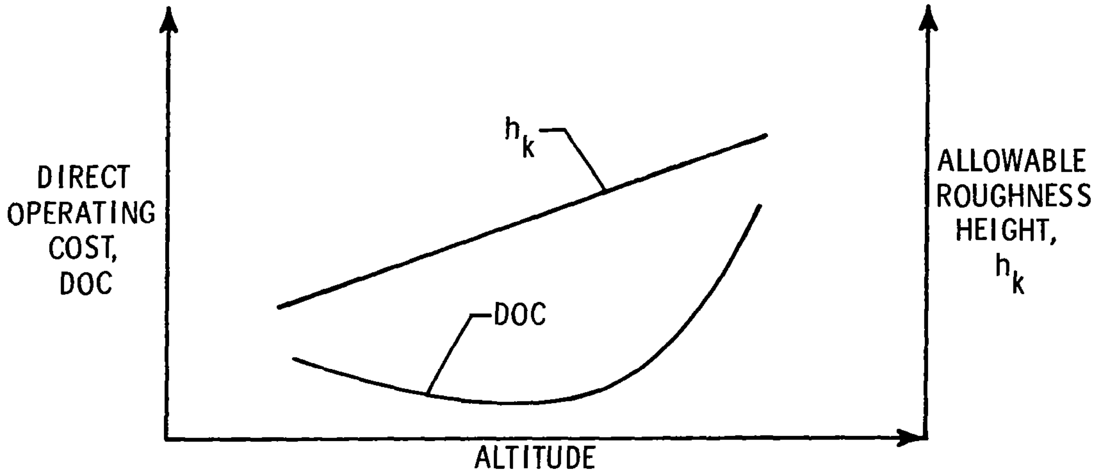

Figure 7.- Effect of altitude on aircraft direct operating cost and allowable roughness height h_k.

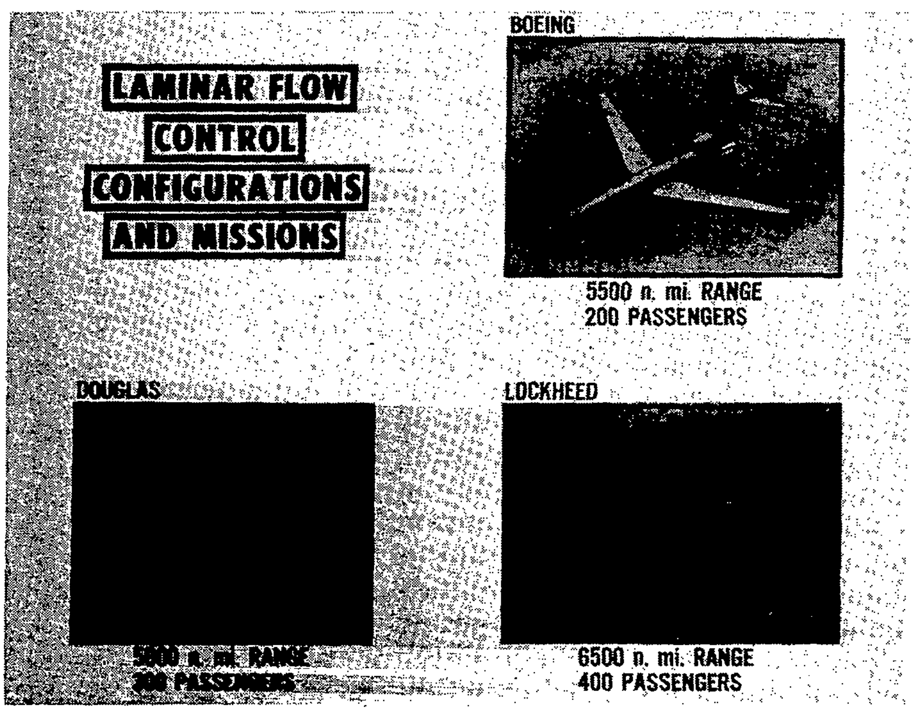

Figure 8.- Selected LFC missions and baseline aircraft configurations.