A Method for Predicting Low-Speed Aerodynamic Characteristics of Transport Aircraft

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A preliminary design level methodology for predicting the global aerodynamic characteristics of transport aircraft in low-speed/high-lift configurations has been developed, based on recent advances in computational aerodynamics analysis methods. The new method involves two economical, user oriented, computer programs. One, an advanced lifting-surface theory for the potential flow analysis of swept-wing/body combinations with multi-element high-lift devices, provides the basic theoretical structure. The second program combines potential flow analysis results with available data from previous airplane models to predict the performance of new designs. The overall procedure is highly automated and produces generally satisfactory results for preliminary design purposes. Example results based on recent transport aircraft wind tunnel data are shown.

Nomenclature

AePP	= Aerodynamic Prediction Program
Æ	= aspect ratio, b^2/S
b	= wing span
c	= wing chord
$\bar{c}$	= average wing chord S/b
C_ℓ	= two-dimensional section lift coefficient, lift/qc
C_D, C_L, C_M	= configuration drag, lift and pitching moment coefficients, force/qS and moment/qSc
C_{L_I}	= (see Fig. 7)
DVM	= Distributed Vorticity Method
G, H	= scaling factors
M	= Mach number
q	= dynamic pressure
Re	= Reynolds number
S	= wing area (high-lift devices retracted)
S_f	= flap area
x	= longitudinal coordinate
y	= lateral coordinate
α	= angle of attack
Δ	= differences (residuals)
δ_f	= flap deflection
η	= non-dimensional spanwise wing station, $2y/b$
Λ	= sweep angle measured at wing quarter chord

Subscripts

a	= baseline (input) configuration
b	= configuration whose characteristics are to be predicted (output)
dvm	= distributed vorticity method (potential flow lifting surface theory)
eff	= "effective" viscous condition
exp	= experimental (e.g., wind tunnel) value
f	= flap
geo	= geometric value
max	= maximum
min	= minimum
o	= reference value (high lift system retracted)
visc	= viscous

Superscripts

$(\hat{\ })$	= adjusted or scaled quantity
(*)	= critical section

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Introduction

IN recent years considerable progress has been made in the development of computational methods for both the analysis and design of transport aircraft in low-speed/high-lift configurations. The development and application of several of these computational tools to practical project-level high-lift system design problems at Boeing has been described recently.[1-3] The applications discussed in Refs. 2 and 3 are typical of those which might be encountered in the detailed design phase of an overall configuration aerodynamic development process. As shown in the overview diagram (Table 1), at the detail design level computational methods intended to complement extensive testing must be highly accurate. Thus, costs may be high although fully justified if an enhanced (compared with traditional cut-and-try) design process results.

In a preceding preliminary design phase of aerodynamic configuration development, computational methods are also of major importance. In this case, however, where many continually changing configuration variables must be considered and their effects on the global aerodynamic characteristics readily evaluated, the conflicting requirements of computational accuracy, ease of use, rapidity of turnaround, and low cost make the development of appropriate computational methodology challenging.

It should be observed that the flow fields associated with the complex geometry of a modern transport aircraft during takeoff and landing approach are extremely complicated and may involve numerous vortical and partially separated flows even under normal operating conditions, as shown in Fig. 1. No available computational methods are capable of analyzing the full range of such flows. Similarly, past handbook build-up methods offer little hope of predicting the global aerodynamic characteristics of such configurations to the levels of accuracy and reliability required for modern preliminary design purposes.

The need for a modern predictive methodology appropriate to preliminary design level aerodynamic analyses (at a point in the design process where extensive wind-tunnel testing cannot be justified) remains, however. Recognizing the limitations of existing theoretical tools, a better computationally-based predictive methodology can be devised if one accepts certain underlying assumptions. A description of such a method is the subject of this paper.

While the method described here is based on two Boeing proprietary computer programs (to be described presently), it should be observed that the central purpose of this paper is to describe and demonstrate the results of a general procedure and the assumptions upon which the procedure is based. Any other available computer programs capable of providing the required data could, in principle, be equally well-employed.

A Preliminary Design Level Prediction Method

The method devised to fill the block for a preliminary design-level predictive tool in Table 1 is semi-empirical and relies on two computer programs. The new method is made possible and practical by the existence of a potential-flow lifting-surface theory computer program specifically developed for the analysis and design of multi-element swept-wing and fuselage combinations. This program, developed by M.I. Goldhammer,[3] will be referred to in the remainder of this paper as the DVM (Distributed Vorticity Method) program.

The second program in the system, developed by the authors, will be identified as AePP (Aerodynamic Prediction Program). AePP is a highly automated system of bookkeeping, interpolation/extrapolation, scaling, and post-processor routines which produce predictions of global aerodynamic characteristics of a configuration in a subsonic viscous flow.

The DVM potential-flow lifting-surface theory program uses a distributed vorticity singularity (Fig. 2) in contrast to earlier vortex lattice representations. The program is highly user-oriented. One need only specify gross geometric parameters for multi-element wings (e.g., planform, twist, camber, flap deflections) and the program generates its own detailed vorticity networks. The vorticity distribution automatically satisfies the Kutta condition at each trailing edge. A two-dimensional algorithm is used by the program to specify downstream wake shapes. Provision is made for multi-element wings with part-span flaps, a slender body theory representation for the fuselage, and a ring-wing model of nacelles. Wing thickness is not accounted for. The DVM program also calculates and stores additional geometric parameters (e.g., flap and leading edge device areas) necessary for execution of the AePP prediction method. Thus, the DVM program also provides a powerful reference geometry definition capability requiring a minimum of user manipulation and input.

The DVM program has been in routine project group use since 1979. Typical test/theory comparison results are shown in Fig. 3. The remarkably good agreement in lift level for the cases of zero or small flap deflections demonstrated is attributable to the fact that neglect of both attached boundary layer flow and wing thickness in the potential flow analysis produces partially compensating errors. At high flap settings, where the flow may be partially separated and/or the boundary layers are much thicker, the potential flow results generally overpredict lift levels.

Table 1 Low-speed aerodynamic prediction methods

Design level	Accuracy required	Turnaround time	Cost	Method
Conceptual	Approx. (±10–20%)	Neglig.	Neglig.	Handbook/ Calculator
Preliminary	Good (±5–10%)	Rapid	Low	Improved Semi-empirical (Present paper)
Detail (Project	High (±2–5%)	Reasonable	As required	Full analysis and design Viscous 2-D Inviscid 3-D Emerging (3-D viscous)

The basic structure of the overall methodology, based on a framework (in terms of potential flow lift curve, pitching moment, induced drag and span loading) provided by independent runs of the DVM program, is shown in Fig. 4. It provides the engineer with two options:

1) For cases where experimental data for a baseline configuration exists, the effects of changes in the baseline geometry (e.g., flap span, flap chord, number of flap elements) can be estimated with good accuracy. In this case the full procedure shown in Fig. 4 is used.

2) This option pertains to cases where no explicit baseline experimental data exists. By combining generic empirical data stored in AePP with results of DVM analyses of the study geometry, the global aerodynamic characteristics of the new configuration can be estimated with adequate accuracy.

To date the emphasis has been on development of the first option with exploration of the empiricism required to complete the methodology at traditional wind-tunnel Re levels. The problem of extending the methodology to predict the aerodynamic characteristics of a given configuration at flight Re scale conditions from wind-tunnel data remains to be fully addressed. The method has been structured, however, to allow extension to arbitrary subsonic scale conditions.

Discussion of the Method

An outline of the overall method and its program elements is shown in Fig. 4. How the method works, the assumption on which it is based, and some of the higher order empiricism used requires further clarification and discussion however.

The advent of methods such as the DVM lifting-surface theory described above makes conceptually possible the development of a better predictive methodology, if one makes

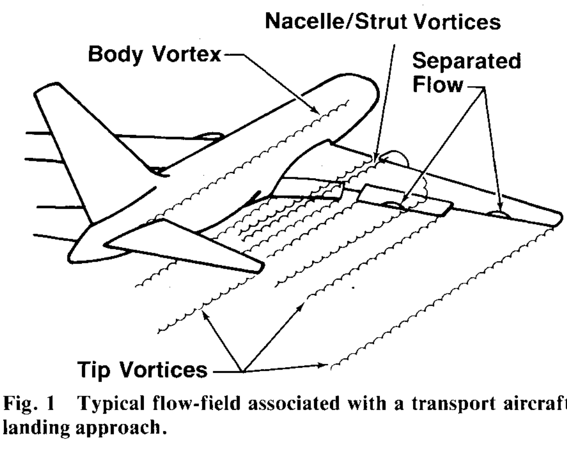

Fig. 1 Typical flow-field associated with a transport aircraft during landing approach.

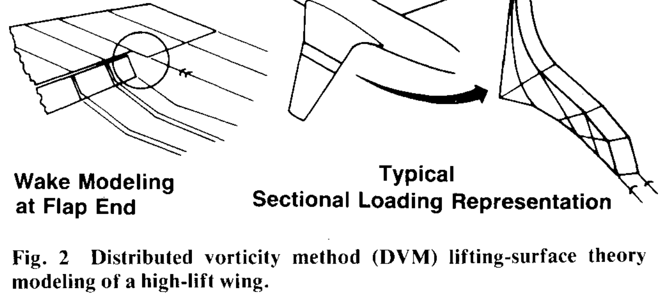

Fig. 2 Distributed vorticity method (DVM) lifting-surface theory modeling of a high-lift wing.

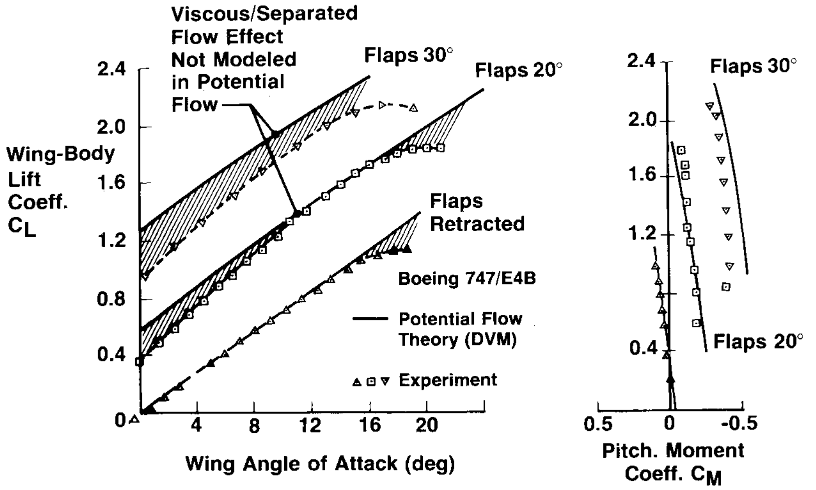

Fig. 3 Typical distributed vorticity method (DVM) results.

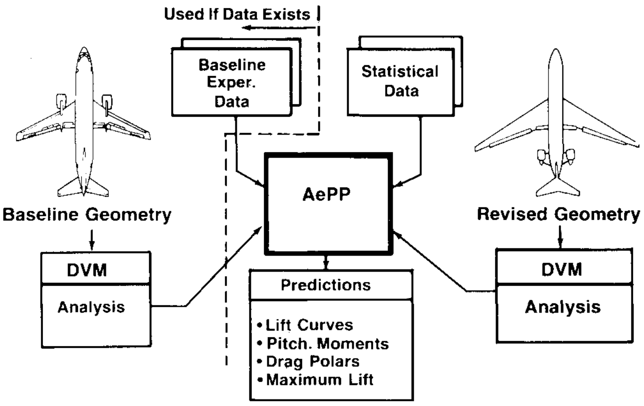

Fig. 4 Outline of the (low-speed) Aerodynamic Prediction Procedure.

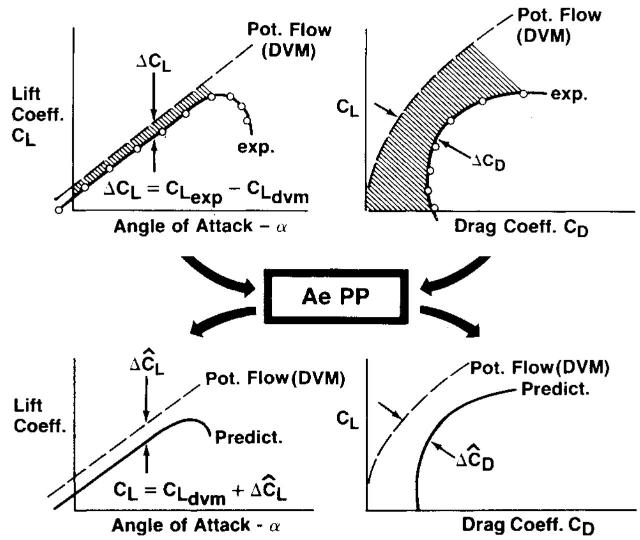

Fig. 5 (Low-speed) Aerodynamic Prediction Procedure to predict lift and drag.

a major assumption based on the following observations:

1) Past production transport aircraft have been subjected to thousands of hours of wind-tunnel testing and years of development. While each model may differ dramatically from previous designs in detail, all tend to be of a generally similar configuration (e.g., swept wings, empennage aft). Further, within a given company (e.g., Boeing), certain philosophies regarding high-lift system design in terms of performance and associated airplane handling characteristics goals produce a level of underlying commonality.

2) The "ideal" performance (lift, induced drag and moments) of a configuration such as that shown in Fig. 1 can be calculated reasonably well with inviscid methods. Extensive experience with the DVM program has demonstrated this (cf. Fig. 3 and Ref. 2).

3) Deviations from this ideal performance are attributable to thickness, viscous effects, and flow separations - most of which cannot be explicitly calculated with existing methods.

Thus, the central assumption of the present method is this: if the configuration whose characteristics are to be predicted does not deviate "too much" from past configurations which have been well designed, then deviations from ideal performance in a new configuration will be of comparable order and arise from similar sources. From this assumption, it follows that estimates of acceptable accuracy of new configuration performance at comparable viscous and compressibility scale conditions can be made *if* careful attention is paid to the geometric details of the various baseline and new configurations. This last point implies that any computational tool employed must have the ability to adequately account for relatively small but significant geometry changes. In general, handbook methods cannot. The DVM program can.

If one accepts the validity of the basic assumption above, it becomes possible to construct a semi-empirical predictive methodology involving AePP built on the theoretical base provided by the DVM program (Figs. 4 and 5). The outline shown in Fig. 5 is based on a case where experimental (e.g., wind-tunnel) data for a baseline configuration exists. The initial step in the procedure is to analyze the baseline configuration(s) in potential flow—including use of some empiricism to be described presently—to obtain lift curves, induced drag polars, and pitching moment curves. These data together with detailed geometry data (e.g., individual flap element areas) obtained from the DVM program are then stored in a data base for access by AePP.

At this point the decomposition mode of AePP compares the DVM analysis data (labeled by the subscript dvm) with the experimental data for that same configuration at equal angles of attack and extracts a set of residual terms for lift, drag, and pitching moment coefficients as per the following formulas:

$$
\begin{aligned}
\Delta C_L(\alpha,\delta_f,\mathrm{Re},\mathrm{M}) &= C_{L_{\mathrm{exp}}} - C_{L_{\mathrm{dvm}}}\\
\Delta C_D(\alpha,\delta_f,\mathrm{Re},\mathrm{M}) &= C_{D_{\mathrm{exp}}} - C_{D_{\mathrm{dvm}}}\\
\Delta C_M(\alpha,\delta_f,\mathrm{Re},\mathrm{M}) &= C_{M_{\mathrm{exp}}} - C_{M_{\mathrm{dvm}}}
\end{aligned}
\qquad (1)
$$

A set of these residuals are then stored as *baseline viscous data* as functions of angle of attack and flap deflections. Identifying the basic residuals obtained from Eq. (1) for the cruise configuration ($\delta_f = 0$ deg) by the subscript o, a second set of baseline residuals reflecting coefficient increments due to high-lift system deflection are obtained from:

$$\Delta C_{L_f}(\alpha, \delta_f, \mathrm{Re,M}) = \Delta C_L - \Delta C_{L_o}$$
$$\Delta C_{D_f}(\alpha, \delta_f, \mathrm{Re,M}) = \Delta C_D - \Delta C_{D_o} \tag{2}$$
$$\Delta C_{M_f}(\alpha, \delta_f, \mathrm{Re,M}) = \Delta C_{\mathrm{M}} - \Delta C_{M_o}$$

The residuals in Eq. (2) can be interpolated to obtain other values for flap deflection increments as required. It should also be noted that, in addition to the parameters listed, these flap increment residuals are functions of high-lift system complexity. Thus, additional adjustments must be made if, say, the baseline has a single slotted flap system and the study configuration has double slotted flaps.

To complete the procedure and produce the desired predictions for the new configuration (b), the new geometry is analyzed in the DVM program. The resulting lift curves, induced drag polars, pitching moment curves, and required geometry data are then combined with the appropriate baseline (a) data according to the typical relation:

$$C_{L_b} = C_{L_{\mathrm{dvm_b}}} + \Delta C_{L_{o_a}} \times G + \Delta C_{L_{f_a}} \times H \tag{3}$$

where

$$G = G(\mathrm{Re})$$
$$H = H(S_a, S_b, S_{f_a}, S_{f_b}, \mathrm{Re})$$

Corresponding relations can be written for drag and moment coefficients. It should also be noted that many of the scaling relations in traditional handbook methods (such as flap span ratios, etc.) are automatically accounted for in the DVM analyses. The final results of the analyses are then made available for tabular listing or graphical display through AePP post-processing routines.

The process outlined in Fig. 5 pertains to the case where experimental data for the baseline exists. If such data is not available, the process is truncated. In this case it is assumed that generic data (residuals) from aircraft of similar type exist in a previously constructed statistical data base. Here only the study configuration (configuration b) is analyzed in the DVM program and adjusted residuals obtained from the generic data are added to the basic potential flow results to yield the final predictions.

Some Empiricism in the Method

The accuracy of the results obtained with the above procedure is strongly dependent on the magnitude and behavior of the viscous residuals. In this connection, early experiments aimed at validating the DVM program produced an interesting result. As briefly described in Ref. 2, calculations of two dimensional airfoil characteristics

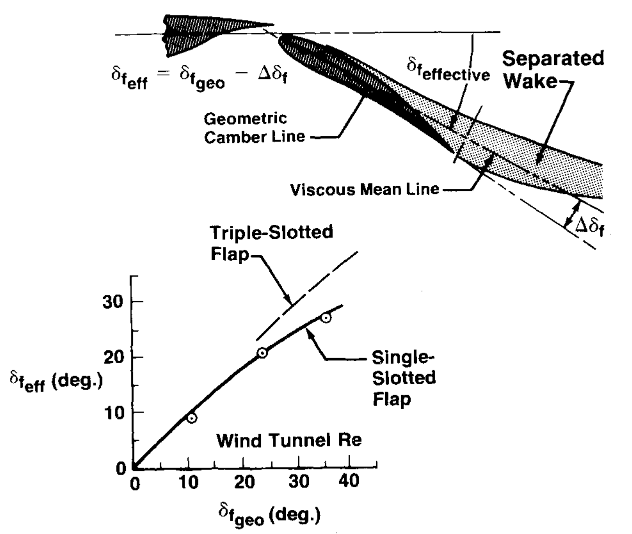

Fig. 6a Effective flap deflection.

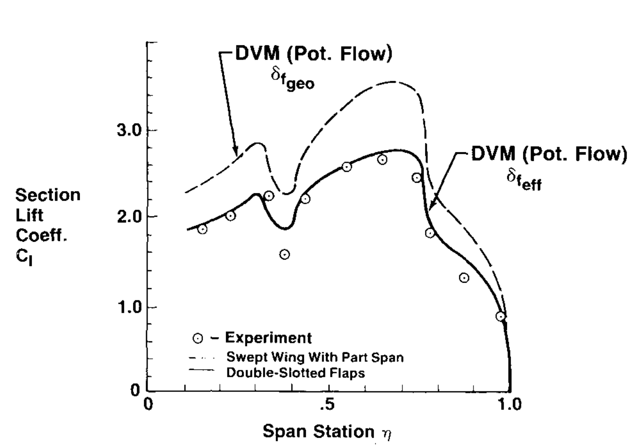

Fig. 6b Influence of effective flap deflection on wing span loading.

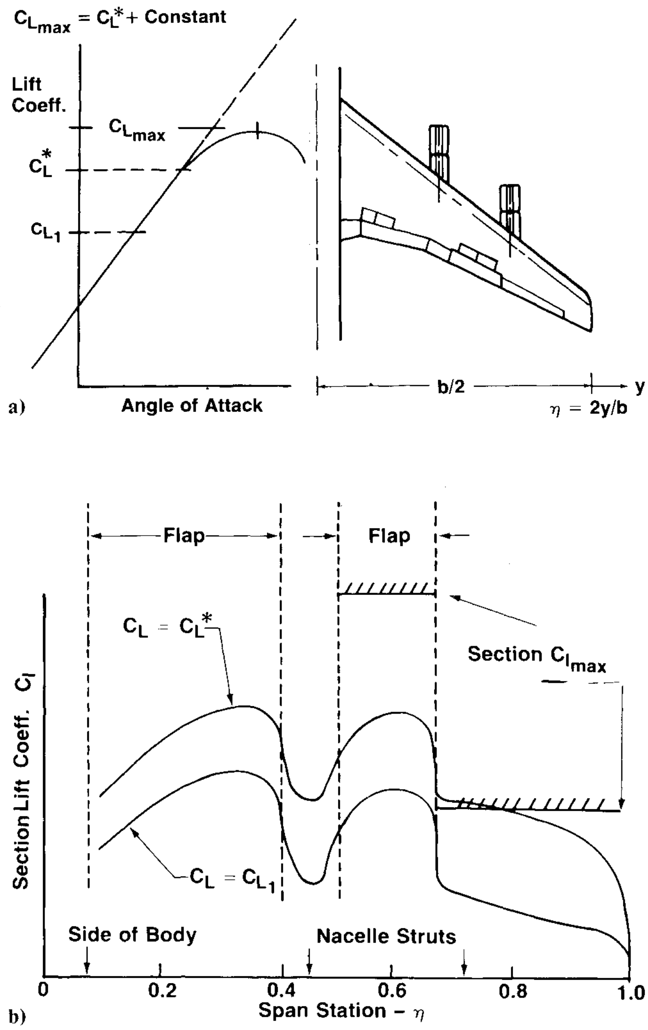

Fig. 7 Critical section analysis approach to maximum lift prediction.

(corrected for sweep) at selected stations across the span of a flap-deflected transport wing, including calculation of the separated wake shape, suggested that there is an "effective viscous" camber shape (or flap deflection) associated with a given geometric input shape. It then became possible to construct the generalized curves relating geometric and effective flap deflection for a given number of flap elements and at a given Re (Fig. 6) for a large sample of diverse Boeing transport aircraft. Input of the appropriate effective (viscous flow) camber lines into the DVM program can result in a dramatic improvement in predicted span loading (Fig. 6) and, hence, induced drag. Assuming the deflection curves in Fig. 6 apply (approximately) to all similar airplane configurations at the scale condition at which they were derived, a very utilitarian, simple, and physically-sound means of reducing the magnitude of the residuals is provided in the present method. This will be demonstrated in the context of the first example to be discussed.

A second empiricism has to do with the evaluation of the maximum lift capability of a given high-lift configuration. Detailed span load distributions are part of the output of the DVM program and, as demonstrated in Fig. 6, of high quality. As an alternative to simple interpolation and scaling (the default in the present method) to obtain the maximum lift coefficient and the angle at which it occurs, it is possible to compare changes in span loading between various configurations in a critical section analysis sense (Fig. 7).[2]

Using this procedure, evaluations of a number of Boeing transports lead to the result:

$$C_{L_{\max}} = C_L^* + \text{constant} \tag{4}$$

where C_L^* corresponds to the wing lift coefficient at which one constituent airfoil first reaches its maximum section lift coefficient. The value of the constant in Eq. (4) depends, of course, on Re.

Results

Three example test/theory comparisons have been selected to demonstrate the capability of the prediction methodology and to further clarify the way in which the procedure works. It should also be noted that the previously described empiricism was developed prior to, and independent of, the examples discussed.

1) Reference 4 contains results of a very extensive wind-tunnel test program conducted at the British Royal Aeronautical Establishment (RAE) on a 28 deg swept wing/fuselage model representative of a transport aircraft in a variety (92) of high-lift and flaps-retracted configurations. The data presented thus forms an excellent basis for an initial validation of the prediction method. The results of one such test/theory comparison are shown in Fig. 8. In this example two changes from the baseline are involved. The predictions made are for a wing with part-span flap deflected at 25 deg from data for configurations with full-span flaps at 0, 10, and

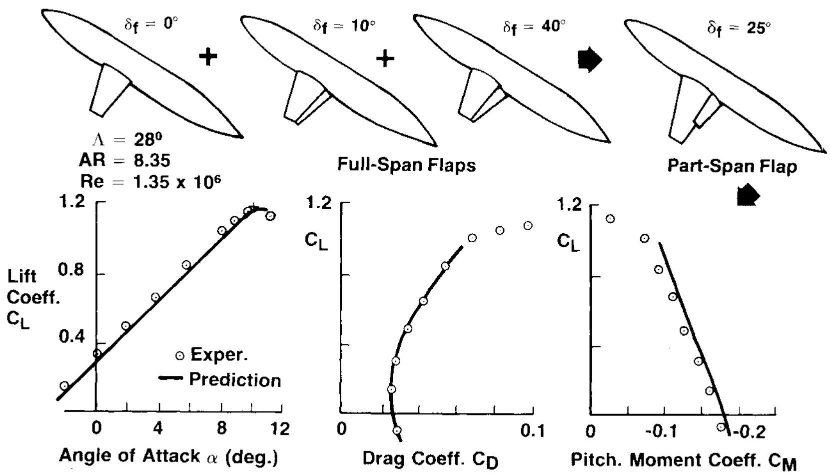

Fig. 8 Prediction of the global aerodynamic characteristics of an RAE high-lift wing/ body combination.

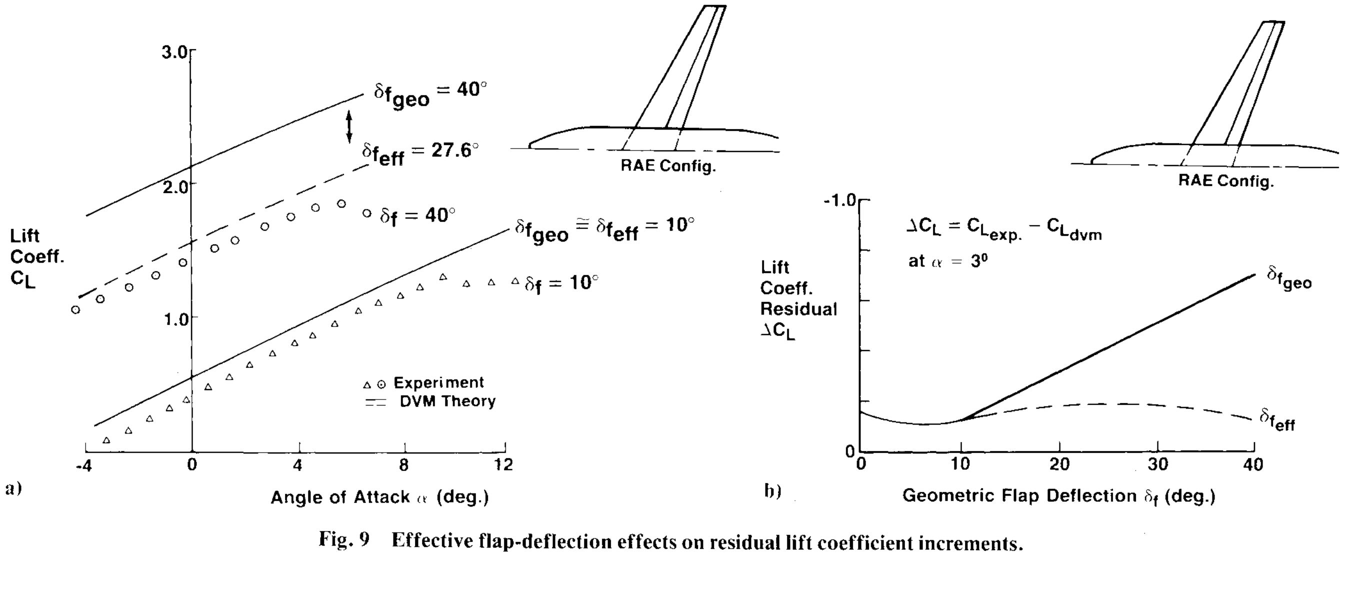

Fig. 9 Effective flap-deflection effects on residual lift coefficient increments.

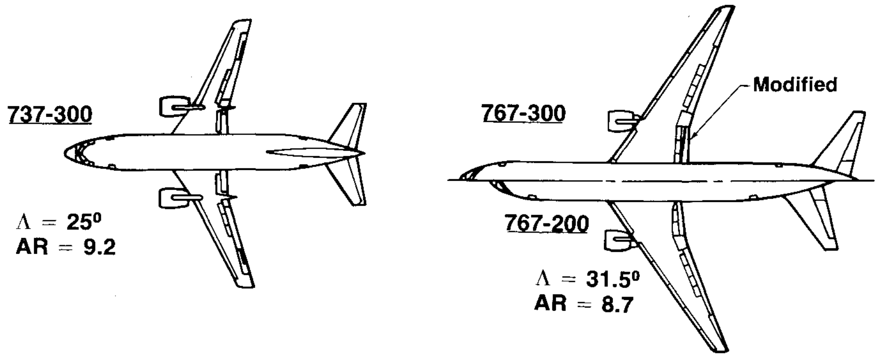

Fig. 10 Planform comparison of several Boeing transport aircraft.

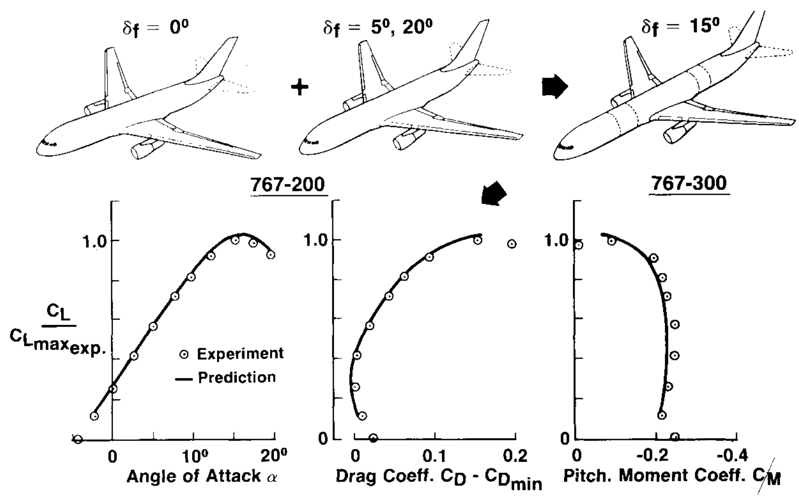

Fig. 11 Prediction of the aerodynamic characteristics of a Boeing 767-300 from data for a 767-200.

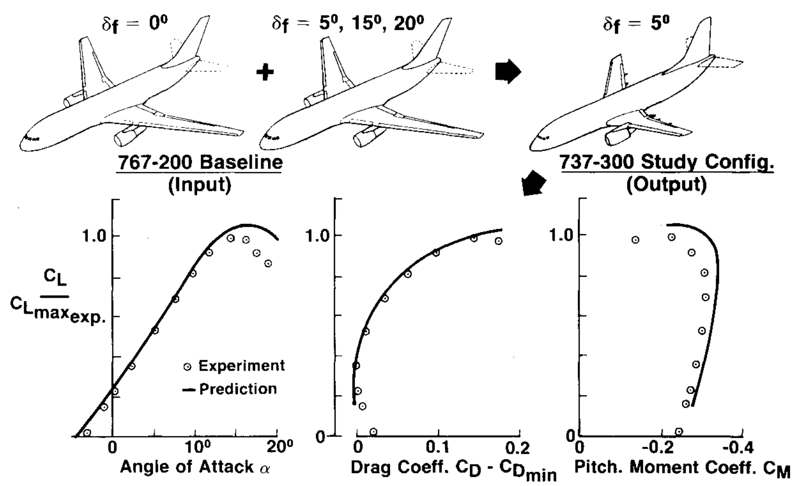

Fig. 12 Prediction of the characteristics of a Boeing 737-300 from data for a 767-200.

40 deg deflection. The flaps in all cases were single-slotted but the wing did not have a leading-edge high-lift device. The predictions of all characteristics, including maximum lift coefficient, are quite satisfactory.

This example also serves to demonstrate the effect on the residuals of using effective instead of geometric flap deflections in the analysis. Figure 9 shows a comparison of the DVM predictions of the lift curves for two of the baseline configurations calculated on the basis of both geometric and effective flap deflections, the latter value taken from Fig. 6. It will be observed that the DVM program results do not match completely with the experimental data for any of the RAE configurations. However, the auxiliary plot of the trend in residual values vs flap deflection at a given angle of attack shows that the magnitudes of the residuals are greatly diminished for higher deflection angles when the effective flap deflections (derived from data on wings with leading-edge devices) are used in place of the geometric values. Any subsequent adjustments of these smaller residuals due to area ratioing etc., can be expected to lead to a better final prediction.

2) The final results to be presented come from applications of the methodology to recently developed Boeing transport aircraft. The geometries of the aircraft evaluated are shown in Fig. 10, and the experimental data is from tail-off wind tunnel-tests conducted at the University of Washington Aeronautical Laboratory (UWAL) at chord Re on the order of 1.5×10^6 and a M of about 0.2.

In the first case the characteristics of a stretched fuselage 767-300 with flaps deflected at 15 deg are to be predicted from data for a baseline 767-200 with flaps deflected 0, 5 and 20 deg. The results are shown in Fig. 11. Note that agreement between test data and predictions of all aerodynamic quantities is excellent.

3) As the final example, predictions of the characteristics of a completely different aircraft, a 737-300 (Fig. 10), were based on data for the 767-200 (of similar configuration but dramatically different in most details). As input in this case, the geometry of the 767-200 at flap deflections of 0, 5, 15, and 20 deg was used to predict the characteristics of the 737-300 with flaps deflected 5 deg, representative of a takeoff configuration. Again the test/theory comparison results (Fig. 12) are quite satisfactory.

Conclusions

A preliminary design-level method for predicting the global aerodynamic characteristics of transport-type aircraft in low-speed/high-lift configurations has been described. The method is semi-empirical and the overall procedure is economical, user oriented, and highly automated. Results obtained with the method so far are very encouraging, as demonstrated by the test/theory comparisons presented.

The feasibility and practicability of the overall method described strongly depends on the availability of a potential-flow lifting-surface theory computer program for the analysis of multi-element swept wings. The DVM program used in the present method provides the basic skeletal structure of the procedure and strikes the right balance between the conflicting demands of ease of use, economy of operation, and accuracy and reliability of result. When combined with the empiricism discussed, the DVM program provides a very powerful and utilitarian engineering tool aside from its use in conjunction with the AePP method discussed in this paper.

The main line of development of the methodology to date has been to devise a procedure applicable to cases where well-defined baseline configurations and associated wind-tunnel data exist. Predictions of the characteristics of a new configuration are then made at the same M and Re scale conditions. In these cases the quality of the predictions can be expected to be directly proportional to the degree of geometrical deviation of the study configuration from the baseline, as well as the quality and quantity of baseline data available.

Despite these limitations on the present version of the method, the procedure has been structured to provide a good deal of flexibility and potential for extension. For example, repeated applications of the present version of the method make possible construction of generic data bases necessary for estimates of the wind-tunnel level characteristics of configurations for which no explicit baseline data exists and by extending the scaling laws applied to the residual coefficient values generated by AePP, estimates of the characteristics of a given configuration at flight Re from wind-tunnel data can be made on a rational basis.

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