Aerodynamic Characteristics of an Airfoil in a Nonuniform Wind Profile

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An experimental wind tunnel investigation was carried out to determine the influence of a nonuniform wind profile on the static longitudinal aerodynamic coefficients (c_ℓ, c_d, c_m) of an airfoil. Force balance and surface pressure measurements were obtained from an NACA 0018 airfoil in a linear velocity gradient. The airfoil was tested in a Reynolds number range from 7.5×10^4 to 2.0×10^5, with endplates to simulate an infinite wing, and with the outboard endplate removed to simulate a finite wing. The effect of grit on the surface of the airfoil was also investigated. The influence of the velocity gradient on the aerodynamic characteristics of the airfoil was found to be small, especially in comparison to the effects of the grit.

Nomenclature

b	= wing span of the model
c	= chord of the airfoil
c_d	= sectional drag coefficient
c_ℓ	= sectional lift coefficient
C_L	= wing lift coefficient
c_m	= sectional moment coefficient
C_p	= pressure coefficient
R	= Reynolds number based on chord
t/c	= airfoil thickness-to-chord ratio
x/c	= nondimensional distance along chord
$Z/(b/2)$	= nondimensional distance along span
α	= angle of attack

Introduction

ALTHOUGH wind shear has been recognized as a hazard to aviation for some time, it was not until the last decade when several accidents involving commercial aircraft[1,2] were attributed to severe wind shear that an intense effort by the aviation community was begun to investigate this phenomenon. The task of evaluating the wind shear problem includes accident/incident analysis, meteorological studies, wind shear characterization, experimental and analytical wind shear modeling, and computer simulation of aircraft response.

In most computer simulations of aircraft encountering a wind shear, it has been assumed that the effect of a velocity gradient on the static aerodynamic coefficients can be neglected. It is the purpose of this study to assess the validity of that assumption using a wind tunnel experiment. A relatively low Reynolds number range for the experiment was dictated by model size and wind tunnel conditions; however, the results are believed to be applicable to higher Reynolds number conditions.

In this paper, an experimental study to investigate the influence of a nonuniform flowfield on the static aerodynamic characteristics of an airfoil section and a finite wing will be discussed. There have been a limited number of theoretical studies aimed at determining the influence of a velocity gradient on the longitudinal and lateral aerodynamic coefficients. In 1942, Tsien[3] derived the equations which represent a symmetrical Joukowsky airfoil in a linear shear flow. Tsien generalized the well-known Blasius theorem for calculating aerodynamic forces acting on an airfoil to apply in a shear flow, he then applied the results to the case of symmetrical Joukowsky airfoils. Tsien's results indicate that the effect of a velocity gradient on the lift coefficient is equivalent to a shift in the angle of zero lift. The amount of the shift is dependent on the magnitude of the velocity gradient and the thickness-to-chord ratio (t/c). For realistic values of velocity gradient and t/c, the shift in the angle of zero lift is less than 0.2 deg. A positive velocity gradient will cause a negative shift in the angle of zero lift, which corresponds to a positive increment of lift at any given angle of attack.

In 1973, Frost and Hutto[4] analytically studied the influence of wind shear on the lift, drag, roll and yaw moments of a wing in a horizontal wind gradient at various elevations and roll angles. Frost and Hutto employed a general series solution for the distribution of lift along the wing span to compute loads and moments on the airfoil. The system of equations governing the lift, drag, roll and yaw moments for a variety of wind conditions was solved on the computer. The results of the foregoing computations indicated that wind shear can have a significant effect on the rolling and yawing moments of an aircraft flying with one wing low in the atmospheric boundary layer. The influence of wind shear on lift and drag for the same parametric conditions was estimated to be less than 1%.

An extensive literature search which included a Federal Aviation Administration wind shear survey[5] and a Defense Documentation Center survey[6] revealed minimal experimental wind tunnel research aimed at determining the effects of wind shear on an aircraft. Published experimental research related to the influence of wind shear on the longitudinal or lateral aerodynamic coefficients is either very rare or nonexistent. It is the purpose of this investigation to provide experimental data on the influence of vertical wind shear on static longitudinal aerodynamic coefficients.

Experimental Equipment

The tests were conducted at the University of Notre Dame's low-speed wind tunnel laboratory. The tunnel used was a low-turbulence, indraft (open-circuit) type with 12 antiturbulence screens at the inlet, a 24:1 contraction cone, and a $0.61 \times 0.61 \times 1.83$ mm test section. A sketch of the tunnel is

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shown in Fig. 1. In this configuration, the tunnel is capable of producing velocities in the range of 5-30 m/s with a turbulence intensity of approximately 0.10% over the entire velocity range.

The NACA 0018 airfoil model used with the force balance had a chord of 12.7 cm (5.1 in.) and a span of 39.4 cm (15.4 in.). A relatively thick airfoil profile was chosen for ease in construction of a pressure model. The pressure model had exactly the same dimensions as the force balance model, and was fitted with seven spanwise rows of 25 pressure taps. These pressure taps extended from the leading edge across the upper and lower surfaces to a distance of $X/c = 0.85$. Figure 2 shows the pertinent geometric characteristics of the airfoil.

For the tests that required a shear flow, a curved, uniform-mesh screen was placed upstream of the test section to produce a linear velocity gradient. The shear screen has the effect of turning the streamlines upwards and producing a higher mass flow at the top of the tunnel section than exists at the bottom, thereby causing a higher velocity at the top of the tunnel. Further downstream, the streamlines again become parallel. The shear screen was built by Fiscina[7] following a method first derived by Elder[8] and later revised by Maull.[9] The velocity profile produced by the screen is shown in Fig. 3. In wind tunnel tests of a model in a shear flow, a relatively severe velocity gradient is required because of the small size of the model. The shear screen was also responsible for an increase of the freestream turbulence level in the test section from 0.1 to 0.5%. Figure 4 indicates the turbulence intensity at the model location.

An externally mounted, two-component strain gage balance with a dual flexure system was used to measure lift and drag on the airfoil. The dual flexure system was designed to allow maximum sensitivity for large or small loads. For low loads from 0.01 to 13.0 N, a very sensitive flexure was used; at higher loads a stiffer flexure engaged. The signal from the strain gage was amplified and filtered to remove high-frequency oscillations before being fed into a Soltec VP-52325 chart recorder. Figure 5 is a sketch of the experimental setup. For the force measurement tests, the shear screen was rotated 90 deg so that the linear velocity gradient was normal to the airfoil.

A relatively simple and economical method was used to survey the 175 pressure ports of the airfoil model. A single pressure transducer was used in conjunction with a Scanivalve automatic pressure sampling unit and a set of fluid switches to measure the pressure at each port in sequence.

The Scanivalve model 48-J9 scanner, controlled by a Scanivalve CTLR 10P/52-56 solenoid controller, is capable of sequentially scanning up to 48 pressure ports at a variable rate. A set of Scanivalve fluid switch wafers was used to expand the capability of the scanner to sample all 175 airfoil pressure ports, while still using only the one transducer. A Setra System Model 237 low-range pressure transducer was used. This transducer was designed to measure pressure in the range of ± 0.1 psi (1.73×10^3 N/m^2) with high accuracy.

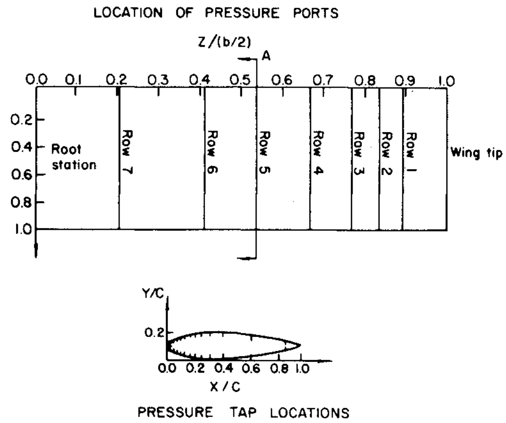

Fig. 2 Pressure model—location of pressure ports.

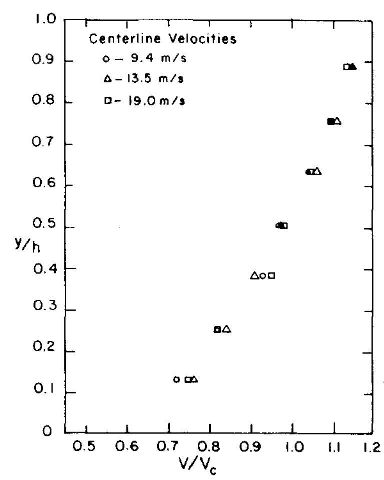

Fig. 3 Velocity profile downstream of the shear screen.

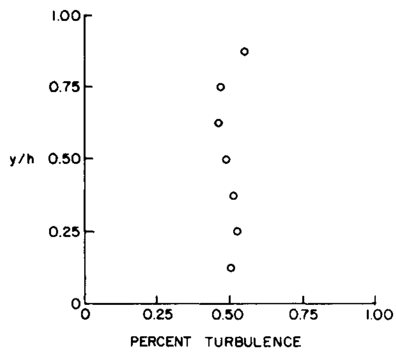

Fig. 4 Turbulence intensity vs y/h.

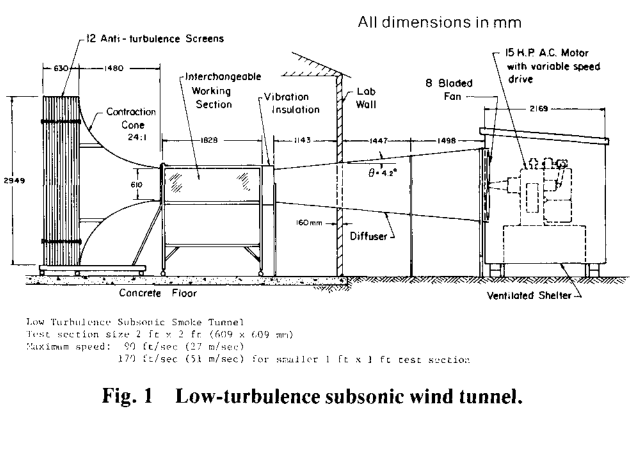

Fig. 1 Low-turbulence subsonic wind tunnel.

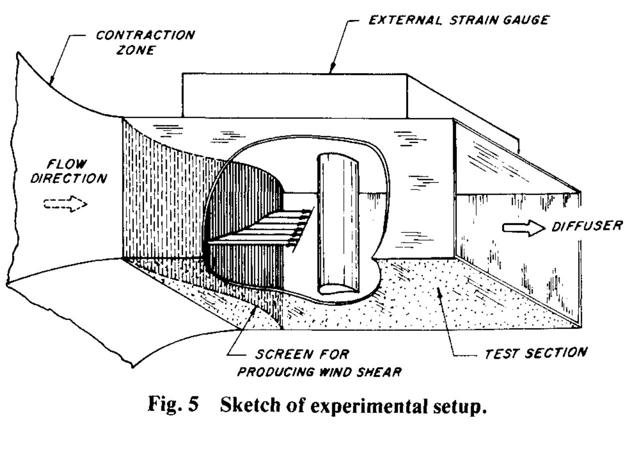

Fig. 5 Sketch of experimental setup.

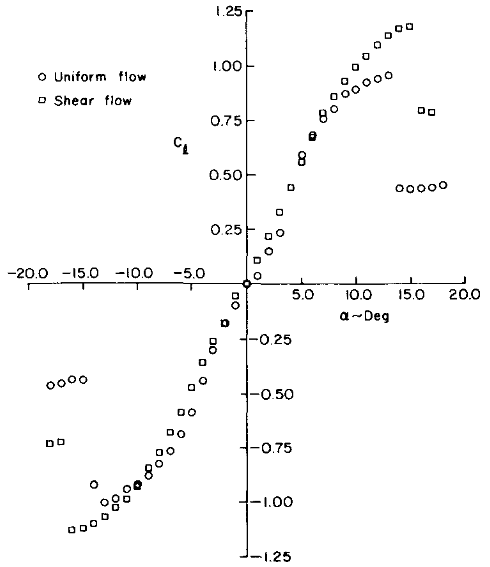

Fig. 6 c_ℓ vs α, uniform and shear flows; $R = 150{,}000$, force balance data.

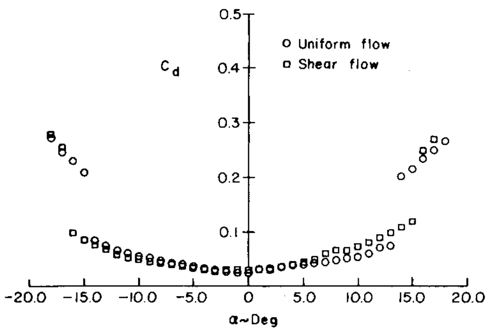

Fig. 7 c_d vs α, uniform and shear flows; $R = 150{,}000$, force balance data.

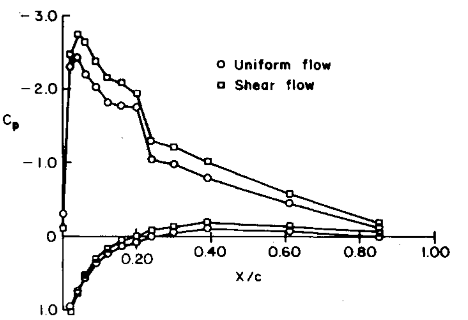

Fig. 8 C_p vs X/c, uniform and shear flows; $R = 150{,}000$, row 5, $Z/(b/2) = 0.538$, $\alpha = 10$ deg.

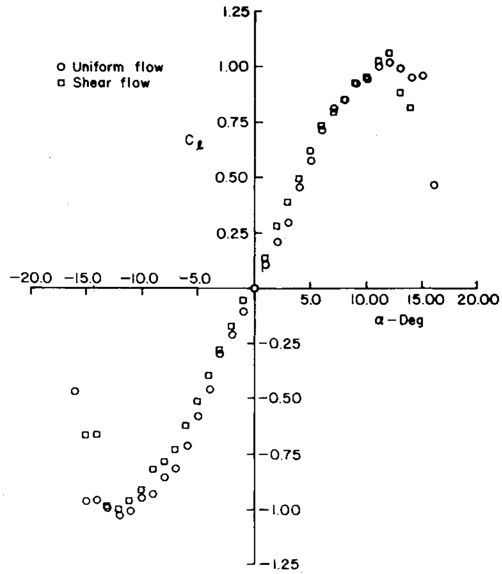

Fig. 9 c_ℓ vs α, uniform flow, at $R = 200{,}000$, shear flow at $R = 75{,}000$, infinite wing.

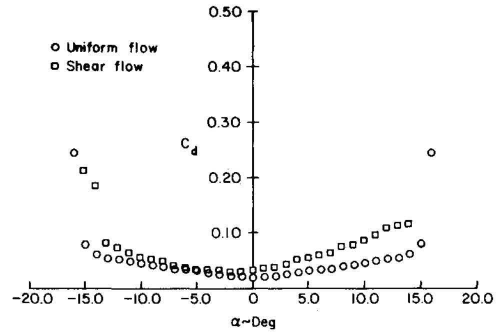

Fig. 10 c_d vs α, uniform flow at $R = 200{,}000$, shear flow at $R = 75{,}000$, infinite wing.

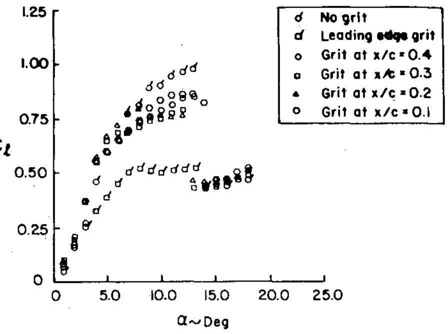

Fig. 11 c_ℓ vs α, effect of grit, uniform flow, $R = 150{,}000$.

Wind tunnel tests were run to identify the characteristics of an airfoil in a shear flow. The NACA 0018 airfoil was tested at various tunnel velocities for positive and negative angles of attack up until stall. The airfoil was tested in both a uniform and shear flow. Test Reynolds numbers ranged from 75,000 to 200,000.

Discussion of Results

Infinite Wing—Force Balance Data

A strain gage force balance was used to obtain lift and drag data in wind tunnel tests of an NACA 0018 airfoil model in uniform and shear flows. Endplates were used to simulate an infinite wing. The asymmetric nature of the velocity gradient was reflected in the data obtained; however, these effects were generally found to be small and the aerodynamic characteristics of the airfoil remained largely unchanged by the gradient. Effects directly attributable to the velocity gradient were found to be of the same order of magnitude as those caused by other phenomena, i.e., turbulence generated by the shear screen and laminar separation and turbulent reattachment of the flow on the airfoil's leading edge. Because the effects caused by these phenomena, including those caused by the velocity gradient, are generally hard to isolate and, in some cases, are of the same order of magnitude as the margin of error for these experiments, it is possible to identify only some of the particularly distinctive characteristics of the simulated wind shear.

Figure 6 compares the c_ℓ vs α curves for the airfoil in uniform and shear flows at a Reynolds number of approximately 150,000. The most significant effect attributable to the simulated shear flow is a delay of the stall by 2 to 3 deg and an increase in the maximum lift coefficient. In the shear flow, at positive angles of attack, stall is delayed from 14 to 16 deg. The maximum lift coefficient is increased by 22% from a value of 0.96 in the uniform flow to 1.18 in the shear flow. At negative angles of attack, stall is delayed from -14 deg in the uniform flow to 17 deg in the shear. The magnitude of the maximum lift coefficient at negative angles is increased by 13% from a value of -1.00 in the uniform flow to -1.13 in the shear flow. The increase of the maximum lift coefficient in the simulated shear flow is not entirely a consequence of the velocity gradient but is due, in part, to the increase of turbulence generated by the shear screen. The effect of this turbulence is discussed in a later section. The asymmetry of the shear flow is reflected in the fact that $c_{\ell_{max}}$ is increased by a larger percentage at positive angles (22%) than at negative angles (13%).

The effect of the shear on the drag coefficient is plotted in Fig. 7. At 13 deg, the measured coefficient of drag is increased from a value of 0.075 in the uniform flow to 0.097 in the shear flow. At -13 deg, the drag coefficient is reduced from 0.074 in the uniform flow to 0.066 in the shear flow. Note, that, in the shear flow, the coefficient of drag is higher at positive angles of attack than at the corresponding negative angles. At angles of attack greater than ± 13 deg, the airfoil begins to stall, and lift and drag comparisons become less meaningful.

The observed asymmetry in the c_ℓ vs α and c_d vs α curves in the shear flow are the most obvious consequences of the velocity gradient. Considering the effects of the velocity gradient alone, the observation that a slightly higher (magnitude) $c_{\ell_{max}}$ was measured in the shear flow at a negative angle of attack is contrary to what is expected and is probably a consequence of the increased freestream turbulence.

Infinite Wing—Pressure Survey Data

The pressure survey measurements provide a more detailed description of the flow characteristics and confirm the results obtained with the force balance. The pressure distributions shown are at $Z/(b/2)=0.538$ or approximately midspan of the model. It is to be noted that the shear flow did not significantly alter the shape of the pressure curves, however, in almost every case, the magnitude of the recorded pressures differed between the uniform and shear flows. A close examination of these curves reveals that the shear flow seems to have an effect on the relative contribution of the upper and lower surfaces to the total lift, depending on whether the airfoil is at a positive or negative angle of attack. Note that this is a consequence of using the centerline pressure in the shear flow as a reference for computing the pressure coefficients. Figure 8 compares the pressure distribution around the airfoil for a shear and uniform flowfield.

Effect of Freestream Turbulence

Analysis of the lift, drag, and pressure data of the airfoil in the uniform and shear flows indicates that other phenomena, in addition to the velocity gradient, have important effects on the results. The pressure plots indicate that a laminar separation bubble forms near the leading edge of the airfoil's upper surface at angles of attack greater than 10 deg. The sharp increase in the pressure, characteristic of a separation bubble, is easily recognizable in Fig. 8. From the force balance and pressure survey data, it is apparent that turbulence produced by the shear screen increases the effective Reynolds number of the airfoil in the shear flow, thereby reducing the size of the laminar separation bubble and increasing lift at a given angle of attack.

Gault[11] conducted an experimental investigation of laminar separation bubbles at Ames Aeronautical Laboratory. He determined that an increase in the freestream turbulence level reduces the extent of separated flow by moving the point of transition farther upstream (the bubble becomes shorter) in a manner analogous to an increase in the Reynolds number. In his experiment, Gault raised the freestream turbulence level from a value of 0.2% to 1.1% by the insertion of a turbulence net upstream of the test section. He noted that this fivefold increase in turbulence intensity reduced the extent of separated laminar flow near the leading edge in almost the same proportion as a twofold increase in Reynolds number. This is consistent with the observed effect of the turbulence generated by the shear screen in this investigation. The shear screen caused a fivefold increase of the turbulence intensity in the test section from 0.1 to 0.5%. Gault's findings suggest it may be more appropriate to compare the shear flow results at a Reynolds number of 75,000 to the uniform flow results at a Reynolds number of 150,000, assuming the increase in turbulence generated by the shear screen effectively doubles the Reynolds number of the airfoil in the shear flow. In fact, the shear flow results at a Reynolds number of 75,000 appear to be more comparable to the uniform flow results at a Reynolds number of 200,000. c_ℓ vs α and c_d vs α for these Reynolds numbers are plotted in Figs. 9 and 10, respectively. Note that, compared to the uniform flow condition, the coefficient of lift is slightly increased at positive angles of attack in the shear flow and is slightly reduced (in magnitude) at negative angles of attack in the shear flow. This is precisely what is predicted from theory. Also, as expected in the shear flow, the drag coefficient is found to be higher at positive angles of attack than at negative angles.

Effect of Roughness

The NACA 0018 airfoil model used in this investigation demonstrated extremely sensitive behavior with respect to freestream turbulence level and Reynolds number. This is primarily because early separation and, in particular, laminar separation near the leading edge has such a significant effect on the aerodynamic characteristics of an airfoil. Various means which can be used to reduce or eliminate the effects of Reynolds number were studied by Miller[12] at the U.S. Army Armament Research and Development Command. All of these methods require some form of boundary-layer control to reduce the effect of flow separation. One of the classical and simple methods of boundary-layer control involves a strip of grit applied to the surface of the airfoil as a means of creating a turbulent boundary layer, thereby preventing early laminar boundary-layer separation.

Grit was applied to the airfoil used with the force balance in this study, and the airfoil was tested in the uniform and shear flows described previously. Double-stick tape was coated on one side with 0.636-0.762-mm-diam grit and applied to the airfoil. Several tests were run to determine the effect of the grit at five locations on the airfoil. The grit was applied to a 25.4-mm-wide strip at the leading edge, and on a 12.7-mm-

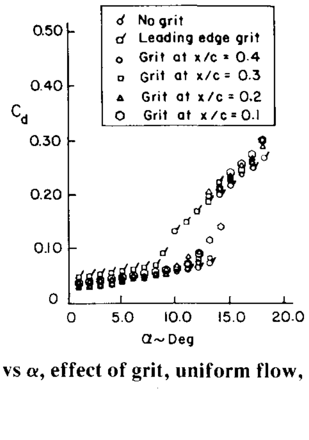

Fig. 12 c_d **vs** α**, effect of grit, uniform flow,** $R=150{,}000$**.**

wide strip at $X/c = 0.1$, 0.12, 0.3, and 0.4. c_ℓ vs α and c_d vs α for the airfoil with the grit is plotted in Figs. 11 and 12, respectively. At angles of attack less than 8 deg, the 12.7 mm strips of grit slightly increase lift and drag on the airfoil. At higher angles, lift is reduced and drag is increased. The 25.4-mm-wide strip of grit on the leading edge dramatically reduces lift and increases drag at all angles. The pressure distribution of the airfoil with grit on the leading edge is compared with that of a smooth airfoil in Fig. 13. Note that there is no evidence of a laminar separation bubble on the airfoil with the leading-edge grit. c_ℓ vs α and c_d vs α for the airfoil with the leading-edge grit in the uniform and shear flows are presented in Figs. 14 and 15, respectively. The curves are nearly identical and any influence of the velocity gradient is not apparent or is insignificant in comparison to the effects of the grit.

Although these tests are carried out at a relatively low Reynolds number (150,000), the results are consistent with data obtained at higher Reynolds numbers. Hoerner and Borst[13] show that roughness on an NACA 0012 airfoil tested at $R = 6{,}000{,}000$ reduced lift and the maximum lift coefficient.[14] This is clearly illustrated in Fig. 16. The lift curve slope is reduced and the maximum lift is cut down from 1.48 to 1.07. It appears that roughness on the leading edge takes away a specific amount of momentum from the suctionside boundary layer, thus reducing pressure recovery at the trailing edge. The lift coefficient was found to be further reduced by roughness with increasing Reynolds number. Hoerner and Borst point out in full-scale airplane operations that paint, dust, and or insects picked up by the airplane on the ground or in flight can easily make the nose of the wing section sufficiently rough to affect its maximum lift coefficient.

The results of this investigation indicate that roughness can seriously alter the aerodynamic characteristics of an airfoil and that these effects can be far more severe than those caused by a velocity gradient for the range of Reynolds numbers tested. This is especially significant in light of a recent study at the University of Dayton Research Institute. In this study, Luers and Haines[15] conclude that heavy rain which usually accompanies wind shears produced by thunderstorms can cause severe aerodynamic penalties on aircraft, including both a momentum penalty due to the impact of rain and a lift and drag penalty due to rainroughening of the airfoil and fuselage. This study indicated that the magnitude of penalties associated with heavy rain can be of the same order as that associated with wind shear. Luers and Haines evaluated these penalties using a computer model that, when incorporated into a landing simulation program, was used to assess the relative influence of heavy rain vs wind shear. The results of the computer simulation indicated that the aerodynamic effects of heavy rain may have been significant contributors to wind-shear-attributed accidents. The above results were obtained totally by a theoretical analysis with no experimental wind tunnel or flight data, and did not consider the lift penalty due to airfoil roughness.

The observed effect of grit on the airfoil model in this study supports Luers and Haines' conclusions. The aerodynamic characteristics of the airfoil were influenced far more by the grit than by the velocity gradient. The airfoil with the grit on the leading edge displayed greatly reduced lift and increased drag, especially at high angles of attack.

However, note that the above comparison does not address the large-scale problem of an aircraft descending from a region of high relative wind speed to one of low relative wind speed. In this experiment only the effects of the velocity gradient on an airfoil in horizontal flight are considered. Therefore, no conclusions on the relative importance of wind shear to heavy rain should be drawn from these results.

In the preceding sections, the influence of a linear shear profile and surface roughness were examined for an infinite wing. A finite wing was also used in this study and the experimental data exhibited the same trends as the infinite wing results reported in this paper. For more information on the finite wing results, the reader is referred to Ref. 16.

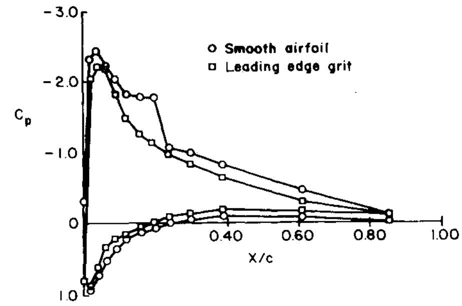

Fig. 13 C_p vs X/c, with and without leading-edge grit, row 5, $Z/(b/2) = 0.538$, $\alpha = 10$ deg.

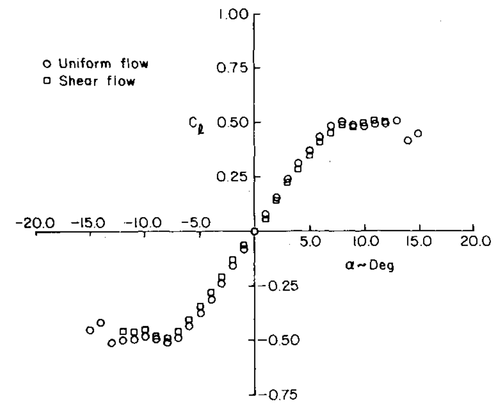

Fig. 14 c_ℓ vs α, effect of grit, uniform and shear flows, $R = 150{,}000$.

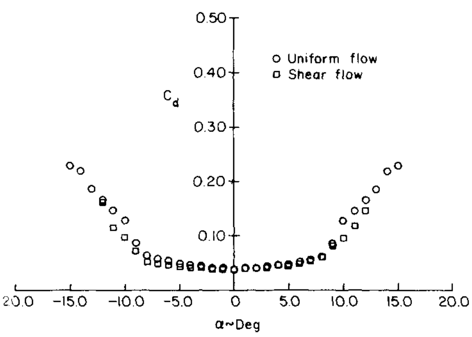

Fig. 15 c_d vs α, effect of grit, uniform and shear flows, $R = 150{,}000$.

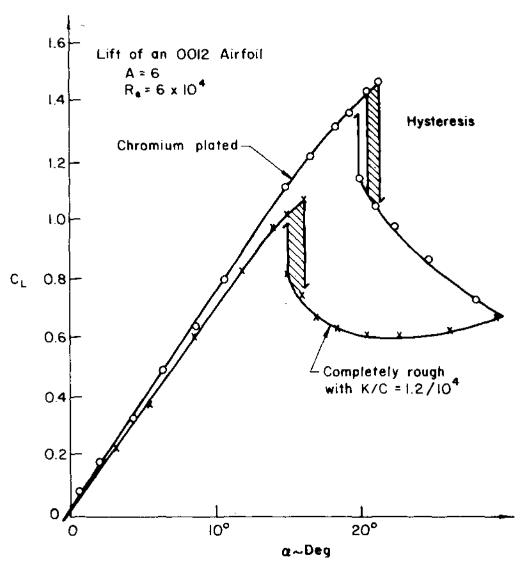

Fig. 16 Influence of grit on an NACA 0012 airfoil at $R = 6 \times 10^6$ (from Ref. 14).

Conclusions

The influence of a velocity gradient on the static longitudinal aerodynamic coefficients was found to be small. Experiment and theory agree that the effect of a velocity gradient on the lift coefficient is equivalent to a small shift in the angle of zero lift, which corresponds to an increment of lift at any given angle of attack. The influence of the gradient on the drag coefficient was reflected by an asymmetry in the c_d vs α curves. In a positive shear, the drag coefficient was higher at positive angles of attack than at the corresponding negative angles. The velocity gradient had no noticeable effect on the moment coefficient.

The velocity gradient did not significantly alter the shape of the pressure curves; however, the necessity of choosing a reference pressure of the shear flow to be used in computing the pressure coefficients was responsible for an apparent change in the relative contributions of the upper and lower surface pressure distributions.

The aerodynamic characteristics of the airfoil were influenced far more by the placing of grit on the surface than by the velocity gradient. The airfoil with the grit on the leading edge displayed greatly reduced lift and increased drag, especially at high angles of attack. The same trends were observed using the finite wing model.

The results of this study indicate that, when mathematically modeling an aircraft in a shear flow, it is reasonable to assume that the velocity gradient has a negligible effect on the static longitudinal aerodynamic coefficients. However, if the shear flow is accompanied by heavy rain, the effects of roughness may be very significant and should be considered carefully.

Acknowledgment

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References

[1]Aircraft Accident Report: Iberia Lineas Aereos de Espana (Iberian Airlines), McDonnell Douglas DC-10-30. EC CBN Logan International Airport, Boston, Mass. , Dec. 17, 1973, National Transportation Safety Board, NTSB-AAR-74-14, Nov. 3, 1974.

[2]Aircraft Accident Report: Eastern Air Lines, Inc., Boeing 727-255, John Kennedy International Airport, Jamaica, New York, June 24, 1975. National Transportation Safety Board, NTSB-AAR-76-8, March 12, 1976.

[3]Tsien, H. S., "Symmetrical Joukowsky Airfoils in Shear Flow," *Quarterly of Applied Mathematics*, Vol. 1, 1943, pp. 130-148.

[4]Frost, W. and Hutto, E., "The Influence of Wind Shear on Aerodynamic Coefficients," University of Tennessee Space Institute, Tullahoma, Tenn.

[5]Shrazer, J., "Wind Shear: A Literature Search, Analysis, and Annotated Bibliography," FAA-RO-76-114, Feb. 1977.

[6]Wind Shear Report Bibliography, Defense Documentation Center, Defense Logistics Agency, Cameron Station, Alexandria, Va., 1980.

[7]Fiscina, C., "An Investigation into the Effects of Shear on the Flow Past Bluff Bodies," Master's Thesis, University of Notre Dame, Notre Dame, Ind., June 1977.

[8]Elder, J., "Steady Flow through Non-Uniform Gauges of Arbitrary Shapes," *Journal of Fluid Mechanics*, Vol. 5, 1959, p. 355.

[9]Maull, D., "Wake Characteristics of a Bluff Body in a Shear Flow," AGARD-CP 48, 1969.

[10]Milne-Thomson, L. M., *Theoretical Hydrodynamics*, The MacMillan Co., New York, 1960, p. 184.

[11]Gault, D. E., "An Experimental Investigation of Regions of Separated Laminar Flow," NACA TN-3505, 1955.

[12]Miller, M. C., "The Groove Trip," unpublished research conducted at U.S. Army Research and Development Command, Chemical Systems Laboratory, Aberdeen Proving Ground, Md., 1981.

[13]Hoerner, S. and Borst, H., *Fluid-Dynamic Lift*, Hoerner Fluid Dynamics, Irish Town, N. J., 1975, pp. 4-18.

[14]Jones, R. and Williams, D. H., "Effects of Surface Roughness on Characteristics of Aerofoils," NACA 0012 and RAF 34, Air Ministry Aeronautical Research Committee, R&M 1708, Feb. 1936.

[15]Luers, J. K. and Haines, P. A., "The Effects of Heavy Rain on Windshear Attributed Accidents," AIAA Paper 81-0390, 1981.

[16]Payne, F. M., "An Experimental Investigation of the Influence of Vertical Wind Shear on the Aerodynamic Characteristics of an Airfoil," Master's Thesis, University of Notre Dame, Notre Dame, Ind., June 1981.