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TWO-DIMENSIONAL SUBSONIC WIND TUNNEL  
EVALUATION OF A 20-PERCENT-THICK  
CIRCULATION CONTROL AIRFOIL

Jane Abramson

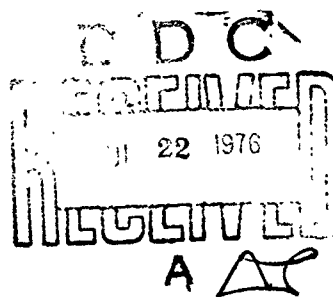
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## ABSTRACT

A circulation control uncambered elliptic airfoil section with a thickness-to-chord ratio of 0.20 was tested subsonically to determine its aerodynamic characteristics. Lift coefficients up to 5 were produced at momentum coefficients of 0.24. The initially high unblown drag coefficients, characteristic of bluff trailing edge airfoils, were greatly reduced at low values of momentum coefficient. It was therefore possible to produce equivalent lift-to-drag ratios in excess of 30 when  $C_L = 1.0$ . The ability to produce high lift coefficients essentially independent of angle of attack is indicated by the results of this investigation.

## INTRODUCTION

Tangential blowing over the bluff trailing edge of a 20-percent uncambered ellipse was investigated experimentally. This configuration is one of a continuing series of two-dimensional circulation control airfoil sections<sup>1-5</sup> which employ the Coanda effect to obtain high lift augmentation by tangentially ejecting a sheet of air near the trailing edge on the upper surface. Because of the Coanda effect, the jet sheet remains attached to the rounded trailing edge and provides a mechanism for boundary layer control. The blowing can be thought of as a movement of the effective aft stagnation point thereby producing an increase in circulation. For further discussion of this circulation control concept and its potential applications, the reader is referred to other studies in the series.<sup>6-10</sup>

The results of this investigation are being used to ascertain the effects of camber on the aerodynamic characteristics of a two-dimensional circulation control airfoil section by comparing the data in this report to that presented earlier by Williams and Howe.<sup>1</sup> Wind tunnel data were generated during July 1974.

## MODEL AND TEST APPARATUS

The fiberglass model is a modification of one previously tested<sup>4</sup> and is based on an analytical ellipse with an 8-inch major axis (chord) and a 20-percent thickness-to-chord ratio. The rounding of the trailing edge to produce a 0.31-inch radius reduced the chord to 7.908 inches. An upper surface tangential slot consisting of a knife-edged steel blade was placed at the 97-percent chord position. The slot exit was the throat of a converging nozzle whose height was adjustable through the use of pitch screws. An undercut was made on the blade in the vicinity of the slot to ensure that flow would exit tangentially to the model surface (see Figure 1). High pressure internal plenum chambers and flow fences were also incorporated into the model. Tables 1 and 2 give coordinates for the model.

The two-dimensional tests were conducted in the 15 x 20 inch subsonic tunnel with a vented test section and plexiglass walls. The plexiglass permits flow visualization by means of tufts and oil day-glo pigment solution. The model was pressure tapped as shown in Table 2. Lift and pitching moment coefficients were obtained by numerical integration of pressure tap readings as recorded on a multiple-port scanivalve readout system. These coefficients were corrected by the addition of jet reaction components. Standard solid blockage corrections<sup>11</sup> were applied to the measured freestream dynamic pressure; no wake blockage factor was used because of the uncertain effects of the jet.

Drag measurements were made by using a drag rake placed 1.5 chord lengths downstream of the model inclined at 15 degrees to the freestream. The rake employs 54 total and 8 static pressure tubes, with the heaviest concentration of tubes near the center height. The momentum deficit methods of Betz and Jones<sup>12</sup> were then used to determine the drag coefficient. An addition of  $\dot{m}V_{\infty}/q_{\infty}S$  was then made to the drag coefficient to account for the additional jet momentum.

Past practice has been to employ separate plenums with high pressure air sources at the junction of the model and tunnel wall to prevent wall boundary layer separation. Although the present model was equipped with such plenums, it was decided after careful analysis of preliminary data

that they would not be used because of damage previously sustained by the model. A series of model spanwise taps located near the trailing edge was utilized to record the lateral pressure distribution which was carefully monitored during the test run as an indication of two-dimensionality. The corrections to the resulting data using potential flow will be discussed later in the report.

Mass flow rate ( $\dot{m}$ ) was measured by a calibrated orifice plate inserted in the supply line. To ensure high accuracy for low mass flow data, a second orifice plate with the appropriate calibration range was used for the lower values of  $C_\mu$ . The jet velocity was calculated by assuming isentropic expansion from duct stagnation pressure to the freestream static pressure as follows:

$$V_j = a_j M_j = (\gamma R T_j)^{1/2} M_j = \left[ 2 R T_t \left( \frac{\gamma}{\gamma-1} \right) \left[ 1 - \left( \frac{P_\infty}{P_t} \right)^{\frac{\gamma-1}{\gamma}} \right] \right]^{1/2}$$

The momentum coefficient was then defined as  $C_\mu = (\dot{m} V_j / q_\infty S)$ . The limiting value of  $C_\mu$  was determined by consideration of the maximum safe internal plenum pressure for this particular model and/or that pressure which would result in jet impingement on the tunnel floor. Such impingement could cause separation of the floor boundary layer as well as inaccuracies in the drag rake data.

A series of runs was made at freestream dynamic pressures from 10 to 30 psf (Figure 2) corresponding to a model Reynolds number range from  $2.4 \times 10^5$  to  $4.2 \times 10^5$ . No significant effect of Re on the data was noted and  $q_\infty = 20$  psf was chosen to allow for a wider range of  $C_\mu$ .

## RESULTS AND DISCUSSION

The characteristics of the 20-percent uncambered ellipse were evaluated for a single slot height of 0.01 inch (slot height/chord = 0.00126), momentum coefficient  $C_\mu$  ranging from 0 to 0.26, and angles of attack  $\alpha$  ranging from -20 to 8 degrees. Figure 3 depicts the variation of momentum coefficient with duct pressure for the test dynamic pressure of 20 psf.

The expansion of the slot caused by the pressurization of the duct is shown in Figure 4. These data were obtained by pressurizing the duct and measuring the resulting slot height with a thickness gage under quiescent tunnel conditions.

#### LIFT

Figures 5 and 6 show the sectional lift coefficients determined by integration of the midspan taps. Figure 5, which is an expanded scale plot including closely spaced low momentum coefficient data, revealed the possible existence of a discontinuity in the lift slope. The density of data points taken in previous investigations of circulation control two-dimensional models has been such that detection of a discontinuity in the lift curve slope ( $dC_l/dC_\mu$ ) would be unlikely. However, a change in the slope was reported by Englar<sup>3</sup>. Oil flow studies performed during the evaluation of this model indicated that the flow ahead of the slot was separated under conditions of no blowing ( $C_\mu = 0$ ). This discontinuity may correspond to the level of blowing required for flow attachment to occur at the slot position. Therefore, the existence of such a discontinuity would depend on the chordwise location of the slot in relation to the flow separation point with no blowing; the possible dependency on Reynolds number was not investigated at this time.

An examination of Figure 6 shows that  $C_l$  continually increased with increasing  $C_\mu$ , indicating that " $C_\mu$  stall" had not yet been reached, and it appeared that the lift coefficient could have been increased still further with increased blowing.

Another characteristic evident from Figure 6 was a tendency of the lift curve to "lie over" for  $C_\mu > 0.08$ , resulting in a smaller lift coefficient than anticipated in view of results reported by Englar<sup>1,2</sup>. Additionally a deviation from the expected lift curve was experienced at  $\alpha = +8$  and  $+5$  degrees. This phenomenon was particularly pronounced at  $\alpha = 8$  degrees and has been noted previously<sup>3</sup>; however in this case a return to predicted values was never obtained. This behavior is apparently due to the aft separation experienced on this model.

Further insight may be gained by examining Figure 7 which presents the augmentation ratio as a function of momentum coefficient. The augmentation ratio is defined as  $\Delta C_l / C_{\mu}$ , where  $C_l$  is the increase in lift coefficient above the unblown value for a given value of  $C_{\mu}$  and incidence. A significant loss of augmentation is apparent at  $\alpha = +8$  degrees and to a lesser extent at  $\alpha = +5$  degrees; this affirms the deviation from the expected lift curve slope noted previously in Figure 6. In general the augmentation at higher values of momentum coefficient fall off faster than with previous models. It should be noted at this point that data for  $\alpha = 20$  degrees were deliberately omitted; the recording of accurate unblown data was not possible and therefore a computation of augmentation ratio could not be made.

With few minor exceptions, an examination of  $C_p$  plots revealed no evidence of leading edge separation bubbles although minor, local upper and lower surface trailing edge separations were common. At large negative angles of attack ( $\alpha = -20$  degrees), the lower surface was initially completely separated, but reattachment occurred with increased blowing due to the movement of the leading edge stagnation point to the lower surface. As the jet velocity was increased still further, the lower surface again showed areas of separation in the vicinity of the trailing edge.

The variation of lift coefficient with geometric angle of attack is presented in Figure 8. The slopes of the curves were similar for unstalled flow conditions. Agreement between the theoretical lift curve and experimental results was good for conditions of no blowing.

To complete the discussion of the lift characteristics of the 20-percent ellipse, consideration of effects induced by spanwise nonuniformity is required. The suggested use of flow fences and tip jets (see Englar<sup>3</sup> and Englar and Williams<sup>8</sup>) was not possible in this case for reasons previously discussed, and therefore a determination of the effective angle of incidence was made. For the experimental cases selected, potential flow pressure distributions for several incidences and an adjusted  $C_l$  were produced. The adjustment to the lift coefficient required that the increment of lift due to the jet suction peak be determined and subtracted from the experimental lift coefficient. Since this increment would not be

theoretically predicted, these distributions were then compared to the experimental pressure distribution until the leading edge stagnation point coincided. A resulting experimental-potential flow match is shown in Figure 9. The agreement was good except for the additional jet suction peak and minor lower surface separation (both not predictable with the use of potential flow). The effective angle of incidence for the experimental data is depicted in Figure 10.

The value of the minimum pressure on the airfoil as a function of lift coefficient is presented in Figures 11 and 12. These data are mainly intended for marine applications of circulation control systems, where cavitation is a function of minimum pressure. Figure 12 is the result of the low-blowing, small alpha test series which would be most appropriate for the above-mentioned application.

#### DRAG

Figures 13 and 14 indicate the variation of a modified drag coefficient with momentum coefficient. These data result from an integration of the wake deficit using the methods of Jones and Betz<sup>12</sup> which were then modified to account for the additional momentum of the jet, thereby becoming  $C_d = C_{d_{rake}} - (\dot{m}V_\infty/qS)$ . Both figures indicate a high initial drag at all alphas primarily because of the nature of bluff trailing edge airfoils. The highest initial drag was at  $\alpha = -20$  degrees; visually monitoring by manometer tubes indicated that the wake was extending over the entire rake before a no-blowing condition could be reached, and this was attributed to extensive separation on the lower surface. The secondary rise in the drag curve at both  $\alpha = -15$  and  $-20$  degrees at  $C_\mu \leq 0.2$  was again the result of lower aft separation after reattachment had occurred.

The initial variation of drag with trailing edge blowing can be more easily observed in Figure 13. An initial decrease in drag was immediately noted whenever  $\alpha \leq 0$  an initially flat drag distribution was evident for  $\alpha = +8$  or  $+5$  degrees. This was also evident to a lesser extent at  $\alpha = +3$  degrees where the initial decrease in drag was less than at any nonpositive alpha. For  $\alpha = 8$  and  $5$  degrees, this region was found to correspond to

the deficit in the lift curve slope previously discussed. Significant thrust recovery was noted in Figure 14 for most alphas, as evidenced by the decreasing drag coefficients.

#### PITCHING MOMENT

Figure 15 depicts pitching moment about the midchord ( $C_{m_{50}}$ ). As was the case with previous circulation control sections, a negative pitching moment was produced by the relatively high trailing edge suction peaks. The only notable exceptions were at  $\alpha = -15$  and  $-20$  degrees for  $C_\mu \geq 0.134$ . In both those cases, there were large regions of separation on the lower surface of the trailing edge. The resulting region of low pressure reduced the negative pitching moment somewhat.

#### EQUIVALENT LIFT-DRAG RATIO

Comparison of data taken with and without blowing can best be made when account is taken of the energy expended to produce blowing. Figure 16 presents the lift-to-equivalent-drag ratio as a function of lift coefficient; the equivalent drag is defined here as:

$$d_e = d + \frac{\dot{m} V_j^2}{2V_\infty} + \dot{m} V_\infty$$

The first term  $d$  is the momentum deficit as measured by the drag rake (corrected for jet efflux), the second term is the kinetic energy flux, and the third is an intake momentum flux. Thus in coefficient form:

$$\frac{l}{d_e} = \frac{C_l}{C_d + C_\mu \frac{V_j}{2V_\infty} + C_\mu \frac{V_\infty}{V_j}}$$

A more comprehensive derivation of the above may be found in Englar<sup>3</sup>.

The highest value for  $l/d_e$  occurred at very low blowing and the maximum value was approximately 40, despite the relatively high lift coefficients. Since the measured value of drag was low throughout a great portion of the experimental test range, the results show the importance of "blowing power" ( $C_\mu V_j/2V_\infty$ ) in the expression for equivalent drag. Thus to obtain high

values for  $l/d_e$  it becomes necessary to produce high lift coefficients at relatively low values of the blowing coefficients.

### CONCLUSIONS

The 20-percent thick circulation control ellipse was evaluated in a subsonic wind tunnel to provide continuing information on a new family of airfoils. The following conclusions were drawn from an examination of the subsonic data:

1. Despite the fact that augmentation ratios were generally lower than obtained in previous test of circulation control airfoils, section lift coefficients of 5.0 were generated for  $C_\mu = 0.24$  at an angle of attack of 3 degrees. A lift coefficient of 2 was generated by the section at  $\alpha = -20$  degrees.

2. Augmentation ratios in excess of 75 (see Figure 7) were produced at low blowing rates for negative angles of incidence.

3. At  $C_\ell = 1.0$ , lift-to-equivalent-drag ratios of over 30 were generated.

4. In most cases initiation of blowing reduced the high unblown drag coefficient. In those cases where the value of the drag coefficient remained unchanged until a substantial level of blowing was reached, a low initial lift slope ( $dC_\ell/dC_\mu$ ) was also indicated.

5. The presence of a possible discontinuity in the lift curve slope ( $dC_\ell/dC_\mu$ ) may correspond to the movement of the separation point to a position aft of the slot location.

## REFERENCES

1. Williams, R. M. and H. J. Howe, "Two-Dimensional Subsonic Wind Tunnel Tests on a 20-Percent Thick, 5-Percent Cambered Circulation Control Airfoil," NSRDC Technical Note AL-176 (AD 877-764) (Aug 1970).
2. Englar, R. J., "Two-Dimensional Subsonic Wind Tunnel Tests of Two 15-Percent Thick Circulation Control Airfoils," NSRDC Technical Note AL-211 (Aug 1971).
3. Englar, R. J., "Two-Dimensional Subsonic Wind Tunnel Tests of a Cambered 30-Percent Thick Circulation Control Airfoil," NSRDC Technical Note AL-201 (May 1972).
4. Williams, R. M., "Some Research on Rotor Circulation Control," Proceedings, Third CAL/AVLABS Symposium, Aerodynamics of Rotary Wing and V/STOL Aircraft, Vol. 2, Buffalo, New York (Jun 1969).
5. Englar, R. J., "Two-Dimensional Transonic Wind Tunnel Tests of Three 15-Percent Thick Circulation Control Airfoils," NSRDC Technical Note AL-182 (Dec 1970).
6. Williams, R. M. and E. O. Rogers, "Design Considerations of Circulation Control Rotors," 28th Annual National Forum of the American Helicopter Society, Washington, D.C. (May 1972; (Available as Preprint 603).
7. Englar, R. J. and R. M. Williams, "Design of a Circulation Control Stern Plane for Submarine Applications," NSRDC Technical Note AL-200 (Mar 1971).
8. Englar, R. J. and R. M. Williams, "Test Techniques for High Lift Two-Dimensional Airfoils with Boundary Layer and Circulation Control for Application to Rotary Wing Aircraft," Canadian Aeronautics and Space Journal, Vol. 19, No. 3 (Mar 1973).
9. Englar, R. J., "Subsonic Wind Tunnel Investigation of the High Lift Capability of a Circulation Control Wing on a 1/5-Scale T-2C Aircraft Model," NSRDC Technical Note AL-299 (May 1973).

10. Wilkerson, J. B., "Design and Performance Analysis of Prototype Circulation Control Helicopter Rotor," NSRDC Technical Note AL-290 (Mar 1973).
11. Pope, Alan, "Wing-Tunnel Testing," Second Edition, John Wiley & Sons, Inc., New York, (1964), pp. 307-311.
12. Schlichting, Hermann, "Boundary Layer Theory," Sixth Edition, McGraw-Hill Book Company, New York (1968), pp. 708-713.

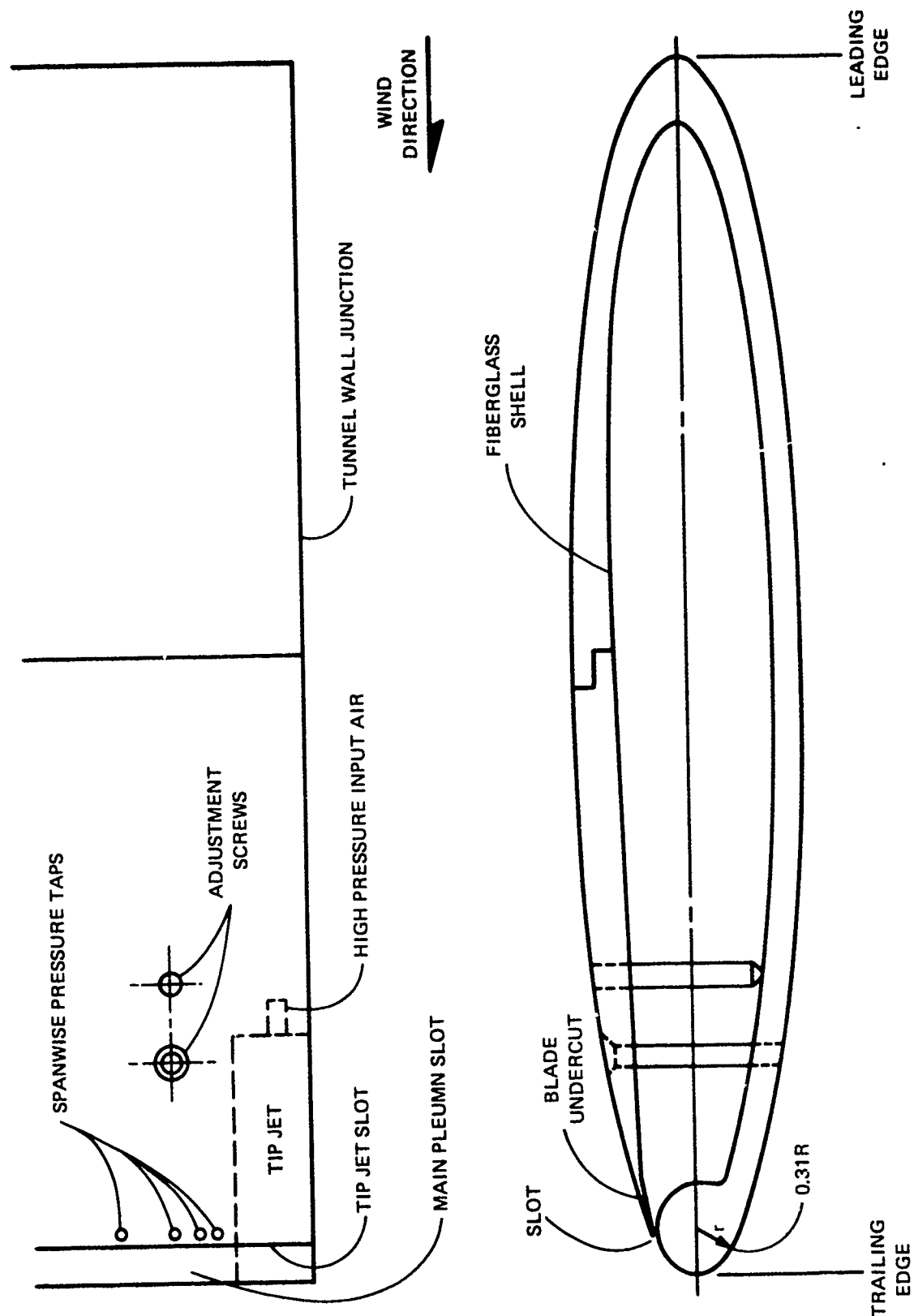


Figure 1 — Subsonic Two-Dimensional Model Geometry

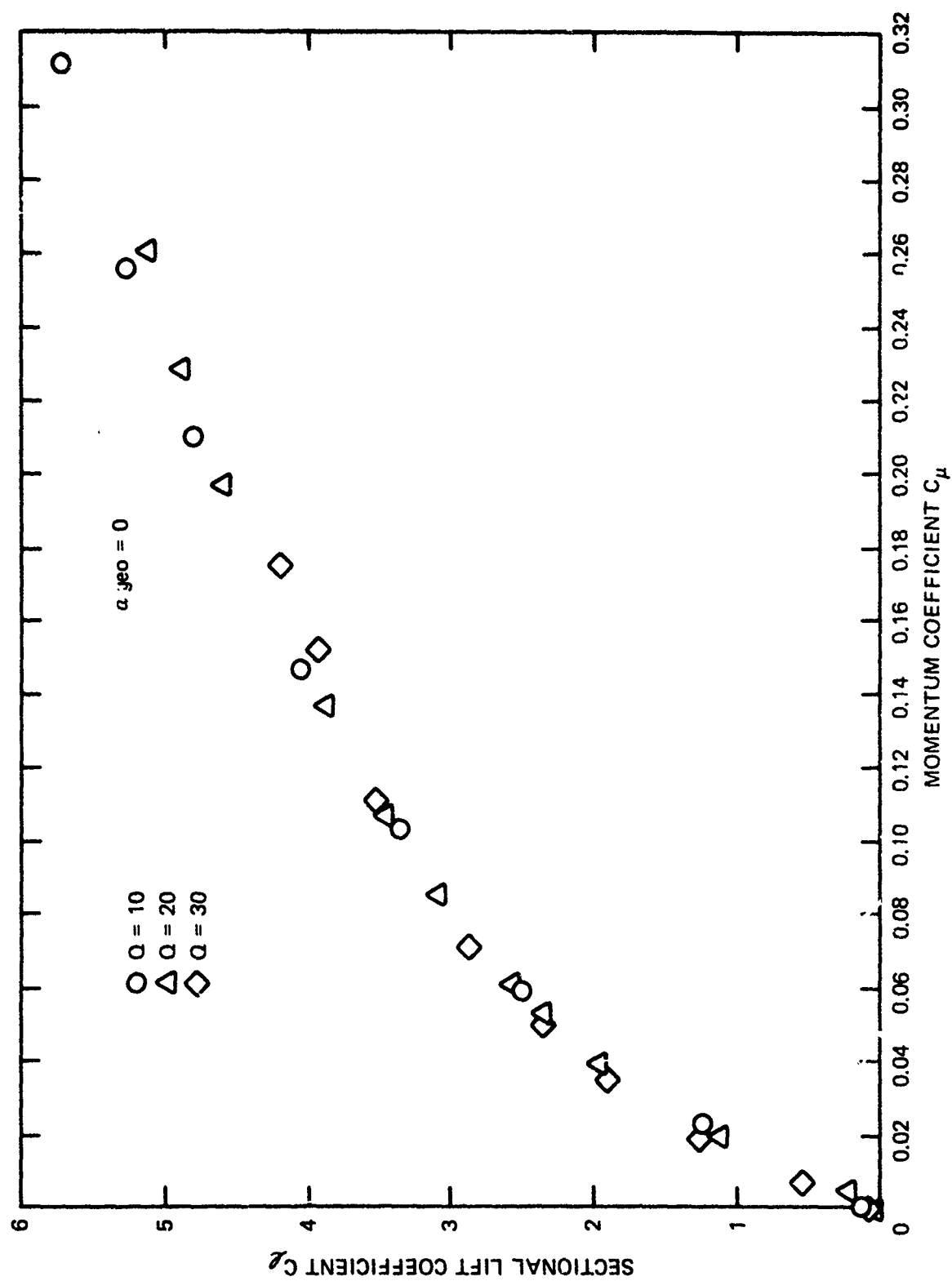


Figure 2 -- Lift Variation with Dynamic Pressure

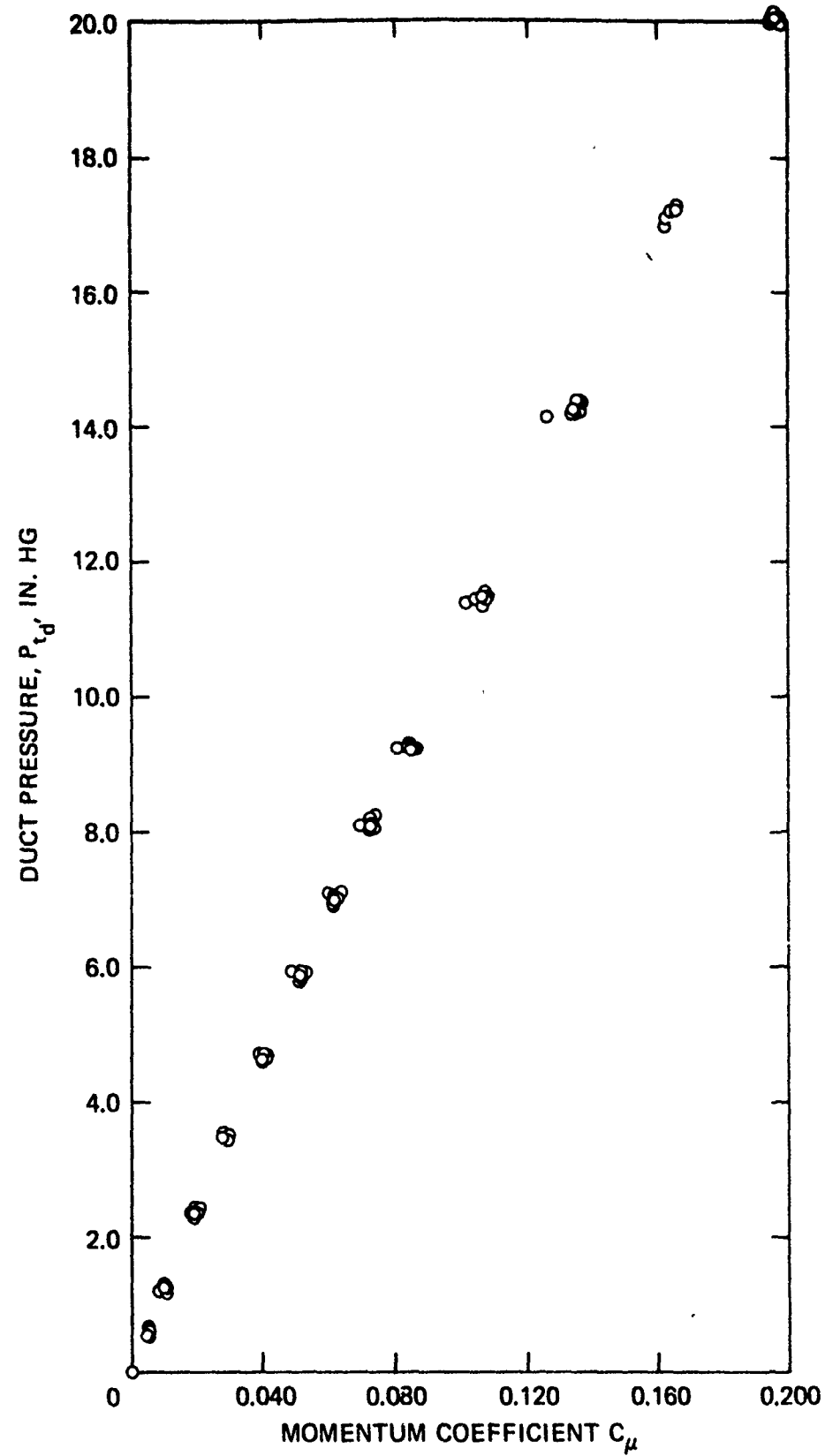


Figure 3 - Experimentation Variation of Momentum Coefficient with Duct Pressure

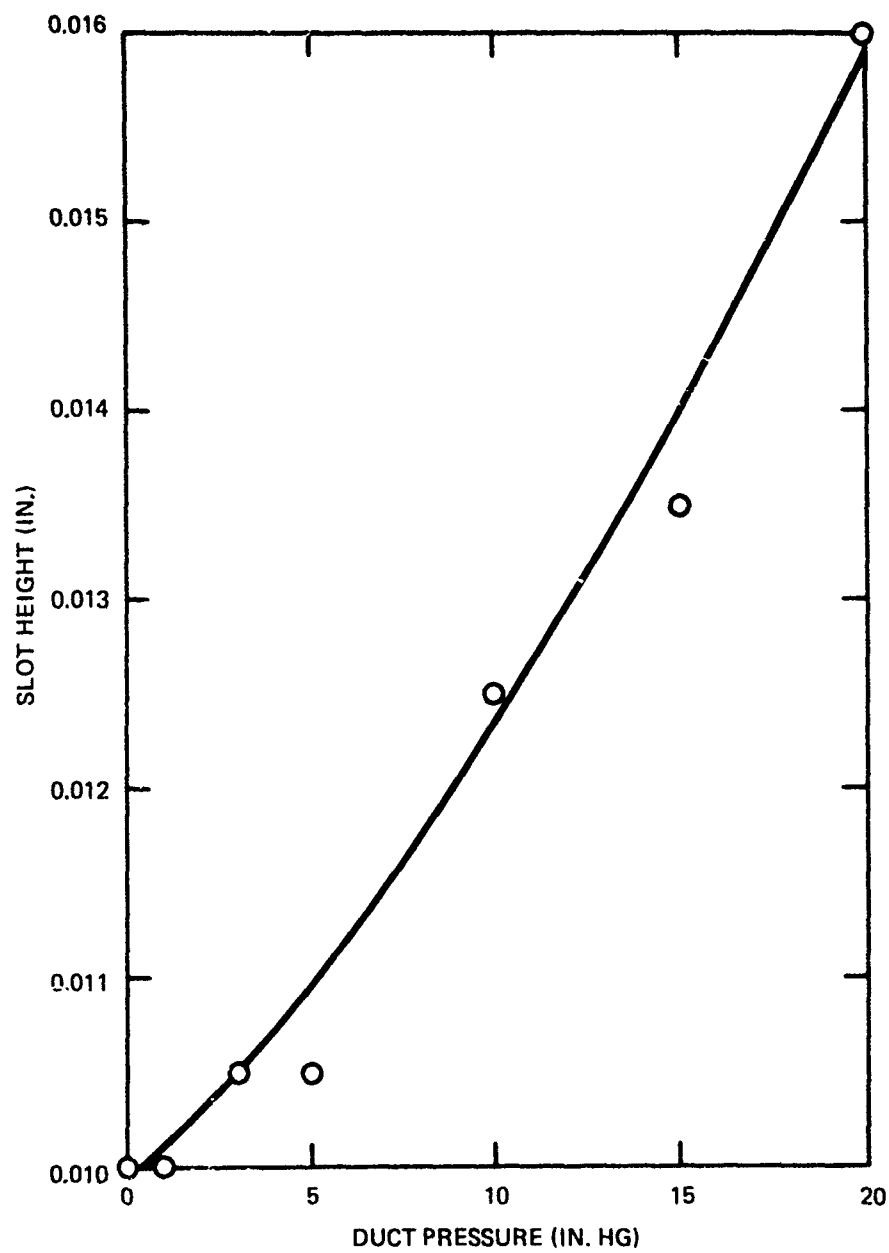


Figure 4 - Variation of Slot Height with Duct Pressure

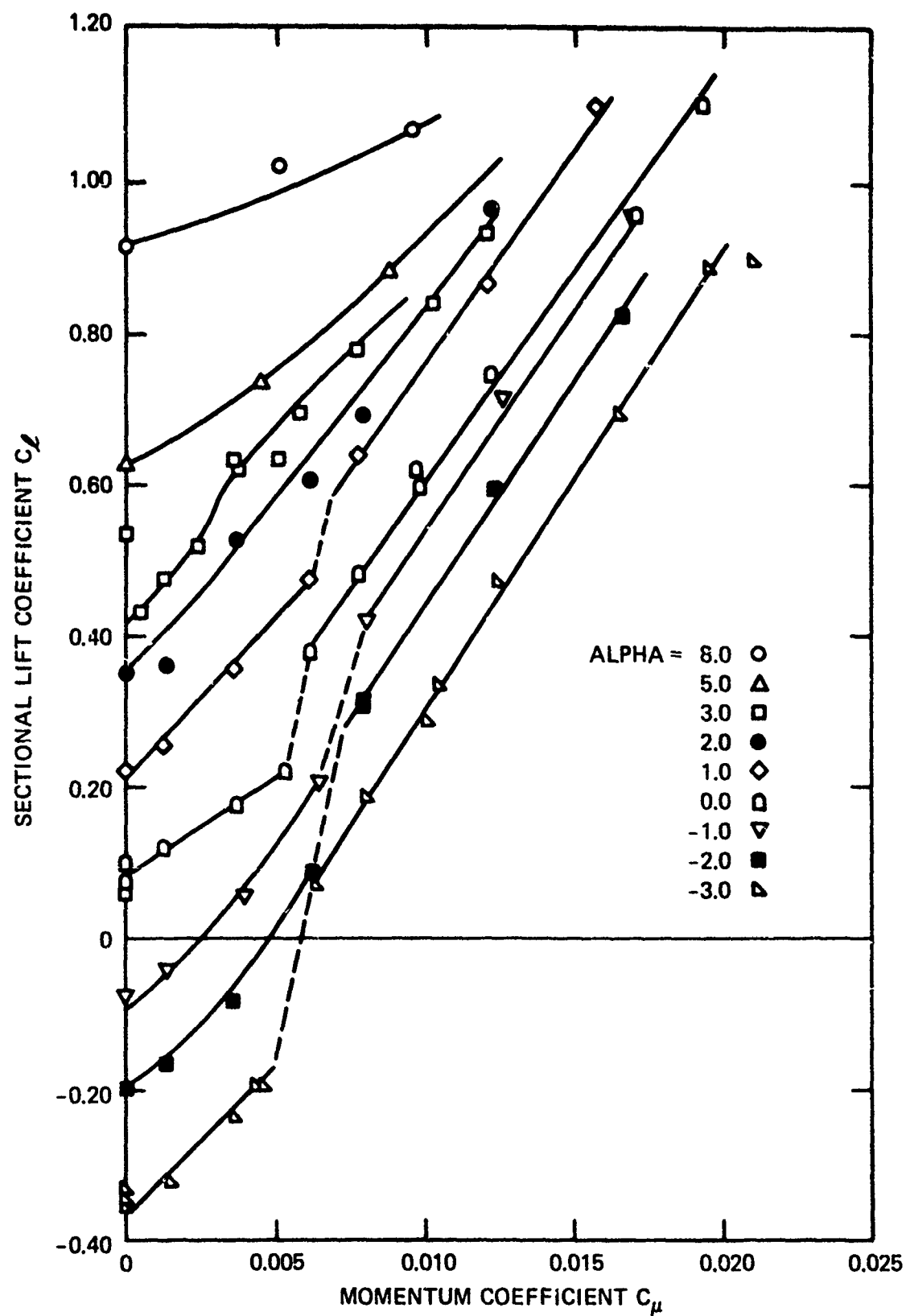


Figure 5 -- Lift Variation with Momentum Coefficient  
(Expanded Scale)

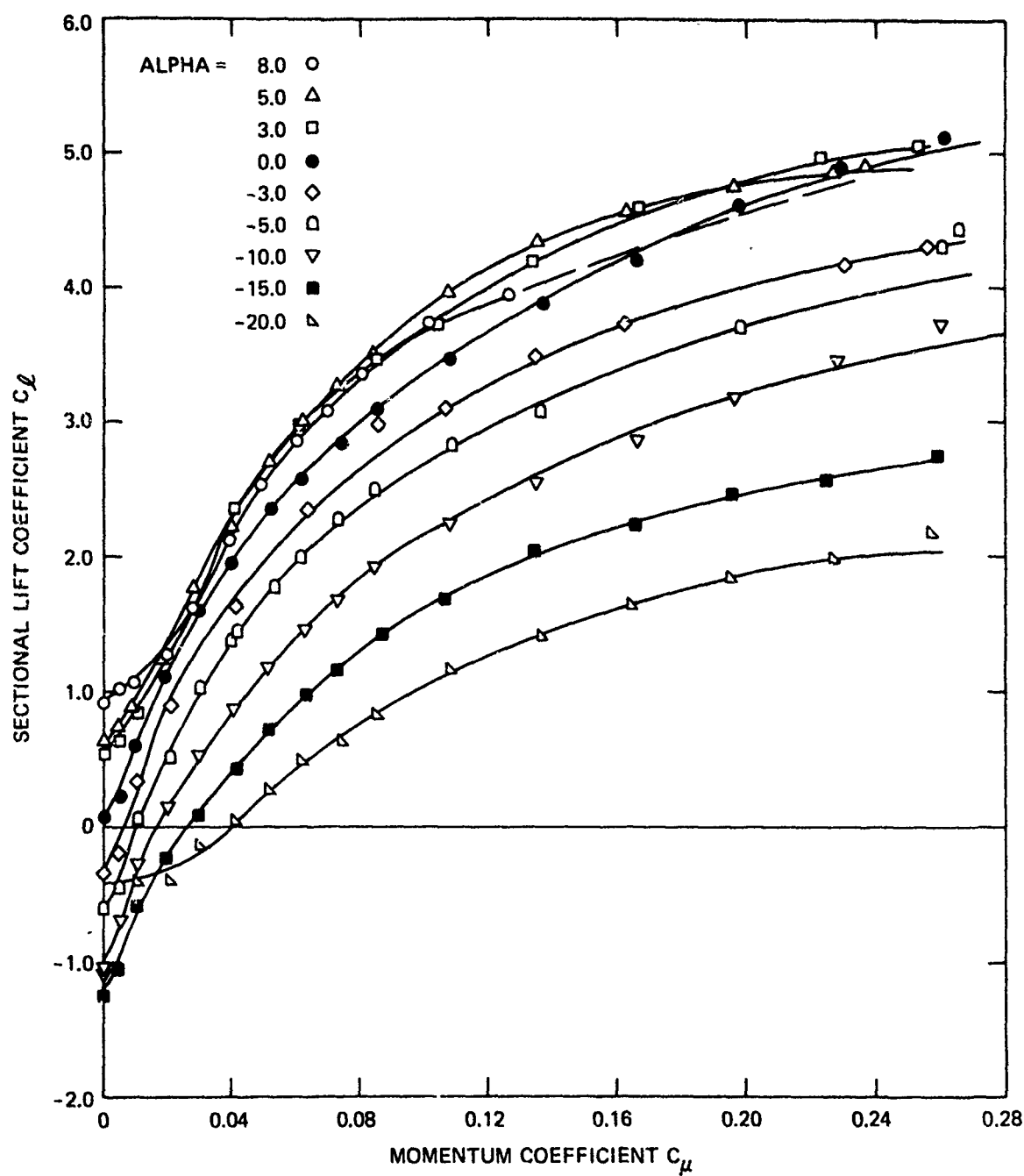


Figure 6 – Lift Variation with Momentum Coefficient

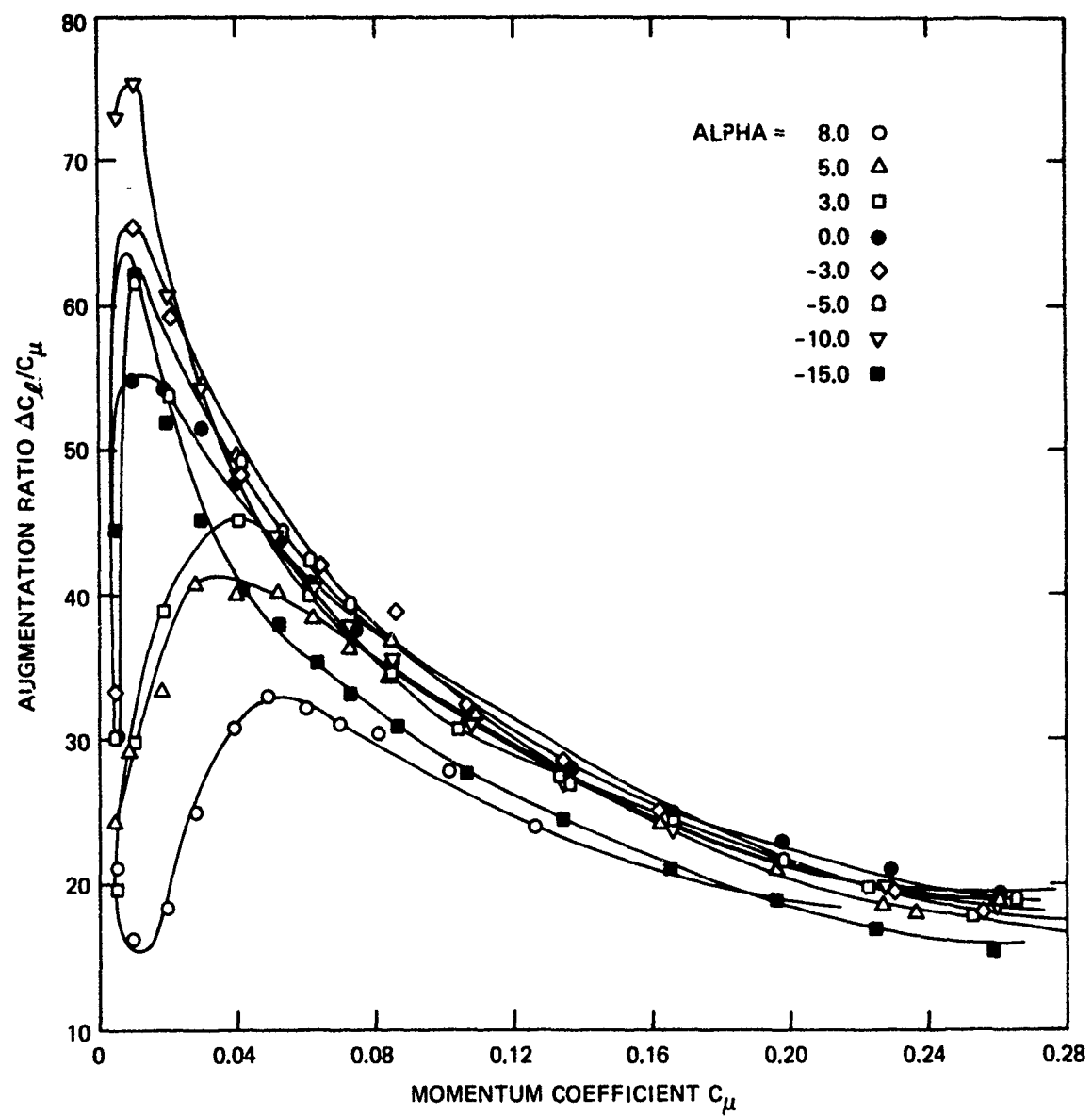


Figure 7 – Lift Augmentation

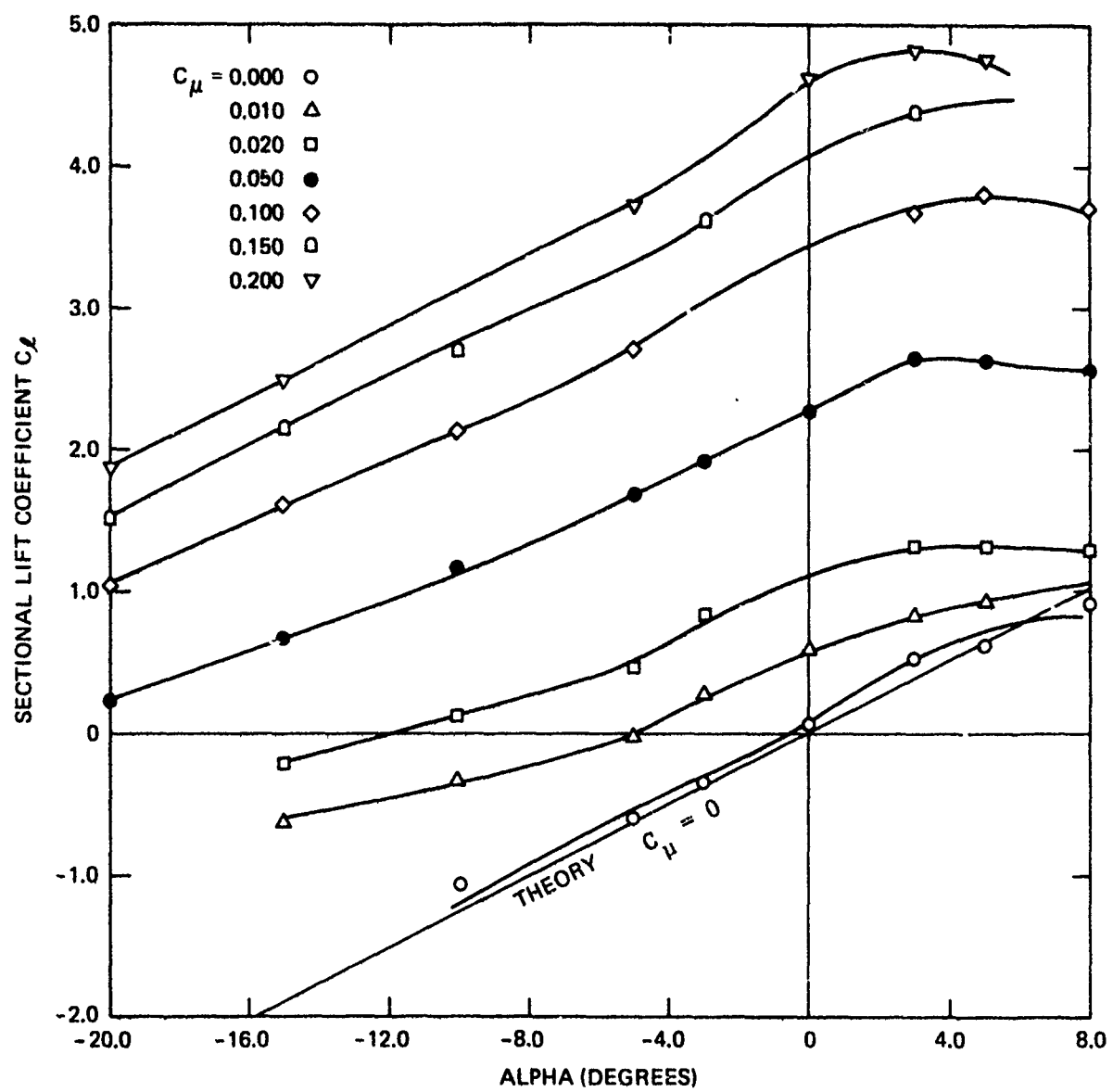


Figure 8 – Lift Variation with Geometric Angle of Attack

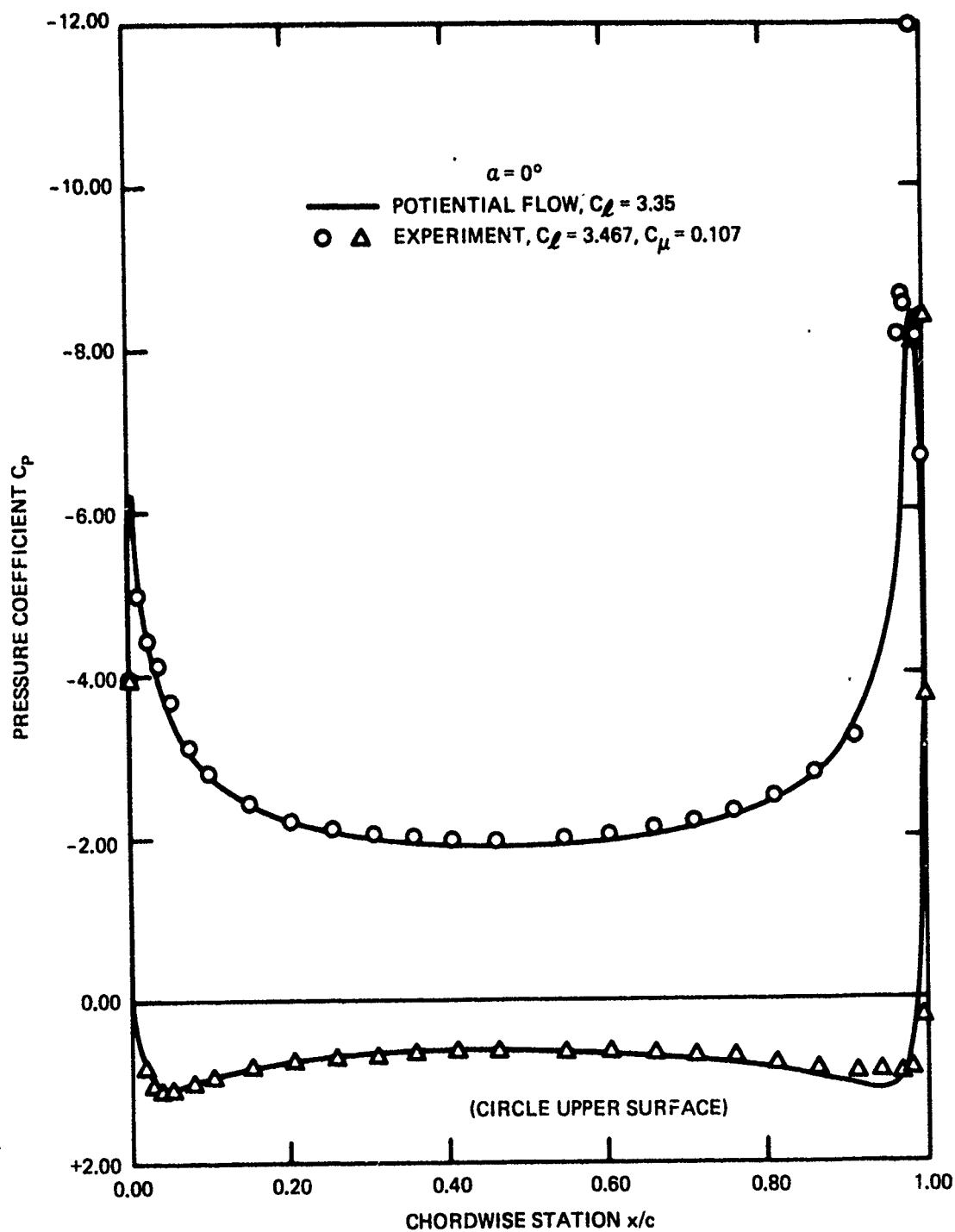


Figure 9 – Comparison of Potential Flow and Experimental Pressure Distribution

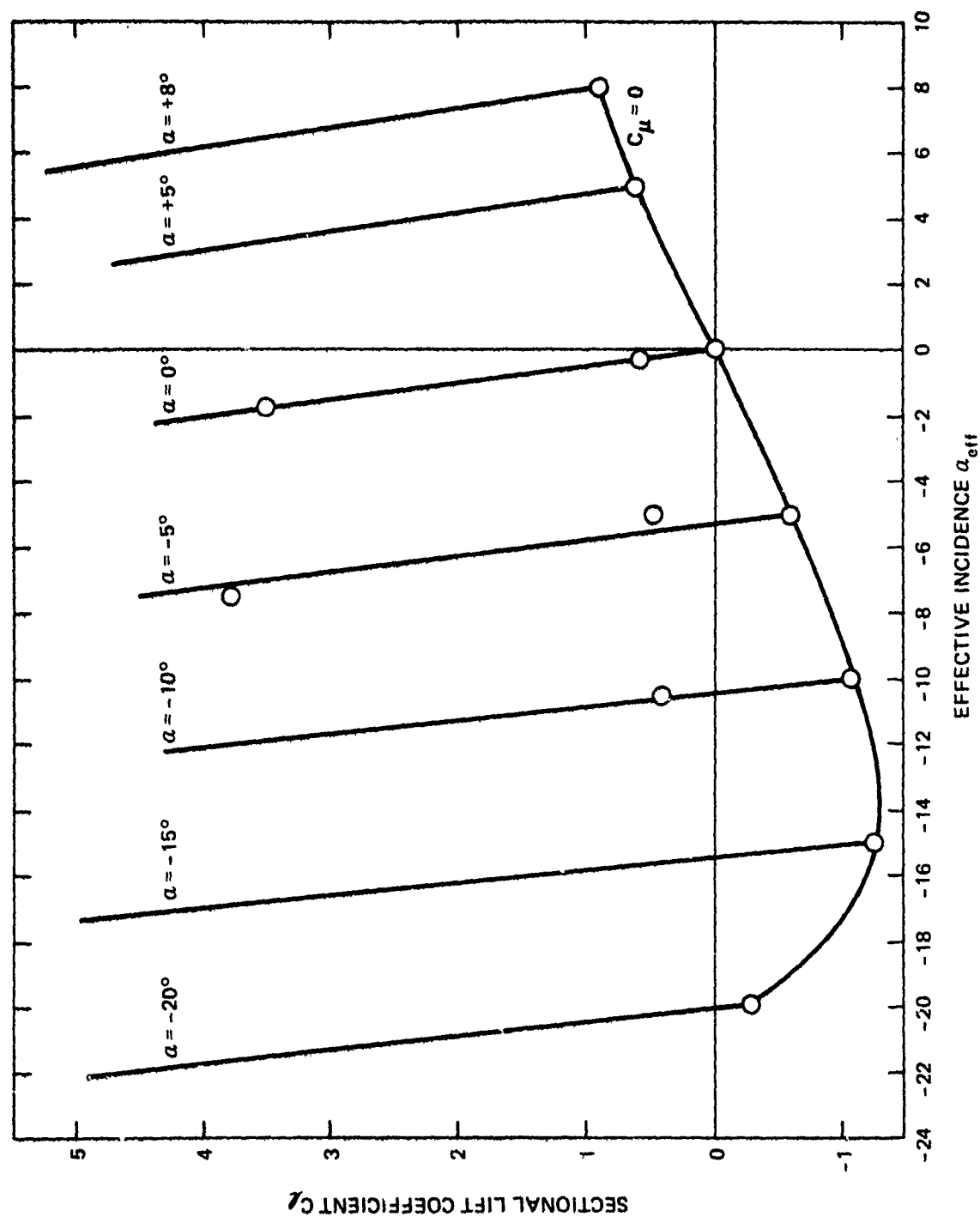


Figure 10 - Induced Angle Corrections to Geometric Incidence

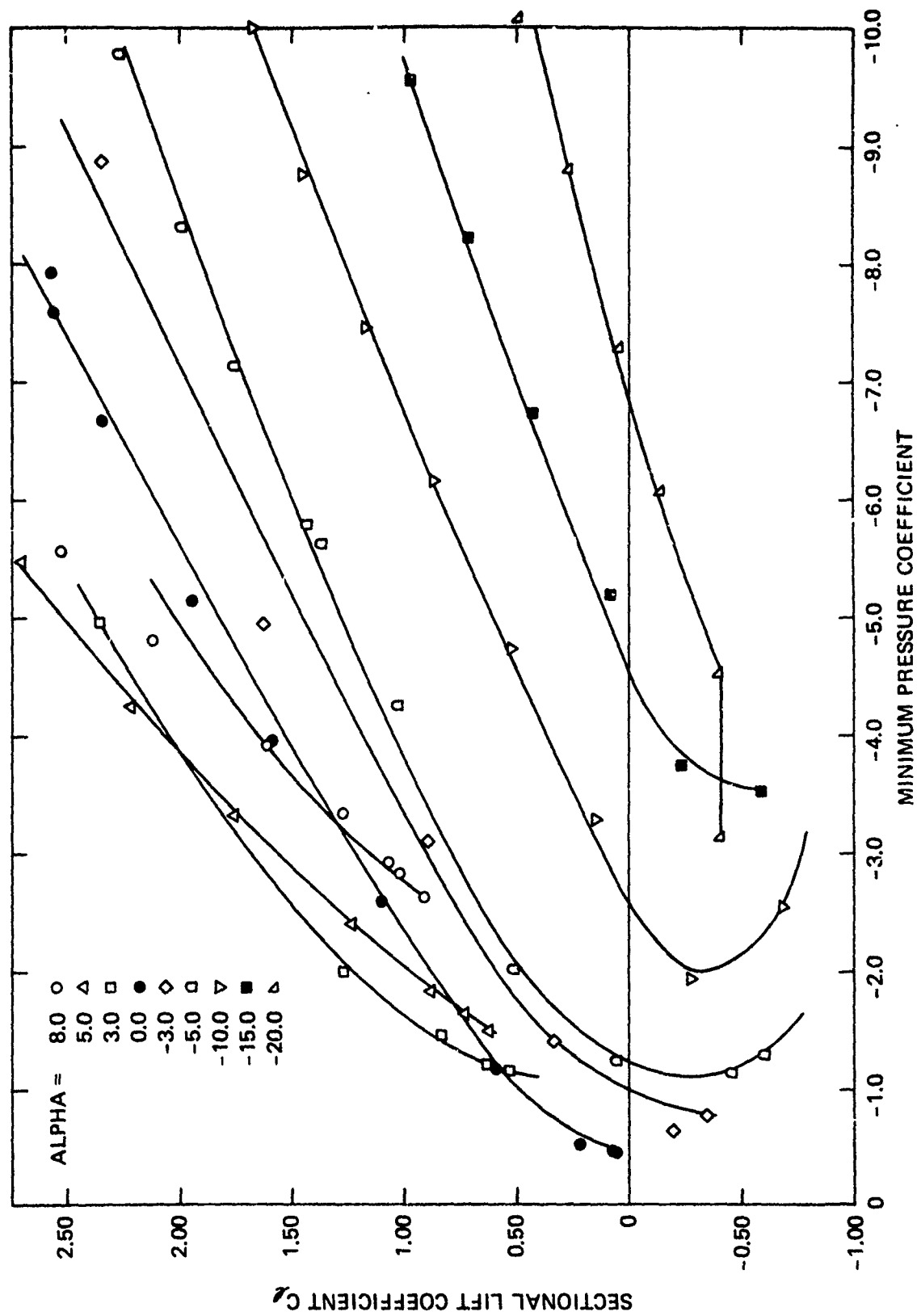


Figure 11 - Minimum Pressure Coefficient

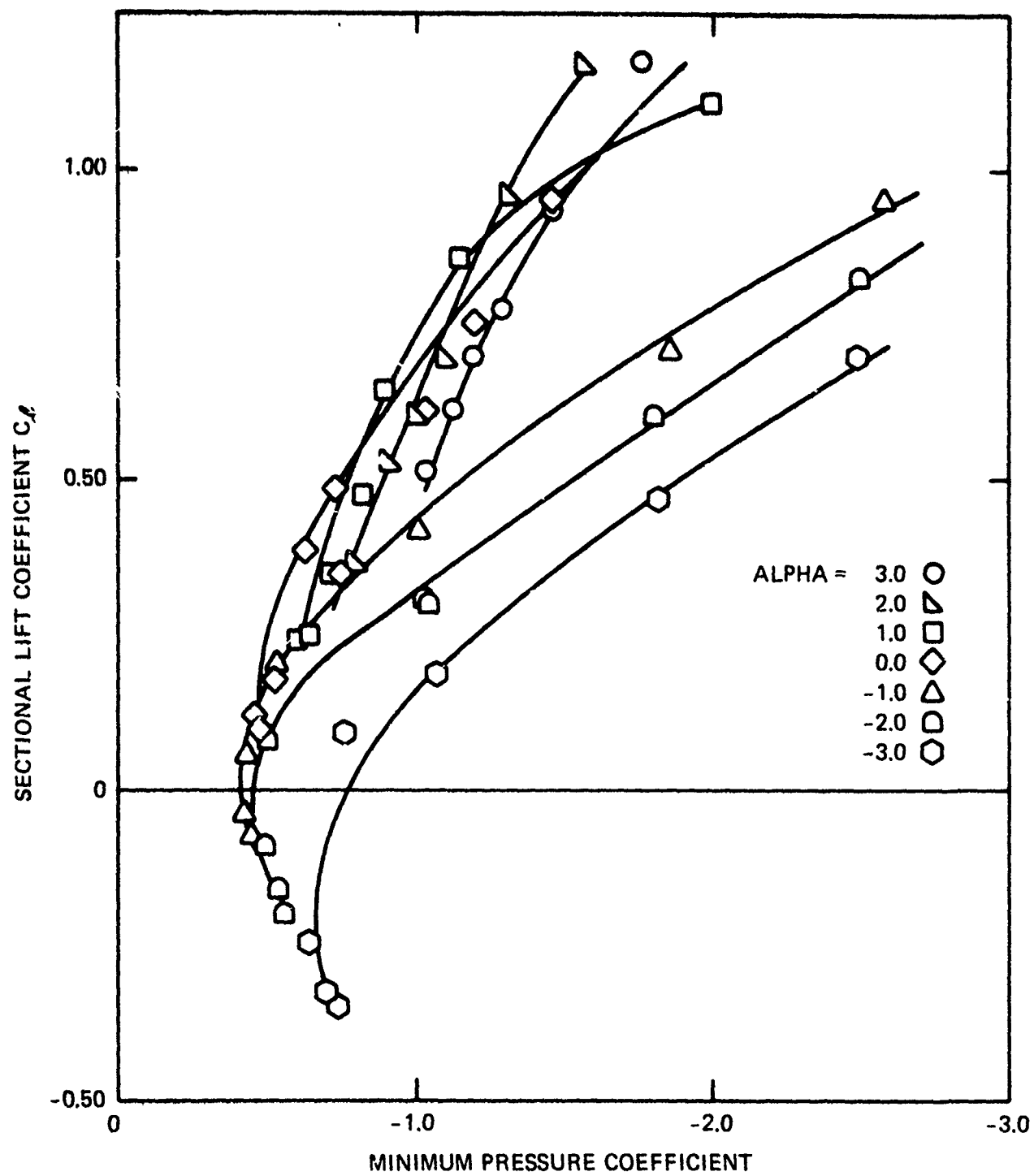


Figure 12 - Minimum Pressure Coefficient for Low Momentum Coefficients

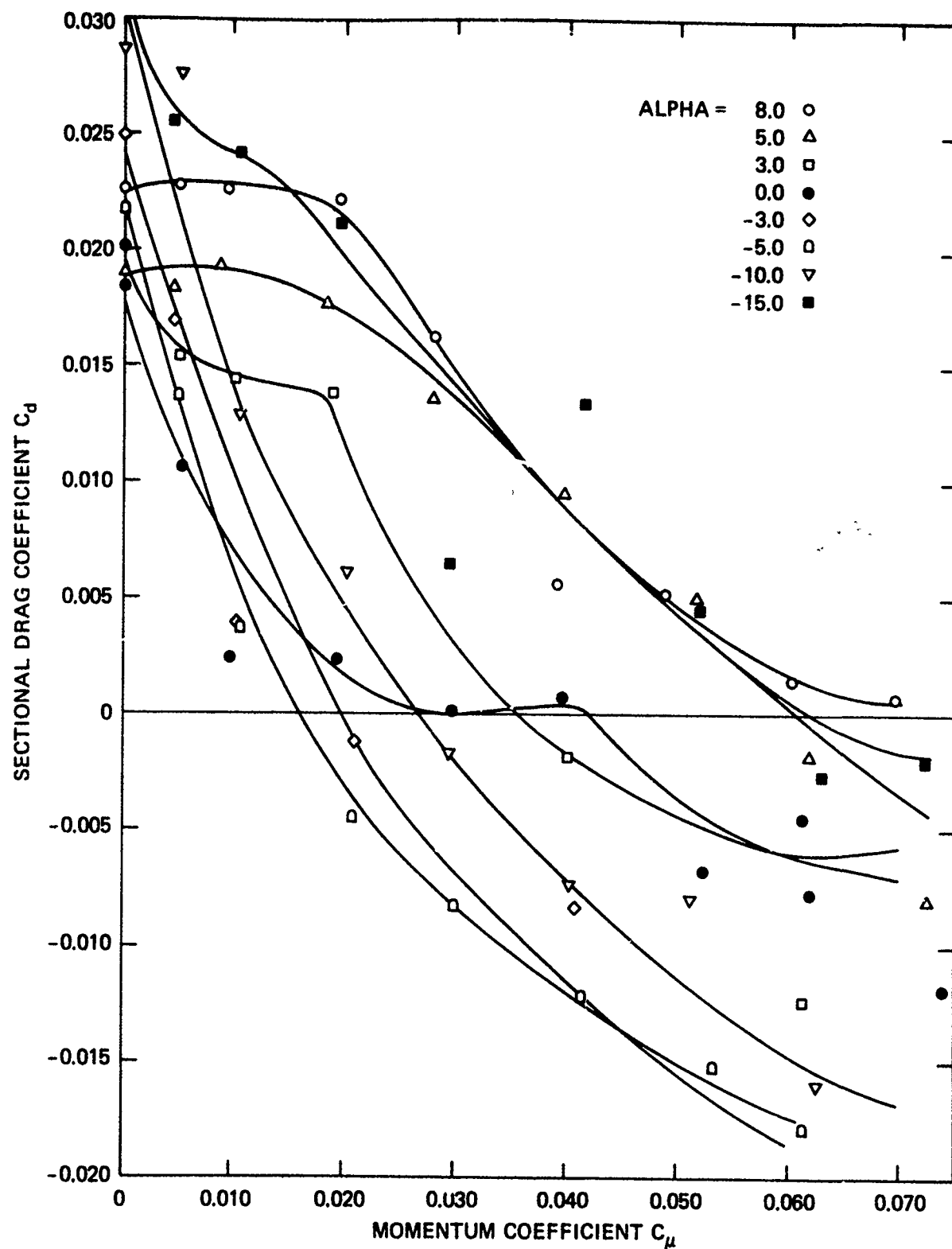


Figure 13 - Drag Coefficient Variation with Momentum Coefficient (Expanded Scale)

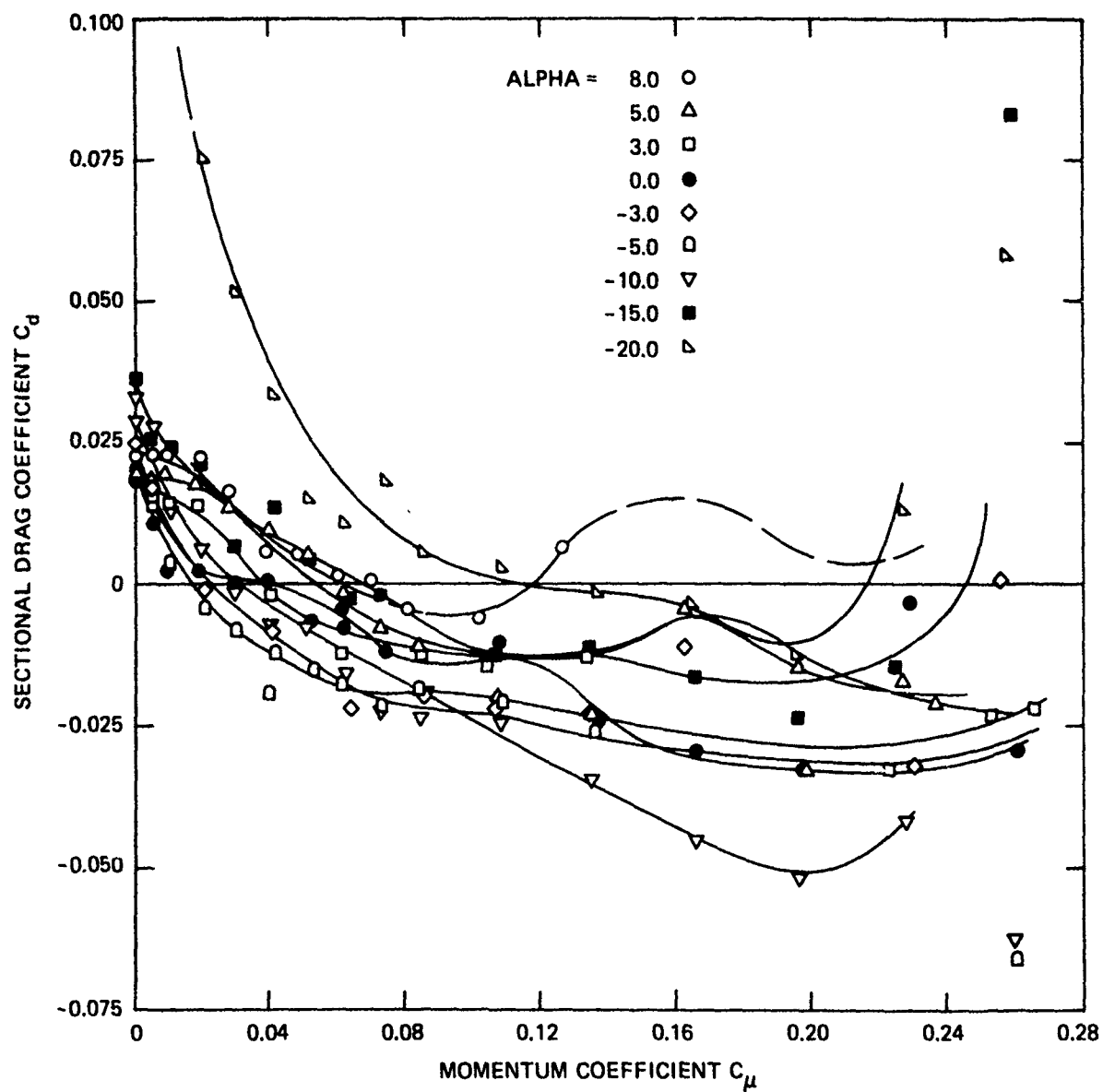


Figure 14 – Drag Coefficient Variation with Momentum Coefficient

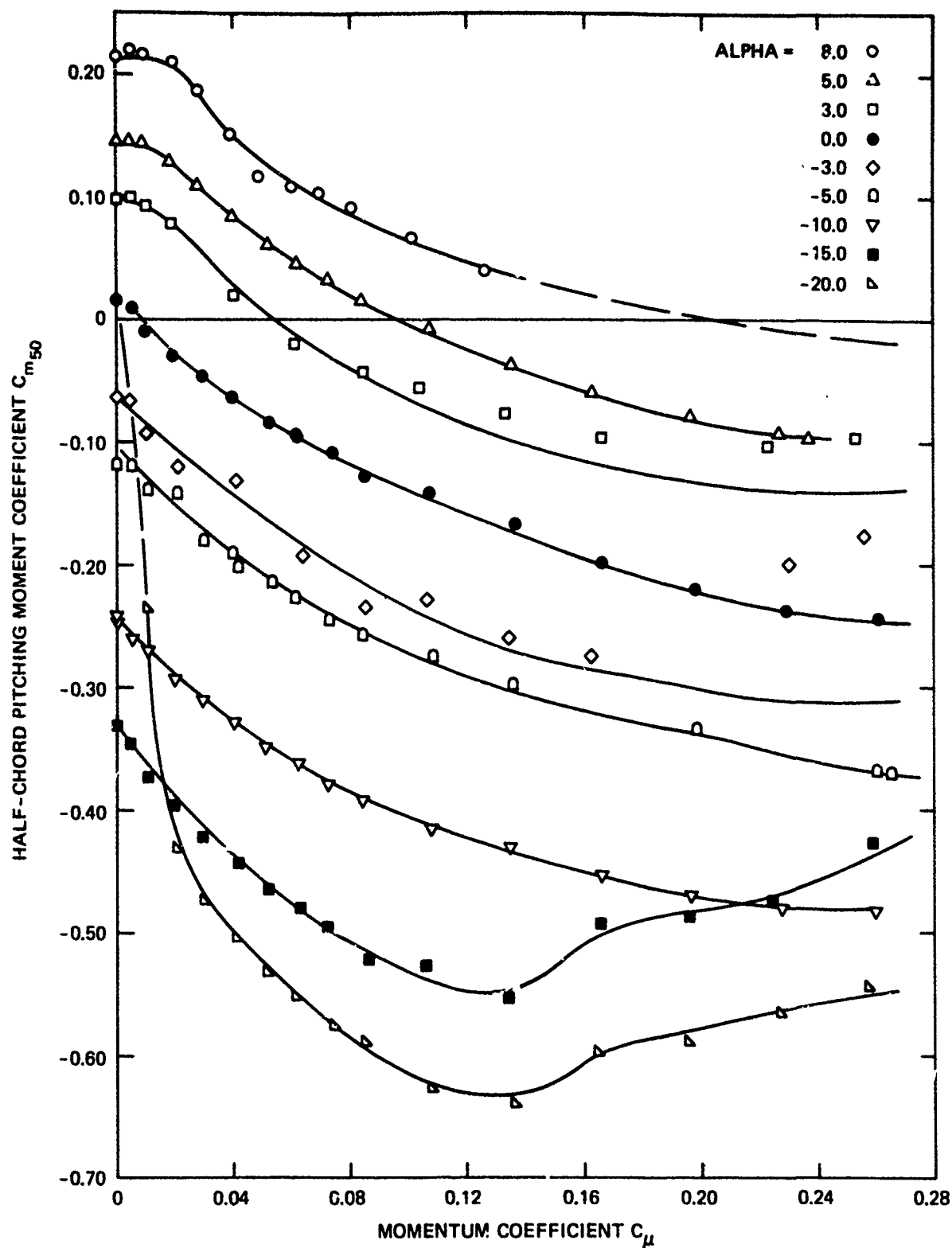


Figure 15 - Variation in Half-Chord Pitching Moment Coefficient

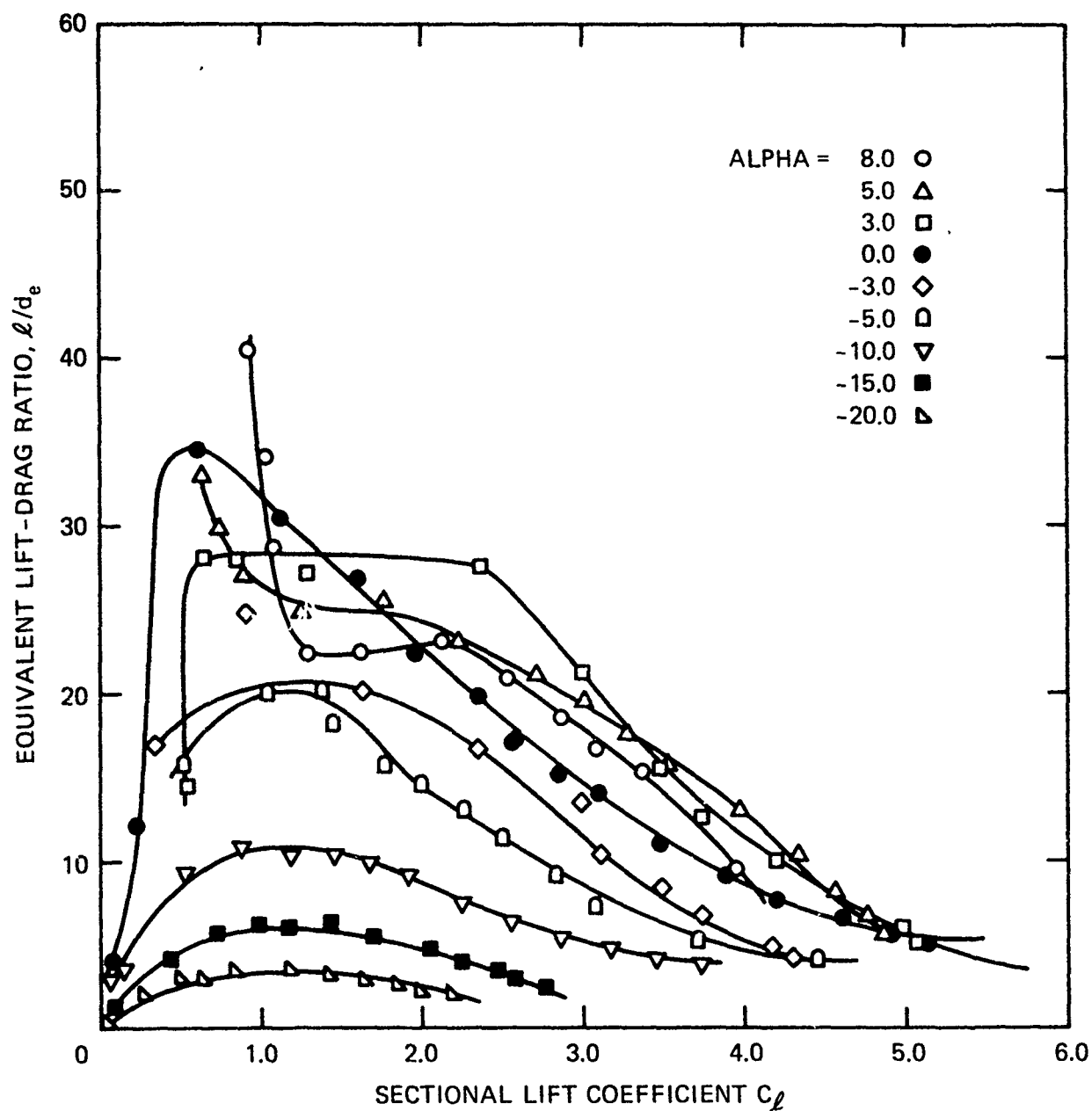


Figure 16 – Equivalent Lift-Drage Ratio as a Function of Lift Coefficient

**TABLE 1**  
**Two-Dimensional Model Coordinates for Upper and Lower Surfaces**

**Table 1A -- Upper Surface**

| X      | Y      |               |
|--------|--------|---------------|
| 0.0000 | 0.0003 | LEADING EDGE  |
| 0.0200 | 0.0682 |               |
| 0.0400 | 0.1095 |               |
| 0.0600 | 0.1402 |               |
| 0.0799 | 0.1648 |               |
| 0.1000 | 0.1859 |               |
| 0.1300 | 0.2103 |               |
| 0.1600 | 0.2288 |               |
| 0.1800 | 0.2429 |               |
| 0.2200 | 0.2527 |               |
| 0.2500 | 0.2838 |               |
| 0.2950 | 0.2993 |               |
| 0.3400 | 0.3140 |               |
| 0.3850 | 0.3288 |               |
| 0.4300 | 0.3429 |               |
| 0.4750 | 0.3569 |               |
| 0.5450 | 0.3784 |               |
| 0.7050 | 0.4245 |               |
| 0.8650 | 0.4651 |               |
| 1.0250 | 0.5010 |               |
| 1.2250 | 0.5401 |               |
| 1.3850 | 0.5672 |               |
| 1.6050 | 0.6008 |               |
| 2.0050 | 0.6509 |               |
| 2.4050 | 0.6893 |               |
| 2.8050 | 0.7181 |               |
| 3.2050 | 0.7367 |               |
| 3.6300 | 0.7485 |               |
| 4.1300 | 0.7522 |               |
| 4.5050 | 0.7464 |               |
| 5.0051 | 0.7257 |               |
| 5.5050 | 0.6930 |               |
| 6.0050 | 0.6428 |               |
| 6.3350 | 0.6000 |               |
| 6.4950 | 0.5771 |               |
| 6.6550 | 0.5520 |               |
| 6.8150 | 0.5238 |               |
| 6.9750 | 0.4922 |               |
| 7.1350 | 0.4557 |               |
| 7.2700 | 0.4191 |               |
| 7.3300 | 0.4011 |               |
| 7.3900 | 0.3814 |               |
| 7.4500 | 0.3595 |               |
| 7.5100 | 0.3357 |               |
| 7.5500 | 0.3180 |               |
| 7.5900 | 0.2988 |               |
| 7.6300 | 0.2779 |               |
| 7.6700 | 0.2546 |               |
| 7.7100 | 0.2292 |               |
| 7.7500 | 0.2015 |               |
| 7.7900 | 0.1696 |               |
| 7.8201 | 0.1418 |               |
| 7.8500 | 0.1099 |               |
| 7.8800 | 0.0696 |               |
| 7.9000 | 0.0281 |               |
| 7.9080 | 0.0000 | TRAILING EDGE |

**Table 1B -- Lower Surface**

| X      | Y       |               |
|--------|---------|---------------|
| 7.8980 | -0.0364 | TRAILING EDGE |
| 7.8780 | -0.0742 |               |
| 7.8580 | -0.1010 |               |
| 7.8280 | -0.1340 |               |
| 7.7980 | -0.1628 |               |
| 7.7680 | -0.1861 |               |
| 7.7380 | -0.2081 |               |
| 7.6980 | -0.2339 |               |
| 7.6580 | -0.2569 |               |
| 7.6180 | -0.2774 |               |
| 7.5781 | -0.2972 |               |
| 7.5380 | -0.3152 |               |
| 7.4930 | -0.3340 |               |
| 7.4230 | -0.3611 |               |
| 7.3630 | -0.3819 |               |
| 7.3030 | -0.4017 |               |
| 7.2530 | -0.4166 |               |
| 7.0930 | -0.4595 |               |
| 6.9330 | -0.4963 |               |
| 6.7730 | -0.5291 |               |
| 6.6130 | -0.5584 |               |
| 6.4530 | -0.5829 |               |
| 6.2930 | -0.6055 |               |
| 5.8779 | -0.6551 |               |
| 5.3780 | -0.7010 |               |
| 4.8780 | -0.7328 |               |
| 4.3780 | -0.7499 |               |
| 3.8780 | -0.7545 |               |
| 3.4030 | -0.7515 |               |
| 3.0030 | -0.7403 |               |
| 2.6030 | -0.7169 |               |
| 2.2030 | -0.6828 |               |
| 1.8030 | -0.6363 |               |
| 1.4630 | -0.5851 |               |
| 1.3030 | -0.5573 |               |
| 1.1430 | -0.5279 |               |
| 0.9830 | -0.4947 |               |
| 0.8230 | -0.4569 |               |
| 0.6630 | -0.4130 |               |
| 0.5030 | -0.3622 |               |
| 0.4430 | -0.3419 |               |
| 0.3830 | -0.3208 |               |
| 0.3229 | -0.2993 |               |
| 0.2630 | -0.2761 |               |
| 0.2180 | -0.2565 |               |
| 0.1680 | -0.2311 |               |
| 0.1380 | -0.2121 |               |
| 0.1080 | -0.1898 |               |
| 0.0780 | -0.1617 |               |
| 0.0480 | -0.1236 |               |
| 0.0280 | -0.0883 |               |
| 0.0080 | -0.0346 | LEADING EDGE  |

**TABLE 2**  
**Two-Dimensional Model Pressure Tap Coordinate Listing**

| Upper Surface |            | Lower Surface |            |
|---------------|------------|---------------|------------|
| Tap No.       | X Position | Tap No.       | X Position |
| 1             | 0          | 55            | 0.125      |
| 2             | 0.084      | 54            | 0.205      |
| 3             | 0.177      | 53            | 0.301      |
| 4             | 0.285      | 52            | 0.396      |
| 5             | 0.410      | 51            | 0.606      |
| 6             | 0.590      | 50            | 0.801      |
| 7             | 0.782      | 49            | 1.188      |
| 8             | 1.186      | 48            | 1.601      |
| 9             | 1.591      | 47            | 2.011      |
| 10            | 2.001      | 46            | 2.421      |
| 11            | 2.403      | 45            | 2.801      |
| 12            | 2.795      | 44            | 3.210      |
| 13            | 3.184      | 43            | 3.624      |
| 14            | 3.618      | 42            | 4.293      |
| 15            | 4.295      | 41            | 4.743      |
| 16            | 4.747      | 40            | 5.194      |
| 17            | 5.201      | 39            | 5.601      |
| 18            | 5.603      | 38            | 5.991      |
| 19            | 5.996      | 37            | 6.400      |
| 20            | 6.394      | 36            | 6.806      |
| 21            | 6.799      | 35            | 7.191      |
| 22            | 7.201      | 34            | 7.437      |
| 23            | 7.666      | 33            | 7.649      |
| 24            | 7.710      | 32            | 7.737      |
| 25            | 7.723      | 31            | 7.848      |
| 26            | 7.801      | 30            | 7.888      |
| 27            | 7.843      | 29            | 7.906      |
| 28            | 7.885      |               |            |
| 29            | 7.906      |               |            |