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RECENT ADVANCES IN BOEING HIGH-LIFT TECHNOLOGY

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ABSTRACT

An overview of recent developments at Boeing in unpowered high-lift aerodynamics for transport airplanes is presented. Results for two-dimensional multielement airfoils and finite wings, and advances related to testing are summarized. These include means of designing desirable pressure distributions and the corresponding geometry in two dimensions, and three-dimensional multielement lifting surface theory to relate the airfoil results to finite wings. With these methods, the high lift designer can account for the section effects of Reynolds number and modify his designs accordingly.

I. INTRODUCTION

Reviews of advances in high-lift aerodynamics have occurred periodically in the past.(1)-(5) The traditional development of high-lift aerodynamic systems has relied heavily on experimental and empirical techniques.

Six years ago, the Boeing Commercial Airplane Company began a concerted effort to develop new technology for unpowered high-lift aerodynamics as applied to commercial transport airplanes. The emphasis has been on analytical methods, although empirical and experimental techniques have not been ignored. This paper summarizes the developments and results obtained to the present and has sections on two-dimensional airfoils, finite wings, and advances related to testing. Both analysis and design methods are discussed; the former produces aerodynamic characteristics as a function of geometry, while the latter is the inverse process.

The achievements listed are perhaps best described as applied research. The objective of this work is to provide improved theoretical, empirical, and experimental technology in readily usable form to those aerodynamicists at Boeing who design unpowered high-lift systems. Specifically excluded from this paper is the large body of research and development work that has led to the design and flight-testing of the QSRA and YC-14 airplanes.

II. TWO-DIMENSIONAL METHODS

The development of two-dimensional methods continues to make heavy demands. Potential flow solutions for multielement airfoils are well understood and available in several forms; they are not a concern here. The work described in this section concerns improved calculation methods for viscous flows, airfoil design, and separated flows.

Viscous Algorithms

One recent effort has concentrated on the development of improved viscous algorithms for multielement airfoils.(6)-(8) Improvements in both lift level and slope have been demonstrated (Figure 1). Results for drag and pitching moment are encouraging (Figures 2 and 3), but the method is restricted to angles of attack for which the boundary layer remains attached.

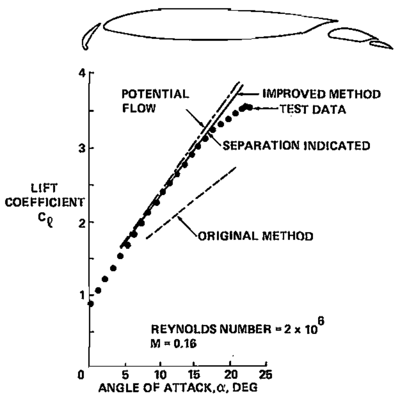

Figure 1. – Multielement Airfoil Lift Curve

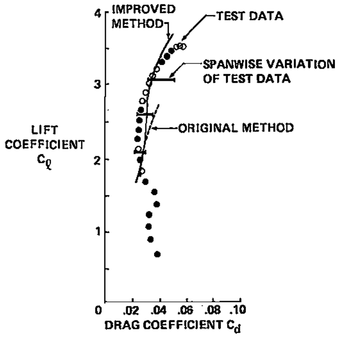

Figure 2. – Multielement Airfoil Drag

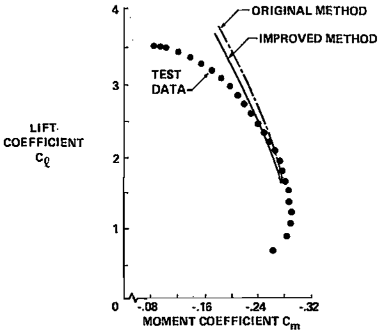

Figure 3. – Multielement Airfoil Pitching Moment

First results of an emerging technology for confluent boundary layers are promising. Figure 4 shows a comparison of velocity profiles predicted by this technology with test data.(9) A description of the final form of the technology and additional results will be published at a later date. Experiments to obtain additional data for confluent boundary layers and for flow in flap coves have begun.

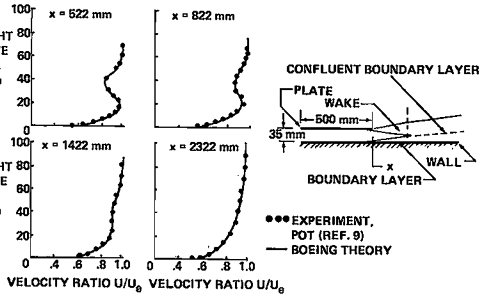

Figure 4. — Velocity Profiles of Confluent Boundary Layer

Design and Separated Flow Modeling

Another effort on two-dimensional multielement airfoils is directed toward both design and analysis capability. The design method includes potential flow panel algorithms, is iterative, and can be used to design either complete airfoil elements or only parts of elements, the balance of which remain fixed. An inverse boundary layer method is available to determine desirable pressure distributions.(10) For those cases when no geometry will produce precisely a specified pressure distribution, the desired pressure distribution is satisfied in a least-squared-error sense.

Results of a design study for an airfoil are shown in Figure 5. An initial shape and pressure distribution are shown together with the desired pressure distribution. In four iterations, the airfoil shape having the desired pressure distribution is computed to within plotting accuracy in pressure coefficient. The algorithm is a true design method—calculate geometry as a function of specified aerodynamics, and is a two-dimensional prototype of a more general three-dimensional design method.(11)

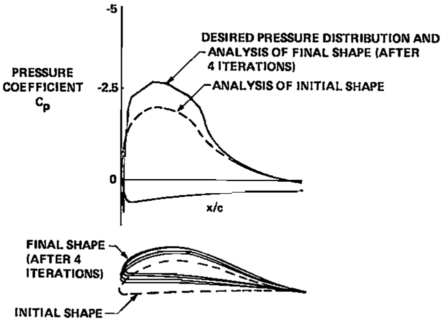

Figure 5. — Airfoil Design

Results for a flap design study are given in Figure 6. The main airfoil geometry is fixed. The desired flap pressure distribution and the corresponding flap geometry are obtained in four iterations.

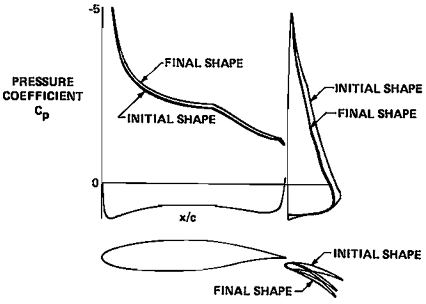

Figure 6. — Flap Design

In the analysis mode, boundary layer properties are accounted for by state-of-the-art methods. Laminar flow, transition, laminar short bubble separation and possible turbulent reattachment, turbulent flow, and turbulent separation are all predicted as a function of pressure distribution. The influence of boundary layer displacement is included by an iterative process.

At higher angles of attack, separation is no longer confined to the immediate vicinity of trailing edges; its effects must be accounted for in the solution for pressure distribution.(12) An initial shape corresponding to a steady-state wake is assumed, and the design methodology is used to determine a wake shape that carries no load. This, too, is an iterative solution if separation occurs on one airfoil element, since separation location varies with pressure distribution; it becomes a series of imbedded iterations if separation is modeled on more than one element.

Figure 7 shows the importance of modeling the separated wake.(12) Note the agreement between theoretical result and test data, particularly in the separated wake on the main airfoil. Potential flow theory without modeling of the separated wake is clearly inadequate. Figures 8 and 9 illustrate the effectiveness of the method in modeling separated flow about highly deflected control surfaces and spoilers.(13)

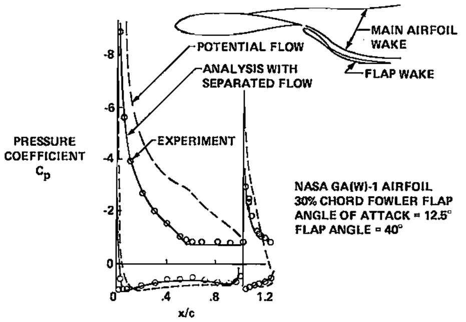

Figure 7. — Comparison of Theoretical and Experimental Pressure Distributions on a Two-Element Airfoil With Separations on Both Surfaces

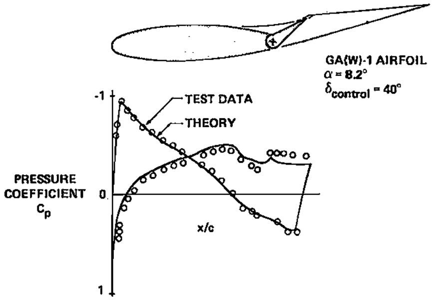

Figure 8. — Comparison of Theoretical and Experimental Pressure Distributions on an Airfoil With Deflected Control Surface

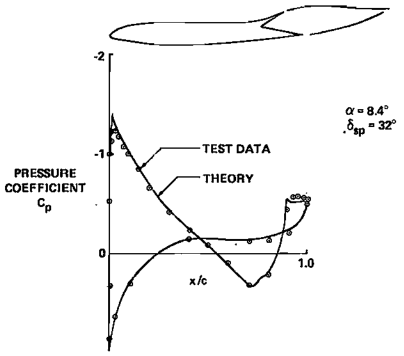

Figure 9. — Comparison of Theoretical and Experimental Pressure Distributions on an Airfoil With Deflected Spoiler

All of this design and analysis technology has been incorporated into a single computer code which has recently gone into production usage at Boeing.

These developments are significant for they change fundamentally the techniques for designing and analyzing multielement airfoil sections. The inverse boundary layer technique greatly reduces the task of defining a desirable pressure distribution and provides a largely automated rational method. The design technique is essential to produce the geometry corresponding to the desired pressure distribution. The analysis capability including separation is important for predicting off-design aerodynamic characteristics.

Throughout all of these is the explicit use of Reynolds number as an independent variable. It is now possible to design airfoil sections for flight conditions, rather than for the conditions of substantially lower Reynolds number typically used to develop and validate designs in low-speed wind tunnels. The final, essential element is production software that produces results quickly, so that production aerodynamicists can apply all of the technology routinely.

III. FINITE WING METHODS

The development of analysis and design capability for three-dimensional wings in high-lift configuration proceeded in two stages. First a vortex lattice method was developed, and was followed by the development of a distributed vorticity lifting surface method. This Section discusses these developments as well as a collection of achieved airplane maximum lift coefficients for comparative purposes.

Vortex Lattice Methodology

The development of vortex lattice capability did not involve new methods, but concentrated instead on producing a reliable computer code. However, to the vortex lattice code has been added capability to model thickness with source panels from an established method.(14) This is particularly important for the modeling of the fuselage, but less important for modeling wing thickness, at least for high-lift configurations. The analysis capability is especially complete. Theoretical forces and moments are computed as a function of pitch, roll, and yaw attitudes and steady-state rates of change of pitch, roll, and yaw. Flow field velocities, streamlines, ground effects, and linear free surface effects are all included in the analysis mode.

In addition, significant design capability has been incorporated.(15) It is possible to solve for the load distribution, and the corresponding geometry, for minimum induced drag, subject to one or more of a number of constraints, such as:

- A given bending moment at any span station of the wing.
- A specified amount of lift or side force carried by the whole configuration or by parts of it.
- A specified pressure on certain panels.
- A specified shape of the chordwise loading.
- A relationship between deflection angles of specified panels of the configurations.

Some results of the vortex lattice method for high-lift analysis of multielement wings have been disappointing. The difficulty lies in the sensitivity of the results to the assumed position of the trailing vorticity near the spanwise edges of flaps. Large changes in lift curve level and slope result from seemingly modest changes of shed vorticity at flap ends. The expert user can achieve good results, but confidence in results produced by the average user is not high. An example of the variations in lift curve and span loading produced by different models of shed vorticity is shown in Figures 10 and 11. Pressure distributions compare well with test data when the comparison is made at the same lift, rather than the same angle of attack.

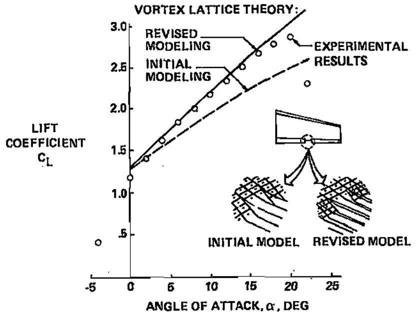

Figure 10. – Comparison of Vortex Lattice Theory and Experimental Lift Curve for a Full Span Flapped Wing With Aileron Cut Out

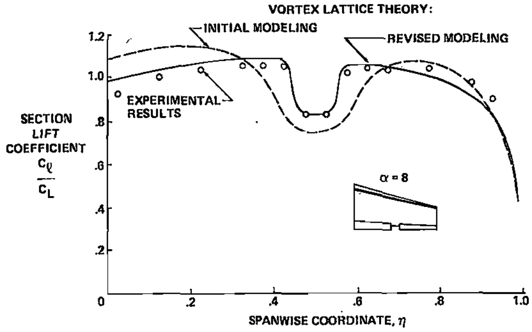

Figure 11. – Comparison of Vortex Lattice Theory and Experimental Span Flapped Wing With Aileron Cut Out

Results for aerodynamic design applications of the vortex lattice code are promising, although the applications to date are primarily for cruise configurations rather than for high-lift configurations. Winglets have been designed for the KC-135 by this method.(16) Other examples demonstrate further the flexibility of this method.(17),(18)

The importance of the vortex lattice code, apart from the obvious increment in capability, is that it demonstrates the possibilities of analyzing high-lift configurations. Difficulties with the shed vorticity are manageable by experienced users. These difficulties are not present for design applications.

Lifting Surface Method

A computer program utilizing an established distributed vorticity singularity(19) has been tailored for high-lift applications. A great deal of emphasis has been placed on automation. The user need only specify gross geometry for multielement wings primarily in terms of the airplane parameters he is accustomed to, 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. The analysis capability differs primarily from that developed earlier(19) in that provisions are made for multielement wings, a slender body, and a ring-wing representation of nacelles; none are made for representation of wing thickness. The latter omission is justified on the grounds that surface pressures due to lift are much greater than those due to thickness at high-lift conditions; in addition, the ignored effects of airfoil thickness and boundary layer displacement are in opposition. Design capability has been provided similar to that in the vortex lattice program already described.

At low angles of attack and small-to-moderate flap deflections, the method provides both lift and span load distributions that agree with test data. Little separation is present, and the physics of the flow are modeled reasonably well.

When separation becomes substantial, the model no longer applies strictly. Lift is overestimated, as shown in Figure 12, and the shape of the span loading might be incorrect, depending on the spanwise variation of separation.

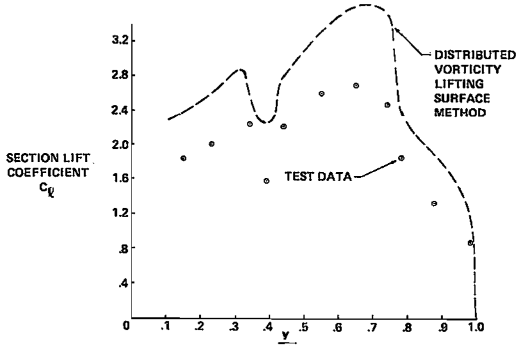

Figure 12. – Span Loading Discrepancy Due to Separation

However, the two-dimensional method described in Section II that models separated flow can be used to improve the theoretical three-dimensional lift results when separation is sufficient to affect overall lift. Figure 13 shows a flapped airfoil with substantial separation. The two-dimensional method is used to predict lift and the shape of the separated wake. The effective camberline for the potential flow solution that determines the pressure distribution lies midway between the upper surface of the separated wake and the outer edge of the boundary layer on the lower surface. The two-dimensional method can be used to calculate a corresponding effective flap deflection defined by this aerodynamic camberline as a function of the flap deflection defined in the usual way by the geometric camberline. Figure 14 shows that the theoretical results predict test data reasonably well.

The effective flap deflection is then used in place of the geometric flap deflection in the calculation of three-dimensional lift by the distributed vorticity lifting surface method. Figure 15 shows that this method significantly improves the span loading calculation.

The distributed vorticity lifting surface method has been used in combination with the two-dimensional method to design a leading edge device that improves lift-to-drag ratio in takeoff for a twin-engine study airplane. The three-dimensional method is used to compute span loading at the design lift; the choice of the span station for the slat design is then based on the span loading. The two-dimensional design method is used to design both a better pressure distribution on the leading edge slat, and the revised slat geometry. The result is a 5 percent improvement in lift-to-drag ratio demonstrated in the wind tunnel. This work has been described previously.(20)

The design method has only been applied to test cases thus far to demonstrate its capacity to treat many types of cases. One of these has been the subject of speculation and is worth mentioning because of the largely negative result.

Designers of high-lift systems having one or more spanwise breaks have speculated that significant reductions of induced drag could be achieved by setting the various spanwise flap segments at different deflections, each differing moderately from the nominal uniform deflection. For a swept wing planform typical of today's jet transports having inboard and outboard flaps, the design method has been used to select the inboard and outboard flap deflections that would minimize induced drag, subject to a constraint on lift. The resulting reduction of induced drag is very small, indicating that differential flap deflection does not necessarily offer a powerful means of idealizing span loading. Continously varying twist of the flaps would, of course, be required to minimize induced drag by means of the flaps.

Maximum Lift Coefficient Compilation

The maximum lift coefficients of a number of airplanes have been collected and compared.(21) The objective is to develop a data base to establish technology levels and trends, not to establish a simple predictive procedure of coarse accuracy as a function of a few geometric parameters.

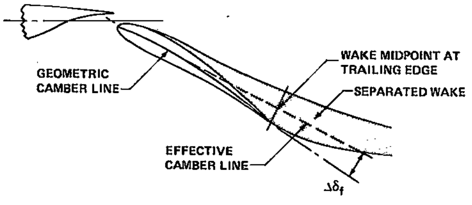

Figure 13. – Wake of Separated Flap

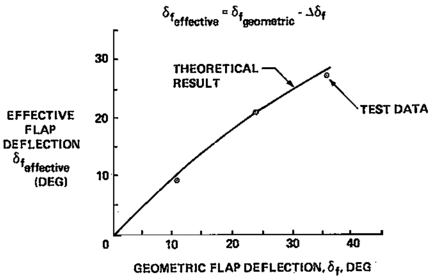

Figure 14. – Comparison of Theoretical and Experimental Effective Flap Deflection

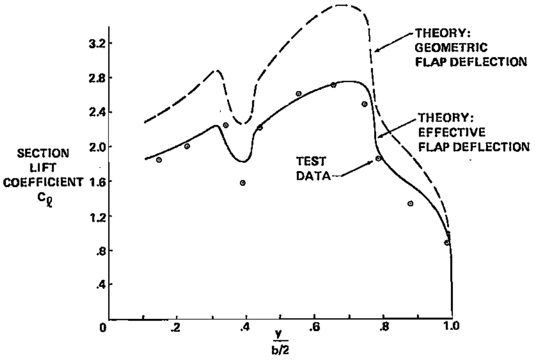

Figure 15. – Improvement in Span Loading Prediction Due to Use of Effective Flap Deflection

Figure 16 shows maximum lift coefficient data for 30 transport airplanes as a function of quarter-chord sweep angle. The data have been fitted with four cosine trend curves corresponding to configurations with only trailing edge flaps, and single-, double-, and triple-slotted flaps with leading edge devices.

FITTED CURVES: $C_{L_{max}} = K \cos \Lambda_{c/4}$

SYMBOL	LEADING EDGE DEVICE	TRAILING EDGE SLOTS	K	SYMBOL NUMBER	AIRPLANE
○	Yes	3	3.17	1.	B737-200
				2.	B737-100
				3.	B727-200
				4.	TU-154
				5.	B747-100
△	Yes	2	2.95	6.	DC-9-30
				7.	A300 B4
				8.	FALCON 10
				9.	DC-10-10
				10.	L-1011-1
				11.	DC-10-30
				12.	TRIDENT 3B
				13.	B707-320B
▽	Yes	1	2.74	14.	C5A
				15.	SABRE-LINER
				16.	FALCON 20F
				17.	VC-10
				18.	B747 SP
□	No	1 or 2	2.49	19.	VFW 614
				20.	FOKKER F28
				21.	BAC 111-500
				22.	BAC 111-400
				23.	HS 125
				24.	CARAVELLE
				25.	DC-9-10
				26.	C141
				27.	DC-8-63
				28.	DC-8-50
				29.	TRIDENT 1C
				30.	B707-120B

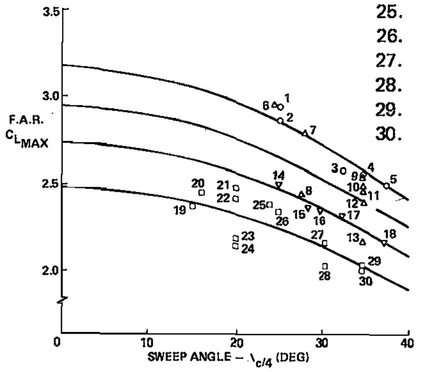

Figure 16. – Maximum Lift Coefficients of Some Transport Airplanes

These data are used to assess the relative capabilities of new airplanes and to rationalize their performance differences in terms of detailed configuration differences.

IV. ADVANCES RELATED TO TESTING

Two advances related to testing are discussed in this Section. One is the design of a thick symmetrical airfoil section to be used as a strut for mounting instrumentation to survey flow fields. While the section will certainly be useful, a larger result obtained from the validation testing of the section is improved empirical methodology in the design method described in Section II. The second advance is an improved method for the analysis of the dynamic stall maneuver in flight test.

Design of Thick Strut

The High-Lift Research Group has received a request to design a thick symmetrical strut from the Boeing Wind Tunnel Testing Methods Group. They want to survey the flow in various sections of Boeing wind tunnels, apart from the test sections themselves, to determine the potential for improving flow qualities and for reducing losses. The Methods Group proposes to mount suitable instrumentation on a long strut to be moved at will in the low-speed flow in the closed circuit wind tunnel legs, and want the thickest symmetric airfoil section that can be designed conservatively to have little separation. The operating Reynolds number range is 10^5 to 10^6. The section should not separate badly for angles of attack up to three-to-five degrees; this will allow for small local crossflows.

The inverse boundary layer method(10) has been used to design a pressure distribution that satisfies the airfoil design requirements, and the two-dimensional airfoil design computer program has been used to compute the corresponding airfoil section. This section has a thickness-to-chord ratio of 0.288. Figure 17 shows the airfoil section, the design pressure distributions at zero angle of attack, and an experimental pressure distribution measured in the Boeing Research Wind Tunnel. At the indicated condition, the design pressure distribution has been achieved.

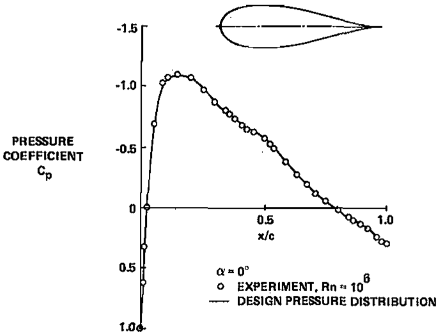

Figure 17. – Thick Strut and Its Design Pressure Distribution

Figure 18 shows the predicted separation location as a function of angle of attack for the limits of the available Reynolds number testing range. Here it can be seen that the design is conservative, and in fact, the results of this test have been used to recalibrate empirical elements of the methodology of Section II at low Reynolds number.

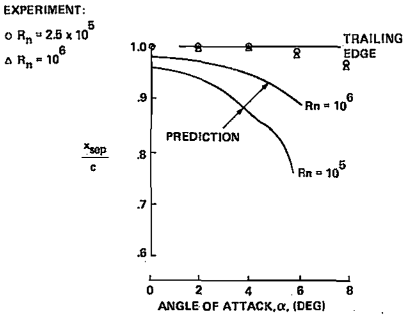

Figure 18. – Separation Location of the Thick Strut

The results of the test, therefore, include not only the strut section itself but also improved methodology for airfoil design at low Reynolds number. The latter is particularly important, for the various segments of a three-dimensional high-lift system tested in a low-speed wind tunnel frequently operate within the low Reynolds numbers range of this design study. The capability to design and analyze models in these conditions has thus been improved.

Dynamic Analysis of Airplane Stall

The principles of the dynamic stall maneuver and its importance to certified stall speeds are understood.(22) Before the development of this technology, stall dynamics were accounted for by empirical factors, which led to imprecise prediction of stall speed. An accurate means of calculating airplane and flight path parameters as a function of time and specific airplane characteristics is essential to the accurate prediction of stall speeds. Figure 19 compares flight test data for the 747 with theoretical results from a new dynamic stall computer program. This code does not represent inherently new technology. However, the development of a dynamic analysis code tailored for this problem, rather than the adaptation of a more general dynamic maneuver code, is indicative of the importance of the problem.

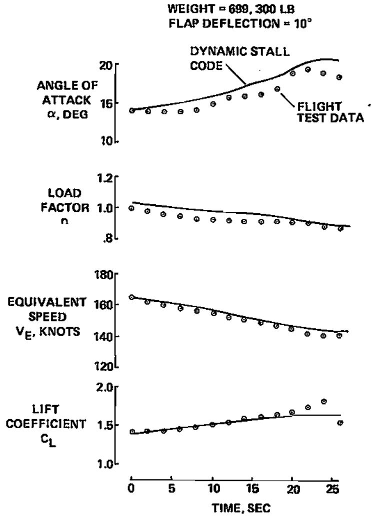

Figure 19. – Dynamic Stall Maneuver for the 747

V. CONCLUDING REMARKS

The applied research in high-lift aerodynamics described in this overview has brought advances in capability in several areas to the Boeing high-lift designer. Improvement in viscous aerodynamic analysis has been restricted to two dimensions thus far, but the acquisition of more powerful and efficient computing machines leads to optimism that productive work on three-dimensional, multielement viscous methods can proceed within a year or two. Candidate technological elements include PAN AIR, (11) for potential flow analysis and design, and a three-dimensional boundary layer analysis.(23),(24) The two-dimensional viscous developments will lead to a better understanding of such phenomena as the separated flow in flap coves, which hopefully will be applicable to airplane detailed design.

The inverse boundary layer method provides a readily usable and effective means of obtaining desirable pressure distributions for airfoil and/or flap elements; the design methodology provides the corresponding geometry. The appearance of Reynolds number as a design variable is important, for it permits the designer to account for the differences in viscous aerodynamics between the wind tunnel model and the airplane, both for the analysis of defined geometry and for the design of new geometry. This development has led the author to the growing belief that high-lift wind tunnel models should be designed to simulate the aerodynamics of the airplane; currently, great pains are taken to ensure that the airplane's geometry is simulated.

If this view is accepted, then the wind tunnel model geometry should be different from that of the airplane. The detailed geometry of each element of the wind tunnel model high-lift system, and perhaps even the relative lengths of the elements, should be changed as necessary to achieve the aerodynamic goal. That goal should be a high-lift wind tunnel model test for which viscous phenomena occur at the same angle of attack as they do for the airplane. The two-dimensional design method, coupled with the three-dimensional lifting surface method, provides a first means of accomplishing this. This combination has already achieved some success, even though it does not account for the nonlinear aerodynamics of wing-mounted engine nacelles and their pylons that are caused by separated and vortex flows.

A necessary element for succesful production use of both the two-dimensional design method and the three-dimensional lifting surface method is tailoring of the computer software for high-lift application. The tailoring includes suitable representation of multielement airfoils and wings, the use of configuration specification variables that are natural to the production aerodynamic designer of high-lift systems (such as flap gap and overlap, deflection angles, and the like), and a high degree of automation of such details as locating the individual vorticity elements and positioning the shed vorticity. These features together produce a method that gives reasonable results in a brief period of time, which is a necessity in the production aerodynamic design environment.

The design and validation of the thick strut airfoil is instructive. The developer of the technology was involved in this application and was thus in a position to immediately assess its conservative nature and promptly revise it. The timely recalibration of the empirical methodology in the two-dimensional design and analysis computer program has justified all of the effort.

The work described in this paper has been directed toward providing the high-lift designer with improved methods. While it has been successful in those terms, much remains to be done.

ACKNOWLEDGEMENTS

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