Prediction of Ground Effects for VTOL Aircraft with Twin Lifting Jets

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An empirical method has been developed for predicting ground-effect thrust losses, often called "suckdown" losses, for side-by-side rectangular-jet configurations. The method combines available flat-plate single-jet suckdown correlations (adapted to high- and low-wing airplane configurations) with a new correlation for the fountain effect associated with twin jets. The fountain correlation is based on a new experimental investigation in which nozzle variables were varied parametrically. Properly configured rectangular nozzles were found to produce a favorable fountain effect that largely cancels the suckdown losses. Considerably weaker fountains were observed for twin round nozzle configurations.

Nomenclature

A = amplitude of fountain effect (see Fig. 12)
A_j = total jet area
d = jet diameter
D_e = equivalent jet diameter, $(4A_j/\pi)^{1/2}$
D = plate diameter
$\bar{D}$ = angular mean diameter, $(1/\pi)\int_0^{2\pi} r d\theta$
F = effective thrust
F_∞ = effective thrust out of ground effect
H = height above the ground
K = roundness factor
$r;\theta$ = polar coordinates for edge of planform
S = nozzle spacing (see Fig. 10)
W = half-width of fountain effect (see Fig. 12)
α_{eff} = nozzle outboard cant angle
ΔF = thrust loss, $F_\infty - F$
δ = H/D_e for peak fountain effect
Φ,ψ = correlation functions

Introduction

WHEN a VTOL aircraft with a vertically directed exhaust jet operates in the vicinity of the ground, the induced flowfield associated with the spreading of the jet along the ground creates negative pressures on the underside of the aircraft. Such a flowfield is illustrated schematically in Fig. 1. The resulting forces, often called suckdown forces, can result in an effective vertical thrust loss of as much as 40%.[1]

When multiple jets are involved, however, many investigators (for example, Refs. 2-6) have observed a "fountain" created by the interaction of adjacent jets. Such a fountain, illustrated in Fig. 2, can produce very large positive pressures on the underside of the aircraft between the nozzles It is possible for the favorable effects of the fountain to eliminate a major percentage of the suckdown losses.

Because of the magnitude of the forces involved, the preliminary aircraft designer clearly needs a suckdown prediction capability in order to size the engines and/or the airplane. The present paper is directed toward filling this need for the specific case of twin rectangular jets (at static conditions).

Previously developed suckdown prediction methods have been based on flat-plate correlations for a single round jet. Wyatt[7] demonstrated an excellent correlation of this type, shown in Fig. 3, by characterizing the effective plate size by an angular mean diameter $\bar{d}$. His correlation covers a variety of planform shapes (circles, triangles, and rectangles with aspect ratios as large as four) and was well represented by the expression

$$\Delta F/F_\infty = 0.012\ [H/(\bar{D}-d)]^{-2.30}$$

Similar data from Refs. 1 and 8-10 also are shown in the figure. These additional data, as several investigators[7,11] have noted, suggest a somewhat modified curve-fit, particularly at the larger values of the normalized height, $H/(\bar{D}-d)$. The authors have selected the fit shown as a dashed line, which corresponds to the expression

$$\Delta F/F_\infty = 0.025\ [H/(\bar{D}-d)]^{-1.70}$$

The resulting correlation has been applied by the authors to predict the suckdown losses for two single-jet VTOL airplane

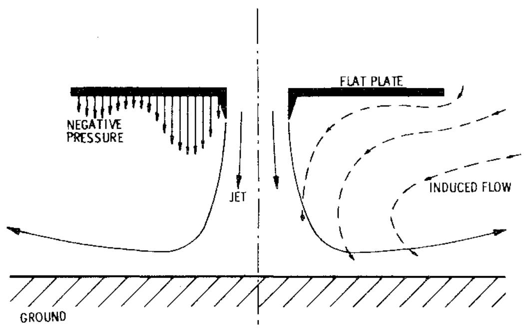

Fig. 1 Flowfield schematic (single jet).

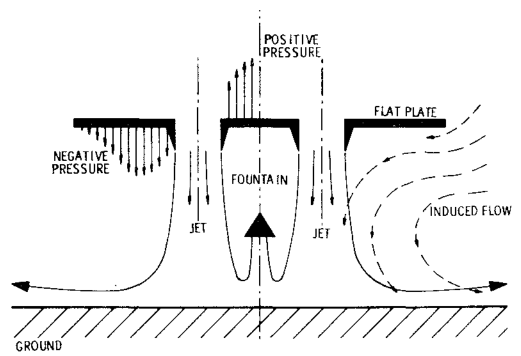

Fig. 2 Flowfield schematic (twin jet).

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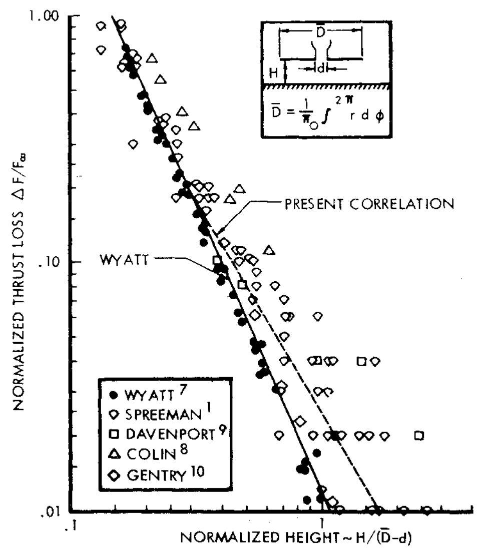

Fig. 3 Thrust loss in ground plane proximity for flat-plate planform shapes with single round jets.

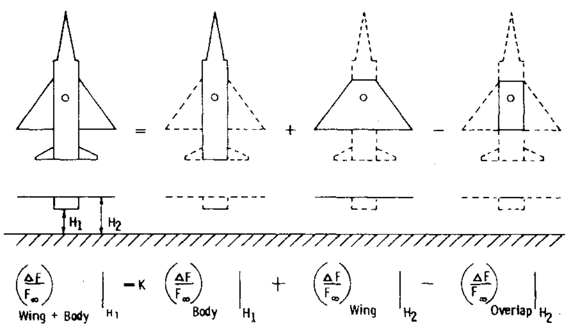

Fig. 4 Suckdown calculation procedure for wing-body combinations.

configurations for which published suckdown characteristics are available: 1) a high-wing airplane with a flat-bottomed fuselage[12], and 2) a low-wing airplane with a rounded fuselage.[1]

For the high-wing configuration, an approach similar to that suggested by Hammond,[13] illustrated in Fig. 4, was used to account for the vertical displacement between the wing and the fuselage. The resulting prediction is compared to the data in Fig. 5. For the rounded fuselage configuration, the factor K (see Fig. 4) was introduced to account for the reduced suckdown losses relative to a flat plate of equivalent planform shape. A K factor of 0.7, derived from the author's own data[14] was applied, and the resulting prediction is shown in Fig. 6. In both cases, the prediction method worked well, in spite of fuselage aspect ratios of about seven or eight.

The results presented in the following sections represent an attempt to build on this single-jet prediction capability by developing a method of accounting for the additional forces attributable to twin-jet effects. A new experimental investigation was undertaken with a high-wing twin-jet V/STOL fighter model. Key nozzle configuration variables (nozzle spacing and nozzle outboard cant angle) were varied parametrically, and the resulting fountain characteristics have been correlated as a function of these variables.

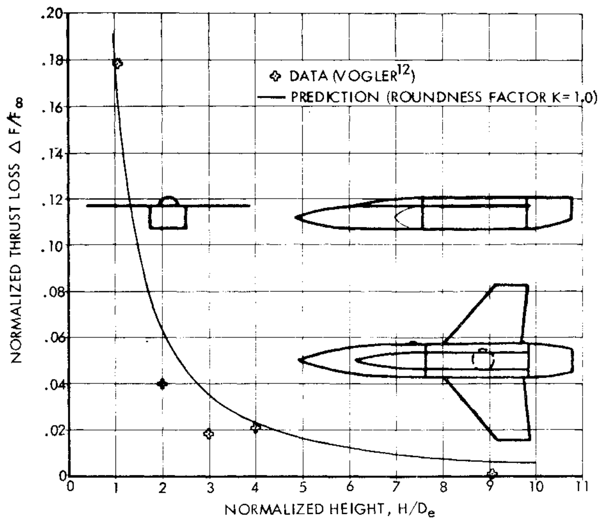

Fig. 5 Suckdown characteristic of a "flat-bottomed," single-jet wing-body combination.

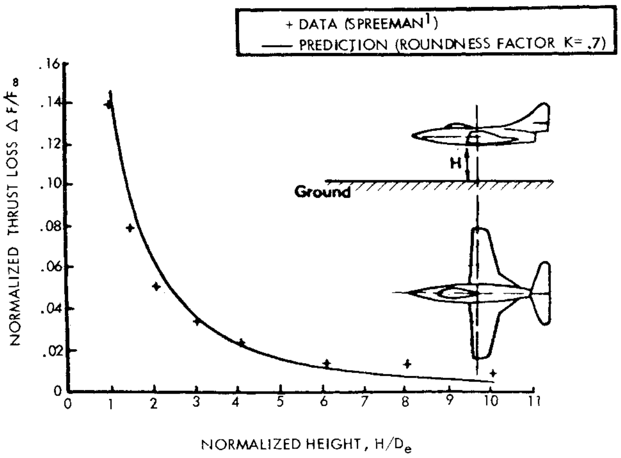

Fig. 6 Suckdown characteristic of a "rounded," single-jet wing-body combination.

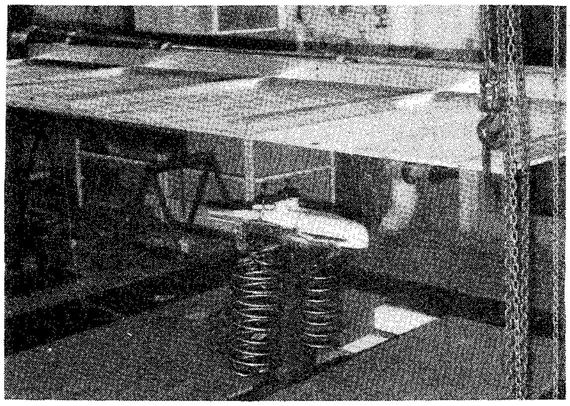

Fig. 7 Suckdown test setup.

Test Results

The general arrangement of the test setup is shown in Fig. 7. A 0.075-scale model was mounted upside-down on a six-component balance. A ground plane (10 × 16 ft) was placed over the model on a wind-tunnel sting, which could be raised or lowered electrically. The chain hoist visible in the photograph was attached to the ground plane to prevent vibration of the ground plane. The coils beneath the model were used to cross the balance with high-pressure nozzle air.

In total, five nozzle configurations, one circular and four rectangular, each having a different spacing and outboard cant angle relationship, were tested. Each set of nozzles could be swiveled from 5° inboard to 16° outboard. The nozzle pressure ratio was 2.55 for the major part of the test.

Figure 8 compares the suckdown characteristics for round nozzles, rectangular nozzles (of aspect ratio 1.83) with the

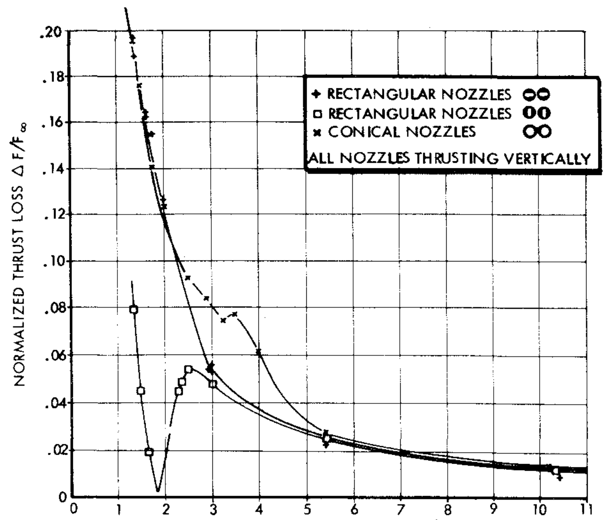

Fig. 8 Effect of nozzle shape.

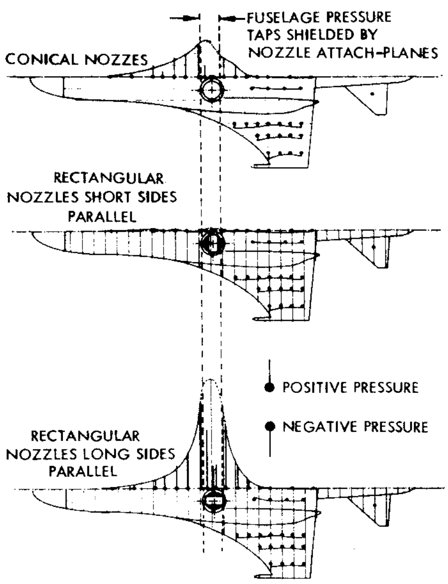

Fig. 9 Effect of nozzle shape on pressure distribution at a normalized height of 2.0.

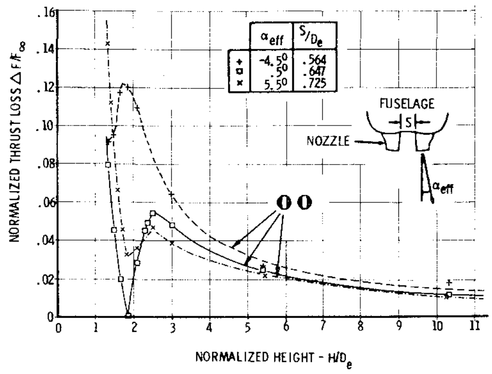

Fig. 10 Effect of nozzle outboard vectoring.

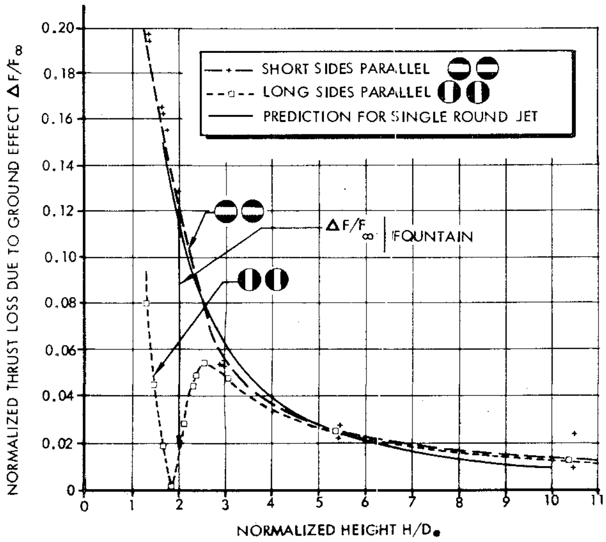

Fig. 11 Comparison between twin rectangular nozzzle data and single-jet prediction.

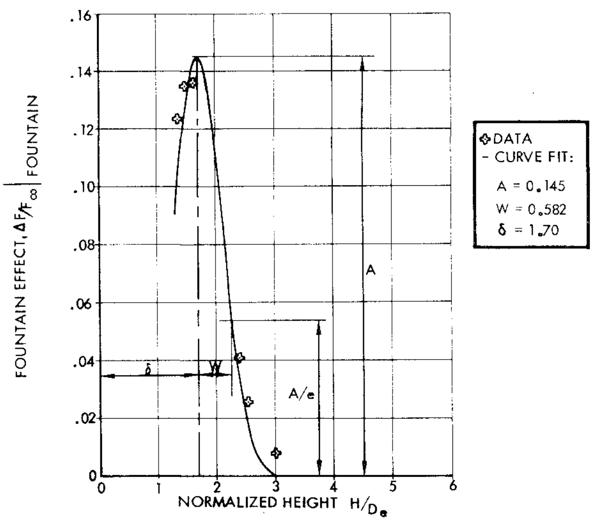

Fig. 12 Example of fitting analytic expression to the data.

long sides parallel to the airplane centerline, and the rectangular nozzles with short sides parallel to the centerline. Figure 9 shows the corresponding static pressure distributions measured on the underside of the model at a normalized height H/D_e of 2.0. The case of twin round jets generally produced the greatest suckdown losses in spite of a sizeable fountain effect apparent in the fuselage pressure distribution. The wing pressure distribution indicates negative pressures much larger than occurred for either orientation of the rectangular nozzles.

The rectangular nozzle configuration with long sides parallel to the centerline offers the greatest potential for reduced suckdown losses. A very large fountain effect is evident in the fuselage pressure distribution. The fountain was found to be a strong function of nozzle outboard cant angle and nozzle spacing (see, for example, Fig. 10), whereas the wing pressure fields were largely unaffected by these variables. [In addition, suckdown characteristics were not affected significantly by changes in nozzle length, nozzle pressure ratio (between 2.4 and 2.8), or landing gear configuration.]

The force data, reproduced in Fig. 11, show that the configuration with the short sides parallel has suckdown characteristics very similar to those predicted for an equivalent single round jet using the method described earlier. The pressure data show that this configuration produces no fountain, except for normalized heights H/D_e less than 2.0. The wing pressure distribution, however, was virtually identical to that for the long-sides-parallel case.

Thus, the short-sides-parallel case, adjusted using the single-jet prediction method at the low H/D_e's, was used as a

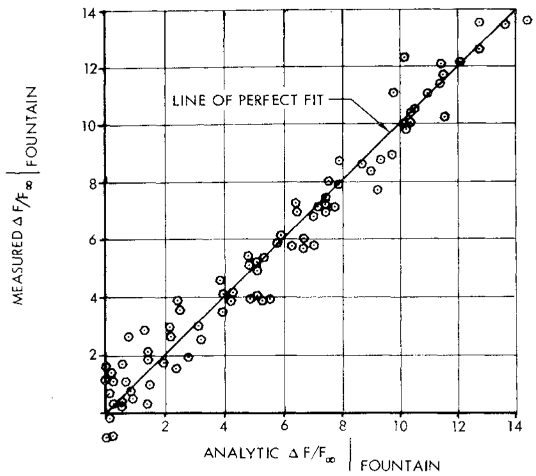

Fig. 13 Evaluation of curve-fitting procedure.

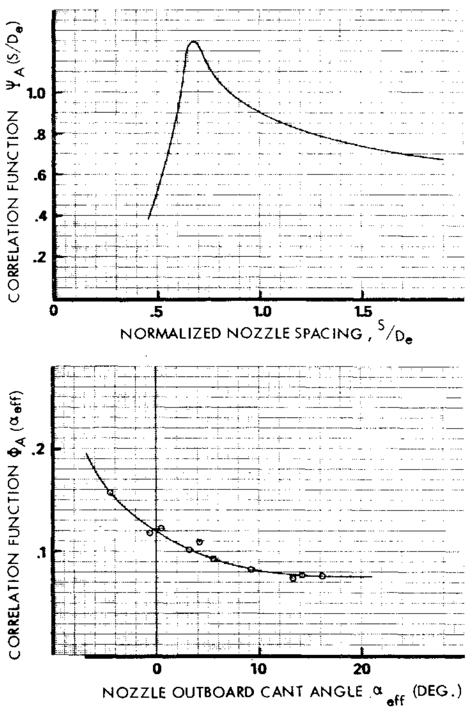

Fig. 14 Correlation functions for amplitude A.

baseline from which to isolate the fountain effect, as illustrated in Fig. 11, for all angle and spacing combinations tested.

Fountain Correlation

For each nozzle angle and spacing tested in the long-sides-parallel configuration, the increment in $\Delta F/F_\infty$ attributed to the fountain was plotted as a function of H/D_e, as shown in Fig. 12. In each case, it was possible to find a curve of the form

$$\Delta F/F_\infty |_{\text{fountain}} = A \exp\{ -[(H/D_e - \delta)/W]^2 \} \tag{1}$$

which closely matched the curve suggested by the data points. The three free parameters used to match the curve to the data, A, W, and δ, have the physical significance indicated in Fig. 12.

With W taken to be 90% of the spacing ratio

$$W = (0.90)\ S/D_e \tag{2}$$

it was possible to find values of A and δ giving a good match between the data and Eq. (1) for all cases tested, as shown by Fig. 13.

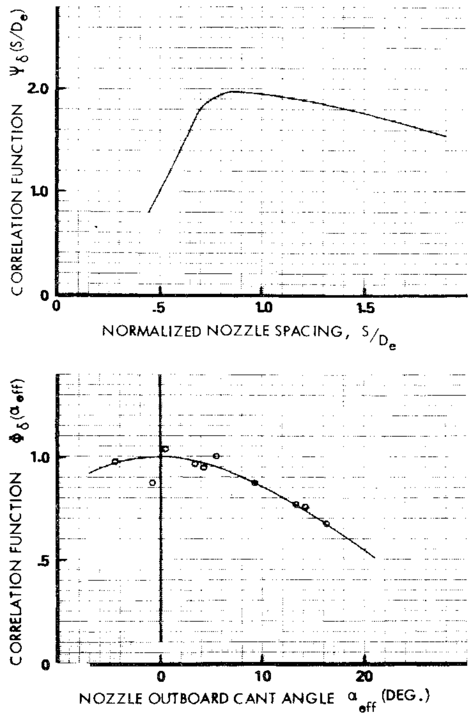

Fig. 15 Correlation functions for fountain "offset."

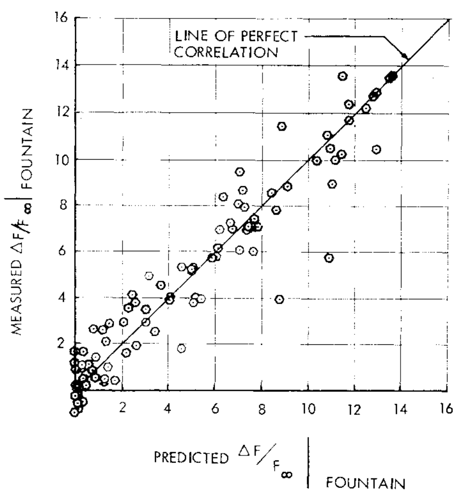

Fig. 16 Evaluation of fountain correlation.

Thus, in order to correlated the fountain effect, the functional relationship between each of the two parameters A and δ and the nozzle angle α_{eff} and spacing ratio S/D_e was sought. In the case of each parameter, it was possible to account for the effects of these nozzle variables with the product of a function of α_{eff} only and a function of S/D_e only.

The two functions $\psi_A(S/D_e)$ and $\Phi_A(\alpha_{\text{eff}})$, whose product gives the measured value of the amplitude A,

$$A = \psi_A(S/D_e)\ \Phi_A(\alpha_{\text{eff}}) \tag{3}$$

are given in Fig. 14. Figure 15 shows the corresponding functions $\psi_\delta(S/D_e)$ and $\Phi_\delta(\alpha_{\text{eff}})$, whose product yields δ:

$$\delta = \psi_\delta(S/D_e)\ \Phi_\delta(\alpha_{\text{eff}}) \tag{4}$$

Figure 16, comparing predicted vs measured values of $\Delta F/F_\infty |_{\text{fountain}}$, illustrates the degree of correlation achieved with this approach. The values of W, A, and δ used to obtain the predictions were derived from Eqs. (2-4) and the curves of Figs. 14 and 15, rather than from the original fountain curve fits.

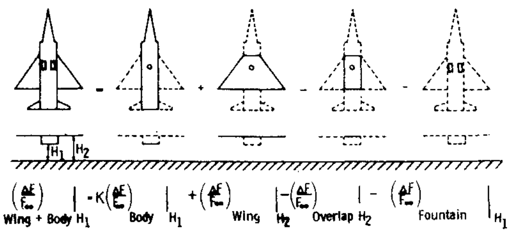

Fig. 17 "Suckdown" calculation procedure for twin-jet wing-body combination.

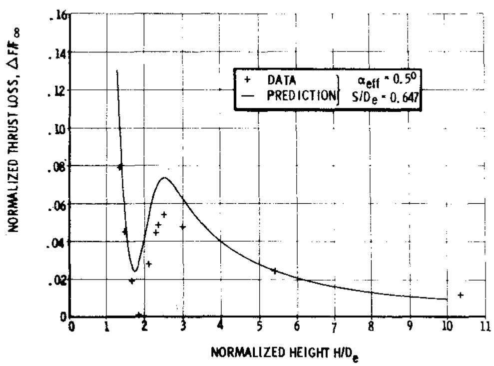

Fig. 18 Typical example of twin-jet suckdown prediction.

Suckdown Prediction Method

The resulting twin-jet suckdown prediction method is illustrated schematically in Fig. 17. It is based on adding an increment for the fountain effect to the single-jet prediction obtained using the method described in the Introduction. The method assumes that the fountain effect is independent of planform shape. Figure 18 shows a typical example of the application of the procedures of Fig. 17 to one of the configurations tested.

Summary of Results

The fountain effect created by adjacent side-by-side lifting jets can be exploited by the VTOL aircraft designer to minimize the ground-effect suckdown losses. Rectangular jets with the longer sides parallel to the airplane centerline have been shown to be considerably more effective in this regard than round jets. For the specific case of rectangular jets of aspect ratio 1.83, a correlation for the magnitude of the fountain-related forces as a function of nozzle spacing ratio and outboard cant angle has been found. This correlation can be combined with available single-jet flat-plate suckdown correlations to produce a general method for predicting the total suckdown losses for a complete twin-jet VTOL airplane.

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