High-Lift Design Methodology For Subsonic Civil Transport Aircraft[1]

C.P. van Dam*, J.K. Paris**, and J.C. Vander Kam***
Department of Mechanical and Aeronautical Engineering
University of California Davis
One Shields Avenue
Davis, CA 95616-5294
*(530) 752-7741, cpvandam@ucdavis.edu
**Presently at the Boeing Company, (818) 586-4675, john.k.paris@boeing.com
***(530) 752-7479, jcvanderkam@ucdavis.edu

Abstract— This paper presents a high-lift system design methodology that can be incorporated during the early stages of aircraft development, and thus has the potential to provide a superior and more cost effective vehicle than one developed utilizing traditional linear design methods. The present methodology offers two different levels of fidelity, one applicable to the conceptual design stage and the other to the preliminary design stage. The underlying flow solver couples a three-dimensional nonlinear Weissinger method with two-dimensional viscous data to provide fast and accurate aerodynamic predictions for high-lift configurations. Several test cases that illustrate the capabilities of this hybrid flow solver are presented.

TABLE OF CONTENTS

1. INTRODUCTION

Although the design methods and tools used in commercial aircraft development have changed over the years, the overall goal of aircraft production has remained the same; to provide the customer with a cost-effective, high quality product that meets a desired set of mission requirements.

In the highly competitive and economically driven commercial aviation market of today, the trend is to make aircraft systems simpler, which results in lower production and operational costs. One such system is the high-lift system. An aircraft's high-lift system is vital for the take-off and landing stages of flight and accounts for somewhere between 6% and 11% (potentially higher for some extremely complex configurations) of the production cost of a typical jet transport [1].

It is important to understand the significant impact that the early stages of design have on the overall complexity and cost of the resulting high-lift system. As outlined by Nield [2], aircraft have traditionally been designed in a sequential fashion, leaving the high-lift design to near the end when much of the aircraft geometry has already been committed. This approach can be very costly as illustrated in Fig. 1 which shows that much of the cost of a product is committed during the initial stages of the design cycle. Knowing this, it is critical that the design tools used in the early stages of design be able to provide high-fidelity and "cost aware" predictions for all major aircraft components, including high-lift systems. A few changes to the aircraft geometry in the early stages of design may make it possible to utilize a simpler high-lift system and thus reduce the cost from a potential 11% to 6% (or less) of the total production cost. For a Boeing 757-200 type aircraft, this translates to approximately a $1.9 million savings in production costs and also a notable reduction in direct operating costs because of reduced system complexity [1]. Additionally, the ability to evaluate high-lift system considerations early on in the design process makes it possible to design for growth of the high-lift system for derivative aircraft, or to simply avoid problems later in the design process.

This paper presents a methodology for incorporating high-lift system design considerations in the early stages of an aircraft development cycle. The goals of this continuing effort are to design and develop a high-lift methodology that:

(1) encompasses all critical design elements,
(2) is fast and accurate,

[1] 0-7803-5846-5/00/$10.00 © 2000 IEEE

(3) is fully scalable with respect to hardware, software, and high-lift technology advancements, and
(4) can be applied early on in the airplane development process.

A high-lift system design code, referred to as the high-lift module, was developed as a "plug-in" module for an existing aircraft conceptual design package called the AirCraft SYNThesis (ACSYNT) program [4]. ACSYNT, developed by the Systems Analysis Branch at NASA Ames Research Center, allows an engineer to perform trade-off studies, sensitivities, and optimizations of various aircraft configurations. Analysis modules include aerodynamics, weights, propulsion, mission performance, geometry, stability and control, economics, and the newly developed high-lift module. The present work is an extension of the work by Pepper et al [5] offering a methodology for the conceptual design of high-lift systems including cost, weight, and aerodynamic prediction methods for multi-element high-lift configurations. Recently the method was modified to allow for more flexibility in terms of wing geometry, to include the aerodynamics of main/aft double-slotted flaps, and, in addition, to provide a methodology capable of producing higher fidelity aerodynamic predictions, including maximum lift coefficient, for use at the preliminary design stage. Not only does this paper build upon previous high-lift research, it also complements the efforts by Shaw et al [6] who developed an aero-mechanical design methodology for high-lift deployment systems.

The proposed improved high-lift design methodology is presented in Fig. 2. This approach has advantages over the conventional approach in that it integrates critical high-lift design elements into the early stages of the aircraft design process. One of the key components of this improved approach is the high-lift module. The high-lift module provides the necessary high-lift system cost, weight, and aerodynamic performance predictions utilized at the conceptual and preliminary stages of an aircraft design. This paper focuses on the aerodynamic portion of the high-lift module, which is depicted in Fig. 3. In order to utilize the high-lift module at the conceptual and preliminary design stages of an aircraft design, it is essential that the aerodynamic predictions be made quickly. For this reason, a fast lifting-line method (modified Weissinger method) closely coupled with two-dimensional (2-D) viscous data is utilized to calculate the three-dimensional (3-D) aerodynamic characteristics. The result is a high-lift module that has a good balance between speed and accuracy, making it an effective tool for use at the early stages of aircraft design.

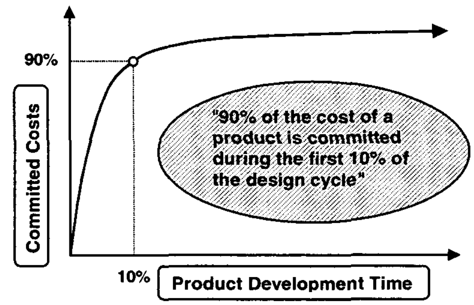

Fig. 1 Committed cost as they relate to product development time [3].

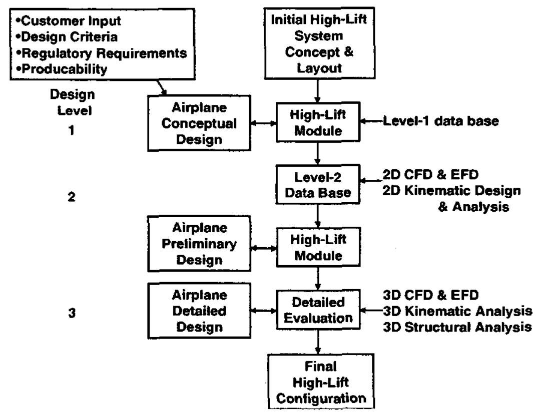

Fig. 2 High-lift design methodology – improved approach.

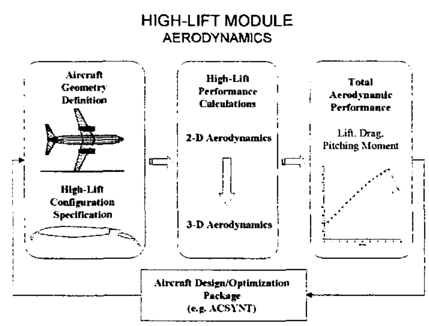

Fig. 3 Overview of the high-lift module aerodynamic analysis.

2. 2-D AERODYNAMIC MODELING

Given the current fiscal climate, it is very difficult to conduct extensive experimental high-lift research programs such as those conducted in the United States in the 1940's [7] and the United Kingdom in the 1970's [8]. Fortunately, computer technology and algorithms for solving complex flow problems have improved rapidly in the recent years, making computational fluid dynamics (CFD) an efficient and cost-effective method of analyzing high-lift airfoils. Although a good deal of experimental data exists for a variety of high-lift systems, most of it is at low Reynolds numbers and is based on out-dated high-lift configurations. Therefore, CFD provides the necessary and cost-effective means of acquiring 2-D high-lift data of modern high-lift configurations at flight Reynolds numbers.

A well-validated incompressible Reynolds-averaged Navier-Stokes solver called INS2D [9] was selected for the 2-D CFD analysis. This code has been validated as an accurate tool in the simulation of viscous flow over multi-element airfoils at high Reynolds numbers [10,11]. In addition, the code's ability to accurately predict trends due to geometric changes of high-lift airfoils has been verified in a design optimization environment by Eyi et al [12]. Shaw et al [6] also show that the trends in lift and drag due to changes in trailing-edge flap gap and overlap predicted by INS2D correspond very well with experiment. Although there are other tools available for the analysis of high-lift systems, INS2D was chosen because of its proven accuracy and reliability, and also because the tools for pre- and post-processing of INS2D simulations are readily available at UC Davis.

The Spalart-Allmaras [13] turbulence model was used which solves one transport equation for a non-dimensional eddy viscosity variable. This model, unlike many other turbulence models, provides a smooth laminar to turbulent transition at points specified by the user. This "ramping" effect from laminar to turbulent flow can be troublesome at times when precise control of the transition point is desired. Nonetheless, this model in conjunction with INS2D has been shown to produce results that compare very well with experimental multi-element aerodynamic data.

Of particular interest to high-lift design, the Spalart-Allmaras turbulence model seems to be the best in predicting sectional stall angle and maximum lift coefficient, $C_{l_{max}}$, as shown by Rogers et al [14] in their evaluation of four different turbulence models available in INS2D. Similar results demonstrating the excellent $C_{l_{max}}$ predictive capabilities of INS2D using the Spalart-Allmaras turbulence model are shown in Fig. 4. The airfoils (cruise and single-slotted flap) analyzed were rotated to 10° angle-of-attack and then the grids were generated. This allowed the flow physics in the wake to be captured more accurately at higher angles-of-attack, which experience has shown to be an important factor in accurate $C_{l_{max}}$ predictions.

Due to the sensitivity of high-lift aerodynamics to boundary-layer transition, some attention must be paid to transition location on the airfoil elements. Recently, a transition prediction algorithm has been incorporated into the INS2D flow solver that makes it possible to determine the onset of transition automatically as the flow solution converges. This methodology identifies several transition mechanisms. In two-dimensional airfoil flows, where surfaces are generally smooth and freestream turbulence levels are low, transition is governed by Tollmien-Schlichting (TS) instability, laminar separation, or turbulence contamination [15]. The latter mechanism is often overlooked, but can be important when, for instance, the flap boundary layer is contaminated by the wake of the main element and/or the slat [16]. The method is described in more detail by Brodeur and van Dam [17]. The Navier-Stokes flow solver including the transition prediction formulation has been applied to the NLR 7301 flapped airfoil. The test was conducted for the airfoil with a flap angle of 20°, flap gap of 0.026c and flap overlap of 0.053c at a chord Reynolds number of 2.51 million and an angle of attack of 6°. This particular multi-element airfoil was selected due to the extensive experimental data available, which includes transition measurements [18]. The predicted transition locations are compared to the experimentally observed locations in Fig. 5. On the lower surface of the main element transition is calculated within the range observed in the experiment, whereas transition on the upper surface is predicted slightly aft of the observed range. Transition on the upper surface of the flap is predicted slightly ahead of that seen in the experiment. On the lower surface of the flap the flow is predicted to remain laminar as in the experiment. In general, the calculated transition points agree well with the experimental observations.

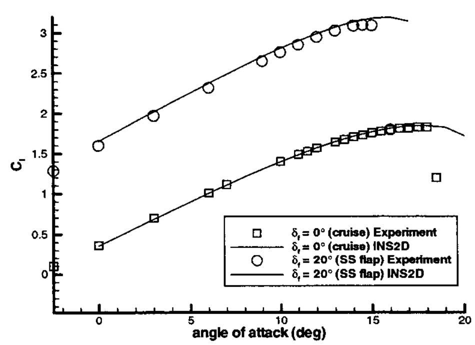

Fig. 4 Comparison of measured and predicted (INS2D) lift curves for a modern civil transport aircraft airfoil in cruise configuration and with a single-slotted Fowler flap in takeoff position, Re = 6.9 million, $xtran_{upper}$ = 0.02c, $xtran_{lower}$ 0.20c, flap fully turbulent.

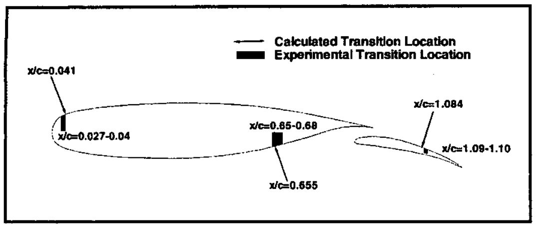

Fig. 5 Measured and predicited transition locations for NLR-7301 flapped airfoil, $\alpha = 6°$, $\delta_f = 20°$, Re = 2.51 million, flap gap = 0.026c, flap overlap = 0.053c.

3. LEVEL-1 AERODYNAMIC DATABASE

As mentioned earlier, historically the task of high-lift system design has been conducted during the latter stages of the design process after which much of the aircraft geometry has already been frozen. This less-than-optimal approach is a result of the high level of complexity associated with high-lift system design and the lack of efficient and accurate prediction methods that can be used at the conceptual design stage. Critical elements that must be considered in the design of a high-lift system include aerodynamics, cost, weight, mechanics, and noise. The daunting task alone of determining the 2-D aerodynamic performance of high-lift systems includes challenges such as confluent shear layers, massive separation, and inverse Reynolds number effects. Typically, computational methods based on the Reynolds-averaged Navier-Stokes equations are required to accurately capture complex flow physics such as these. Given the current state of computing technology, it is still not practical to utilize Navier-Stokes CFD codes at the conceptual design stage because the solutions tend to take too much time. For this reason, semi-empirical methods such as those found in DATCOM [19] remain widely used, but these methods are not sufficiently accurate for the design of a modern civil transport aircraft because they are often based on low-Reynolds-number data and outdated high-lift system technology. To overcome these limitations, a new methodology for conceptual high-lift system design has been developed.

One key element of the methodology is called the Level 1 Aerodynamic Database (Fig. 2). This is an extensible database containing 2-D aerodynamic performance characteristics of a variety of high-lift systems. From the information in this database, semi-empirical relationships used for 2-D aerodynamic performance prediction of high-lift systems are developed and updated. The resulting high-lift predictive capabilities are well suited for the conceptual design stage of modern civil transport aircraft because the method reflects the current state of high-lift technology and provides fast predictions based on data attained at flight Reynolds numbers.

A database for single-slotted trailing-edge and a variety of leading-edge devices was developed previously and the resulting semi-empirical relationships are presented by Pepper et al [5]. More recently, these semi-empirical relationships were extended to include 2-D aerodynamic prediction capabilities for main/aft double-slotted trailing-edge devices [20].

4. 3-D AERODYNAMIC MODELING

A modified lifting-line method based on theory originally developed by Mutterperl [21] and Weissinger [22] and later simplified by Campbell [23] and Blackwell [24] is used to compute the load distribution in subsonic compressible flow of arbitrary wings and lifting surface arrangements. The simplification involves replacing the continuous lifting line of varying strength by a system of horseshoe vortices, each of which is of constant strength. The resulting method, called finite-step method or vortex step method [25], allows one to couple sectional (2-D) viscous results with inviscid wing (3-D) theory in order to determine the total aerodynamic coefficients for configurations including wings with dihedral, endplates/winglets, pylons, and biplanes, joined-wings, etc. The present method has advantages over the traditional panel or vortex lattice methods because it incorporates the critical viscous nature of high-lift devices and is also significantly faster since the chordwise panels are modeled as single "strips."

The modified Weissinger method used in the high-lift module is discussed in more detail by Paris [20]. This method represents the lifting surfaces by a system of rectangular horseshoe vortices placed along the quarter-chord line of the lifting surfaces as illustrated in Fig. 6. The load distribution is calculated by solving a linear system of equations that enforce a flow tangency condition at the specified control points. For subsonic flow, the effects of Mach number on lift-curve slope and control point position are taken into account using the Prandtl-Glauert equation. The lift is integrated directly from the calculated load distribution. The induced drag is calculated based on the velocities in the Trefftz plane. If the parasite drag of the individual airfoil sections is available, it can be integrated along the span of the wing and added to the induced drag to get the total drag of the configuration. The total pitching moment is calculated by translating the sectional pitching moment to a wing reference line and integrating along the span of the wing.

Although the modified Weissinger method reduces the lifting surfaces to flat plates, various airfoil shapes, including high-lift configurations, can be successfully modeled. This is done by adjusting the location of the control points to reflect the proper lift-curve slope and the panel incidence angles to reflect the zero-lift angle of attack of the airfoil. Using this methodology, a variety of test cases have been analyzed to validate the three-dimensional portion of the high-lift module. These test cases will be discussed in the sections to follow.

The modified Weissinger method is capable of analyzing complete aircraft lifting surface configurations, including the main wing with high-lift system, horizontal tail and/or canard, and vertical tail. The geometry of these surfaces can include sweep, taper, twist, and dihedral. Additional features that have been added to the three-dimensional portion of the high-lift module include a simple fuselage model, a non-linear $C_{L_{max}}$ prediction routine, and a wind-tunnel wall model. The $C_{L_{max}}$ prediction routine is discussed in the next section whereas more information regarding the fuselage and wind-tunnel wall models can be found in [20].

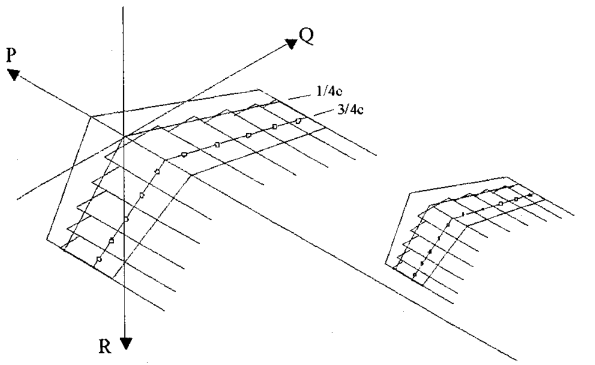

Fig. 6 Distribution of horseshoe vortices over a multiple lifting-surface configuration [24].

5. MAXIMUM LIFT PREDICTION

The non-linear method for predicting $C_{L_{max}}$ couples the modified Weissinger method with 2-D viscous flow calculations (or experimental data). At a minimum, 2-D viscous data is required for the wing root and wing tip sections. If there exists a significant variation in the spanwise airfoil geometry, such as the case of high-lift configurations and most cruise wings, viscous data for additional stations along the wing should be used. INS2D has shown much promise in its ability to accurately predict two-dimensional viscous flows for both single- and multi-element airfoils. Considerable success has been achieved using the Spalart-Allmaras turbulence model [13] and by exercising special care in the specification of boundary-layer transition locations.

The viscous data for each defining airfoil section is compiled into a single data file that is read by the high-lift module. The lift-curve slope, C_{l_α}, and zero-lift angle of attack, α_o, are then calculated for each section. This information is used in the present method to calculate the initial load distribution from which the local coefficient of lift is calculated for each spanwise station. After this initial 3-D calculation, the following iterative procedure is performed for each angle of attack being examined:

1. Calculate the effective local angle of attack for each station using:
$$\alpha_{local} = \frac{C_{l_w}}{C_{l_\alpha}} + \alpha_o - \Delta\alpha_{visc}$$
where the local lift coefficient, C_{l_w}, is calculated for each station from the bound vortex strength and, $\Delta\alpha_{visc}$, is the viscous correction angle (see step 3) which is initially equal to zero.

2. Find $C_{l_{visc}}$ at the local angle of attack, α_{local}, by interpolating the 2-D viscous section input data.

3. If $\left|C_{l_{visc}} - C_{l_w}\right| > \varepsilon$, with a typical value for $\varepsilon = 0.01$, determine the appropriate viscous correction angle for each section such that at the local angle of attack the lift coefficient of the corrected section equals $C_{l_{visc}}$ using the following:
$$\Delta\alpha_{visc} = \frac{C_{l_{visc}} - C_{l_w}}{C_{l_\alpha}}$$
See Fig. 7 for a graphical description of $\Delta\alpha_{visc}$.

4. Adjust the α-distribution (left hand side of system of equations in the modified Weissinger method) by the appropriate local viscous correction angle, $\Delta\alpha_{visc}$, and calculate the resulting load distribution.

5. Repeat steps 1-4 until $\left|C_{l_{visc}} - C_{l_w}\right| < \varepsilon$ for all spanwise stations.

This iterative procedure is performed for a complete angle-of-attack sweep. The maximum lift coefficient and stall angle can easily be determined from the resultant lift curve. Several validation test cases used in the validation of the $C_{L_{max}}$ prediction routine are presented and discussed next.

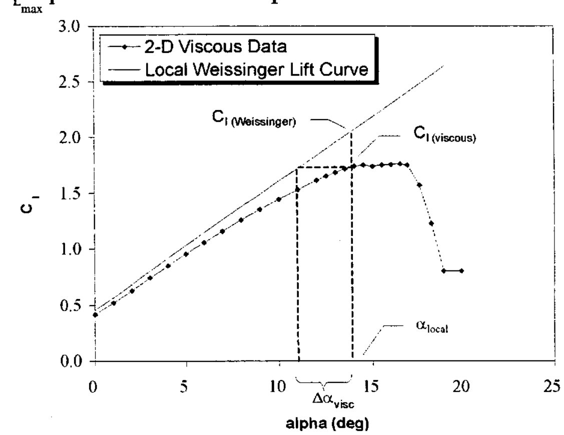

Fig. 7 Definition of viscous correction angle as part of non-linear $C_{L_{max}}$ prediction routine.

6. RESULTS AND DISCUSSION

Three test cases are presented that depict the capabilities and accuracy of the hybrid flow solution method and in particular the $C_{L_{max}}$ prediction routine. These test cases are:

1. F-29, cruise configuration
   - Demonstrates accuracy of $C_{L_{max}}$ prediction routine for a cruise configuration
2. Flapped half-span wing, full-span flaps
   - Demonstrates accuracy of $C_{L_{max}}$ prediction routine for a high-lift configuration
   - Validates wind-tunnel wall model in high-lift module
3. Flapped half-span wing, part-span flaps
   - Demonstrates importance of non-planar wake effect
   - Validates modified trailing-wake model

The first test case (1) is of the F-29 swept cruise wing configuration shown in Fig. 8 [26]. The wing has 21° of sweep at the quarter-chord, aspect ratio 10, and taper ratio 0.23. The high-lift module utilized 2-D aerodynamic data at nine different spanwise locations, as indicated in Fig. 8, for the non-linear $C_{L_{max}}$ calculations. The correlation with experimental data is excellent and can be seen in Fig. 9. The good agreement between the experimental data and the present prediction demonstrates that the non-linear $C_{L_{max}}$ prediction routine works very well for cruise wing configurations, provided accurate 2-D sectional data is available.

The next high-lift test case (2) was chosen as an example application of the wind-tunnel wall correction capabilities and also to further validate the method. The configuration selected was a wing with no sweep or taper having AR = 5.9 and NACA 0012 airfoil sections [27, 28]. The half-span wing model, shown in Fig. 10 was tested in the Langley 14 × 22 Ft subsonic wind-tunnel and the data reported had no wind-tunnel wall corrections applied. The lift-curves for the full-span flapped high-lift test case, as shown in Fig. 11, demonstrate that the vortex image method for modeling wind-tunnel walls does indeed provide accurate predictions in lift. In addition, Fig. 11 shows that the non-linear $C_{L_{max}}$ prediction routine continues to accurately predict the stall angle and maximum lift of the high-lift wing.

The half-span NACA 0012 wing from the previous test case was also analyzed in the part-span flap configuration (test case 3). As in the full-span flapped case, the results verify that the wind-tunnel modeling method used in the high-lift module does indeed provide results consistent with test data. The lift-curves presented in Fig. 12 show that with the wind-tunnel wall corrections inactive, the lift-curve-slope predicted by the high-lift module is less than the experimental lift-curve-slope. Turning the wind-tunnel wall model on brings the high-lift module lift prediction into agreement with the experimental data.

Unexpectedly, the prediction of $C_{L_{max}}$ for the part-span test case was much lower than the experimentally determined value as shown in Fig. 12. Up to this point, the non-linear $C_{L_{max}}$ prediction method had produced results very consistent with experiment. After further investigation, it was discovered that this discrepancy in test case 3 arises from a smearing of the spanwise load distribution that occurs at the flap break (or other discrete change in geometry such as a thrust gate) and is a result of the simplifying assumptions of the modified Weissinger method. The smearing effect occurs because the planar wake assumption tends to cause an overshoot in the effective angle of attack on either side of the flap break. This results in an artificially increased loading of the unflapped region, thus causing a premature stall of the unflapped region. This effect is exhibited in the spanwise load distribution for test case 3, as shown in Fig. 13.

The smearing in the load distribution is believed to occur because the modified Weissinger method models the trailing vortex wake in a single plane. Experimental and computation results indicate that the wake is not planar, but rather has discrete jumps where geometric discontinuities exist in the lifting surface. Figure 14 illustrates this non-planar wake development behind the part-span high-lift wing. This picture illustrates that the trailing vortical wake just downstream of the flapped region is in a completely separate plane from the vortical trailing wake of the unflapped region.

It became evident that a different method, one that allows for non-planar wake modeling, is required to accurately predict the 3-D aerodynamic characteristics of high-lift wings. After implementing a non-planar wake model in the Weissinger code, the spanwise load distribution depicts the steep drop at the flap break (Fig. 15). Also, the maximum lift prediction is much improved and much better agreement with the experimental results is obtained as shown in Fig. 16.

In summary, the flow solver that is part of the high-lift module produces excellent results for cruise and high-lift wings including wings with part-span flaps. In addition, the wind-tunnel wall model and fuselage models are working quite well. It provides an excellent compromise between computing time and accuracy for calculating the high-lift performance of an aircraft at the conceptual and preliminary design stages.

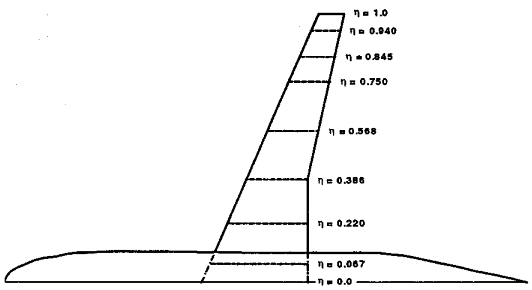

Fig. 8 Wing-body configuration with 2-D aerodynamic data specified at nine stations indicated [26].

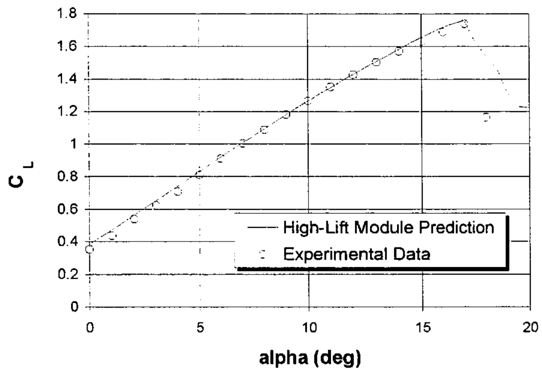

Fig. 9 Comparison of predicted and measured lift curves for wing-body configuration at $M_\infty = 0.19$, $Re_{MAC} = 5.0$ million

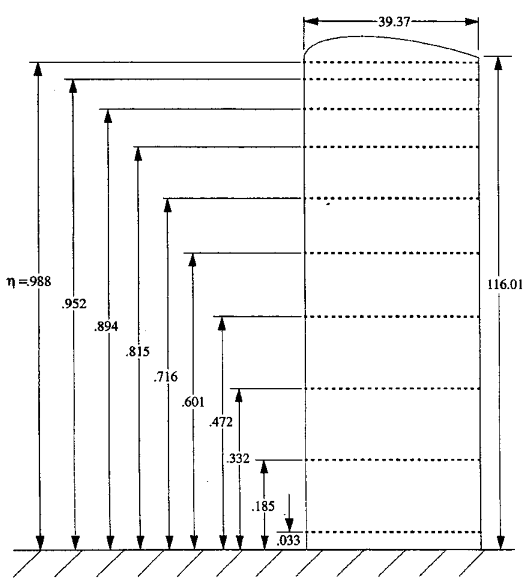

Fig. 10 Geometry description and pressure tap locations of NACA 0012 semispan testcase [27].

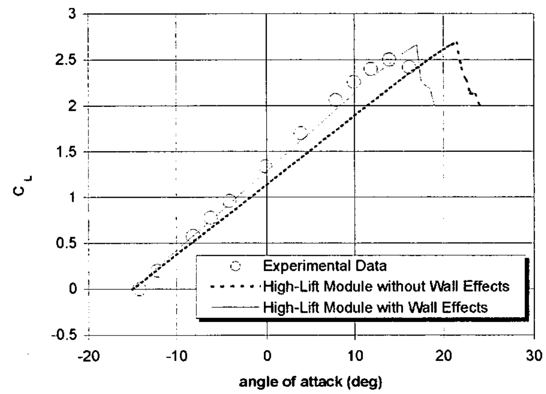

Fig. 11 Lift curves with and without wind-tunnel wall effect for NACA 0012 full-span flap test case at $M_\infty = 0.15$, Re = 3.3 million.

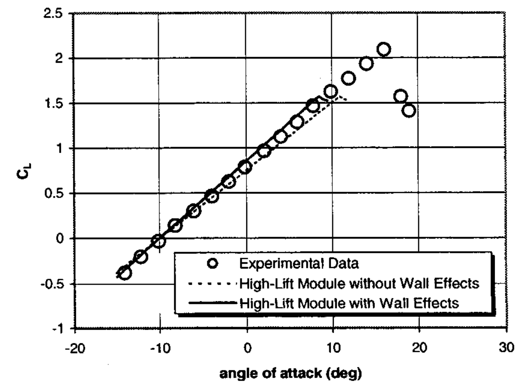

Fig. 12 Lift curves with and without wind-tunnel wall effect for NACA 0012 partial-span flap test case at $M_\infty = 0.15$, Re = 3.3 million (modified Weissinger method with planar wake).

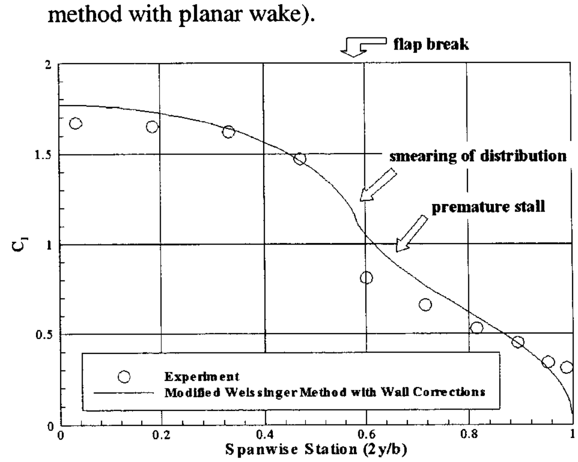

Fig. 13 Spanwise load distribution for NACA 0012 partial-span flap test case at $\alpha = 4°$ (modified Weissinger method with planar wake).

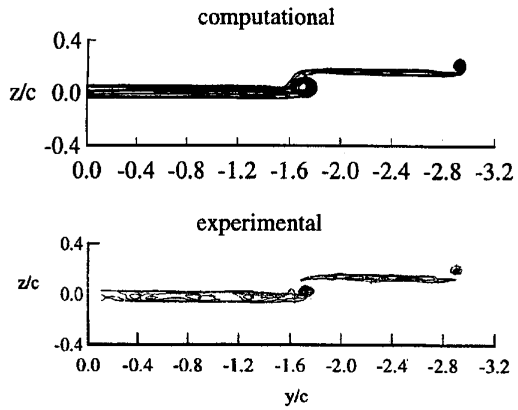

Fig. 14 Wake contours (total pressure) measured at 0.1c aft of flap trailing edge of NACA 0012 partial-span flap wing at $\alpha = 4°$ [29].

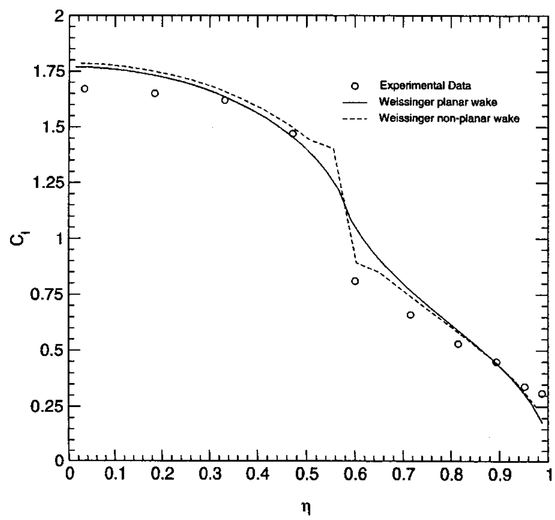

Fig. 15 Predicted spanwise load distribution for NACA 0012 partial-span flap test case at $\alpha = 4°$.

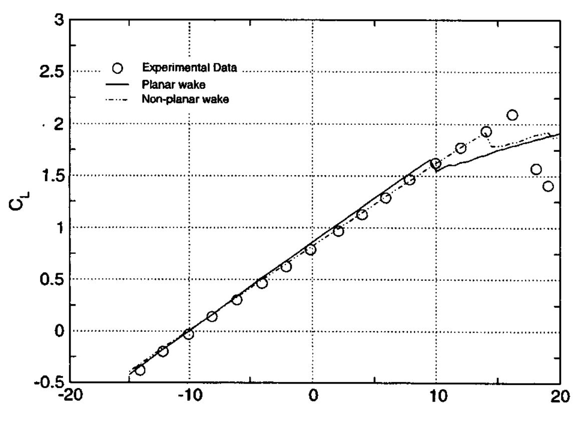

Fig. 16 Lift curves with wind-tunnel wall effect for NACA 0012 partial-span flap test case at $M_\infty = 0.15$, Re = 3.3 million.

7. CONCLUDING REMARKS

The highly competitive and economically driven commercial aviation market of today requires that aircraft manufacturers be able to provide customers with a high-quality product within the shortest amount of time at the lowest possible cost. The key to reducing both the investment and operating cost of an aircraft is to keep the systems as simple as possible. At one point in history, the complexity of high-lift systems was gradually increasing in order to achieve higher aerodynamic performance, but recent trends are headed in the opposite direction and aircraft companies are designing high-lift systems that achieve given levels of lift with simpler systems. In order to facilitate the efforts to design simpler, and thus more cost-effective high-lift systems, the present high-lift design methodology has been developed to offer significant improvements over traditional methods.

Noting the importance of designing simpler high-lift systems, it is critical that high-lift system considerations be included at even the earliest stages of the design process. In response to this need, a high-lift system design methodology has been developed which can be effectively utilized in both the conceptual and preliminary design stages of an aircraft. This makes it possible for the designer or aircraft optimization package to examine, early on in the design process, the effects that various high-lift configurations have on the overall cost and performance of a transport aircraft.

For a design tool be to effective at the conceptual and preliminary design stages, it must provide a reasonable balance between speed and accuracy. Keeping this in mind, a fast modified Weissinger method was chosen for the three-dimensional aerodynamic analysis. The three-dimensional calculations are coupled with two-dimensional viscous data, which enables the method to produce good results at a fraction of the time required for three-dimensional Navier-Stokes solutions. The test cases and sample application presented in this report demonstrate that this method does indeed provide the necessary accuracy to be useful at the conceptual and preliminary design stages, while being fast enough to be used during the early stages of design where thousands of iterations may be examined.

The methodology presented in this report has been integrated into an existing high-lift system design computer code, referred to as the "high-lift module". This high-lift module is simple to use and is capable of analyzing a wide range of high-lift systems found on civil transport aircraft.

ACKNOWLEDGEMENTS

This work has been supported by the NASA Ames Research Center under Consortium Agreements NCC2-5188 and NCC2-5255 and by the NASA Langley Research Center under Grant NAG-1-2215.

REFERENCES

[1] Rudolph, P.K.C., "High-Lift Systems on Commercial Subsonic Airliners," NASA CR 4746, Sep. 1996.

[2] Nield, B.N., "An Overview of the Boeing 777 High-Lift Aerodynamic Design," Aeronautical Journal, Nov. 1995, pp. 361-371.

[3] Davis, P., "Industrial Strength Optimization at Boeing," SIAM News, Jan./Feb. 1996.

[4] Myklebust, A., and Gelhausen, P., "Putting the ACSYNT on Aircraft Design," Aerospace America, Sep. 1994, pp. 26-30.

[5] Pepper, R.S., van Dam, C.P., and Gelhausen, P.A., "Design Methodology for High-Lift Systems on Subsonic Aircraft," AIAA Paper 96-4056-CP, Sep. 1996.

[6] van Dam, C.P., Shaw, S.G., Vander Kam, J.C., Brodeur, R.R., Rudolph, P.K.C., and Kinney, D., "Aero-Mechanical Design Methodology for Subsonic Civil Transport High-Lift Systems," NATO Research & Technology Agency Applied Vehicle Technology Panel Symposium on Aerodynamic Design and Optimization of Flight Vehicles in a Concurrent Multi-Disciplinary Environment, Ottawa, Canada, Oct. 18-21, 1999.

[7] Cahill, J.F., "Summary of Section Data on Trailing-Edge High-Lift Devices," NACA Report 938, 1949.

[8] Woodward, D.S., and Lean, D.E., "Where Is High-Lift Today? - A Review of Past UK Research Programmes," *High-Lift System Aerodynamics*, AGARD CP-515, Sep. 1993, pp. 1/1-45.

[9] Rogers, S.E., and Kwak, D., "An Upwind Differencing Scheme for the Incompressible Navier-Stokes Equations," Applied Numerical Mathematics, Vol. 8, No. 1, Aug. 1991, pp. 43-64.

[10] Rogers, S.E., Wiltberger, N.L., and Kwak, D., "Efficient Simulation of Incompressible Viscous Flow over Single and Multielement Airfoils," Journal of Aircraft, Vol. 30, No. 5, Sep.–Oct. 1993, pp. 736-743.

[11] Lin, J.C., and Dominik, C.J., "Parametric Investigation of a High-Lift Airfoil at High Reynolds Numbers," Journal of Aircraft, Vol. 34, No. 4, July–August 1997, pp. 485-491.

[12] Eyi, S., Lee, K. D., Rogers, S. E., and Kwak, D., "High-Lift Design Optimization Using Navier-Stokes Equations," Journal of Aircraft, Vol. 33, No. 3, May–June 1996, pp. 499-504.

[13] Spalart, P.R., and Allmaras, S.R., "A One-Equation Turbulence Model for Aerodynamic Flows," La Recherche Aérospatiale, No. 1, 1994, pp. 5-21.

[14] Rogers, S.E., Menter, F., Durbin, P.A., and Mansour, N.N., "A Comparison of Turbulence Models in Computing Multi-Element Airfoil Flows," AIAA Paper 94-0291, 1994.

[15] Kusunose, K., and Cao, H.V., "Prediction of Transition Location for a 2-D Navier-Stokes Solver for Multi-Element Airfoil Configurations," AIAA Paper 94-2376, 1994.

[16] van Dam, C.P., Los, S.M., Miley, S., Roback, V.E., Yip, L.P., Bertelrud, A., and Vijgen, P.M.H.W., "In-Flight Boundary-Layer Measurements on a High-Lift System: Main Element and Flap," Journal of Aircraft, Vol. 34, No. 6, 1997, pp. 757-763.

[17] Brodeur, R.R., and van Dam, C.P., "Transition Prediction for a Two-Dimensional Navier-Stokes Solver Applied to Wind-Turbine Airfoils," AIAA Paper 2000-0047, Jan. 2000.

[18] van den Berg, B., "Boundary-Layer Measurements on a Two-Dimensional Wing with Flap," NLR TR 79009U, Jan. 1979.

[19] Hoak, D., "USAF DATCOM Section 6 - Characteristics of High-Lift and Control Devices," Flight Control Division, Air Force Flight Dynamics Laboratory, WPAFB, Ohio, 1974, revised.

[20] Paris, J.K., "Advancements in the Design Methodology for Multi-Element High-Lift Systems on Subsonic Civil Transport Aircraft," M.S. Thesis, University of California, Davis, 1999.

[21] Mutterperl, W., "The Calculation of Span Load Distributions on Swept-Back Wings," NACA TN 834, Dec. 1941.

[22] Weissinger, J., "The Lift Distribution of Swept-Back Wings," NACA TM 1120, 1947 (translation of Feb. 1942 publication).

[23] Campbell, G.S., "A Finite-Step Method for the Calculation of Span Loadings of Unusual Plan Forms," NACA RM L50L13, 1951.

[24] Blackwell, J.A., "A Finite-Step Method for Calculation of Theoretical Load Distributions for Arbitrary Lifting-Surface Arrangements at Subsonic Speeds," NASA TN D-5335, July 1969.

[25] Barnes, J.P., "Semi-Empirical Vortex Step Method for the Lift and Induced Drag Loading of 2D or 3D Wings," SAE Paper 975559, Oct. 1997.

[26] Obert, E., "Forty Years of High-Lift R&D – An Aircraft Manufacturer's Experience," *High-Lift System Aerodynamics*, AGARD CP-515, Sep. 1993, pp. 27/1-28.

[27] Weston, R.P., "Refinement of a Method for Determining the Induced and Profile Drag of a Finite Wing from Detailed Wake Measurements," Ph.D. Thesis, University of Florida, 1981.

[28] Applin, Z.T., "Pressure Distributions from Subsonic Tests of a NACA 0012 Semispan Wing Model," NASA TM 110148, Sep. 1995.

[29] Jones, K.M., Biedron, R.T., and Whitlock, M., "Application of a Navier-Stokes Solver to the Analysis of Multielement Airfoils and Wings Using Multizonal Grid Techniques," AIAA Paper 95-1855, 1995.

C.P. (Case) van Dam is a professor of aeronautical engineering at the University of California at Davis, where he teaches courses in aerodynamics and aircraft performance and design in the Department of Mechanical

and Aeronautical Engineering. He previously was employed as a National Research Council (NRC) post-doctoral researcher at the NASA Langley Research Center and as a research engineer at Vigyan Research Associates, Inc. Van Dam's current research includes the prediction, measurement and reduction of aerodynamic drag; the aerodynamics and design of high-lift systems; infrared imaging of boundary-layer transition and separation; and the aerodynamics of wind turbines and aircraft forebodies at dynamic conditions. He is a past recipient of the AIAA Lawrence Sperry Award as well as several NASA awards. Van Dam received B.S. and M.S. degrees in aerospace engineering from the Delft University of Technology, The Netherlands, and M.S. and Doctor of Engineering degrees in aerospace engineering from the University of Kansas.

John Paris is an engineer/scientist at The Boeing Company – Rocketdyne Propulsion & Power, where he acquires and develops state-of-the-art CFD technologies for use in rocket engine design. In addition, he supports current development programs with CFD analysis and multi-disciplinary optimization. He has experience using CFD to predict turbopump and nozzle performance. Paris received B.S. degrees in both aeronautical and mechanical engineering, and a M.S. degree in engineering from the University of California at Davis. While at UC Davis, his research focused on the aerodynamics and design of high-lift systems.

Jeremy Vander Kam is a graduate research assistant at the University of California at Davis working towards his M.S. Degree in Aeronautical Engineering. He received B.S. degrees in both aeronautical and mechanical engineering from the University of California at Davis and has previously worked in the commercial satellite division of Lockheed Martin Missiles and Space and at the NASA Ames Research Center. Vander Kam's thésis research is in the area of high-lift system design and analysis