# Development and Validation of the V/STOL Aerodynamics and Stability and Control Manual

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**The "V/STOL Aerodynamics and Stability and Control Manual" has been developed to provide prediction methods applicable to a wide range of V/STOL configurations in hover and transition flight in- and out-of-ground effects. Empirical methods were developed to predict the aerodynamic/propulsion induced characteristics. For the jet-lift concept, propulsion induced effects combine with unpowered aerodynamics in a buildup of total forces and moments. Total aerodynamics can then be used to predict aircraft stability and control and flying qualities characteristics. Methods for predicting the induced aerodynamics in the hover and transition flight regimes of the jet-lift concepts are discussed in detail. Results of longitudinal aerodynamic predictions compared with test data are then presented indicating the manual capability and generality of application.**

## Nomenclature

$A$ = jet exit area
$A_{\mathrm{HI}}$ = inlet highlight area
$A_{\mathrm{TH}}$ = inlet throat area
$AR$ = aspect ratio
CCW = circulation controlled wing
$C_{D_r}$ = augmenter ram drag coefficient
$C_e$ = elevon chord length
$C_t$ = elevon tab chord length
$C_\mu$ = blowing coefficient
$d$ = jet diameter
$d_e$ = equivalent jet diameter
$\bar{D}$ = equivalent planform diameter
$D'$ = "bolt circle" diameter of jet pattern
$D_{\mathrm{HI}}$ = inlet highlight diameter
$D_M$ = inlet maximum diameter
EBF = externally blown flap
$h$ = height above the ground
$h'$ = height at which fountain positive pressures are first realized
LID = lift improvement device
$N$ = number of jets in multiple-jet configuration
NPR = nozzle pressure ratio
$P_n$ = jet total pressure
$p$ = ambient static pressure
$S$ = wing planform area
$T$ = thrust
USB = upper surface blowing
$V$ = velocity
$V_e$ = effective velocity ratio = $V_\infty / V_j$
$x$ = distance downstream from the nozzle exit plane
$\alpha$ = angle of attack
$\delta$ = deflection
$\Delta D$ = inlet momentum drag
$\Delta L$ = propulsion induced lift increment
$\theta$ = fraction of jet pattern circumference blocked by individual jets
$\phi$ = augmentation ratio
$\psi$ = meridian angle around the inlet

*Subscripts*

$F$ = fountain
$j$ = jet
$S$ = suckdown
$\infty$ = conditions at infinity

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## Introduction

THE aerodynamics and stability and control characteristics of V/STOL aircraft involve major propulsion induced aerodynamics and inlet momentum effects which are normally of much less importance in CTOL aircraft. Until recently, the methods available for the prediction of propulsion induced aerodynamics for both hovering and transition flight consisted of the computerized techniques using potential flow analysis with empirical modifications. The considerable effort expended in their development resulted in techniques which were not readily useful owing to the time required to model the aircraft, the excessive computational time, and a less than desired accuracy. A definite need existed for rapid, accurate, and less costly methods to predict the propulsion induced aerodynamics of V/STOL aircraft which could be used at least in the preliminary design stage. To address this need, the development of the "V/STOL Aerodynamics and Stability and Control Manual"[1] was undertaken. This manual is to provide relatively simple but accurate prediction methods which will be applicable to a wide range of V/STOL types and configurations in hover and transition flight in- and out-of-ground effects. A parallel objective in the manual development was to identify critical gaps in the technology which could be filled with research investigations.

It is the purpose of this paper to overview the contents and capability of the V/STOL manual in its present stage of development. The methods used to predict the propulsion induced aerodynamics in the hover and transition flight regimes will be discussed in detail. This discussion will include their background, development, application, and limitations. In addition, a brief review of other major contents of the manual will be presented to provide a complete indication of the manual scope and capability. Results of longitudinal aerodynamic predictions for several jet-lift-type V/STOL configurations will also be presented, indicating the manual capability and generality of application.

## Development Approach

The intent of the manual is to provide aerodynamics and stability and control prediction methods applicable to the four major regions of V/STOL flight: the hover in-ground effect; hover and low-speed out-of-ground effect; transition out-of-ground effect; and transition, or STOL, in-ground effect. To satisfy the requirement for rapid, accurate, and less costly prediction methods, the approach was to develop empirical or semiempirical methods to predict the aerodynamic/propulsive induced characteristics of V/STOL aircraft. The manual is reasonably self-contained but can also be used to advantage in conjunction with the U.S. Air Force DATCOM[2] for unpowered aerodynamics in a buildup of the total forces and moments. The developed methods apply to a wide variety of V/STOL configurations without restriction to propulsive concept. Since the concepts are sufficiently different to preclude the development of one basic method common to all, the manual was sectioned according to the following classes of V/STOL aircraft: 1) lift-lift/cruise fanjet, 2) augmented jet, 3) propeller, 4) tilt rotor, and 5) deflected slipstream.

The lift-lift/cruise aircraft category includes all arrangements of direct lift and/or vectored thrust or rotating nacelle configurations. In these types, the basic unpowered aerodynamics and the propulsion induced effects are largely separable. The augmented jet category incorporates the augmenter wing concept but can include other augmenter arrangements by addition of further subsections on transition aerodynamics. The propeller V/STOL category is included for completeness but presently incorporates Sec. 9 of the U.S. Air Force DATCOM[2] by reference. The development of the section on tilt rotor V/STOL configurations is now being completed through a contractural effort to Bell Helicopter. Finally, the deflected slipstream category will become the major section for STOL concepts, i.e., EBF, USB, CCW, etc.

The prediction methods are intended to involve a component buildup approach consisting of the unpowered aerodynamics of the airframe, including interference effects, propulsion induced aerodynamics, and the effectiveness of aerodynamic and propulsive controls. The total aerodynamics thus obtained can then be used to predict stability and control and flying qualities characteristics by the analysis techniques contained in the final section of the manual. This section contains the linear and nonlinear equations of motion, and the means of estimating trim states, stability derivatives, and common transfer functions.

Simple aircraft geometry and jet parameters are the only data required to exercise these methods, which is in keeping with the objective of using the manual in a preliminary design stage environment.

## Methods Summary

At present, the prediction methods for two classes of V/STOL aircraft are essentially complete: the lift-lift/cruise fan/jet aircraft and the augmented jet aircraft.

Two hover jet induced methods for the jet-lift type of aircraft applicable to in- and out-of-ground effects are presently included in the manual, together with one method applicable to the transition flight out-of-ground effect.

The first hover method, the components of which are illustrated in Fig. 1, was originally developed by Kuhn[3] and subsequently revised and improved.[4] Two alternative expressions are used for the out-of-ground-effect lift loss.

$$\frac{\Delta L_\infty}{T} = -\sqrt{\frac{S}{A}}(0.016)\left(\frac{P_n}{p}\right)^{-0.64}\sqrt{\left(\frac{\partial q/(P_n-p)}{\partial x/d_e}\right)_{\max}\Big/\left(\frac{x}{d_e}\right)} \tag{1}$$

$$\frac{\Delta L_\infty}{T} = -\sqrt{\frac{S}{A}}(0.0002528)\left\{\left(\frac{P_n}{p}\right)^{-0.64}\frac{\Sigma\pi d}{d_e}\right\}^{1.581} \tag{2}$$

Equation (1), developed by Shumpert and Tibbetts,[5] relies on a knowledge of the jet dynamic pressure decay rate, while Eq. (2), developed by Byrne,[6] correlates basic lift loss with the total jet perimeter and nozzle pressure ratio. The in-ground-effect suckdown, $\Delta L_s/T$,

$$\frac{\Delta L_s}{T} = -0.015\left(\frac{h/d_e}{\bar{D}/d_e - 1}\right)^{-[2.2-0.24(P_n/p-1)]} \tag{3}$$

is formulated according to the earlier Wyatt[7] expression, with modifications to the coefficient and exponent and with proper accounting of the nozzle pressure ratio. The resulting expression yields an "equivalent single-jet" suckdown as a fundamental base upon which additional suckdown for multiple jets, $\Delta L_1/T$, is added

$$\Delta L_1/T = 0.5\Delta L_s/T \tag{4}$$

The fountain effect, formulated into two expressions, was determined by extracting the suckdown from the existing data base using Eqs. (1) or (2-4). The first fountain expression, $\Delta L_2/T$, is referred to as the $h'$ method

$$\frac{\Delta L_2}{T} = \left(\frac{h'}{\bar{D}} - \frac{h}{\bar{D}}\right)(0.135)N^2\theta$$

where $h'$ is the height of first appearance of the fountain positive pressures and is given by

$$\frac{h'}{\bar{D}} = 1.22\,\frac{1}{N}\left[\frac{D'}{d_e}\right]^{0.65}$$

This fountain component is related to the jet number and spacing, which are the key parameters associated with jet merging. However, this component is zero at heights above $h'$ and also for configurations with only two jets. The second fountain expression,

$$\Delta L_3/T = 10^{(0.9-10h/\bar{D})}$$

gives a logarithmic fountain increase at very low hover heights and is felt to be associated with a region of pressurization such as that which occurs in air cushion vehicles. The overall technique is very readily applied to any configuration—the major time-consuming item being the determination of the value of $\bar{D}$ for a particular configuration. Its ease of application and relative accuracy of prediction—as will be shown in the subsequent validation analysis—can have significant value at the early conceptual design stage when configurational tradeoffs are made. A limitation, which was later removed, is that the method does not account for undersurface contouring; although, the effect of adding lift improvement devices (LID) is treated.

A second hover method was developed through systematic tests of an array of two-, three-, and four-jet V/STOL configuration models by Foley.[8] This method is also a combination of hover induced suckdown and fountain components:

$$\frac{\Delta L}{T} = \frac{\Delta L_s}{T} + \frac{\Delta L_F}{T}$$

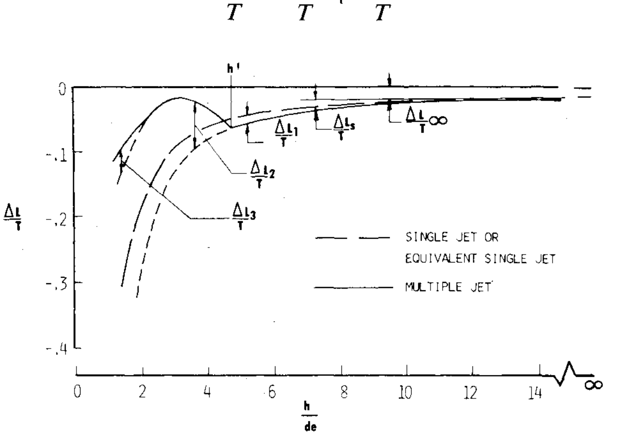


**Fig. 1 Component buildup procedure for calculating jet induced lift in hover.**

The total suckdown, $\Delta L_s/T$, is calculated by a superposition of the individual jet suckdown weighted-averaged by the thrust of the individual jets:

$$\frac{\Delta L_s}{T} = \left(\frac{\Delta L_s - \Delta L_{s\infty}}{T}\right)_{\text{wa}} + \left(\frac{\Delta L_{s\infty}}{T}\right)_{\text{wa}}$$

The out-of-ground-effect suckdown, $\Delta L_{s\infty}/T$, is the original Wyatt[7] expression.

$$\frac{\Delta L_{s\infty}}{T} = 0.067\left(\frac{d_i}{\bar{D}i} - 0.420\right)$$

In-ground-effect suckdown was empirically formulated from a number of single-jet tests using a variety of planforms and nozzle pressure ratios and is given by

$$\frac{\Delta L_s - \Delta L_{s\infty}}{T} = -0.00125\left(\frac{\bar{D}_i}{d_i} + 0.0185\right)C_{s_i} \times \left(\frac{h}{\bar{D}_i - d_i}\right)^{-1.59}$$

where $C_{s_i} = C_{s_I} \cdot C_{s_2}$; $C_{s_I} = 1$, reserved for scale effects; and, $C_{s_2}$ denotes the effect of nozzle pressure ratio and is represented by the following equations:

$$C_{s_2} = 1.173 - 0.2495\ell n(\text{NPR}) \qquad \text{NPR} \leq 2.0$$

$$= 1.061 - 0.0889\ell n(\text{NPR}) \qquad \text{NPR} \geq 2.0$$

The fountain component is obtained from

$$\frac{\Delta L_F}{T} = C_{F_2}\left(\frac{\Delta L_F''}{T} \cdot C_{F_3}'' + \frac{\Delta L_F'''}{T} \cdot C_{F_3}''' + \ldots\right)$$

where the terms $\Delta L_F''/T$, $\Delta L_F'''/T$, etc., were developed for two-, three-,..., jet configurations by subtraction of the total suckdown from the total induced lift data, where $C_{F_I} = 1$, reserved for scale effects; $C_{F_2}$ denotes the effect of nozzle pressure ratio and is represented by the following equations:

$$C_{F_2} = 0.736\ell n(\text{NPR}) + 0.481 \qquad \text{NPR} < 2.0$$

$$= 0.035\ell n(\text{NPR}) + 0.930 \qquad \text{NPR} \geq 2.0$$

and $C_{F_3}$ denotes the effect of jet merging.

These terms were then graphically correlated according to the dominating parameters of $\bar{D}$ (equivalent planform diameter) and the height above the ground. The correlating coefficients were then developed to account for the various geometry and operating condition effects to obtain the overall fountain effects.

A somewhat greater effort is needed to apply this method to a given configuration. This occurs not only because of the need for determining the $\bar{D}$ of each jet in the configuration, but also because of the need to obtain the jet merging coefficients; e.g., four jets in a rectangular arrangement merge into two which then merge into one, as a function of altitude and jet spacing. However, the method accuracy is somewhat improved over that of the previous method, as will be shown later.

The empirically derived transition prediction method[9] is illustrated in Fig. 2. It consists of a basic flat plate lift-loss term with adjustment factors derived from a large body of wind tunnel test data. The basic lift-loss term was developed using a polynomial curve fit of jet-induced pressure coefficients measured on a flat plate.[10] Pressure integrations were carried out for a range of planform-to-jet area ratios, $S/A$,

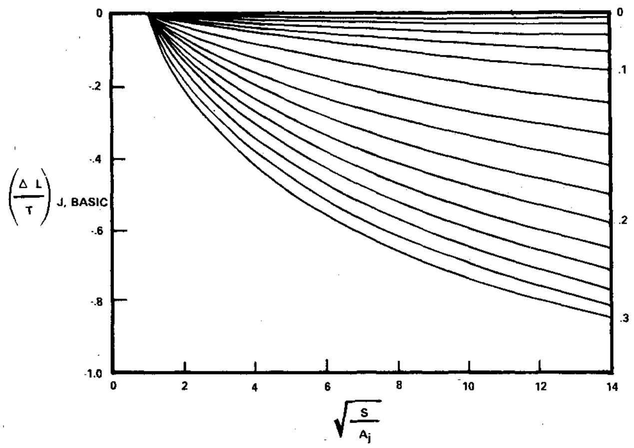


**Fig. 3 Basic jet induced lift loss in transition, $\mathcal{R} = 1.0$.**

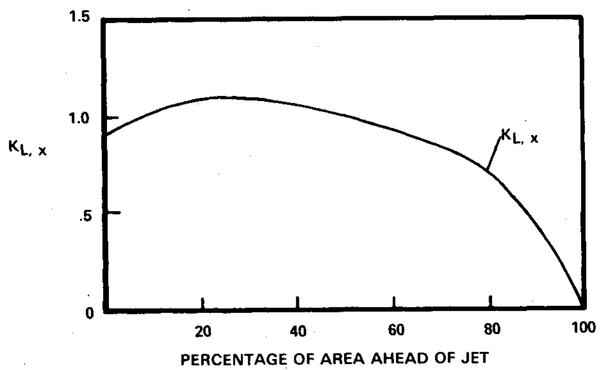


**Fig. 4 Adjustment factors for longitudinal position of jet.**

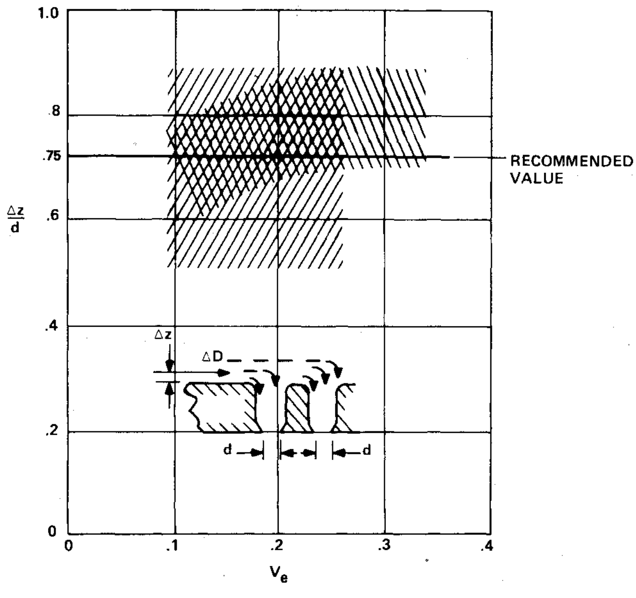


**Fig. 5 Effective moment arm of inlet momentum drag.**

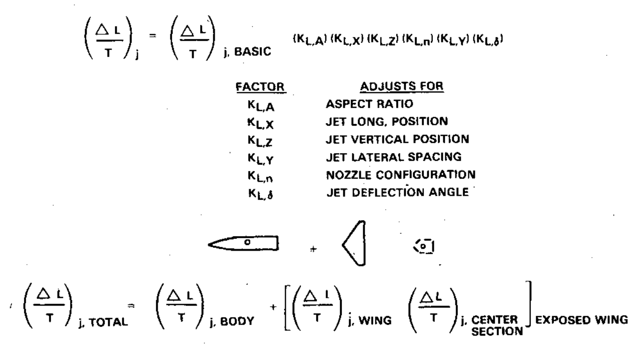


**Fig. 2 Equation for calculating jet induced lift in transition.**

and velocity ratios, $V_e$, resulting in the basic lift-loss chart of Fig. 3. Kuhn developed the adjustment factors in design chart form from a large array of wind tunnel test data, typical of which is the effect of jet position, shown in Fig. 4.

Additional methods are contained in the manual pertaining to the prediction of other important aspects of V/STOL aerodynamics. One such method addresses the potentially large inlet momentum effects associated with V/STOL aircraft. Figure 5 shows the effective moment arm (above the inlet) of the inlet momentum drag for flush mounted inlets. The band of data scatter was attributed to the difficulty of extracting inlet drag and moments from the main balance data in many cases. The recommended value is a reasonable estimate of this effect, which is to be added as an increment to the drag and moment data for the configuration. Similar results are also presented in the manual for tilt-nacelle-type inlets. In these, the nacelle angle as well as the velocity ratio are variables.

Another section of the manual pertains to the prediction of the conditions for subsonic nacelle lip separation. Lip separation is considered the most serious type of inlet separation for subsonic V/STOL inlets. Diffuser separation may in some cases precede lip separation but it is usually of a less serious extent. It is the large distorted flow regions occurring after lip separation that can cause excessive cyclic loadings on the turbofan. Figure 6 is a typical chart showing the nacelle incidence angle at flow separation as a function of the inlet throat Mach number and highlight to the maximum diameter ratio of 0.905. The flow separation charts were determined by parametric exercise of the Stockman viscous inlet routine in the V/STOL aerodynamics propulsive effects (VAPE) computational aerodynamics program.[11] This method was validated against the NASA Lewis model test results.[11]

Methods to predict the effectiveness of propulsion augmented controls are also treated in the manual. The control types covered are jet vane controls, i.e., control surfaces immersed in a jet/fan exhaust stream; control surface blowing; and reaction controls. A sample comparison of various jet vane controls is presented in Fig. 7. Analytical methods are presented for estimating the effectiveness of a plain jet vane flap control. Amplification factors can then be applied for the more complex control types of double-hinged and triplane arrangements, as shown in Fig. 7.

Modifications of the jet flap method contained in the augmented jet sections are to estimate augmenter wing performance. Modification of the lift coefficient prediction method is accomplished by simply replacing the blowing coefficient $C_\mu$ by the augmenter exit momentum, $\phi C_\mu$. Pitching moment predictions are modified primarily to account for the large pitching moment added owing to the augmenter ram drag, $C_{D_r}$, and of course the location of the effective augmenter thrust vector relative to the center of gravity. The modification due to the ram drag moment arm was developed in a recent study/test program conducted by Rockwell.[12] The drag equation incorporates a thrust recovery term and the all-important augmenter ram drag.

## Discussion of Validation Results

Following a limited publication and distribution, a validation study was initiated to verify the adequacy, identify the limitations, and establish a basis for confidence in the prediction capability of the manual. Four V/STOL configurations, including two contemporary designs, for which sufficient test data existed, were used in correlating manual predictions for both the hover and transition flight regimes. These designs represent simple and more realistic V/STOL designs of one-, two-, three-, and four-jet arrangements. The manual was used to predict the aerodynamics of these configurations for flight conditions of varying freestream to jet velocity ratio, angle of attack, and height above the ground. Induced lift was calculated for all configurations, along with total (unpowered plus induced) lift and pitching moments for two configurations for which appropriate correlating data were available.

The results of the validation effort are presented in Figs. 8-14 in the form of comparisons between manual predictions and test data. There are essentially three groups of comparisons: induced lift in hover, which validated the hover methods; the induced lift in transition, which validated the transition method; and the total (aerodynamic plus induced) lift and pitching moment variation with angle of attack in transition to validate the combining of unpowered and induced aerodynamics.

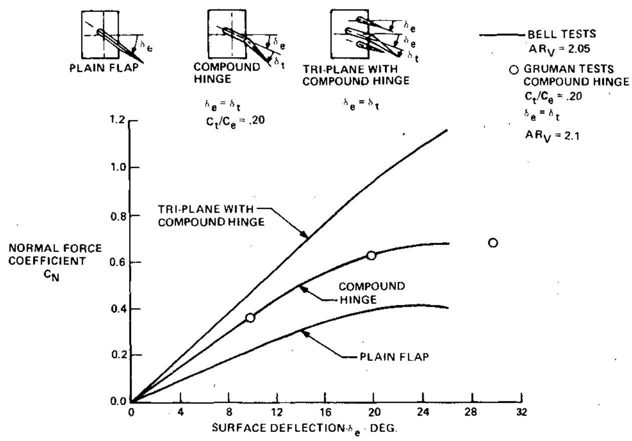


Fig. 7 Comparison of controls effectiveness.

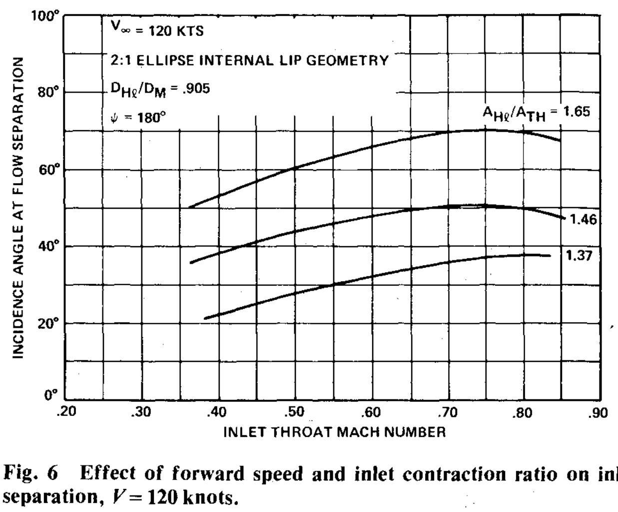


Fig. 6 Effect of forward speed and inlet contraction ratio on inlet separation, $V = 120$ knots.

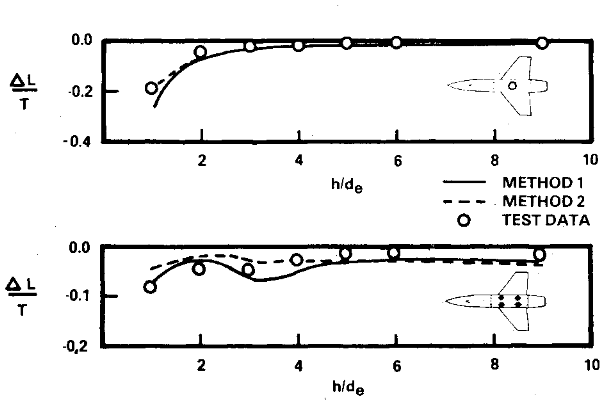


Fig. 8 Comparison of prediction and test data for induced lift of a single- and four-jet high-wing supersonic configuration in hover.[13]

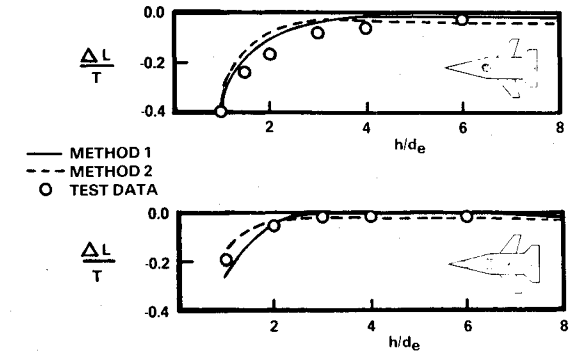


**Fig. 9 Comparison of prediction and test data for induced lift of a two- and three-jet low-wing two-dimensional supersonic configuration in hover.[14]**

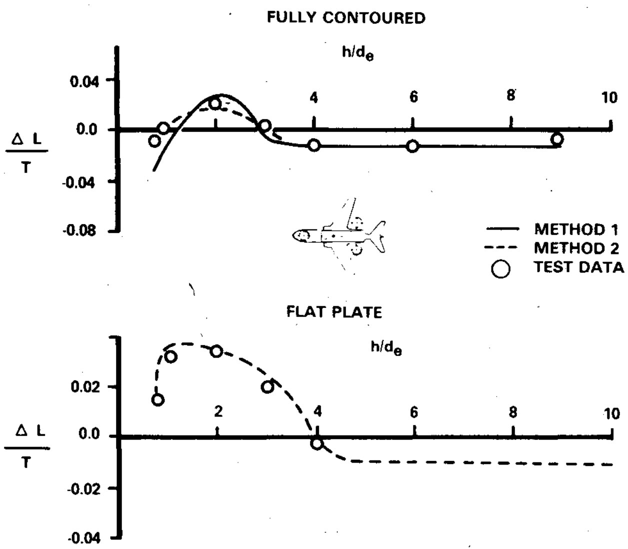


**Fig. 10 Comparison of prediction and test data for induced lift of a three-jet low-wing subsonic configuration in hover.[14]**

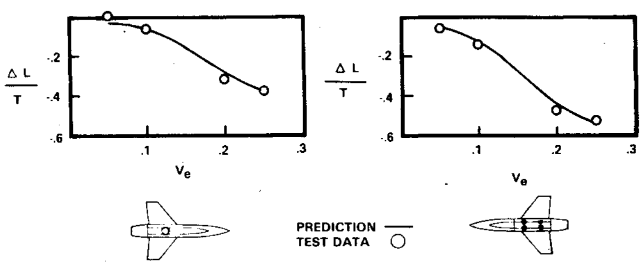


**Fig. 11 Comparison of prediction and test data for induced lift of a single- and four-jet high-wing supersonic configuration in transition.[13]**

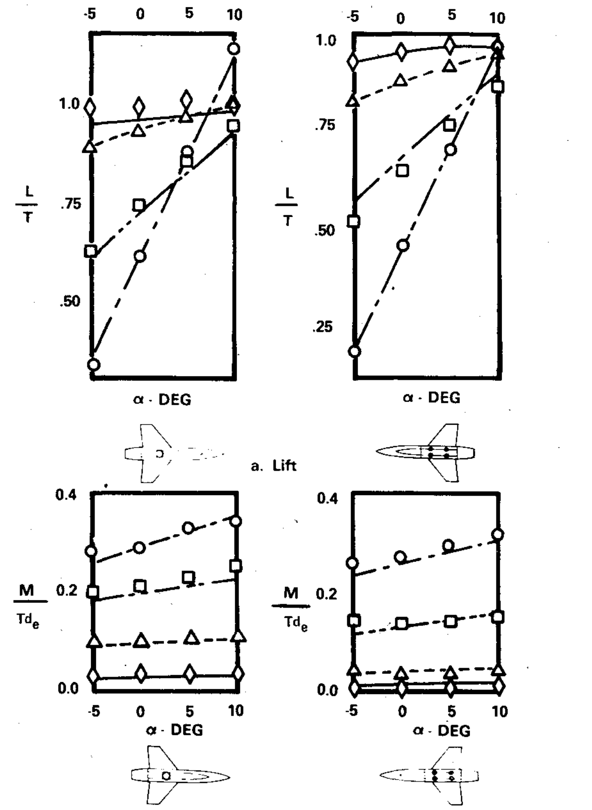


**Fig. 12 Comparison of prediction and test data for the alpha effects on total lift and pitching moment of a single- and four-jet high-wing supersonic configuration in transition.[13]**

Figure 8 contains comparisons of induced lift predicted by both hover methods and wind tunnel model test data.[13] This suckdown dominated design is predicted very well, with method 2[8] indicating excellent agreement throughout the entire height range for the single-jet configuration and method 1[3] resulting in similar agreement except at $h/d_e = 1$, where the suckdown is overpredicted. The results for the four-jet configuration, although reasonable, are not quite as good. Both methods over- and underpredict the data at various heights. Method 1 tends to overpredict the fountain effects compared to the rather small variation due to the fountain, as indicated by the data. Method 2 predicts the same muted fountain but at a slightly lower level of suckdown than indicated by the data.

Results of the comparison of induced lift in hover for the two-dimensional low-wing supersonic configuration[14] are presented in Fig. 9. This configuration, representative of a supersonic V/STOL design, is also a suckdown dominated design because of large planform area surrounding the jets. Method 2 results in an excellent correlation for the three-jet configuration except for the slight underprediction at $h/d_e = 1$. Method 1 tends to slightly underpredict throughout the height range with the exception of $h/d_e = 1$, where it reverses and slightly overpredicts the suckdown. Both methods tend to underpredict the suckdown for the two-jet configuration. It should be noted that although a three-jet fountain is created, the suckdown still predominates for this configuration. Although the correlation is not exact, both methods handle this flow situation quite well.

Correlations for the induced lift in hover of the three-jet subsonic V/STOL design[14] are contained in Fig. 10. This realistic V/STOL design has a distinct fountain effect, which was predicted by method 2 with excellent results. Method 1 accentuates the effect of the fountain at various heights followed by accurate prediction of the suckdown at heights above four-jet diameters. Method 2 also accurately predicts the induced lift of the two-dimensional flat plate representation of the same subsonic design, as seen in the same figure. The increased fountain effect realized by the flat undersurface of the model is effectively treated by method 2. Results are not shown for method 1 for this configuration because this method cannot differentiate between flat and fully contoured undersurface, as explained in the methods summary.

Figure 11 contains the results of validating the transition method for induced lift of the high-wing supersonic configuration.[13] Excellent agreement was obtained for both the single- and four-jet arrangements throughout the velocity ratio range. The unpowered lift was then calculated for an angle-of-attack range of from −5 to 10 deg and combined with the induced effects, resulting in the comparisons shown

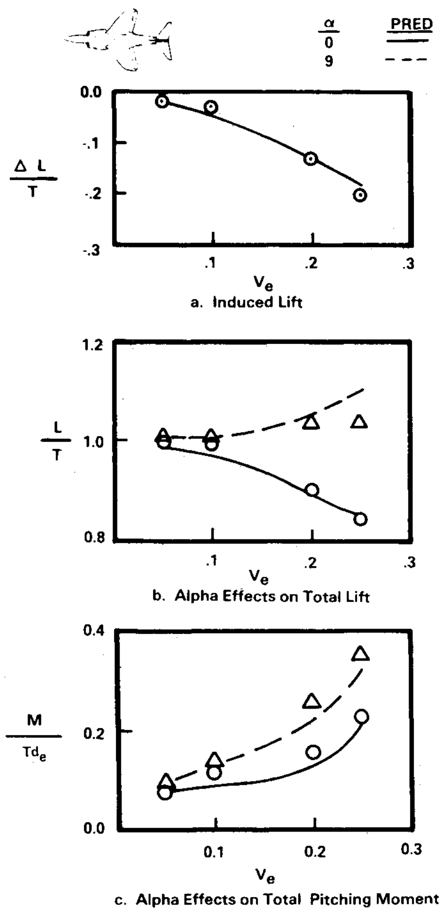


**Fig. 13 Comparison of prediction and test data for the four-jet high-wing supersonic XV-6A Kestral in transition.[15]**

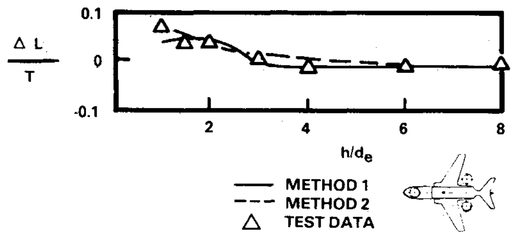


**Fig. 14 Comparison of prediction and test data for the induced lift of a three-jet subsonic configuration with LIDs.[14]**

in Fig. 12, with the subsequent pitching moment calculations also compared in the same figure. Excellent agreement was again obtained for all velocity ratios at each angle of attack with the exception of the small difference shown for single-jet lift at $V_e = 0.05$.

The induced lift and total lift and pitching moment associated with the XV-6A Kestral[15] were similarly calculated and compared with test data; the results of which are shown in Fig. 13. For this configuration, the total lift and pitching moment were calculated for angles of attack of 0 and 9 deg only, to coincide with the available data. Good agreement is indicated throughout except for lift at $V_e = 0.25$ and $\alpha = 9$ deg, Fig. 13b. Reference 15 is the only data source which contains alpha effects in the induced lift. These effects, which cannot be accounted for in the present transition method, cause the discrepancy shown in Fig. 13b, and subsequently in Fig. 13c.

The prediction of induced lift resulting from the inclusion of a LID on the three-jet subsonic configuration[14] is compared with test data for both hover methods in Fig. 14. Method 2 alternates between slightly over- and under-estimating the data but, overall, correlates quite well. Method 1 also correlates quite well but seems to be diverging at the lowest height. Kuhn[3] acknowledges shortcomings in predicting the effects of LIDs and has recently revised his method to accurately account for these effects.[4]

## Conclusions

In conclusion, the development of the "V/STOL Aerodynamics and Stability and Control Manual" represents a unique source of empirical methods with which to predict the propulsion induced aerodynamics of V/STOL aircraft in hovering or transition flight. The results of the validation study indicate the methods to be not only quick and inexpensive to use, but also to be quite accurate, and well within the accuracy desired for the objective preliminary design stage.

Future efforts are planned to incorporate prediction methods pertaining to the remaining sections of the manual as currently formatted. Kuhn's revised hover method, mentioned previously, will be incorporated along with a method to predict the lateral-directional forces and moments associated with transition (OGE) flight. Additionally, methods are currently being developed to predict the ground effects associated with STOL flight which will be applicable to as many V/STOL types as available data permit. The present effort to develop a prediction method applicable to the tilt rotor concept will also be included, as well as a continuation of the validation efforts as new methods are incorporated or new data sources become available.

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