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EXTERNAL AERODYNAMIC DESIGN FOR A LAMINAR FLOW CONTROL GLOVE ON A LOCKHEED JETSTAR WING

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Abstract

A recent study contract for a subsonic laminar flow control (LFC) transport with a supercritical wing and recent Lockheed research are discussed as background information leading to the design of a JetStar part-span LFC glove to be flight-tested. The special design requirements needed to develop the glove and some of the problems encountered during the process are presented. The following topics are discussed: a method of simulating the interference effects of the body/pylons/nacelles on wing pressures when using an isolated-wing code, wind-tunnel testing of a JetStar model with a wing glove and correlation with theoretical glove pressures, and suction requirements for maintaining a laminar boundary layer.

Nomenclature

ALPHA	Angle of attack
c, C	Local wing chord or airfoil chord
C_D	Drag coefficient
C_L	Wing or airfoil lift coefficient
C_M	Pitching moment coefficient about the quarter chord
C_p	Pressure coefficient
C_q	Slot suction mass flow coefficient, $\frac{\rho_w}{\rho_\infty} \frac{v_s}{U_\infty}$
DP/Q	Pressure coefficient
DY/DX	Airfoil surface slope
f	Disturbance frequency
M	Free-stream Mach number
N-Factor	Integrated disturbance amplification rate over a distance
PSI	Sideslip angle
U_∞	Free-stream velocity
v_s	Mean slot suction velocity
w	Slot width
x/c, X/C	Fraction of chord
Y/C	Ratio of airfoil surface coordinate to chord
α	Angle of attack
η, ETA	Fraction of wing semi-span
$\Delta\theta_t$	Incremental wing twist angle - degrees
λ/C	Ratio of disturbance wavelength to chord
ρ_w	Density at the wall
ρ_∞	Free-stream density

Introduction

The recognition of potential long-term shortages of petroleum-based fuel, evidenced by dramatic increases in costs and periods of limited availability since 1972, has emphasized the need for improving the fuel efficiency of long-range transport aircraft. In 1976, in response to this need, NASA established the Aircraft Energy Efficiency (ACEE) program to develop new technology for fuel efficiency. Of all advanced technology concepts currently under consideration for application during the next two decades, laminar flow control (LFC) offers one of the greatest potentials for improving the fuel efficiency of transport aircraft. Recent studies (Ref. 1-3) have validated the potential economic advantages of LFC in an airline operations environment.

The external aerodynamic design effort summarized in this technical paper is a key element of Lockheed work in the current LFC program entitled "Laminar Flow Control Leading Edge Glove Flight - Aircraft Modification Design, Test Article Development, and Systems Integration" (LEFT). This program continues the development of leading edge systems for future LFC aircraft identified during earlier Lockheed and NASA LFC efforts.

As reflected in Figure 1, since 1962 Lockheed has engaged in a wide variety of studies and programs devoted to the development and application of laminar flow control technology. In addition to the investigations conducted jointly with Northrop in the 1960's and the contractual activities sponsored by NASA as part of the ACEE program, Lockheed has maintained continuing company-funded efforts in the development of fundamental LFC technology since 1974.

External Aerodynamic Design of the Glove

Basic Objectives of the LEFT Contract

The overall objective of the LEFT program is "to provide operational LFC leading edge systems for

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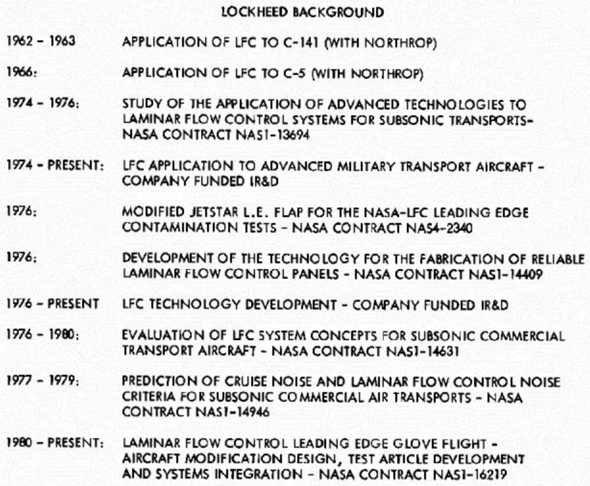


LOCKHEED BACKGROUND	
1962 - 1963	APPLICATION OF LFC TO C-141 (WITH NORTHROP)
1966:	APPLICATION OF LFC TO C-5 (WITH NORTHROP)
1974 - 1976:	STUDY OF THE APPLICATION OF ADVANCED TECHNOLOGIES TO LAMINAR FLOW CONTROL SYSTEMS FOR SUBSONIC TRANSPORTS-NASA CONTRACT NAS1-13694
1974 - PRESENT:	LFC APPLICATION TO ADVANCED MILITARY TRANSPORT AIRCRAFT - COMPANY FUNDED IR&D
1976:	MODIFIED JETSTAR L.E. FLAP FOR THE NASA-LFC LEADING EDGE CONTAMINATION TESTS - NASA CONTRACT NAS4-2340
1976:	DEVELOPMENT OF THE TECHNOLOGY FOR THE FABRICATION OF RELIABLE LAMINAR FLOW CONTROL PANELS - NASA CONTRACT NAS1-14409
1976 - PRESENT	LFC TECHNOLOGY DEVELOPMENT - COMPANY FUNDED IR&D
1976 - 1980:	EVALUATION OF LFC SYSTEM CONCEPTS FOR SUBSONIC COMMERCIAL TRANSPORT AIRCRAFT - NASA CONTRACT NAS1-14631
1977 - 1979:	PREDICTION OF CRUISE NOISE AND LAMINAR FLOW CONTROL NOISE CRITERIA FOR SUBSONIC COMMERCIAL AIR TRANSPORTS - NASA CONTRACT NAS1-14946
1980 - PRESENT:	LAMINAR FLOW CONTROL LEADING EDGE GLOVE FLIGHT - AIRCRAFT MODIFICATION DESIGN, TEST ARTICLE DEVELOPMENT AND SYSTEMS INTEGRATION - NASA CONTRACT NAS1-16219

Figure 1. Lockheed LFC Background

testing under flight conditions which are representative of future commercial LFC transport operations." In this program, Lockheed and Douglas Aircraft Company (DAC) have developed one mutually acceptable external contour for two leading-edge gloves to be fitted to a NASA-owned JetStar. A Lockheed-designed slotted surface LFC system will be installed on the left wing and a Douglas-designed porous surface LFC system will be installed on the right wing. These two gloves will simulate alternative LFC concepts for a section of the wing of the 1993 LFC transport design illustrated in Figure 2. An artist's drawing of the Lockheed glove installed on the JetStar is presented in Figure 3.

The LFC-modified JetStar will be capable of attaining cruise speeds of M = 0.7 to M = 0.8 at altitudes of 35,000 to 40,000 feet. These cruise conditions are representative of those predicted for operational LFC commercial transports in the 1990's.

Glove Geometry Constraints and Aerodynamic Requirements

The major aerodynamics challenge of the leading-edge flight test (LEFT) program was to design a part-span part-chord LFC glove to achieve a representative 1993 aircraft pressure distribution on the glove. Figure 4 shows the overall geometry of the wing and glove. Figure 5 shows the design pressure distribution. Necessary modifications to the JetStar wing include removal of the external fuel tank and the remaining wing leading-edge structure between wing stations 122 and 205. The glove contour is within these stations, with end fairings closing the glove contour to the wing surface. The glove contour was faired into the JetStar wing upper surface at the rear beam location. On the lower surface, the glove fairs into the wing at approximately 20 percent chord. Both surfaces of the Lockheed glove leading edge are slotted for controlling the boundary layer to the front beam location at 12 percent chord. This slotted area includes the region of maximum boundary layer crossflow, which would cause boundary layer transition without the suction through the slots.

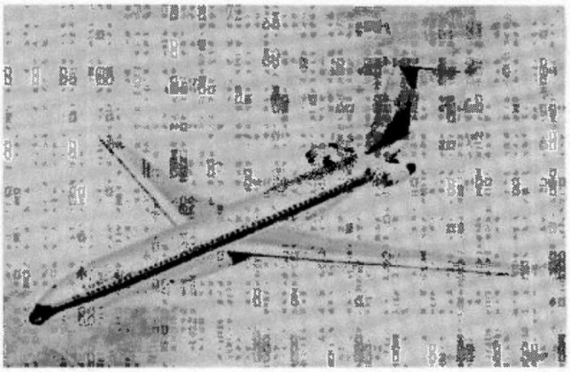


Figure 2. 1993 LFC Transport

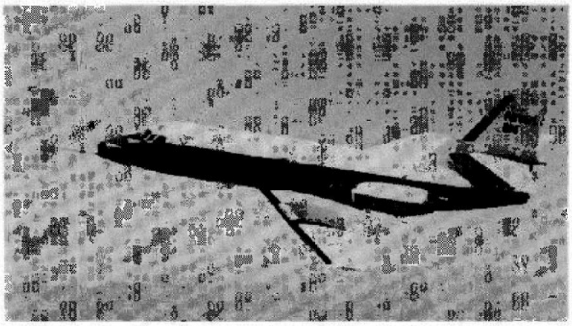


Figure 3. LFC JetStar

Basic Design Background and Approach

Maintaining laminar boundary layer flow by the use of wall suction through narrow slots or porous strips has previously been demonstrated by the early British flight test programs (Ref. 4-7) and the later Northrop programs (Ref. 8-11). However, the design and optimization of a laminar flow control airfoil requires a specialized synthesis of the different technologies of transonic aero-

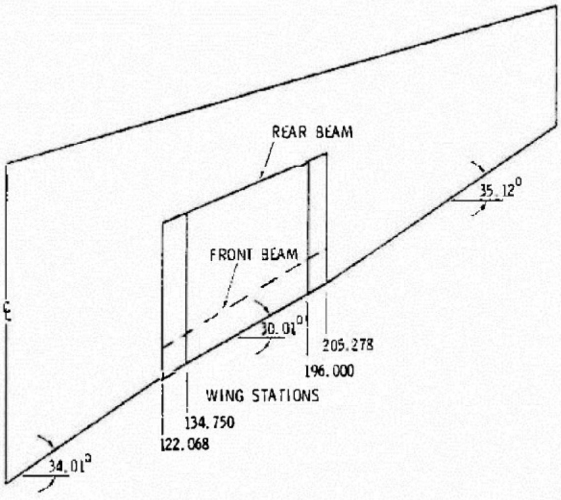


Figure 4. JetStar LEFT Wing Planform

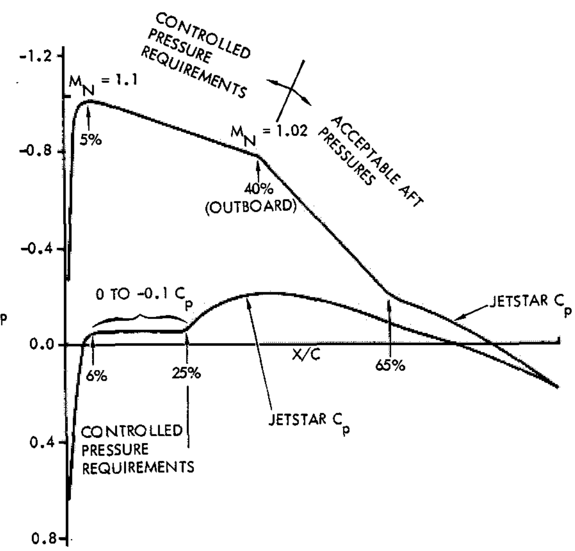


Figure 5. JetStar LEFT Design Pressure Distribution

dynamics, viscous aerodynamics, and viscous fluid mechanics. The wing geometry must not only efficiently provide the required aerodynamic qualities, but must also provide the desired hydrodynamic stability characteristics. Furthermore, the external aerodynamics must be configured to permit an economically sized suction system to control these stability characteristics so that transition is prevented in both design cruise and moderately off-design conditions.

These are difficult tasks, and success requires access to suitable design tools (primarily computer codes) and design criteria based upon sound physical principles. The following specific LFC topics have been addressed by Lockheed and others:

1. Boundary layer code development (Ref. 12-15)
2. 2-D stability analysis (Ref. 16, 17)
3. 3-D compressible stability analysis (Ref. 18)
4. Experimental and numerical investigation of suction slot flow (Ref. 19, 20)
5. The influence of sound upon stability (Ref. 21)

The interaction of various technologies is illustrated by the diagram of Figure 6, which depicts the necessary flow of design work for an LFC wing. The design problems within the dotted lines constitute what is labelled "External Aerodynamics" in the title of this paper. LFC aerodynamics work during the last eight years has been structured to address each design topic and to develop the design tools necessary for successful LFC wing design on the basis of complementary numerical and experimental studies.

Boundary Layer Code Development. Accurate calculation of the laminar boundary layer over a suction surface is a primary requirement for successful design of an LFC aircraft. Since 1974, the several boundary layer codes summarized in

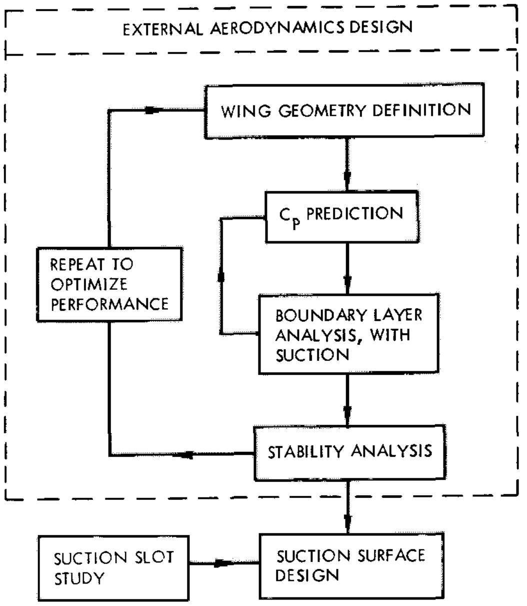


Figure 6. Laminar Flow Control Wing Design

Figure 7 have been evaluated and used in direct support of Lockheed contract work with NASA. Significant differences exist in the capabilities of each of these codes. However, formulation details of the codes make them useful for the suction surface concepts illustrated. The Nash code from Lockheed (Ref. 12) and the Cebeci/Kaups code from NASA-Langley (Ref. 14) are best suited to calculation of the boundary layer over a porous surface with distributed suction over the entire area. On the other hand, if the suction is concentrated in discrete slots or porous strips, the Beasley/Carter code from NASA-Langley (Ref. 13) and the Bennett/Malone code (Ref. 15) developed under Lockheed funding are more useful for boundary layer calculations. The Bennett/Malone code is currently used for design and analysis work. By revising the original Cebeci/Kaups code to represent the discrete suction surfaces, a better description of the boundary layer is obtained while still maintaining close agreement of boundary layer results with results from the original code for the case of distributed suction.

YEAR	BOUNDARY LAYER CODE
1975	NASH (LOCKHEED)
1976	BEASLEY/CARTER (NASA-LANGLEY)
1977	CEBECI (NASA-LANGLEY)
1979	BENNETT/MALONE (LOCKHEED MODIFICATIONS OF CEBECI/KAUPS)

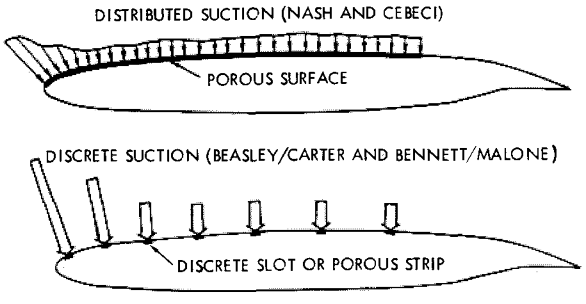


Figure 7. Boundary Layer Analysis Methods

Stability Code Development. Early LFC design work (Ref. 22) utilized the Srokowski and Orszag stability code, "SALLY" (Ref. 17). This code provides capability for evaluation of both cross-flow and Tollmien-Schlichting instabilities. Incompressible conditions are assumed for stability calculations in this code. A Lockheed compressible stability code developed later by Lekoudis (Ref. 18) demonstrated that SALLY code instability growth values were slightly larger than values calculated with compressibility considered. Because of the many uncertainties involved in stability calculations and the significantly greater computational cost for the compressible code, effort was concentrated on use of the SALLY code for all subsequent stability work. An updated version of the code called "SALLY II" has been used since 1978 for stability calculations.

Final Glove Design

Preliminary aerodynamic design of the JetStar LFC glove during feasibility study work revealed the need for improved aerodynamic methodology for estimating the flow field distortion effects in the LFC glove region because of the presence of body, pylons, and nacelles. This need arises from the relatively low aspect ratio of the JetStar wing and the close proximity of the body, nacelles, and pylons to the test area when compared with the 1993 transport being simulated. At the time glove design work was initiated, a transonic pressure prediction code with wing/body/nacelle analysis capability was not available. This fact required development of a method for accounting for body/pylon/nacelle effects which could be used in conjunction with an existing wing-alone or wing/body transonic code.

A survey of available transonic codes revealed that of the codes summarized in Figure 8 (Ref. 23-25), only the FL022 transonic wing code was readily available and also fully compatible with NASA-Langley and Douglas methods. The Lockheed-Georgia version of the FL022 pressure code is internally coupled with the Nash-MacDonald boundary layer code and is known as FL022NM (Ref. 26). This code was chosen for use in the final design of the glove in the place of the Bailey-Ballhaus-3 (TWP) code (Ref. 23), which was used in early design efforts.

In preparation for final design work, NASA-Langley modified an existing Lockheed wind-tunnel model of the JetStar to incorporate a Lockheed-designed preliminary glove configuration and tested the configuration at high speed. Data from this test provided initial validation of a method developed by Lockheed for accounting for body/pylon/nacelle pressure effects in the glove region. This method is called "The Equivalent Wing Perturbation Method."

CODE	APPLICATION	FLOW EQUATIONS	BOUNDARY CONDITIONS	ORIGIN
BAILEY-BALLHAUS 1	WING	CLASSICAL SMALL DISTURBANCE	SMALL DISTURBANCE	NASA-AMES
BAILEY-BALLHAUS 3 (TWP)	WING-BODY	EXTENDED SMALL DISTURBANCE	SMALL DISTURBANCE	NASA-AMES
BAILEY-BALLHAUS 5	WING-BODY	FULL X-Y POTENTIAL	SMALL DISTURBANCE	NASA-AMES
BOPPE	WING	EXTENDED SMALL DISTURBANCE	SMALL DISTURBANCE	NASA-LANGLEY
JAMESON (FLO22)	WING	FULL POTENTIAL	EXACT	NASA-LANGLEY/NYU

Figure 8. Transonic Code Survey

The Equivalent Wing Perburbation Method. The basic concepts underlying the equivalent wing perturbation method are that:

1. The basic thickness shape, camber shape, and incidence of an actual airfoil shape can be modified to an equivalent airfoil which has surface pressures matching those of the actual airfoil immersed in a non-uniform flow field.

2. Even though subsonic flow methods are used in deriving the airfoil shape and incidence changes necessary to simulate the non-uniform flow field velocities, the shape perturbations will produce the proper non-uniform free-stream flow pressure increments if evaluated with a transonic pressure code.

3. To derive a perturbation method quickly enough to be of use in an ongoing project, previously developed, well-correlated calculation methods have to be linked in a series calculation procedure.

A search was made of readily available, well-correlated Lockheed computer codes to identify code elements that could be used for:

1. Estimating and checking wing surface pressure increments because of the interfering remote flow field of other components located at a moderate distance from the surface under consideration.

2. Calculating the airfoil shape and incidence changes necessary to simulate the indicated remote field pressure increments.

The search and subsequent analysis indicated that the Hess subsonic pressure code, available at both NASA-Langley and Lockheed, and three existing Lockheed airfoil design and analysis codes (Ref. 27-29) could be linked with simple interfacing input and output codes into the desired equivalent wing perturbation method. Figure 9 shows the overall flow of calculations in the method.

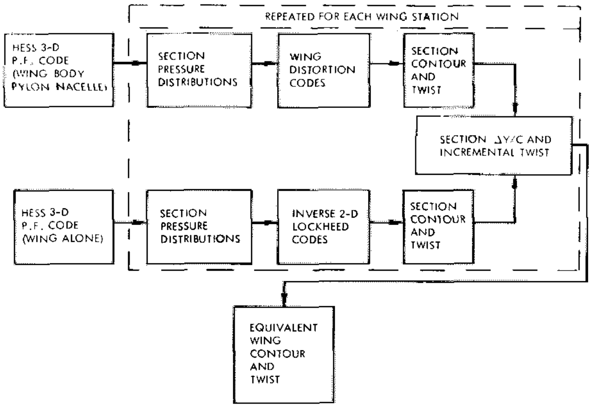


Figure 9. Flow Diagram of Equivalent Wing Method

First, a preliminary wing-alone and wing-plus-other-components geometries are prepared for input to the Hess code as depicted in Figures 10 and 11. Hess code calculations are then performed for both configurations. Airfoil section geometry and pressure distributions at a number of spanwise stations are output to computer storage files for each of these runs. Automated plots of the geometries and pressures are performed as illustrated in Figures 12 and 13, so that a visual check can be made for any possible data file errors. For the JetStar glove design case, airfoil section perturbations at 15 wing stations were made to derive the equivalent wing. Therefore, 15 sets of plots of the type shown were generated. The wing airfoil section pressure plots illustrated are for the wing station closest to the wing/body intersection. This station has the largest pressure changes because of the body/pylon/nacelle interference. Comparison of the wing-alone pressure with the wing/body/pylon/nacelle pressures in Figure 13 shows the significant loss of aft loading and increase of lower surface velocities caused by the body/pylon/nacelle interference.

Next, an actual wing section and its two sets of pressures are input to the interfaced set of wing distortion codes to distort the original Hess output airfoil section shape into an equivalent airfoil. This process is illustrated in Figure 14 for JetStar wing station 59. The process uses small perturbation assumptions in the distortion codes to derive the perturbations by calculating two theoretical airfoils, one with interference effects and one without. The geometry and incidence changes because of interference are then derived as simple differences between the two cases and added to the original contour to produce the "equivalent airfoil." Note the significant shape change produced.

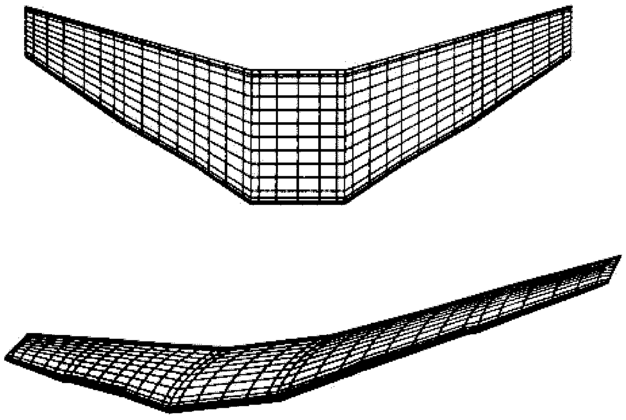


Figure 10. GELAC Hess Code Wing Representation

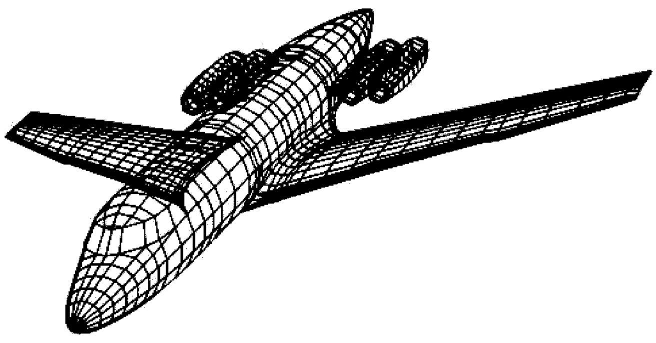


Figure 11. GELAC Hess Code Wing/Body/Pylon/Nacelle Representation

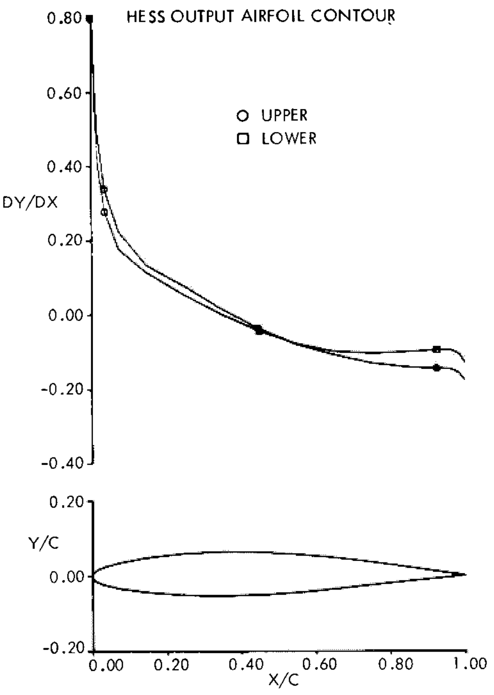


Figure 12. Hess Output Airfoil Contour Used as Input to Wing Distortion Codes - WS 59

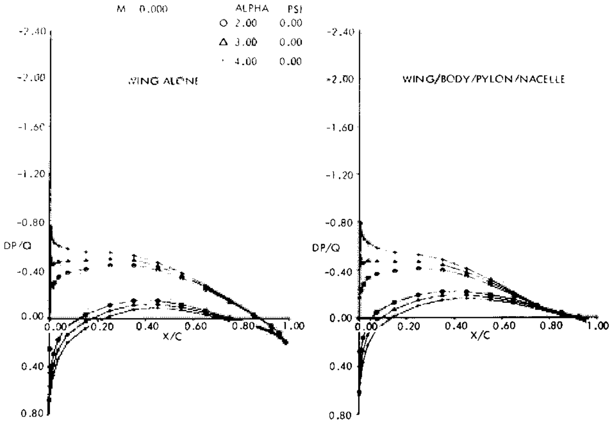


Figure 13. Comparison of Hess Outputs at Eta = 0.185 (WS 59)

Then, the original Hess code wing-alone input geometry is replaced by the complete series of "equivalent airfoils," producing the geometry shown in Figure 15. Hess calculations are next performed and the equivalent wing pressure output compared to the wing-alone and the complete configuration pressures as illustrated in Figure 16. The procedure has produced an equivalent wing which has almost the same surface pressures as the total configuration at Wing Station 59. This station is typical of the fifteen wing stations evaluated. A similar comparison is shown in Figure 17 for Wing Station 224, which is just outboard of the area of the LFC glove modification.

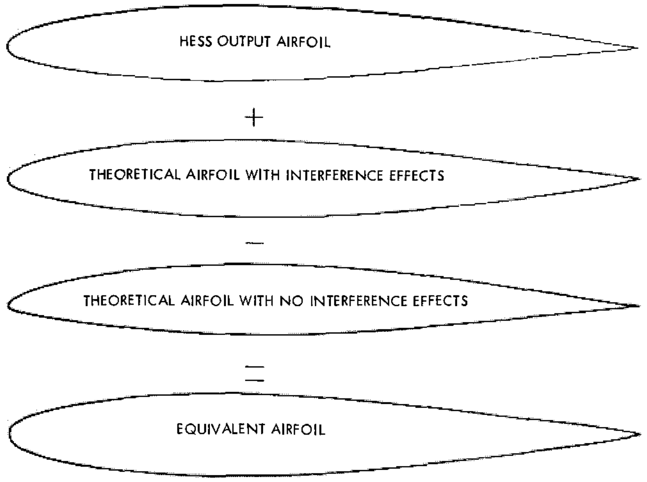


Figure 14. Pictorial Representation of Wing Distortion Process - WS 59

Pressures estimated for several angles of attack for each of the configurations are shown in Figure 13. These data are used to make slight adjustments to the incidence angle of each wing station to further refine the agreement between the equivalent wing pressures and the total configuration pressures at each station. The final twist angle adjustment schedule is illustrated in Figure 18. Using this twist adjustment schedule, a final equivalent wing geometry can be determined as indicated in Figure 9. This geometry then may be input to a transonic wing-alone code.

In developing the equivalent wing method, the TWP pressure code was used for equivalent wing calculations at the basic transonic design Mach number and lift coefficient. The TWP results for wing-alone and total configuration were then compared to the limited amount of wing pressure data available from NASA wind-tunnel tests of the JetStar with a preliminary glove configuration. Correlation of estimated and test pressures was found to be greatly improved by use of the equivalent wing perturbation method. The shock movement caused by addition of the pylon/nacelle combination to the basic JetStar wing/body model was well approximated and therefore the method was considered to be verified and adequate for use in the final glove design and analysis.

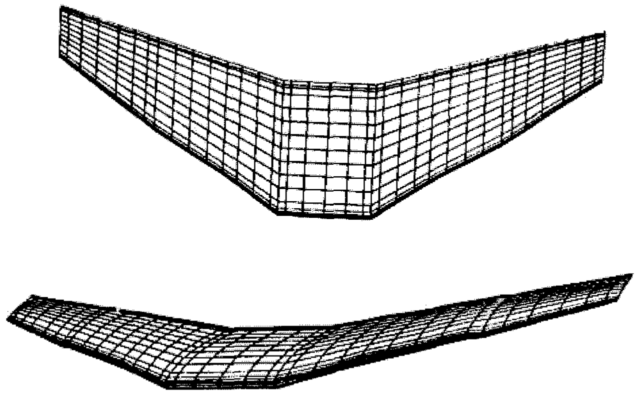


Figure 15. Hess Code Representation of Wing Distorted to Account for Body/Pylon/Nacelle Interference

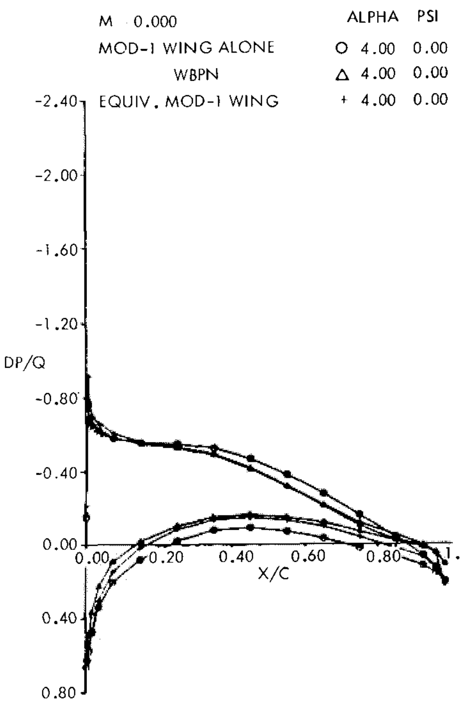


Figure 16. JetStar Equivalent Wing Comparison - Eta = 0.185 (WS 59)

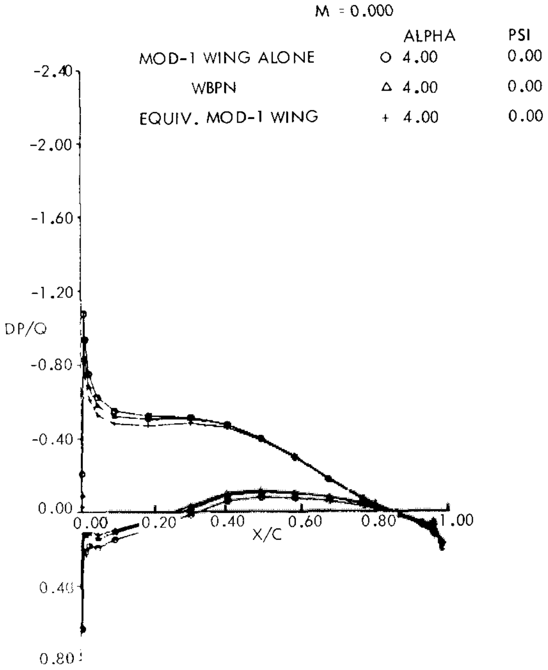


Figure 17. JetStar Equivalent Wing Comparison - Eta = 0.699 (WS 224)

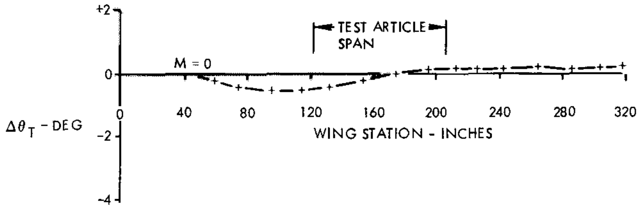


Figure 18. JetStar Wing/Body Plus Pylons/Nacelles Effective Twist Distribution

Detailed Design Process. Because the LFC glove aerodynamic design problem required definition of a new contour over a portion of an existing wing, the use of complete-wing design programs was not appropriate for initial or final contour design work. A contour perturbation method, involving the Lockheed inverse two-dimensional subsonic code based on NACA "a" mean-line theory (Ref. 30, 31) was used to define initial glove contours. Later detailed design efforts were accomplished in a cooperative effort with Douglas using a DAC transonic wing design code (Ref. 32) with results cross-checked by use of Lockheed codes. This cooperative approach avoided any potential disagreements between Douglas and Lockheed regarding acceptability of the glove contours.

Pressure distributions were calculated using the FL022NM code at both Douglas and Lockheed. The Lockheed input geometry for glove sections was defined at wing stations identical to those output by FL022NM. This approach ensures compatibility of geometry and pressure data for design code calculations without spanwise interpolations of pressure results. The actual Lockheed section geometry inputs were corrected by adding equivalent wing geometry increments to account for the body/pylon/nacelle interference effects.

The overall design process involved resolution of five closely-interacting types of design requirements:

(1) chordwise pressure distribution

(2) spanwise pressure gradients

(3) suction distribution

(4) boundary layer profile and stability

(5) JetStar geometry constraints

The design process for resolving conflicting requirements in the above areas is depicted in Figure 19.

Starting with a preliminary wing loft, as noted in Block 1, and using an initial glove geometry definition, the equivalent wing perturbation method was exercised, as indicated in Block 2, to produce the equivalent wing geometry noted in Block 3. This equivalent wing geometry was then input to FL022NM, as indicated in Block 4, to estimate section pressure distributions at the basic wing/glove design point. As shown by the block indicating a chordwise pressure distribution check, the inverse code was used for redesign of wing/glove control stations if the estimated pressures were not satisfactory. The redesigned control stations were then used to reloft the actual glove portion of the wing as shown in Block 5, the equivalent wing corrections were again made, and the pressure distributions were again calculated for the revised glove. Check of the output pressures against the chordwise pressure

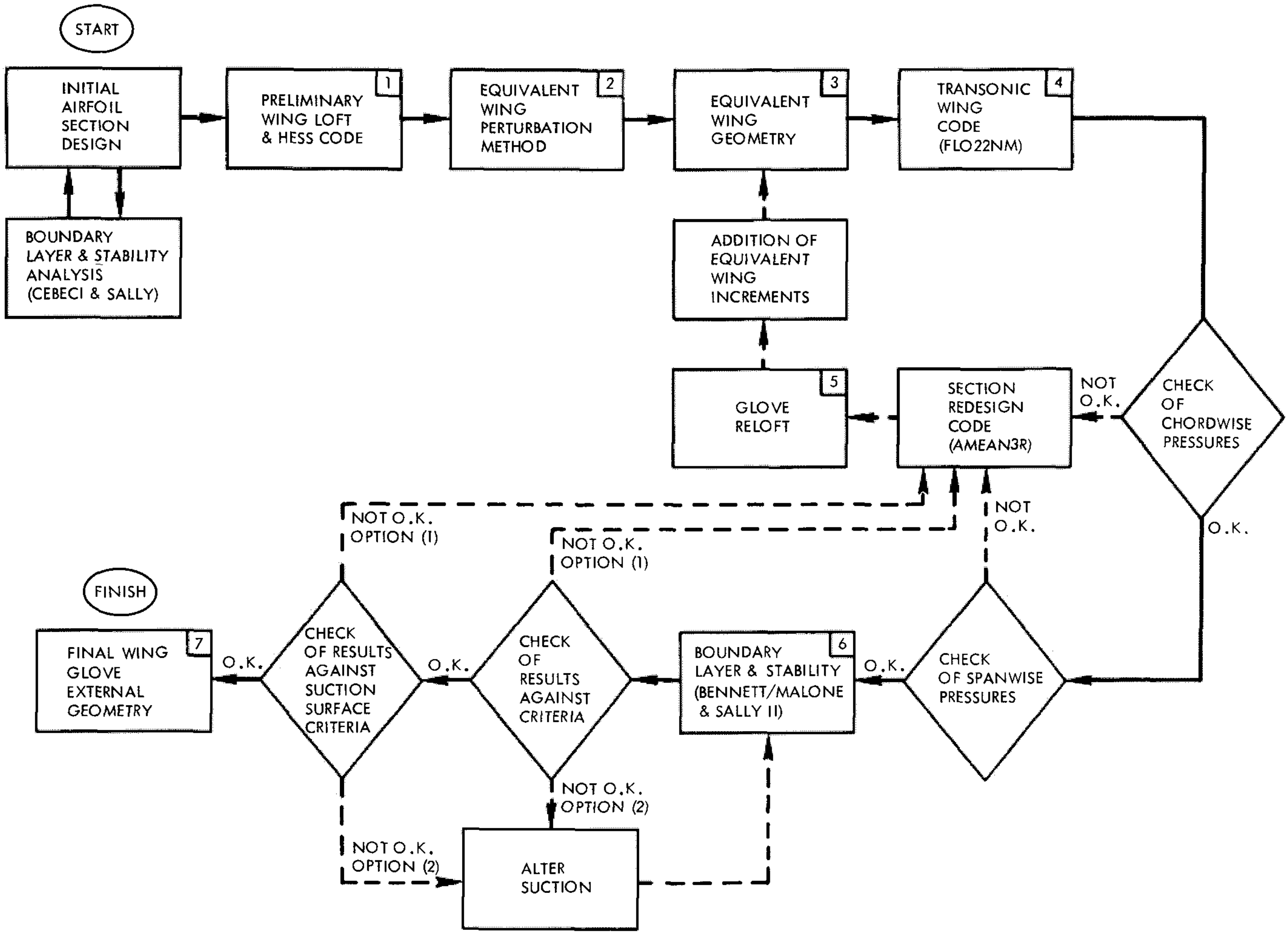


Figure 19. Final Glove Design Flow Chart

design objective was repeated and redesign was continued until satisfactory chordwise pressures were obtained.

When chordwise pressures were satisfactory at each wing station, the spanwise pressure variation along the lengths of the suction slots was checked against X-21 criteria (Ref. 11) to assure that excessive spanwise pressure gradients were avoided. Redesign of the control station sections to avoid excessive spanwise pressure gradients was repeated as illustrated until satisfactory.

Next, boundary layer calculations and stability analyses were performed as indicated in Block 6. These calculations were made using the Bennett/Malone boundary layer code and the SALLY stability code. The amplification N-factors for the laminar boundary layer were then checked against allowable limits. If not satisfactory, either the pressure distribution was slightly altered as indicated by Option (1), or the suction distribution was altered as indicated by Option (2). The indicated redesigns were thus repeated until the calculated N-factors were within allowable limits.

At this point the external aerodynamic design was considered complete, except for the indicated final suction surface design criteria checks. Two possible methods were available if required to allow successful slotted suction surface design as follows:

Option (1) - change glove pressures
Option (2) - change glove suction

In the actual design case, only glove suction changes were necessary to allow satisfactory suction surface design. The wing glove external aerodynamics design was complete at this point and all necessary data were available for suction surface, ducting, and suction pump design.

Difficulties in Definition of LFC Glove Geometry. Much of the aerodynamic design effort involved defining the contour at the outboard station of the glove. It proved to be much more difficult to achieve the desired pressure distribution on the outboard portion of the glove than the inboard portion. There were several reasons for this difficulty. The glove thickness was much greater than the JetStar wing at the outboard glove station. Additionally, the basic JetStar wing pressure distributions outboard of the glove were considerably different from those desired on the glove. This difference produced a strong three-dimensional effect adverse to achieving the desired pressure distributions on the outboard portions of the glove. Figure 20 shows an isometric view of the upper surface pressure distributions at various stations across the wing. Note the pressure spike followed by the "sway-back" pressure distribution in the leading-edge region for the outboard portion of the basic JetStar wing. It was this pressure characteristic which greatly influenced pressures on the outboard sections of the glove.

Laminar Boundary Layer Stability Considerations

As experience was gained using the boundary layer codes and stability codes, problem areas were identified regarding code usage and interpretation of output data. These were: (1) the number of input pressure values and their chordwise spacing, and (2) the determination of the stagnation pressure and its location. The Cebeci/Kaups code was sensitive to the number of input values from two-dimensional and three-dimensional pressure codes. It was decided that for the three-dimensional FL022NM output, using every point gave the most reasonable answers.

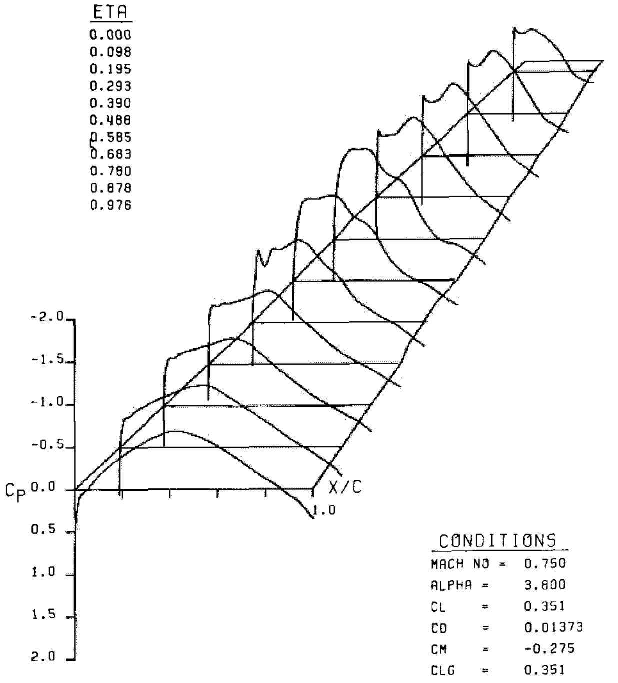


Figure 20. LFC JetStar Wing Pressures from FL022NM Calculations

The determination of the stagnation pressure and location, from FL022NM data at a given wing station, had a large effect on the amplification N-factors calculated by the SALLY code. The method used to determine this corrected stagnation point is shown in Figure 21. The pressures are plotted against $\sqrt{X/C}$ to expand the scale. A smooth curve is faired through the data. The zero slope tangent at the point of highest positive pressure defines the corrected stagnation pressure and location. The effect on stability predictions of varying the stagnation pressure and location over a relatively small range of values is shown in Figure 22. Another investigation studied the effect of substituting the graphically determined stagnation pressure in place of the value indicated by FL022NM, as opposed to inserting the graphically determined value into the calculated pressure array while also retaining the point calculated by FL022NM. Results of this study indicated that it would be conservative to insert a corrected stagnation value into the FL022NM pressure array.

Initially, all SALLY runs were made using the envelope mode. However, as the glove contours became more established, SALLY was also run in the fixed-wavelength mode. Both modes were run to ensure an adequate suction distribution. With the agreement of NASA-Langley personnel, a predicted critical N-factor value of 11 was established for the envelope mode and 8 for the fixed wavelength mode. Neither mode was found to be consistently more critical than the other when compared to the appropriate critical value.

When running in the fixed-wavelength mode, an investigation should first be made to determine the critical wavelength. Figure 23 shows the results of this type study for the glove contour and suction distribution established just prior to the Calspan wind-tunnel test. The most critical non-dimensionalized wavelength is seen to be 0.0006. As can also be seen, the frequency of the input disturbance has only a small effect on the calculated N-factors. Typically, the N-factors calculated by the fixed wavelength mode will approach critical values at a much closer distance from the wing leading-edge than will those N-factors calculated by the envelope mode. This is illustrated in typical comparisons shown in Figure 24. However, as previously stated, neither mode was found to be consistently more critical than the other.

JetStar LFC Model Calspan Wind Tunnel Test

In order to verify the wing/glove design, a 0.10-scale model of the JetStar was modified and tested by Lockheed in the Calspan 8-foot transonic wind tunnel (Ref. 33). The model had a 64-inch wing span and a 13-inch mean aerodynamic chord. The glove contours were made of a hard plastic resin which was built onto the original steel wing. Both sides of the wing incorporated the same glove contours, but only the left glove contained pressure taps. Although the glove contour was designed for the use of suction to control the boundary layer, no provision for suction was made for the test. There were several major objectives of the test, but the one which this paper addresses required obtaining measured pressure distributions on the glove for correlation with equivalent wing theoretical data.

Pretest checks of the glove contour showed significant deviations from the specified contour. A contributing cause to the inaccuracies may have been that a very tight manufacturing schedule resulted in the contours being inspected and approved before the resin used to make the glove had fully cured. As expected, because of the contour deviations the experimental pressure distributions did not match required distributions well enough to verify the glove design or design methodology. To correct the contour problem and complete the test in a timely manner, a series of systematic in-tunnel changes were made to the glove by filing down some areas and filling in other areas. Dr. Richard Whitcomb, who was among those monitoring the test for NASA-Langley, provided his valuable experience in helping to alter the glove contour. Each new contour modification was based on the change in pressure distribution resulting from the previous modification. Upon test completion, the model was returned to Lockheed where the glove

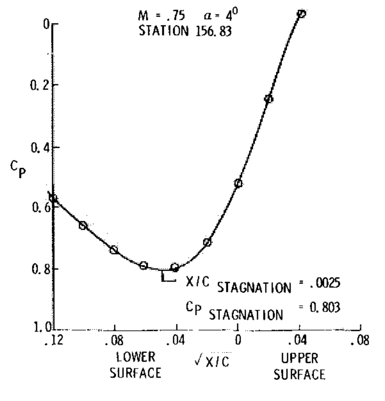


Figure 21. Stagnation Point Location Method

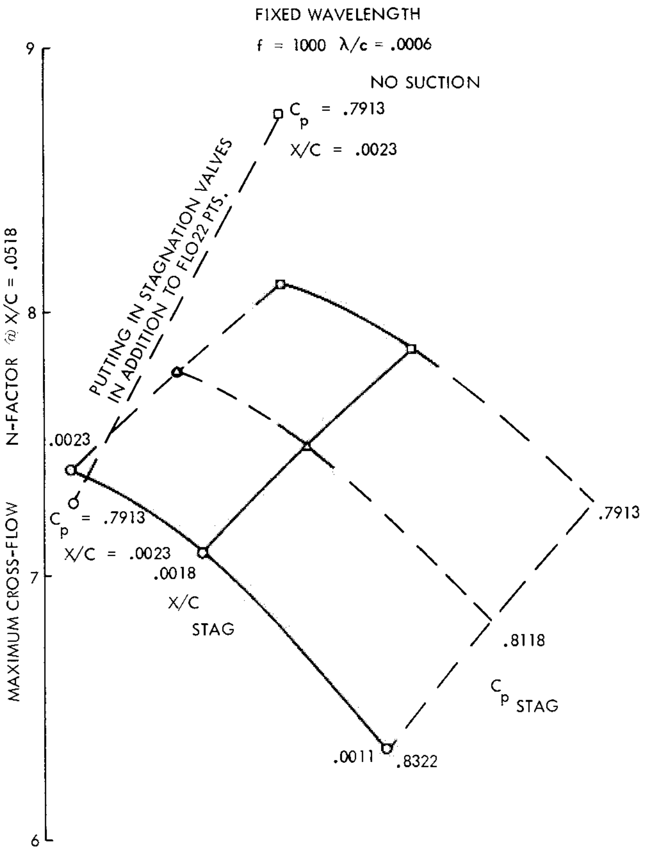


Figure 22. Effect of Stagnation Pressure Values and Location on Maximum N-Factors

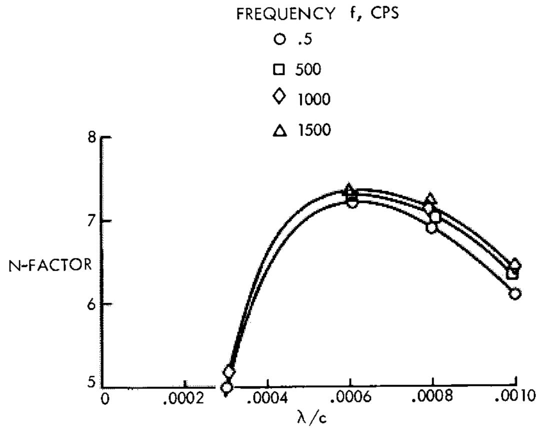


Figure 23. Cross-Flow Maximum N-Factors

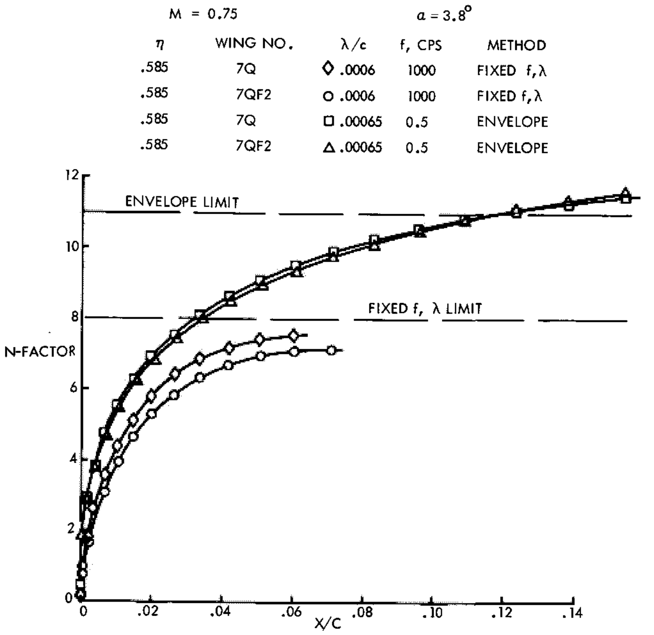


Figure 24. Cross-Flow Instability Growth

contours were carefully measured on a Cordax machine.

Figure 25 compares the experimental pressure distributions for the pretest model glove contour and the final tested contour. Pressures on the model before contour changes had a high forward spike and were very wavy. The main effect of the in-tunnel recontouring was a smoothing of the pressure distributions.

Theoretical pressure distributions for the final contours were compared to experimental values to validate the equivalent wing methodology. Figure 26 compares equivalent wing theoretical pressures from FL022NM with experimental data for pylon/nacelles off and on. The interference effects of the pylon/nacelles lower the leading edge pressure peak and move the shock wave forward. The FL022NM equivalent wing pressures match experimental values quite well, especially back to 20 percent chord, which is aft of the region where active suction will occur for the flight test glove. The waviness of the FL022NM pressures is a result of the slightly non-smooth contour produced by the in-tunnel recontouring. The code is very sensitive to non-smooth surfaces.

Figures 27 and 28 show the data correlation near the design point across the span of the glove. Generally there is good correlation in the region where active suction will occur. The equivalent wing representation must also be valid at conditions other than the design point. Figure 29 shows a comparison at an end-cruise condition, a Mach 0.70 condition, and a Mach 0.77 condition. In each case good correlation is obtained for the extent of the active suction region.

Final Adjustments to Glove Design. Subsequent to the wind tunnel test, final adjustments were made to the glove design as described in Reference 34. The final glove control stations are shown in Figure 30. Two major changes were made to the measured wind-tunnel model glove contours to define these control stations. These changes were:

1. The contours were smoothed analytically by Douglas Aircraft personnel to reduce the waviness of the calculated pressure distributions.
2. The outboard control station contour was altered slightly in the 2 percent chord region to decrease the spanwise pressure gradient, thus minimizing potential slot design problems.

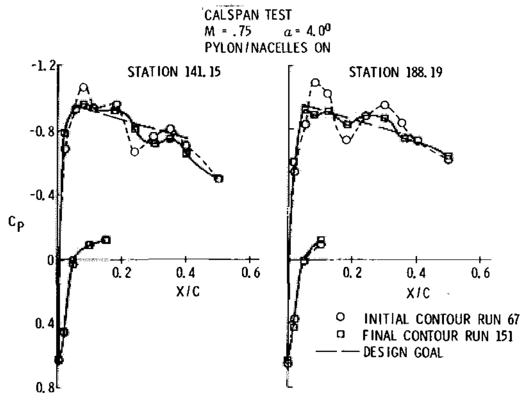


Figure 25. Effect of Recontouring During Wind-Tunnel Testing

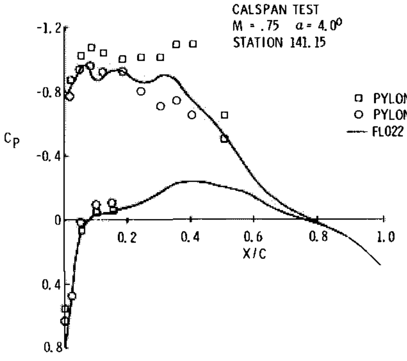


Figure 26. Effect of Pylon/Nacelles on Pressures

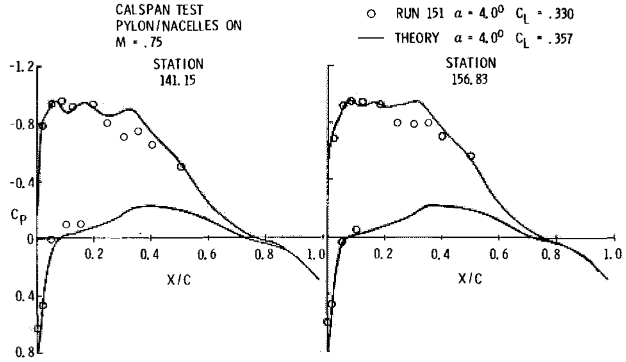


Figure 27. Pressure Data Correlation for Inboard Stations

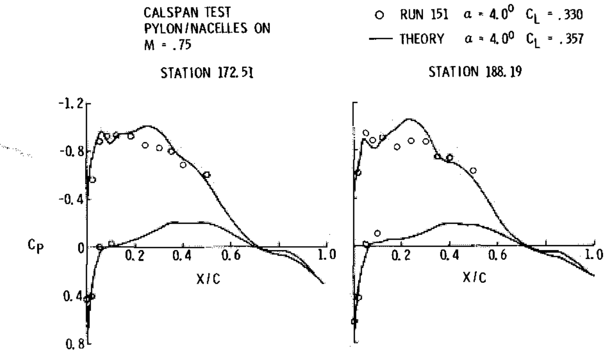


Figure 28. Pressure Data Correlation for Outboard Stations

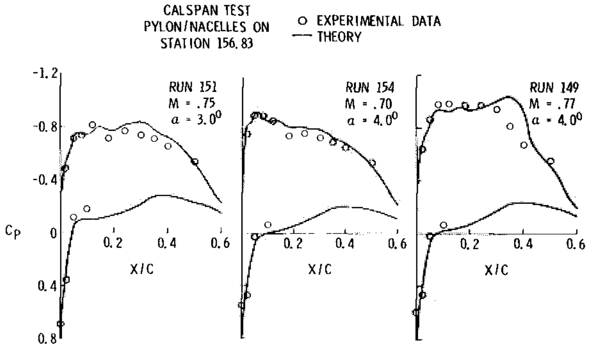
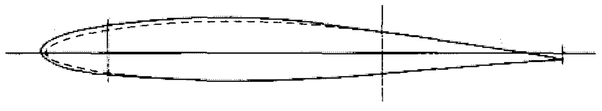


Figure 29. Off-Design Data Correlation



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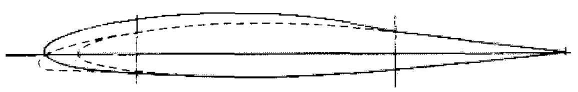

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Figure 30. Final LFC Glove Contours

Theoretical design point pressure distributions for the final glove contours are shown in Figure 31. Required suction distributions were established using these pressure distributions. The final design suction distributions are shown in Figure 32.

Final boundary layer crossflow stability estimates at the design point are shown in Figure 33 for the envelope method and in Figure 34 for the fixed wavelength method. Both figures show the results for four stations on the glove. The envelope method and the fixed wavelength method indicate that the stability is less critical on the outboard portions of the glove. However, while the envelope method indicates that critical levels are never reached anywhere on the glove, the fixed wavelength method does indicate the critical crossflow N-factor levels are just approached at the inboard station. Calculations of the Tollmien-Schlichting N-factor levels indicated that these levels are significantly below critical values.

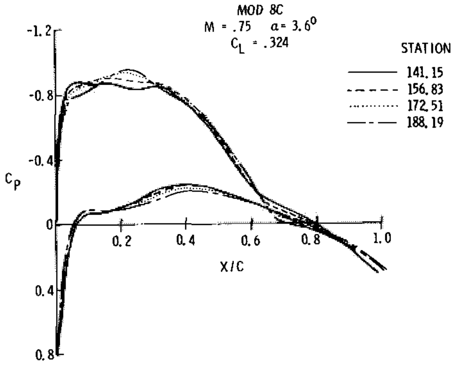

Figure 31. Mid-Cruise Pressure Distributions

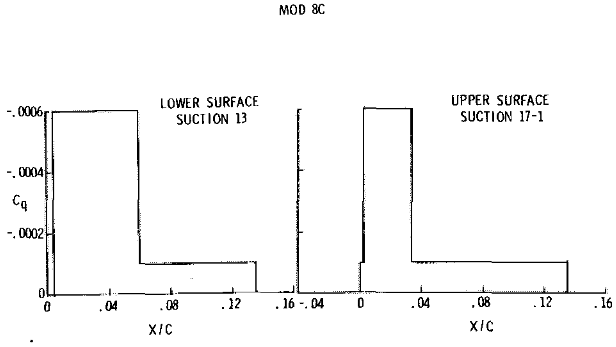

Figure 32. Final Design Point Suction Distributions

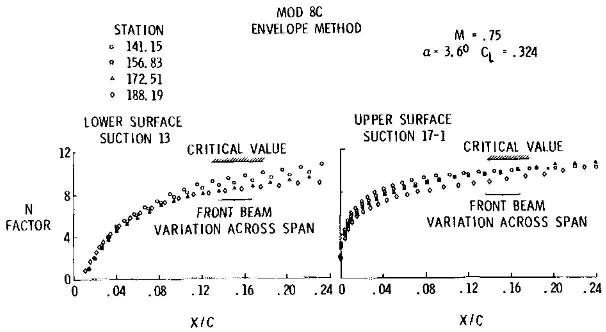

Figure 33. Mid-Cruise Crossflow N-Factors

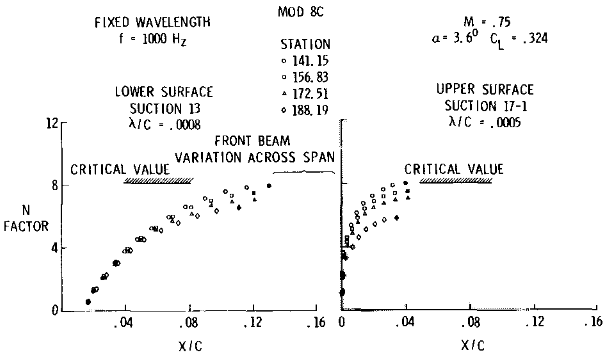

Figure 34. Mid-Cruise Crossflow N-Factors

Concluding Remarks

Since the Northrop X-21A laminar flow control (LFC) demonstration program, many advances in computer codes have been made. During a joint NASA-Lockheed program, Lockheed has developed a design process for LFC wings using computer codes available in the late 1970's. Based on use of this design process, the following comments are offered:

- A good correlation of wind-tunnel data for the LFC JetStar glove with wing-alone analytical data was obtained by use of the "Equivalent Wing Method." Additional code development is required for more accurate analysis of closely-coupled wing/body/pylon/nacelle configurations.
- Boundary layer stability results using the SALLY code indicate that the JetStar LFC glove will permit achievement of laminar flow.
- Although good progress has been made on development of computer codes, a significant amount of work needs to be done to develop better LFC design criteria. Results of currently planned NASA-Langley large-scale LFC model wind-tunnel testing should provide a good first step toward experimental derivation of updated design criteria. Additional experiments in the future would be useful in establishing updated design criteria and improved computational methods.

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