Performance, Operation, and Use of Low Aspect Ratio Jet-Flapped Wings

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The characteristics of a jet-flapped wing of aspect ratio 6 are presented, discussed, and evaluated for STOL application. Again, as for high aspect ratio ($AR = 20$) jet-flapped wings, a range for most economical jet-flap operation is well defined. The angle of attack as an efficient means of lift production loses its usefulness with low aspect ratio jet-flapped wings, whereas the optimum jet deflection angle seems hardly to be affected ($\theta \simeq 55°$). A most efficient jet-flap application for STOL calls for a complete integration of the lifting and propulsive systems. In the range of most economical jet-flap operation, semi-empirical relationships predict parameter changes accurately enough for many practical purposes.

Nomenclature

AR = aspect ratio
C = jet momentum coefficient = $J/q \cdot S_w$
J = jet momentum = $M \cdot V_J$
M = jet mass flow
q = undisturbed freestream dynamic head = $(\rho/2)V^2$
V_J = jet flow velocity
V_T = takeoff velocity of jet-flap aircraft
V_T' = takeoff velocity of conventional aircraft
S_w = gross wing area
θ = jet deflection angle
α = angle of attack
$C\mu$ = jet momentum coefficient
$C\mu_E$ = jet momentum coefficient, based on the entire jet engine exhaust
$C\mu_L$ = jet momentum coefficient, based on the rate of blowing required for production of the desired lift
$C\mu_R$ = jet momentum coefficient, based on measured jet momentum
$C\mu_T$, $C\mu_C$ = jet momentum coefficients at takeoff and cruise, respectively, of conventional aircraft
C_1' = a constant
C_1 = a constant [see Eq. (2.3)]
C_D' = drag coefficient of wing without blowing
C_{DT} = total drag coefficient of jet-flapped wing
ΔC_{DT} = change in total drag coefficient due to blowing
C_{LT} = total lift coefficient of jet-flapped wing
ΔC_{LT} = change in total lift coefficient due to blowing
C_{TM} = total measured thrust coefficient as measured with a balance
ΔC_{TM} = change in total thrust coefficient due to blowing
ΔC_{Di} = change in induced drag due to blowing
$\Delta C_{Di}'$ = change in induced drag due to ΔC_{LT}^2 and AR
$\Delta C_{Di}''$ = change in induced drag due to ΔC_{LT}^2 and $C\mu_R$
K = a constant [see Eq. (2.5)]
K' = a constant [see Eq. (2.1)]
K'' = a constant [see Eq. 2.6)]
K''' = a constant = $1/\pi AR$
K^{IV} = a constant [see Eq. (2.7)]
ΔC_{DP} = change in profile drag coefficient due to blowing = C_{DJ}
$a(\theta)$ = drag parameter, a function of θ
$a(\alpha)$ = drag parameter, a function of α
ΔC_{DT_0} = change in total drag, if $\Delta C_{Di}''$ is ignored [see Eq. (2.8)]
C_2 = a constant [see Eq. (3.3)]
$a(0)$ = drag parameter for $\alpha = 0$
$C(x)$ = drag parameter, an unknown function
x = takeoff distance of a specific conventional aircraft
ρ = air density

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Introduction

IN Ref. 1, characteristics of truly and quasi-two-dimensional jet-flapped wings are presented, and jet-flap performance, economy of operation, application to STOL aircraft, etc. are discussed. Three "constants" were found to dominate that portion of the characteristics which confines the range of most economical jet-flap operation. Naturally, in this range, any increment in the rate of flap blowing is, at constant lift, completely (100%) recovered as (balance) measured thrust.

In operational applications for, e.g., STOL aircraft, two-dimensional jet-flap results are of rather academic value. The effect of aspect ratio on the economy of lift production is crucial and the drag penalty commensurate with high lift-producing, low aspect ratio jet-flapped wings needs careful study and evaluation.

Unfortunately, there is only one set of test results of a low aspect ratio ($AR = 6$) jet-flapped wing available which, however, is not as complete as is desirable for the unambiguous construction of its characteristics. It is this set of test data[2] which is evaluated in this paper.

I. Available Experimental Data

In Ref. 2, the results of wind-tunnel experiments with a rectangular jet-flapped wing of aspect ratio 6 are reported. At blowing rates up to $C\mu = 2.3$, the lift and thrust (drag) was measured at 4 jet sheet deflection angles and angles of attack ranging from $-8°$ to $+20°$. Unfortunately, these test results were obtained only for a wing-body combination (with and without tail).

In this paper, the over-all momentum coefficient, the lift and thrust (drag) coefficient are related to the gross wing area and for the jet sheet momentum, the actual (real) jet momentum at the trailing edge of the jet control flap is used. Furthermore, the lift and thrust data of Ref. 2 are converted to ΔC_{LT} and $\Delta C_{TM}(\Delta C_{DT})$ values, where the Δ designates the increments in lift or thrust (drag) due to blowing.

II. Low Aspect Ratio Jet-Flapped Wing at Zero Angle of Attack

2.1 A Qualitative Jet Flap Characteristic

If the converted jet-flap data of Ref. 2 for the full span blowing wing-body combination (without tail) are evaluated, the balance measured thrust due to blowing ΔC_{TM} can be plotted vs $C\mu_R$ for various jet sheet deflection angles θ (see Fig. 1). This plot does not yet constitute a jet-flap char-

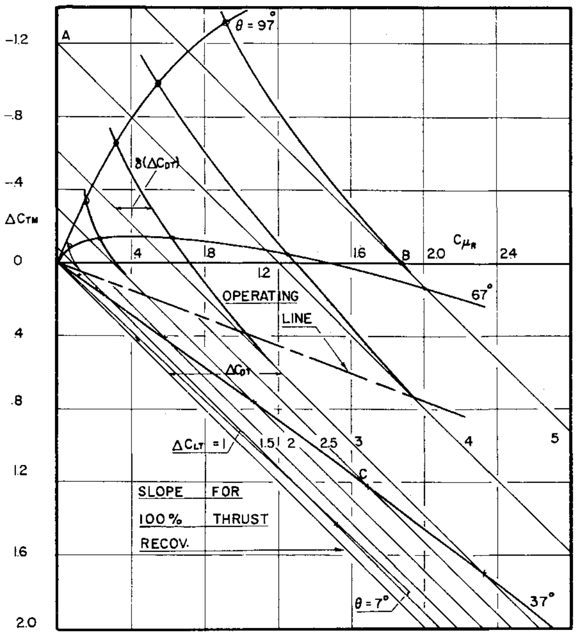

Fig. 1 Idealized jet-flap characteristics for an $AR = 6$ jet-flapped wing at zero angle of attack (test data of Ref. 2).

acteristic. The ΔC_{LT} = const lines have still to be added. Unfortunately, the test data of Ref. 2 are not comprehensive enough to do this unambiguously. For instance, there are not sufficient test points available to define either the direction of the straight portions of the $\Delta C_{LT} = 1$, 1.5, 2, 2.5, and 3 lines; or the location and direction of the $\Delta C_{LT} = 4$ and 5 lines. This is the reason, why, as a first approximation, the straight portions of the ΔC_{LT} = const lines are drawn as lines parallel to the 100% thrust recovery slope line. This approximation was chosen because of two observations: 1) that ΔC_{LT} = const lines are parallel to the 100% thrust recovery slope line if the aspect ratio of the jet-flapped wing is large or infinite[1]; and 2) that the change of induced drag ΔC_D with rate of blowing, $C_{\mu R}$ (which is the only reason for an inclination of the ΔC_{LT} = const lines with the 100% thrust recovery slope line) is small, at least for the $AR = 6$ jet-flapped wing here under consideration.

Drawing ΔC_{LT} = const lines through the corresponding test points of the $\theta = 37°$ curve leads to the qualitative jet-flap characteristic presented in Fig. 1. The $\Delta C_{LT} = 4$ and 5 lines are lines through points A and B, respectively, where A and B were calculated, (assuming that the $\theta = 37°$ curve is a straight line, which it is not), from

$$\Delta C_{DT} = (C_1'/K'^2)\Delta C_{LT}^2 \tag{2.1}$$

after C_1'/K'^2 was obtained from $\Delta C_{DT}/\Delta C_{LT}^2 = 0.47/6.25 = 0.0753$ at point C.

Now comparing Fig. 1 with characteristics of truly or quasi-two-dimensional jet-flapped wings (see Figs. 10, 11, and 12 of Ref. 1), the effect of aspect ratio becomes quite apparent. The lines of θ = const fan out stronger, move closer to or even above the $C_{\mu R}$ axis, and strongly depart from straight lines at higher values for θ. The lines of ΔC_{LT} = const are further apart. Both observations reflect the expected appreciable total drag increase of low aspect ratio jet-flapped wings operating under high lift conditions.

Again, as in the high aspect ratio jet-flap characteristics of Ref. 1, the ΔC_{LT} = const lines in Fig. 1 seem basically to be straight lines. Above the "operating line" (the locus of the points where the ΔC_{LT} = const lines depart from a straight line), operation of the jet-flapped wing at fixed ΔC_{LT} can no longer be achieved (neglecting still the effect of $C_{\mu R}$ on the induced drag) at a constant profile drag. The increase in profile (and total) drag ($\delta\Delta C_{DP} = \delta\Delta C_{DT}$) with jet-flap operation above the operating line is given by the horizontal distance between the extended straight ΔC_{LT} = const line and its real counterpart (see Fig. 1). The changes in blowing rate, thrust, and drag above the operating line are related[1] as

$$\delta(\Delta C_{TM}) = \delta C_{\mu R} - \delta(\Delta C_{DT}) \tag{2.2}$$

which for jet-flap operation along or below the operating line [where $\delta(\Delta C_{DT})$ is presently assumed to be zero] reduces to

$$\delta(\Delta C_{TM}) = \delta C_{\mu R}$$

Also in Ref. 1, the following relationships were derived for truly and quasi-two-dimensional jet-flapped wings:

$$\Delta C_{DT} = a(\theta)C_{\mu R} = C_1 \sin^2\theta C_{\mu R} \tag{2.3}$$

and

$$\Delta C_{DT} = (C_1/K^2)\Delta C_{LT}^2 \tag{2.4}$$

Equation (2.4) is obtained, when Eq. (2.3) is combined with Spence's expression[3]:

$$\Delta C_{LT}^2 = K^2 \sin^2\theta C_{\mu R} \tag{2.5}$$

where K is a characteristic "constant" of the jet-flap configuration in question.

In subsequent sections of this paper, the effect of induced drag on jet-flap characteristics as a whole and on "constants" such as C_1, K, and K'' in particular is summarized. A detailed analysis can be found in Ref. 4.

2.2 Total Drag as a Function of ΔC_{LT}

For spanwise elliptic loading the total drag of jet-flapped wings due to blowing is given by

$$\Delta C_{DT} = K'' \, \Delta C_{LT}^2 + \frac{\Delta C_{LT}^2}{\pi AR(1 + 2C_\mu/\pi AR)} \tag{2.6}$$

For low aspect ratio wings, the effect of C_μ on the induced drag, ΔC_{D_i}, can no longer be ignored as demonstrated in Fig. 2 for two aspect ratios, $AR = 6$ and 3. Whereas for aspect ratios of 6, the change in ΔC_{D_i} with $C_{\mu R}$ (at ΔC_{LT} = const) can, for all practical purposes, be represented by a linear function, this seems to be possible for an $AR = 3$ wing only if $\Delta C_{LT} < 3$. If nevertheless we approximate also the $\Delta C_{LT} = 4$ and 5 lines (for $AR = 3$) in Fig. 2 by straight lines and plot the slopes of all ΔC_{LT} = const lines vs ΔC_{LT}^2, Fig. 3

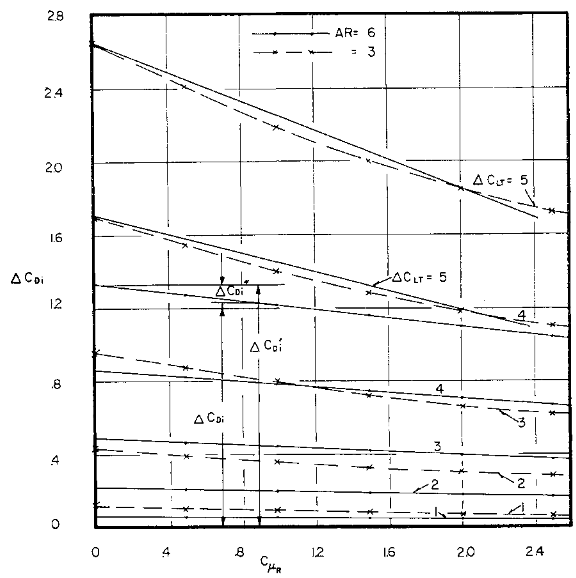

Fig. 2 Calculated induced drag components $\Delta C_{D_i}'$ due to aspect ratio; $\Delta C_{D_i}''$ due to blowing for various lift values and two aspect ratios.

results. It indicates that the change in ΔC_{Di} due to blowing can be expressed as

$$
\begin{aligned}
d\,\Delta C_{Di}/dC\mu_R &= \text{const}\ \Delta C_{LT}^2 \\
&= K'^V\ \Delta C_{LT}^2
\end{aligned}
\tag{2.7}
$$

The total drag of a low aspect ratio jet-flapped wing follows then[4] as

$$
\begin{aligned}
\Delta C_{DT} &= (K'' + K''')\Delta C_{LT}^2 - K'^V\ \Delta C_{LT}^2 C\mu_R \\
&= \Delta C_{DT_0} - \Delta C_{Di}''
\end{aligned}
\tag{2.8}
$$

In case of nonelliptical spanwise wing loading, the constants K''' and K'^V would have to be multiplied by a factor which accounts for the actual wing loading.

2.3 "Constructed" Jet-Flap Characteristics

Because of the lack of test points for the $AR = 6$ jet flapped wing of Ref. 2, an attempt is made to construct its characteristics by supplementing the original test data of Ref. 2 with the help of semi-empirical relationships derived from the experimental evidence.

The characteristics presented in Fig. 1 was obtained under the unappropriate assumption that the ΔC_{LT} = const lines are also lines of ΔC_{DT} = const and therefore parallel to the 100% thrust recovery slope line. Equation (2.8) demonstrates, however, that along the ΔC_{LT} = const lines, the total drag $\Delta C_{DT} \neq$ const. Assuming now (and this assumption is established reasonably well) that the profile drag of jet-flapped wings ($\Delta C_{DP} = K''\Delta C_{LT}^2$) does not change at fixed ΔC_{LT} and small jet deflection angles (say $\theta < 50°$), Eq. (2.8) can be used to calculate

$$\Delta C_{DT_0} = \Delta C_{DT} + \Delta C_{Di}''$$

If we plot again the converted test data of Ref. 2, for instance, point A in Fig. 4 would define the thrust ΔC_{TM}, the total drag ΔC_{DT}, and the rate of blowing commensurate with a $\Delta C_{LT} = 2.5$ at $\theta = 37°$. If now $\Delta C_{Di}''$, is calculated from

$$\Delta C_{Di}'' = K'^V\ \Delta C_{LT}^2 C\mu_R \tag{2.9}$$

and added to ΔC_{DT} at point A, point B is obtained, and a line through B, parallel to the 100% thrust recovery slope line, would represent the locus of $\Delta C_{LT} = 2.5$ for an $AR = 6$ jet-flapped wing, the induced drag of which would be independent of the rate of blowing. Where this line intersects the vertical axis (at point C), $\Delta C_{DT_0} = \Delta C_{DT}$, since $\Delta C_{Di}'' = 0$ because of zero blowing ($C\mu_R = 0$). If point C is connected with A by a straight line, this line should represent the real $\Delta C_{LT} = 2.5$ line so long as the profile drag does not change or ΔC_{DT_0} = const.

The foregoing procedure can be repeated for points D, E, etc., to furnish the real ΔC_{LT} = 3.0, 2.0, 1.5, and 1.0 lines. A simpler way, however, to find the points F, G, etc., is via the relationship[4]

$$\Delta C_{DT_0} = \text{const}\ \Delta C_{LT}^2 = (K'' + K''')\ \Delta C_{LT}^2 \tag{2.10}$$

where $(K'' + K''')$ can be obtained from point C.

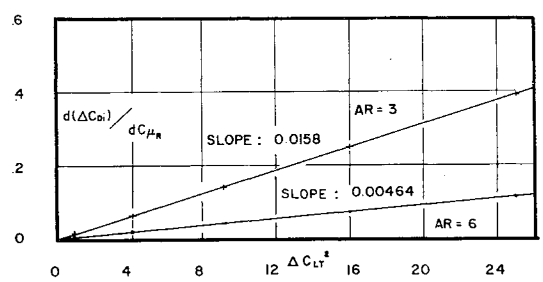

Fig. 3 Slope $d(\Delta C_{Di})/dC\mu_R$ as a function of ΔC_{LT}^2 for $AR = 6$ and 3.

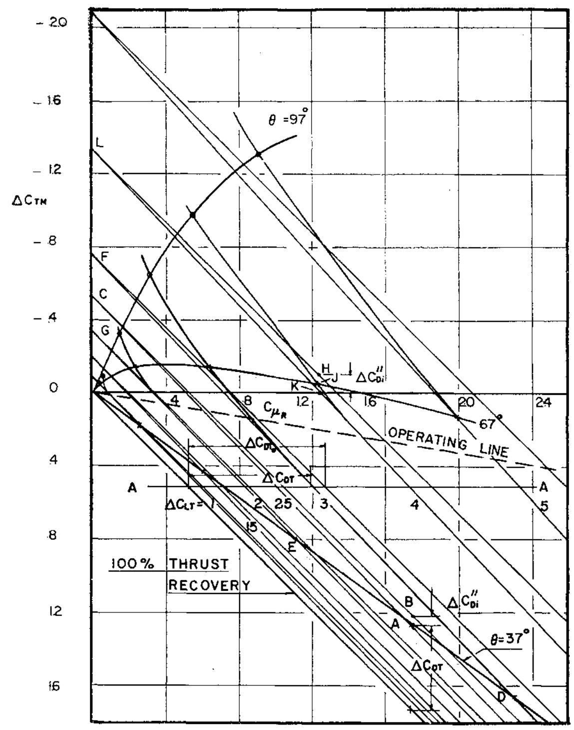

Fig. 4 Jet-flap characteristics for an $AR = 6$ jet-flapped wing at zero angle of attack (test data of Ref. 2).

There is some complication in finding the location of the real $\Delta C_{LT} = 4$ line. At an angle $\theta = 67°$, it seems evident (note location of operating line) that the ΔC_{LT} = const lines have already deviated from a straight line. This suggests that, for instance, the $\Delta C_{LT} = 4$ line cannot be drawn as a straight line through L and J. If, however, one calculates $\Delta C_{Di}''$ at point J from

$$
\begin{aligned}
\Delta C_{Di}'' &= K'^V\ \Delta C_{LT}^2\ C\mu_R \\
&= 0.00464 \times 16 \times 1.24 = 0.092
\end{aligned}
\tag{2.9a}
$$

and subtracts 0.092 from the $\Delta C_{DT_0} = 1.333$ at point H, one obtains point K, through which the real $\Delta C_{LT} = 4$ line should run, provided it would be still straight at $\theta = 67°$. Since point J is above K, this indicates that the $\Delta C_{LT} = 4$ line must have already departed from a straight line at an angle $\theta < 67°$.

2.4 "Constants" C_1 and K

For truly and quasi-two-dimensional jet-flapped wings,[1] Eq. (2.4) was shown to apply along or below the operating line. Let us now consider the effect of aspect ratio on C_1 and K.

2.4.1 Effect of aspect ratio on C_1

It is quite obvious from Fig. 5 that, the straight line relationship shown in Eq. (2.3) and found to apply in Ref. 1 for truly and quasi-two-dimensional jet flapped wings, no longer applies for low aspect ratio wings at large jet deflection angles, and only approximates the test data at small θ values ($\theta \leqslant 37°$). Theoretically, the drag parameter

$$a(\theta) = C_1' \sin^2\theta$$

is no longer a function of θ alone. If Eqs. (2.4) and (2.8) are combined, C_1' can be obtained from

$$C_1' = C_1 - K^2 K'^V C\mu_R \tag{2.11}$$

assuming that $K' = K$. The values of C_1'/K^2, calculated

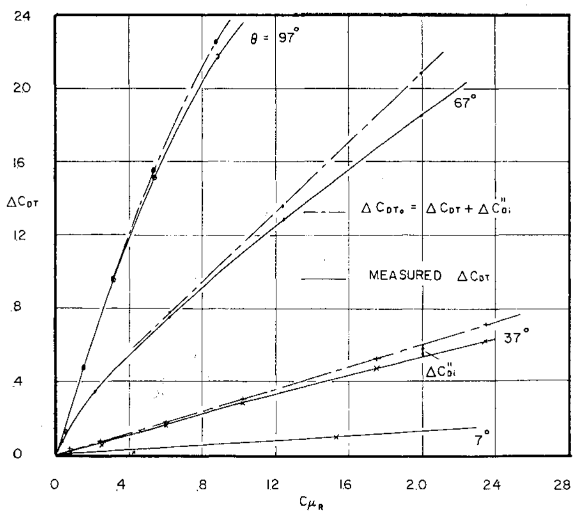

Fig. 5 Variation of the total drag and the induced drag component, $\Delta C_{Di}''$ [see Eq. (3.10)] with $C_{\mu R}$ at various jet deflection angles.

under the assumption that C_1/K^2 is a constant, are shown in Fig. 6.

If one plots the slope $a(\theta) = d\ \Delta C_{DT}/dC_{\mu R}$ of the $\theta = 37°$ line and the approximated slopes of the $\theta = 67°$ and $97°$ curves of Fig. 5 vs $\sin^2\theta$, Fig. 7 results. It shows, as already demonstrated for C_1 of high aspect ratio wings[1] that, as long as θ is smaller than about 55°, C_1' can, in practice, also be approximated by a constant.

2.4.2. *Effect of aspect ratio on K*

This "constant" calculated from Eq. (2.5) is plotted vs $C_{\mu R}$ in Fig. 8, for either θ or ΔC_{LT} as the parameter.

A comparison of Fig. 8 with Fig. 13 of Ref. 1 demonstrates the effect of aspect ratio on K. The $K = 3.15$ for the aspect ratio $AR = 6$ jet-flapped wing operated along or below the operating line is much below that of a similar two-dimensional wing ($K > 5$).

If, to experimentally prove or disprove Eq. (2.5) for low aspect ratio jet-flapped wings, ΔC_{LT}^2 is plotted against $C_{\mu R}$ for fixed θ values, Fig. 9 is obtained. If next the slopes $b(\theta)$ of the θ = const curves are plotted against $\sin^2\theta$, Fig. 10 results which suggests that Eq. (2.5) holds for jet deflection angles of up to approximately 55°, the angle at which the ΔC_{LT} = const lines seem to depart from straight lines.

2.4.3. *$d(\Delta C_{DT})/d(\Delta C_{LT}^2)$ = const relationship*

Since $d(\Delta C_{DT})/d(\Delta C_{LT}^2) = C_1'/K^2$, and since C_1'/K^2 changes with $C_{\mu R}$ as shown in Fig. 6, theoretically this relationship no longer holds. In practice, if, in Fig. 4, the values are read off at which the line A-A intersects the ΔC_{LT} and ΔC_{LT_0} = const lines, the curves for ΔC_{DT} and ΔC_{DT_0} in Fig. 11 are obtained. The straight line relationship for the

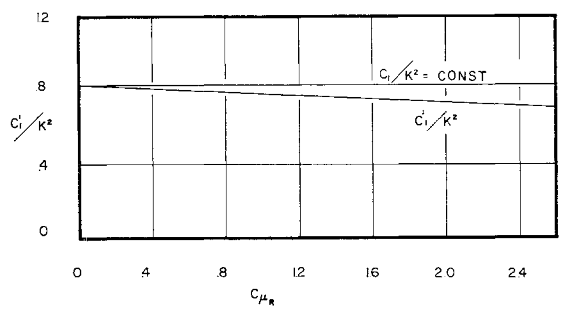

Fig. 6 Variation of C_1'/K^2 [see Eq. (3.12)] with $C_{\mu R}$.

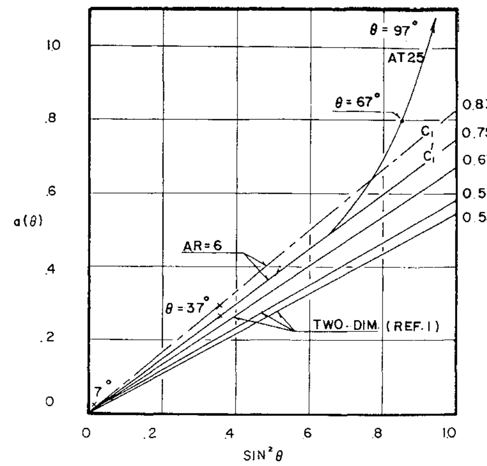

Fig. 7 Slopes $d\ a(\theta)/d \sin^2\theta = C_1'$ and C_1 for $AR = 6$ and for quasi-two-dimensional jet-flapped wings.

$d(\Delta C_{DT_0})/d(\Delta C_{LT}^2) = C_1/K^2$ curve is expected, whereas the ΔC_{DT} curve can be approximated reasonably well by a straight line only up to ΔC_{LT} values of about 4.

Further, in Fig. 11, the drag-lift relationship at three constant jet deflection angles is shown and the change of both C_1' and K with θ is demonstrated. It was shown in Sec. 2.4.2 that, at $\theta = 37°$, K can be considered as a constant. Therefore, it must be C_1' (actually $\Delta C_{Di}''$) that causes the departure of the $\theta = 37°$ curve from a straight line. In the case of the $\theta = 67°$ curve, both C_1' and K^2 increase, but their ratio is only little affected. At $\theta = 97°$, the effect of $\Delta C_{Di}''$ diminishes (because of smaller rates of blowing) and the increase in profile drag dominates.

In conclusion, it can be said that, at still lower aspect ratios ($AR \simeq 3$), the linear relationship between the total drag and the lift, found to apply for wings of large aspect ratios ($AR > 10$) does no longer hold, even approximately.

III. Low Aspect Ratio Jet-Flapped Wing at Angles of Attack

As Fig. 4 demonstrates, operation of a jet-flapped wing at $\theta = 7°$ or $\theta = 97°$ is unwarranted. At $\theta = 7°$, the rates of blowing required for the production of lift magnitudes, which would justify the use of a jet flap, are uneconomically high. At $\theta = 97°$, the drag penalty for high lift operation is prohibitive. Since this paper is intended to deal primarily with the practical operation and performance of jet-flapped wings, subsequent considerations are restricted to operational jet deflection angles ($\theta = 37°$ and 67°).

3.1 Test Data Evaluation

The converted test data of Ref. 2 for $\theta = 37°$ and 67° at various angles of attack (α) are presented below.

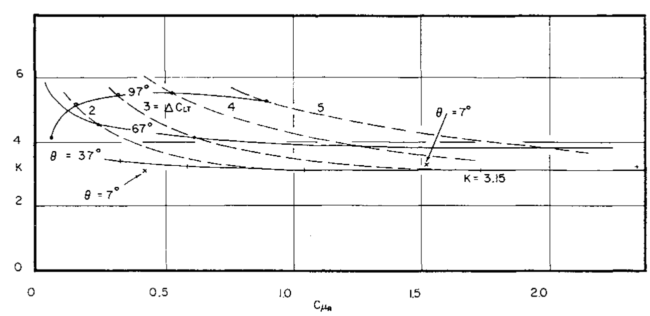

Fig. 8 Factor K, as obtained from the test data of Ref. 2.

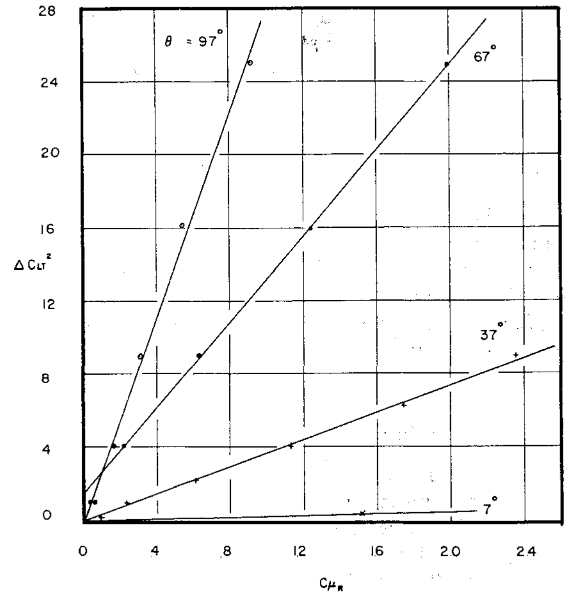

Fig. 9 Lift squared for various jet deflection angles as a function of blowing (test data of Ref. 2).

3.1.1 $\theta = 37°$; $0° \leqslant \alpha \leqslant 12°$

If we plot ΔC_{DT} vs $C\mu_R$ for various angles of attack, a family of straight lines (for all practical purposes) is obtained. If the points of constant ΔC_{LT} are connected, the plot of Fig. 12a results. If the slopes, $a(\alpha)$, of the ΔC_{DT} lines are plotted vs $\sin^2\alpha$, Fig. 12b results.

Figure 12 demonstrates that ΔC_{DT} at fixed $\theta = 37°$ obeys the relationship

$$\Delta C_{DT} = a(\alpha) C\mu_R \tag{3.1}$$

and that

$$d[a(\alpha)]/d \sin^2\alpha = C_2 = 6.2 \tag{3.2}$$

From Eq. (3.2) it follows that

$$a(\alpha) + C = C_2 \sin^2\alpha \tag{3.3}$$

The constant C (see Ref. 4) can be expressed as

$$C = a(0) + C(x) = a(\theta) + C(x) \tag{3.4}$$

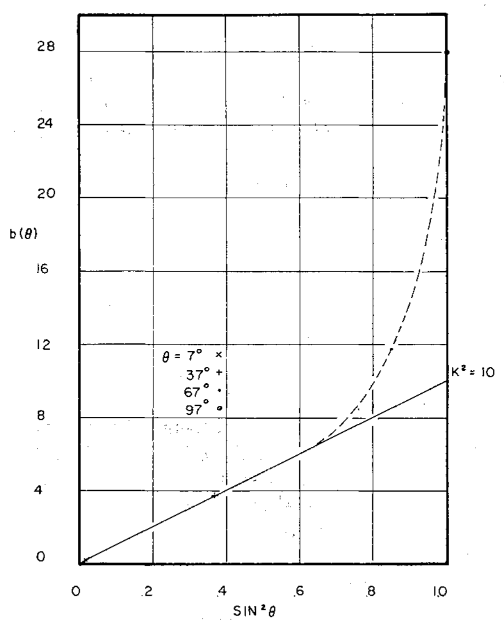

Fig. 10 Slope $K^2 = d\ b(\theta)/d \sin^2\theta$, as obtained from test data of Ref. 2.

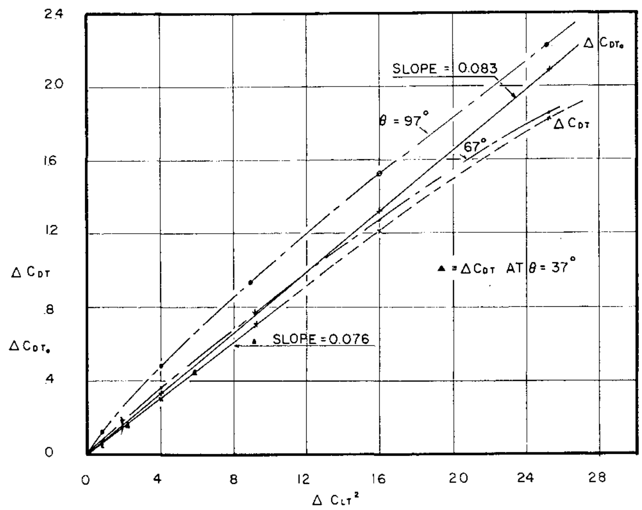

Fig. 11 Slope of the ΔC_{DT} vs ΔC_{LT}^2 curves for various jet deflection angles.

where $C(x)$ is an unknown function and

$$\Delta C_{DT} = C(x) + [a(\theta) + C_2 \sin^2\alpha]\ C\mu_R \tag{3.5}$$

or

$$\Delta C_{DT} = C(x) + (C_1' \sin^2\theta + C_2 \sin^2\alpha) C\mu_R \tag{3.6}$$

This latter equation accounts for the fact that actually the ΔC_{DT} line for $\alpha = 0$ is theoretically not a straight line and, because of $\Delta C_{D_i}''$, increasingly departs from a straight line as the aspect ratio decreases.

3.1.2 $\theta = 67°$; $0° \leqslant \alpha \leqslant 12°$

If at $\theta = 67°$, ΔC_{DT} vs $C\mu_R$ is plotted for several fixed angles of attack, Fig. 13 is obtained, in which also the lines of constant ΔC_{LT} are added. As Fig. 5 previously demonstrated the inapplicability of Eq. (2.3) at large jet deflection angles, Fig. 13 illustrates the inapplicability of Eq. (3.1) at large angles of θ. It is to be expected that when the profile

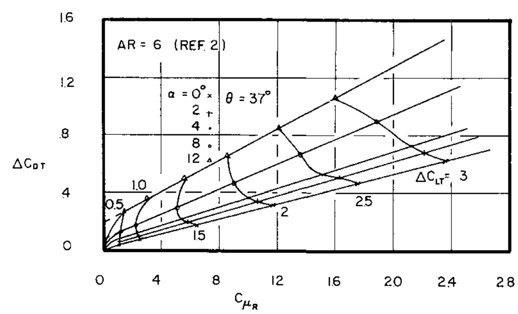

Fig. 12a Total drag variation at a fixed $\theta = 37°$ and various angles of attack as a function of blowing (test data of Ref. 2).

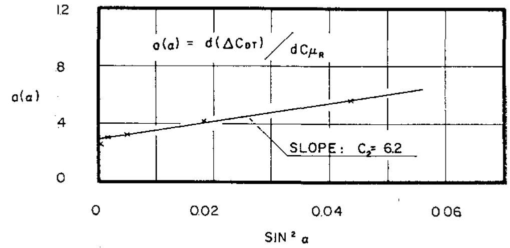

Fig. 12b Slope $C_2 = d\ a(\alpha)/d \sin^2\alpha$ for the constant jet deflection angle $\theta = 37°$.

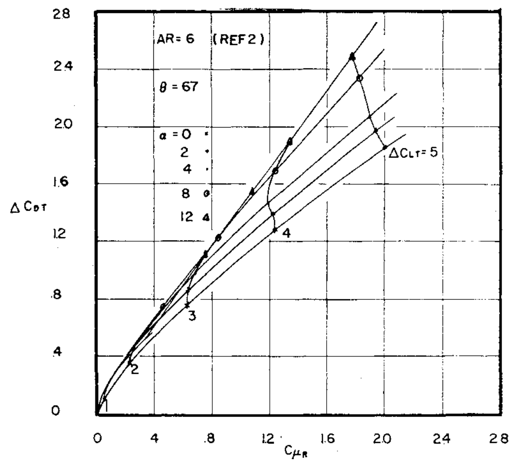

Fig. 13 Total drag variation at a fixed $\theta = 67°$ and various angles of attack as a function of blowing (test data of Ref. 2).

drag along the ΔC_{LT} = const lines is no longer constant, drag, lift, and drag-lift relationships can no longer be represented by simple linear functions.

3.2 Jet-Flap Characteristics

If in the characteristics of Fig. 4, the ΔC_{LT} = const lines obtained by varying $C\mu_R$ and the angle of attack at fixed jet deflection angle are added, Fig. 14 results. Since the lines for $\theta = 37°$ and $67°$ are far enough apart, the ΔC_{LT} = const lines for changing α are shown in this figure for both $\theta = 37°$ and $67°$. The location of the operating line is rather vague since the points where the ΔC_{LT} = const lines depart from straight lines are hard to define.

To facilitate comparison of Fig. 14 with the characteristics of a similar, but high aspect ratio (AR = 20) jet-flapped wing, Fig. 19b of Ref. 1 is added to this paper as Fig. 15. The effect of aspect ratio materializes in the following differences of the two figures: 1) the strong increase in drag; 2) the appreciable reduction in measured thrust (ΔC_{TM}) (a jet flap operated at $\theta = 67°$ would not at all contribute to the propulsive thrust); 3) the straight portions of the ΔC_{LT} = const lines are no longer parallel to the 100% thrust recovery slope line; their angle with the 45° line is a function of ΔC_{LT}, and the total drag along any of the straight line portions decreases with increasing $C\mu_R$; and 4) the departure of the ΔC_{LT} = const lines from a straight line (where the operating line intersects) is more gradual with low aspect ratio jet-flapped wings.

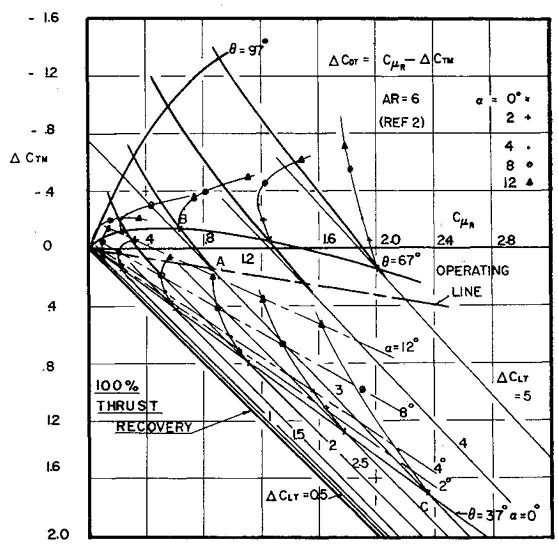

Fig. 14 Jet-flap characteristics for an AR = 6 jet-flapped wing at various angles of attack for two fixed jet deflection angles ($\theta = 37°$ and $67°$) (test data of Ref. 2).

IV. Performance and Jet-Flap Operation

The jet flap is by its very nature a high lift device. High lift can be obtained by a combination of jet sheet blowing with either jet deflection angle or angle of attack or both. A desired lift is produced most economically if the required rate of blowing and the inherent drag are the smallest values possible. Automatically, this defines the operating line as the line along which a jet-flapped wing should be operated.

4.1 Jet-Flap Performance

For a lift of say $\Delta C_{LT} = 3$, point A (see Fig. 14) would be the proper operating point. If at constant ΔC_{LT}, the jet deflection angle is increased to $\theta = 67°$ (point B), $C\mu_R$ is decreased from 0.84 to 0.62, but the total drag is somewhat increased (from 0.70 to 0.76). If at $\Delta C_{LT} = 3$, the jet deflection angle is reduced to say $\theta = 37°$, the total drag (see point C) decreases to $\Delta C_{DT} = 0.62$ (because of C_{Di}''), but now the blowing rate is prohibitively high ($C\mu_R = 2.3$).

If the angle of attack would be used to assist in the production of lift, Fig. 14 illustrates that under all circumstances ΔC_{DT} would increase. This fact alone should, in practice, eliminate the use of α. As will be shown more clearly in Sec. 4.3, it is the total drag penalty commensurate with the high lift production of jet-flapped wings, which is the most important and crucial parameter to watch.

The optimum jet deflection angle, as defined by the operating line, seems to be still of the order of $\theta = 55°$ to $60°$. Note, that in the case of low aspect ratio jet flaps, the adherence to the optimum θ is less critical because of the very gradual departure of the ΔC_{LT} = const lines from a straight line.

4.2 Most Economical Jet-Flap Operation

If a jet-flapped wing of the characteristics shown in Fig. 14 is to be incorporated in an aircraft design, economy of operation of the integrated lift and propulsive systems have to be considered. In other words, a specific lift has to be produced not merely at the smallest possible drag and blowing rate, but, in addition, the losses in providing the propulsive thrust must be considered and kept at a minimum.

From the view point of lift production alone, lift could most economically be generated if the jet-flapped wing is operated along the operating line. For instance, for the specific lift of $\Delta C_{LT} = 3$, point A would specify the conditions for most economical operation.

Theoretically, the rate of blowing ($C\mu_L$) through the wing trailing edge slots required solely for the production of the desired lift, may be smaller or equal to the optimum rate of blowing ($C\mu_E$) which would result, if the entire jet engine exhaust is expelled through the wing trailing edge slots. If $C\mu_L < C\mu_E$, one can[4] either 1) eject the entire jet engine exhaust through the trailing edge slots, or 2) operate the jet-flapped wing at point A by feeding only the required $C\mu_L = 0.84$ to the wing trailing edge slots.

The first alternative has the advantage of reducing the total drag because of the increase in $\Delta C_{Di}'' = K^{IV}\,\Delta C_{LT}^2 C\mu_R$ with $C\mu_R$. Its disadvantages impose primarily mechanical problems except for the frictional losses in the ducts to the wing's trailing edge which may outweigh any gain in total drag due to C_{Di}''.

Economically, the second alternative seems, at least theoretically, to be the more attractive one. As discussed in Ref. 4, it is not before the instant of takeoff from the ground that the jet-flap system should be put into operation. The advantages of this scheme are obvious. Ducts can be smaller and can be dimensioned for low duct flow velocities and frictional losses. Rates of blowing are small enough to reduce the mechanical problems encountered in the deflection of large and fast moving mass flows of hot gases. During cruise, the 2–5% loss in propulsive thrust due to duct and slot nozzle losses is avoided.

Whether, in practice, $C\mu_L$ is smaller or equal to $C\mu_E$ depends primarily on the extent to which use is made of the high lift potential of jet-flapped wings and on the mission requirements of the aircraft in question (rate of climb, cruising, and top speed, etc.). In the following section, this point is discussed further.

4.3 Jet-Flapped Wing and STOL

The aircraft chosen to subsequently demonstrate the potential of the jet flap for STOL application demands magnitudes of lift and rate of blowing, which are far beyond the experimental ranges investigated in Ref. 2, and presented in the jet-flap characteristics of Fig. 14. Because of this lack of experimental evidence, the following discussion is qualitative rather than quantitative.

If one divides the takeoff and cruising thrust data of fighter aircraft, bombers, airliners, and trainers by the $(\rho/2)V^2$ at the instant of takeoff from the ground and at cruise, respectively, the resulting thrust coefficients were found to group around these values:

$$C\mu_T = 0.5 \text{ takeoff}$$

$$C\mu_C = 0.025 \text{ cruise}$$

Let us consider now an airliner that at a distance x takes off the ground at $C\mu_T = 0.5$. This airliner is to be converted into a STOL aircraft by means of the jet-flap principle, and its conventional takeoff distance x is to be shortened to $x/6$. Weight and propulsive thrust are assumed to be the same for both aircraft. Since at takeoff, the lift acting on both aircraft must be the same, the following relationship holds

$$C_L'\frac{\rho}{2}V_T'^2 = C_{LT}\frac{\rho}{2}V_T^2 = C_{LT}\frac{\rho}{2}\frac{V_T'^2}{6} \qquad (4.1)$$

assuming constant acceleration during the ground run. From Eq. (4.1) then follows that $C_{LT} = 6C_L'$. If C_L' for the conventional airliner at takeoff is assumed to be 1.2, C_{LT} becomes 7.2. Similarly, $C\mu_T = 0.5$ becomes $C\mu = 6C\mu_T = 3$.

In Ref. 1, it was demonstrated that an $AR \simeq 20$ jet-flapped wing with jet control flaps of $K = 4.8$, $\theta = 60°$, $\alpha = 0°$, and $C\mu = 3$ would be able to furnish the desired lift of $\Delta C_{LT} = 7.2$ without any increase in engine thrust. This high lift cannot be obtained without a simultaneous (induced) drag penalty, reducing the propulsive thrust available for climb and resulting in a grossly reduced climb rate. In this case of the $AR \simeq 20$ jet-flapped wing, the propulsive thrust at the instant of takeoff is only about half the thrust produced by the jet engines. Of course, things get worse with operational (low aspect ratio) jet-flapped wings. It will be shown next, that the jet-flapped wing of Ref. 2 ($AR = 6$) is not able to lift the converted airliner off the ground at $\frac{1}{6}$ of the conventional takeoff distance. This is because of the fact that the entire engine exhaust ($C\mu = 3$) at the takeoff point, is not large enough, to satisfy the blowing rate ($C\mu_L$) required to produce the desired lift of $\Delta C_{LT} = 7.2$.

If we use the $AR = 6$ jet-flapped wing of Ref. 2 (see Fig. 14) at $\theta = 55°$ and $\alpha = 0°$, we can calculate ΔC_{DT_0} from Eq. (2.11) as

$$\Delta C_{DT_0} = 0.0833 \cdot \Delta C_{LT}^2 = 4.33$$

and a $\Delta C_{LT} = 7.2$ line could be added in Fig. 4 as a straight line parallel to the 100% thrust recovery slope line. This ΔC_{LT} line would be a line along which ΔC_{DT_0} = const = 4.33. The real $\Delta C_{LT} = 7.2$ line can be found by subtracting

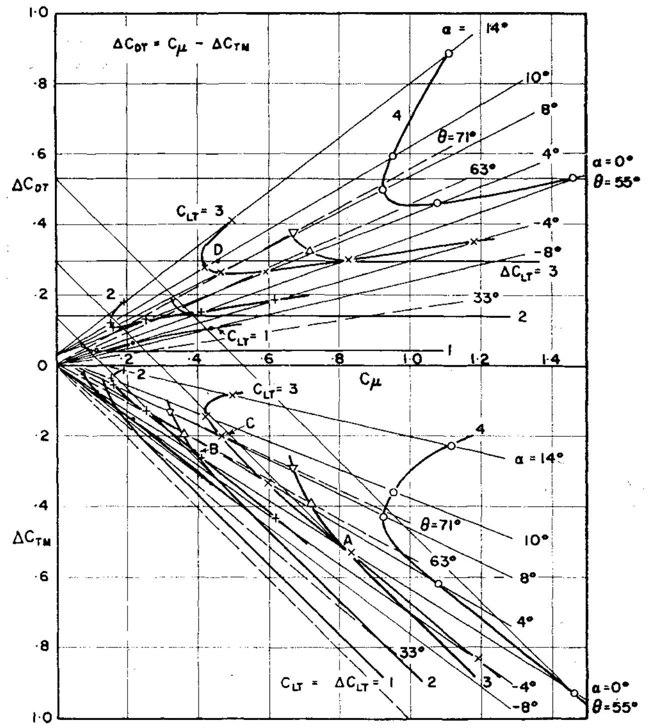

Fig. 15 Jet-flap characteristics for an AR = 20 jet-flapped wing at a fixed jet deflection angle (θ = 55°) and various angles of attack.

$\Delta C_{D_i}'' = 0.00464 \cdot \Delta C_{LT}^2 \cdot C\mu_L$ from ΔC_{DT_0} at $\theta = 55°$. To do this, we need to know $C\mu_L$, which we obtain from

$$C\mu_L = \Delta C_{DT_0}/C_1 \sin^2 55 = 7.75$$

Then

$$\Delta C_{D_i}'' = 0.00464 \cdot \Delta C_{LT}^2 \cdot 7.75 = 1.87$$

$$\Delta C_{DT} = \Delta C_{DT_0} - \Delta C_{D_i}'' = 4.33 - 1.87 = 2.46$$

We see that the required $C\mu_L = 7.75$ and that the available rate of blowing is only $C\mu = 3$. To get the jet-flap airliner off the ground, the thrust of the engines would have to be raised in the ratio of $7.75/3 = 2.58$. Then the entire jet engine exhaust has to be ejected through the nozzle slots at the wing trailing edge. The propulsive thrust is thus produced exclusively by the jet-flap. Its magnitude at the instant of takeoff from the ground and during climb is

$$C_T = C\mu_L - \Delta C_{DT} = 7.75 - 2.46 = 5.29$$

This means an approximately 75% increase in propulsive thrust for climb in comparison with the conventional airliner ($C\mu = 3$). Furthermore, because of the increased thrust of the jet engines, the takeoff speed is achieved in a still shorter takeoff ground run, the actual distance being

$$x/6 \cdot 2.58 = x/15.5$$

This turns the jet-flap version of the airliner into quite a potential STOL aircraft.

In order to be able to compare the jet-flap version with the conventional airliner on an equal footing, let us equip also the conventional airliner with the same more powerful jet engines. Both aircraft would equally accelerate during the takeoff run up to the point $x/15.5$, at which the jet flap version becomes airborne. The conventional airliner reaches its takeoff speed now at $x/2.58$ or at a takeoff distance of 6 times that of the jet flap version. During climb, the conventional airliner is superior in get-away speed and rate of climb because of higher initial takeoff speed and propulsive thrust (less drag). Finally, at cruise both aircraft should be equivalent except for the higher losses accrued in the production of the propulsive thrust with the jet-flap version, provided that the engine exhaust is still ejected through the slot nozzles at the wing's trailing edge.

4.4 Integration of the Lifting and Propulsive Systems

In the early days of the jet flap, Constant observed that, "the propulsive jet of a modern aircraft, being a very powerful physical entity, should be one hundred per cent combined with the wing in flight near the ground." In other words, Constant suggested, at least for takeoff, the complete integration of the propulsive system of a jet aircraft with its lifting system. In practice, this would mean that during takeoff, the entire jet engine exhaust is to be ejected through the slot nozzles at the wing's trailing edge.

It appears that when full use is made of the jet-flap's high lift potential (in STOL application for instance), blowing rates for the production of the extremely high lift coefficients required make it necessary to expel the entire engine exhaust through the slot nozzles (see Sec. 4.3). Over this portion of a flight mission, complete integration of the propulsive and lifting systems seems to evolve naturally. It stands to reason that the mechanical complexity of such an integrated system would eliminate the "luxury" of the conventional system as a standby for cruise, in spite of some undeniable advantages which the latter has to offer. Furthermore, the lower total drag (due to the larger $\Delta C_{D_i}''$ with $C\mu_L$) makes the integrated system still more attractive.

4.5 Wind-Tunnel Testing of Jet-Flapped Wings

It is one of the benefits of jet-flap characteristics to clearly define the most economical range of jet-flap operation. Information outside this range (above the operating line) is of no direct practical significance. It is therefore suggested to streamline in future the test programs in such a way as to furnish data which can directly be plotted in the form of a jet-flap characteristic. The following procedure may be helpful.

The jet-flapped wing to be tested (three-dimensional) is set up on a lift-drag (thrust) balance at $\alpha = 0°$, the wind tunnel is running at a fixed speed, and the jet control flap is set at a specific angle. At zero blowing, the C_L' and C_D' are recorded. Then blowing is initiated and $C\mu$ is increased until a predetermined $\Delta C_{LT} = C_{LT} - C_L'$ is reached. Now C_{TM} is recorded and ΔC_{TM} is obtained from $\Delta C_{TM} = C_{TM} + C_D'$. These data provide the first experimental point for a $\Delta C_{LT} =$ const line in the prospective jet-flap characteristics after $C\mu$ is calculated. Next, the jet deflection is changed and the whole procedure repeated for another test point on the same $\Delta C_{LT} =$ const line, etc.

V. Conclusions

The presented material and evidence indicate that: 1) the performance and operation, also of low aspect ratio jet-flapped wings can be most instructively demonstrated in the form of a jet-flap characteristic; 2) a jet-flapped wing should be operated along or below (and not above) the operating line for most economical (low drag) operation; 3) the optimum jet deflection angle (as defined by the operating line) is still (at $AR = 6$) of the same order ($50° < \theta < 60°$) as that observed with truly and quasi-two-dimensional jet-flapped wings; 4) the angle of attack has become a rather uneconomical and inefficient means for lift production in combination with low aspect ratio jet-flapped wings; 5) the complete integration of the propulsive and lifting systems becomes a natural for jet-flapped wings, the lower the aspect ratio and the higher the lift requirements for takeoff; 6) also low aspect ratio jet-flap characteristics below and including the operating line can be constructed from "constants"; 7) semi-empirical relationships, almost identical (except for the magnitude of the "constants") with those derived for truly and quasi-two-dimensional jet-flapped wings[1] apply.

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