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LOW-SPEED WIND-TUNNEL INVESTIGATION TO DETERMINE THE AERODYNAMIC CHARACTERISTICS OF A RECTANGULAR WING EQUIPPED WITH A FULL-SPAN AND AN INBOARD HALF-SPAN JET-AUGMENTED FLAP DEFLECTED 55°

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Langley Field, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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LOW-SPEED WIND-TUNNEL INVESTIGATION TO DETERMINE THE AERODYNAMIC CHARACTERISTICS OF A RECTANGULAR WING EQUIPPED WITH A FULL-SPAN AND AN INBOARD HALF-SPAN JET-AUGMENTED FLAP DEFLECTED 55°

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SUMMARY

An investigation to determine the aerodynamic characteristics of a rectangular wing equipped with a full-span and an inboard half-span jet-augmented flap has been made in the Langley 300 MPH 7- by 10-foot tunnel. The wing had an aspect ratio of 8.3 and a thickness-chord ratio of 0.167. A jet of air was blown backward through a small gap, tangentially to the upper surface of a round trailing edge, and was separated from the trailing edge by a very small flap at an angle of 55° with respect to the wing-chord plane.

The results of the investigation showed that the ratio of total lift to jet-reaction lift for the wing was about 35 percent less for the half-span jet-augmented flap than for the full-span jet-augmented flap. The reduction of the span of the jet-augmented flap from full to half span reduced the maximum value of jet-circulation lift coefficient that could be produced from about 6.8 to a value of about 2.2. The half-span jet-augmented flap gave thrust recoveries considerably poorer than those obtained with the full-span jet-augmented flap. Large nose-down pitching-moment coefficients were produced by the half-span flap, with the greater part of these being the result of the larger jet reactions required to produce a given lift for the half-span flap compared with that required for the full-span flap.

INTRODUCTION

The jet-augmented flap has received considerable attention as a high-lift device capable of reducing the take-off and landing distances and velocities of jet aircraft (refs. 1 to 4), but at present very little partial-span jet-augmented-flap data are available. Partial-span jet-augmented flaps might be used on airplanes having large jet engines and wings having outboard sections too thin to accommodate the internal ducting required for full-span jet augmentation. Partial-span jet flaps might also be used to advantage on swept wings where an inboard arrangement would reduce the large nose-down pitching moments produced by full-span blowing. In addition, engine-out considerations might necessitate the grouping of engines near the airplane center line.

The purpose of the present investigation was to obtain a comparison of the aerodynamic characteristics of full-span and half-span jet-augmented flaps. These results can be extended to other flap spans to give an indication of the compromises in performance that would be required by the use of partial-span rather than full-span blowing. Tests were made in the Langley 300 MPH 7- by 10-foot tunnel on a rectangular wing with an aspect ratio of 8.3 and a thickness-chord ratio of 0.167. Both jet-augmented flaps were tested with jet deflections of 55°, through a momentum-coefficient range up to about 5, and at a Reynolds number of about 158,000. The data of this report include aerodynamic characteristics in pitch through an angle-of-attack range from -8° to about 24°.

SYMBOLS

A	aspect ratio
b_f/b	ratio of flap span to wing span
$\bar{c}$	wing mean aerodynamic chord, 0.60 ft
C_D	drag coefficient, $\frac{\text{Drag}}{qS}$
$C_{D,i}$	induced-drag coefficient
C_L	lift coefficient, $\frac{\text{Lift}}{qS}$
$(C_L)_{C_\mu=0}$	lift coefficient for $C_\mu = 0$ or jet off
$(C_L)_\Gamma$	jet-circulation lift coefficient, $C_L - (C_L)_{C_\mu=0} - C_\mu \sin(\alpha + \delta)$
C_m	pitching-moment coefficient about $0.276\bar{c}$, $\frac{\text{Pitching moment}}{qS\bar{c}}$

$(C_m)_{C_\mu=0}$ pitching-moment coefficient for $C_\mu = 0$ or jet off

$(C_m)_\Gamma$ jet-circulation pitching-moment coefficient, $C_m - (C_m)_{C_\mu=0} - x_{cp}\, C_\mu \sin(\alpha + \delta)$

C_μ momentum coefficient, $\frac{w_j V_j}{gqS}$

c^2

ft

b/sq ft

to free-stream

$RT_g\left[1 - \left(\frac{p}{p_p}\right)^{\frac{\gamma-1}{\gamma}}\right]$,

/sec

ift, percent chord

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δ jet-deflection angle, measured with respect to the wing-chord plane extended, deg

ρ mass density of air, slugs/cu ft

Subscript:

max maximum

APPARATUS AND MODEL

The investigation was made with a semispan wing model in the Langley 300 MPH 7- by 10-foot tunnel. The geometric characteristics of the model are shown in figure 1. The wing was rectangular and unswept and had a full-span aspect ratio of 8.3. The jet-augmented flap arrangement was made by removing the rear 30 percent of a 10-inch-chord NACA 0012 wing and installing a 3/4-inch-diameter tube and a plenum chamber, as shown in figure 1. Compressed air flowed through the tube into the plenum chamber through a series of holes of 1/16-inch diameter located in the tube at spanwise intervals of 1/2 inch. The trailing edge of the wing was fitted with a 60° wedge attachment which deflected the jet sheet of air at an angle of 55° with respect to the wing-chord plane. For the partial-span blowing configuration, the small gap through which the air escaped over the flap was sealed along the outboard half of the span.

Compressed air was brought into the wing in the same manner as that described in reference 1. The weight rate of air flow was determined by means of a calibrated sharp-edge-orifice flowmeter, and the pressures and temperatures for determining jet-exit velocities were measured in the plenum chamber in the wing.

TESTS

Tests were made in the Langley 300 MPH 7- by 10-foot tunnel at a dynamic pressure of 2 lb/sq ft which corresponds to a velocity of about 40 ft/sec and a Reynolds number based on the wing chord of about 158,000. The angle-of-attack range investigated extended from -8° to about 24°, and momentum coefficients ranged from 0 to about 5.

CORRECTIONS

Jet-boundary corrections applied to the data were obtained by the method outlined in reference 5. The corrections were based only on the aerodynamic lift coefficient obtained by subtracting the jet reaction from the total measured lift as indicated by the following equations:

$$\alpha = \alpha_{tunnel} + 0.142\left[C_L - C_\mu \sin(\alpha + \delta)\right]$$

$$C_D = (C_D)_{measured} + 0.00247\left[C_L - C_\mu \sin(\alpha + \delta)\right]^2$$

Blocking corrections have not been applied to the data because they were believed to be negligible in view of the small size of the model with respect to the tunnel test section.

RESULTS AND DISCUSSION

Momentum Coefficient

The momentum coefficient used in analyzing the data of this report is based on the product of the mass of air discharged through the slot and the theoretical velocity obtained by assuming isentropic expansion to free-stream static pressure. In a converging nozzle, efficiencies of nearly 100 percent are obtained up to choking velocity, above which a slight loss occurs as the pressure ratio is increased. The calibration for a nozzle similar to the one used in the present investigation is shown in reference 1 and indicates that the measured reaction obtained from such a nozzle is approximately 75 percent of the calculated value. The half-span nozzle used in the present investigation was not statically calibrated, but it was assumed that it would show a similar variation of measured thrust to theoretical thrust. It was also assumed that the jet-deflection angle of the half-span configuration was the same as that for the full-span configuration. The theoretical momentum coefficient has been used because the momentum of the jet at the nozzle exit is believed to be largely responsible for the change in circulation around the wing and because losses in the jet due to overexpanding, turning, and base pressure could not be individually evaluated.

Lift Characteristics

The lift of a wing equipped with a jet-augmented flap consists of the lift due to angle of attack and camber with no blowing, the jet-reaction lift or component of momentum coefficient in the lift direction, and the jet-circulation lift induced by the jet sheet acting as a flap. The aerodynamic characteristics in pitch of the wing equipped with the full-span and inboard half-span jet-augmented flaps with jet deflections of 55° are presented in figure 2. The data of figure 3(a) were obtained by cross-plotting from figure 2 and show the breakdown of the total lift coefficient into its components for the two jet-augmented flaps at an angle of attack of 0°. It can be seen in figure 3(a) that, at momentum coefficients above those necessary for flow attachment, the full-span flap develops about 50 percent more lift than the half-span flap as a result of the larger jet-circulation lift coefficients induced by full-span blowing. Jet-circulation lift coefficients $(C_L)_{\Gamma}$ from figure 3(a) are plotted against momentum coefficient C_{μ} in figure 3(b). This plot shows that values of $(C_L)_{\Gamma}$ for both flaps increase rapidly with increase in C_{μ} in the low momentum-coefficient range but tend to reach maximum values at higher values of C_{μ}. For the full-span flap, $(C_L)_{\Gamma}$ does not reach its maximum within the limited C_{μ} range presented in figure 3(b). Reference 2 shows, however, that this maximum for a given wing is a function of the wing aspect ratio, and, for the aspect-ratio-8.3 wing tested in the present investigation, the maximum value would be about 6.8 (corrected for $\delta = 55^{\circ}$) at $C_{\mu} \approx 12$. As indicated in figure 3(b), the reduction from full-span to half-span blowing reduces this maximum jet-circulation lift coefficient to a value of about 2.2 which occurs at $C_{\mu} \approx 3$.

The bottom curve in figure 3(b) is an estimate obtained by the method given in reference 2 for an aspect-ratio-4.15 wing with a full-span jet-augmented flap, but is based on the same area as the wing of the present investigation. This curve represents the case of an aspect-ratio-8.3 wing with half-span blowing in which no jet-circulation lift is carried by the outboard half of the wing. The jet-circulation lift coefficient for this configuration is seen to reach a maximum of only 1.50 (corrected for $\delta = 55^{\circ}$); this fact indicates that on the actual half-span blowing configuration, jet-circulation lift is carried over to the outboard portion of the wing.

The maximum values of jet-circulation lift coefficient are used as an upper limit for the plot of $(C_L)_{\Gamma}$ as a function of flap span presented in figure 4 for several momentum coefficients. Figure 4 may be considered a preliminary design chart to be used in conjunction with figure 4 of reference 2 for estimating the lift coefficients of wings with partial-span jet-augmented flaps. Lift coefficients can be calculated from the equation

$$C_L = (C_L)_{C_{\mu}=0} + C_{\mu} \sin(\alpha + \delta) + (C_L)_{\Gamma} \frac{\delta}{55}$$

where $\delta/55$ corrects for flap deflections other than 55°.

In figure 5, values of the lift magnification factor, defined as the ratio of total lift C_L to the reaction component of lift $C_\mu \sin(\alpha + \delta)$, are plotted as a function of C_μ for the full-span and half-span jet-augmented flaps at an angle of attack of 0°. It can be seen that the magnification factor of the full-span flap is reduced by about 35 percent as the result of the 50-percent reduction in the blowing span. Although this represents a considerable reduction, figure 5 shows that at the value of C_μ for maximum $(C_L)_\Gamma (C_\mu \approx 3)$, the half-span flap is effective in producing a lift about twice as large as that due to the jet reaction alone.

Figure 6 shows the variation of maximum lift coefficient with momentum coefficient for the full-span and half-span flaps. Although the full-span flap develops about 50 percent more lift than the half-span flap at an angle of attack of 0° (fig. 3(a)), it develops only about 25 percent more lift at maximum lift coefficient because of the higher angle of attack for $(C_L)_{max}$ of the wing with the half-span flap. This might be the result of the greater local C_μ for the half-span flap than for the full-span flap at a given C_μ based on wing area, since the angle of attack for $(C_L)_{max}$ increases as C_μ is increased above 2. (See ref. 3.) This might also be attributed to the lower effective aspect ratio of the half-span configuration.

Drag Characteristics

Figure 7 shows the variation of drag coefficient with lift coefficient at an angle of attack of 0° for the full-span and half-span jet-augmented flap configurations obtained by cross-plotting from figure 2. The greater thrust for the half-span flap indicated in this figure results from more jet reaction in the thrust direction than for the full-span flap at a given lift coefficient. An important factor to be considered in comparing the drag characteristics of the two configurations, however, is thrust recovery, since reference 3 shows this to affect the take-off performance of airplanes with jet-augmented flaps.

In evaluating thrust recovery, consideration must be given to induced drag, which can be expressed by the equation

$$C_{D,i} = \frac{(C_L)_\Gamma^2}{e\pi A}$$

From tests with and without blowing at $\alpha = 0^\circ$ the induced drag and circulation lift may be easily determined, and, hence, values of the efficiency factor e may be determined. Figure 8 shows values of e

for the full-span and half-span jet-augmented flap configurations through a range of momentum coefficients obtained from the data of figures 3 and 7. The average values of the efficiency factor usually range from 0.75 to 0.85 for wings of this plan form without blowing. For the full-span flap, the average value of e shown in figure 8 is about 0.8, a value which indicates a thrust recovery approximately equal to that resulting from the component of the jet reaction in the thrust direction. (See ref. 3.) The efficiency factor of the half-span flap decreases from a value of 0.8 at $C_\mu = 0$ to a value of about 0.20 at $C_\mu = 3.6$; this decrease indicates thrust recoveries considerably less than those that would be obtained from reaction considerations alone.

In view of the poor thrust recovery of the partial-span flap, it might be expected that its use would require compromises in the take-off performance that could be attained with jet aircraft equipped with full-span jet-augmented flaps. It should be pointed out, however, that the wing tested in this investigation had poor thrust recovery at $\delta = 0^\circ$ which was reflected in the thrust recovery at other flap deflections. Therefore, it is believed that the values of e given in figure 8 are considerably lower than might be expected on a wing with a more efficient jet-augmented flap installation. It should also be pointed out that the effect of thrust recovery on take-off distance is important only for aircraft with thrust-weight ratios lower than about 0.4. (See ref. 3.)

Pitching-Moment Characteristics

Pitching-moment characteristics at $\alpha = 0^\circ$ with respect to a point located $0.276\bar{c}$ rearward of the leading edge are given in figure 9(a) for the full-span jet-augmented flap and in figure 9(b) for the half-span jet-augmented flap. Both flaps give large nose-down pitching-moment coefficients which become more negative as the lift is increased by increasing the momentum coefficient. It can be seen by comparing figures 9(a) and 9(b) that the jet-circulation component of the total pitching moment is slightly less for the half-span flap at a given C_L than for the full-span flap. The half-span flap, however, gives larger nose-down pitching moments at a given C_L because it requires a larger jet reaction at the trailing edge to produce a given lift than does the full-span flap.

The importance of the jet-reaction contribution to the pitching moment of the jet-augmented flap is indicated by the relatively far rearward locations of the centers of pressure of the total lift, particularly for the half-span flap, compared with that for the centers of pressure of the jet-circulation lift. Pitching moments could be made very small by locating the wing center of gravity at $(x_{cp})_\Gamma$ and directing the jet reaction through this point. A device for doing this, known as the jet-augmented trim flap, is described in reference 1.

CONCLUSIONS

A wind-tunnel investigation at low speeds to compare the aerodynamic characteristics of an unswept, untapered wing equipped with a full-span and an inboard half-span jet-augmented flap deflected 55° indicated the following conclusions:

1. The ratio of total lift to jet-reaction lift for the wing was about 35 percent less for the half-span jet-augmented flap than for the full-span jet-augmented flap.

2. The maximum jet-circulation lift coefficient produced on the aspect-ratio-8.3 wing was reduced from a value of about 6.8 with full-span blowing to a value of about 2.2 with half-span blowing. The momentum coefficient at which maximum jet-circulation lift occurred was about 12 with full-span blowing and about 3 with half-span blowing.

3. The thrust recovery of the half-span jet-augmented flap was considerably poorer than that of the full-span jet-augmented flap. Because of the poorly designed jet-augmented flap installation, the half-span flap gave thrust recoveries considerably lower than would be expected from reaction considerations alone.

4. The half-span flap gave larger nose-down pitching-moment coefficients than the full-span flap at a given lift coefficient because of the larger jet reaction required to produce a given lift for the half-span flap compared with that required for the full-span flap.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., October 24, 1958.

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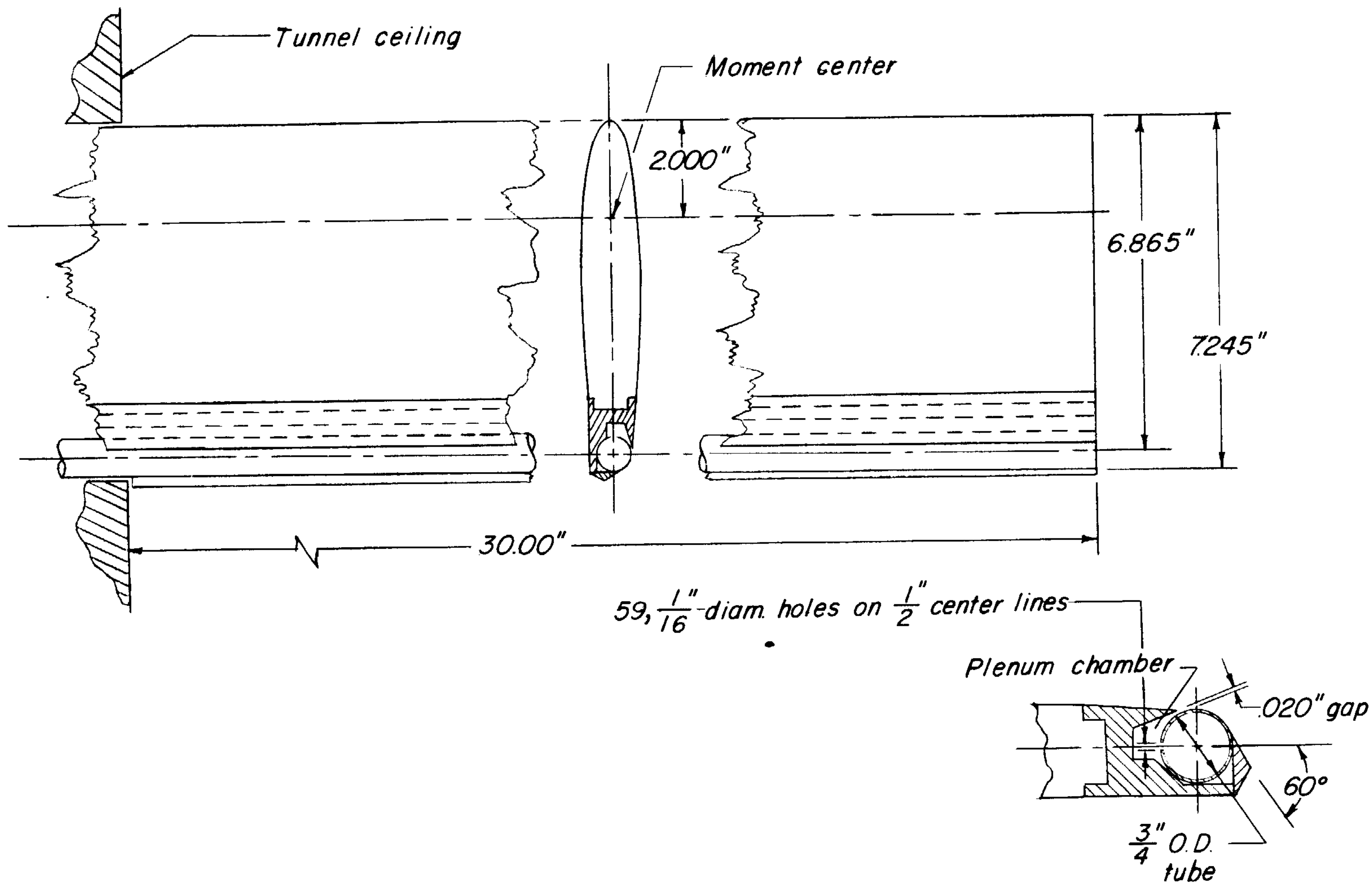
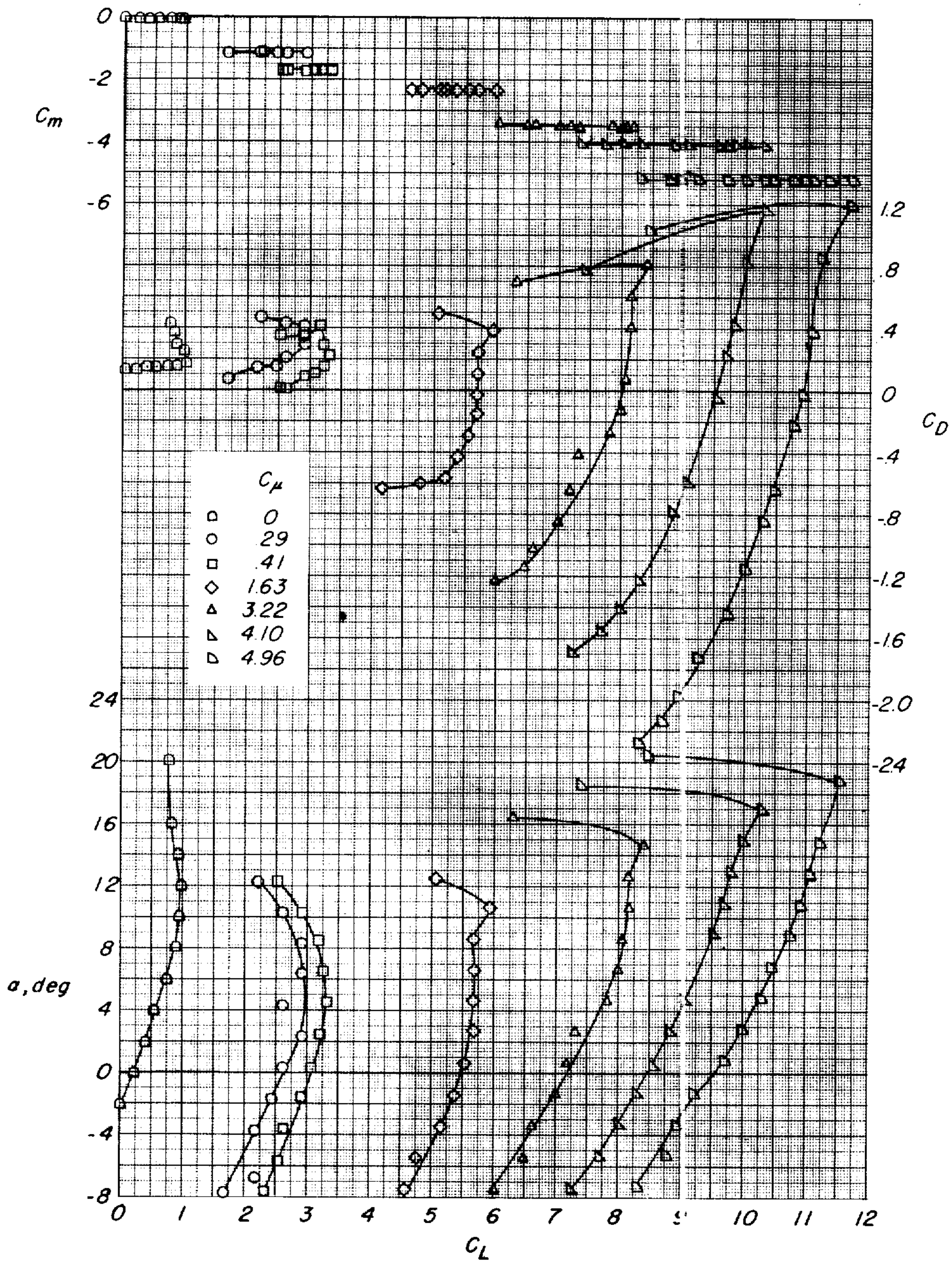
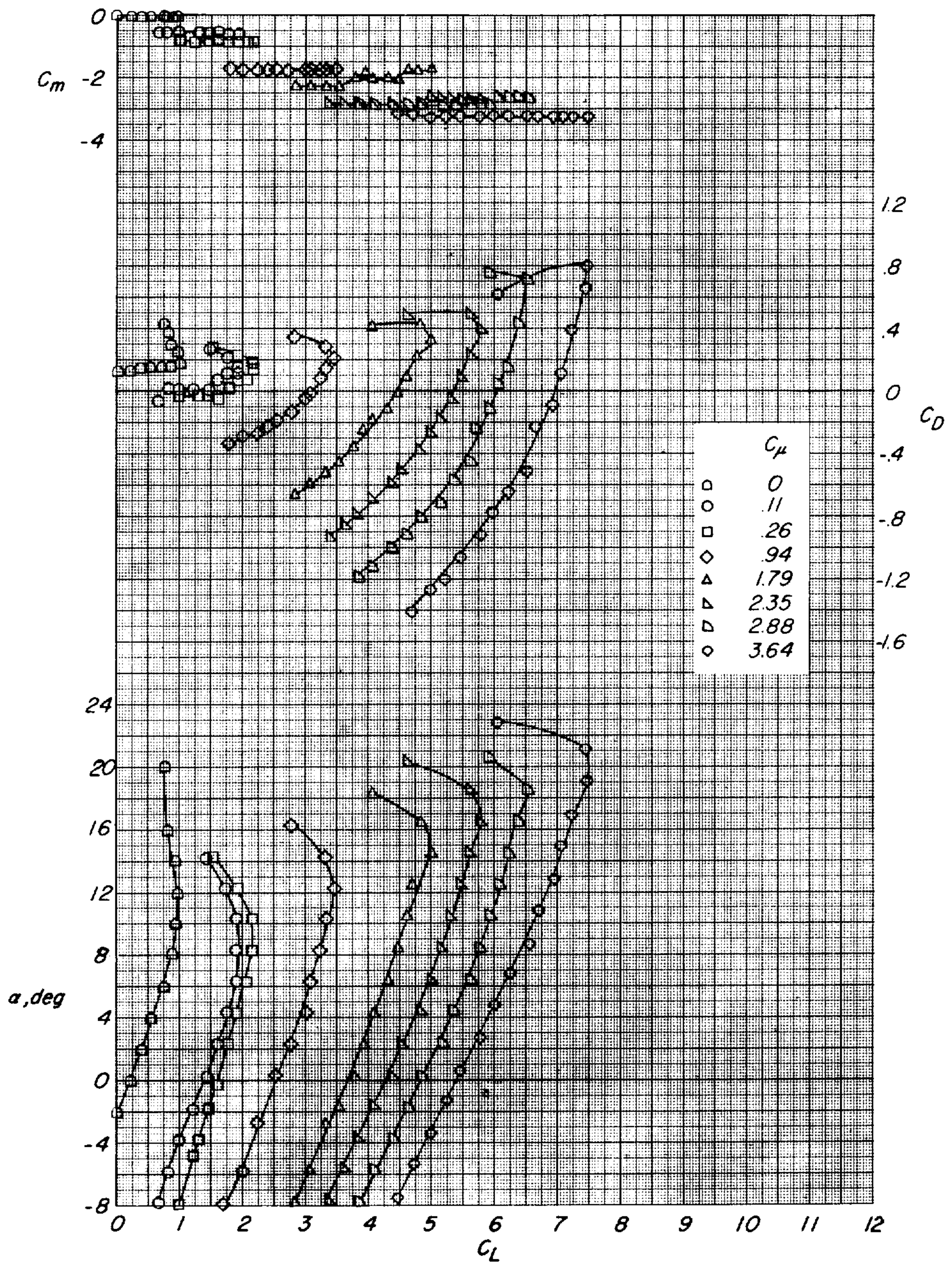


Figure 1.- Details of the jet-augmented flap arrangement investigated on a rectangular wing with an aspect ratio of 8.3 and a thickness-chord ratio of 0.167.



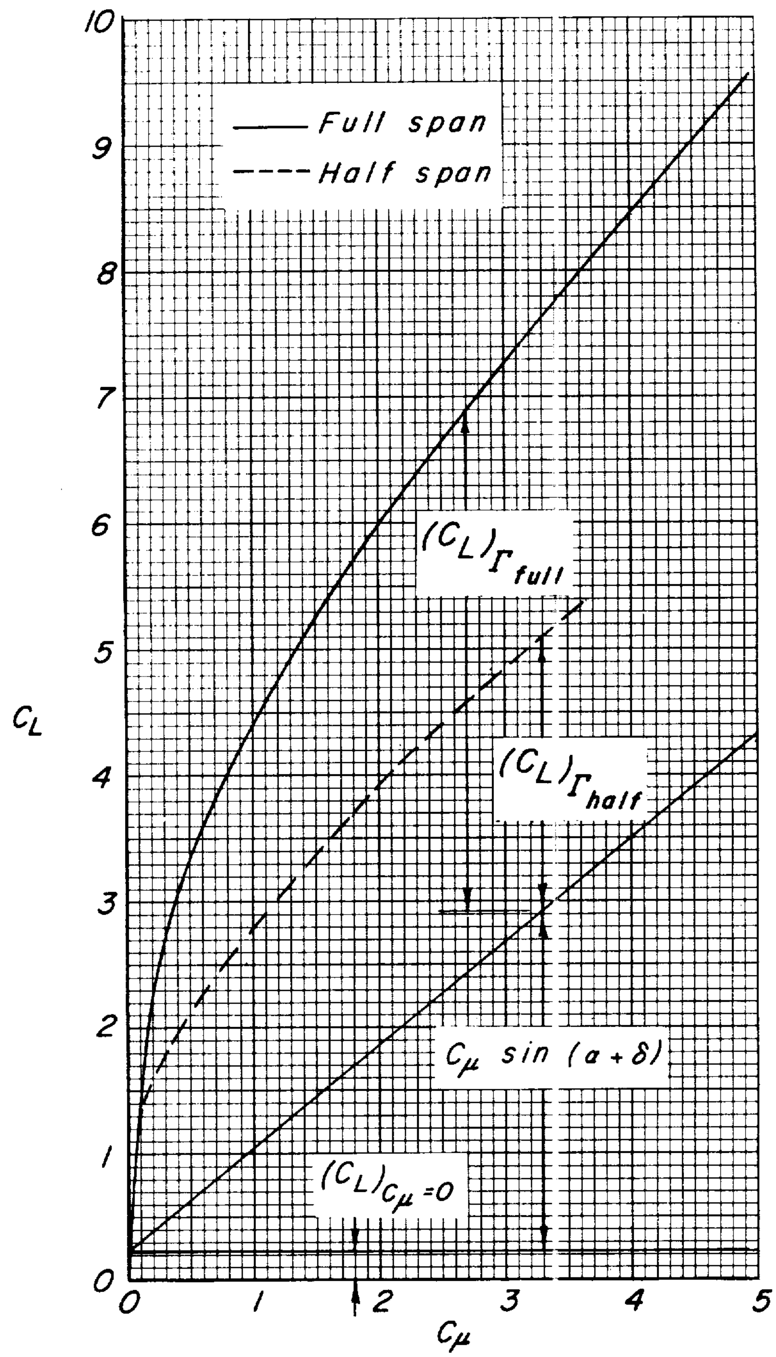
(a) Full-span blowing.

Figure 2.- Aerodynamic characteristics in pitch at various momentum coefficients for a rectangular wing with an aspect ratio of 8.3 and a thickness-chord ratio of 0.167 equipped with a jet-augmented flap deflected 55°.



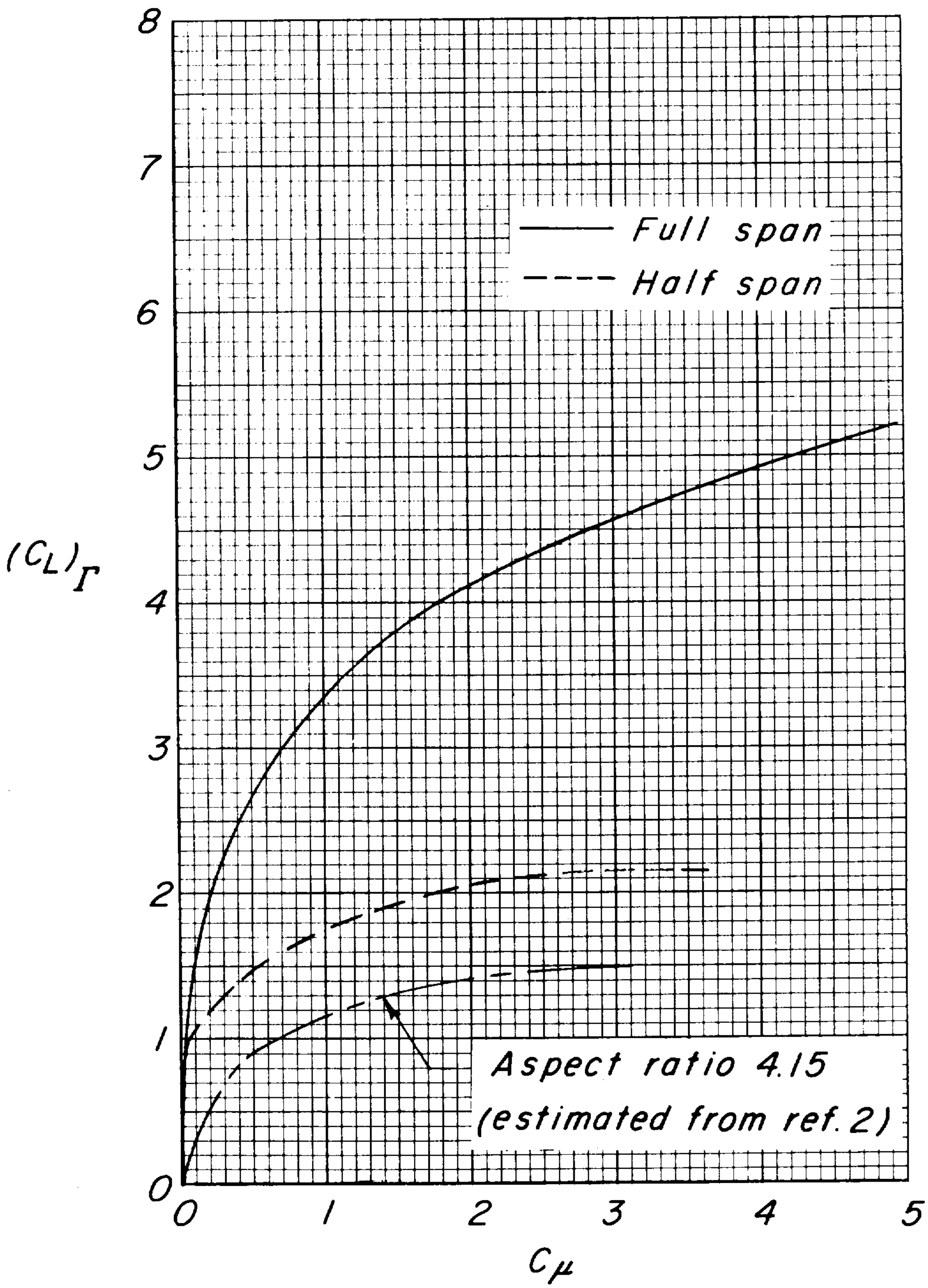
(b) Half-span blowing.

Figure 2.- Concluded.



(a) Variation of C_L with C_μ.

Figure 3.- Lift characteristics as a function of momentum coefficient for the jet-augmented flap configurations at $\alpha = 0^\circ$.



(b) Variation of $(C_L)_\Gamma$ with C_μ.

Figure 3.- Concluded.

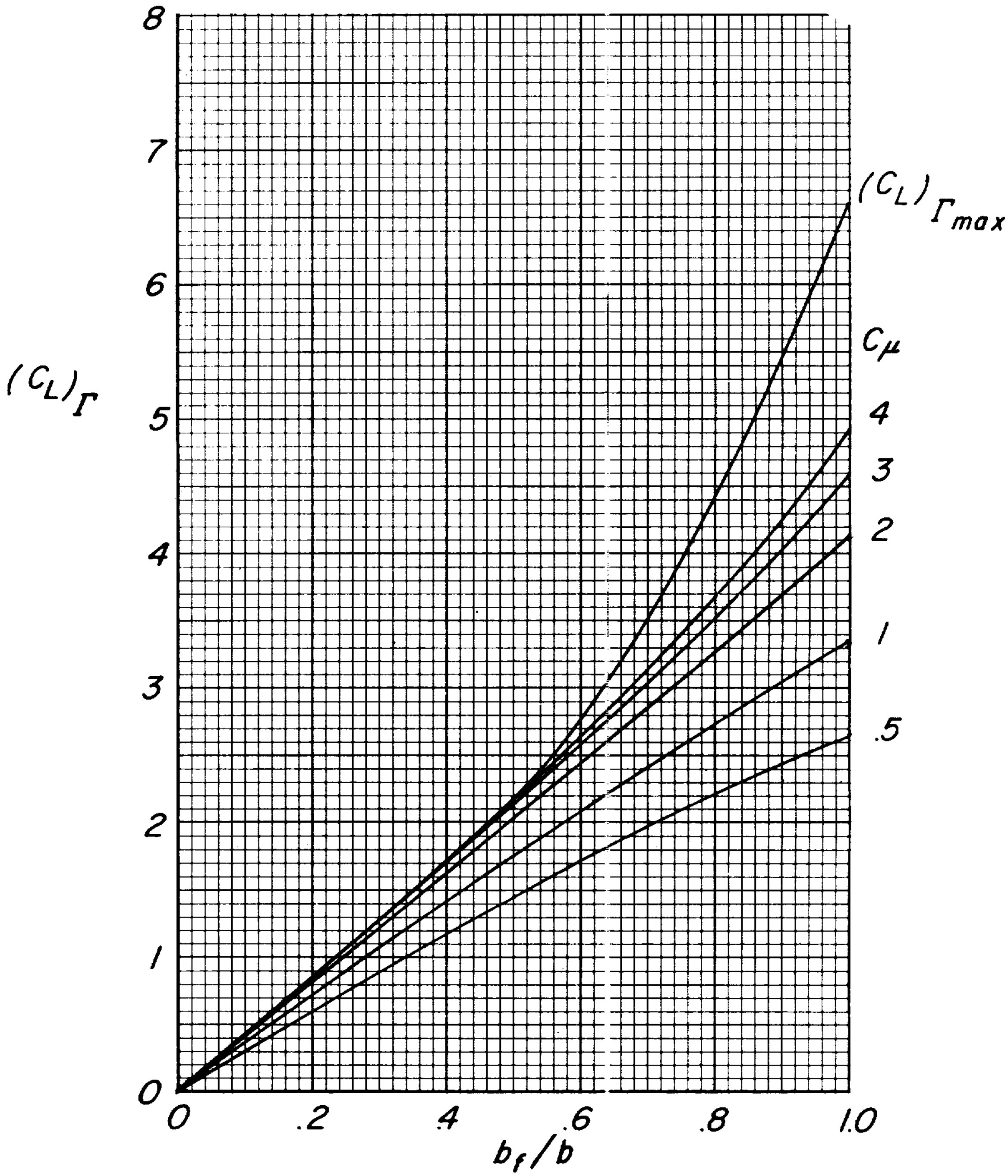


Figure 4.- Chart for estimating the jet-circulation lift coefficient of wings with partial-span jet-augmented flaps.

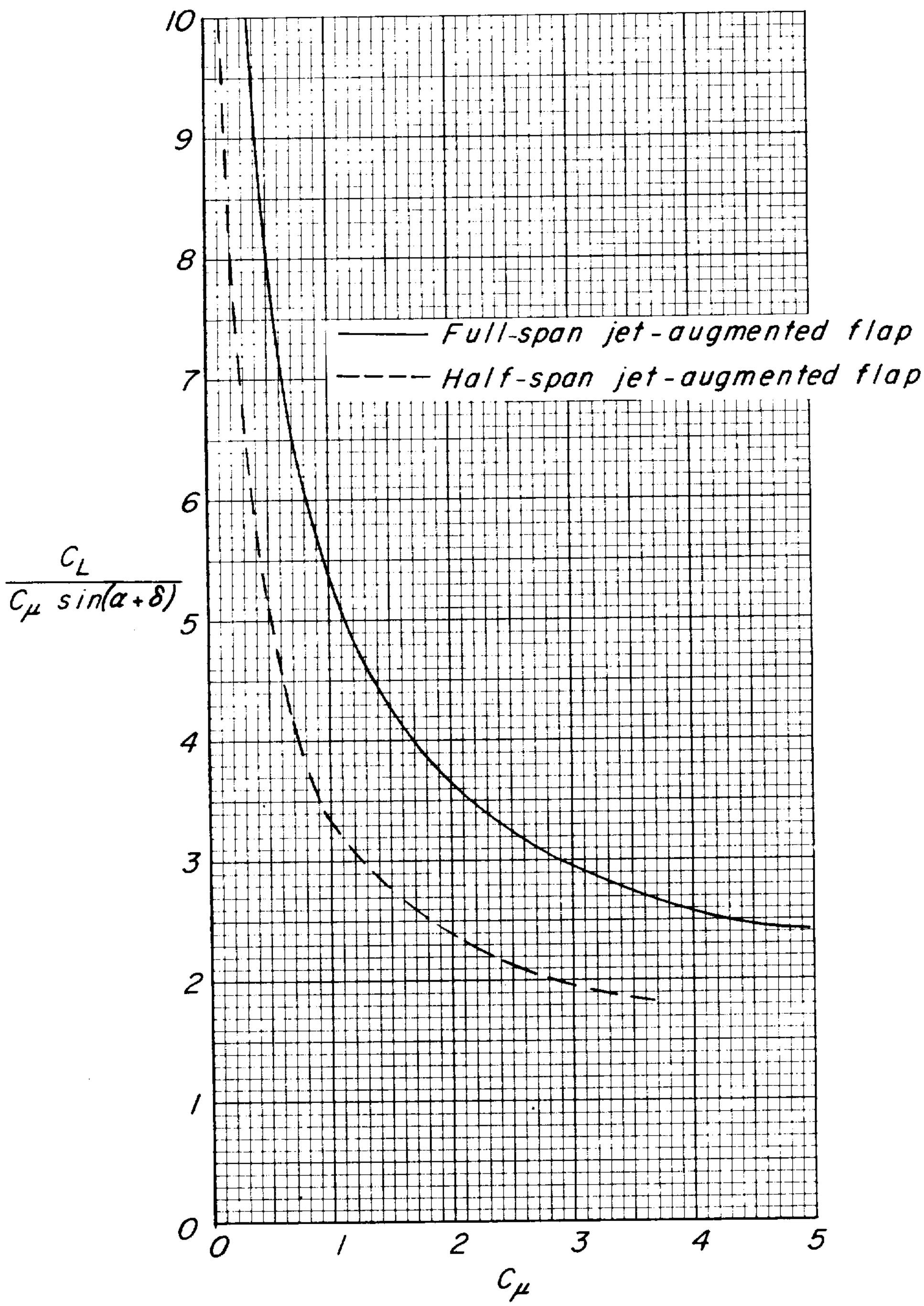


Figure 5.- Variation of the magnification factor $\dfrac{C_L}{C_\mu \sin(\alpha + \delta)}$ with momentum coefficient. $\alpha = 0^\circ$; $\delta = 55^\circ$.

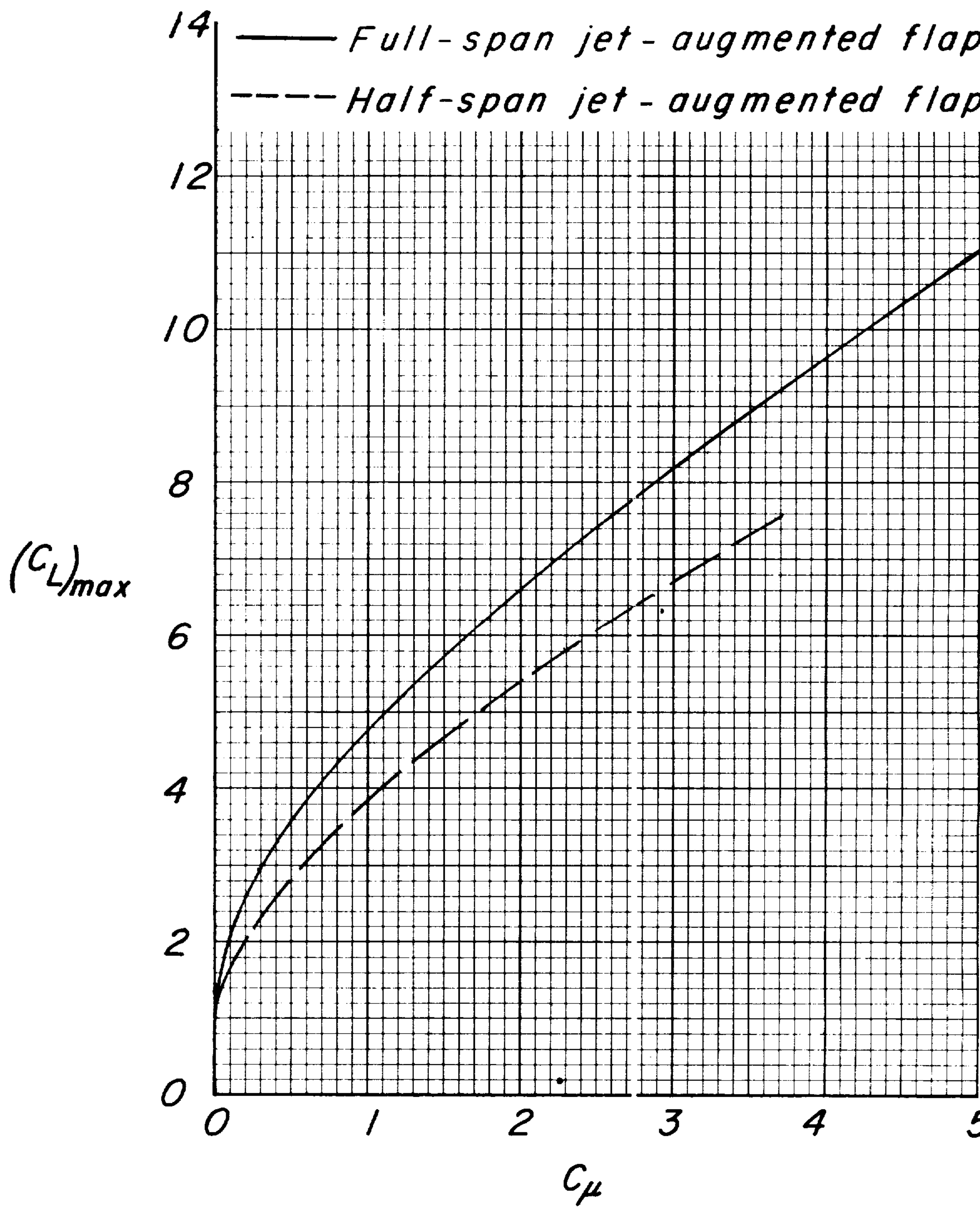


Figure 6.- Variation of maximum lift coefficient with momentum coefficient for the full-span and half-span jet-augmented flap configurations.

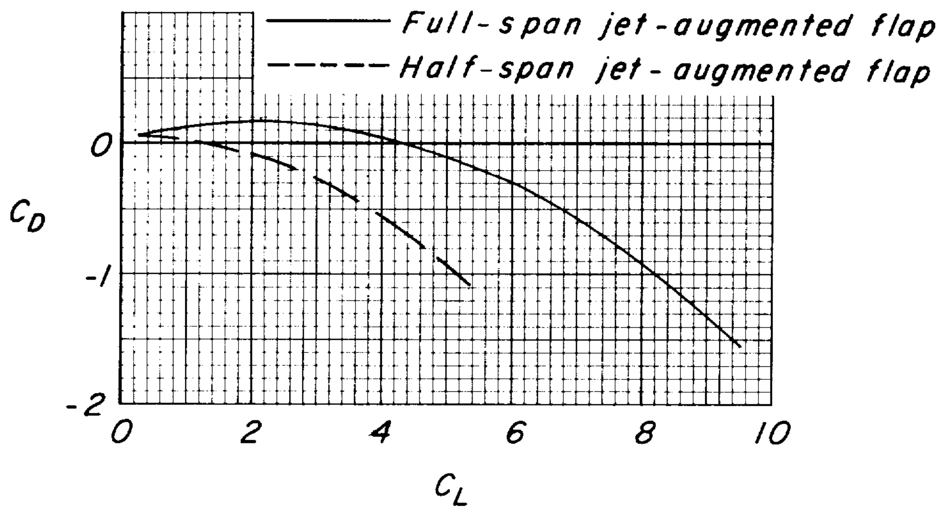


Figure 7.- Effect of flap span on the variation of drag coefficient with lift coefficient at $\alpha = 0^{\circ}$.

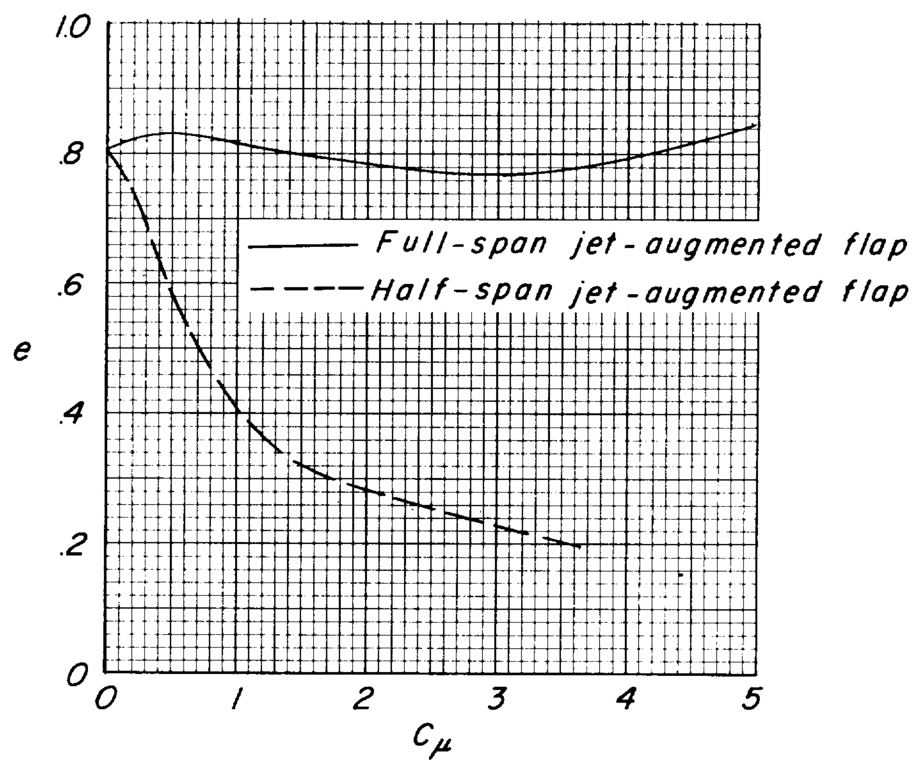
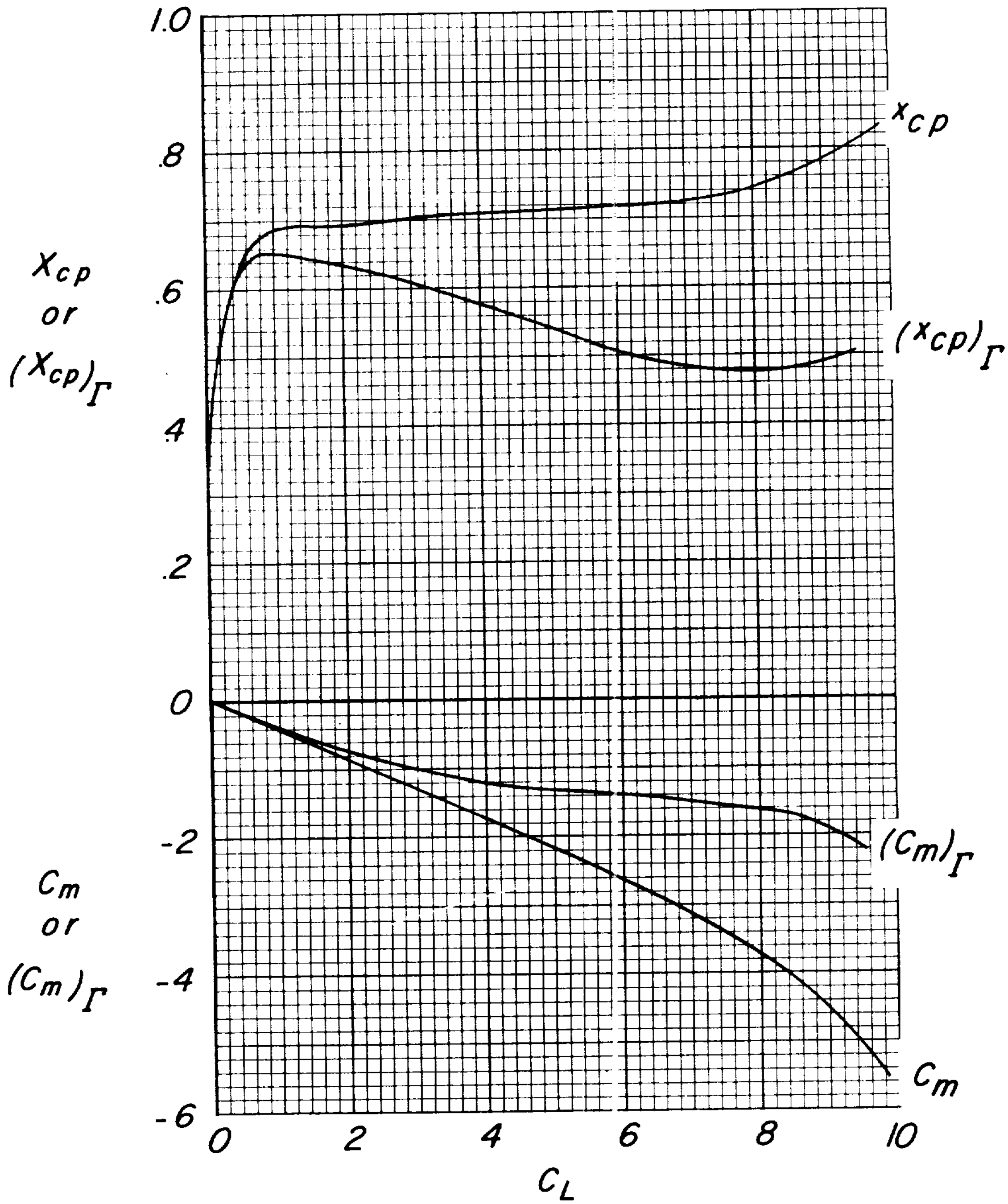
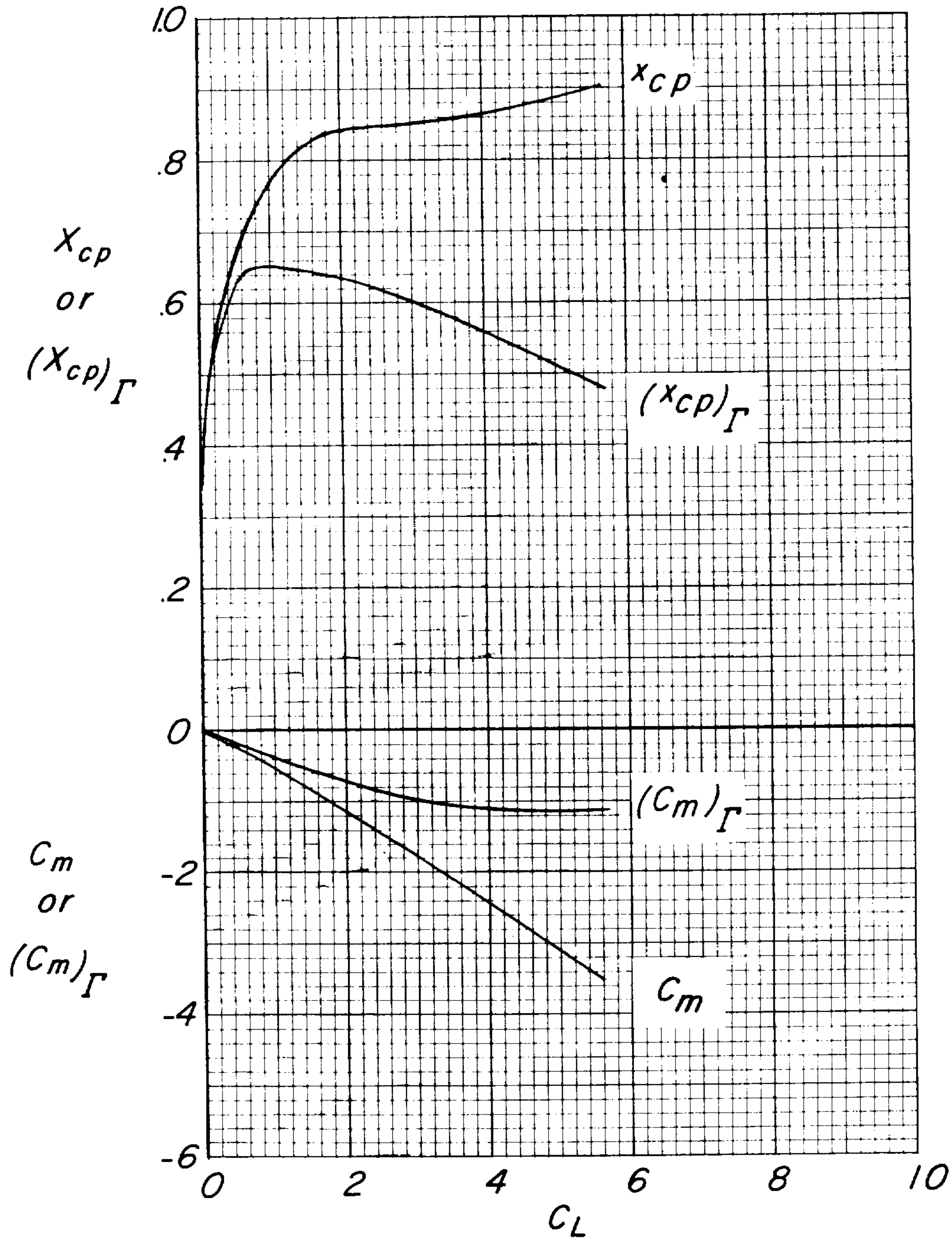


Figure 8.- Variation with momentum coefficient of the wing efficiency factor e of the induced-drag equation.



(a) Full-span jet-augmented flap.

Figure 9.- Variation of pitching-moment coefficient and center of pressure with lift coefficient for a momentum coefficient range from 0 to about 5 at $\alpha = 0^{\circ}$.



(b) Half-span jet-augmented flap.

Figure 9.- Concluded.