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AERODYNAMIC DEVELOPMENT OF LAMINAR FLOW CONTROL ON SWEPT WINGS USING DISTRIBUTED SUCTION THROUGH POROUS SURFACES

J. A. Thelander, J. B. Allen and H. R. Welge
Douglas Aircraft Company
McDonnell Douglas Corporation
Long Beach, California

Abstract

Development of a laminar flow control system utilizing distributed suction through porous strips is reviewed. Recent improvements in electron beam perforation technology have greatly enhanced the potential for practical LFC application. The design of airfoil shapes compatible with LFC on swept wings is outlined. Boundary layer stability analysis results and determination of suction distributions are reviewed. Considerations for an operational system for protection from ice and insect contamination are noted. Results of a swept wing model test and plans for a LFC leading edge glove flight test program are reviewed.

I. Introduction

Laminar Flow Control (LFC) has been the subject of aerodynamic analysis and experimental investigations for several decades. Laminar flow has been successfully achieved in flight and wind tunnel tests using suction to suppress growth of instabilities in the laminar boundary layer and thus delay boundary layer transition to aft regions of the wing chord. Although LFC has been successful under carefully controlled test conditions, general application of LFC to operational aircraft has proven to be impractical. Contamination and deterioration of the aerodynamic surface due to ice, insect, and airborne debris have precluded achieving the benefits of LFC in the practical sense. However, recent advances in surface material and structural technologies have eliminated shortcomings of earlier systems and stimulated renewed interest in LFC. This interest has received further impetus due to the issues arising from energy considerations - fuel conservation and fuel cost.

A laminar flow control program has been in progress at Douglas Aircraft Company since the latter part of 1976. This program has been a cooperative effort with the major funding support from NASA. The NASA program is the first substantial LFC development since the X-21 flight test program conducted by Northrop during the late 1950's which used spanwise slots to apply suction for LFC. Douglas Aircraft Company's interest and effort in the NASA LFC program has been focused on the use of distributed suction through a porous aerodynamic surface. Initial development utilized a woven stainless steel surface material known as Dynapore. However, during the course of the program, improved methods for making perforated titanium provided a superior and most promising material for the LFC aerodynamic surface.

A companion paper presented at this Congress reviews Douglas progress in LFC surface material and structural development for transport aircraft.(1)

II. Basic Airfoil Design

Initial analytical studies were conducted to develop a series of airfoils having aerodynamic characteristics compatible with those necessary for successful laminar boundary layer flow control on swept wings. In addition, it was required to determine the sensitivity of these aerodynamic characteristics to variations in Reynolds number, airfoil thickness, and the extent of laminarization.

A series of airfoils was designed having varying thickness-chord ratios. The suction flow quantities and wake drag characteristics of each airfoil were then determined as a function of Reynolds number and chordwise extent of laminar flow. Two sets of airfoils were designed corresponding to the normal sections of 25 degree and 30 degree swept wings at a freestream Mach number of 0.80.

Design Guidelines

Since it is unlikely that laminar flow can be maintained behind a shock downstream of the supersonic flow region on a conventional supercritical airfoil, the LFC airfoils were designed to remain shock-free. Furthermore, from operational considerations it is important to prevent buffet in the event that laminar flow is lost during flight. This condition requires that pressure recovery gradients on the aft portion of the airfoil satisfy separation criteria for turbulent boundary layer flow on the laminarized portion of the airfoil. While the likelihood of suction system failure is remote, the possibility of partial loss of laminar flow due to environmental disturbances must be a consideration.

A two-dimensional infinite swept wing design procedure was used to develop LFC compatible airfoils. The upper surface pressure distribution, normal to the leading edge, was similar for all airfoils. The upper surface pressure peak was constrained to limit the maximum local Mach number to 1.1 near the leading edge, with gradual supersonic compression to a local Mach number of 1.02 in the vicinity of 65-percent chord. Over the aft portion of the airfoil the adverse pressure gradient was limited so that separation would not occur if laminar flow was interrupted or lost.

Airfoil Design Procedure

Airfoils of varying relative thickness and design section lift coefficients were defined by adjusting the airfoil lower surface pressure profile. A slightly favorable pressure gradient was maintained from the leading edge to 65-percent chord on the lower surface with the adverse gradient near the trailing edge constrained to assure attached flow with fully turbulent boundary layer.

Airfoil profiles were developed for the specified pressure distributions using the Tranen code(2) which is an inverse transonic analytical procedure. This method is an extension of the 2-D Garabedian airfoil analysis method. Pressure distributions and resulting airfoil geometry for representative cases are shown in Figures 1 and 2. For the 25-degree swept wing, the design section lift coefficients are 0.73 for the 11.3-percent-thick airfoil and 0.54 for the 14.3-percent-thick airfoil. Similarly for the 30-degree swept wing the design section lift coefficients are 0.78 and 0.60 for the 12.8-percent-thick and 15.8-percent-thick airfoils, respectively. Displacement thickness for the turbulent boundary layer without suction was determined for the various airfoils using the Cebeci boundary layer program.(3)

LFC Suction Requirements

Suction requirements for the laminar flow airfoils were based on the Cebeci three-dimensional boundary layer analysis.(4) A specialized version of the program was developed to compute suction velocities which satisfy the laminar boundary layer stability criteria established empirically during the Northrop X-21 program.(5) A subsequent modification of the computer program provided an interactive mode through a remote graphics terminal. This modification greatly expedited the solution of suction requirements.

Determination of the suction distribution for a given geometry and pressure distribution was accomplished by computing the suction necessary to satisfy the appropriate stability criteria; namely, attachment line, cross-flow, or Tollmein-Schlichting. The procedure consisted of a "marching" solution, beginning at the attachment line and progressing downstream. At each chordwise station the critical instability was identified and the corresponding suction velocity requirement was calculated using an iterative procedure based on an estimated initial value.

Typical results using this procedure are shown in Figure 3. The surface pressure profile is given along with the corresponding suction velocity distribution. These data are for a 30-degree swept wing at M = 0.80 and $C_L = 0.56$. Noted on the figure are the regions where the cross-flow instability or the Tollmein-Schlichting instability is the flow mechanism causing boundary layer transition. As expected, the cross-flow instability requires significantly greater suction to control the boundary layer and is associated with the steep favorable pressure gradient near the leading edge and the unfavorable gradient in the aft pressure recovery portion of the airfoil.

Suction requirements are sensitive to scale (Reynolds number) effects; particularly at the attachment line as leading edge radius and sweep are varied and in the aft pressure recovery region. Variation of suction with Reynolds number for the 12.8-percent-thick 30-degree swept wing is indicated in Figure 4. Two cases are shown: one with suction to 70-percent chord and one with suction to 85-percent chord. It is evident that the adverse gradients and consequent increased suction required in the aft portions of the airfoil result in the total suction flow quantity which almost doubles as laminar flow is extended from 70- to 85-percent chord on both surfaces. Included in Figure 4 for comparison is the classic assumption of suction varying inversly with the square root of chord Reynolds number. This assumption is optimistic with respect to the effect of increasing Reynolds number.

The variation of profile drag for representative airfoils used in the preceding discussion as a function of Reynolds number is shown in Figure 5. Extending the suction from 70-percent to 85-percent chord reduces profile drag by approximately one half. However, as noted previously, this extension of laminarization requires a substantial increase in the suction required. This situation suggests a very practical alternative in which suction is applied on the upper surface only to 85-percent chord. Profile drag for such a case is included in Figure 5 and it is only slightly higher than the drag for both surfaces laminar to 70-percent chord.

Airfoil profile drag for the LFC sections was found to have only a very small variation with thickness ratio and sweep at the design C_L. This was due to the similarity of the design pressure distributions.

The initial suction flow analysis outlined above was accomplished using the simple and convenient X-21 boundary layer stability criteria. Such results were limited, however, in that stability conditions are evaluated at a single station and there is no analytical procedure to trace development of instabilities upstream in the boundary layer. Recent analytical developments using more comprehensive advanced stability analysis computer codes have confirmed the conservatism of the foregoing methods.

III. Wing and Configuration Concept

In order to evaluate the relative merits and performance trade-offs between the reduced drag and the increased suction which result as laminar flow is extended further downstream into the aft regions of the airfoil, it was necessary to conduct a configuration study. Two LFC concepts noted in Figure 5 were used:

- Suction on upper and lower surface to 70-percent chord.
- Suction on upper surface only to 85-percent chord.

A mission of 5000-nautical-mile range with 69,000 pounds of payload was selected for the configuration comparison. Also takeoff length was limited to 10,000 feet and the maximum approach speed was 130 knots. The general configuration arrangement was similar for both cases; three aft mounted advanced turbofan engines, DC-10 wide body fuselage, and a 30-degree swept wing with aspect ratio 10 and 0.25 taper ratio. Details of the configuration study are presented in Reference 1.

Results of the configuration study showed that the aircraft with LFC on the upper surface only, to 85-percent chord, was the lighter and more efficient aircraft. A summary of key comparison parameters is given in the table below.

	Suction on Upper and Lower Surface to 70-percent chord	Suction on Upper Surface Only to 85-percent chord
Wing Area (FT^2)	3,560	3,100
TOGW (LB)	415,930	404,320
Fuel Burned (LB)	109,670	108,600
Thrust per Engine (LB)	32,690	31,430

The upper surface only LFC configuration is more efficient overall. It provides greater effective structural depth, resulting in a lower wing weight which compensates for the slightly larger profile drag. The upper surface only LFC configuration improves accessibility to the wing lower surface for fueling and maintenance, reduces requirements for surface contamination avoidance systems, and allows for practical use of a leading edge shield and high lift device.

Economic analysis of the LFC configurations, in comparison with an equivalent conventional (turbulent) aircraft, further emphasize the benefits of LFC on a long-range transport aircraft.(1)

IV. Low Speed Swept Wing Model Test

Wind tunnel tests of a swept wing model were conducted in the Douglas Long Beach Low Speed Wind Tunnel to demonstrate the effectiveness of distributed suction in maintaining laminar flow under conditions approximating the flow on the upper surface of a swept wing and to evaluate the suction analysis method discussed previously. The model was designed to have a specified upper surface pressure distribution, similar to that discussed earlier, in the presence of the test section floor and ceiling. It was necessary to have a large model because the porous LFC surface could not be scaled down to smaller dimensions. A 30-degree sweep angle was selected and the tunnel side walls were contoured to better simulate the flow on a high aspect ratio swept wing. The model had a normal constant chord of 6-feet.

The principal objective of the test was to demonstrate the ability to sustain laminar flow on a swept wing, using suction through a porous surface, at representative full-scale flight Reynolds numbers on a model constructed with practical production fabrication techniques and surface quality. The test surface contained weld joints in both the steel mesh (Dynapore) porous surface material and the perforated titanium. Also the spanwise joint along the main spar, between the leading edge and upper surface panels, was a representative juncture between the porous panels. This joint resulted in a nonporous spanwise strip approximately 4-inches wide directly in the LFC test region.

A sketch of the major model components is provided in Figure 6, and a photograph of the model in the Douglas Wind Tunnel is shown in Figure 7. A cross section of the leading edge panel, illustrating the fluted substructure, is shown in Figure 8. The surface resulting from the fluted panel construction is a series of porous (perforated) strips extending spanwise along the LFC suction panels.

Initial tests were made with nonporous panels in order to verify the pressure distribution and conduct flow visualization on the upper surface. The pressure distribution is shown in Figure 9. These tests generally confirmed the design of the model and sidewall fairings.

The basic swept wing model was tested first with the Dynapore leading edge and upper surface panels. Suction was varied chordwise to generally minimize the suction flow needed to maintain laminar flow. The extent of laminar flow obtained with the Dynapore LFC surface is illustrated in Figure 10. Application of suction extended the boundary layer transition location to beyond the end of the porous surface at 70-percent chord by as much as 5- to 10-percent of the chord. The extent of laminar flow obtained with the perforated titanium leading edge was essentially the same.

As noted in Figure 10, venting through the suction system, to the low pressure region of the upper surface from the leading edge region, resulted in a more-or-less natural LFC flow condition which delayed transition to the region from 16- to 20-percent chord.

The suction velocity distribution for the basic model with the Dynapore leading edge and upper surface panels is shown in Figure 11. The stepwise distribution is due to the grouping of several flutes into a single suction manifold. Included in this figure is the suction velocity distribution predicted according to X-21 criteria. Suction velocities are in reasonable agreement with predicted values. To compensate for the nonporous joint between the LFC panels increased suction ahead of, and behind, the nonporous front spar joint was required. The integrated suction is approximately equivalent to that which would have been required for a continuous porous surface.

It should be noted that during the initial phase of the LFC program, the available perforated titanium was rather coarse (0.004-inch diameter holes spaced 0.040 inches apart) and it was not of a consistent quality. The stainless steel Dynapore was selected as the primary surface material and the perforated titanium was considered only as an alternative LFC surface material.(1) Consequently, perforated titanium was tested on the leading edge panel only. Subsequently, the electron beam perforation technique was substantially improved so that a very good quality perforated titanium became available. This material, having 0.0025 inch diameter holes at 10 diameter spacing, was then evaluated by comparatively testing 18 inch spanwise leading edge segments of titanium and Dynapore LFC surfaces inserted in the center of the nonporous leading edge panel. Results of this comparative test showed the new perforated titanium to be aerodynamically superior to the Dynapore. Since the titanium was obviously superior structurally, it was selected as the LFC surface material for the LFC leading edge flight test article on the NASA Jetstar and the NASA LFC high speed swept wing tunnel test.(1)

V. Boundary Layer Stability Analysis

Advanced boundary layer stability analysis methods have been developed recently. These methods utilize small perturbation theory to describe and analyze the propagation and amplification of disturbances in the laminar boundary layer. Computation codes have been programmed to quantify and describe the growth of disturbances in the laminar boundary layer. These methods provide a significant improvement in the analysis of boundary layer stability and the evaluation of suction requirements, relative to the previously mentioned X-21 criteria.

Two advanced boundary layer stability analysis computer codes, both developed by NASA, are currently in use at Douglas Aircraft Company. The SALLY code solves linearized, incompressible boundary layer stability equations using a spectral technique. Amplification factors for cross-flow and 2-D Tollmein-Schlicting disturbances are determined for waves of given frequency and wave length. By evaluating amplification factors for a range of frequencies and wave lengths, the characteristic and maximum values of amplification factors are determined. Correlation of calculated amplification factors with experimental boundary layer transition data then provided the "calibration" to utilize analytical amplification factor values for prediction of boundary layer transition.(6)

The second computer code, identified as MARIA, is a derivative of the SALLY analysis developed by NASA.(7) The MARIA code considers only the cross-flow disturbances when solving the boundary layer stability equations. This modification along with other computational simplifications reduced computing cost by an order of magnitude and greatly increased the utility of the stability analysis for most design applications. A comprehensive computergraphic display of the MARIA output has been developed by Douglas and is shown in Figures 12 through 15. This display enhanced the interpretation and usefulness of the MARIA code as a design tool. A plot of amplification factor versus chord station for each wave length is presented. Input pressure and suction distributions are included for reference.

Representative results from the MARIA boundary layer stability analysis for the Jetstar LFC glove flight test design condition are presented in Figures 12 and 13. Amplification factors without suction are shown in Figure 12. The range of amplification factor values, indicative of cross-flow instability in the boundary layer, is between 7 and 9. This relation is based on correlation with the SALLY code which treats both the cross-flow and Tollmein-Schlichting (streamwise) instabilities. The condition shown in Figure 12 is judged to be a marginally stable cross-flow situation in which transition would be expected to occur at 7- to 10-percent chord.

The effects of several suction distributions on the amplification factor envelope at the same flight condition are illustrated in Figure 13. There is a very dramatic effect of suction applied at the leading edge, encompassing the attachment line, on the amplification factor envelope. For the nominal case with no suction at the leading edge and a primary suction level of $C_Q = -0.0005$* from $x/c = 0.01$ to 0.07 and a sustaining level of $C_Q = -0.0001$ thereafter, there is only a slight reduction in amplification factor relative to the preceding case without suction (Figure 12). Increasing the primary suction to $C_Q = -0.0009$ does not appreciably reduce the amplification factor envelope. However, extending the primary suction, (at the nominal value of $C_Q = -0.0005$), forward to the attachment line, results in a substantial reduction of the amplification factor envelope. This effect is due to suction being applied at the attachment line and reducing the severity of the cross-flow instability development in the flow downstream. It is evident that modest suction applied upstream of a region subject to cross-flow in the boundary layer is a key factor in controlling growth of the cross-flow instability.

Off-design flight test conditions were investigated to confirm that a flight condition could readily be achieved where transition would certainly occur near the leading edge. An example from this investigation is presented in Figures 14 and 15. At an increased Mach number of 0.77 and a lower altitude (h_p = 32,000 FT) the peak value of the amplification factor is 12 without suction, considerably above the transition threshold. In this instance, transition may be expected to occur at 3- to 4-percent chord. The effect of primary suction, applied over the first 4-percent of chord at a level of $C_Q = -0.0004$, reduces the amplification factor from 12 to 8. This result again emphasizes the importance of suction applied along the attachment line.

An important result, which may be attributed to the utility and capability of the MARIA advanced boundary layer stability analysis code, was the dramatic effectiveness of suction applied along the attachment line of a swept wing (Figure 13). This result is particularly significant since the previously used X-21 criteria indicated that suction would not be required along the attachment line in the foregoing examples.

It was noted during checkout and use of the MARIA and SALLY stability analysis codes that the results were very sensitive to; (1) location of the attachment line and, (2) the value of pressure coefficient at the attachment line. Analyses were carried out to assure the most accurate prediction of these critical parameters. In the case of the Jetstar leading edge flight test article, it was found that simple sweep theory was seriously deficient in prediction of attachment line location and pressure coefficient.

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*$C_Q = (\rho_w v_w)/(\rho_\infty V_\infty)$
= suction mass flow relative to free stream conditions.

VI. LFC Leading Edge Glove Flight Test

A NASA flight test program is currently in progress to evaluate aerodynamic performance and operational suitability of LFC on transport type aircraft. This program involves Douglas and Lockheed LFC systems on the NASA Jetstar aircraft. A comprehensive presentation of aerodynamic development pertinent to this flight test is presented at this Congress.(8)

Demonstation of a practical LFC system in flight is the basic purpose of the LFC flight test program. Such a demonstration requires that the aerodynamic suction system be able to maintain laminar boundary layer flow after clearing surface contamination, such as might be caused by ice formation or entrapped fluid used for deicing and the prevention of contamination by insect debris. The present effort has involved development of the airfoil shape for the leading edge glove and integration of the glove with the existing Jetstar wing shape and structure.(8) A sketch of the Jetstar flight test aircraft is shown in Figure 16. The Douglas LFC test article is located on the starboard wing (shaded) while the Lockheed test article is on the port wing. Each test article consists of a 6-foot spanwise section forward of the front spar at approximately midspan. The Douglas test article utilizes a leading edge shield, which is deployed when operating near the ground or in icing conditions, to protect the leading edge of the LFC surface from insect and/or ice impingement. This shield also provides support for the nozzles used to dispense deicing fluid over the LFC surface.

The leading edge glove flight test program will provide a direct comparison of two LFC system concepts. The Douglas system incorporates perforated titanium skin bonded to a fluted composite substructure, while the Lockheed system uses fine spanwise slots, to apply the stabilizing suction flow. Design of the flight test articles has been completed and fabrication of the LFC systems, support structure, fairings, and auxiliary systems is in progress. Flight testing is expected to begin in 1983.

VII. Concluding Remarks

Recent materials technology development has provided a breakthrough in the practical application of LFC. High quality perforated titanium is now readily available as a surface material which provides a very good aerodynamic surface, has excellent structural properties, and uniform porosity. This surface, bonded to a fluted composite substructure, provides a very practical means of applying distributed suction to stabilize and sustain laminar boundary layer flow on a swept wing.

Analytical and experimental studies have confirmed the theory and principles involved with development and design of an LFC system. These studies also indicate that applying distributed suction through a porous or perforated surface provides a relatively "gentle" means of stabilizing the laminar flow which tends to be tolerant of pressure gradients and surface irregularities.

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8. Bennett, J.A. and Brandt, L.B.: "External Aerodynamic Design for a Laminar Flow Control Glove on a Lockheed Jetstar Wing," ICAS-82-5.1.3, August 1982.

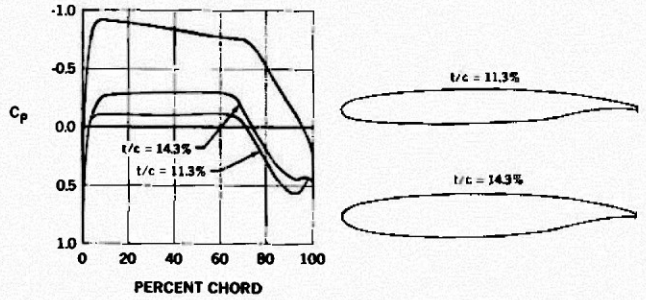

FIGURE 1. DESIGN PRESSURE DISTRIBUTIONS AND AIRFOIL SHAPES M_∞ = 0.80, Λ = 25 DEG

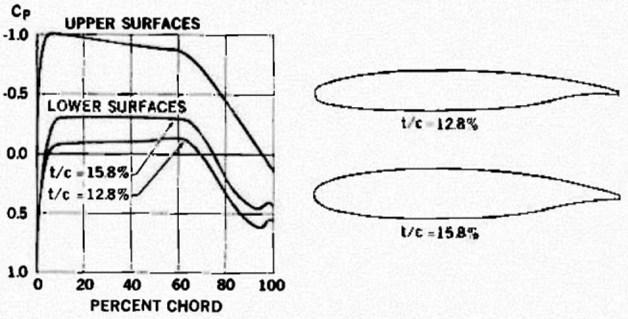

FIGURE 2. DESIGN PRESSURE DISTRIBUTIONS AND AIRFOIL SHAPES M = 0.80, Λ = 30 DEG

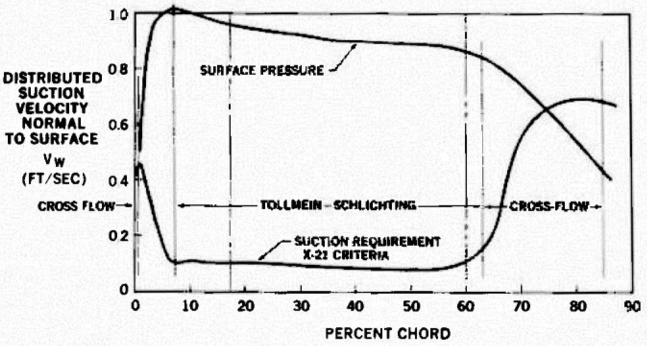

FIGURE 3. TYPICAL SUCTION DISTRIBUTION, M = 0.80

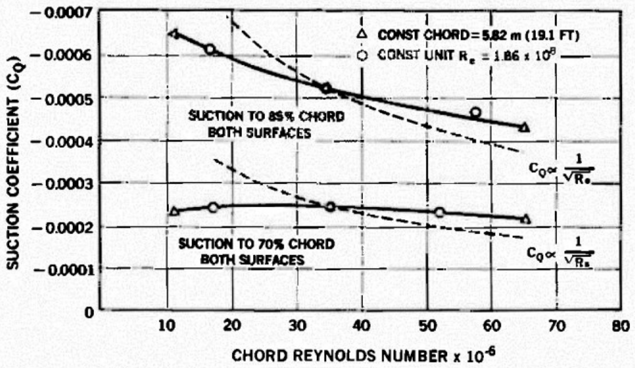

FIGURE 4. VARIATION OF TOTAL SUCTION COEFFICIENT WITH REYNOLDS NUMBER – M = 0.80, Λ = 30 DEG, C_L = 0.50

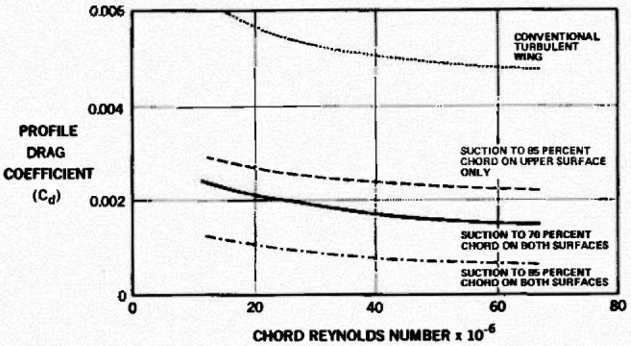

FIGURE 5. EFFECT OF LFC EXTENT ON PROFILE DRAG M = 0.80, Λ = 30 DEG, C_L = 0.50

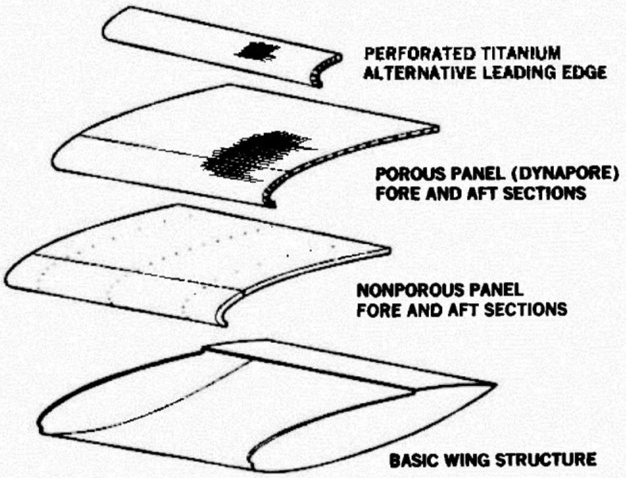

FIGURE 6. SWEPT-WING MODEL COMPONENTS

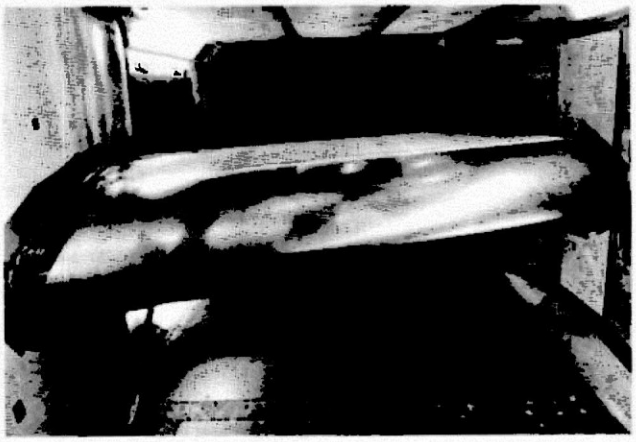

FIGURE 7. SWEPT-WING MODEL PERFORATED TITANIUM LEADING EDGE

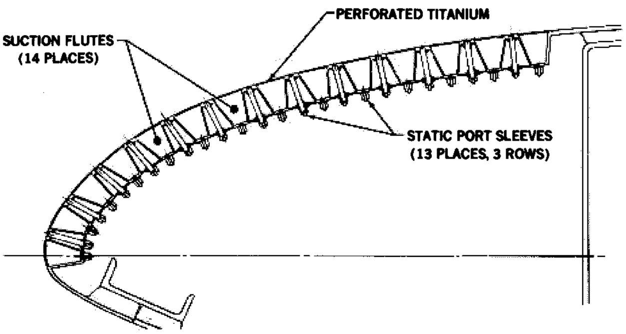

FIGURE 8. SWEPT-WING MODEL LEADING EDGE PANEL CROSS SECTION – PERFORATED TITANIUM SURFACE AND FLUTED SUBSTRUCTURE

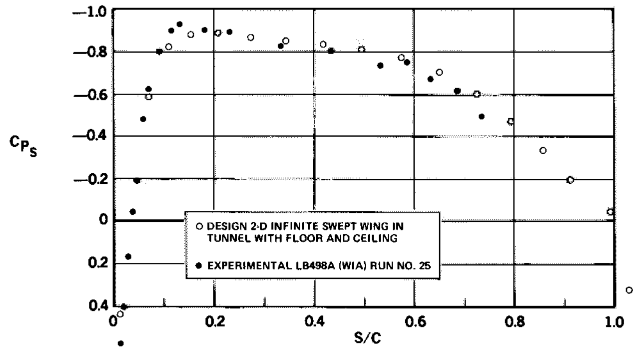

FIGURE 9. SWEPT-WING MODEL STREAMWISE PRESSURE DISTRIBUTION – q_{NOM} = 50 psf

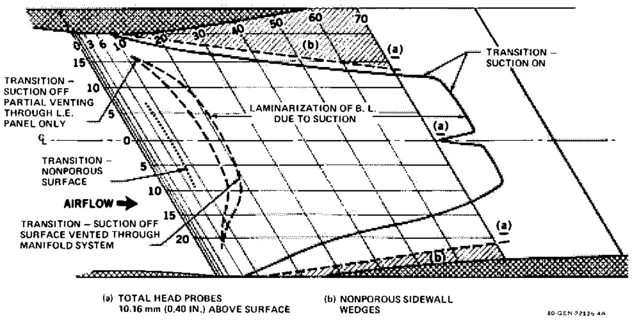

FIGURE 10. SWEPT-WING MODEL – EFFECT OF SUCTION ON TRANSITION – q_{NOM} = 50 psf

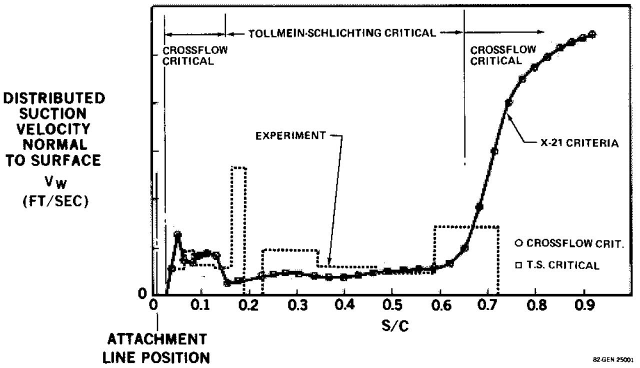

FIGURE 11. SWEPT-WING MODEL TEST SUCTION DISTRIBUTION WITH DYNAPONE LFC SURFACE q_{NOM} = 50 psf, $\sqrt{}_{\infty}$ = 216.7 fps

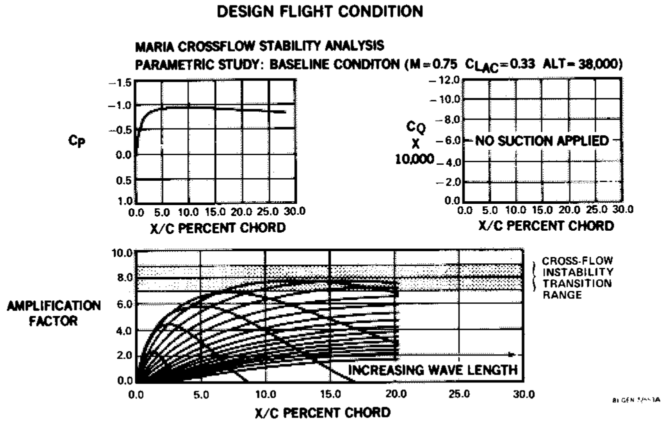

FIGURE 12. BOUNDARY LAYER STABILITY – SUCTION OFF

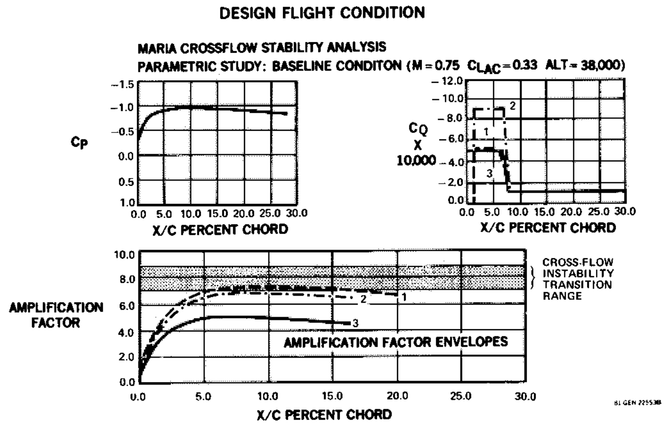

FIGURE 13. BOUNDARY LAYER STABILITY – EFFECTS OF SUCTION DISTRIBUTION

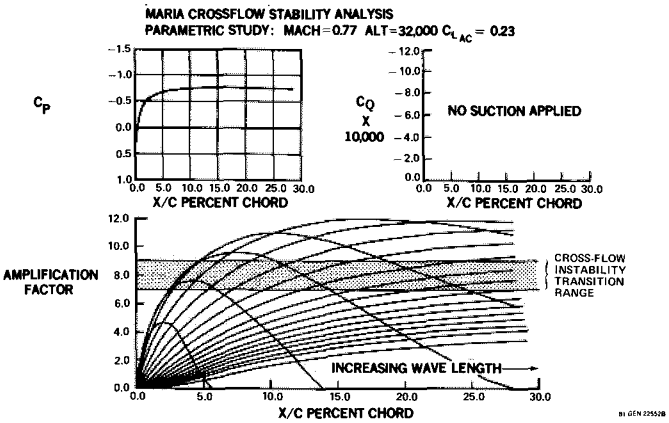

FIGURE 14. BOUNDARY LAYER STABILITY – OFF DESIGN FLIGHT CONDITION – SUCTION OFF

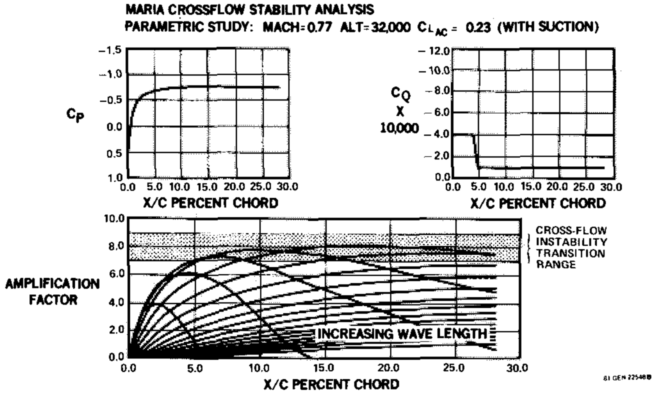

FIGURE 15. BOUNDARY LAYER STABILITY – OFF DESIGN FLIGHT CONDITION – PRIMARY SUCTION C_Q = –0.0004

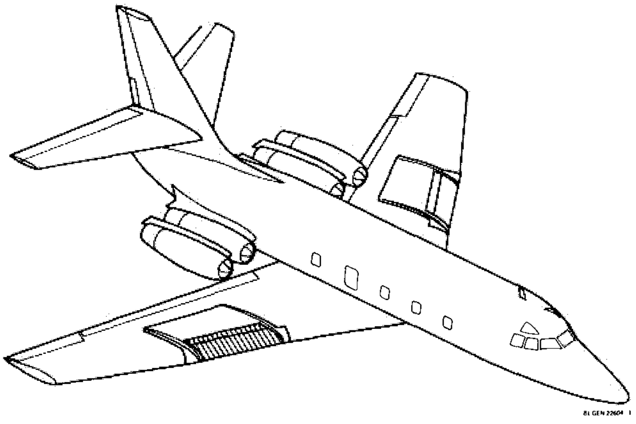

FIGURE 16. NASA JETSTAR TEST AIRPLANE