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AT LOW REYNOLDS NUMBERS

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Abstract

A wind tunnel investigation of the low Reynolds number aerodynamics of a Clark-Y airfoil was performed in the VPI Stability Wind Tunnel at $50{,}000 \leq Re \leq 200{,}000$. Pressure distributions were measured for $0^\circ \leq \alpha \leq 28^\circ$ at each Reynolds number and the results integrated to obtain C_L and C_D plots. The results revealed that the Clark-Y airfoil performs well at these low Reynolds numbers obtaining $C_{L_{max}}$ values above 1.0 and low pre-stall drag coefficients. There was little evidence of any hysteresis effect in stall.

Introduction

In recent years there has been a renewed interest from a wide range of people in low Reynolds number aerodynamic problems. Reasons for this interest vary widely but include concerns about hang glider and ultralight aircraft performance, military concerns about uses for remotely piloted vehicles (RPV's) and even some interest in a very large, very high altitude aircraft designed to merely fly a station keeping pattern to provide a communications relay platform.

While hang glider and ultralights do fly at relatively low speeds, their flight Reynolds numbers would be in the 900,000-1,000,000 range, well within the range of Re where ample data exists for wing aerodynamics and performance. On the other hand, either a high altitude (60,000-100,000 ft) airborne communications relay aircraft or a low altitude RPV designed for ECM flights at very low speeds (≈ 20 kts) would both fly at Reynolds numbers of 200,000 or less. Little reliable aerodynamic data exists for any type of wing in this range of Reynolds number. Most data which does exist was obtained in less than rigorous testing performed by model airplane enthusiasts.

Some data does exist for a few airfoil shapes at Reynolds numbers of 500,000 or less; however, it has not been widely reported and it often raises more questions than it answers. One generally known effect of lowering the Reynolds number is a reduction of $C_{L_{max}}$; however, even that data may be questionable due to the nature of flow separation at low Reynolds number and a hysteresis effect in stall reported in some investigations(1). Figure 1 shows an example of this hysteresis as discussed in Reference 1 for an N60 airfoil. Such an effect could be extremely dangerous since stall recovery could require a large decrease in angle of attack rather than the customary procedure of simply reducing the back pressure on the controls. The nature of stall at low Reynolds numbers is complicated by laminar separation bubbles which may form before full stall and the sensitivity of these bubbles to other influences such as noise or surface roughness. Recent experiments reported by Mueller, et.al.(2) indicate that this hysteresis effect may be a function of wind tunnel noise and, hence, that noisy wind tunnel data may not compare well with that taken in quiet wind tunnels.

Wind tunnel testing at low Reynolds numbers is extremely difficult due to the difficulty of measuring drag at low Reynolds numbers. Some simple calculations will show that for a given aspect ratio and Reynolds number the drag should be constant, regardless of model chord. Hence, testing larger models at lower speeds has no advantage over testing small models at high speeds as far as force measurements are concerned. Typically, airfoil drags at low Reynolds numbers have been measured via the wake rake method rather than force balances due to the small forces involved. The wake rake method itself is, however, somewhat inexact and is far from reliable at high wing angles of attack and in stall where much of the momentum loss in the flow is rotational rather than the linear momentum which most wake rakes measure.

The other major problem in wind tunnel measurements at low Reynolds numbers is due to the quality of flow in most wind tunnels. Since the wing boundary layer at these Re will be laminar and even small disturbances in the flow can alter the character of a laminar boundary layer, a very clean wind tunnel flow is a necessity for low Re testing. Yet, much of the reported data on wings at low Re was obtained in wind tunnel facilities with high flow turbulence levels or high noise. Thus there is a need for systematically collected data on airfoils at low Reynolds numbers obtained using reliable testing methods in wind tunnels with well defined, low turbulence flows.

While much current speculation regarding low Re airfoil performance has centered around newer airfoil designs such as the Wortmann FX-63-137 there are older airfoil designs about which much is already known. One such airfoil which is known to be a good performer at low speeds is the venerable Clark-Y. The Clark-Y has long been a favorite of model builders because of its good aerodynamic performance and its ease of construction. NACA data exists for this airfoil for Reynolds numbers as low as 360,000(3). Therefore, the Clark-Y airfoil was chosen for use in a study of airfoil performance at Reynolds numbers down to 50,000.

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Description of Experiment

After much discussion of possible test procedures it was concluded that the best way to measure lift and drag on a test airfoil at low Reynolds numbers would be by way of pressure distribution measurement around the surface of the model and integration of those pressures. There were three reasons for their choice. First, as previously mentioned, direct force measurements via strain gauge or mechanical balance would be difficult due especially to the small drag values to be measured. For this same reason most previous investigations have avoided force balance measurements at low Re. Second, while other investigators had used the wake rake for drag measurements, this method does not measure lift and suffers from decreasing accuracy at higher angles of attack. Since the stall region was of concern and the wake rake is less than reliable there, this method was rejected. The third reason was that the use of pressure distributions around the airfoil allowed direct comparison with similar data at higher Re which is available in abundance for the Clark-Y(3).

An untapered Clark-Y, 12% thick airfoil with aspect ratio 5.75 and a chord of 6 inches was constructed of wood for these tests. Copper tubing was inlaid in portions of the upper and lower surface to allow pressure measurement. The surface was epoxy coated and finished to a high degree of smoothness.

The wing was mounted on a variable angle of attack strut mount in the 6 x 6 foot test section of the VPI Stability Wind Tunnel. Pressure lines were run out the bottom of the wing at the mounting point and connected to a Scanivalve pressure measurement system equiped with a Setra Systems pressure transducer. Different pressure transducers were used to provide optimum accuracy at different test speeds. The largest used had a range of 0-0.25 psig. Forty-seven pressure taps were drilled through the wing surface into the inlaid tubing in a pattern shown in Figure 2. These were staggered to avoid interference in a downstream measurement due to an upstream tap. End plates were used on the wing to simulate 2-D flow.

The use of the VPI Stability Wind Tunnel was an important factor in these tests. This tunnel has a turbulence level of 0.05% or less. Hence, some of the problems seen in earlier tests conducted in tunnels with much greater free stream turbulence should be avoided.

hysteresis

The test procedure was straight forward with a full pressure distribution being taken at each angle of attack at a given Reynolds number. The angle of attack was varied from zero to twenty-eight degrees in four degree increments. Data was taken at each angle from 0 to 28 degrees and again as the wing was run back from 28 to 0 degrees. It was hoped that this procedure would insure accuracy and possibly detect any hysteresis effect, should one exist. An occasional test was conducted at other angles of attack to give more complete data.

All data was recorded and processed on a Hewlett Packard digital data acquisition system and printed out in terms of pressure coefficient distributions around the wing.

Tests were conducted at Reynolds numbers of 50,000, 75,000, 100,000, 150,000, 200,000 and 500,000. After testing the data was transferred to a Sharp PC-1500 computer which plotted the pressure coefficient distributions at each angle of attack and integrated the data around the wing to calculate axial and normal force coefficients and, subsequently, lift and drag coefficients.

Data and Results

Because of the large magnitude of data recorded in the tests only limited representative results can be shown in this paper. The most extensive set of data was taken at a Reynolds number of 75,000. Hence, this is selected for analysis here.

Figure 3 shows a set of pressure distributions for the airfoil at a Reynolds number of approximately 75,000 at angles of attack from zero through 14 degrees. These show nicely the progression of flow separation on the airfoil with the separated region spreading from the rear 20% chord position at four degrees α to 50% chord at eight degrees. Two sets of data are shown at twelve degrees angle of attack, one with attached flow over the first 20% chord of the upper surface and the second with full separation on the upper surface. This difference may result from a slight difference in Reynolds number or a hysteresis effect. The non-stalled case was recorded during tests as angle of attack was being increased while the separated distribution was found as α was being reduced from stall. This will be discussed later in the paper. Above twelve degree angle of attack the flow was separated and, hence, the data measured at α's up to 28° is not shown since it matched that at 14°.

Integrating these pressure distributions and plotting the resulting C_L and C_D data versus angle of attack gives the curves shown in Figures 4 and 5. NACA data (3) for the Clark-Y at a Reynolds number of 6.7 million is shown for comparison. As expected the value of C_{Lmax} is much lower at the lower Reynolds number. Also noted is the non-linear pre-stall lift curve which also seems to be a characteristic behavior of airfoils at lower Reynolds numbers. As might be expected, the low Reynolds number case exhibits a lower drag coefficient than the high Re case until stall. This low pre-stall drag coefficient will obviously lead to much larger values of L/D for the low Re case, especially at angles of attack around 6 to 8 degrees.

Similar data was collected at Reynolds numbers of 50,000, 100,000, and 200,000. The resulting integrated pressure data is shown in plots of C_L and C_D versus angle of attack in Figures 6 and 7. Several trends are noted in Figure 6. The first is that C_L at zero angle of attack increases steadily as Reynolds number increases. This is shown in more detail in Figure 8. Also, the curves in the pre-stall region become somewhat more linear as Re is increased. The 50,000 Re case is very different from the others for reasons not yet understood. As evidenced by the data points there was more scatter in the 50,000 Re data although the character of the results was consistent in each test.

The angle of attack for $C_{L_{max}}$ is seen in Figure 6 to increase from about eight degrees at 50,000 Re to 12° at 100,000 as compared with 16° in the NACA data. The two very different values of C_L found in the Re = 75,000 case suggest either a hysteresis effect in stall or that at this Re the angle for stall is passing through the 12° range. The higher value of C_L found at this nominal 75,000 Reynolds number case was actually found for Re ≅ 76,000 while the lower was closer to 75,000. Hence the effect seen could be one of Reynolds number rather than any hysteresis effect. Such an effect was not noted at other Reynolds numbers; however, testing over a finer grid of angles of attack might have revealed similar variations of C_L near stall at other Reynolds numbers.

An examination of the C_D data (Figure 7) reveals low C_D values up to stall for all the low Re cases. C_D at $\alpha = 0$ is comparable to that for the 6.7 million Re case as is the value of C_D after stall. The general shape of the curves resembles the "drag buckets" seen in NACA 6 series "laminar flow" airfoils, a fact which is not too surprising considering that most of the pre-separation flow over the wing will be laminar at these low Reynolds numbers.

Conclusions

This study has examined the low Reynolds number aerodynamics of the Clark-Y airfoil. The general conclusions are that the airfoil should perform well at low Reynolds number with somewhat reduced $C_{L_{max}}$ values as compared to a "normal" Re (10^6) case but with improved lift-to drag ratios due to decreasesin C_D. Stall occurs at lower angles of attack than in the higher Re case; however, pre-stall lift coefficients are usually higher than those at higher Re.

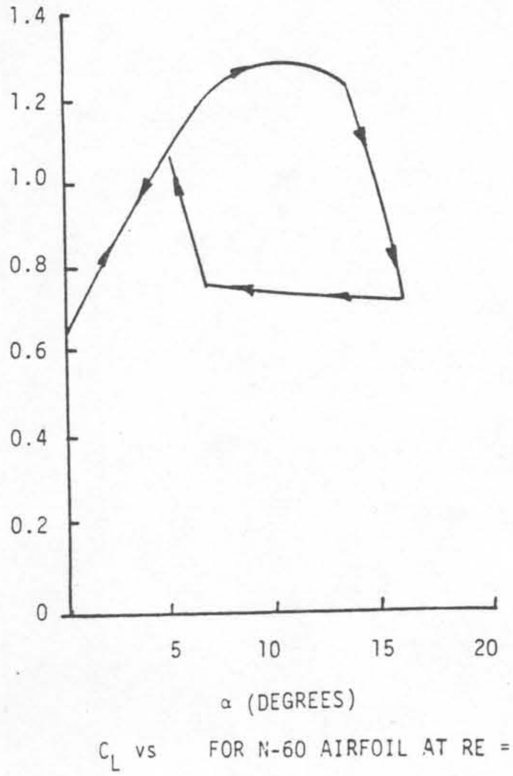
The data appears to show that the stall angle of attack reduces to twelve degrees at a Reynolds number of about 75,000 and that below that Re the aerodynamics of the wing changes somewhat. At Re = 50,000 the shape of the lift curve is substantially different from that at Re ≅ 75,000 and a larger C_D also is seen at Re = 50, 000.

In general, the test results show that the Clark-Y airfoil is an able performer at Reynolds numbers above approximately 75,000. In the Re range from 75,000-200,000 it is possible to obtain $C_{L_{max}}$ of 1.0 to 1.1 accompanied by very low drag coefficients.

The previously reported stall hysteresis effect at low Re was not observed in this study. With one exception at a Reynolds number of 75,000 the data was very repeatable (within expected experimental error ranges) whether data was being taken as α increased or decreased. The two pressure distributions found at an angle of attack of 12 degrees at Re = 75,000 could be due to several factors. Hysteresis could play a part since the unseparated flow was measured as α was being increased and the separated case when α was decreased. On the other hand the attached flow case was actually found at Re ≅ 76,000 as opposed to Re ≅ 75,000 in the separated case which could indicate that the difference was due solely to Reynolds number effects on separation. Lastly there is also the possibility of slight error in angle of attack definition due to angularity in the flow. A more detailed investigation is needed to determine if the noted effect was due to hysteresis or some other phenomenon.

References

1. McCormick, B. W., Aerodynamics, Aeronautics and Flight Mechanics, pg. 154, John Wiley, New York 1979.
2. Mueller, Thomas J., et. al., "The Influences of Free Stream Disturbances on Low Reynolds Number Airfoil Experiments," Experiments in Fluids, Springer-Verlag, Berlin, 1983.
3. Jacobs, Stack and Pinkerton, "Airfoil Pressure Distribution Investigation in the Variable Density Wind Tunnel," NACA Report No. 353, 1930.



C_L vs FOR N-60 AIRFOIL AT RE = 168000[1]

Figure 1: Stall Hysteresis Effects.

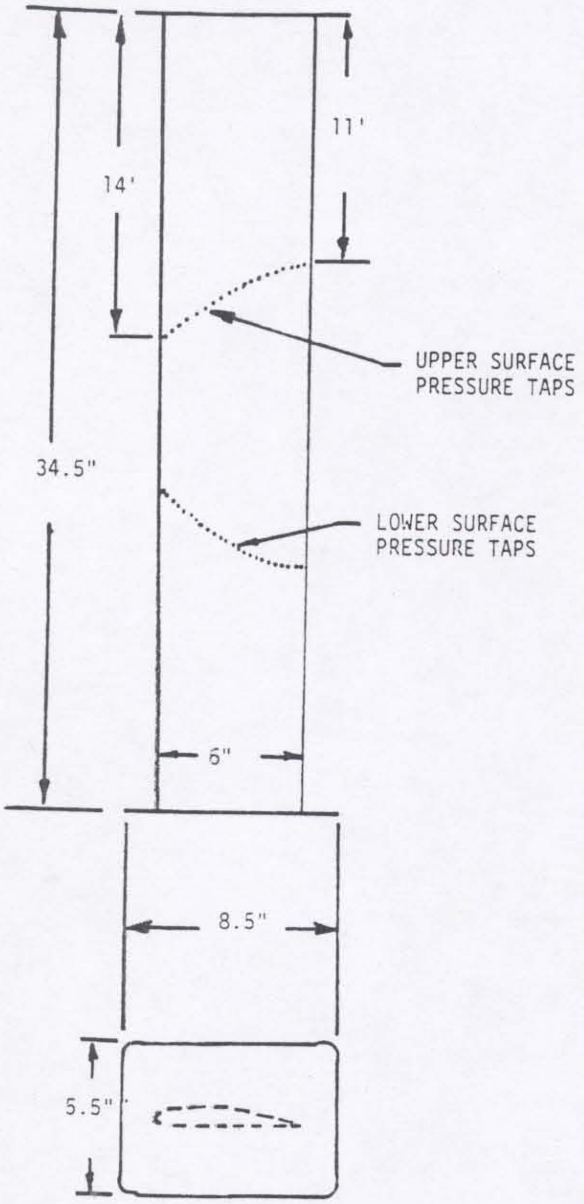


Figure 2: Test Wing Configuration.

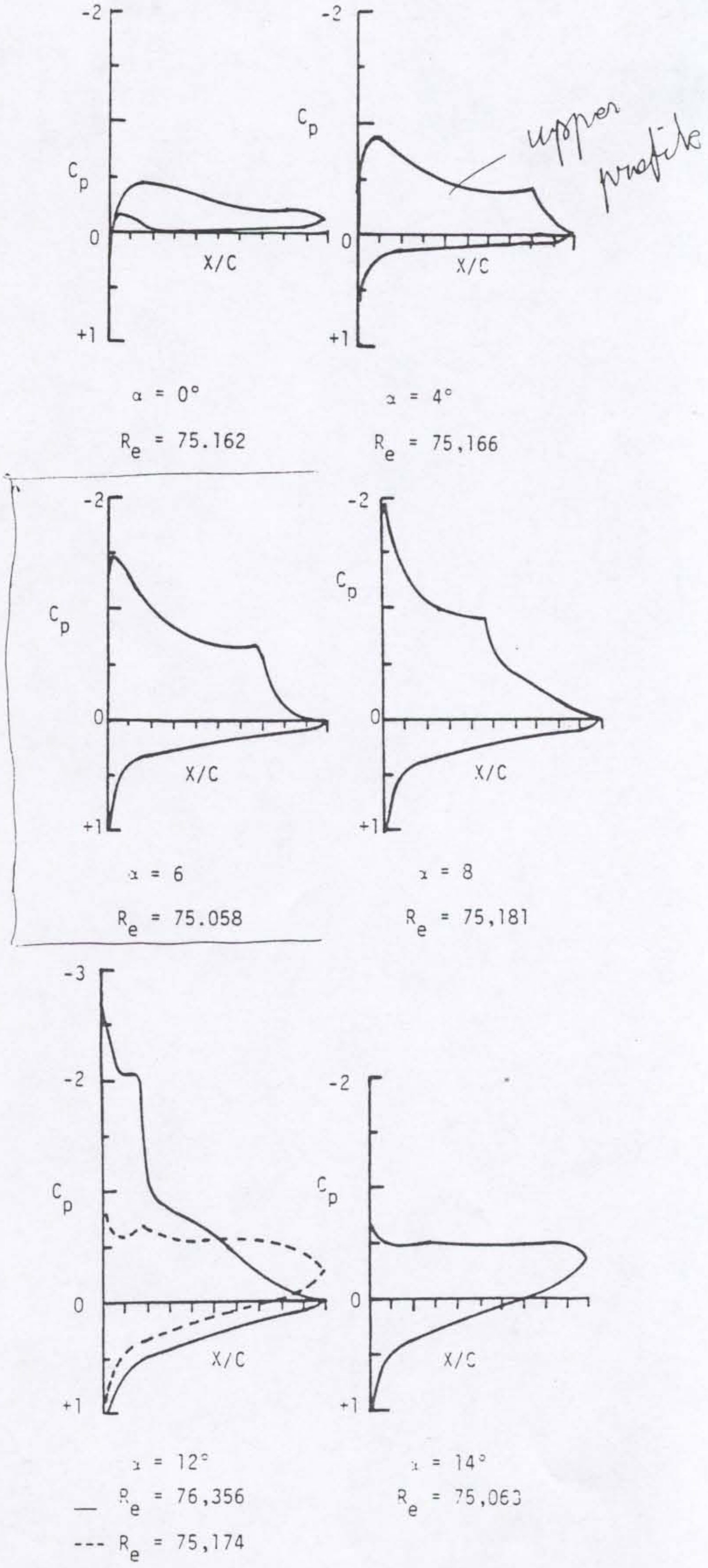


Figure 3: Pressure Distributions at Re ≅ 75,000.

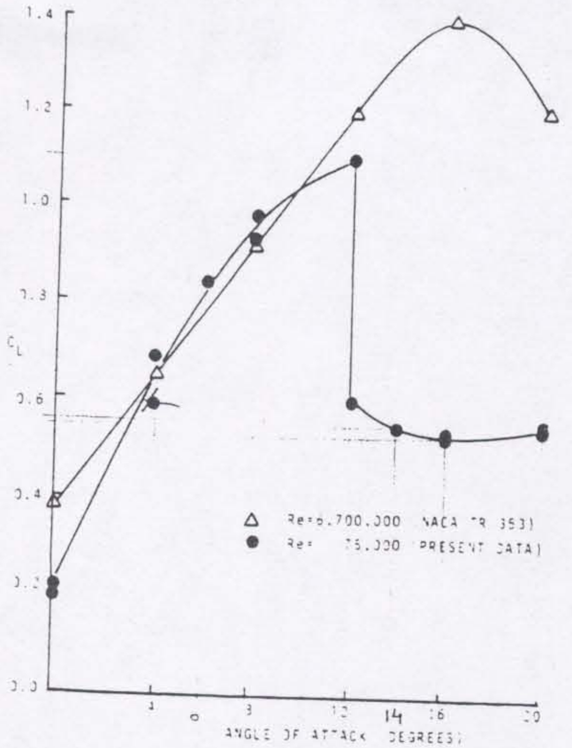


Figure 4: C_L versus α Comparison.

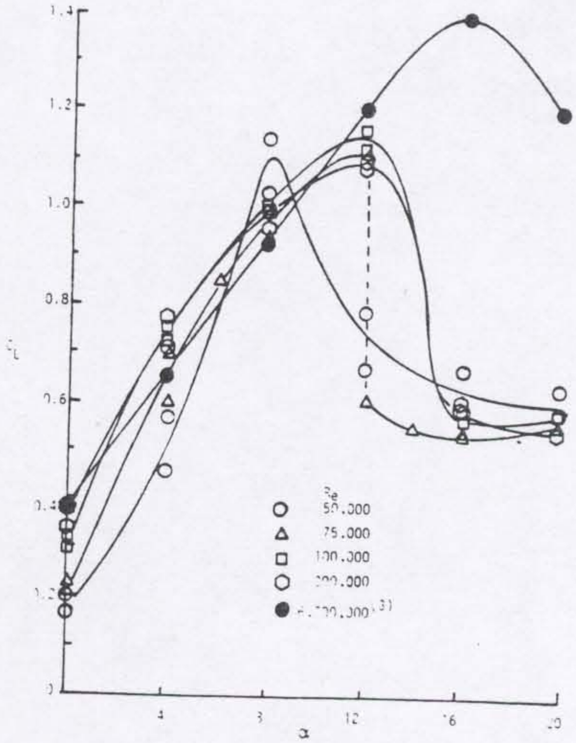


Figure 6: Low Re C_L vs α.

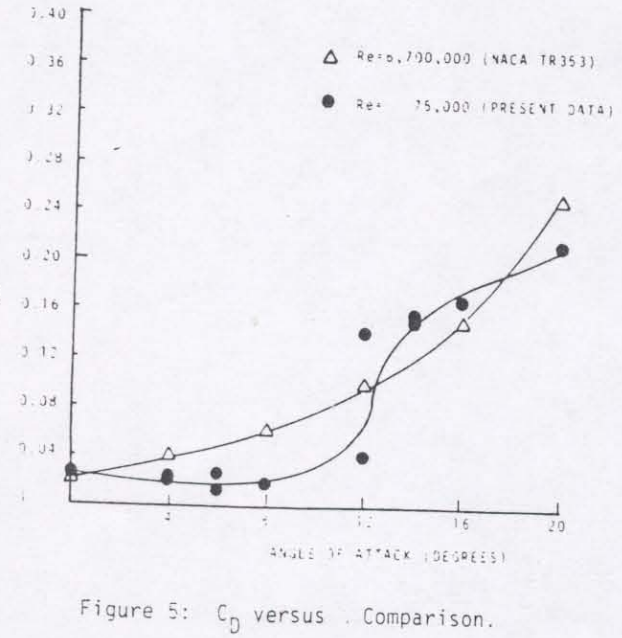


Figure 5: C_D versus . Comparison.

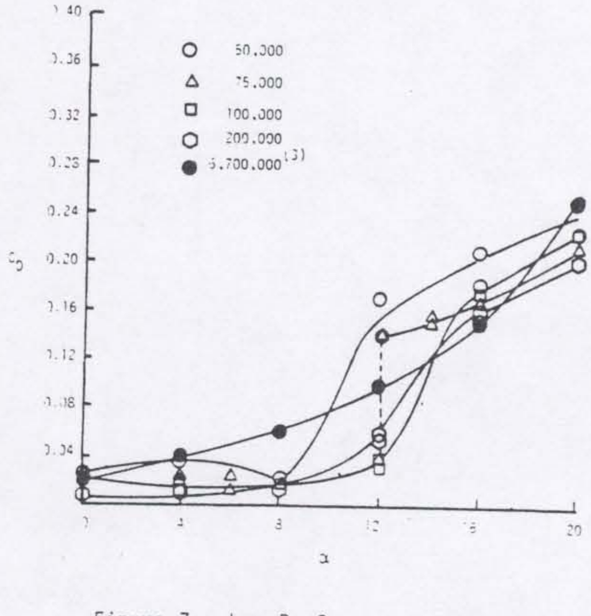


Figure 7: Low Re C_D vs α.

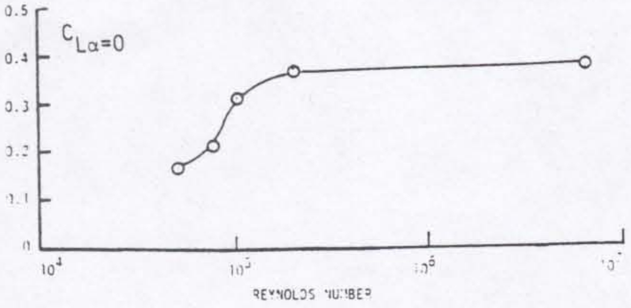


Figure 8: Variation of C_L at Zero Angle of Attack.