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ON THE EFFECT OF LEADING EDGE BLOWING ON CIRCULATION CONTROL AIRFOIL AERODYNAMICS

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Nomenclature

c	airfoil chord
C_ℓ	airfoil section lift coefficient, section lift/qc
C_μ	jet blowing momentum coefficient, $2(h/c)(U_j/U_\infty)^2$
h	jet slot height
q	free stream dynamic pressure, $(1/2)\rho U_\infty^2$
Re	Reynolds number, based on airfoil chord, $U_\infty c/\nu$
U_j	mean jet exit velocity
U_∞	mean free stream velocity
α	geometric angle of attack, deg.
ν	kinematic viscosity
ρ	free stream fluid density
Subscripts	
l.e.	leading edge jet
t.e.	trailing edge jet

Introduction

In the present context the term 'circulation control' is used to denote a method of lift generation that utilizes tangential jet blowing over the upper surface of a rounded trailing edge airfoil to determine the location of the boundary layer separation points, thus setting an effective Kutta condition. This form of circulation control applied to rotorcraft eliminates forward flight speed limitations due to conventional rotor retreating blade aerodynamic problems: lift loss due to reverse flow and dynamic stall. Using rotor blade sections symmetric about midchord, with upper surface leading and trailing edge jet blowing slots, permits simultaneous blowing on each edge of the retreating blade enabling the development of high lift coefficient values with the flow relative velocity coming from either direction (reverse or normal). At present little information exists on the flow structure generated by circulation control airfoils under leading edge blowing[1]. Consequently, no theoretical methods exist to predict airfoil performance under such conditions.

In view of this lack of information an experimental study of the flow field generated by a two-dimensional circulation control airfoil under steady leading and trailing edge blowing was undertaken. The objective of this study was to fundamentally understand the overall flow structure generated and its relation to airfoil performance. Flow visualization was

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performed to define the overall flow field structure. Measurements of the airfoil forces were also made to provide a correlation of the observed flow field structure to airfoil performance.

This paper presents preliminary results from that study. It will specifically address the effect on the flow field structure of leading edge blowing, alone and in conjunction with trailing edge blowing. In addition, phenomena concerned with the effect of trailing edge blowing alone on the flow field structure will be addressed.

Description of Experiment

The experiments were performed in the 8.4 × 12.0 in. (21 × 31 cm) rectangular closed circuit water tunnel of the Army Aeromechanics Laboratory at the Ames Research Center. A steel two-dimensional 4 inch (10.2 cm) chord airfoil, horizontally spanning the test section, was tested (see figure 1). The airfoil had an uncambered elliptical section (20 percent thickness to chord ratio) with circular arc leading and trailing edges; upper surface leading and trailing edge jet slots; and, dual plenum chambers.

In the present study the angle of attack was held constant at 0 degree's and the jet slot height at .0015c. Measurements were made of the mean and fluctuating forces at Reynolds numbers, based on chord, ranging from 120,000 to 390,000. Flow visualization was also performed using the hydrogen bubble and air bubble methods for Reynolds numbers of 34,000 and 200,000, respectively. The visual data was recorded on a typical commercial grade video system. The force data presented was not corrected for blockage or jet momentum effects.

Of mention, is that all of the lift curves displayed, except figure 4, were obtained by running the lift load cell output directly to an analog plotter. No time averaging, i.e. filtering, of the load cell output was done. Thus the thickness of the lift curve trace is an indication of the unsteadiness of the lift.

Experimental Results

Trailing Edge Blowing Characteristics

Lift Characteristics

Typical lift characteristics are shown in figure 2. It is evident that as the jet blowing increases, the lift increases in a continuous fashion, and the lift curve slope decreases. A point is reached however where the lift abruptly decreases and with further increases in jet blowing the lift gradually decreases. In this reduced lift region the lift is highly unsteady.

Flow Visualization - Overall Flow Pattern

The major features of the flow pattern associated with trailing edge blowing are represented schematically in figure 3.

Increasing jet momentum moves the jet separation point around the trailing edge towards the lower surface inducing circulation around the airfoil. This increased circulation is reflected in the flow pattern through an increase in the curvature of the streamlines. The pressure field attendant to the increased streamline curvature results in boundary layer separation at the leading edge, with the resulting free shear layer reattaching itself to the airfoil surface at some distance from the leading edge forming a separation bubble. The extent of this separation bubble increases as the trailing edge blowing increases. As the jet momentum increases the wake of the separation bubble becomes highly unsteady and appears visually to affect the jet entrainment process. It is interesting to speculate that the wake of the leading edge separation bubble may be linked to the maximum lift value attainable in free air conditions: that is, the occurrence of jet blowing stall.

Another consequence of the pressure field accompanying the increased streamline curvature is boundary layer separation on the airfoil lower surface and the formation of a separation bubble ahead of the jet. On the other hand, as the jet momentum is increased a point is reached where entrainment of fluid by the jet reattaches the boundary layer and collapses the lower surface separation bubble.

Jet impingement on the lower test section floor occurs for large values of jet blowing. The result is a large blockage effect and the development of a highly unsteady flow condition in the test section. The occurrence of this condition correlates with the abrupt lift decrease and corresponding high lift unsteadiness displayed in figure 2. Thus the abrupt lift loss displayed in the present results is probably due to wall interference and cannot be termed jet blowing stall.

Effect of Boundary Layer State on Lift

The boundary layer state, laminar or turbulent, was found to have a pronounced effect on the lift characteristics displayed for small jet momentum values ($C_\mu < .03$). This effect of boundary layer state on the lift characteristics is shown in figure 4. Both boundary layer state cases display a lift increase as the jet blowing increases. However, for the laminar boundary layer case a discontinuity in the lift curve is apparent, which is in contrast to the turbulent boundary layer case where the lift increases in a continuous fashion as the jet blowing momentum increases.

Through visual observation of the flow it was possible to discover the cause of the above effect. The observed trailing edge flow patterns are illustrated in figure 5. In the absence of trailing edge blowing the boundary layer separates from the upper and lower surface of the airfoil resulting in a large wake characterized by vortex shedding. The boundary layer state determines where separation occurs in relation to the jet slot: ahead of the jet slot location when the boundary layer is laminar; and at the jet slot location when the boundary layer is turbulent. It is entrainment of fluid by the jet that reattaches the upper surface boundary layer. The different lift characteristics displayed by the laminar and turbulent boundary layer states are due to the different amounts of entrainment necessary to reattach the boundary layer in each state. Reattachment of the laminar boundary layer requires a finite amount of jet blowing. It is not a gradual process, visually it occurs abruptly, and results in the discontinuity in the lift curve. Reattachment of the turbulent boundary layer occurs immediately upon the start of trailing edge blowing.

Leading Edge Blowing Characteristics

General Remarks

To a first approximation the trailing edge jet can be thought of as setting the flow field that the leading edge jet initially exits into. A feature that complicates this specific aspect of the overall flow is that the leading edge jet exits against the outer flow. A competition therefore occurs between the velocity and pressure field of the outer flow and the momentum and entrainment of the leading edge jet. The leading edge flow structure is determined by the balance reached between these elements. Flow visualization in the present study indicates that entrainment by the leading edge jet is a major determinant in setting the leading edge flow structure.

Lift Characteristics

The lift characteristics for simultaneous leading and trailing edge blowing were obtained by holding the momentum of one jet constant and varying the momentum of the other jet. A typical result of this procedure is shown in figure 6, where the lift coefficient is plotted[1] as a function of the trailing edge jet momentum coefficient for two constant values of the leading edge jet momentum coefficient, 0 and 0.046. For both leading edge values the lift increases with increasing trailing edge blowing. However, it is clear that the presence of leading edge blowing results in a lift decrease in comparison to the trailing edge blowing alone case. Also of note, is the increased unsteadiness of the lift in the leading edge blowing case.

A representative example of reversing the above procedure is shown in figure 7: displayed is the effect of leading edge jet momentum on the lift for constant trailing edge jet momentum coefficients of 0 and 0.052. In the presence of trailing edge blowing the lift is approximately constant for small to moderate jet momentum coefficients and is lower than the lift generated for jet momentum coefficient values outside that range. A feature to particularly note in the reduced lift zone, over a small jet momentum coefficient range, is a region where the lift is unsteady. In the absence of trailing edge blowing low lift is generated. Yet, the low lift generated does exhibit behavior of note: an abrupt decrease, though slight, in the lift and a change in the sign of the lift curve slope at $C_{\mu_{\text{l.e.}}} \approx .06$.

Flow Visualization - Leading Edge Flow Pattern

The flow visualization revealed that at low values of the leading edge jet momentum coefficient the leading edge jet goes completely over the upper surface, and that at high coefficient values the leading edge jet goes completely over the lower surface. For intermediate coefficient values the leading edge jet behavior is more complicated with the jet bifurcating or becoming bistable. Here the term bifurcation is used to describe the divi-

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[1] In all the lift curves pertaining to leading edge blowing the vertical axis scale, though absent, is the same.

sion of the jet into two parts, one part proceeding over the upper surface, and the other part proceeding over the lower surface. The term bistable is used to denote an unsteady condition. This point will be further elaborated on shortly.

A prominent feature of the leading edge flow field for certain values of leading and trailing edge jet momentum is the formation of a circulatory flow pattern - namely, a 'vortex'. This feature occurs for conditions where the majority of the jet folds back, after extending itself out over the airfoil nose, and proceeds over the upper surface. Entrainment by the jet of part of itself induces the circulatory flow pattern.

The relation of these structural features of the leading edge flow field to the previously displayed lift characteristics is shown in figure 8.

It was possible to make a 'map' of the leading edge flow structure through correlation of the flow visualization observations with the leading and trailing edge jet momentum settings. The 'map' is displayed in figure 9 where the flow features described previously are indicated schematically. As noted already the term bistable is used to denote an unsteady leading edge jet flow state. Referring to figure 9, when bistable, the structure of the leading edge jet appears visually to move between the two steady flow states that border the bistable region along a line of constant $C_{\mu_{t.e.}}$.

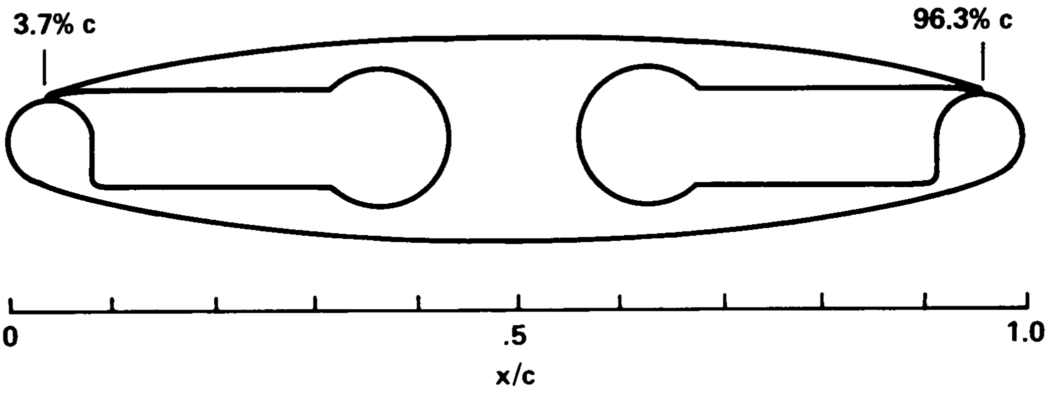
Conclusions

The conclusions pertaining to leading edge blowing may be summarized as follows.

- Simultaneous leading and trailing edge blowing results in a lift decrease in comparison to trailing edge blowing alone. However, it must be noted that appreciable lift is still developed.
- Leading edge blowing can result in an unsteady flow condition.
- The leading edge flow structure is more complicated than previously hypothesized: e.g., under certain conditions jet entrainment induces a circulatory flow pattern at the leading edge of the airfoil.

References

1. Ottensoser, J., "Two-Dimensional Subsonic Evaluation of a 15-Percent Thick Circulation Control Airfoil with Slots at both Leading and Trailing Edges," DTNSRDC Report 4456, July 1974.



AIRFOIL PARAMETERS

CHORD – 4 in. (0.102 m)
THICKNESS – 0.2 c
JET SLOT HT. – 0.0015 c
L.E. & T.E. RADIUS – 0.04 c

Figure 1.-Airfoil geometry and parameters.

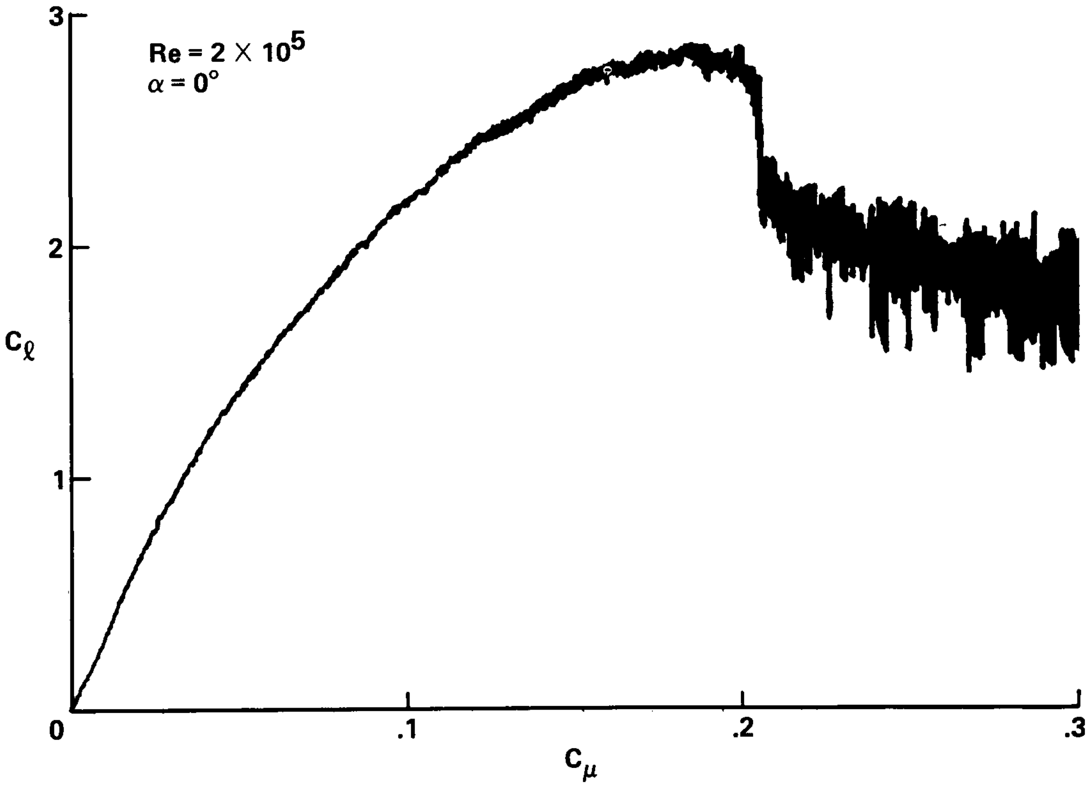


Figure 2.-Airfoil lift characteristics: trailing edge blowing alone; turbulent boundary layer case.

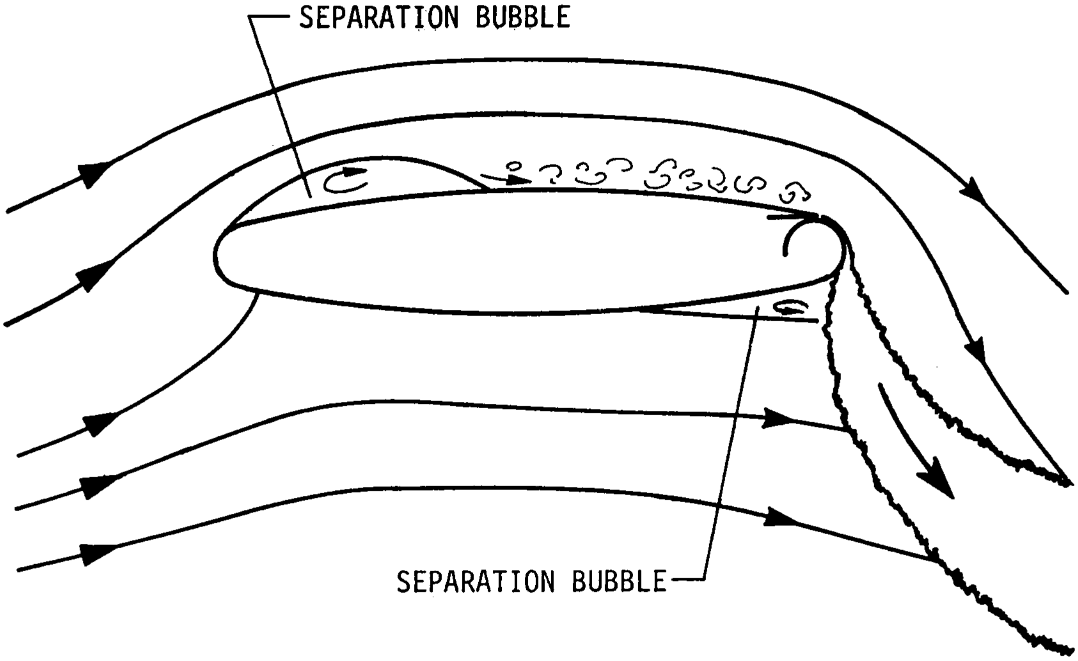


Figure 3.-Schematic of overall flow pattern associated with trailing edge blowing.

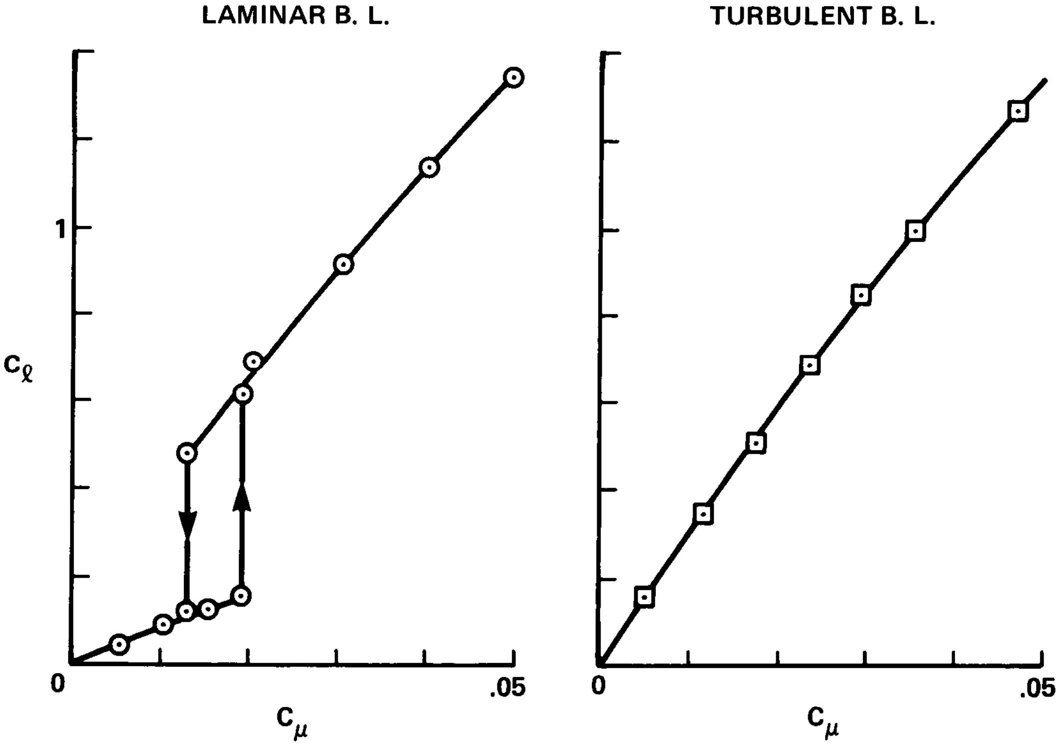


Figure 4.-Effect of boundary layer state on lift characteristics: $Re = 1.93 \times 10^5, \alpha = 0°$.

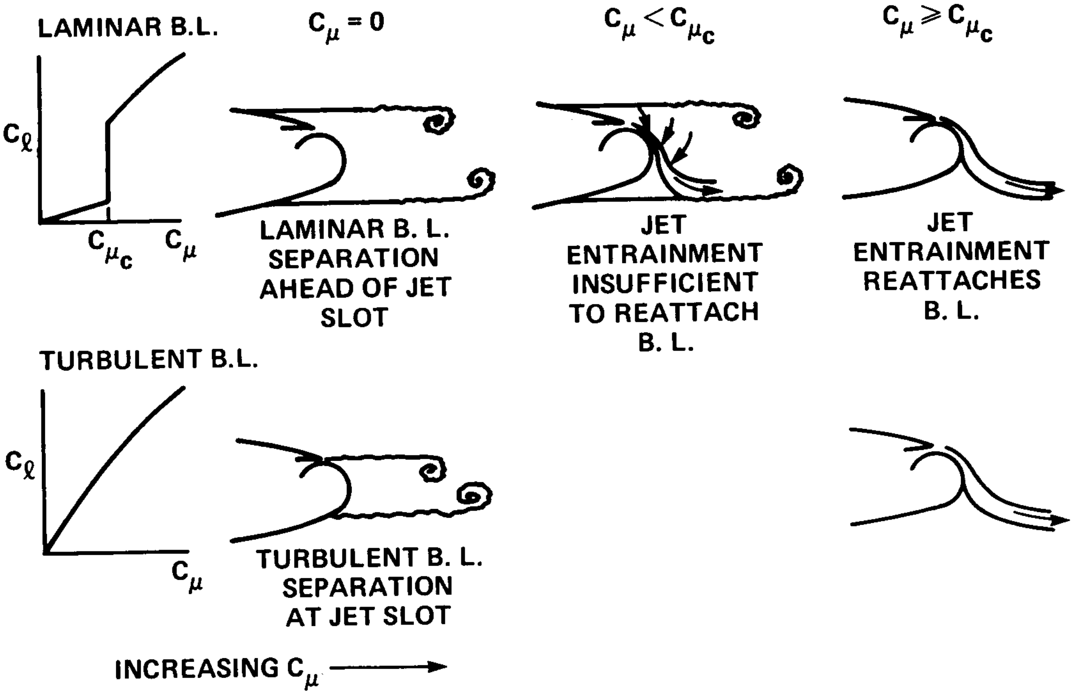


Figure 5.-Effect of boundary layer state on lift characteristics: schematic of trailing edge flow pattern.

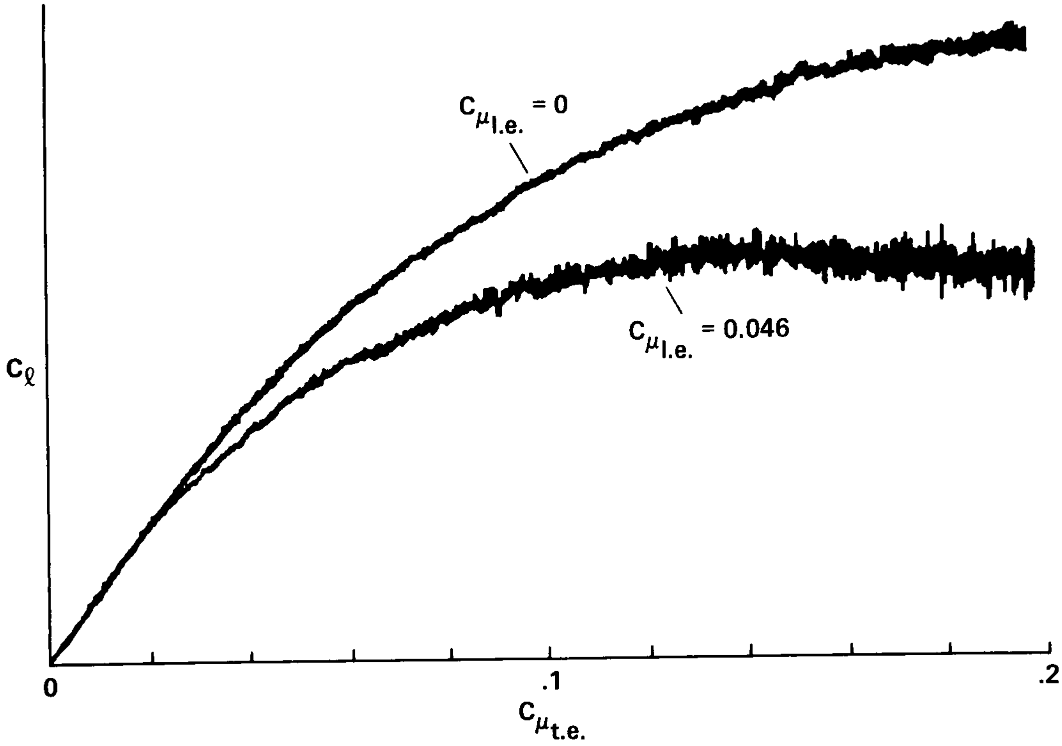


Figure 6.-Effect of trailing edge blowing on lift characteristics: constant leading edge blowing; Re $= 2.1 \times 10^5, \alpha = 0°$. The vertical axis scale is the same for figures 6, 7, and 8.

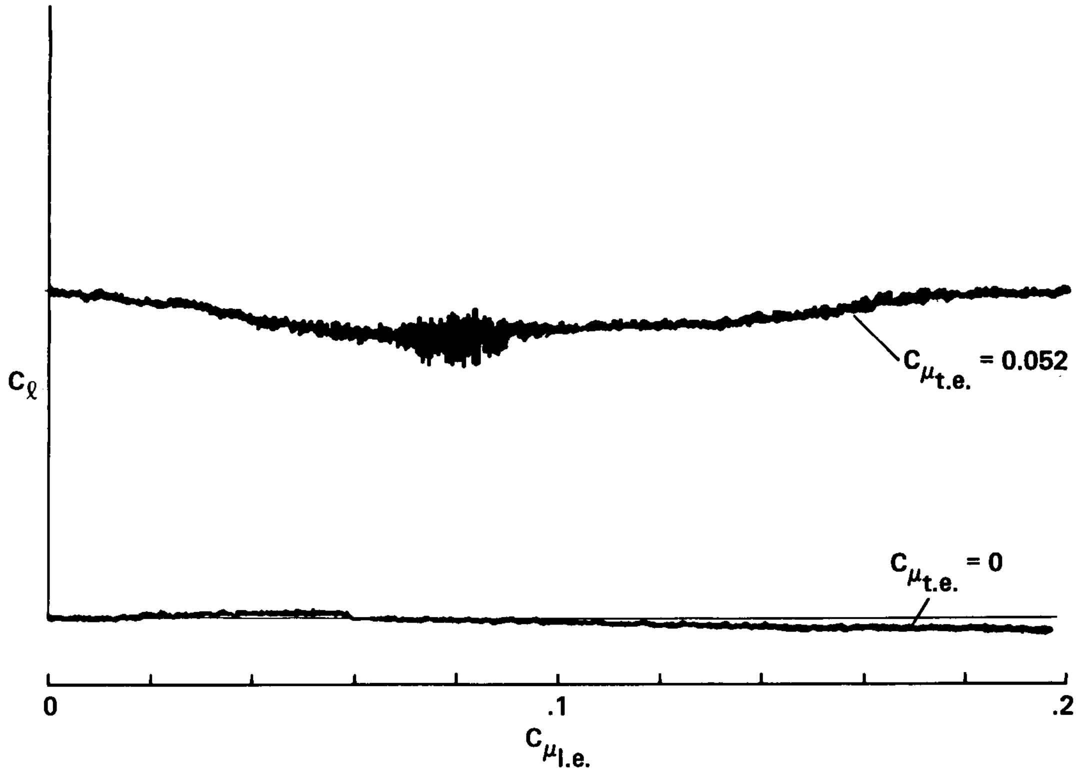


Figure 7.-Effect of leading edge blowing on lift characteristics: constant trailing edge blowing: Re = $2.1 \times 10^5, \alpha = 0°$.

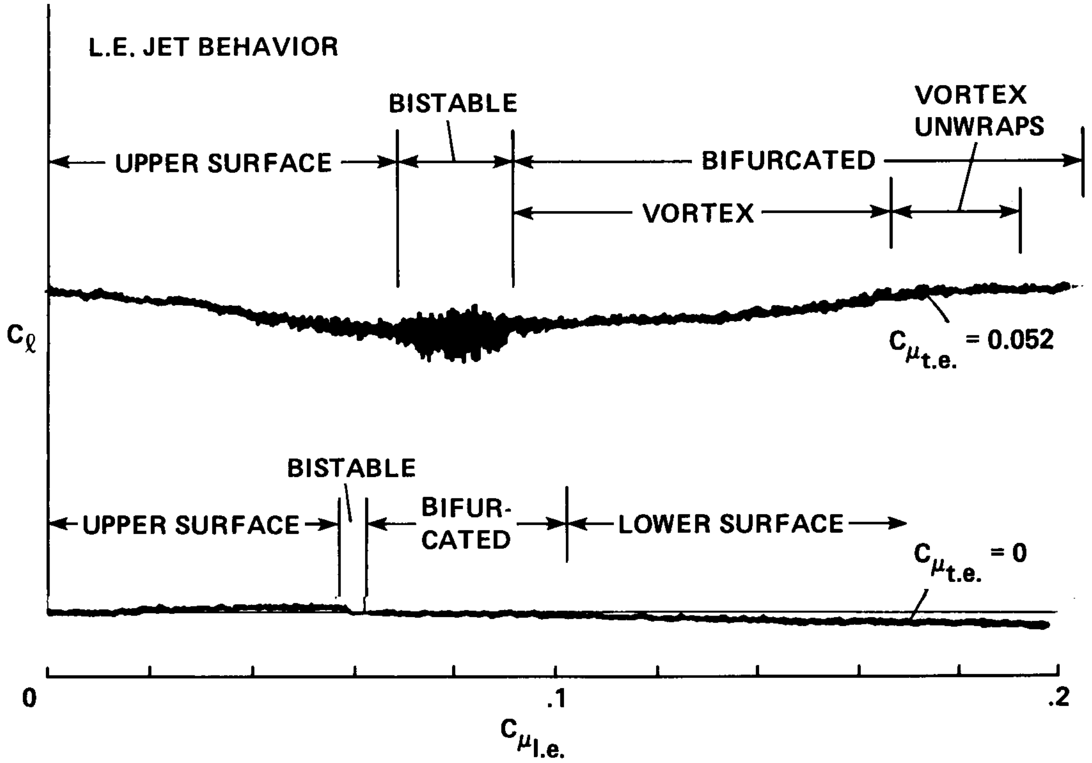


Figure 8.-Correlation of leading edge jet flow field structural features with lift characteristics: Re = $2.1 \times 10^5, \alpha = 0°$.

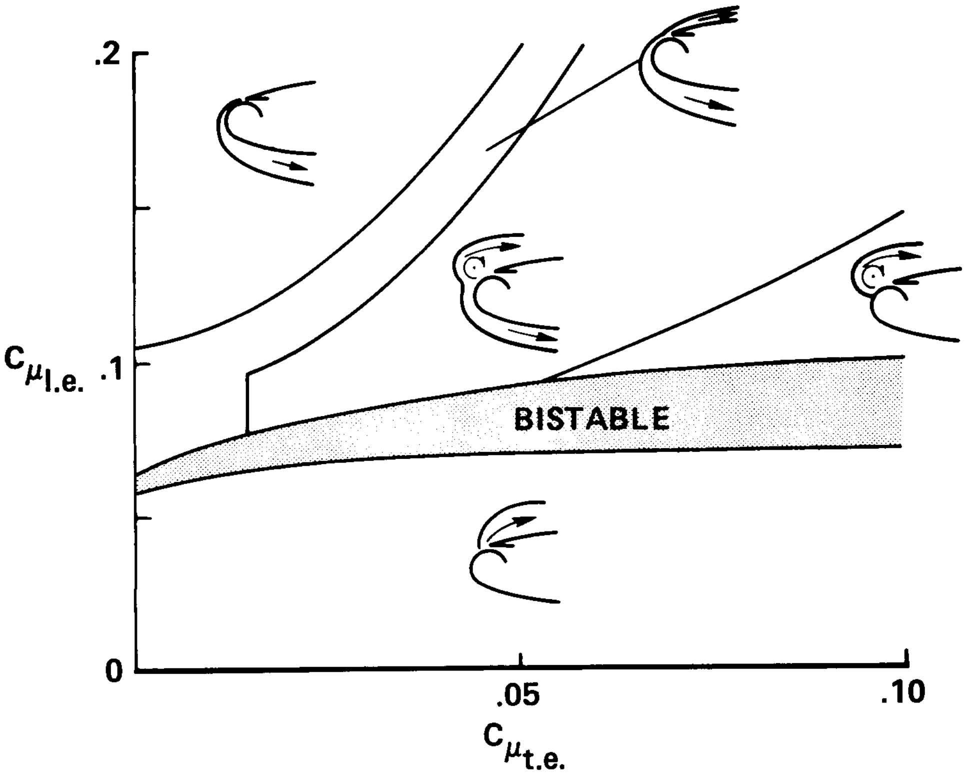


Figure 9.-Map of leading edge jet flow field structure: $\alpha = 0°$.