# Some Recent Applications of High-Lift Computational Methods at Boeing

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**An overview of the long-term research effort at Boeing which has led to the development of a quasi-three-dimensional viscous flow computational analysis/design methodology for multielement high-lift wing/body combinations is presented. Three examples of the application of this methodology are discussed: 1) design of a variable thickness airfoil, 2) takeoff lift-to-drag ratio improvement of a transport aircraft, and 3) maximum lift improvement of a multielement flapped wing.**

## Nomenclature

| | |
|---|---|
| $b$ | = wing span |
| $c$ | = basic cruise wing or airfoil chord |
| $c'$ | = wing chord, with slats/flaps extended |
| $c_d, c_l, c_m$ | = two-dimensional (section) drag, lift, and pitching moment coefficients, force/$qc$ and moment/$qc^2$ |
| $C_D, C_L, C_M$ | = three-dimensional configuration drag, lift, and pitching moment coefficient, force/$qS$ and moment/$qSc$ |
| $C_p$ | = pressure coefficient, $\Delta p/q_\infty = (P_{\text{local}} - P_\infty)/q_\infty$ |
| $H$ | = boundary-layer form parameter $= \delta^*/\theta$ |
| $L/D$ | = ratio of lift to drag |
| $M$ | = Mach number |
| $p$ | = static pressure |
| $q$ | = dynamic pressure |
| $Re$ | = Reynolds number |
| $S$ | = wing area |
| $t$ | = airfoil thickness |
| $x$ | = longitudinal coordinate |
| $y$ | = lateral coordinate |
| $\alpha$ | = angle of attack |
| $\delta^*$ | = boundary-layer displacement thickness |
| $\delta_f$ | = flap deflection angle |
| $\eta$ | = nondimensional spanwise coordinate $= 2y/b$ |
| $\theta$ | = boundary-layer momentum thickness |
| $\Lambda$ | = wing sweep angle measured at wing quarter-chord |

*Subscripts*

| | |
|---|---|
| eff | = "effective" viscous condition |
| geo | = geometric value |
| $o$ | = baseline configuration |
| max | = maximum |
| $r$ | = point at which pressure recovery to freestream conditions begins on an airfoil |
| $\infty$ | = freestream condition |

## Introduction

As transport aircraft technology has matured, increasingly stringent requirements have been imposed upon the design of high-lift systems as these aircraft have become increasingly point designed in the interest of improved cruise efficiency. Traditional airplane performance and cost requirements have also been supplemented with increasingly severe operational (e.g., noise and wake turbulence), safety, and regulatory constraints. The time-honored high-lift design and optimization procedure which relied largely on an iterative wind tunnel testing process, with extrapolation of results to full-scale conditions based on empirical data from past aircraft of similar type, has become inadequate. It has been recognized that computational methods for both the analysis and design of high-lift configured wings over a wide range of scale conditions is an essential element of any modern development process.

For the past seven years, the high-lift technology group within the Aerodynamics Research Unit at Boeing has been developing several powerful computational methods for the design and analysis of both two-dimensional multielement airfoils and corresponding three-dimensional swept wings. In addition, a major effort has been made to apply these emerging methods to practical, project oriented, high-lift design problems. A recent general overview of this work has been published by J.L. Lundry.[1] The purpose of the present paper is to describe the specific results of three applications of the recently developed computational methods to practical high-lift design problems.

Efforts to produce the computational elements of a rational overall high-lift design capability have developed the following fruits.

1) An accurate, reliable, and user-oriented lifting surface theory computer program for the analysis and design of three-dimensional multielement wings in potential flow has been developed. The method, developed by M.I. Goldhammer,[2] utilizes a distributed vorticity singularity and has been specifically tailored to high-lift applications. The program is highly automated and the user need only specify gross geometric parameters for multielement wings (e.g., planform, twist, camber, flap deflection) and the program generates its own detailed vorticity networks. The singularity automatically satisfies the Kutta condition at each trailing edge. A two-dimensional algorithm is used by the program to specify the downstream path of shed vorticity. Provision is made for multielement wings with part span flaps, a slender body, and a ring-wing representation of nacelles. Wing thickness is not accounted for. The program has both analysis and design (inverse) capabilities. Typical test-theory comparison results obtained from use of the program are shown in Fig. 1.

2) A computer program system has been developed for the analysis and design of two-dimensional multielement airfoil sections in viscous flow, including the calculation of the effects of large-scale flow separation from one or more airfoil elements. This method, developed by M.L. Henderson,[3]

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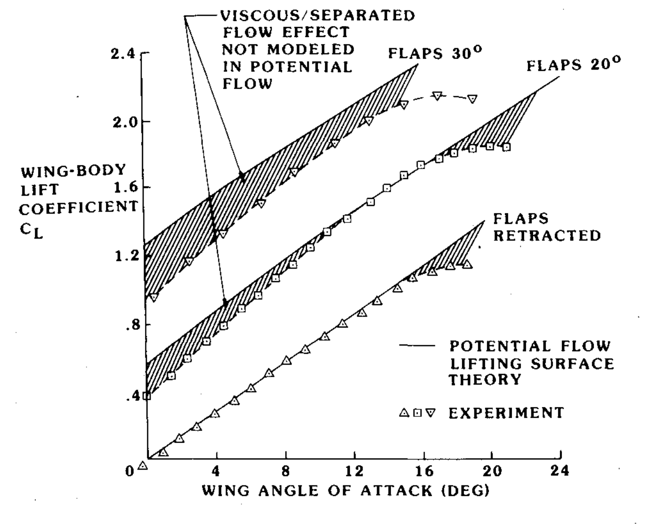


Fig. 1 Typical test-theory comparison results using distributed vorticity lifting surface theory.

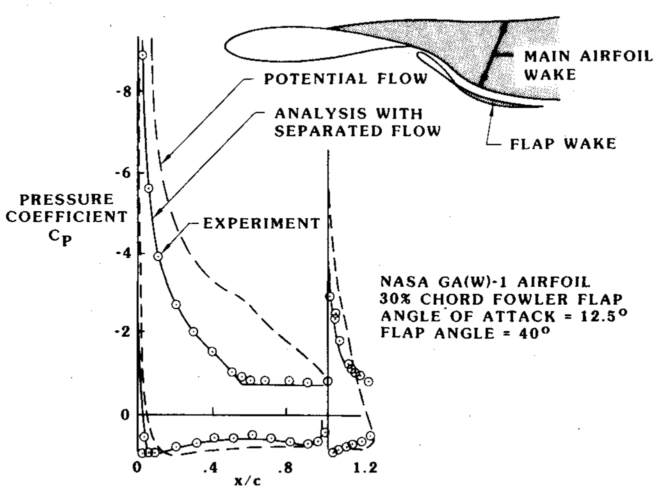


Fig. 2 Typical calculated separated flow results for a two-element airfoil.

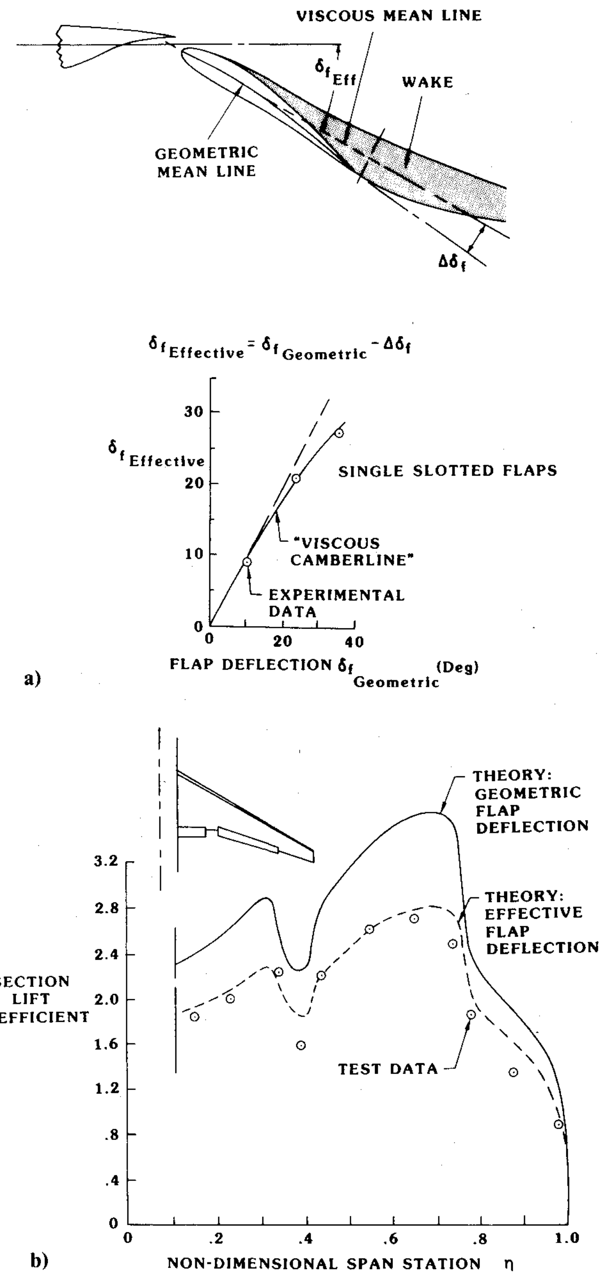


Fig. 3 Effective flap angle and its influence on span loading.

employs panel method algorithms for potential flow and state-of-the-art integral boundary-layer methods for viscous flow computations. The overall program system also incorporates an inverse boundary-layer method for the design and evaluation of desirable pressure distributions for input to the design mode of the program. The inverse boundary-layer method[4,5] is a valuable tool in its own right, and when coupled with the panel method design capabilities of the overall program gives the designer a powerful and flexible tool for the optimization of arbitrary multielement airfoils. Example analysis results for a two-element airfoil operating near maximum-section-lift coefficient conditions are shown in Fig. 2.

Despite the developments outlined above, there is presently no analytic method capable of solving the full problem of viscous flow about three-dimensional multielement high-lift wings, particularly when the flow is partially separated. Thus, with the satisfactory development of programs for the analysis of three-dimensional wing/body combinations in potential flow, and the viscous flow about multielement two-dimensional airfoils, the third task in the development of an intermediate high-lift computational design methodology is to derive and evaluate analytic techiques for correlating two- and three-dimensional flows.

As an example of this work, it has been found that simple sweep theory, which is rigorously valid only for thin wings of constant chord and infinite aspect ratio, should be replaced by the more theoretically correct method due to Lock,[6] which explicitly accounts for taper and aspect ratio effects. It has been found that applications of Lock's method may result in significant changes in chordwise pressure distribution and, hence, in boundary-layer characteristics compared with results obtained using simple sweep theory alone.

By combining the two-dimensional section characteristics in a viscous flow as modified by Lock's correction, it is possible to use the results of the three-dimensional potential flow analysis in "critical section analysis" to predict high-lift wing/body characteristics beyond the linear portion of the lift curve, *provided* section characteristics dominate the lift behavior of the wing. (This also, of course, assumes spanwise boundary-layer flow effects can be neglected.) In these cases, use has been made of the appropriate "viscous" (or "effective") camber lines of a specified airfoil/flap section, rather than the geometric camber line, in the potential flow analysis. A typical result of this approach is shown in Fig. 3, which illustrates the procedure diagrammatically, and shows a test-theory comparison of the span loading obtained by the technique.

As a consequence of this systematic effort, a quasi-three-dimensional viscous flow analysis capability has been developed, at least for the case of wings of high aspect ratio, moderate taper and sweep, and whose high-lift performance is dominated by wing section (as opposed to other aircraft component-induced) characteristics. It should also be noted, that within the fundamental assumptions of the constituent theories, valid results at either wind tunnel or full-scale Reynolds number conditions can be obtained. The upshot has been the formulation of the general high-lift wing design process diagramed in Fig. 4.

## Applications of High-Lift Computational Methods

An important phase of the high-lift research effort has involved development and application of the overall design procedure shown in Fig. 4 to a wide variety of both two- and three-dimensional project-oriented low-speed problems. The objectives of this work have been 1) to develop a flexible, unified, and well-validated high-lift design procedure based on computational methods; 2) to explore the strengths and weaknesses of presently available tools as a guide to future research efforts and to establish the proper balance between use of theory and experiment in project level high-lift system design and optimization; and 3) to explore new high-lift concepts which suggest themselves during the standard applications of the analysis/design process.

To amplify and clarify these points, three examples have been selected for discussion here. Others have been presented in Refs. 1, 5, 7, and 8.

### Example 1: A Variable Camber Airfoil

The first application example involves the design of an airfoil intended to operate at very low Reynolds numbers for use on an ultralight sailplane being designed at Rensselaer Polytechnic Institute (RPI) in Troy, N.Y., under a joint NASA/AFOSR grant. This glider is one of a sequence[8,9] of student level projects demonstrating the use of advanced composite material (carbon fiber, DuPont Kevlar) in lightweight aircraft construction. An airfoil for this proposed application was designed at Boeing as a low priority effort.

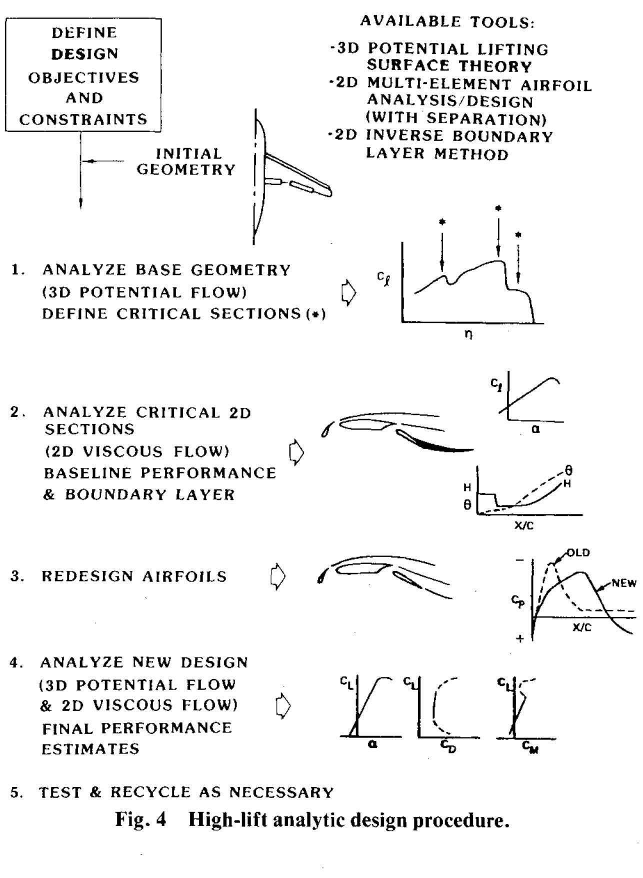

Fig. 4 High-lift analytic design procedure.

Although apparently irrelevant to the problem of transport aircraft design, the effort at Boeing was considered justified for several reasons. While full-scale transport aircraft operate in a Reynolds number range far beyond that of a small sailplane, most low-speed wind tunnel testing is conducted at scale conditions where flow problems confronted by sailplanes (e.g., laminar separation) are commonplace. It is important to understand these phenomena, and to have in hand computational tools which reliably predict their effects, and provide the capability to design around them. In addition, the particular problem posed to Boeing by RPI presented a substantial challenge and valuable test case for the design capabilities of the two-dimensional viscous portion of the overall design methodology. The problem is both simple to understand and challenging to solve, and provided a valuable learning exercise.

This application is discussed here because it demonstrates the use of the basic design methodology and approach to high-lift design in a simply grasped situation. This design problem goes beyond the normally posed requirement of optimal design of a section for one single performance objective (e.g., maximum-lift coefficient). Several conflicting performance requirements are specified and several important (nonaerodynamic) project-type constraints are imposed. This example also demonstrates that application of the methods, which allow a very systematic parametric evaluation at the correct scale conditions, can suggest nonobvious new design concepts (e.g., a practical variable thickness wing).

The basic RPI airfoil design specification is listed in Table 1. The results of the trade studies (which were performed using the two-dimensional inverse boundary-layer analysis method) are shown in schematic form in Fig. 5. The parametric analysis indicated that no fixed geometry single-element airfoil could meet the full set of requirements. However, it was found that a number of compromises in both the aerodynamic and structural design might allow an ingenious solution to the problem of attaining most of the performance envelope desired. The result was the concept of a variable thickness (and, consequently, variable camber) airfoil as shown in Fig. 6.

In this concept the "high-speed" wing is a thick section of modest camber and low pitching moment which achieves

**Table 1 Design specification for Rensselaer Polytechnic Institute ultralight glider airfoil**

| Design parameter | Baseline Wortmann FX 63-137 airfoil | New airfoil specification |
|---|---|---|
| Maximum section-lift coefficient ($C_{\ell_{max}}$) at $Re=6\times10^5$ | 1.78 | 2.0 |
| Section drag coefficient ($C_d$) at $C_\ell=1.0$, $Re=10^6$ | 0.009 | 0.010 |
| Low drag over range $1.0\geq C_\ell\geq C_{\ell_{min}}$ $10^6\geq Re\geq1.5\times10^6$ (to avoid overspeed) | $C_{\ell_{min}}=0.5$ | $C_{\ell_{min}}=0.4$ |
| Pitching moment coefficient, cm $C_{\ell_{min}}\leq C_\ell\leq1.0$ | −0.25 | ≤ −0.05 |
| Gentle stall characteristics | Yes | Desired |
| Thickness/chord ratio | 13.7% | ≥12% |

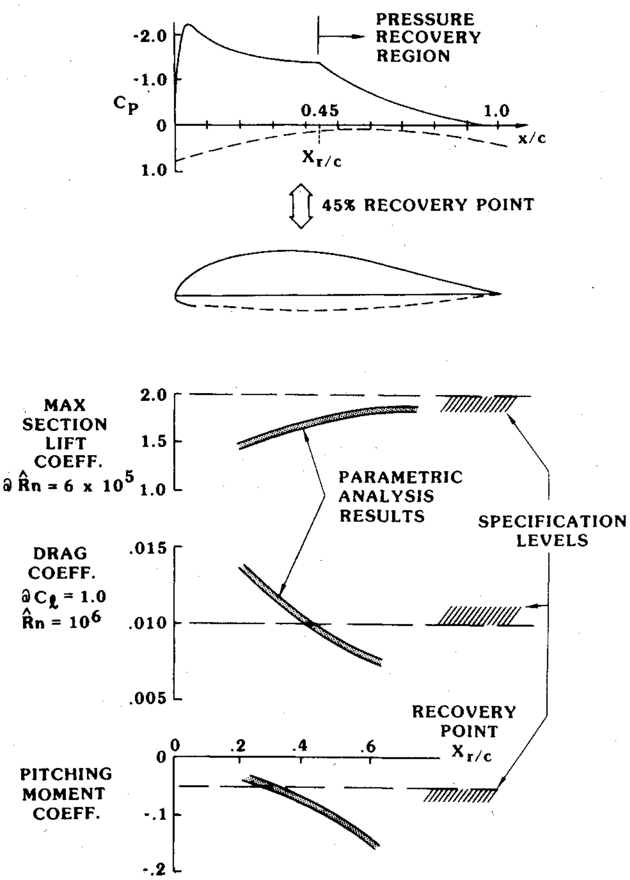


**Fig. 5 Airfoil parametric analysis results.**

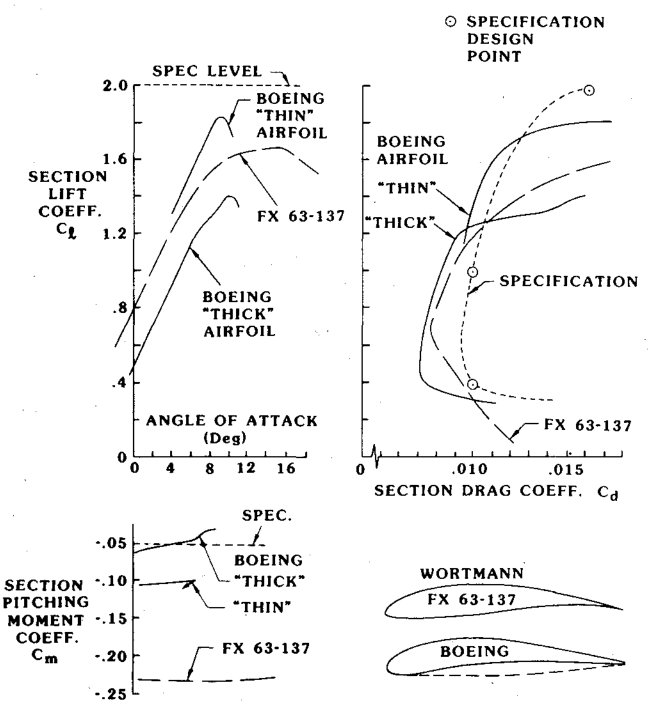


**Fig. 6 Predicted performance of Boeing variable thickness airfoil.**

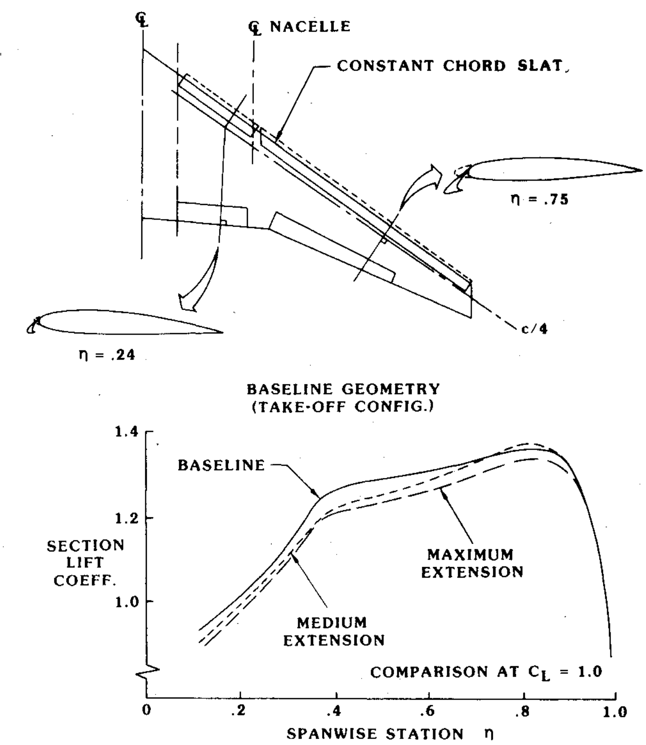


**Fig. 7 Baseline geometry and computed span loading for slat redesign problem.**

better than specified drag values at low-to-moderate lift coefficients. When higher lift levels are desired, one can capitalize on the properties of the composite material lower wing skin (formed as a single large panel of fiberglass/foam sandwich over the entirety of each wing semispan in the RPI application) and mechanically flex it to form a thin (12%) cambered section of near optimum contour for the production of high lift at low Reynolds number. The proposed new configuration appears structurally feasible based upon test samples built at RPI, and is aerodynamically satisfactory. *For this particular application*, the proposed scheme appears to be both simpler and lighter than the obvious alternative of fitting the wing with a simple hinged flap. Further details may be found in Ref. 8.

#### Example 2: Transport Aircraft Takeoff Lift/Drag Ratio Improvement

The second application to be discussed, and one for which wind tunnel data exist, concerns an investigation of possible improvements in takeoff $L/D$ of a twin turbofan powered, swept wing transport aircraft configuration operating out of high altitude airfields. Takeoff from such airports, particularly under high ambient temperature conditions, is typically limited by second segment climb $L/D$ characteristics. The basic problem posed follows: Given a baseline cruise airplane configuration (i.e., cruise wing geometry completely specified) and high-lift system, establish the upper bound of takeoff lift/drag ratio attainable by 1) allowing "unlimited" chord extension of a leading-edge slat, and/or 2) possible recontouring of the slat. It should be noted here that the baseline high-lift system consisted of a three-position (retracted, takeoff, and landing) slat. While the computational methods are capable of handling any of these configurations, this example concentrates on the slat in its takeoff configuration where it is in a sealed (unslotted) position.

The approach to the design problem was to first analyze the baseline configuration using the three-dimensional potential flow lifting surface theory to obtain predicted sectional and total aerodynamic characteristics of the wing. Configuration geometry and span loadings thus obtained are shown in Figure 7.

Next, two-dimensional section coordinates were extracted from the baseline wing at "critical" spanwise stations as shown in Fig. 7. These sections were then used as starting airfoils for the redesign investigation. In the subsequent analysis, the two-dimensional inverse boundary-layer method was used to design improved pressure distributions on the forward portion of the sections as the "slat" chord was increased, while maintaining the baseline pressure distribution (and hence baseline airfoil contour) on the aft portion of the wing. Based on the optimized pressure distributions thus obtained, the airfoil sections were reshaped in the design region. A typical pressure distribution and the overall result of the design effort are shown in Fig. 8. The study showed that recontouring the leading-edge slat proved to be the most important contribution toward improving performance. Simple chord increase (Fowler motion of the slat) also provided some performance increase, but only at unrealistically high extensions. In addition to establishing the performance gain to be had by slat recontouring, a practical scheme for mechanizing the required geometry change was devised. This "variable camber slat," wherein the upper surface of the slat is made of a flexible composite material which assumes the proper aerodynamic contour as the slat is extended, is shown in Fig. 9.

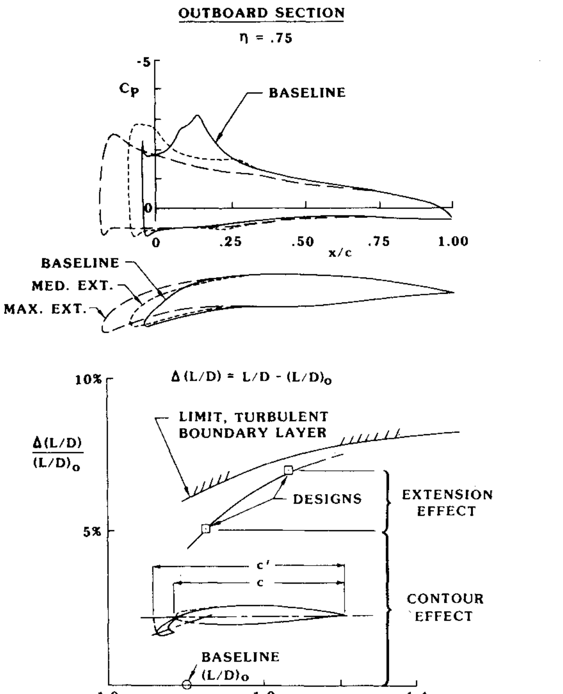


**Fig. 8 Predicted results of improved leading-edge device design effort.**

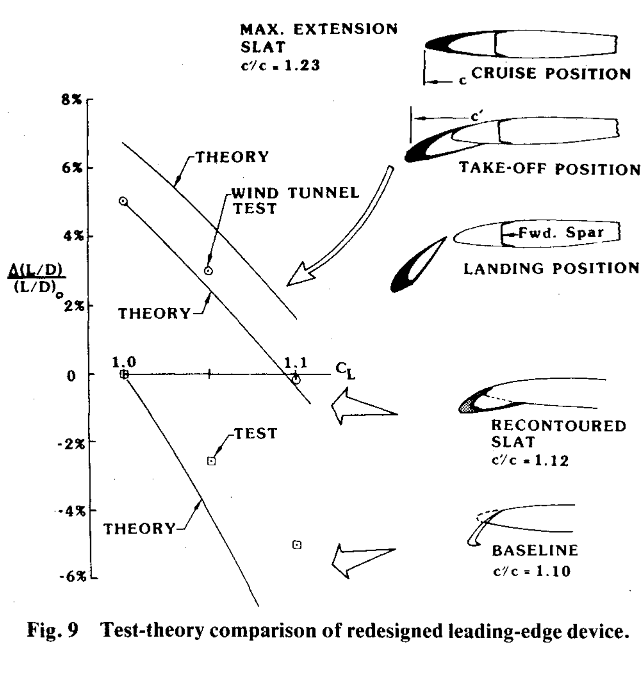


**Fig. 9 Test-theory comparison of redesigned leading-edge device.**

A medium extension version of this final configuration was subsequently selected for direct comparison wind tunnel testing with the baseline. The comparison between wind tunnel test results and computer $L/D$ at takeoff conditions is shown in Fig. 9. Note that the analysis did not include nacelles, whereas the wind tunnel model had nacelles installed. In the region of design point lift coefficients, the test verified the analysis of the baseline. However, at higher-lift coefficients the analysis predicted some separation that was alleviated in the test owing to favorable nacelle interference. Predicted performance of the new slat was fully verified by the test. Specifically, the new slat resulted in a takeoff lift/drag ratio increase from 5% (sea level, standard conditions) to 7% (high altitudes, 33°C). Additionally, maximum-lift coefficient at the various takeoff flap settings increased by increments of up to 10%, and high angle-of-attack pitching moment characteristics were improved.

#### Example 3: Transport Aircraft Maximum-Lift Performance Improvement

The final application example to be discussed is of interest for several reasons. Both wind tunnel and flight test validation results exist. The full computational methodology previously described was applied to a difficult flow problem involving an extremely complex airplane geometry. While the computational methods alone were inadequate to cope with the full problem, when used to augment and guide carefully conducted wind tunnel testing, they provided the crucial element in achieving a difficult aerodynamic goal. And finally, a potentially powerful approach to partially circumventing some major limits of conventional low Reynolds number testing in high-lift system development was demonstrated. This approach can only be pursued efficiently by application of computational techniques.

The problem confronted in this example was as follows: Given a well proven and thoroughly tested (both in the wind tunnel and in-flight) baseline transport airplane powered by four low-bypass ratio turbofan engines in "slender" nacelles, how does one retrofit this basic airframe with four large diameter high-bypass ratio turbofan engines, with minimum modification to the remainder of the airframe and without an off-design (i.e., low-speed) performance penalty. The new nacelles were apparently compatible with the baseline airframe, provided the nacelle struts of the new installation were shorter than those of the baseline, resulting in the nacelles being placed in closer proximity to the wing. Wind tunnel tests comparing the baseline and retrofit airplanes showed no low-speed performance penalty. Corresponding flight tests showed a 10% loss in airplane maximum-lift capability. The comparison results are shown in Fig. 10, and are dreadful. Further, based on low Reynolds number wind tunnel force data alone, there appears to be no obvious experimentally derivable aerodynamic "fix-up," and a major puzzle was presented.

The puzzle regarding the cause of the lift loss was rather easily solved by additional wind tunnel testing with particular emphasis placed on carefully documented flow visualization. Nacelle-on and -off tests clearly showed that flow separation occurred on the sides of the large diameter nacelles at high angles of attack and high flap deflection conditions, leading to the formation of large vortices which flowed streamwise over the wing. While the section characteristics of the wing were very strongly Reynolds number scale dependent, the paths and strength of the nacelle-shed vortices were almost scale independent. Further, under certain conditions, the nacelle vortices interacted in a complex and unfavorable way with the boundary layer on inboard sections of the wing downstream. The upshot of all this was that, at wind tunnel Reynolds numbers, the maximum-lift characteristics of the wing were dominated by the outboard section characteristics. At flight Reynolds numbers, the outboard wing sections benefited from the increased Reynolds number so that

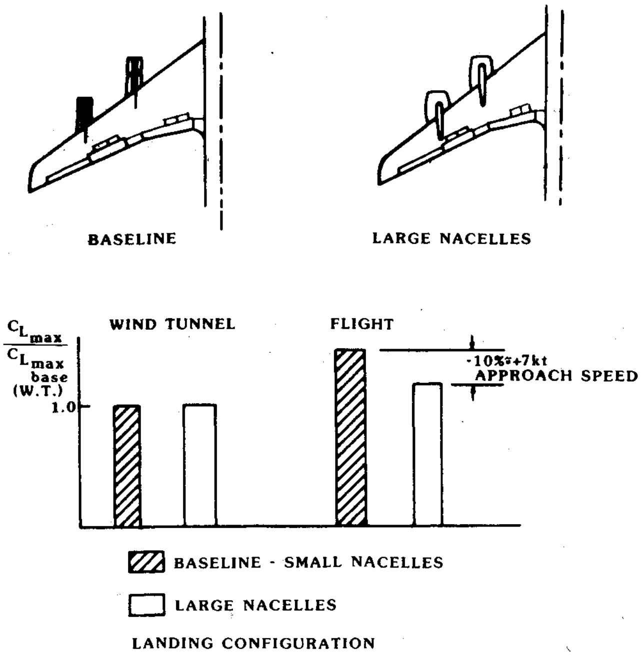


**Fig. 10 Nacelle influence on maximum-lift performance.**

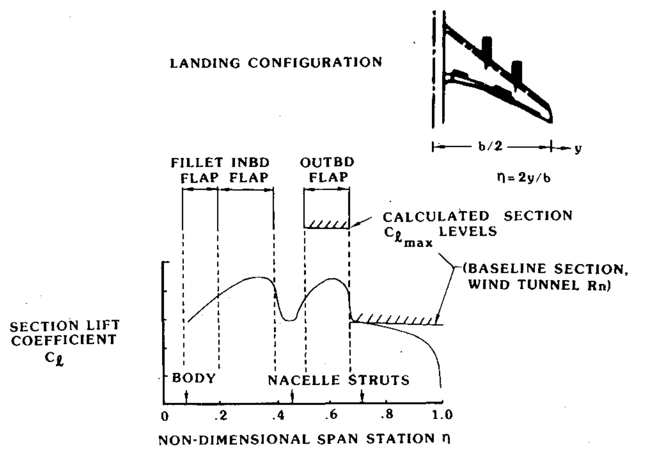


**Fig. 11 Diagnosis of wing maximum-lift performance.**

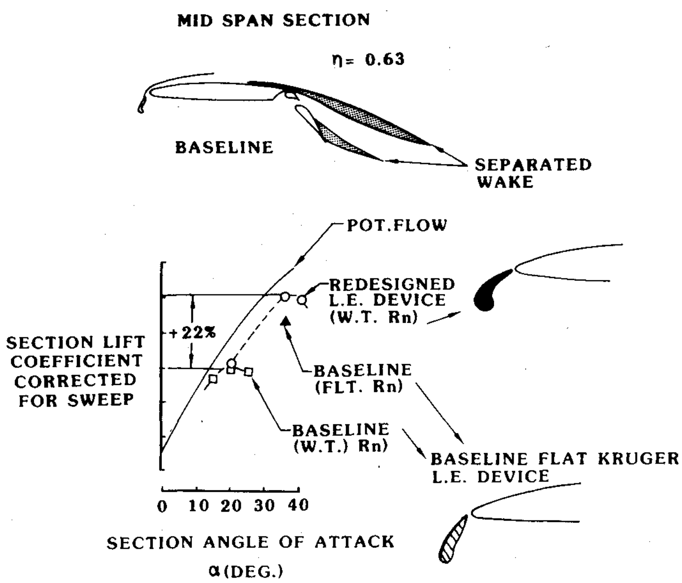


**Fig. 12 Typical results of two-dimensional viscous analysis and redesign.**

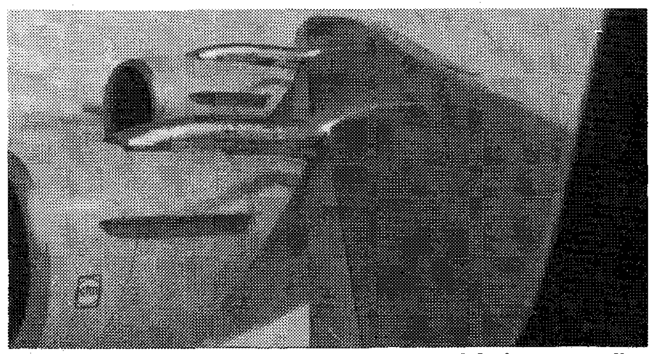

**Fig. 13 Re-engined transport with vortex control devices on nacelles executing a stall maneuver.**

maximum-lift performance was limited by the unfavorable inboard wing boundary-layer/nacelle vortex interaction. Thus the two configurations, both with identical wing and high-lift systems, exhibited almost equal maximum lift performance in the wind tunnel, but not at flight conditions. Subsequent analysis of the wing using the quasi-three-dimensional viscous approach described earlier further validated (and clarified) this diagnosis, as shown in Figs. 11 and 12.

Thus the puzzle was solved, but the problem was not. Having clearly observed that a wind tunnel model which carefully stimulated the full-scale geometry of the proposed configuration, could not duplicate the necessary flow phenomena, the traditional approach would be to embark on an expensive and time consuming flight test fix-up program, with the fear that a substantial revision of the baseline high-lift system might prove to be the only satisfactory solution. However, with the availability of computational tools, a quite different approach became feasible.

This approach was merely to implement the old idea of attempting to simulate the full-scale *aerodynamics*, rather than the full-scale geometry in defining the parts of the wind tunnel model. While conceptually appealing, this course is almost impossible to follow economically, unless one has sufficiently powerful computational tools with *design* (inverse) capability.

In the case under discussion, the full-scale simulation was rather crude but extremely effective. Having determined both by flow visualization and analysis that the low Reynolds number stall characteristics were driven by outboard wing section characteristics, it was a straightforward procedure to *design* an alternative, nonstandard, leading-edge device (Fig. 12) which could be fitted to the outboard wing of the wind tunnel model. (Note: At no time was it intended to fit such an alternative leading-edge device to the baseline full-scale wing.) In this way, the outboard wing behaved at wind tunnel Reynolds number very much like the full-scale wing did in-flight; i.e., nacelle vortex/wing boundary-layer interactions determined the stall in the wind tunnel.

Having now radically adjusted the wing's stall patterns in the wind tunnel, attention could turn to necessary modifications of the nacelles, to improve the (wind tunnel level) maximum-lift performance. Relying on the flow visualization work done previously, a simple fix in the form of a nacelle-mounted vortex control device (VCD) shown in Fig. 13 was found which, at full-scale conditions, required no change to the baseline high-lift system. Subsequently, the modified nacelles were flown with the result that with a VCD on each nacelle, the baseline flight level maximum-lift performance was fully regained.

## Concluding Comments

An outline of a portion of Boeing's low-speed/high-lift aerodynamic research program, and the quasi-three-dimensional viscous flow computational methodology which has been developed has been presented. To demonstrate the overall utility of this methodology, three examples of its application to practical, project-oriented design/analysis problems have been described.

The conclusion to be drawn from these examples is that modern high-lift computational methods have become sufficiently well developed to allow a designer to use them in a greatly improved (compared to experimental/analytical cut-and-try) design process. Modern computational methods now allow the high-lift system designer to do many of the things that were once conceptually possible, but impractical owing to either lack of physical understanding or budget limitations. Both the multipoint optimization process which led to the variable thickness airfoil, and the modeling of "full-scale" aerodynamics rather than full-scale geometry in the wind tunnel, are examples of these emerging capabilities.

However, in the forseeable future, management cannot be expected to make decisions which risk millions of dollars based solely on "analytic wind tunnel" results alone. Thus the objective of a practical research effort should be to derive computational tools which will both augment and improve the efficiency of what remains an experimental process. The role of the wind tunnel will change, however, as computational methods of increasing power become available. Much routine parametric evaluation can now be conducted with the computer, with the wind tunnel acting as both the vehicle for visualization of complex flows and the final arbiter of predicted results. Thus theory and experiment form a necessarily complementary pair.

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