

Effects of Grit Roughness and Pitch Oscillations on the NACA 4415 Airfoil

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MASTER

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
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Foreword

Airfoils for wind turbines have been selected by comparing data from different wind tunnels, tested under different conditions, making it difficult to make accurate comparisons. Most wind tunnel data sets do not contain airfoil performance in stall commonly experienced by turbines operating in the field. Wind turbines commonly experience extreme roughness for which there is very little data. Finally, recent tests have shown that dynamic stall is a common occurrence for most wind turbines operating in yawed, stall or turbulent conditions. Very little dynamic stall data exists for the airfoils of interest to a wind turbine designer. In summary, very little airfoil performance data exists which is appropriate for wind turbine design.

Recognizing the need for a wind turbine airfoil performance data base, the National Renewable Energy Laboratory (NREL), funded by the U.S. Department of Energy, awarded a contract to Ohio State University (OSU) to conduct a wind tunnel test program. Under this program, OSU tested a series of popular wind turbine airfoils. A standard test matrix was developed to assure that each airfoil was tested under the same conditions. The test matrix was developed in partnership with industry and is intended to include all of the operating conditions experienced by wind turbines. These conditions include airfoil performance at high angles of attack, rough leading edge (bug simulation), steady and unsteady angles of attack.

Special care has been taken to report as much of the test conditions and raw data as practical so that designers can make their own comparisons and focus on details of the data relevant to their design goals. Some of the airfoil coordinates are proprietary to NREL or an industry partner. To protect the information which defines the exact shape of the airfoil, the coordinates have not been included in the report. Instructions on how to obtain these coordinates may be obtained by contacting C.P. (Sandy) Butterfield at NREL.



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Preface

The Ohio State University Aeronautical and Astronautical Research Laboratory is conducting a series of steady state and unsteady wind tunnel tests on a set of airfoils that have been or will be used for horizontal axis wind turbines. The purpose of these tests is to investigate the effect of pitch oscillations and leading edge grit roughness (LEGR) on airfoil performance. The study of pitch oscillation effects can help to understand the behavior of horizontal-axis wind turbines in yaw. The results of these tests will aid in the development of new airfoil performance codes that account for unsteady behavior and also aid in the design of new airfoils for wind turbines. The application of LEGR simulates surface irregularities that occur on wind turbines. These irregularities on the blades are caused by the accumulation of insect debris, ice, and the aging process and can significantly reduce the output of horizontal-axis wind turbines. The experimental results from the application of LEGR will help the development of airfoils that are less sensitive to roughness.

This work was made possible by the efforts and financial support of the National Renewable Energy Laboratory which provided major funding and technical monitoring, the U.S. Department of Energy is credited for its funding of this document through the National Renewable Energy Laboratory under contract number DE-AC36-83CH10093 and KENETECH, Windpower Inc. provided technical assistance and funding for the test model. The staff of The Ohio State University Aeronautical and Astronautical Research Laboratory appreciate the contributions made by personnel from both organizations. In addition, the authors would like to recognize the efforts of the following graduate and undergraduate research assistants: Jolanta M. Janiszewska, Fernando Falasca and Monica Angelats i Coll.

Summary

A NACA 4415 airfoil model was tested in The Ohio State University Aeronautical and Astronautical Research Laboratory 3x5 subsonic wind tunnel under steady state and unsteady conditions. The test defined baseline conditions for steady state angles of attack from -10° to $+40^\circ$ and examined unsteady behavior by oscillating the model about its pitch axis for three mean angles, three frequencies, and two amplitudes. For all cases, Reynolds numbers of 0.75, 1, 1.25, and 1.5 million were used. In addition, these were repeated after the application of leading edge grit roughness (LEGR) to determine contamination effects on the airfoil performance.

Steady state results of the NACA 4415 testing at Reynolds number of 1.25 million showed a baseline maximum lift coefficient of 1.30 at 12.3° angle of attack. The application of LEGR reduced the maximum lift coefficient by 20% and increased the 0.0090 minimum drag coefficient value by 62%. The zero lift pitching moment of -0.0967 showed a 13% reduction in magnitude to -0.0842 with LEGR applied.

Data were also obtained for two pitch oscillation amplitudes: $\pm 5.5^\circ$ and $\pm 10^\circ$. The larger amplitude consistently gave a higher maximum lift coefficient than the smaller amplitude, and both unsteady maximum lift coefficients were greater than the steady state values. Stall is delayed on the airfoil while the angle of attack is increasing, thereby causing an increase in maximum lift coefficient. A hysteresis behavior was exhibited for all the unsteady test cases. The hysteresis loops were larger for the higher reduced frequencies and for the larger amplitude oscillations. As in the steady case, the effect of LEGR in the unsteady case was to reduce the lift coefficient at high angles of attack. In addition, with LEGR, the hysteresis behavior persisted into lower angles of attack than for the clean case.

In general, the unsteady maximum lift coefficient was 10% to 55% higher than the steady state maximum lift coefficient, and variation in the quarter chord pitching moment coefficient magnitude was from -30% to +45% relative to steady state values at high angles of attack. These findings indicate the importance of considering the unsteady flow behavior occurring in wind turbine operation in order to obtain accurate load estimates.

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List of Symbols

AOA	Angle of attack
A/C, a.c.	Alternating current
c	Model chord length
C_d	Drag coefficient
C_{dmin}	Minimum drag coefficient
C_{dp}	Pressure drag coefficient
C_{dw}	Wake drag coefficient
C_{du}	Uncorrected drag coefficient
C_l	Lift coefficient
C_{lmax}	Maximum lift coefficient
$C_{l dec}$	Lift coefficient at angle of maximum lift, but with angle of attack decreasing
C_{lu}	Uncorrected lift coefficient
$C_m, C_{m\frac{1}{4}}$	Pitching moment coefficient about the quarter chord
$C_{m dec}$	Pitching moment coefficient at angle of maximum lift, but with angle of attack decreasing
$C_{m inc}$	Pitching moment coefficient at angle of maximum lift, but with angle of attack increasing
C_{mo}	Pitching moment coefficient about the quarter chord, at zero lift
$C_{m\frac{1}{4}u}$	Uncorrected pitching moment coefficient about the quarter chord
C_p	Pressure coefficient, $(p - p_\infty)/q_\infty$
C_{pmin}	Minimum pressure coefficient
f	Frequency
h	Wind tunnel test section height
hp, Hp, HP	Horsepower
Hz	Hertz
k	Grit particle size
k/c	Grit particle size divided by airfoil model chord length
p	Pressure
q	Dynamic pressure
q_u	Uncorrected dynamic pressure
q_w	Dynamic pressure through the model wake
q_∞	Free stream dynamic pressure
Re	Reynolds number
Re_u	Uncorrected Reynolds number
t	Time
U_∞	Corrected free stream velocity
V	Velocity
V_u	Uncorrected velocity
x	Axis parallel to model reference line
y	Axis perpendicular to model reference line

α	Angle of attack
α_{dec}	Decreasing angle of attack
α_{inc}	Increasing angle of attack
α_m	Median angle of attack
α_{mean}	Mean angle of attack
α_u	Uncorrected angle of attack
ϵ	Tunnel solid wall correction scalar
ϵ_{sb}	Solid blockage correction scalar
ϵ_{wb}	Wake blockage correction scalar
Λ	Body-shape factor
π	3.1416
σ	Tunnel solid wall correction parameter
$\omega_{red}, \omega_{reduced}$	Reduced frequency, $\pi fc/U_\infty$

Introduction

Horizontal-axis wind turbine rotors experience unsteady aerodynamics due to wind shear when the rotor is yawed, when rotor blades pass through the support tower wake, and when the wind is gusting. An understanding of this unsteady behavior is necessary to assist in the calculation of rotor performance and loads. The rotors also experience performance degradation due to surface roughness. These surface irregularities are caused by the accumulation of insect debris, ice, and the aging process. Wind tunnel studies that examine both the steady and unsteady behavior of airfoils can help define pertinent flow phenomena, and the resultant data can be used to validate analytical computer codes.

A NACA 4415 airfoil model was tested in The Ohio State University Aeronautical and Astronautical Research Laboratory (OSU/AARL) 3x5 subsonic wind tunnel (3x5) under steady flow and stationary model conditions, as well as with the model undergoing pitch oscillations. To study the possible extent of performance loss due to surface roughness, a standard grit pattern (LEGR) was used to simulate leading edge contamination. After baseline cases were completed, the LEGR was applied for both steady state and model pitch oscillation cases. The Reynolds numbers used for steady state conditions were 0.75, 1, 1.25 and 1.5 million, while the angle of attack ranged from -10° to $+40^\circ$. With the model undergoing pitch oscillations, data were acquired at Reynolds numbers of 0.75, 1, 1.25, and 1.5 million, at frequencies of 0.6, 1.2, and 1.8 Hz. Two sine wave forcing functions were used, $\pm 5.5^\circ$ and $\pm 10^\circ$, at mean angles of attack of 8° , 14° , and 20° . For purposes herein, any reference to unsteady conditions means the airfoil model was in pitch oscillation about the quarter chord.

Experimental Facility

Wind Tunnel

The OSU/AARL 3×5 was used to conduct tests on the NACA 4415 airfoil section. Schematics of the top and side views of the tunnel are shown in Figure 1 and Figure 2, respectively. This open circuit tunnel has a velocity range of 0 - 55-m/s (180-ft/s) produced by a 2.4-m (8-ft) diameter, six-bladed fan.

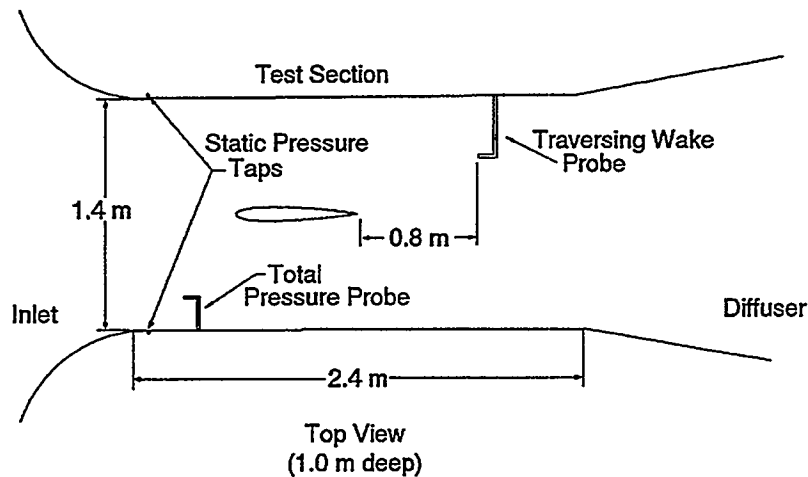


Figure 1. 3x5 subsonic wind tunnel, top view.

The fan is belt driven by a 93.2-kw (125-hp) three phase a.c. motor connected to a variable frequency motor controller. Nominal test section dimensions are 1.0-m (39-in) high by 1.4-m (55-in) wide by 2.4-m (96-in) long. The 457-mm (18-in) chord airfoil model was mounted vertically in the test section.

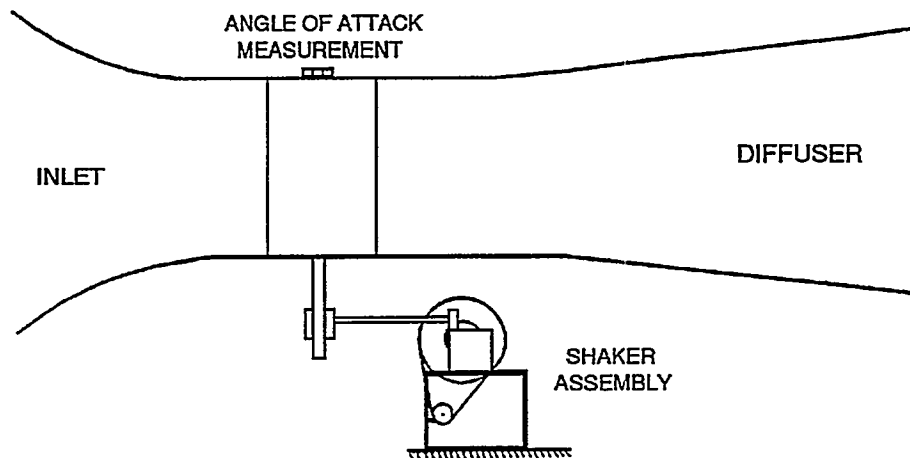


Figure 2. 3x5 subsonic wind tunnel, side view.

A steel tube through the quarter chord of the model attached the model to the tunnel during testing. An angle of attack potentiometer was fastened to the model at the top of the tunnel as shown in Figure 2. The steady state angle of attack was adjusted with a worm gear drive attached to the model strut below the tunnel floor.

Oscillation System

Portions of the airfoil model testing required the use of a reliable pitch oscillation system. The OSU/AARL 'shaker' system incorporated a face cam and follower arm attached to the model support tube below the wind tunnel floor, as shown in Figure 3. The choice of cam governed the type and amplitude of the wave form produced. Sine wave forms with amplitudes of $\pm 5.5^\circ$ and $\pm 10^\circ$ were used for these tests. The wave form is defined by the equation

$$\alpha = \alpha_m + A \sin(2\pi f t)$$

where A is the respective amplitude. The shaker system was powered by a 5-hp AC motor with variable line frequency controller. The useable oscillating frequency range was 0.1 - 2.0 Hz, with three frequencies used for this test: 0.6, 1.2, and 1.8 Hz.

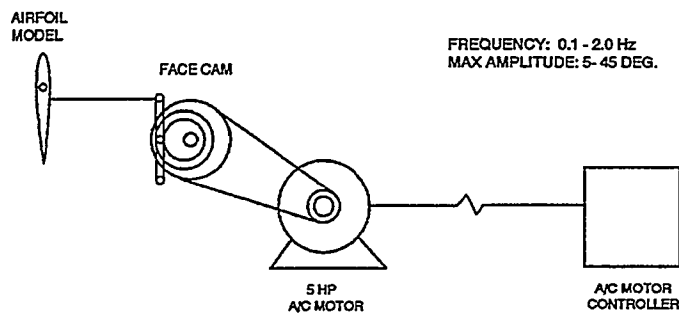


Figure 3. 3x5 wind tunnel oscillation system.

Model Details

A 457-mm (18-in) constant chord NACA 4415 airfoil model was designed by OSU/AARL personnel and manufactured by others. Figure 4 shows the airfoil section; the model measured coordinates are given in Appendix A. The model was made of a carbon composite skin over ribs and foam. The main load

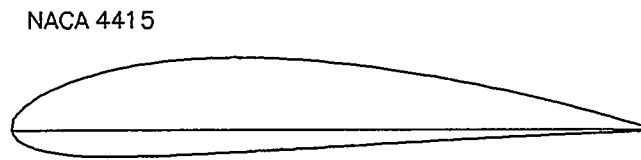


Figure 4. NACA 4415 airfoil section.

bearing member was a 38-mm (1.5-in) diameter steel tube which passed through the model quarter chord station. Ribs and end plates were used to transfer loads from the composite skin to the steel tube. The final surface was hand finished using templates to attain given coordinates within a tolerance of ± 0.25 -mm (± 0.01 -in). The completed model was measured by others using a contact type coordinate measurement machine. Measurements were made in English units and later converted to metric.

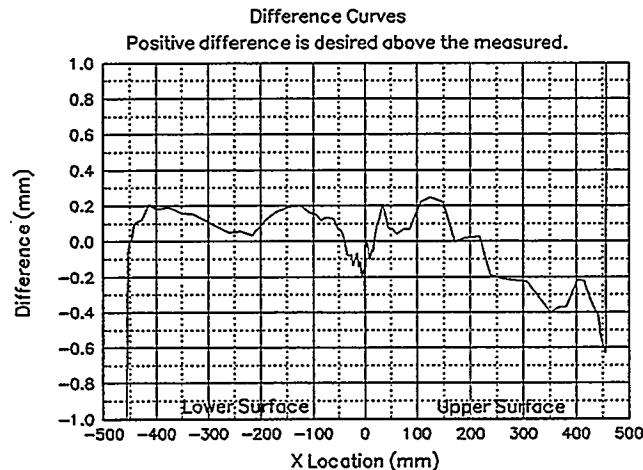


Figure 5. Measured-to-desired model coordinates difference curves.

Figure 5 shows the results of comparing measured-to-desired coordinates by calculating differences normal to the profiled surface at the mid-span station of the model. The spikes apparent near the trailing edge are due to the numerical methods used and are not real.

To minimize pressure response times, which is important for the unsteady testing, the surface pressure tap lead-out lines had to be as short as possible. Consequently, a compartment was built into the model so pressure scanning modules could be installed inside the model. This compartment was accessed through a panel door fitted flush with the model contour on the lower (pressure) surface.

For test cases involving roughness, a standard, repeatable pattern with grit as roughness elements was desired. A roughness pattern was jointly developed by OSU/AARL and KENETECH Windpower personnel from a molded insect pattern taken from a wind turbine in the field by personnel at the

University of Texas Permian Basin. The particle density was 5 particles per cm^2 (32 particles per square inch) in the middle of the pattern, thinning to 1.25 particles per cm^2 (8 particles per square inch) at the edge of the pattern. Figure 6 shows the pattern. To make a usable template, the pattern was repeatedly cut into a steel sheet 102-mm (4-in) wide and 91-cm (3-ft) long with holes just large enough for one piece of grit. Based on average particle size from the field specimen, standard #40 lapidary grit was chosen for the roughness elements, giving $k/c=0.0019$ for a 457-mm (18-in) chord model.

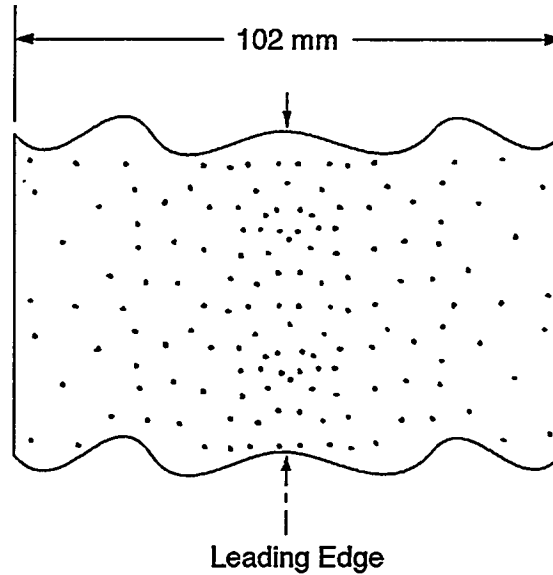


Figure 6. Roughness pattern.

To use the template, 102-mm (4-in) wide double-tack tape was applied to one side of the template and grit was poured and brushed from the opposite side. The tape was then removed from the template and transferred to the model. This method allowed the same roughness pattern to be replicated for any test.

Test Equipment and Procedures

Data Acquisition

Data were acquired and processed from 60 surface pressure taps, four individual tunnel pressure transducers, an angle of attack potentiometer, a wake probe position potentiometer, and a tunnel thermocouple. The data acquisition system included an IBM PC compatible 80486-based computer connected to a Pressure Systems Incorporated (PSI) data scanning system. The PSI system included a 780B Data Acquisition and Control Unit (DACU), 780B Pressure Calibration Unit (PCU), 81-IFC scanning module interface, two 2.5-psid pressure scanning modules (ESPs), one 20-in water column range pressure scanning module, and a 30-channel Remotely Addressed Millivolt Module (RAMM-30). Figure 7 is a schematic the data acquisition system.

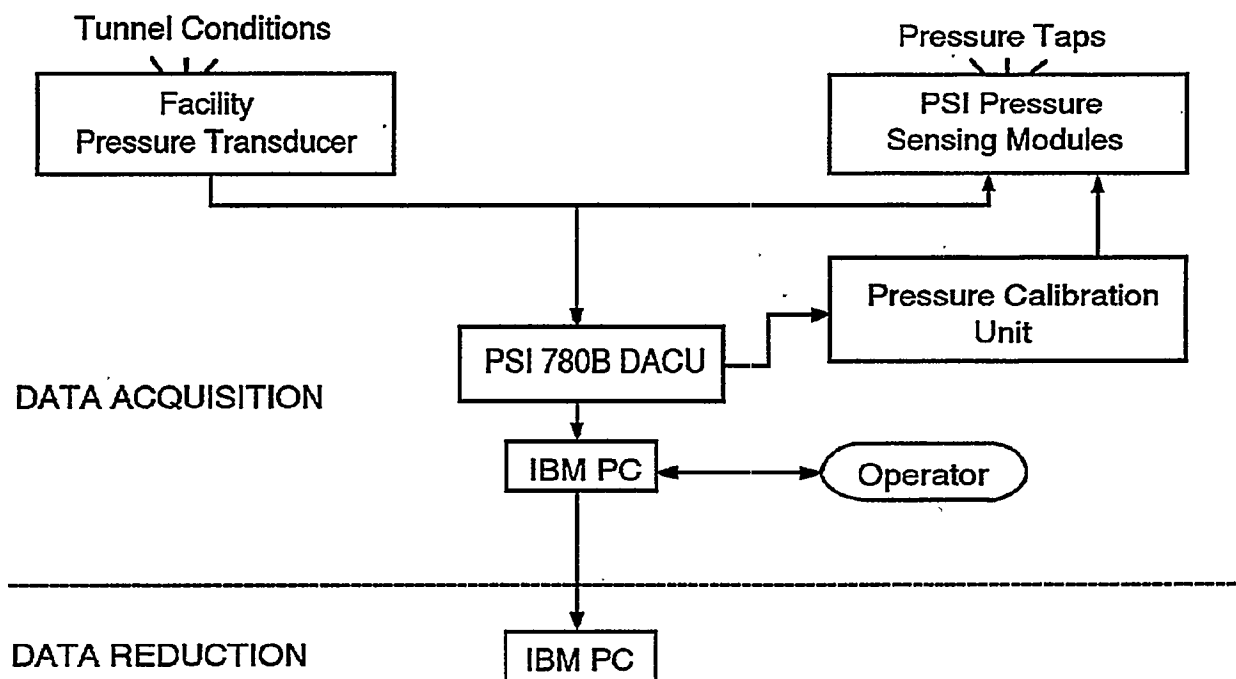


Figure 7. Data acquisition schematic.

Four individual pressure transducers read tunnel total pressure, tunnel north static pressure, tunnel south static pressure, and wake dynamic pressure. Before the test began, these transducers were bench calibrated using a water manometer to determine their sensitivities and offsets. Related values were entered into the data acquisition and reduction program so the transducers could be shunt resistor calibrated before each series of wind tunnel runs.

The rotary angle of attack potentiometer of 0.5% linearity was regularly calibrated during the tunnel pressure transducers shunt calibration. The angle of attack calibration was accomplished by taking voltage readings at known values of set angle of attack. This calibration method gave angle of attack readings within $\pm 0.25^\circ$ over the entire angle range. The wake probe position potentiometer was a linear potentiometer, and it was also regularly calibrated during the shunt calibration of the tunnel pressure transducers.

Calibration of the three ESPs was done simultaneously using the DACU and PCU. At operator request, the DACU commanded the PCU to apply known regulated pressures to the ESPs and read the output

voltages from each integrated pressure sensor. From these values, the DACU calculated the calibration coefficients and stored them internally until the coefficients were requested by the controlling computer. This calibration was done several times during a run set because the ESPs were installed inside the model and their outputs tended to drift with temperature changes during a test sequence. Frequent on-line calibrations minimized the effect.

For steady state cases, the model would be set to angle of attack and the tunnel conditions were adjusted. At operator request, pressure measurements from the airfoil surface taps and all other channels of information were acquired and stored by the DACU and subsequently passed to the controlling computer for final processing. The angles of attack were always set in the same progression, from negative to positive values.

For model oscillating cases, the tunnel conditions were set while the model was stationary at the desired mean angle of attack. The 'shaker' would be started, and after approximately 10 seconds the model surface pressure and tunnel condition data were acquired. Generally, 120 data scans were acquired over three model oscillation cycles. Since surface pressures were scanned sequentially, the data rate was set so the model rotated through less than 0.50° during any data burst. Finally, due to the unsteady and complex nature of the pitch oscillation cases, model wake surveys (for drag) were not conducted.

Data Reduction

The data reduction routine was included as a section of the data acquisition program. This combination of data acquisition and reduction routines allowed data to be reduced on line during a test. By quickly reducing selected runs, integrity checks could be made to ensure the equipment was working properly and to allow timely decisions about the test matrix.

The ambient pressure was manually input into the computer and was updated regularly. This value, along with the measurements from the tunnel pressure transducers and the tunnel thermocouple, were used to calculate tunnel airspeed. As a continuous check of readings, the tunnel total and static pressures were read by both the tunnel individual pressure transducers and the 20-inch water column ESP.

A typical steady state datum point was derived by acquiring 10 data scans of all channels over a 10 second window at each angle of attack and tunnel condition. The reduction portion of the program processed each data scan to coefficients (C_p , C_l , $C_{m/4}$, and C_{dp}) using the measured surface pressure voltages, calibration coefficients, tap locations and wind tunnel conditions. All scan sets for a given condition were then ensemble averaged to provide one data set, and that data set was corrected for the effects of solid tunnel walls. All data were saved in electronic form.

Corrections due to solid tunnel sidewalls were applied to the wind tunnel data. As described by Pope and Harper (1966), tunnel conditions are represented by the following equations:

$$q = q_u(1 + 2\epsilon)$$

$$V = V_u(1 + \epsilon)$$

$$R_e = R_{e_u}(1 + \epsilon)$$

Airfoil aerodynamic characteristics are then corrected by:

$$\alpha = \alpha_u + \frac{57.3\sigma}{2\pi}(C_{l_u} + 4C_{m_{\frac{1}{4}_u}})$$

$$C_l = C_{l_u}(1 - \sigma - 2\epsilon)$$

$$C_{m_{\frac{1}{4}}} = C_{m_{\frac{1}{4}_u}}(1 - 2\epsilon) + \frac{\sigma C_l}{4}$$

$$C_d = C_{d_u}(1 - 3\epsilon_{sb} - 2\epsilon_{wb})$$

where

$$\sigma = \frac{\pi^2}{48} \left(\frac{c}{h} \right)^2$$

$$\epsilon = \epsilon_{sb} + \epsilon_{wb}$$

$$\epsilon_{sb} = \Delta\sigma$$

$$\epsilon_{wb} = \frac{c}{h4} C_{d_u}$$

Model wake data were taken for steady state cases when the wake could be completely traversed. Pressures were acquired from a pitot-static probe that was connected to measure incompressible dynamic pressure through the wake. These pressure measurements were used to calculate drag coefficient using a form of the Jones equation derived from Schlichting (1979):

$$C_{dw} = \frac{2}{c} \int \sqrt{\frac{q_w}{q_\infty}} \left(1 - \sqrt{\frac{q_w}{q_\infty}} \right) dy$$

This equation assumes that static pressure at the measurement site is the free-stream value. The integration was done automatically except the computer operator chose the end points of the integration from a plot of the wake survey displayed on the computer screen.

For pitch oscillation cases, model surface pressures were reduced to pressure coefficient form with subsequent integrations and angle of attack considerations giving lift, moment, and pressure drag coefficients. The wind tunnel was not calibrated for unsteady model pitch conditions; therefore, the unsteady pressure data were not corrected for any possible effects due to time dependent pitching or solid tunnel walls. Also, for these cases, the wind tunnel contraction pressures (used for steady state cases) could not be used to calculate instantaneous freestream conditions due to slow response. The tunnel conditions were obtained from a total pressure probe and the average of opposing static taps in the test section entrance. This gave nearly instantaneous flow pressure conditions for the pitching frequencies used.

Test Matrix

The test was designed to study steady state and unsteady pitch oscillation data. Steady state data were acquired at Reynolds numbers of 0.75, 1, 1.25, and 1.5 million with and without LEGR. Refer to the tabular data in Appendix B for the actual Reynolds number for each angle of attack for the steady state

data. The angle of attack increment was two degrees when $-10^\circ < \alpha < +10^\circ$ or $+20^\circ < \alpha < +40^\circ$ and one degree when $+10^\circ < \alpha < +20^\circ$. Wake surveys were conducted to find total airfoil drag over an approximate angle of attack range of -10° to $+10^\circ$. Unsteady data were taken for Reynolds numbers of 0.75, 1, 1.25, and 1.5 million. Sine wave cams with amplitudes $\pm 5.5^\circ$ and $\pm 10^\circ$ were used for pitch oscillations, and the mean angles for both these amplitudes were 8° , 14° , and 20° . For all these conditions, the frequencies were varied to 0.6, 1.2, and 1.8 Hz. All data points for the unsteady cases were acquired for both clean and LEGR cases.

Results and Discussion

The NACA 4415 airfoil model was tested under steady state and pitch oscillation conditions. A brief discussion of the results follows, beginning with a comparison of experimental data and computational predictions.

Comparison with Theory

The wind tunnel steady state data collected in this study were compared with computed predictions made using the North Carolina State Airfoil Analysis Code. This analysis code has proven to be accurate for moderate angles of attack. The analysis was made with specifications set to allow free transition from laminar to turbulent flow, and the pressure distribution comparisons were matched to the same angle of attack as the wind tunnel cases.

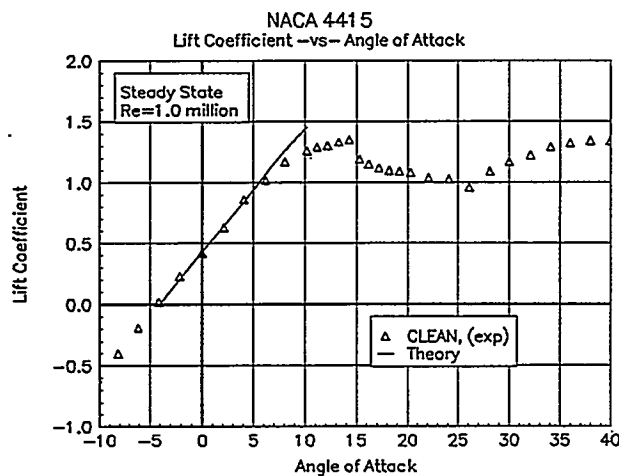


Figure 8. Comparison with theory, C_l vs α .

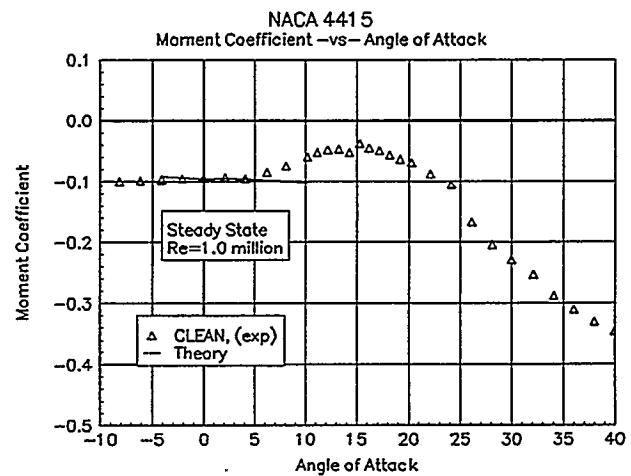


Figure 9. Comparison with theory, C_m vs α .

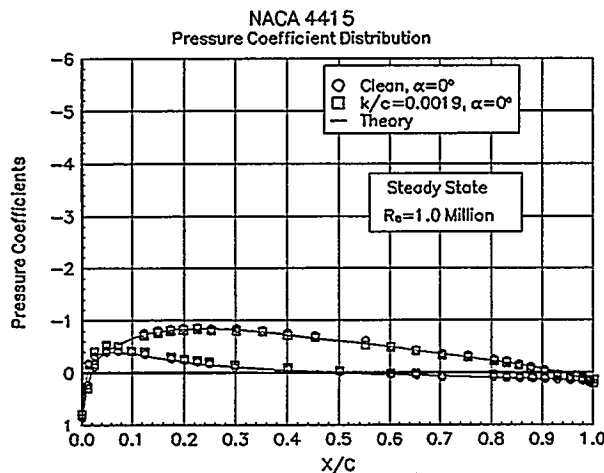


Figure 10. Comparison with theory, C_p vs x/c , $\alpha = 0^\circ$.

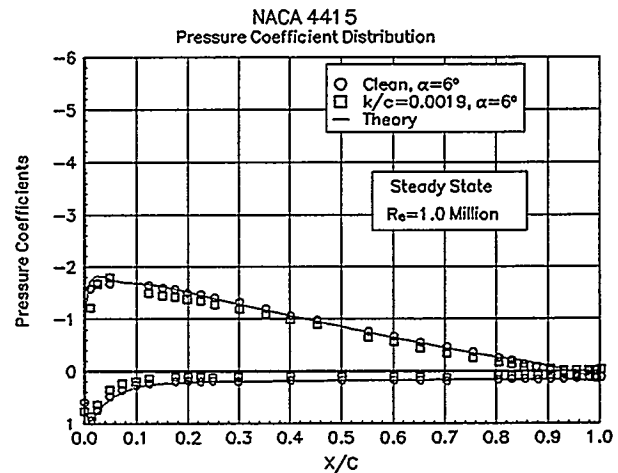


Figure 11. Comparison with theory, C_p vs x/c , $\alpha = 6^\circ$.

Figure 8 shows the lift coefficient versus angle of attack for the 1 million Reynolds number case. For moderate angles of attack, where the analysis code is valid, the comparison shows good agreement. The pitching moment about the quarter chord, Figure 9, also shows good agreement for angles of attack from

-5° to 5°. The pressure distributions shown in Figure 10 and Figure 11 are for angles of attack of 0° and 6°, respectively, and include clean and LEGR wind tunnel data as compared to computed free transition pressure distributions. For both angles of attack, there is excellent correlation between the experimental and predicted values.

Steady State Data

The NACA 4415 airfoil model was tested at four Reynolds numbers at nominal angles of attack from -10° to +40°. Figure 12 and Figure 13 show lift coefficients for all the test Reynolds numbers

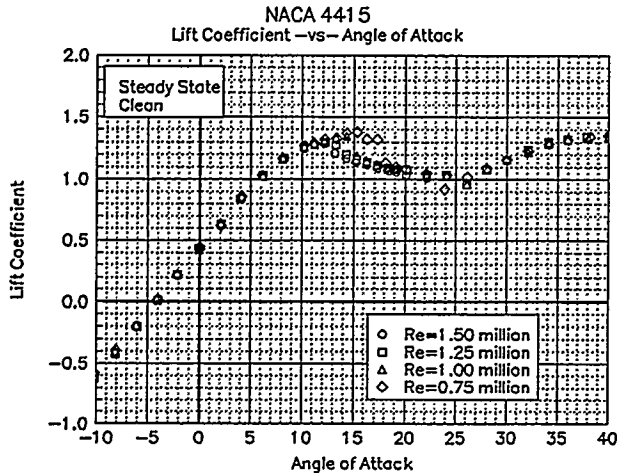


Figure 12. C_l vs α , clean.

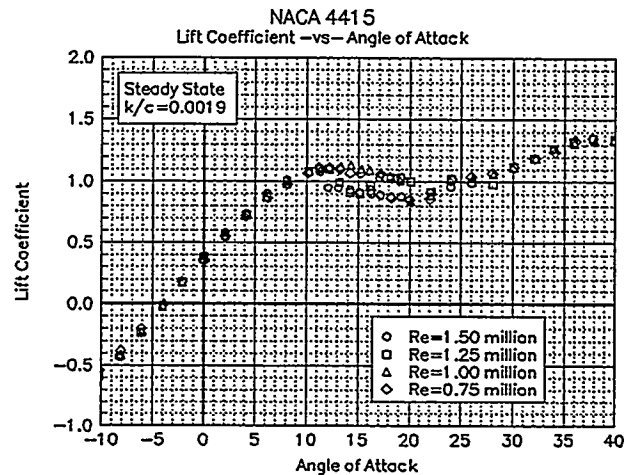


Figure 13. C_l vs α , LEGR, $k/c=0.0019$.

for a clean model and with LEGR applied, respectively. The maximum positive lift coefficient for the clean cases is about 1.38 and about 1.11 for the LEGR cases, a 20% reduction. The stall characteristic is similar for both clean and LEGR cases, with indications of stall occurring at lower angles of attack in

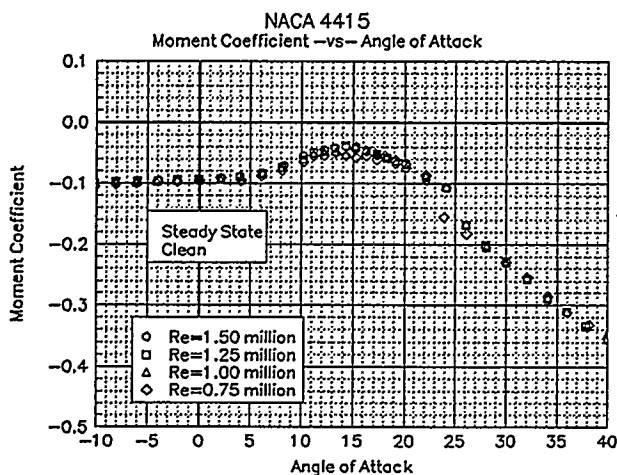


Figure 14. C_m vs α , clean.

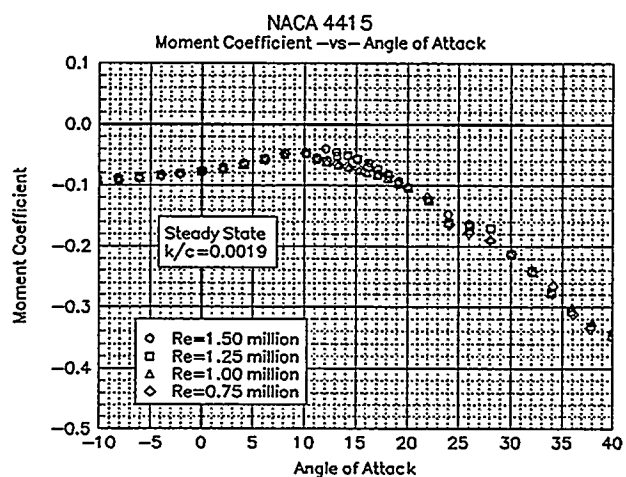


Figure 15. C_m vs α , LEGR, $k/c=0.0019$.

the higher Reynolds number cases. This was an unexpected result that is not yet understood. For the clean cases, surface pressure taps may be locally affecting the boundary layer, resulting in greater energy losses at the higher Reynolds numbers. Fixed grit roughness size and thinning boundary layer with increasing Reynolds number may explain the effect for LEGR cases. Finally, the average lift curve slope

for clean data is about 0.104; it is slightly lower for the LEGR case at 0.095. The associated average lift coefficients at zero angle of attack are 0.42 for the clean case and 0.36 for the LEGR case.

Figure 14 shows the pitching moment about the quarter chord for the clean cases, and Figure 15 shows the same for the LEGR cases. The LEGR data have slightly more positive pitching moment at low angles of attack. The moment coefficient about the quarter chord for the 1 million Reynolds number, is -0.0967 for the clean case and -0.0842 for the LEGR case.

Total wake drag data were obtained for both the clean and LEGR cases over an angle of attack range of -10° to 10° . A pitot-static probe was used to describe the wake profile. This method is reliable when

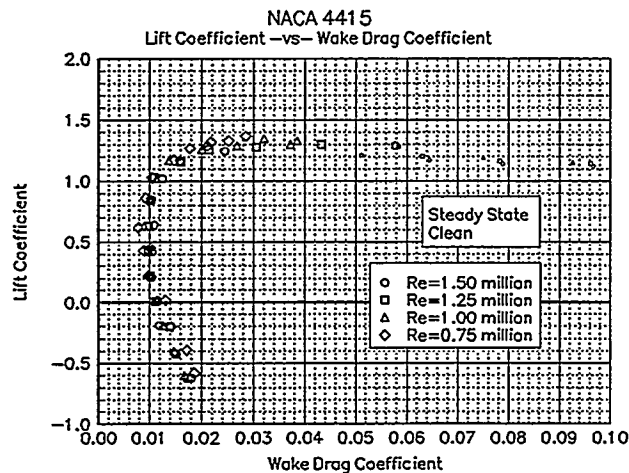


Figure 16. Clean, drag polar.

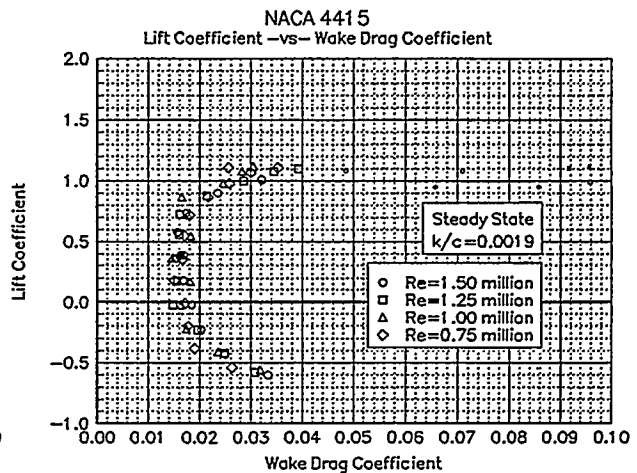


Figure 17. LEGR, drag polar.

there is relatively low turbulence in the wake flow; therefore, only moderate angles of attack have reliable total drag coefficient data. At angles of attack other than -10° to 10° , surface pressure data were integrated to give C_{dp} and are shown in the drag polars as small symbols. The model clean drag data are shown in Figure 16, and the LEGR case is shown in Figure 17. At 1 million Reynolds number, minimum drag coefficient for the clean cases was measured as 0.0090, and 0.0146 for LEGR, a 62% increase. The general effect of LEGR is to increase drag consistently through most angles of attack.

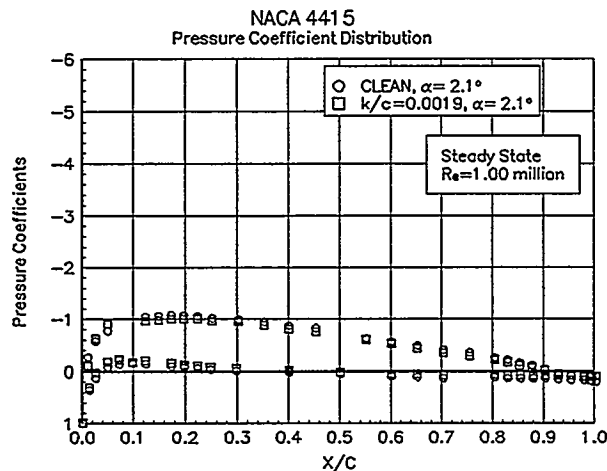


Figure 18. Pressure distribution, $\alpha = 2.1^\circ$.

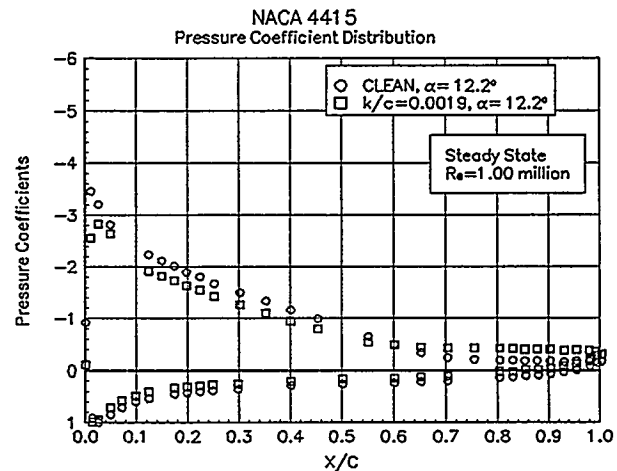


Figure 19. Pressure distribution, $\alpha = 12.2^\circ$.

Two examples of the surface pressure distributions are shown in Figure 18 and Figure 19 for 2.1° and 12.2° , respectively, for 1 million Reynolds number. At the angles of attack close to zero degrees, the effect of LEGR does not appear to significantly affect the pressure distribution compared to the clean case distribution. However, there is an effect apparent in the lift coefficient with values of 0.55 for the LEGR case and 0.63 for the clean case. For the higher angle of attack case, Figure 19, the effect of LEGR is to reduce the magnitude of the pressure peak from -3.5 to -2.9 and generally bring all surface pressures closer to freestream. Also, flow separation occurs earlier in the LEGR case. The net effect is a reduction in lift coefficient from 1.35 to 1.13, a 16% decrease.

Unsteady Data

Unsteady experimental data were obtained for the NACA 4415 airfoil model undergoing sinusoidal pitch oscillations. As mentioned earlier, no attempt was made to calibrate the wind tunnel for the unsteady oscillating model conditions; the steady state tunnel calibration was used to set the flow conditions while the model was stationary at its mean angle of attack. The use of the unsteady data should be limited to comparisons with other models tested in this same facility and can be used to detect possible trends. A comprehensive set of test conditions was used to describe unsteady behavior of an airfoil, including two angle of attack amplitudes, $\pm 5.5^\circ$ and $\pm 10^\circ$; four Reynolds numbers, 0.75, 1, 1.25, and 1.5 million; three pitch oscillation frequencies, 0.6, 1.2, and 1.8; and three mean angles of attack, 8° , 14° , and 20° .

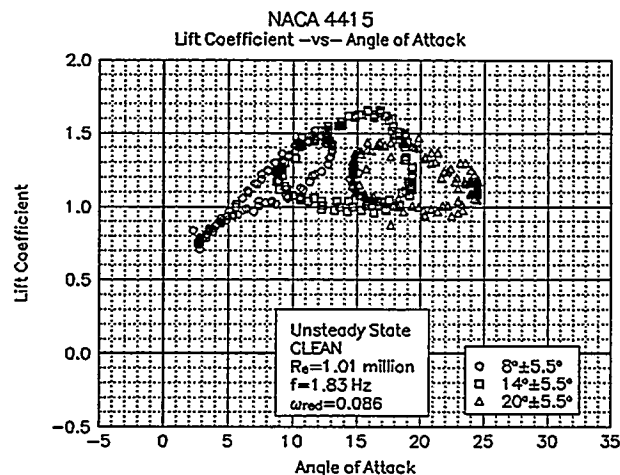
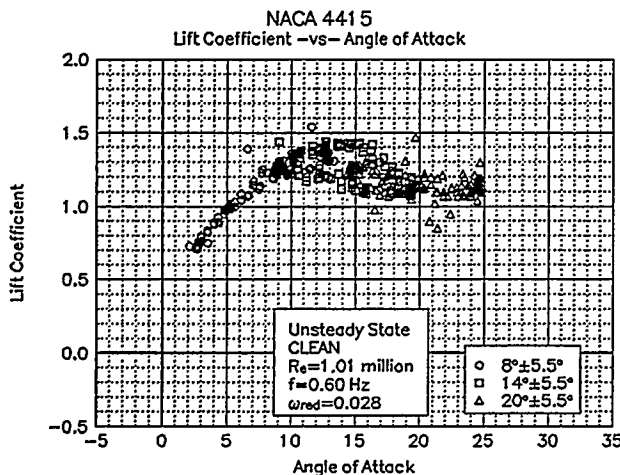


Figure 20. Clean, C_l vs α , $\omega_{red} = 0.028$, $\pm 5.5^\circ$. Figure 21. Clean, C_l vs α , $\omega_{red} = 0.086$, $\pm 5.5^\circ$.

Figure 20 shows the lift coefficient versus angle of attack for the $\pm 5.5^\circ$ amplitude, model clean case, at reduced frequency of 0.028 and 1 million Reynolds number. Note that all three mean angles of attack are plotted on the same figure. The maximum pre-stall lift coefficient for this case is near 1.44 and occurs when the airfoil is traveling with the angle of attack increasing. In contrast, when the model is traveling through decreasing angles of attack, the stall recovery is delayed and a hysteresis behavior is exhibited in the lift coefficient that can be seen throughout all the unsteady data. To obtain some measure of this hysteresis behavior, the lift coefficient on the "return" portion of the curve, at the angle of attack where maximum lift coefficient occurs, can be used. For the case discussed here the hysteresis lift coefficient is 1.21, a 16% decrease from the 1.44 unsteady maximum value. By comparison, the steady state maximum lift coefficient is 1.35. At higher reduced frequency of 0.086, the hysteresis behavior is more pronounced, as seen in Figure 21. In addition to greater hysteresis, the maximum lift coefficient is increased to about 1.66, a 23% increase over the steady state value. The corresponding hysteresis lift coefficient is 1.08. This significant difference between steady state behavior and unsteady hysteresis

behavior is a main reason that unsteady testing should be required for airfoils used in wind turbine applications.

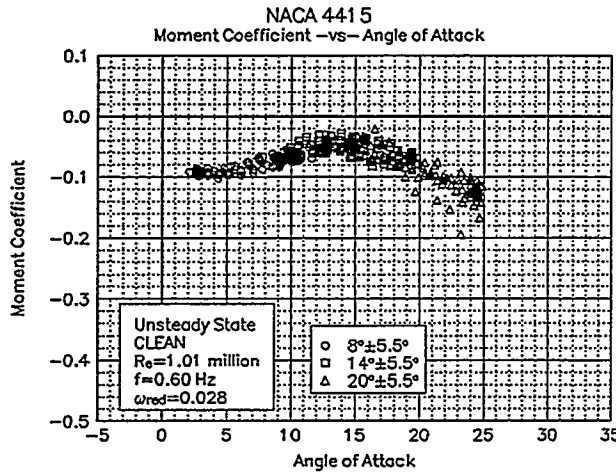
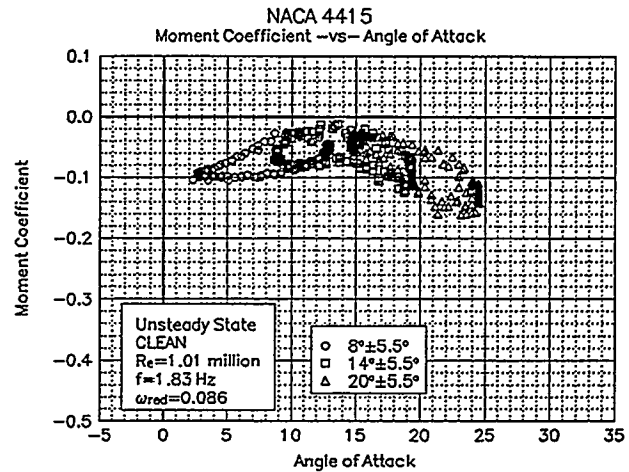


Figure 22. Clean, C_m vs α , $\omega_{red}=0.028$, $\pm 5.5^\circ$. Figure 23. Clean, C_m vs α , $\omega_{red}=0.086$, $\pm 5.5^\circ$.



The pitching moment shown in Figure 22 and Figure 23 corresponds to the same conditions as the two lift coefficient plots previously discussed. Hysteresis behavior is indicated but it is not as apparent as in the lift coefficient plots. However, the higher reduced frequency case does show more hysteresis than the lower reduced frequency case. For reference, the steady state maximum lift occurs near 14° angle of attack, and the steady state pitching moment at this maximum lift point is -0.0526. In comparison, when the airfoil is undergoing pitch oscillation for the lower frequency, pitching moment varies from -0.0593 to -0.0310 (at the angle of attack where maximum lift occurs); a 13% increase to a 41% decrease in magnitude from the steady state value. Note the angle of attack where the maximum lift coefficient occurs does not necessarily show the greatest hysteresis behavior but does give a relative indication of the effect.

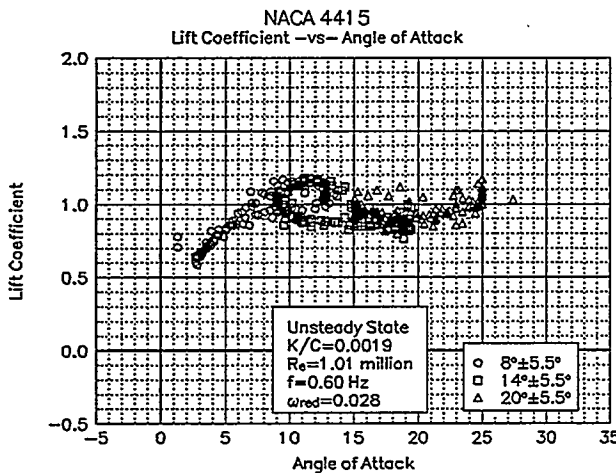
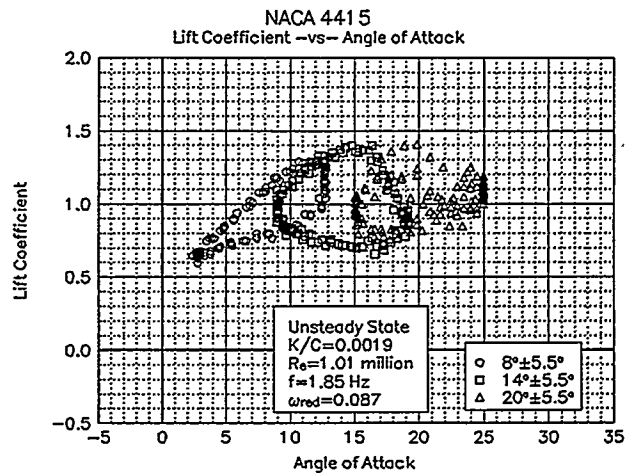


Figure 24. LEGR, C_l vs α , $\omega_{red}=0.028$, $\pm 5.5^\circ$. Figure 25. LEGR, C_l vs α , $\omega_{red}=0.087$, $\pm 5.5^\circ$.



Compared to the clean data, the application of LEGR reduces the maximum lift coefficient in the pitch oscillation cases. Lift coefficient versus angle of attack with LEGR applied is shown in Figure 24 for the 0.028 reduced frequency case. The 0.087 reduced frequency case is shown in ?. Both correspond to the same run conditions that were described earlier for the clean cases. For the lower reduced

frequency, the maximum unsteady lift coefficient is reduced to 1.17 from the corresponding clean case of 1.44, a 19% decrease. Hysteresis behavior is apparent at this frequency and is of similar order to the clean case; the corresponding hysteresis lift coefficient is 0.88 when LEGR is applied. In contrast, the higher frequency LEGR case has a maximum lift coefficient of 1.39 while the model is increasing in angle of attack, and the corresponding decreasing angle of attack lift coefficient is 0.72. In this case, the application of LEGR gives a greater hysteresis loop behavior than the clean case at the same run conditions.

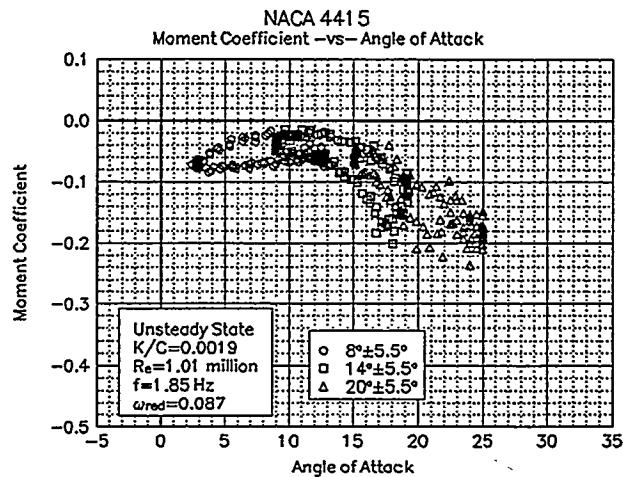
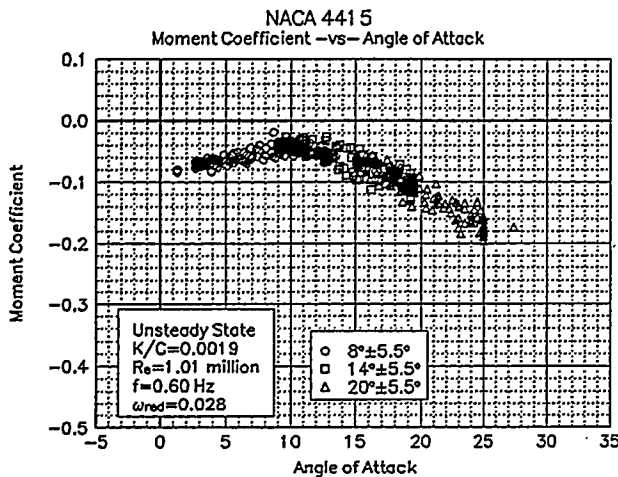


Figure 26. LEGR, C_m vs α , $\omega_{red}=0.028$, $\pm 5.5^\circ$. Figure 27. LEGR, C_m vs α , $\omega_{red}=0.087$, $\pm 5.5^\circ$.

The pitching moment coefficient shown in Figure 26 is for 0.028 reduced frequency with LEGR applied. At the angle of unsteady maximum lift, the pitching moment ranges from -0.0508 to -0.0267, while the steady state LEGR pitching moment is -0.0617 at the steady state stall angle of attack (12.2°). The higher reduced frequency of 0.087 with LEGR applied is shown in Figure 27. As was seen with the lift coefficient, pitching moment hysteresis is more apparent at the higher reduced frequency than in the corresponding clean case (shown in Figure 23). Unsteady maximum lift angle of attack for this reduced frequency occurs at 14.3° , and the pitching moment ranges from -0.0841 to -0.0341 at that angle. Throughout the higher angle of attack range, the magnitude of the unsteady pitching moment can be much different than that resulting from steady state clean conditions (steady state pitching moment at maximum lift is -0.0526). It seems these differences can have an impact on the fatigue life predictions of a wind turbine system.

In addition to the $\pm 5.5^\circ$ unsteady experimental data, $\pm 10^\circ$ unsteady data were obtained with and without LEGR. The data were taken at 1 million Reynolds number using the same mean angles and frequencies as the 5.5° amplitude cases. Figure 28 and Figure 29 show the $\pm 10^\circ$, unsteady, clean, lift coefficient for the reduced frequencies of 0.029 and 0.089, respectively. The maximum lift coefficient for the lower frequency is 1.55 and occurs, as expected, when the airfoil is traveling through increasing angles of attack. The hysteresis lift coefficient (at 14.9°) is 1.07. At the higher reduced frequency, the maximum lift coefficient occurs at a higher angle of attack, 19.4° , and is 1.95. The corresponding hysteresis lift coefficient is 0.92. The difference between the maximum lift coefficient and the hysteresis lift coefficient indicates a much greater hysteresis response than experienced for the lower reduced frequency. The steady state, clean, maximum lift coefficient is 1.35; therefore, the unsteady behavior created lift coefficients up to 44% higher than the steady state conditions.

The quarter chord pitching moments with the same reduced frequencies as the lift coefficient cases are shown in Figure 30 and Figure 31. The hysteresis behavior observed in the lift coefficient plots is also

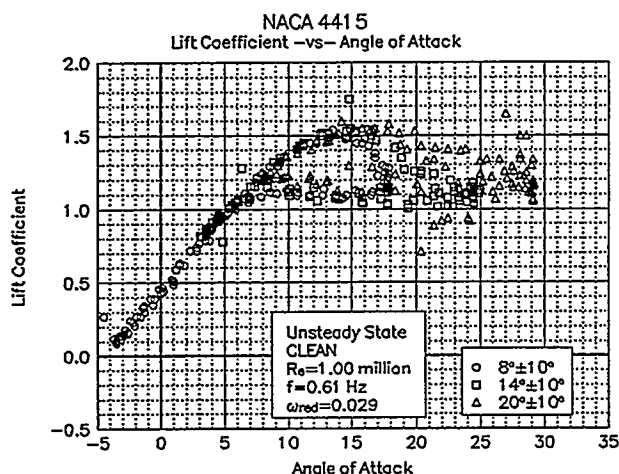


Figure 28. Clean, C_l vs α , $\omega_{red}=0.029$, $\pm 10^\circ$.

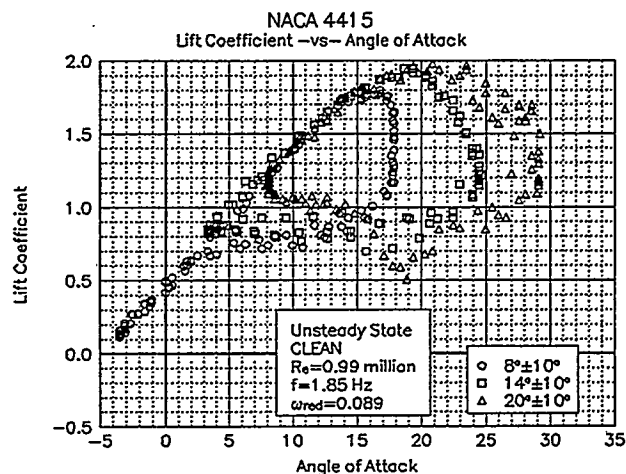


Figure 29. Clean, C_l vs α , $\omega_{red}=0.089$, $\pm 10^\circ$.

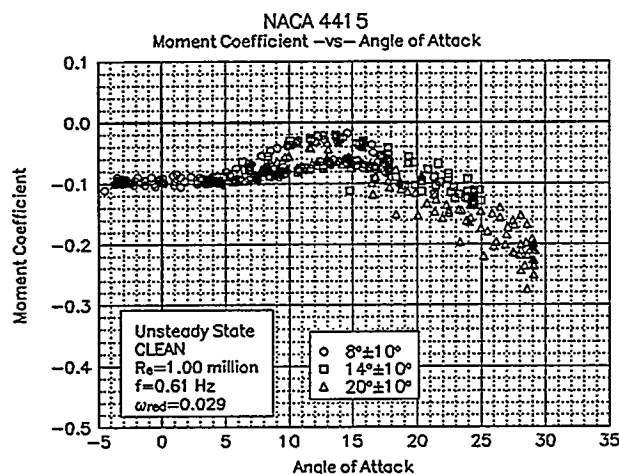


Figure 30. Clean, C_m vs α , $\omega_{red}=0.029$, $\pm 10^\circ$.

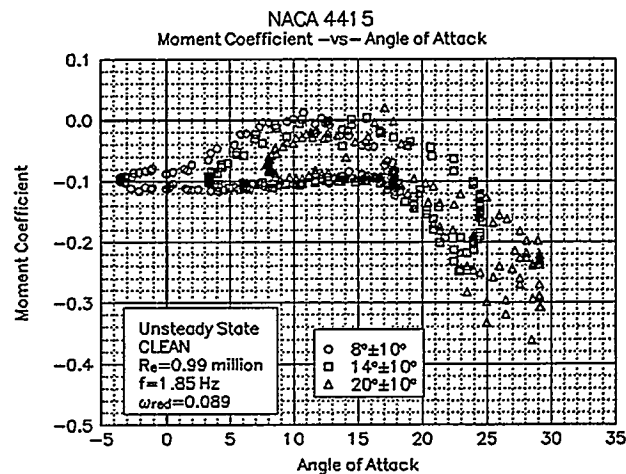


Figure 31. Clean, C_m vs α , $\omega_{red}=0.089$, $\pm 10^\circ$.

reflected in this pitching moment data. Near the maximum lift angle, 14.9° for the lower frequency, the pitching moment coefficient ranges from -0.0743 to -0.0276; the 0.089 reduced frequency case has maximum lift near 19.4° and pitching moment ranges from -0.1399 to -0.0358. The higher reduced frequency again shows large hysteresis loops for all three mean angles of attack. In comparison, the steady state pitching moment is -0.0526 near the steady state maximum lift coefficient angle of attack of 14° .

The application of LEGR degrades the lift performance of the airfoil, as would be expected from the results discussed previously. The LEGR lift coefficient data for reduced frequencies of 0.028 and 0.087 are shown in Figure 32 and Figure 33, respectively. The maximum lift coefficient is reduced to 1.34 from 1.55 for the low frequency clean case. Although there is a reduction, this value is still significantly higher than the LEGR steady state case, which has a maximum lift coefficient of 1.13 at 14.3° angle of attack. The higher reduced frequency has a maximum lift coefficient of 1.80, which occurs near 19° angle of attack. The corresponding lift coefficient at 19° for the airfoil traveling with decreasing angle of attack is 0.71, a 60% reduction from the maximum.

Figure 34 and Figure 35 show the corresponding pitching moment coefficients for the reduced frequencies of 0.028 and 0.087. For the 0.028 reduced frequency case, the pitching moment varies from -0.1119

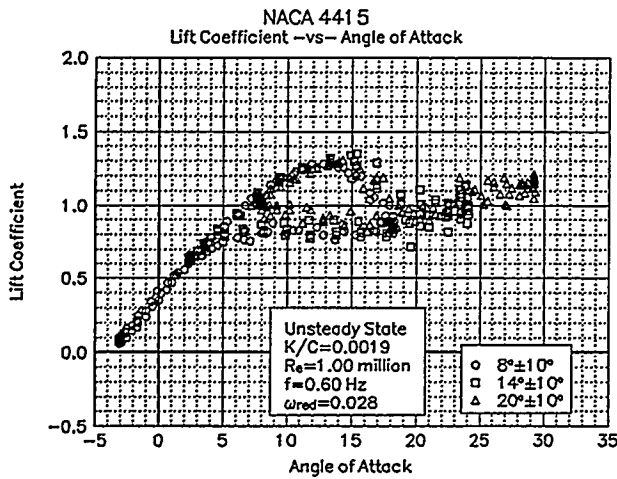


Figure 32. LEGR, C_l vs α , $\omega_{red}=0.028$, $\pm 10^\circ$.

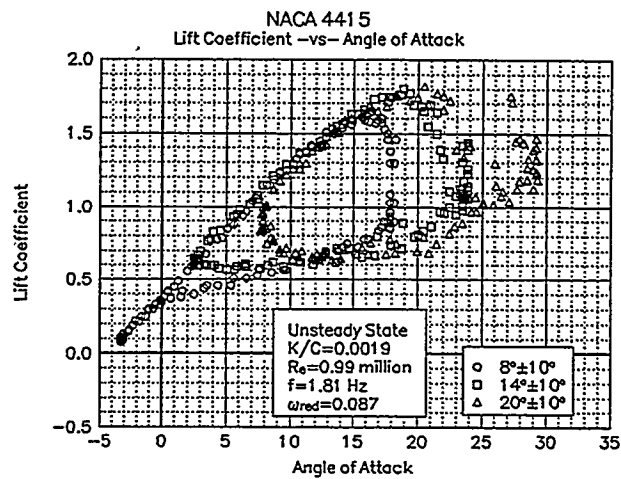


Figure 33. LEGR, C_l vs α , $\omega_{red}=0.087$, $\pm 10^\circ$.

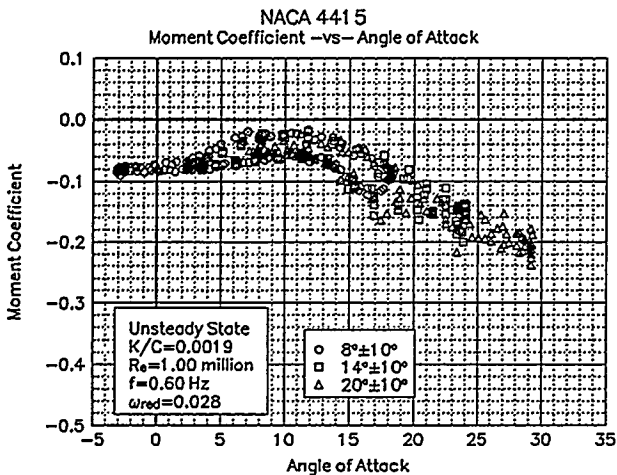


Figure 34. LEGR, C_m vs α , $\omega_{red}=0.028$, $\pm 10^\circ$.

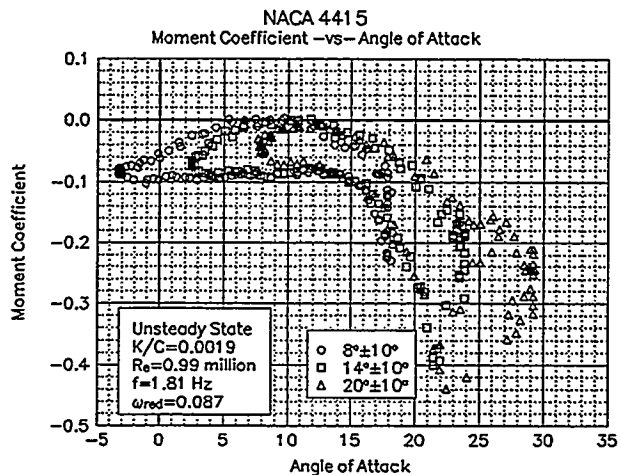


Figure 35. LEGR, C_m vs α , $\omega_{red}=0.087$, $\pm 10^\circ$.

to -0.0488 at 14.9° (where the maximum lift occurs). The hysteresis behavior is more pronounced for the higher reduced frequency case, where the range of pitching moments at the maximum lift angle of 18.9° is from -0.2082 to -0.0625 . These values can then be compared to the steady state LEGR value of -0.0617 .

Although all the unsteady data have not been discussed here, the previous discussion included typical examples of the wind tunnel data. The remaining cases of the $\pm 5.5^\circ$ and $\pm 10^\circ$ oscillation data for all the Reynolds numbers are included in Appendix C.

The following four unsteady pressure distributions show examples of the data used to calculate the lift, pressure drag, and pitching moment coefficients. Figure 36 shows the distribution for a clean model with a reduced frequency of 0.028, mean angle of attack of 8° , and $\pm 10^\circ$ pitch oscillation. For plotting clarity, the model pressures were 'unwrapped' about the trailing edge. The upper surface pressures are depicted on the right side of the surface plot; lower surface values are on the left. The trailing edge is at the midpoint of the x-axis with the leading edge at each extreme. The time scale corresponds to angle of attack. For this case, the separated flow area is defined by the irregular, rough areas of the upper surface portion of the plot. The lower surface stays attached through all airfoil oscillations. Figure 37 shows the LEGR case for the same test conditions as the previous figure. In this case, the pressure peaks

were not as high as for the clean case, and the stall behavior is more pronounced. Also, each case shows the effect of a bad tap on the lower surface near the trailing edge; it is indicated by the line of pressure irregularity. This lower response tap did not significantly affect the integrated results and remained in the reduction process.

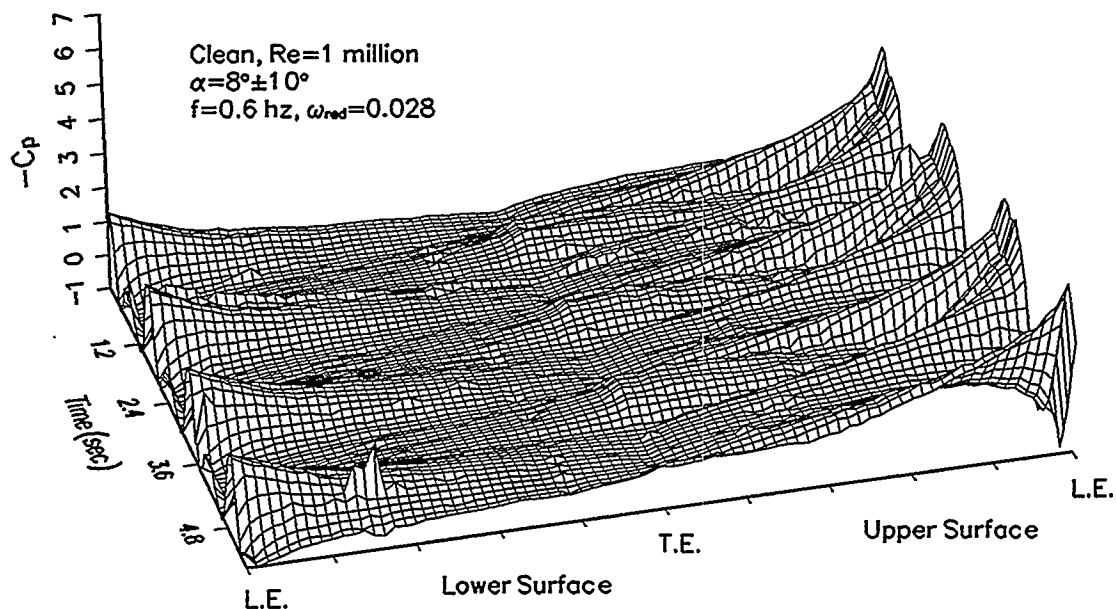


Figure 36. Clean, unsteady pressure distribution, $\pm 10^\circ$.

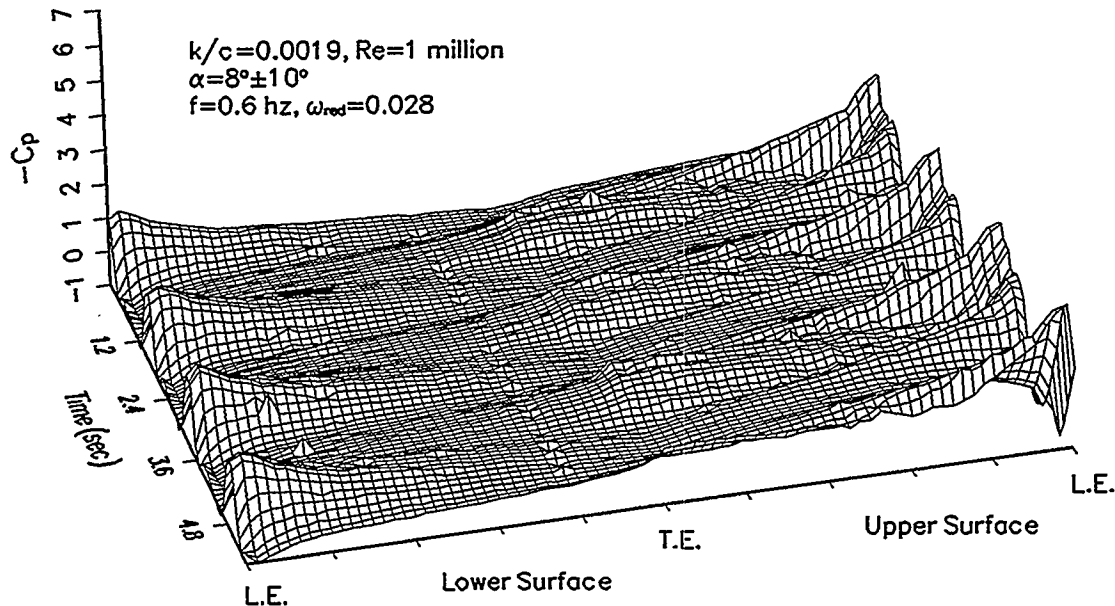


Figure 37. LEGR, unsteady pressure distribution, $\pm 10^\circ$.

Figure 38 shows the same clean run conditions at a higher frequency of pitch oscillation. At this higher frequency, the character of the flow is similar to the previous clean case. Noticeably different, however, are the larger magnitude pressure peaks. This is reflected in the maximum lift coefficient results, with values of 1.95 for this case and only 1.52 for the lower frequency case.

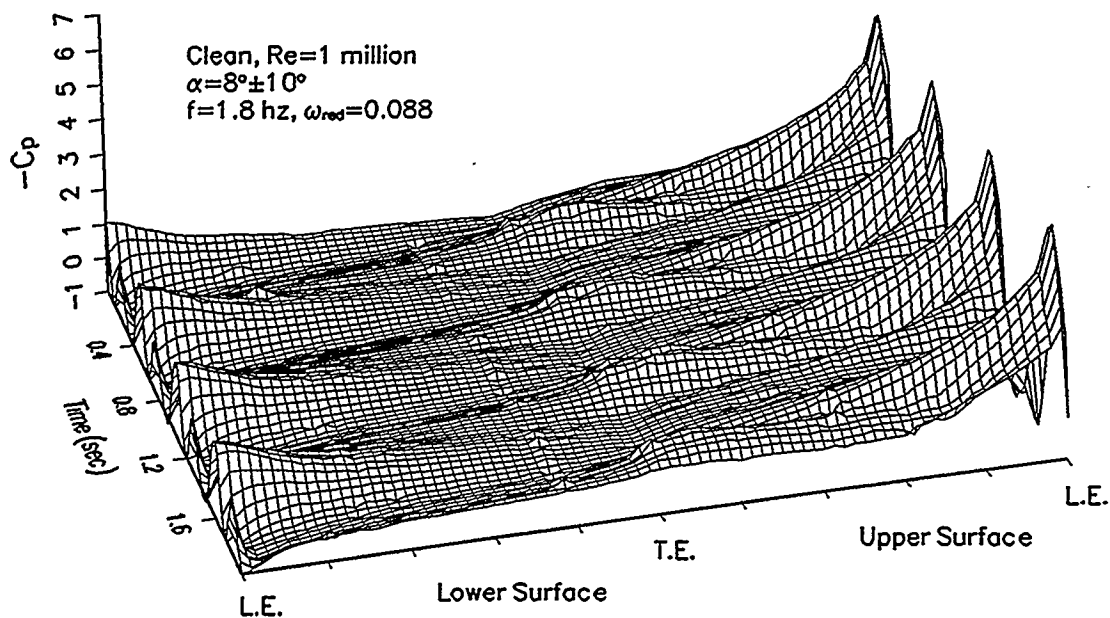


Figure 38. Clean, unsteady pressure distribution, $\pm 10^\circ$.

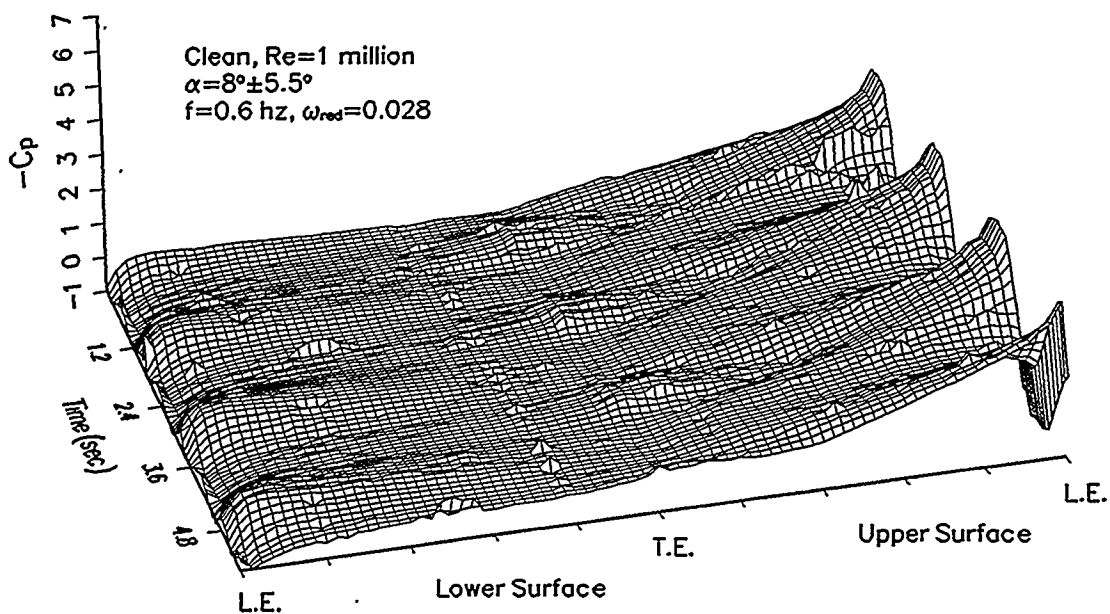


Figure 39. Clean, unsteady pressure distribution, $\pm 5.5^\circ$.

Figure 39 shows the smaller mean angle for the clean case at the same conditions indicated above. The structure is different from the previous figure because less of the upper surface flow is separated, the consequence of lower angles of attack.

Summary of Results

A NACA 4415 airfoil model was tested under steady state and pitch oscillation conditions. Baseline tests were made while the model was clean, and then corresponding tests were conducted with LEGR applied.

A summary of the steady state aerodynamic parameters is shown in Table 1. As observed, the application of LEGR reduced the maximum lift of the airfoil up to 19%, and the minimum drag coefficient on average increased more than 50% on average. LEGR also affects the zero lift pitching moment coefficient by reducing the magnitude by an average of 13%.

Table 1. NACA 4415 Steady State Parameters Summary.

Grit Pattern	Re x 10 ⁻⁶	C _{lmax}	C _{dmin}	C _{mo}
Clean	0.75	1.38 @ 15.3°	0.0078	-0.0962
k/c=0.0019	0.75	1.11 @ 11.2°	0.0150	-0.0835
Clean	1.00	1.35 @ 14.3°	0.0090	-0.0967
k/c=0.0019	1.00	1.13 @ 14.3°	0.0146	-0.0842
Clean	1.25	1.30 @ 12.3°	0.0097	-0.0962
k/c=0.0019	1.25	1.10 @ 11.2°	0.0153	-0.0844
Clean	1.50	1.29 @ 12.2°	0.0105	-0.0947
k/c=0.0019	1.50	1.08 @ 10.2°	0.0163	-0.0827

Table 2. NACA 4415, Unsteady, Clean, ±5.5°.

ω_{red}	Re x 10 ⁻⁶	f	C _{lmax}	α_{max}	C _{l dec}	C _{m inc}	C _{m dec}
0.037	0.75	0.59	1.52	16.8	1.11	-0.0941	-0.0338
0.076	0.75	1.21	1.65	16.5	1.00	-0.0744	-0.0202
0.116	0.75	1.85	1.75	15.7	1.05	-0.0899	-0.0301
0.028	1.01	0.60	1.44	12.7	1.21	-0.0593	-0.0310
0.056	1.01	1.21	1.57	16.3	1.05	-0.0897	-0.0381
0.086	1.01	1.83	1.66	15.8	1.08	-0.0833	-0.0459
0.022	1.26	0.61	1.45	12.7	1.22	-0.0632	-0.0402
0.044	1.26	1.18	1.54	14.8	1.09	-0.0748	-0.0341
0.069	1.26	1.85	1.61	16.3	1.05	-0.0942	-0.0395
0.019	1.51	0.60	1.43	14.3	1.13	-0.0645	-0.0338
0.037	1.50	1.19	1.50	14.3	1.14	-0.0610	-0.0370
0.056	1.51	1.81	1.57	14.8	1.03	-0.0705	-0.0321

The pitch oscillation data can be divided into two groups, the ±5.5° amplitude and ±10° amplitude oscillations, which show similar trends. For both ±5.5° and ±10°, the unsteady test conditions and the maximum lift coefficients are listed in Tables 2, 3, 4, and 5. As the reduced frequency, which takes oscillation and tunnel speed into account, is increased, the maximum lift coefficient also increases. In addition, the hysteresis behavior becomes increasingly apparent with increased reduced frequency.

Table 3. NACA 4415, Unsteady, LEGR, $\pm 5.5^\circ$.

ω_{red}	$Re \times 10^{-6}$	f	C_{lmax}	α_{max}	$C_{l dec}$	$C_{m inc}$	$C_{m dec}$
0.038	0.76	0.61	1.23	14.3	0.83	-0.0991	-0.0400
0.073	0.76	1.17	1.37	14.3	0.72	-0.0971	-0.0334
0.116	0.76	1.85	1.50	16.2	0.80	-0.1274	-0.0556
0.028	1.01	0.61	1.17	11.1	0.88	-0.0508	-0.0267
0.056	1.01	1.19	1.26	13.7	0.81	-0.0793	-0.0340
0.087	1.01	1.85	1.39	14.3	0.72	-0.0841	-0.0341
0.023	1.26	0.61	1.21	11.7	0.97	-0.0700	-0.0403
0.046	1.25	1.21	1.30	13.8	0.87	-0.0907	-0.0388
0.068	1.25	1.83	1.39	13.8	0.82	-0.0899	-0.0212
0.019	1.51	0.61	1.18	11.8	0.98	-0.0705	-0.0350
0.038	1.50	1.21	1.21	13.3	0.86	-0.0764	-0.0258
0.057	1.50	1.83	1.25	13.2	0.76	-0.0766	-0.0307

Table 4. NACA 4415, Unsteady, Clean, $\pm 10^\circ$.

ω_{red}	$Re \times 10^{-6}$	f	C_{lmax}	α_{max}	$C_{l dec}$	$C_{m inc}$	$C_{m dec}$
0.039	0.74	0.61	1.66	15.4	1.18	-0.0812	-0.0679
0.076	0.74	1.18	1.91	17.9	0.54	-0.1018	-0.0692
0.118	0.74	1.83	2.05	18.4	0.73	-0.1168	-0.0899
0.029	1.00	0.61	1.55	14.9	1.07	-0.0743	-0.0276
0.057	0.99	1.18	1.77	16.6	0.88	-0.0831	-0.0495
0.089	0.99	1.85	1.95	19.4	0.92	-0.1399	-0.0358
0.023	1.24	0.61	1.51	14.5	1.09	-0.0747	-0.0257
0.046	1.24	1.21	1.67	16.8	0.95	-0.0893	-0.0241
0.070	1.23	1.83	1.88	17.9	0.97	-0.1064	-0.0265
0.019	1.49	0.60	1.51	14.8	1.06	-0.0709	-0.0364
0.038	1.49	1.21	1.65	17.0	1.01	-0.0895	-0.0348
0.058	1.49	1.83	1.77	18.4	0.96	-0.1129	-0.0448

As expected, the application of LEGR reduces the aerodynamic performance of the airfoil. The maximum lift coefficient is reduced by 15% - 20% for the $\pm 5.5^\circ$ case and 10% - 15% for the $\pm 10^\circ$ case. In addition to following the same trends as the clean, unsteady data discussed previously, the LEGR causes the hysteresis behavior to persist into lower angles of attack than in the clean cases. Overall, the unsteady wind tunnel data show hysteresis behavior that becomes more apparent with increased reduced frequency. The maximum unsteady lift coefficient can be up to 25% higher for the $\pm 5.5^\circ$ amplitude and up to 50% higher for the $\pm 10^\circ$ amplitude than the steady state maximum lift coefficient. Variation in the quarter chord pitching moment coefficient can be 40% greater than that indicated by steady state results. These findings indicate that it is important to consider the unsteady

loading that will occur in wind turbine operation because steady state results can greatly underestimate the forces.

Table 5. NACA 4415, Unsteady, LEGR, $\pm 10^\circ$.

ω_{red}	$Re \times 10^{-6}$	ω	C_{lmax}	α_{max}	$C_{l dec}$	$C_{m inc}$	$C_{m dec}$
0.038	0.75	0.60	1.44	14.3	0.86	-0.0903	-0.0360
0.076	0.75	1.19	1.72	17.1	0.76	-0.1634	-0.0615
0.119	0.74	1.85	1.92	18.4	0.87	-0.1829	-0.0851
0.028	1.00	0.60	1.34	14.9	0.79	-0.1119	-0.0488
0.058	0.99	1.21	1.52	16.9	0.81	-0.1468	-0.0464
0.087	0.99	1.81	1.80	18.9	0.71	-0.2082	-0.0625
0.023	1.25	0.61	1.30	13.1	0.85	-0.0784	-0.0340
0.046	1.24	1.19	1.48	15.1	0.73	-0.1061	-0.0276
0.070	1.24	1.83	1.63	17.8	0.77	-0.1713	-0.0469
0.019	1.50	0.60	1.27	12.8	0.97	-0.0717	-0.0313
0.037	1.49	1.18	1.39	12.8	0.81	-0.0674	-0.0190
0.058	1.49	1.85	1.58	15.9	0.66	-0.1151	-0.0394

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Appendix A: Model and Surface Pressure Tap Coordinates

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A2. NACA 4415, Surface Pressure Taps, Non-Dimensional Coordinates	A-5

Table A1. NACA 4415 Measured Model Coordinates, 18 inch desired chord				
Chord Station (in)	Upper Ordinate (in)		Chord Station (in)	Lower Ordinate (in)
-0.002	0.091		-0.002	0.091
0.000	0.138		0.000	0.039
0.002	0.151		0.002	0.028
0.005	0.174		0.004	0.012
0.009	0.196		0.009	-0.008
0.018	0.234		0.016	-0.035
0.050	0.320		0.045	-0.108
0.077	0.369		0.070	-0.155
0.135	0.450		0.131	-0.232
0.214	0.541		0.205	-0.297
0.315	0.641		0.304	-0.364
0.390	0.705		0.378	-0.405
0.478	0.772		0.466	-0.447
0.613	0.864		0.600	-0.499
0.746	0.945		0.731	-0.540
0.901	1.030		0.886	-0.580
1.052	1.103		1.035	-0.612
1.169	1.158		1.152	-0.633
1.363	1.240		1.345	-0.664
1.574	1.325		1.555	-0.693
1.740	1.386		1.721	-0.711
1.904	1.442		1.887	-0.725
2.037	1.486		2.018	-0.734
2.417	1.600		2.398	-0.752
2.969	1.725		2.950	-0.759
3.349	1.799		3.330	-0.757
3.808	1.872		3.789	-0.747
4.213	1.924		4.196	-0.734
4.891	1.987		4.876	-0.707

Table A1. NACA 4415 Measured Model Coordinates, 18 inch desired chord				
Chord Station (in)	Upper Ordinate (in)		Chord Station (in)	Lower Ordinate (in)
5.836	2.031		5.821	-0.662
6.724	2.035		6.711	-0.616
7.503	2.010		7.492	-0.575
8.515	1.944		8.505	-0.520
9.368	1.863		9.360	-0.471
10.299	1.752		10.293	-0.417
12.066	1.479		12.937	-0.266
13.845	1.138		13.844	-0.219
14.531	0.984		14.535	-0.186
14.997	0.874		14.999	-0.164
15.863	0.653		15.503	-0.141
16.335	0.526		15.867	-0.124
16.828	0.391		16.308	-0.106
17.172	0.296		16.835	-0.081
17.384	0.235		17.302	-0.061
17.526	0.190		17.462	-0.053
17.694	0.147		17.620	-0.044
17.896	0.087		17.703	-0.041
17.946	0.071		17.782	-0.037
18.052	0.039		17.834	-0.033
			17.905	-0.030
			18.052	-0.019
End of Table A1				

Table A2. NACA 4415, Surface Pressure Taps, Non-Dimensional Coordinates		
Tap Number	Chord Station	Ordinate
1	1.0035	-0.0001
2	0.9958	-0.0015
3	0.9807	-0.0032
4	0.9549	-0.0044
5	0.9298	-0.0056
6	0.9047	-0.0067
7	0.8809	-0.0077
8	0.8559	-0.0087
9	0.8296	-0.0099
10	0.8039	-0.0109
11	0.7537	-0.0132
12	0.7041	-0.0159
13	0.6533	-0.0188
14	0.6024	-0.0217
15	0.5545	-0.0244
16	0.5021	-0.0274
17	0.4024	-0.0327
18	0.2989	-0.0379
19	0.2490	-0.0400
20	0.2250	-0.0408
21	0.2000	-0.0413
22	0.1755	-0.0418
23	0.1493	-0.0417
24	0.1252	-0.0411
25	0.1001	-0.0395
26	0.0735	-0.0363
27	0.0496	-0.0319
28	0.0256	-0.0243

Table A2. NACA 4415, Surface Pressure Taps, Non-Dimensional Coordinates		
Tap Number	Chord Station	Ordinate
29	0.0138	-0.0178
30	0.0010	0.0001
31	0.0119	0.0306
32	0.0257	0.0423
33	0.0498	0.0572
34	0.0749	0.0689
35	0.1010	0.0787
36	0.1242	0.0859
37	0.1502	0.0926
38	0.1741	0.0977
39	0.1981	0.1021
40	0.2254	0.1057
41	0.2523	0.1086
42	0.3016	0.1119
43	0.3528	0.1130
44	0.4007	0.1122
45	0.4538	0.1091
46	0.5027	0.1049
47	0.5534	0.0993
48	0.6016	0.0927
49	0.6533	0.0844
50	0.7040	0.0755
51	0.7548	0.0655
52	0.8046	0.0546
53	0.8299	0.0486
54	0.8538	0.0426
55	0.8783	0.0363
56	0.9041	0.0294
57	0.9309	0.0219

Table A2. NACA 4415, Surface Pressure Taps, Non-Dimensional Coordinates		
Tap Number	Chord Station	Ordinate
58	0.9551	0.0152
59	0.9800	0.0081
60	0.9908	0.0043
End of Table A2		

Appendix B: Steady State Data Integrated Coefficients and Pressure Distributions

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Table B1. NACA 4415, Clean, $Re = 0.75 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m\frac{1}{4}}$	$Re \times 10^{-6}$	C_{dw}
76	-20.1	-0.39	0.2599	0.0130	0.77	--
77	-18.0	-0.33	0.2208	0.0062	0.77	--
78	-16.0	-0.26	0.1840	-0.0015	0.77	--
79	-14.1	-0.22	0.1563	-0.0038	0.76	--
80	-12.1	-0.32	0.1501	0.0080	0.77	--
81	-10.2	-0.58	-0.0121	-0.1048	0.76	0.0187
82	-8.1	-0.39	-0.0133	-0.1015	0.76	0.0172
83	-6.1	-0.20	-0.0118	-0.1000	0.76	0.0142
84	-4.0	0.02	-0.0085	-0.0962	0.76	0.0132
85	-2.1	0.22	-0.0059	-0.0958	0.76	0.0097
86	0.0	0.43	-0.0012	-0.0958	0.75	0.0089
87	2.1	0.62	0.0055	-0.0912	0.76	0.0078
88	4.1	0.86	0.0122	-0.0951	0.76	0.0093
89	6.1	1.03	0.0192	-0.0882	0.76	0.0105
90	8.1	1.17	0.0283	-0.0780	0.76	0.0148
91	10.2	1.27	0.0412	-0.0645	0.75	0.0178
92	11.2	1.29	0.0455	-0.0545	0.76	0.0212
93	12.2	1.32	0.0635	-0.0538	0.75	0.0218
94	13.3	1.33	0.0751	-0.0497	0.75	0.0252
95	14.3	1.37	0.0940	-0.0544	0.77	0.0284
96	15.3	1.38	0.1138	-0.0579	0.76	--
97	16.3	1.32	0.1184	-0.0545	0.77	--
98	17.3	1.32	0.1395	-0.0605	0.77	--
99	18.1	1.13	0.1249	-0.0555	0.76	--
100	19.1	1.10	0.1433	-0.0614	0.76	--
101	20.1	1.08	0.1638	-0.0677	0.76	--
102	22.1	1.05	0.2138	-0.0863	0.76	--
103	23.9	0.92	0.4504	-0.1558	0.74	--

Table B1. NACA 4415, Clean, $Re = 0.75 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m\frac{1}{4}}$	$Re \times 10^{-6}$	C_{dw}
104	26.1	1.02	0.5403	-0.1826	0.80	--
105	28.0	1.09	0.6147	-0.2041	0.79	--
106	30.0	1.16	0.7034	-0.2288	0.81	--
107	32.1	1.23	0.7973	-0.2546	0.81	--
108	34.1	1.29	0.9007	-0.2862	0.82	--
109	36.0	1.32	0.9928	-0.3112	0.83	--
110	38.2	1.34	1.0844	-0.3323	0.85	--
111	40.0	1.35	1.1643	-0.3542	0.86	--
End of Table B1						

Table B2. NACA 4415, Clean, $Re = 1.0 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m\frac{1}{4}}$	$Re \times 10^{-6}$	C_{dw}
38	-20.1	-0.38	0.2555	0.0118	1.03	--
39	-18.0	-0.32	0.2181	0.0047	1.03	--
40	-16.1	-0.27	0.1854	-0.0002	1.02	--
41	-14.1	-0.24	0.1613	0.0021	1.02	--
42	-12.1	-0.47	0.1541	0.0058	1.02	--
43	-10.2	-0.60	-0.0141	-0.1014	1.01	0.0168
44	-8.1	-0.40	-0.0139	-0.0990	1.01	0.0148
45	-6.1	-0.19	-0.0123	-0.0981	1.01	0.0127
46	-4.1	0.02	-0.0088	-0.0967	1.01	0.0116
47	-2.1	0.23	-0.0061	-0.0954	1.00	0.0100
48	0.0	0.42	-0.0005	-0.0939	1.01	0.0101
49	2.1	0.63	0.0049	-0.0931	1.00	0.0090
50	4.1	0.86	0.0126	-0.0947	1.01	0.0100
51	6.2	1.02	0.0197	-0.0846	1.01	0.0113
52	8.1	1.17	0.0257	-0.0745	1.01	0.0138
53	10.2	1.26	0.0360	-0.0598	1.01	0.0201
54	11.2	1.29	0.0432	-0.0519	1.01	0.0268
55	12.2	1.30	0.0554	-0.0477	1.00	0.0372
56	13.3	1.33	0.0682	-0.0467	1.01	0.0385
57	14.3	1.35	0.0886	-0.0526	1.01	0.0320
58	15.3	1.19	0.0750	-0.0378	1.02	--
59	16.2	1.15	0.0925	-0.0447	1.02	--
60	17.2	1.12	0.1095	-0.0497	1.02	--
61	18.2	1.10	0.1264	-0.0568	1.02	--
62	19.2	1.09	0.1469	-0.0634	1.02	--
63	20.3	1.08	0.1675	-0.0695	1.02	--
64	22.1	1.04	0.2161	-0.0877	1.03	--
65	24.1	1.03	0.2705	-0.1050	1.03	--

Table B2. NACA 4415, Clean, $Re = 1.0 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m/4}$	$Re \times 10^{-6}$	C_{dw}
66	26.1	0.96	0.5087	-0.1663	1.05	--
67	28.1	1.09	0.6176	-0.2039	1.07	--
68	30.0	1.17	0.7070	-0.2294	1.07	--
69	32.1	1.22	0.7936	-0.2536	1.09	--
70	34.1	1.29	0.9035	-0.2882	1.10	--
71	36.0	1.32	0.9890	-0.3101	1.10	--
72	38.0	1.34	1.0748	-0.3303	1.12	--
73	40.0	1.34	1.1520	-0.3456	1.13	--
End of Table B2						

Table B3. NACA 4415, Clean, $Re = 1.25 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m\frac{1}{4}}$	$Re \times 10^{-6}$	C_{dw}
2	-20.1	-0.39	0.2608	0.0157	1.29	--
3	-18.2	-0.34	0.2247	0.0085	1.28	--
4	-16.0	-0.27	0.1852	0.0000	1.28	--
5	-14.1	-0.30	0.1696	0.0065	1.28	--
6	-12.1	-0.52	0.1608	0.0201	1.28	--
7	-10.2	-0.62	-0.0145	-0.0994	1.26	0.0174
8	-8.1	-0.42	-0.0132	-0.0974	1.26	0.0152
9	-6.0	-0.20	-0.0117	-0.0967	1.27	0.0139
10	-4.0	0.01	-0.0090	-0.0962	1.25	0.0111
11	-2.1	0.22	-0.0053	-0.0948	1.25	0.0102
1	0.0	0.44	-0.0019	-0.0935	1.26	0.0097
12	0.0	0.42	-0.0001	-0.0939	1.26	0.0098
13	2.1	0.63	0.0052	-0.0926	1.26	0.0099
14	4.0	0.84	0.0105	-0.0904	1.26	0.0102
15	6.2	1.03	0.0187	-0.0840	1.26	0.0110
16	8.1	1.16	0.0261	-0.0731	1.26	0.0160
17	10.2	1.26	0.0377	-0.0595	1.26	0.0215
18	11.2	1.28	0.0412	-0.0494	1.26	0.0305
19	12.3	1.30	0.0520	-0.0464	1.26	0.0433
20	13.3	1.28	0.0583	-0.0428	1.27	--
21	14.3	1.20	0.0631	-0.0383	1.27	--
22	15.3	1.16	0.0782	-0.0409	1.26	--
23	16.3	1.14	0.0961	-0.0463	1.27	--
24	17.3	1.11	0.1117	-0.0510	1.27	--
25	18.3	1.09	0.1306	-0.0580	1.27	--
26	19.1	1.08	0.1469	-0.0640	1.27	--
27	20.1	1.08	0.1660	-0.0685	1.28	--
28	22.1	1.03	0.2203	-0.0900	1.28	--

Table B3. NACA 4415, Clean, $Re = 1.25 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m\frac{1}{4}}$	$Re \times 10^{-6}$	C_{dw}
29	24.1	1.04	0.2732	-0.1064	1.29	--
30	26.1	0.96	0.5119	-0.1679	1.32	--
31	28.0	1.08	0.6108	-0.2004	1.32	--
32	30.0	1.16	0.7014	-0.2271	1.35	--
33	32.1	1.24	0.8035	-0.2569	1.35	--
34	34.1	1.30	0.9090	-0.2893	1.36	--
35	36.0	1.32	0.9899	-0.3094	1.38	--
36	37.9	1.34	1.0797	-0.3341	1.41	--
37	40.1	1.34	1.1659	-0.3549	1.41	--
End of Table B3						

Table B4. NACA 4415, Clean, $Re = 1.25 \times 10^6$, Repeat runs						
RUN	AOA	C_l	C_{dp}	$C_{m/4}$	$Re \times 10^{-6}$	C_{dw}
113	-6.0	-0.19	-0.0114	-0.0968	1.26	0.0136
114	-4.0	0.03	-0.0089	-0.0958	1.26	0.0114
115	-2.1	0.21	-0.0057	-0.0956	1.26	0.0097
112	0.0	0.43	-0.0010	-0.0955	0.75	0.0079
116	0.0	0.42	-0.0009	-0.0932	1.26	0.0107
117	2.1	0.64	0.0043	-0.0923	1.25	0.0091
118	4.1	0.86	0.0110	-0.0917	1.25	0.0098
119	6.1	1.03	0.0170	-0.0847	1.27	0.0111
120	8.1	1.17	0.0235	-0.0717	1.27	0.0138
121	10.2	1.26	0.0380	-0.0596	1.26	0.0193
122	11.2	1.29	0.0440	-0.0511	1.25	0.0267
123	12.3	1.30	0.0524	-0.0462	1.26	0.0556
124	13.3	1.28	0.0585	-0.0430	1.27	--
125	14.3	1.19	0.0633	-0.0383	1.28	--
126	15.3	1.17	0.0789	-0.0407	1.27	--
127	16.1	1.14	0.0905	-0.0455	1.27	--
128	17.3	1.12	0.1137	-0.0521	1.27	--
129	18.1	1.10	0.1293	-0.0587	1.27	--
130	19.1	1.08	0.1477	-0.0644	1.30	--
131	20.1	1.06	0.1694	-0.0720	1.30	--
End of Table B4						

Table B5. NACA 4415, Clean, $Re = 1.5 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m\frac{1}{4}}$	$Re \times 10^{-6}$	C_{dw}
132	-20.1	-0.39	0.2596	0.0136	1.55	--
133	-18.0	-0.35	0.2269	0.0104	1.53	--
134	-15.9	-0.29	0.1895	0.0034	1.55	--
135	-14.1	-0.32	0.1767	0.0140	1.54	--
136	-12.1	-0.50	0.1702	0.0265	1.53	--
137	-10.2	-0.62	-0.0142	-0.0981	1.52	0.0182
138	-8.1	-0.41	-0.0137	-0.0968	1.52	0.0148
139	-6.0	-0.19	-0.0106	-0.0958	1.52	0.0119
140	-3.9	0.02	-0.0086	-0.0947	1.51	0.0116
141	-2.1	0.21	-0.0056	-0.0938	1.52	0.0105
142	0.0	0.42	-0.0008	-0.0927	1.52	0.0105
143	2.1	0.64	0.0039	-0.0908	1.52	0.0109
144	4.0	0.85	0.0089	-0.0886	1.52	0.0104
145	6.1	1.02	0.0165	-0.0823	1.52	0.0126
146	8.3	1.17	0.0270	-0.0704	1.53	0.0159
147	10.2	1.25	0.0319	-0.0541	1.52	0.0245
148	12.2	1.29	0.0470	-0.0446	1.52	0.0578
149	13.2	1.21	0.0511	-0.0404	1.52	--
150	14.3	1.17	0.0644	-0.0399	1.53	--
151	15.2	1.14	0.0788	-0.0431	1.52	--
152	16.3	1.12	0.0966	-0.0480	1.52	--
153	17.3	1.09	0.1162	-0.0544	1.53	--
154	18.4	1.07	0.1342	-0.0600	1.53	--
155	19.1	1.06	0.1508	-0.0677	1.53	--
156	20.1	1.03	0.1751	-0.0758	1.54	--
157	22.1	1.01	0.2280	-0.0950	1.55	--
158	24.2	1.03	0.2784	-0.1070	1.54	--
End of Table B5						

Table B6. NACA 4415, Clean, $Re = 1.5 \times 10^6$, Repeat runs						
RUN	AOA	C_l	C_{dp}	$C_{m\frac{1}{4}}$	$Re \times 10^{-6}$	C_{dw}
169	-17.0	-0.36	0.2181	0.0190	1.53	--
168	-16.0	-0.36	0.2091	0.0216	1.54	--
167	-15.1	-0.42	0.2136	0.0387	1.54	--
166	-14.1	-0.40	0.1939	0.0306	1.53	--
165	-13.3	-0.91	-0.0089	-0.0990	1.51	--
164	-12.3	-0.81	-0.0106	-0.0993	1.51	--
163	-11.2	-0.71	-0.0124	-0.0990	1.50	--
162	-10.2	-0.62	-0.0136	-0.0986	1.51	--
161	-8.1	-0.40	-0.0131	-0.0972	1.50	--
160	-3.9	0.03	-0.0087	-0.0950	1.51	--
159	0.0	0.44	-0.0024	-0.0926	1.51	--
End of Table B6						

Table B7. NACA 4415, $k/c=0.0019$, $Re = 0.75 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m\frac{1}{4}}$	$Re \times 10^{-6}$	C_{dw}
180	-20.1	-0.40	0.2352	0.0131	0.77	--
179	-18.0	-0.37	0.1939	0.0065	0.77	--
178	-16.0	-0.35	0.1594	0.0047	0.76	--
177	-14.1	-0.33	0.1300	0.0025	0.76	--
176	-12.1	-0.43	0.1100	0.0093	0.76	--
175	-10.2	-0.54	-0.0132	-0.0960	0.76	0.0263
174	-8.1	-0.38	-0.0175	-0.0930	0.76	0.0190
173	-6.1	-0.20	-0.0161	-0.0889	0.76	0.0177
172	-3.9	-0.01	-0.0113	-0.0835	0.76	0.0171
171	-2.1	0.18	-0.0083	-0.0817	0.76	0.0150
170	0.0	0.36	-0.0031	-0.0785	0.76	0.0166
181	0.0	0.35	-0.0029	-0.0780	0.75	0.0167
182	2.1	0.55	0.0002	-0.0738	0.75	0.0170
183	4.1	0.72	0.0063	-0.0644	0.76	0.0180
184	6.2	0.87	0.0152	-0.0572	0.75	0.0216
185	8.1	0.98	0.0264	-0.0480	0.75	0.0258
186	10.1	1.07	0.0485	-0.0465	0.76	0.0300
187	11.2	1.11	0.0686	-0.0556	0.75	0.0256
188	12.2	1.11	0.0897	-0.0592	0.75	0.0352
189	13.2	1.10	0.1101	-0.0650	0.77	--
190	14.2	1.07	0.1283	-0.0685	0.77	--
191	15.2	1.07	0.1499	-0.0723	0.76	--
192	16.2	0.93	0.1547	-0.0689	0.77	--
193	17.2	1.06	0.1966	-0.0821	0.77	--
194	18.2	0.87	0.2075	-0.0849	0.77	--
195	19.2	1.03	0.2461	-0.0958	0.78	--
196	20.0	0.85	0.2647	-0.1034	0.79	--
197	22.0	0.86	0.3285	-0.1204	0.76	--

Table B7. NACA 4415, $k/c=0.0019$, $Re = 0.75 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m\frac{1}{4}}$	$Re \times 10^{-6}$	C_{dw}
198	24.1	1.02	0.4381	-0.1639	0.78	--
199	26.0	1.04	0.4994	-0.1770	0.79	--
200	28.0	1.07	0.5644	-0.1902	0.80	--
201	30.1	1.12	0.6523	-0.2121	0.80	--
202	32.1	1.19	0.7493	-0.2404	0.82	--
203	34.1	1.24	0.8410	-0.2647	0.83	--
204	36.1	1.33	0.9734	-0.3110	0.83	--
205	37.8	1.35	1.0589	-0.3344	0.84	--
206	40.1	1.33	1.1206	-0.3408	0.85	--
End of Table B7						

Table B8. NACA 4415, $k/c=0.0019$, $Re = 1.0 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m/4}$	$Re \times 10^{-6}$	C_{dw}
217	-20.1	-0.39	0.2349	0.0109	1.03	--
216	-18.1	-0.35	0.1999	0.0067	1.02	--
215	-16.0	-0.33	0.1651	0.0028	1.02	--
214	-14.2	-0.37	0.1333	0.0027	1.02	--
213	-12.2	-0.47	0.1017	-0.0019	1.02	--
212	-10.2	-0.56	-0.0135	-0.0922	1.01	0.0318
211	-8.1	-0.41	-0.0184	-0.0916	1.00	0.0236
210	-6.0	-0.22	-0.0167	-0.0883	1.01	0.0174
209	-4.0	-0.02	-0.0123	-0.0842	1.01	0.0164
208	-2.1	0.17	-0.0087	-0.0811	1.01	0.0182
207	0.0	0.36	-0.0049	-0.0779	1.01	0.0146
218	0.0	0.36	-0.0051	-0.0773	1.01	0.0152
219	2.1	0.55	0.0008	-0.0730	1.02	0.0183
220	4.0	0.72	0.0055	-0.0661	1.01	0.0178
221	6.1	0.87	0.0131	-0.0572	1.02	0.0165
222	8.1	0.98	0.0284	-0.0491	1.02	0.0247
223	10.2	1.08	0.0507	-0.0473	1.01	0.0283
224	11.2	1.12	0.0736	-0.0567	1.02	0.0304
225	12.2	1.12	0.0956	-0.0617	1.02	--
226	13.3	1.12	0.1152	-0.0656	1.02	--
227	14.3	1.13	0.1379	-0.0703	1.00	--
228	15.3	1.10	0.1589	-0.0753	1.04	--
229	16.1	1.09	0.1774	-0.0786	1.03	--
230	17.1	1.07	0.1978	-0.0825	1.02	--
231	18.1	1.05	0.2207	-0.0881	1.03	--
232	19.1	1.01	0.2417	-0.0943	1.04	--
233	20.1	0.84	0.2658	-0.1009	1.04	--
234	22.1	0.89	0.3395	-0.1240	1.06	--

Table B8. NACA 4415, $k/c=0.0019$, $Re = 1.0 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m\frac{1}{4}}$	$Re \times 10^{-6}$	C_{dw}
235	24.0	1.01	0.4355	-0.1608	1.05	--
236	26.1	1.03	0.4968	-0.1737	1.04	--
237	28.1	1.06	0.5643	-0.1875	1.05	--
238	30.0	1.12	0.6480	-0.2103	1.07	--
239	32.2	1.19	0.7573	-0.2422	1.07	--
240	33.9	1.27	0.8627	-0.2770	1.09	--
241	36.0	1.31	0.9549	-0.3004	1.11	--
242	38.0	1.33	1.0436	-0.3246	1.12	--
243	39.9	1.34	1.1294	-0.3462	1.12	--
End of Table B8						

Table B9. NACA 4415, k/c=0.0019, Re = 1.25 x 10 ⁶						
RUN	AOA	C _l	C _{dp}	C _{m¼}	Re x10 ⁻⁶	C _{dw}
254	-20.1	-0.40	0.2384	0.0107	1.29	--
253	-18.1	-0.34	0.2006	0.0038	1.27	--
252	-16.0	-0.32	0.1692	0.0014	1.28	--
251	-14.1	-0.36	0.1394	0.0055	1.28	--
250	-12.2	-0.49	0.1060	0.0006	1.26	--
249	-10.2	-0.58	-0.0150	-0.0926	1.26	0.0308
248	-8.1	-0.42	-0.0181	-0.0900	1.27	0.0248
247	-6.1	-0.23	-0.0146	-0.0868	1.27	0.0197
246	-4.0	-0.02	-0.0124	-0.0844	1.28	0.0148
245	-2.1	0.18	-0.0092	-0.0807	1.27	0.0157
244	0.0	0.36	-0.0050	-0.0775	1.28	0.0156
255	0.0	0.36	-0.0050	-0.0773	1.26	0.0153
256	2.1	0.56	0.0001	-0.0723	1.26	0.0161
257	4.2	0.73	0.0071	-0.0662	1.26	0.0162
258	6.1	0.88	0.0143	-0.0569	1.26	0.0214
259	8.1	1.00	0.0257	-0.0473	1.26	0.0286
260	10.2	1.08	0.0479	-0.0458	1.26	0.0345
261	11.2	1.10	0.0708	-0.0559	1.27	0.0393
262	12.2	1.10	0.0917	-0.0604	1.26	--
263	13.2	0.99	0.0958	-0.0515	1.27	--
264	14.2	0.91	0.1063	-0.0506	1.27	--
265	15.2	0.90	0.1272	-0.0567	1.27	--
266	16.2	0.97	0.1630	-0.0704	1.28	--
267	17.1	1.04	0.1952	-0.0828	1.28	--
268	18.2	1.03	0.2234	-0.0891	1.29	--
269	19.1	1.03	0.2469	-0.0964	1.28	--
270	20.1	1.00	0.2720	-0.1040	1.28	--
271	22.1	0.92	0.3406	-0.1251	1.30	--

Table B9. NACA 4415, $k/c=0.0019$, $Re = 1.25 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m/4}$	$Re \times 10^{-6}$	C_{dw}
272	24.1	1.02	0.4383	-0.1610	1.30	—
273	26.1	1.00	0.4885	-0.1674	1.31	—
274	28.1	0.98	0.5311	-0.1708	1.31	—
275	30.1	1.12	0.6563	-0.2126	1.34	—
276	32.1	1.19	0.7546	-0.2403	1.34	—
277	34.0	1.27	0.8638	-0.2746	1.37	—
278	35.9	1.32	0.9664	-0.3065	1.38	—
279	37.9	1.35	1.0583	-0.3315	1.40	—
280	40.0	1.34	1.1341	-0.3471	1.41	—
End of Table B9						

Table B10. NACA 4415, $k/c=0.0019$, $Re = 1.5 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m/k}$	$Re \times 10^{-6}$	C_{dw}
291	-20.1	-0.39	0.2386	0.0083	1.54	--
290	-18.0	-0.35	0.2035	0.0049	1.53	--
289	-16.1	-0.33	0.1743	0.0037	1.53	--
288	-13.9	-0.38	0.1435	0.0082	1.53	--
287	-12.0	-0.46	0.1145	0.0101	1.52	--
286	-10.2	-0.60	-0.0130	-0.0893	1.52	0.0333
285	-8.2	-0.43	-0.0164	-0.0881	1.52	0.0250
284	-6.1	-0.23	-0.0155	-0.0863	1.52	0.0203
283	-4.0	-0.02	-0.0124	-0.0827	1.53	0.0185
282	-2.1	0.18	-0.0095	-0.0795	1.52	0.0168
292	0.0	0.39	-0.0070	-0.0755	1.51	0.0163
281	0.1	0.39	-0.0065	-0.0752	1.52	0.0169
293	2.1	0.58	-0.0038	-0.0699	1.51	0.0157
294	4.1	0.74	0.0039	-0.0634	1.51	0.0174
295	6.2	0.90	0.0121	-0.0549	1.51	0.0236
296	8.1	1.01	0.0224	-0.0458	1.51	0.0321
297	10.2	1.08	0.0485	-0.0465	1.51	--
298	11.3	1.08	0.0709	-0.0547	1.50	--
299	12.1	0.95	0.0657	-0.0396	1.51	--
300	13.1	0.95	0.0858	-0.0449	1.52	--
301	14.2	0.93	0.1067	-0.0511	1.52	--
302	15.1	0.91	0.1242	-0.0556	1.52	--
303	16.3	0.90	0.1516	-0.0631	1.53	--
304	17.2	0.89	0.1777	-0.0732	1.53	--
305	18.2	0.88	0.2051	-0.0811	1.53	--
306	19.2	0.88	0.2381	-0.0922	1.54	--
307	20.0	0.86	0.2704	-0.1032	1.55	--
308	22.0	0.91	0.3400	-0.1234	1.56	--

Table B10. NACA 4415, $k/c=0.0019$, $Re = 1.5 \times 10^6$						
RUN	AOA	C_l	C_{dp}	$C_{m\frac{1}{4}}$	$Re \times 10^{-6}$	C_{dw}
309	24.0	0.96	0.4137	-0.1473	1.56	--
310	26.0	0.99	0.4775	-0.1627	1.54	--
End of Table B10						

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Pressure Distributions, Steady State, $Re = 0.75$ million

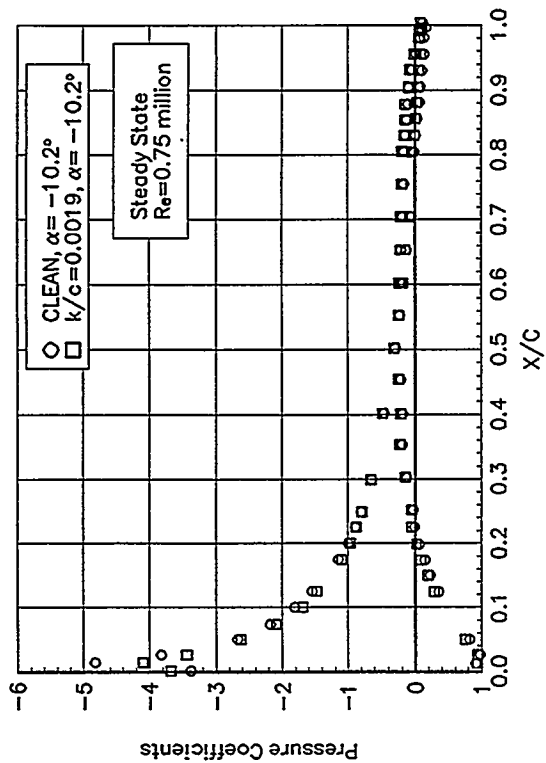


Figure B1. $\alpha = -10.2^\circ$

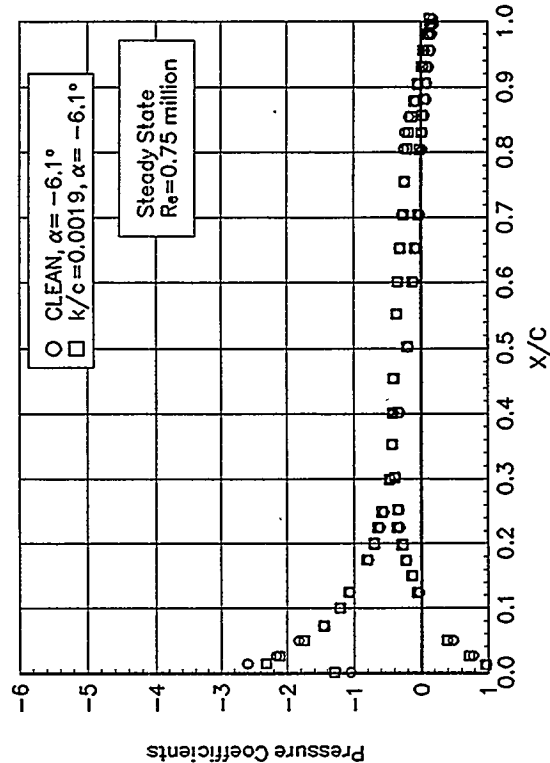


Figure B3. $\alpha = -6.1^\circ$

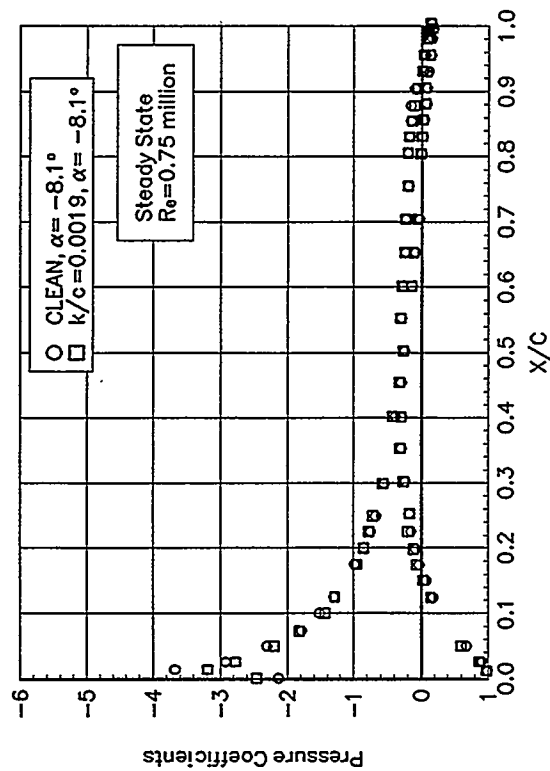


Figure B2. $\alpha = -8.1^\circ$

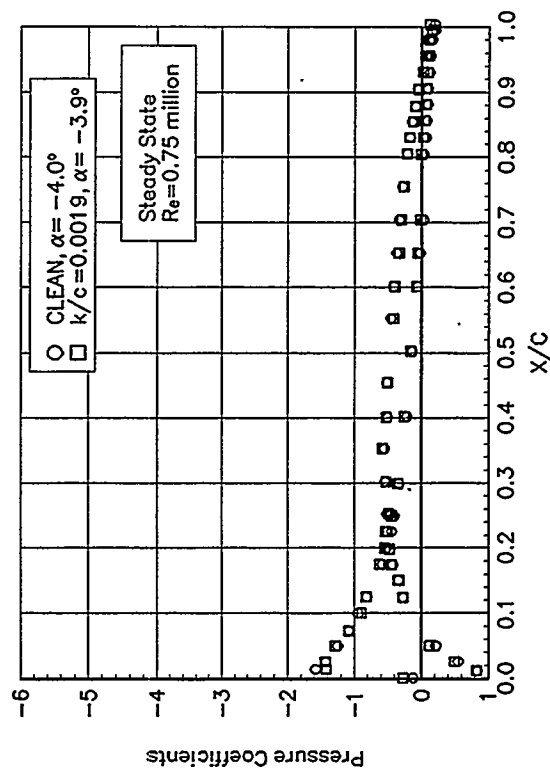


Figure B4. $\alpha = -4.0^\circ$

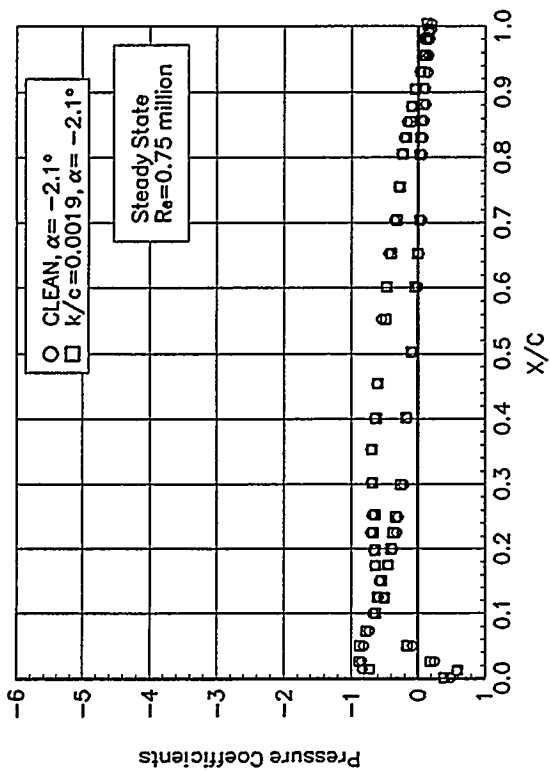


Figure B5. $\alpha = -2.1^\circ$

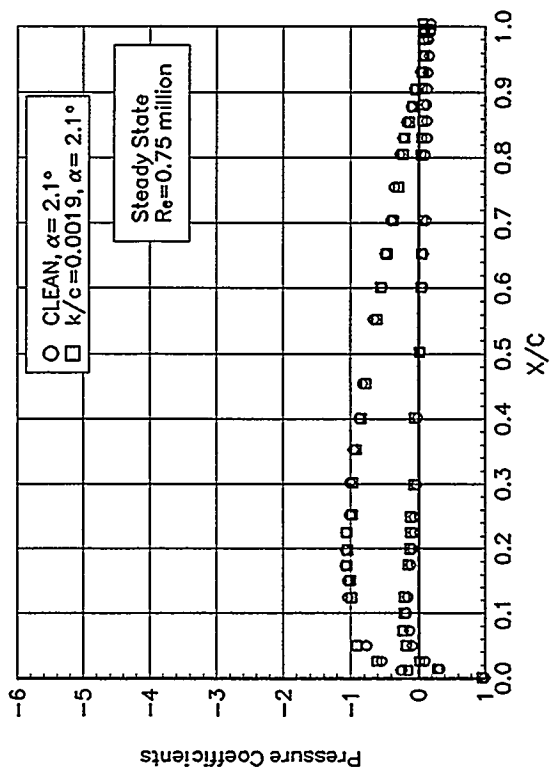


Figure B7. $\alpha = 2.1^\circ$

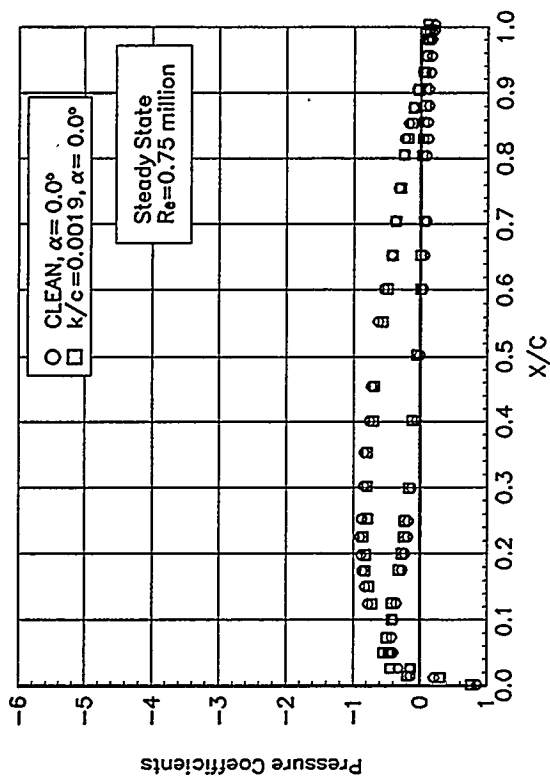


Figure B6. $\alpha = 0.0^\circ$

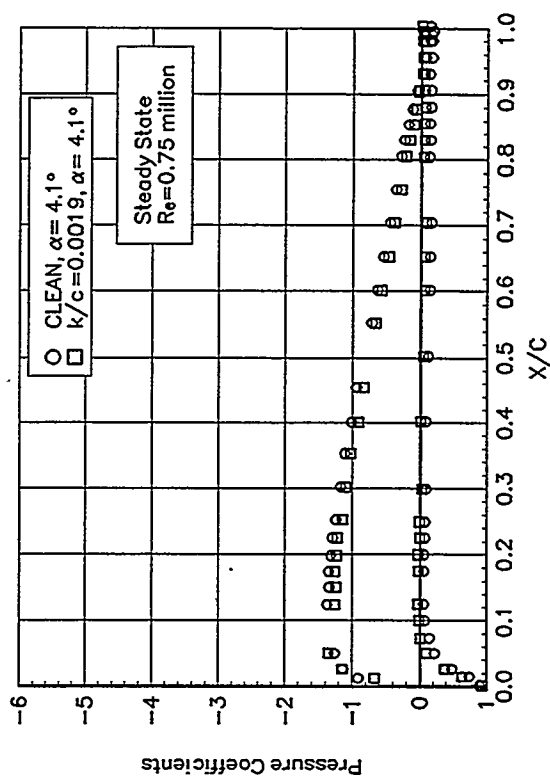


Figure B8. $\alpha = 4.1^\circ$

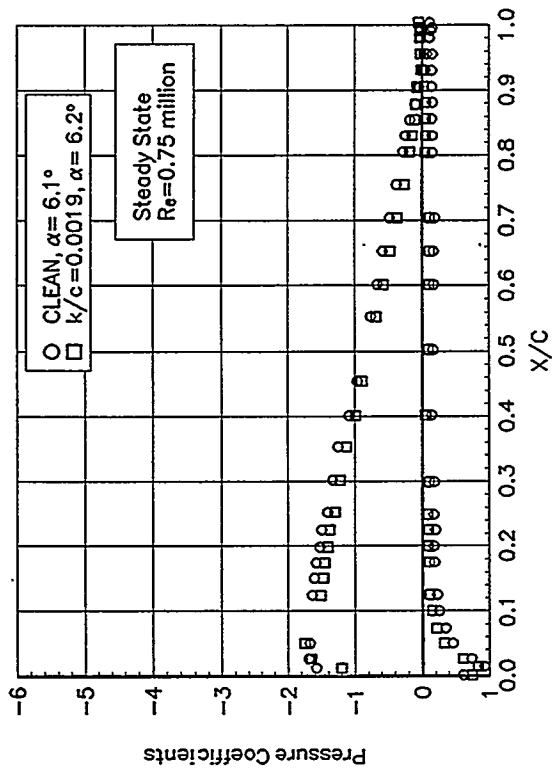


Figure B9. $\alpha = 6.1^\circ$

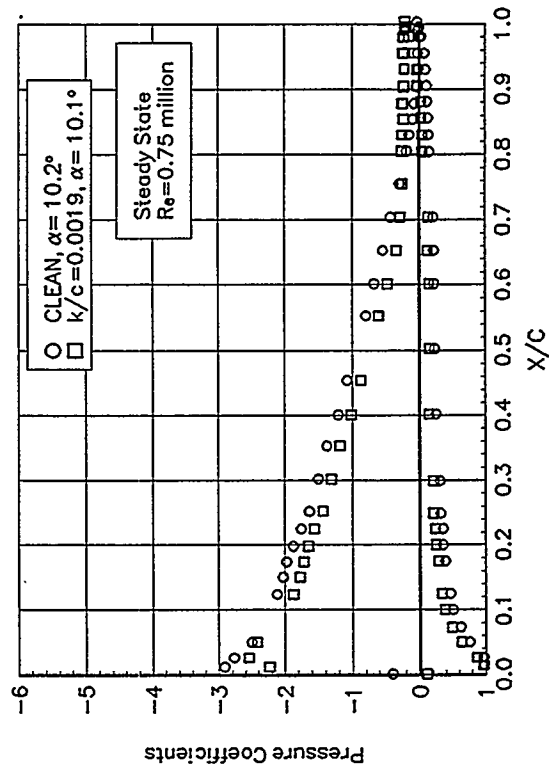


Figure B11. $\alpha = 10.2^\circ$

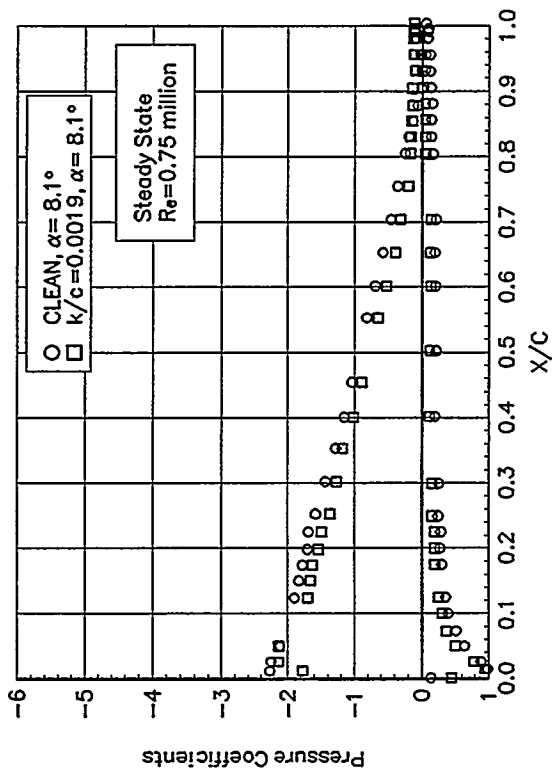


Figure B10. $\alpha = 8.1^\circ$

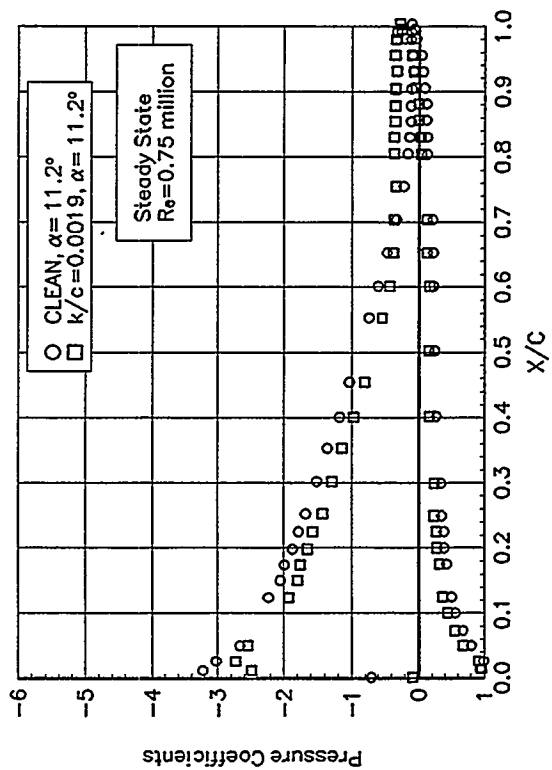


Figure B12. $\alpha = 11.2^\circ$

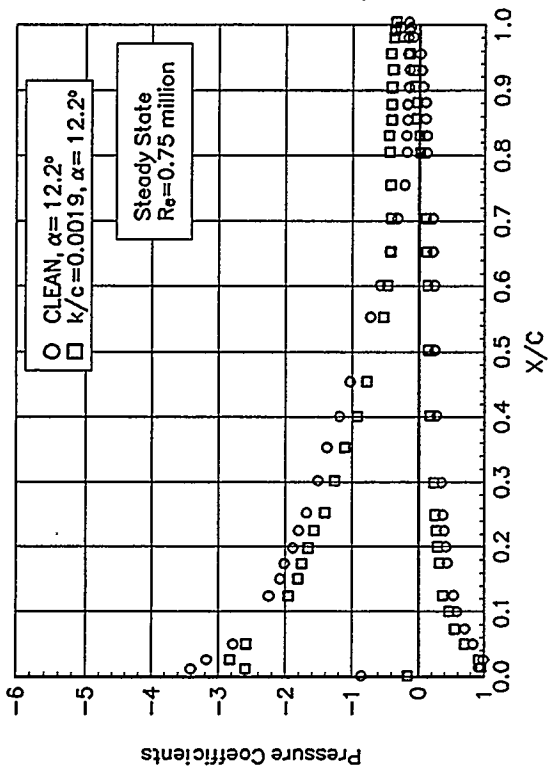


Figure B13. $\alpha = 12.2^\circ$

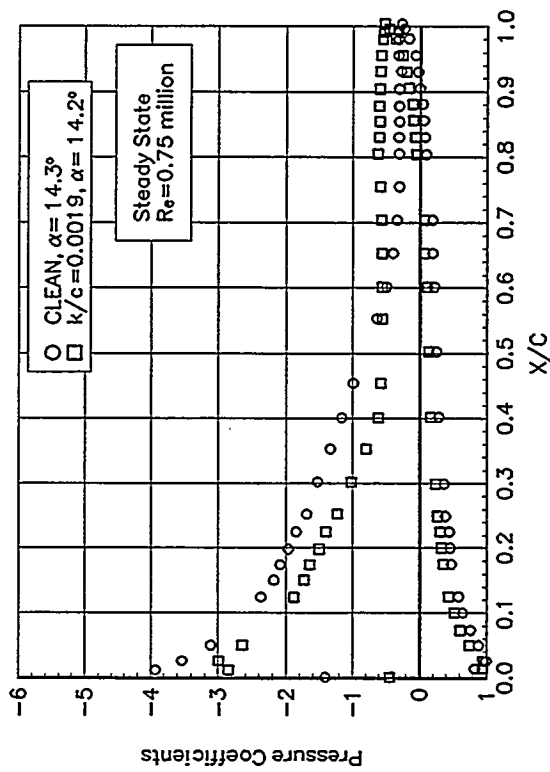


Figure B15. $\alpha = 14.3^\circ$

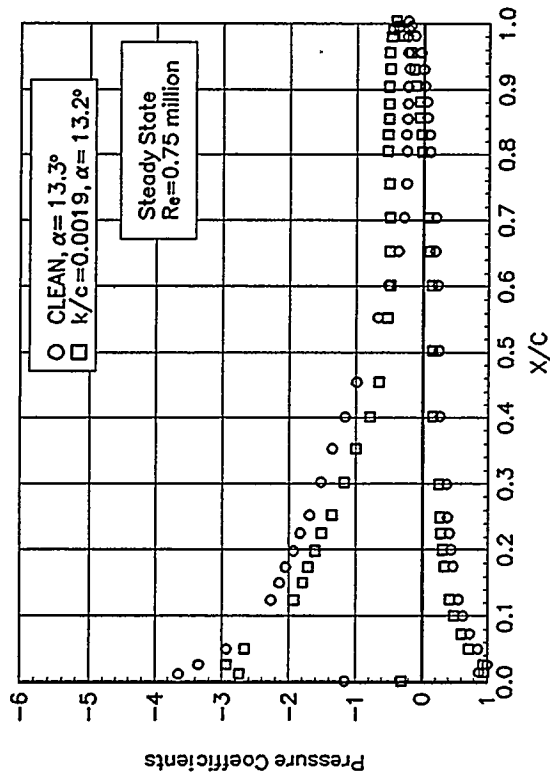


Figure B14. $\alpha = 13.3^\circ$

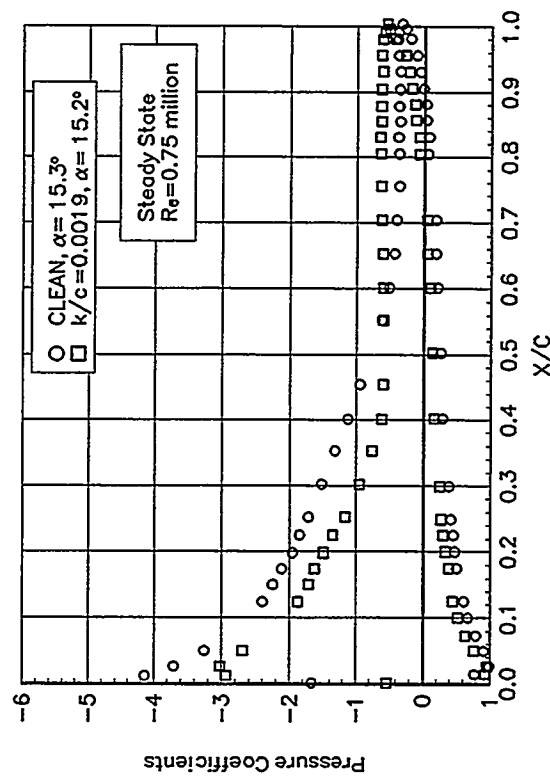


Figure B16. $\alpha = 15.3^\circ$

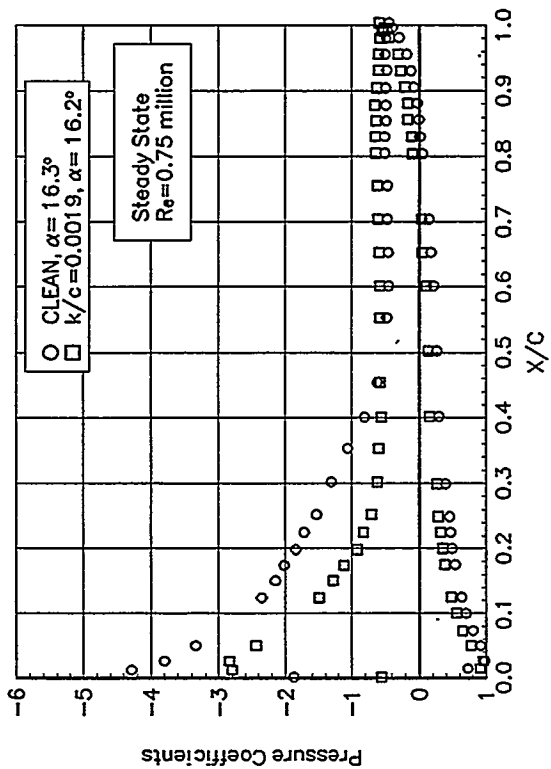


Figure B17. $\alpha = 16.3^\circ$

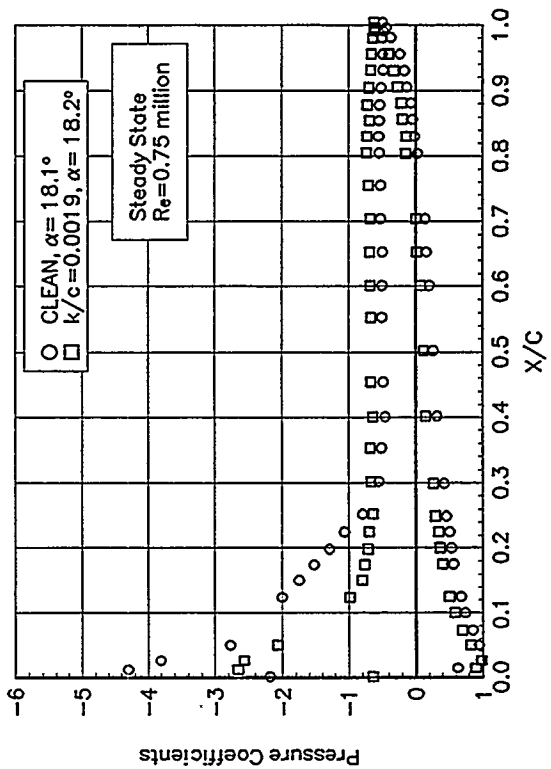


Figure B19. $\alpha = 18.1^\circ$

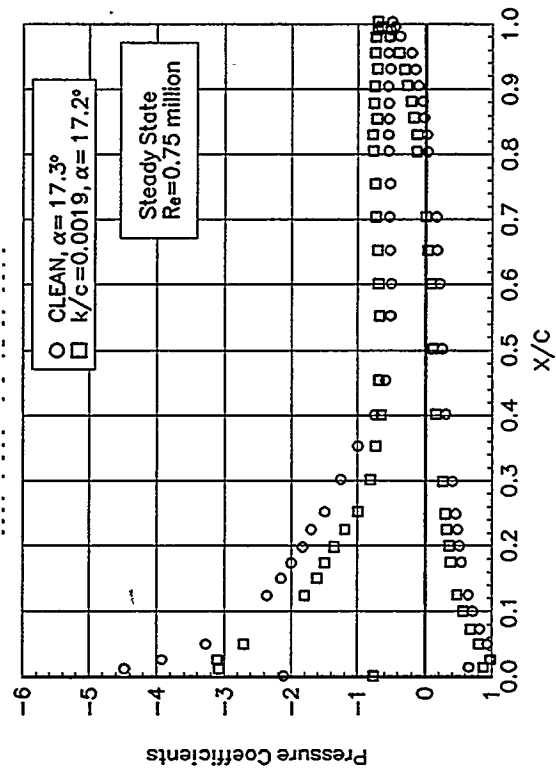


Figure B18. $\alpha = 17.3^\circ$

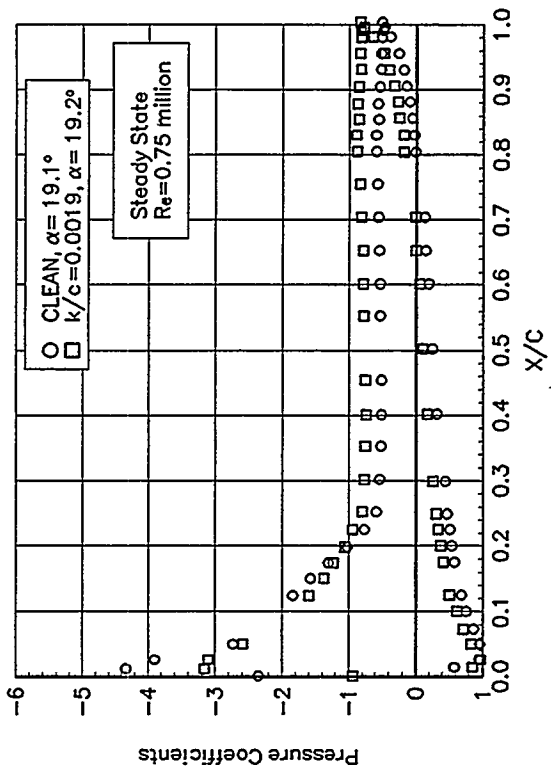


Figure B20. $\alpha = 19.1^\circ$

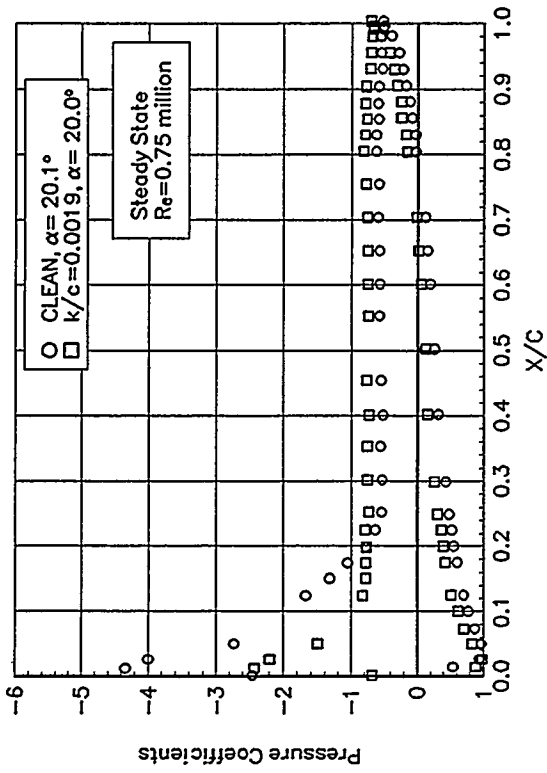


Figure B21. $\alpha = 20.1^\circ$

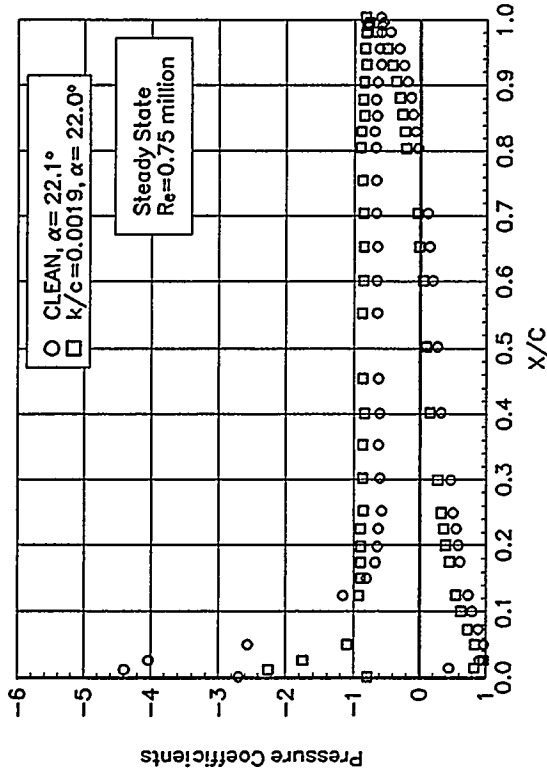


Figure B22. $\alpha = 22.1^\circ$

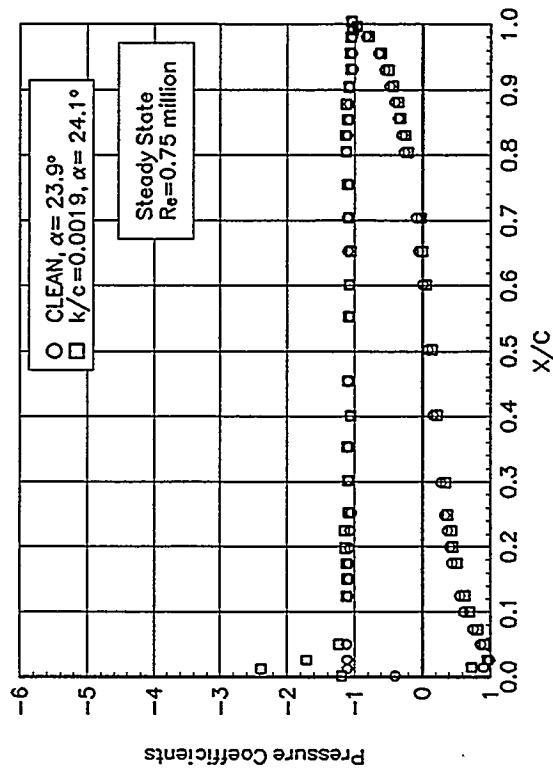


Figure B23. $\alpha = 23.9^\circ$

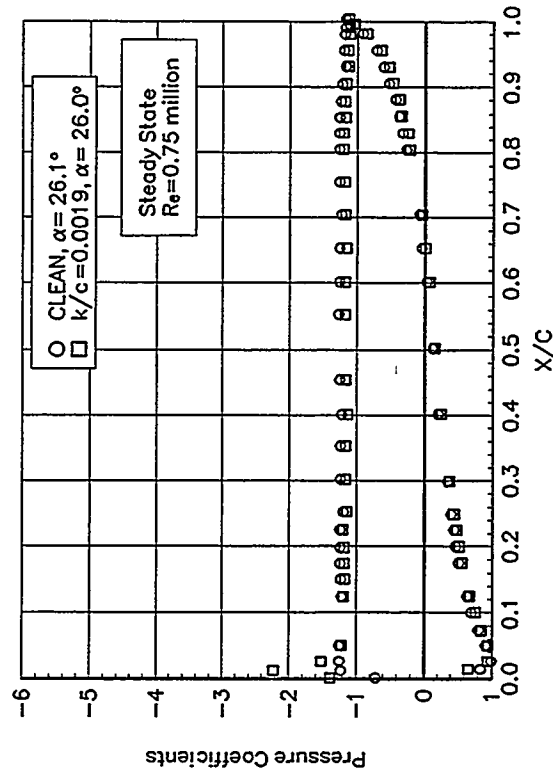


Figure B24. $\alpha = 26.1^\circ$

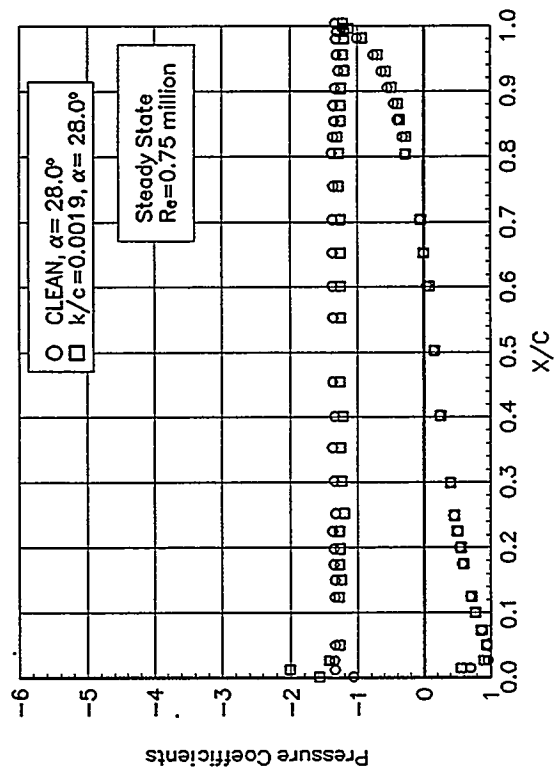


Figure B25. $\alpha = 28.0^\circ$

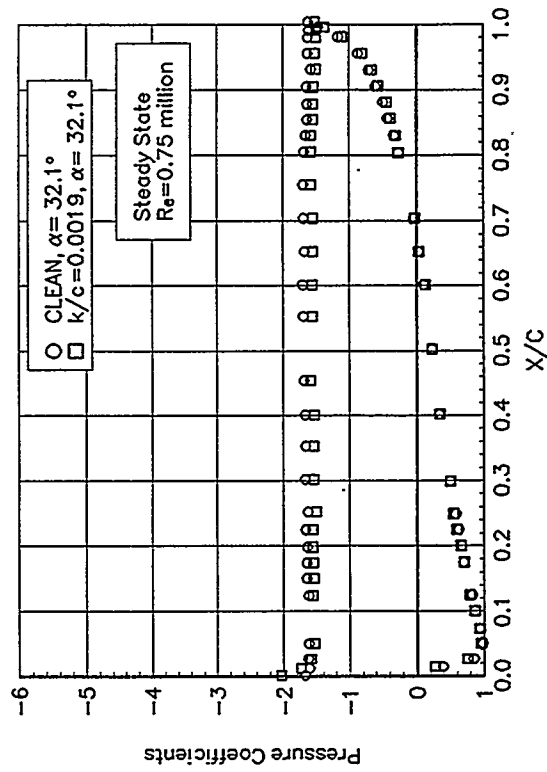


Figure B27. $\alpha = 32.1^\circ$

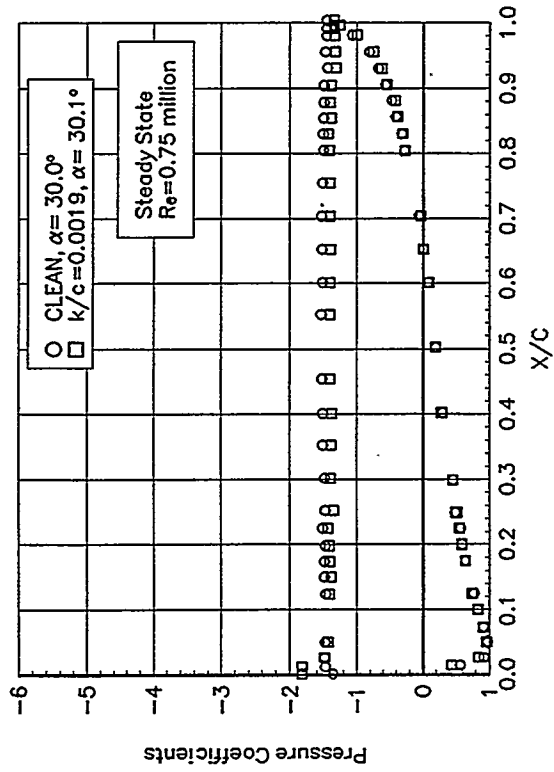


Figure B26. $\alpha = 30.0^\circ$

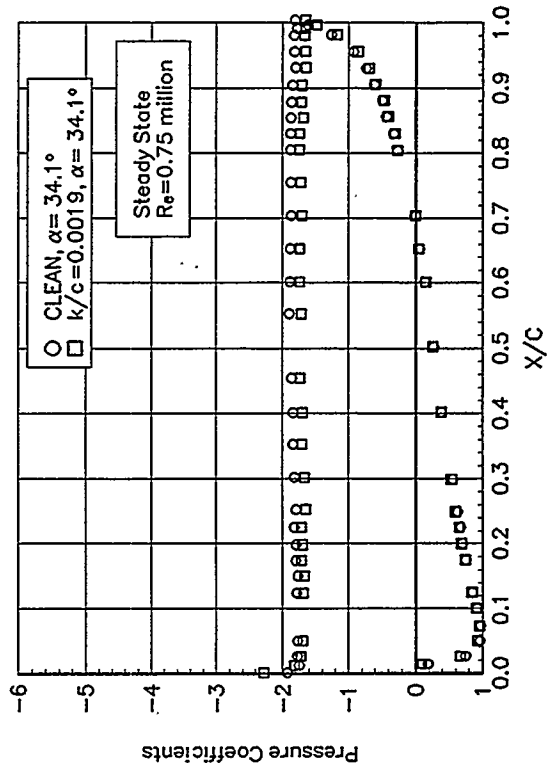


Figure B28. $\alpha = 34.1^\circ$

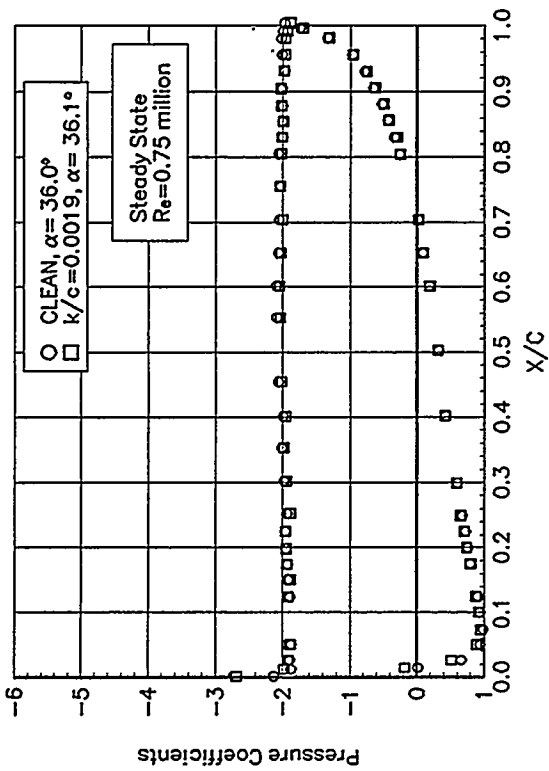


Figure B29. $\alpha = 36.0^\circ$

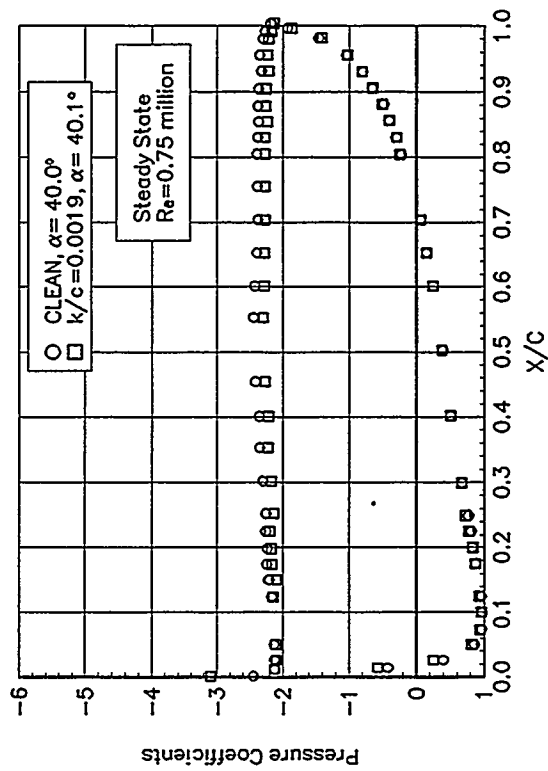


Figure B31. $\alpha = 40.0^\circ$

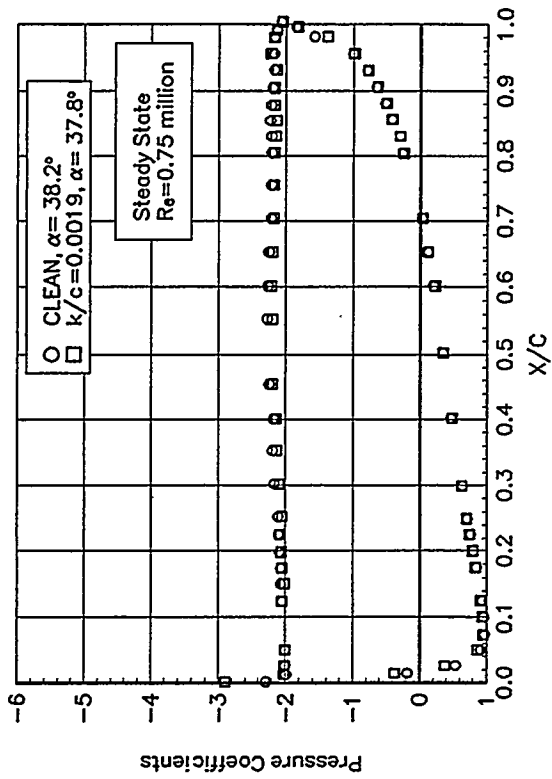


Figure B30. $\alpha = 38.2^\circ$

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Pressure Distributions, Steady State, $Re = 1$ million

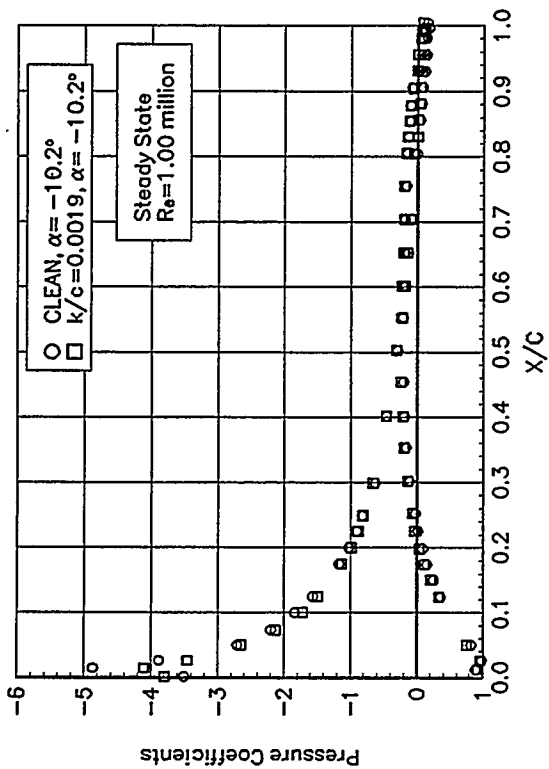


Figure B32. $\alpha = -10.2^\circ$

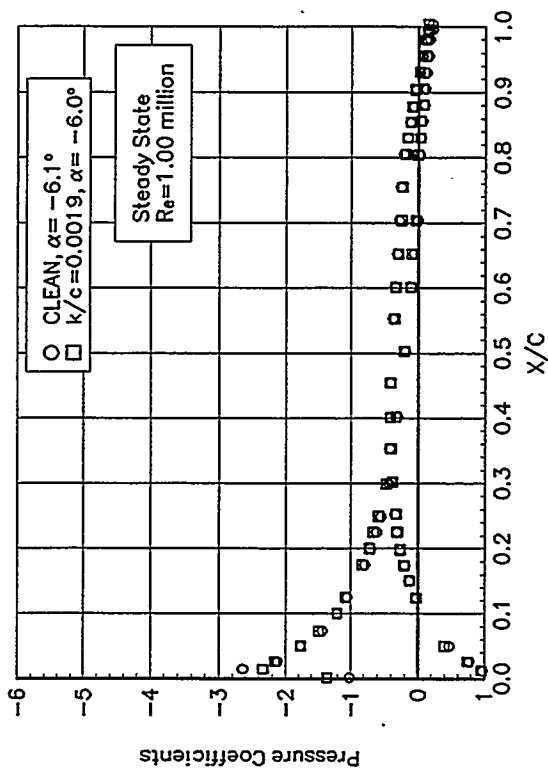


Figure B34. $\alpha = -6.1^\circ$

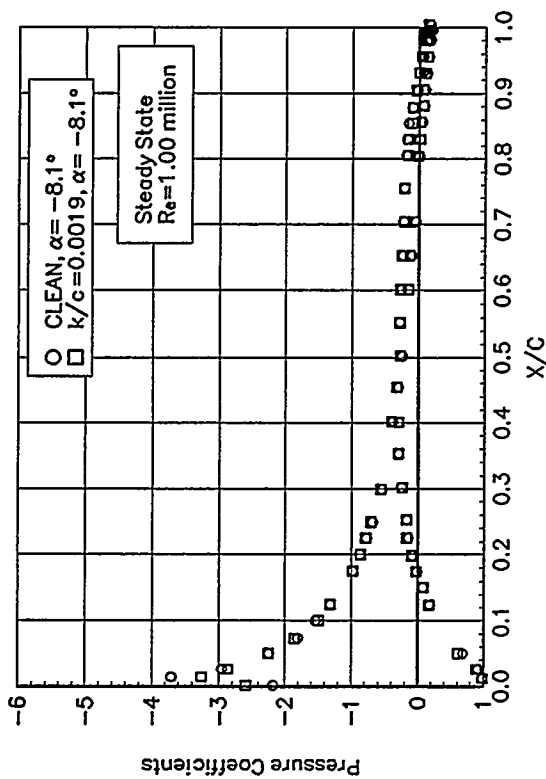


Figure B33. $\alpha = -8.1^\circ$

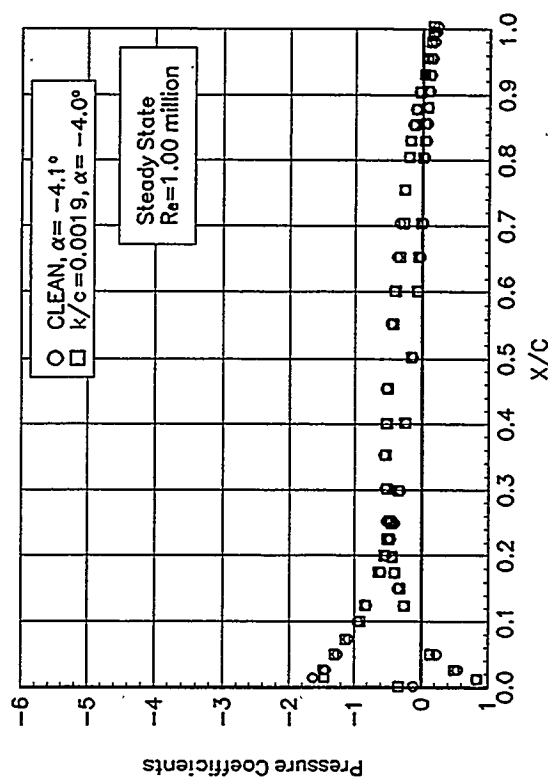


Figure B35. $\alpha = -4.1^\circ$

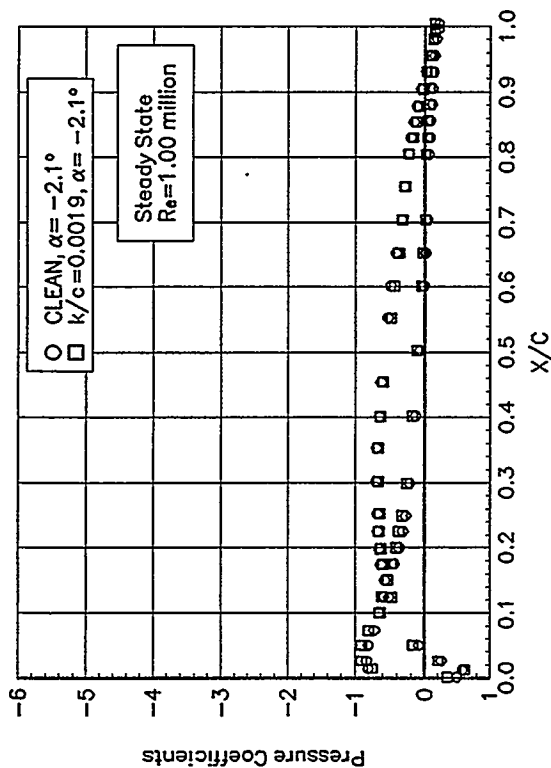


Figure B36. $\alpha = -2.1^\circ$

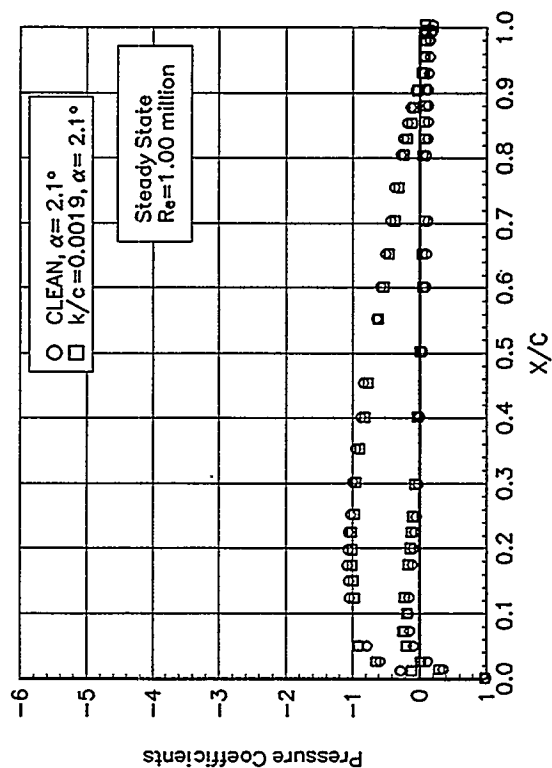


Figure B38. $\alpha = 2.1^\circ$

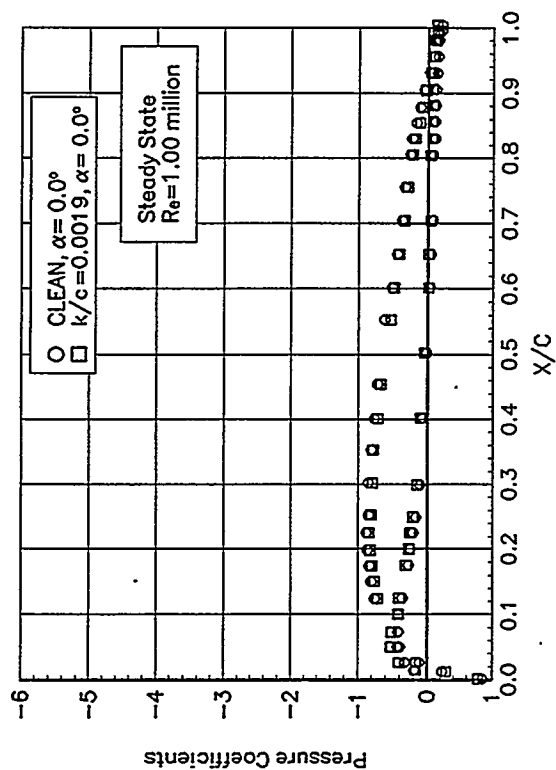


Figure B37. $\alpha = 0.0^\circ$

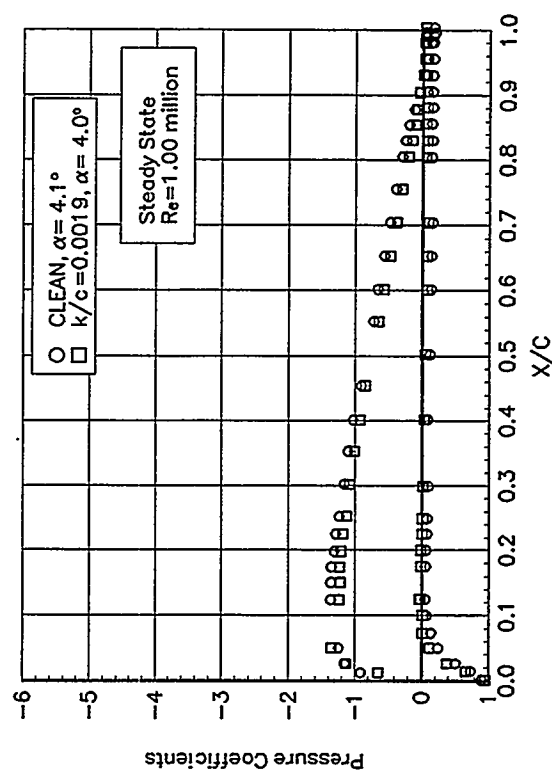


Figure B39. $\alpha = 4.1^\circ$

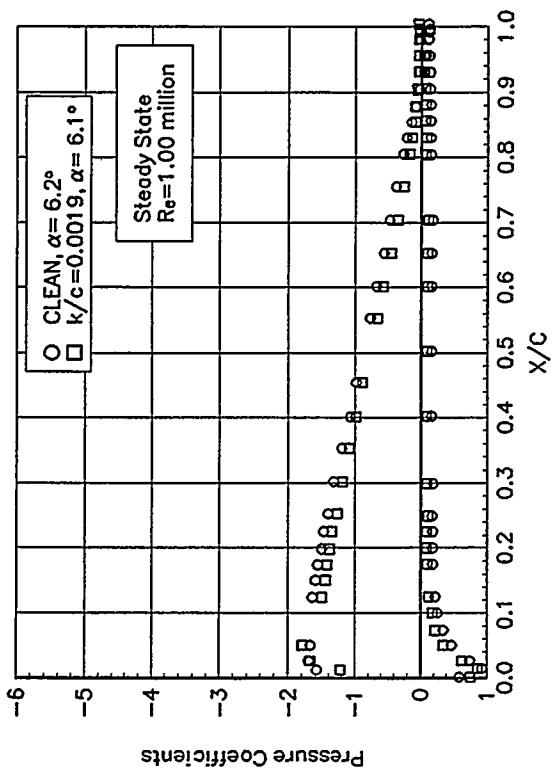


Figure B40. $\alpha = 6.2^\circ$

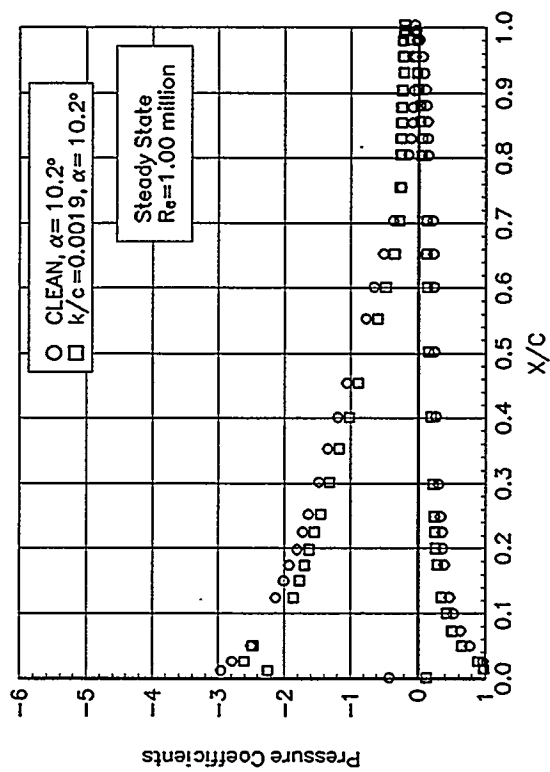


Figure B42. $\alpha = 10.2^\circ$

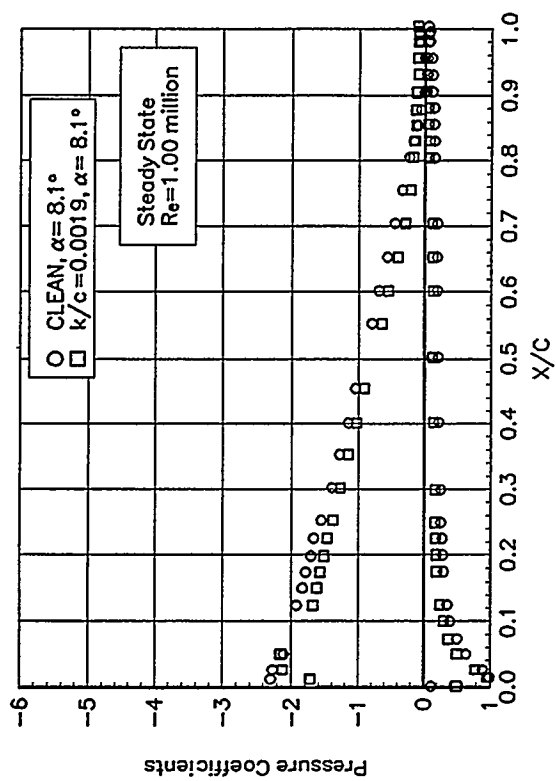


Figure B41. $\alpha = 8.1^\circ$

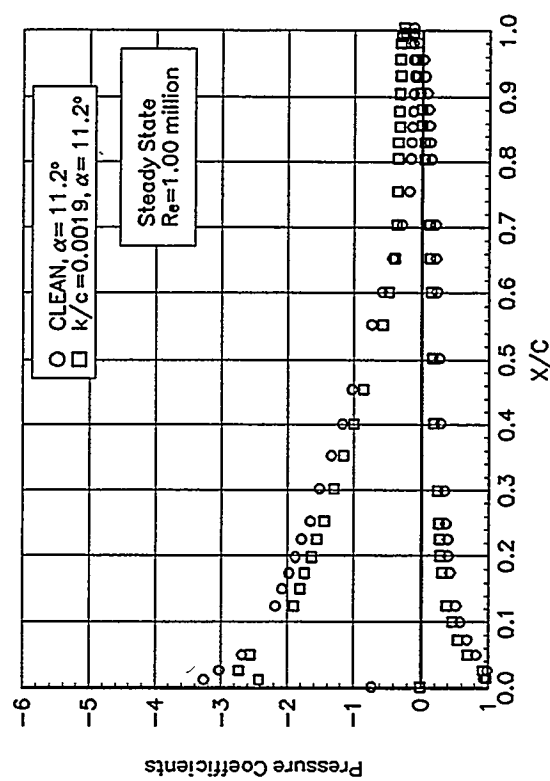


Figure B43. $\alpha = 11.2^\circ$

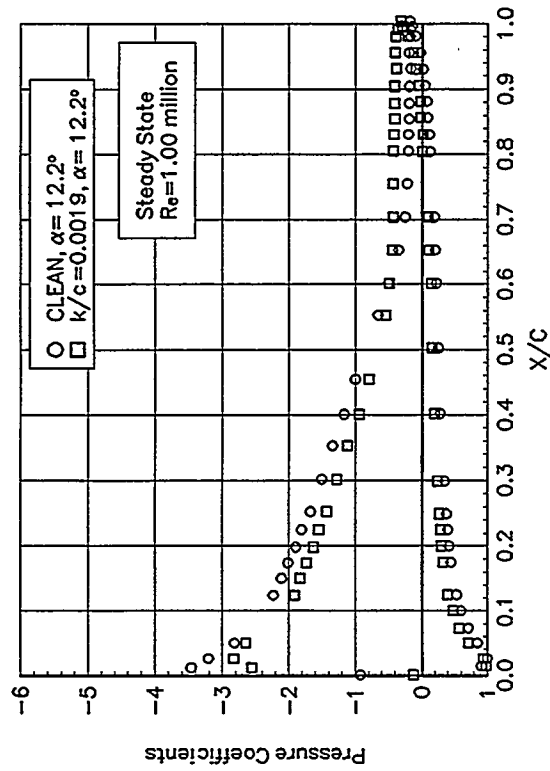


Figure B44. $\alpha = 12.2^\circ$

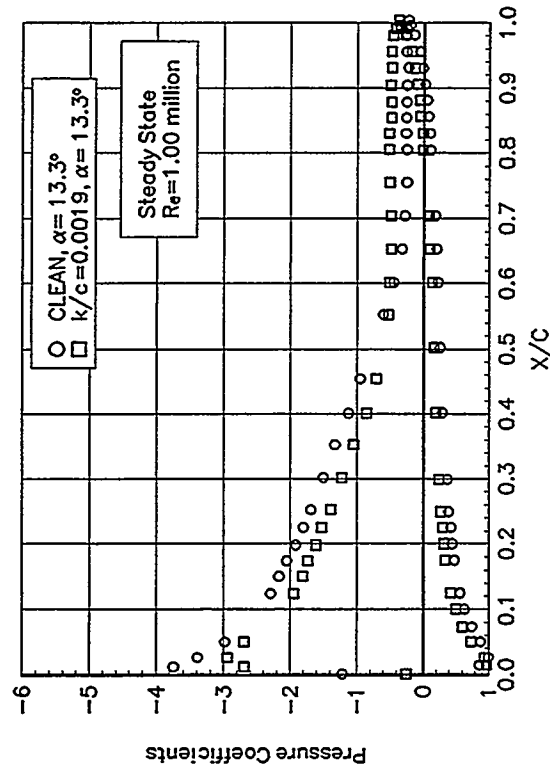


Figure B45. $\alpha = 13.3^\circ$

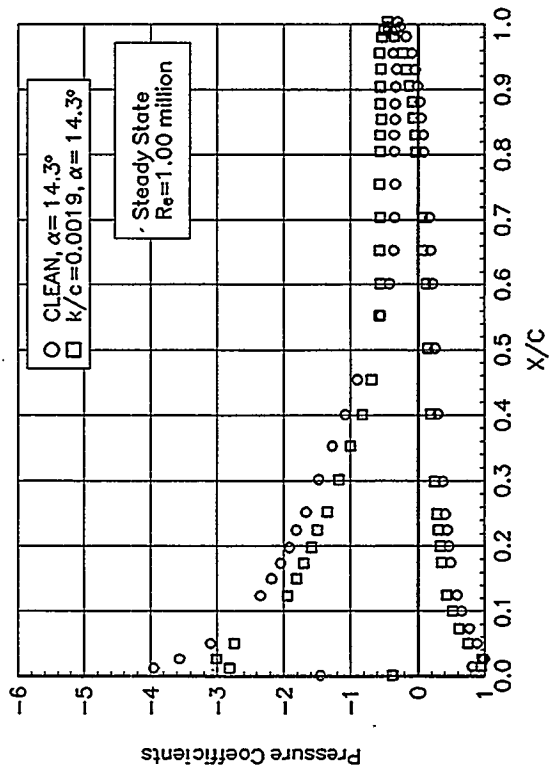


Figure B46. $\alpha = 14.3^\circ$

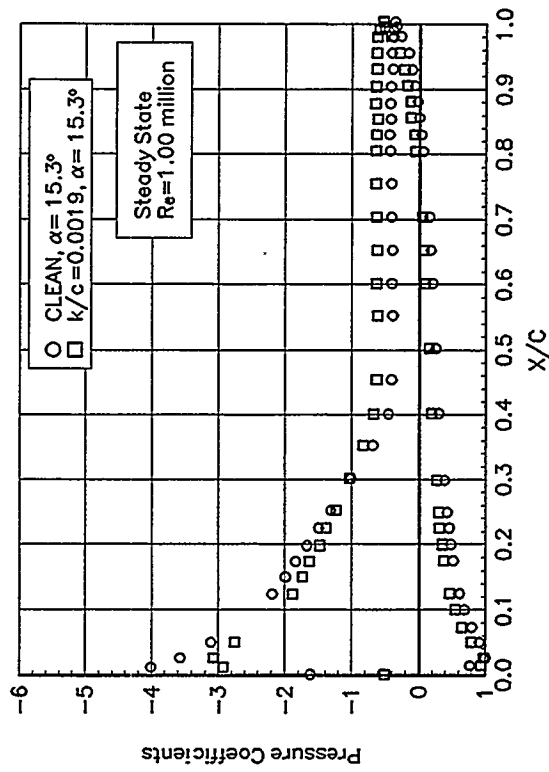


Figure B47. $\alpha = 15.3^\circ$

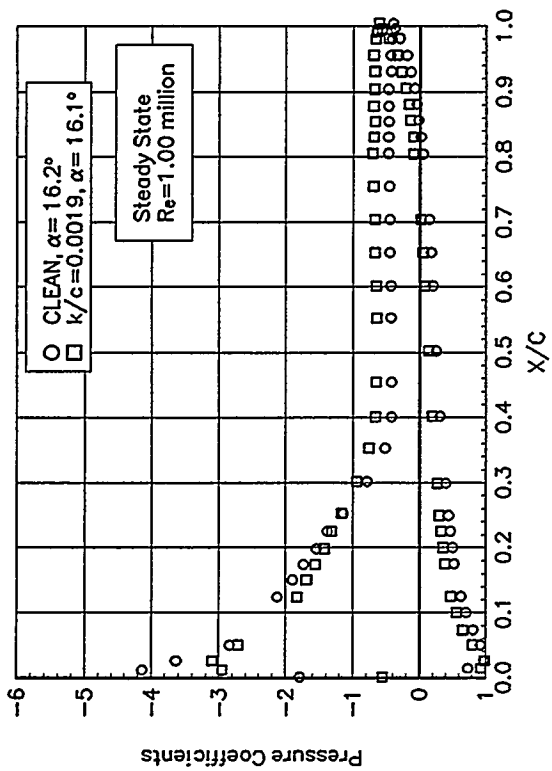


Figure B48. $\alpha = 16.2^\circ$

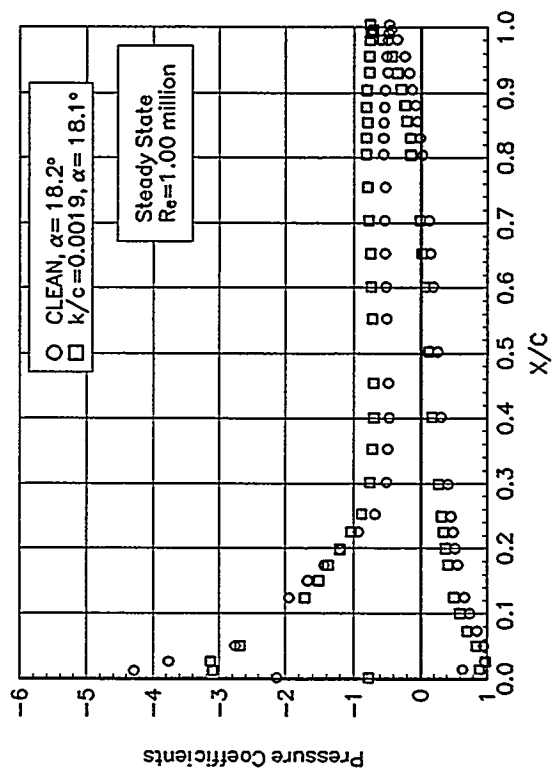


Figure B50. $\alpha = 18.2^\circ$

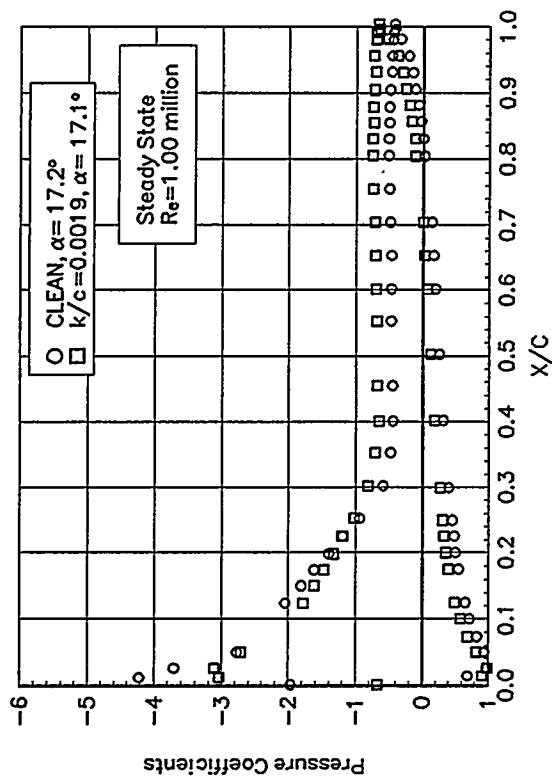


Figure B49. $\alpha = 17.2^\circ$

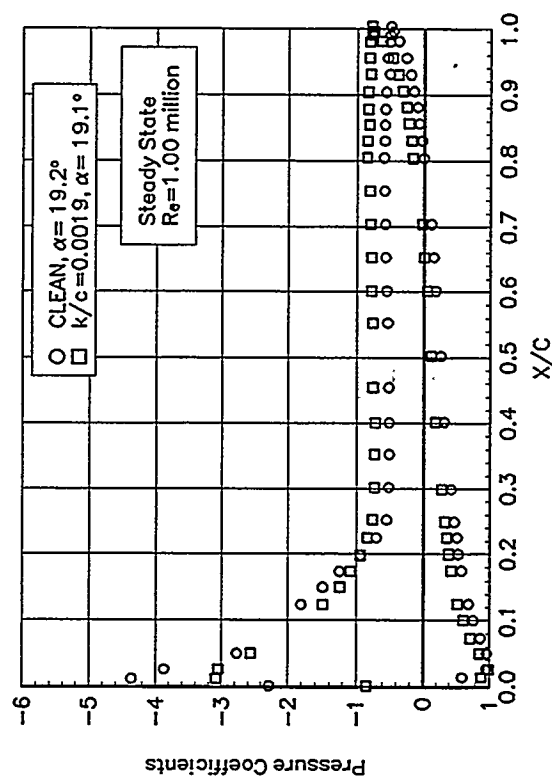


Figure B51. $\alpha = 19.2^\circ$

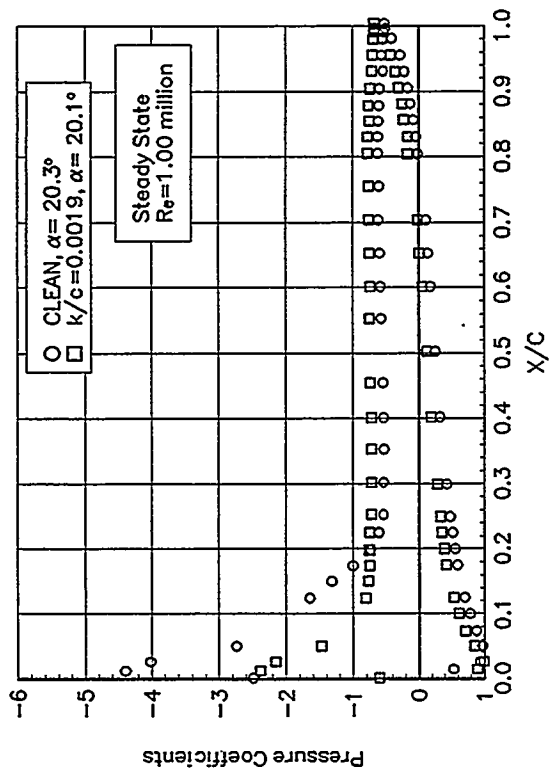


Figure B52. $\alpha = 20.3^\circ$

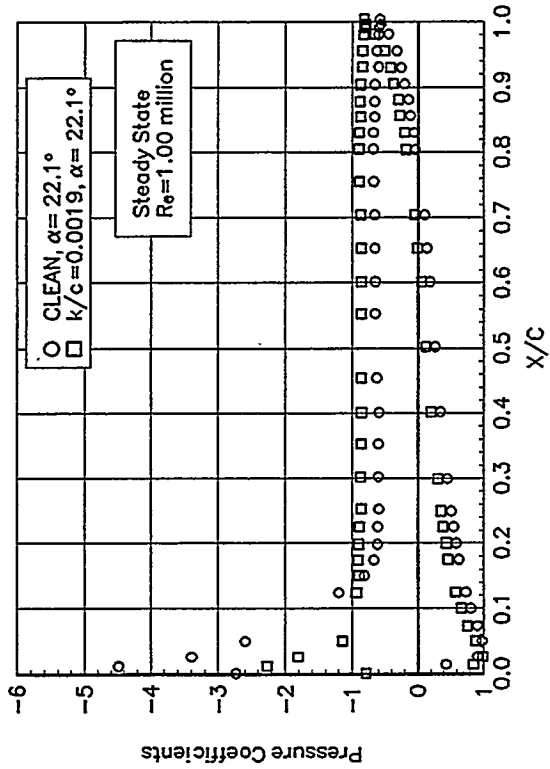


Figure B53. $\alpha = 22.1^\circ$

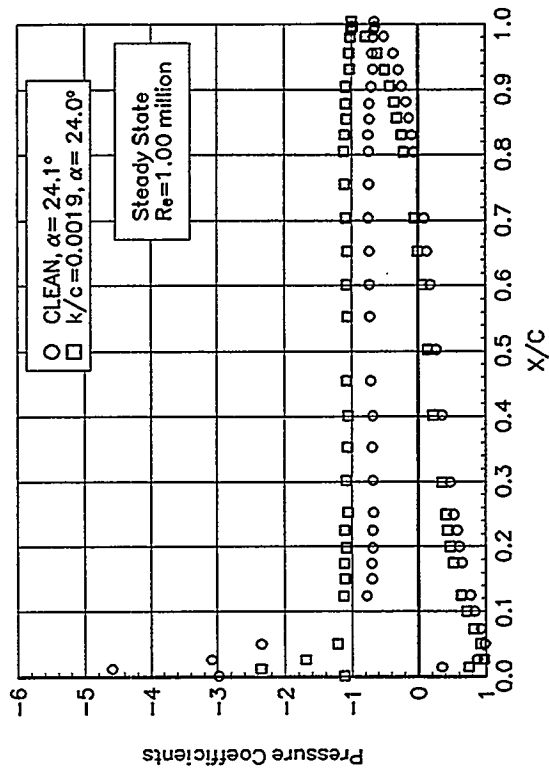


Figure B54. $\alpha = 24.1^\circ$

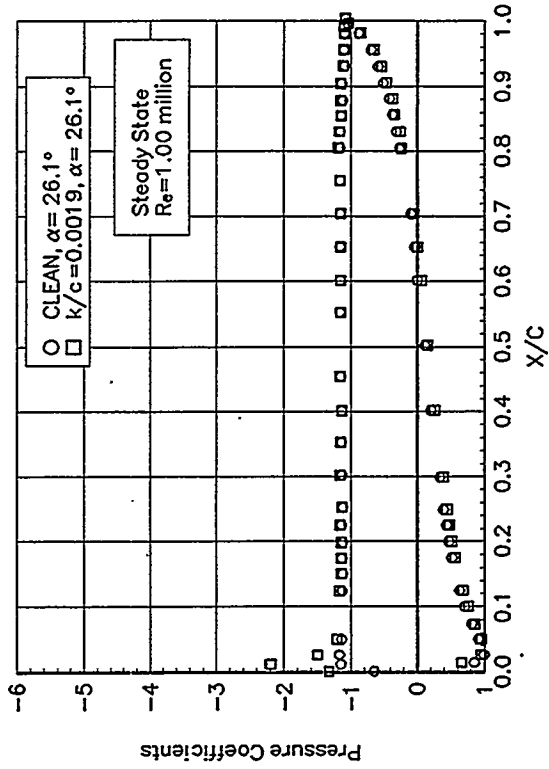


Figure B55. $\alpha = 26.1^\circ$

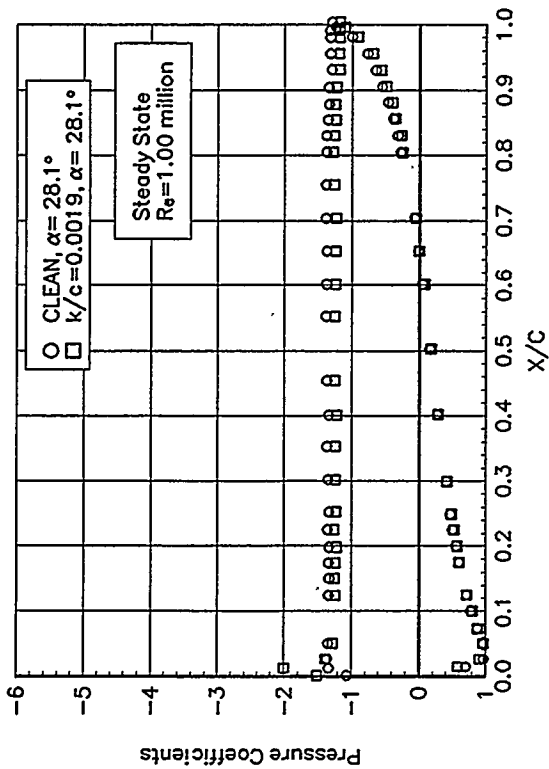


Figure B56. $\alpha = 28.1^\circ$

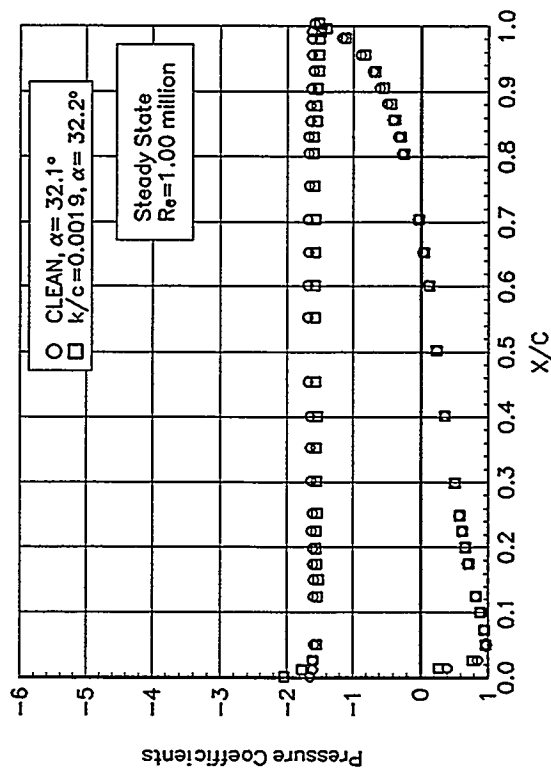


Figure B58. $\alpha = 32.1^\circ$

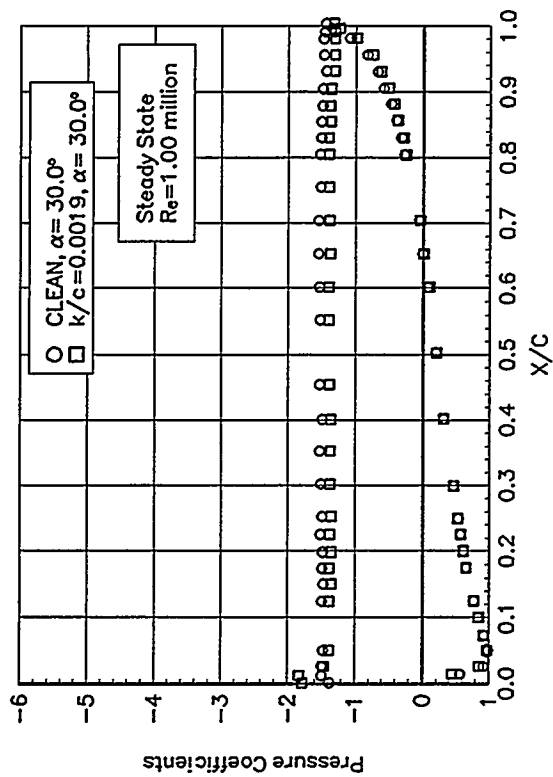


Figure B57. $\alpha = 30.0^\circ$

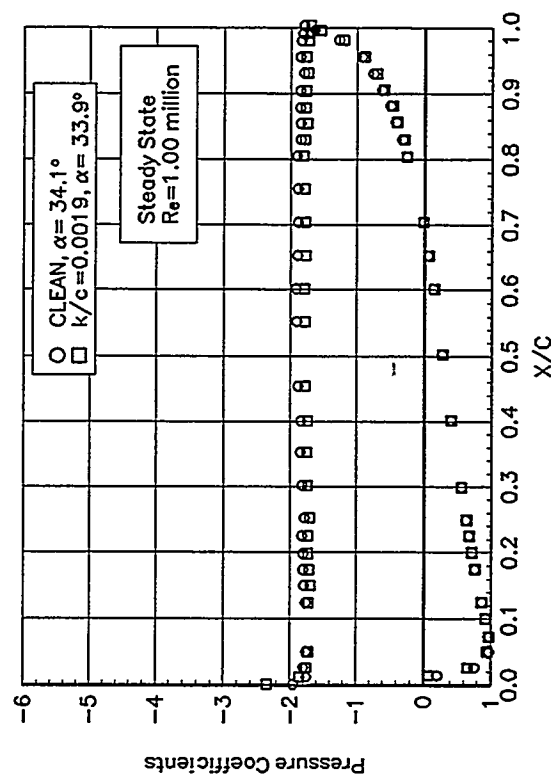


Figure B59. $\alpha = 34.1^\circ$

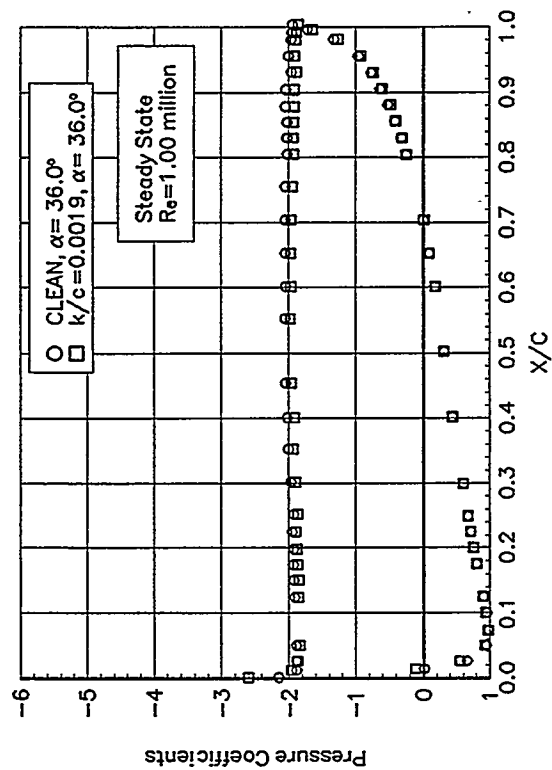


Figure B60. $\alpha = 36.0^\circ$

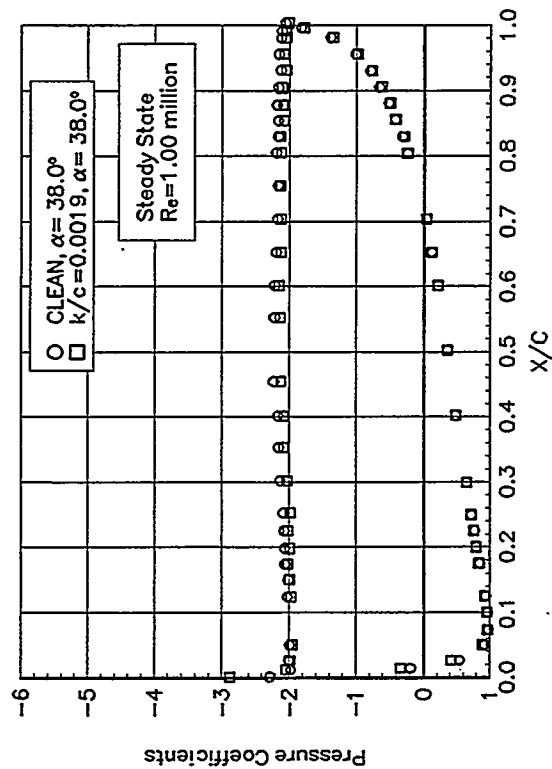


Figure B61. $\alpha = 38.0^\circ$

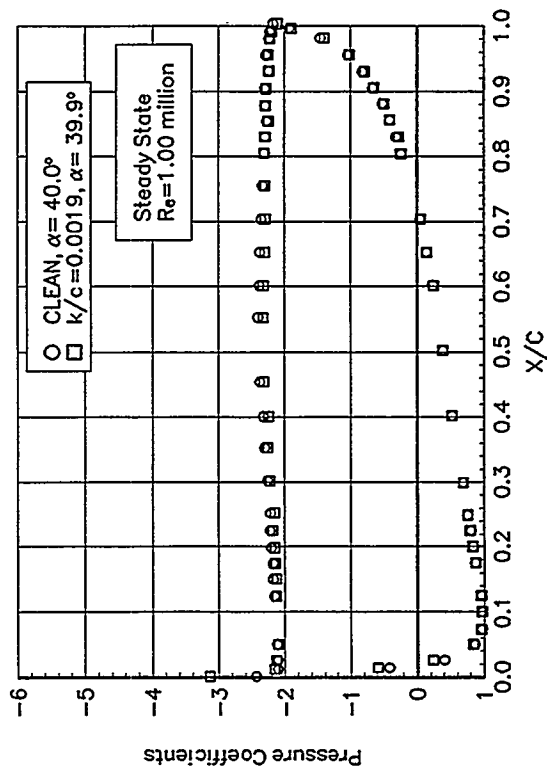


Figure B62. $\alpha = 40.0^\circ$

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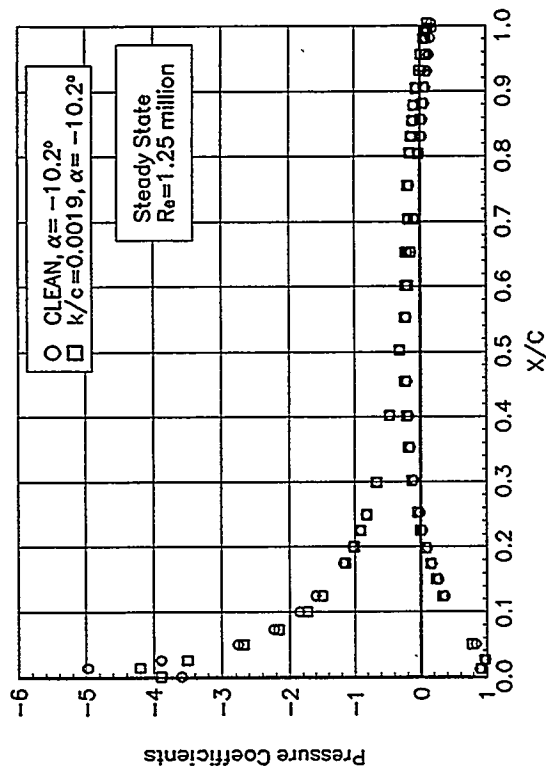


Figure B63. $\alpha = -10.2^\circ$

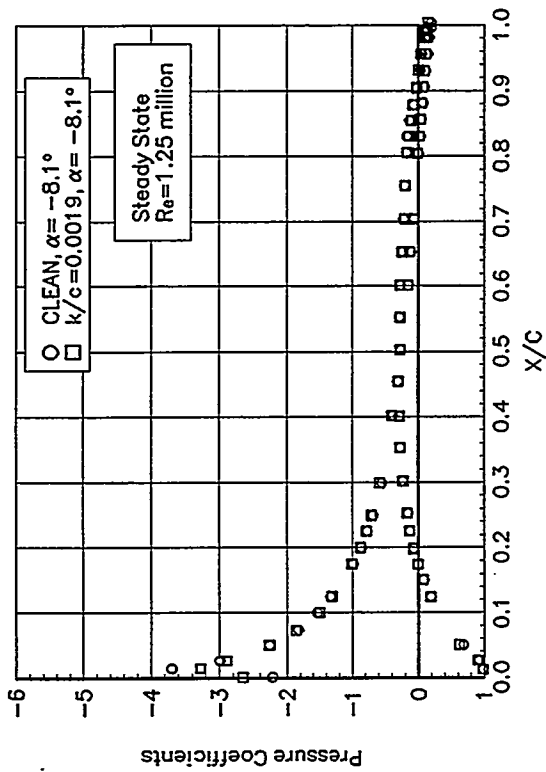


Figure B64. $\alpha = -8.1^\circ$

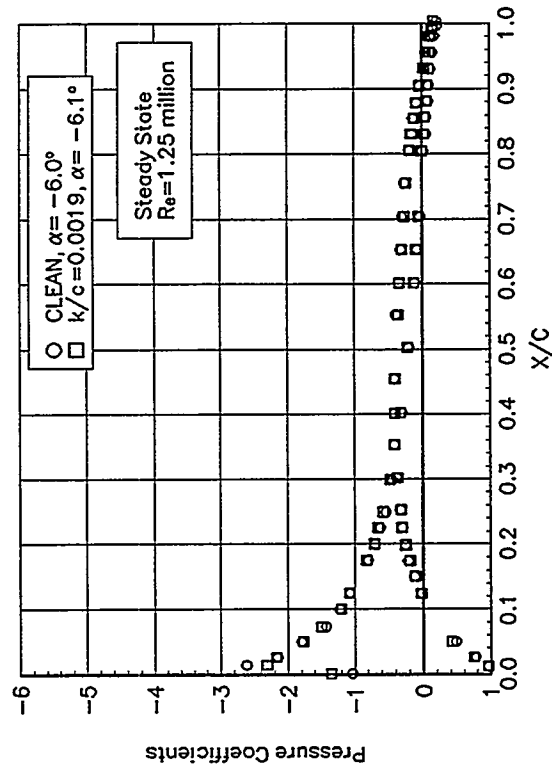


Figure B65. $\alpha = -6.0^\circ$

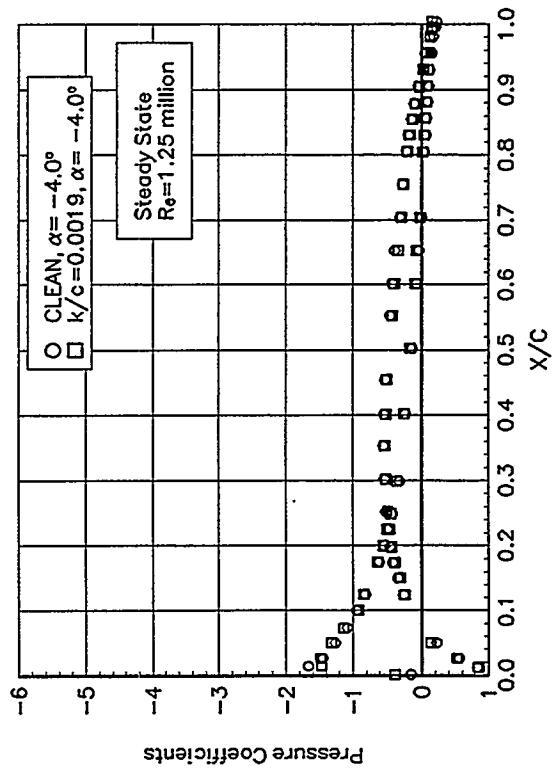


Figure B66. $\alpha = -4.0^\circ$

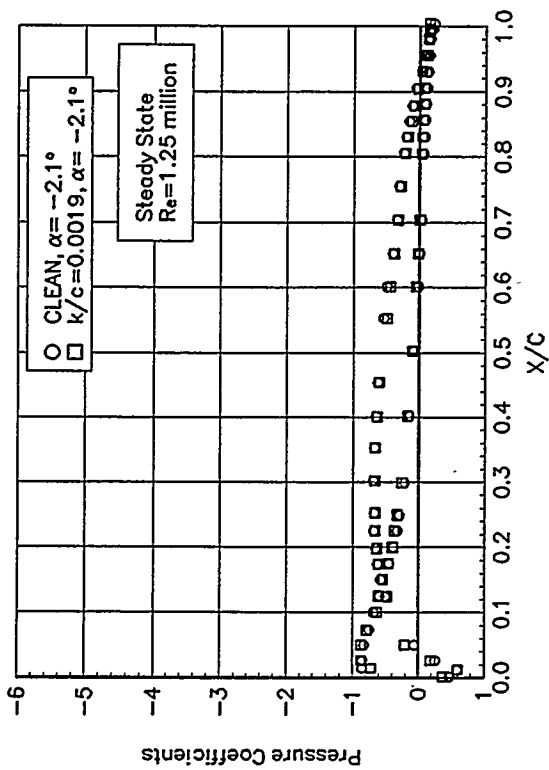


Figure B67. $\alpha = -2.1^\circ$

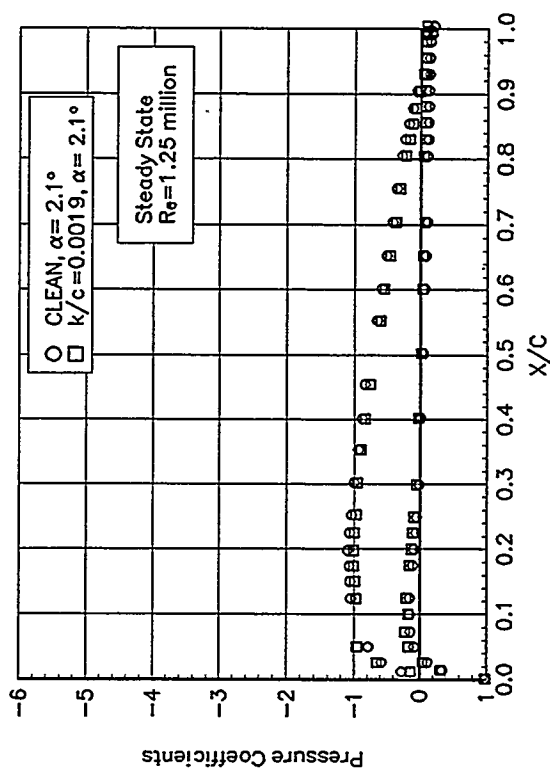


Figure B69. $\alpha = 2.1^\circ$

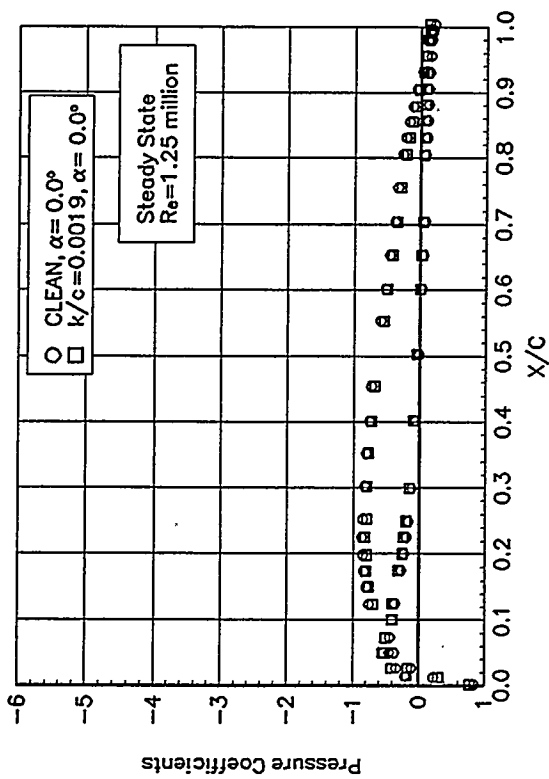


Figure B68. $\alpha = 0.0^\circ$

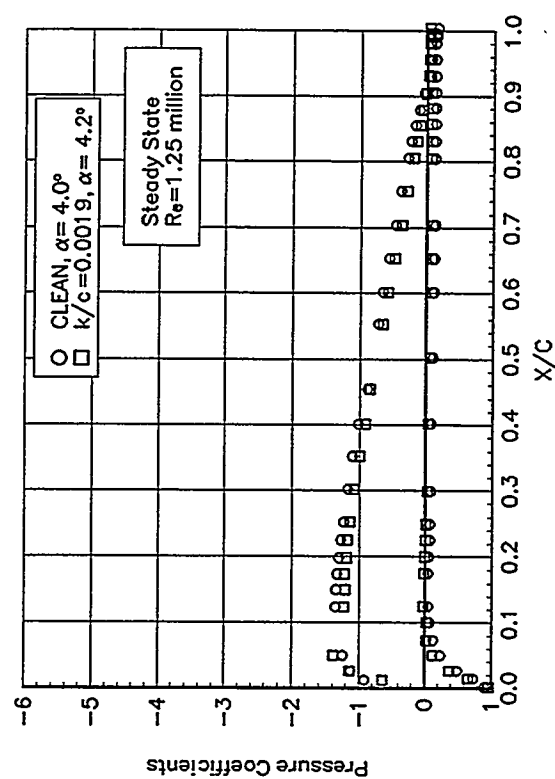


Figure B70. $\alpha = 4.0^\circ$

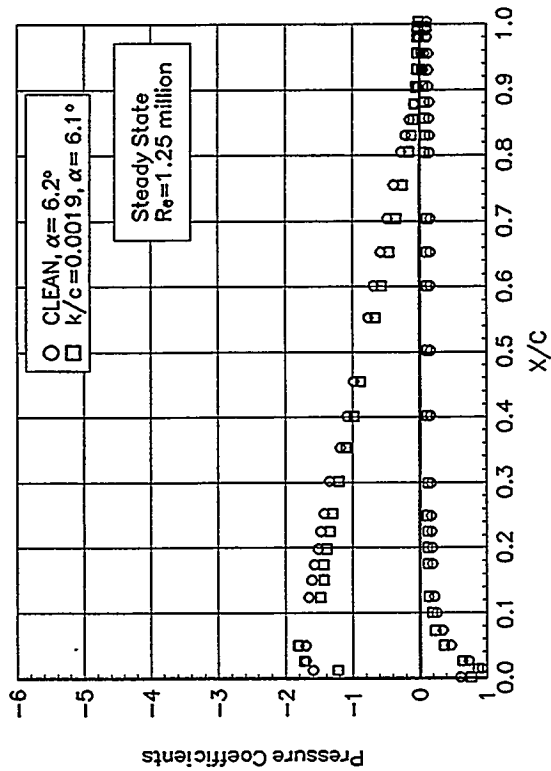


Figure B71. $\alpha = 6.2^\circ$

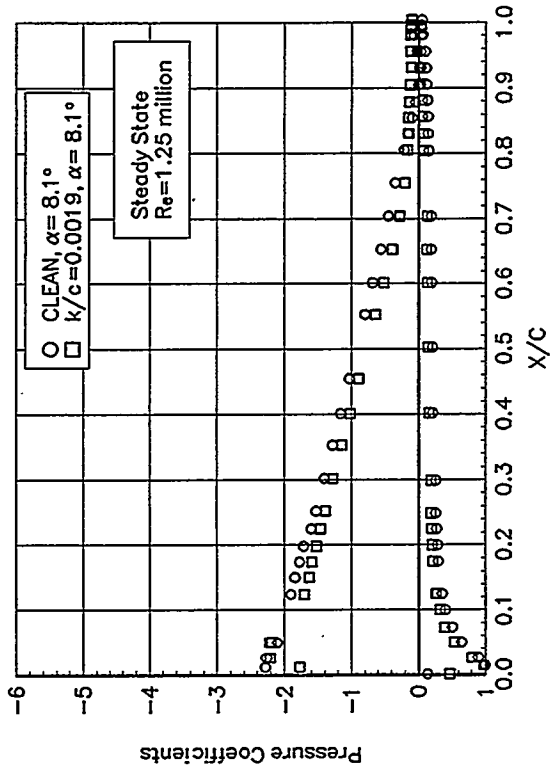


Figure B72. $\alpha = 8.1^\circ$

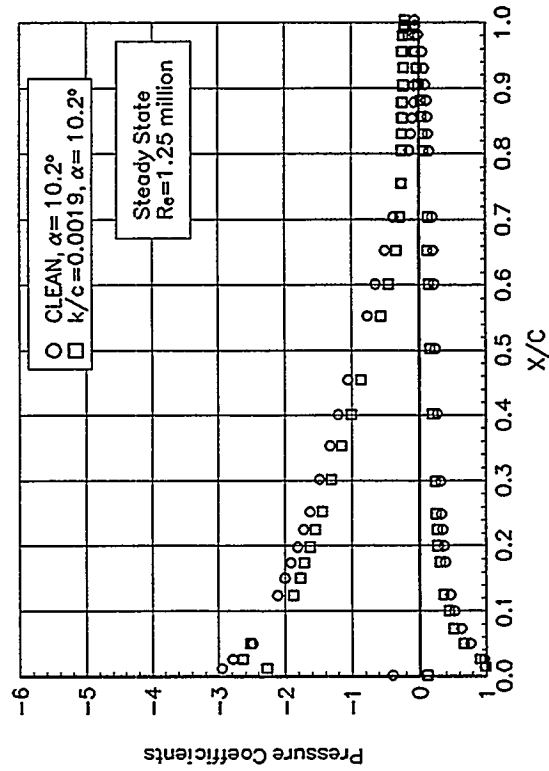


Figure B73. $\alpha = 10.2^\circ$

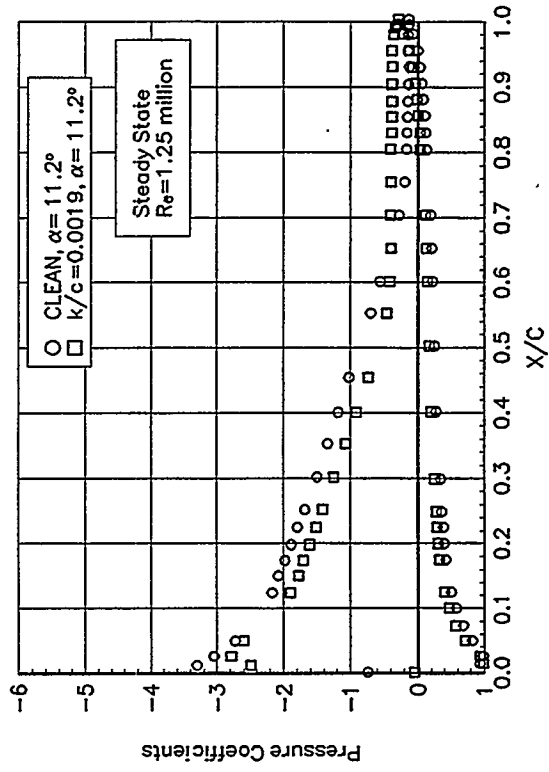


Figure B74. $\alpha = 11.2^\circ$

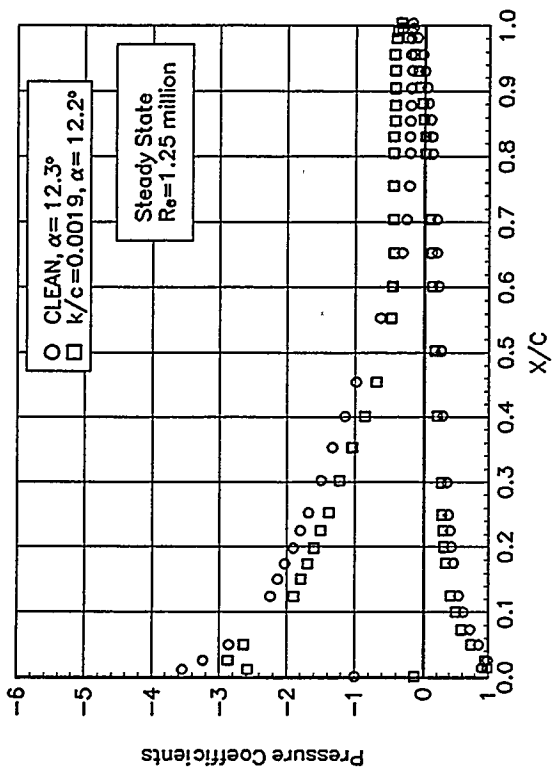


Figure B75. $\alpha = 12.3^\circ$

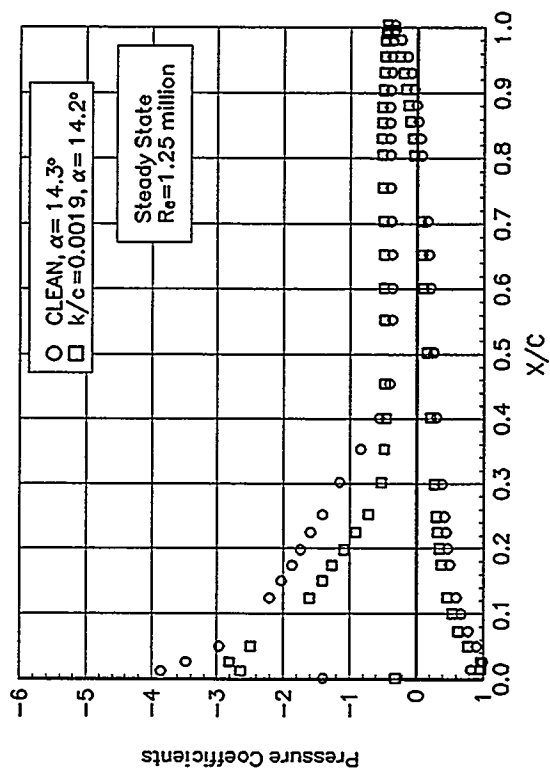


Figure B77. $\alpha = 14.3^\circ$

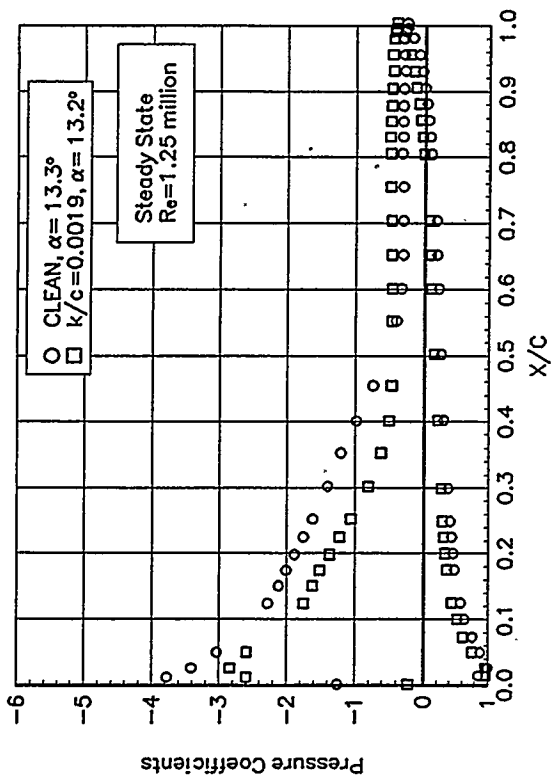


Figure B76. $\alpha = 13.3^\circ$

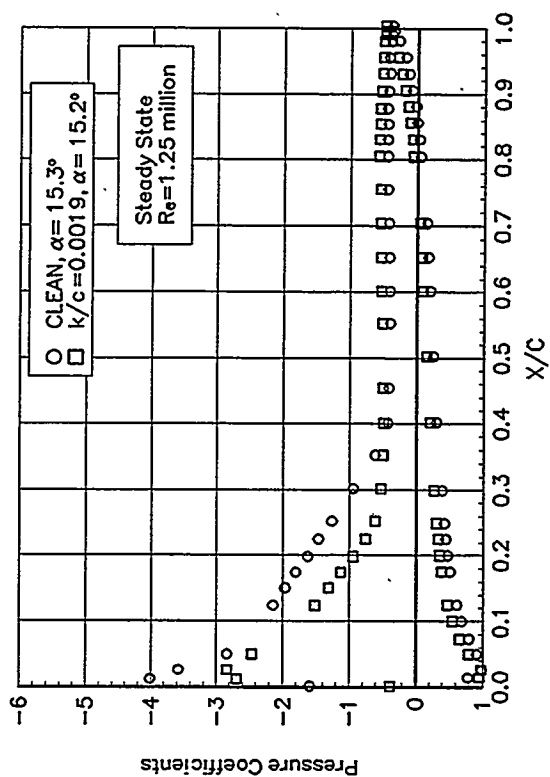


Figure B78. $\alpha = 15.3^\circ$

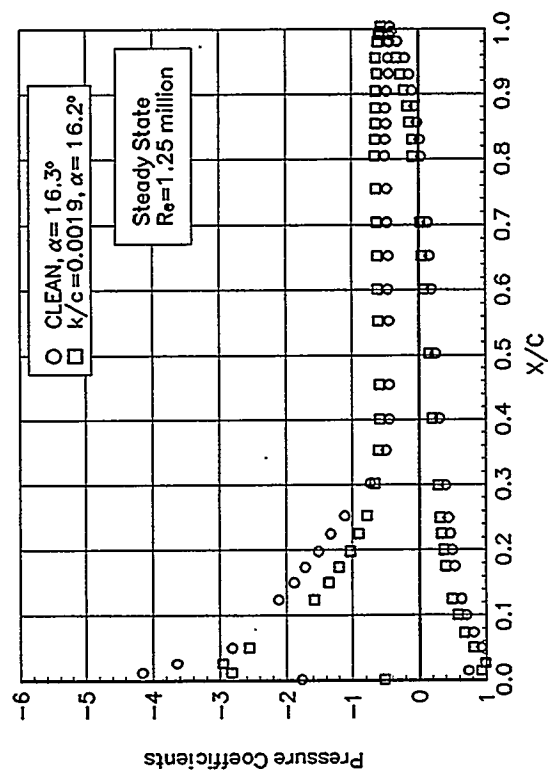


Figure B79. $\alpha = 16.3^\circ$

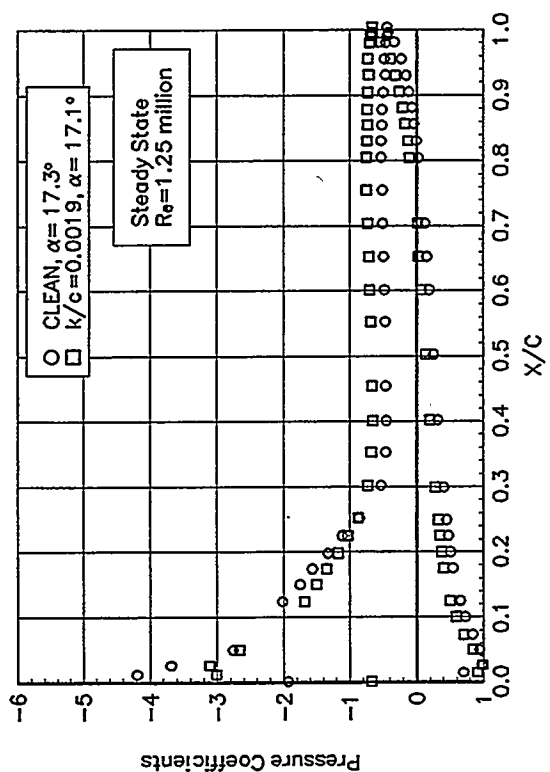


Figure B80. $\alpha = 17.3^\circ$

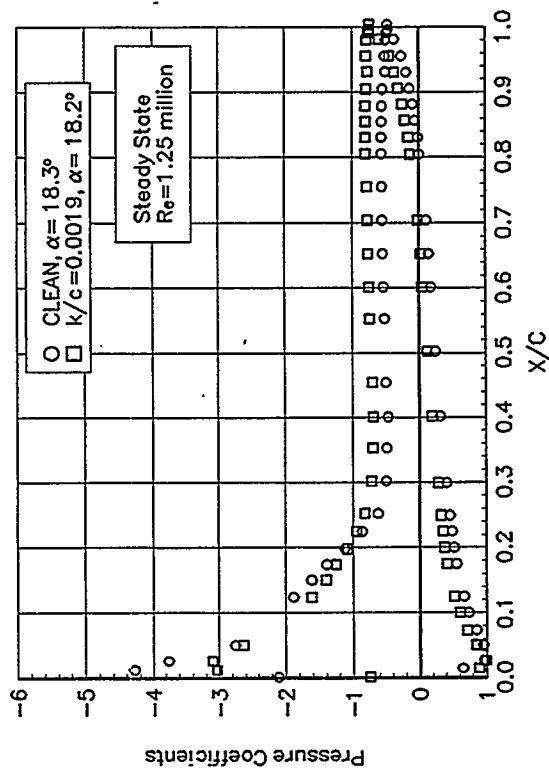


Figure B81. $\alpha = 18.3^\circ$

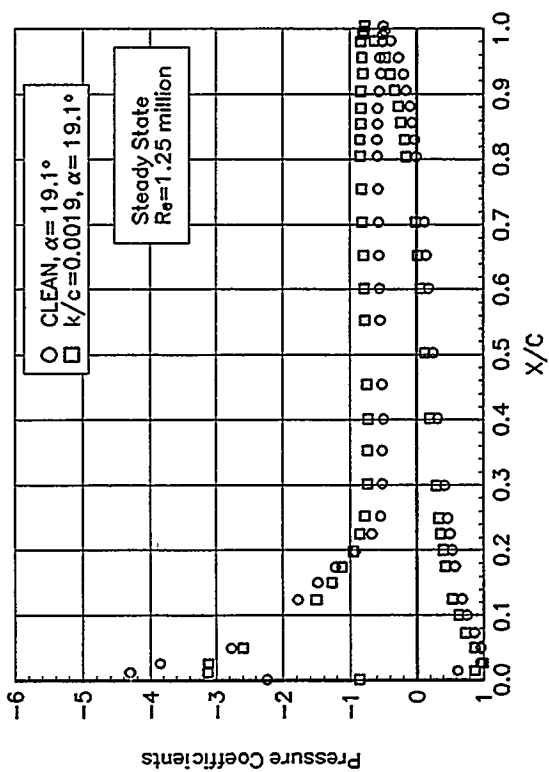


Figure B82. $\alpha = 19.1^\circ$

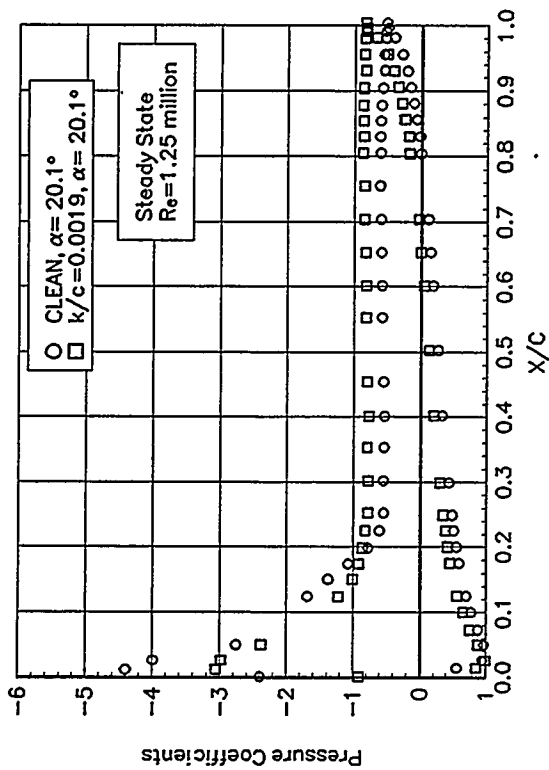


Figure B83. $\alpha = 20.1^\circ$

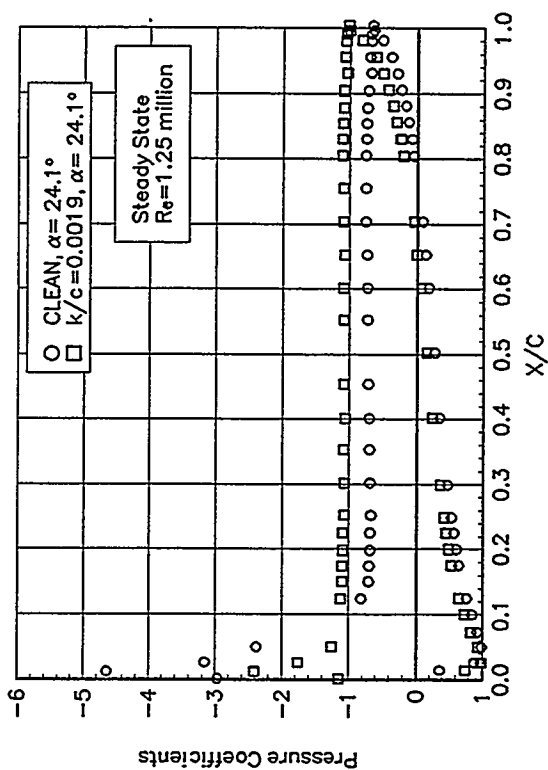


Figure B85. $\alpha = 24.1^\circ$

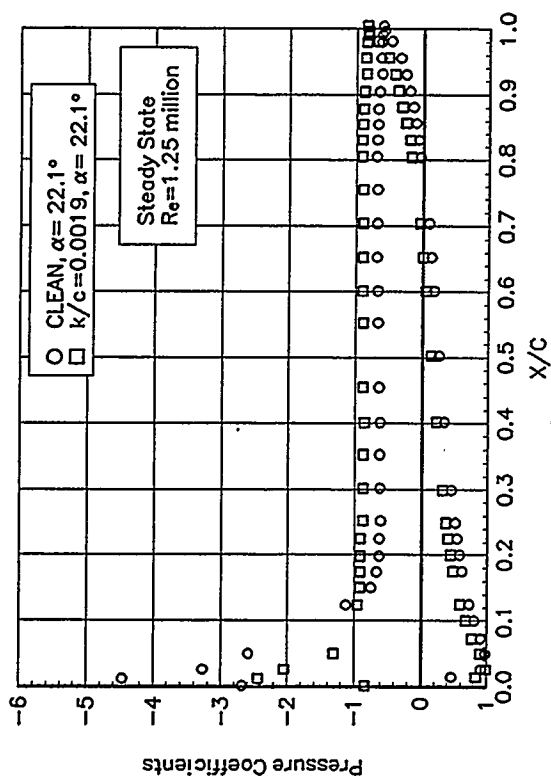


Figure B84. $\alpha = 22.1^\circ$

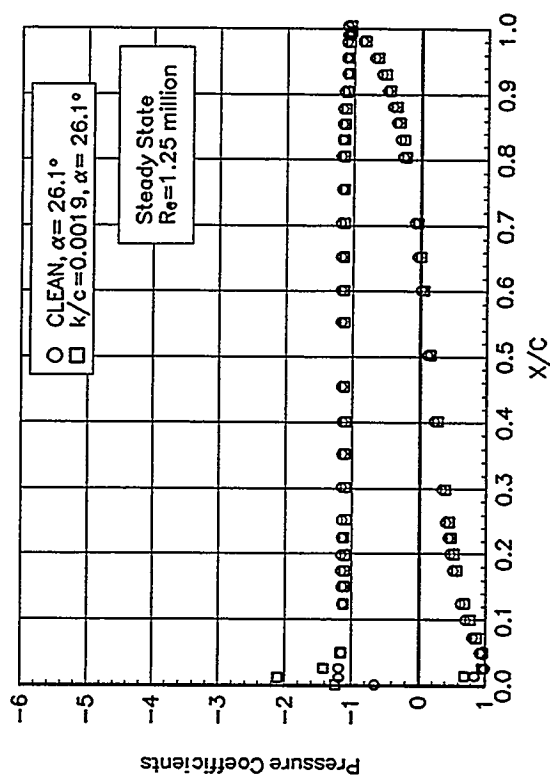


Figure B86. $\alpha = 26.1^\circ$

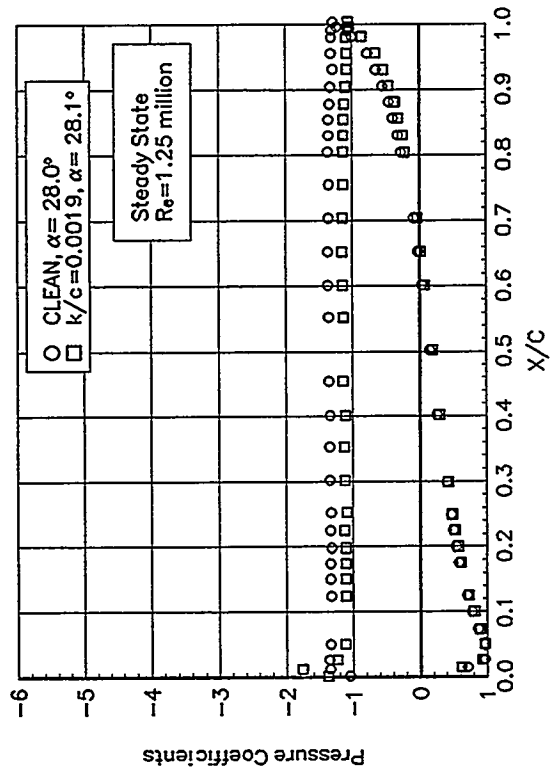


Figure B87. $\alpha = 28.0^\circ$

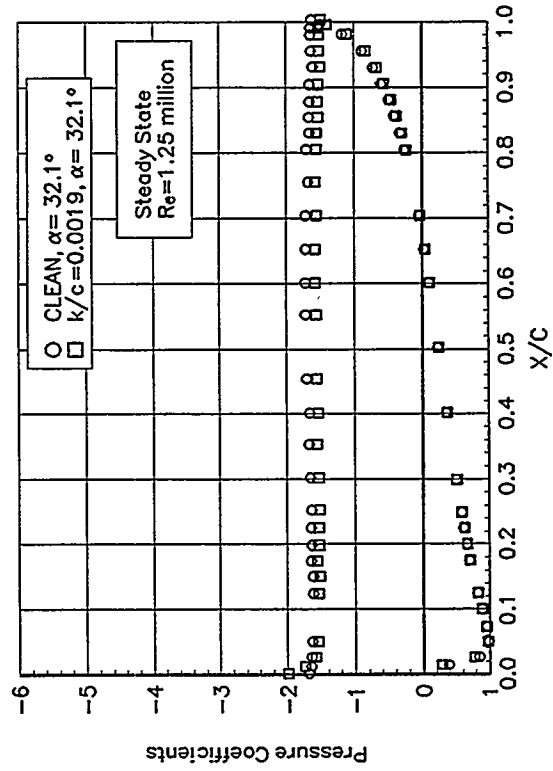


Figure B89. $\alpha = 32.1^\circ$

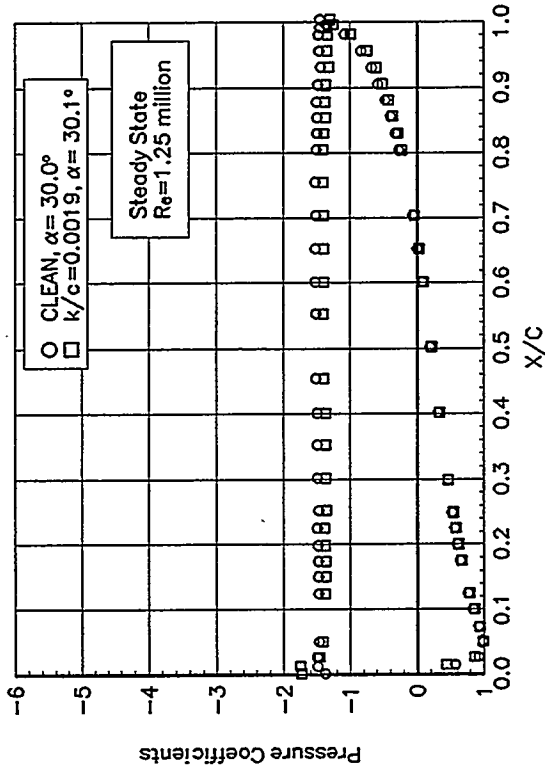


Figure B88. $\alpha = 30.0^\circ$

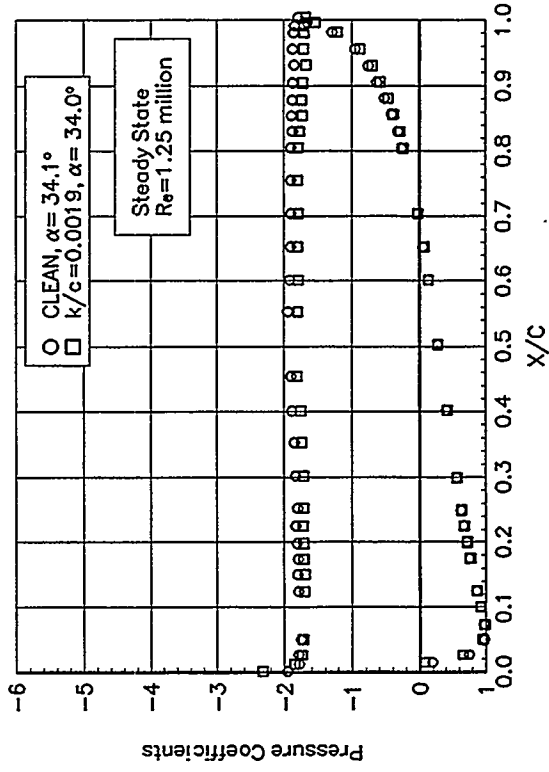


Figure B90. $\alpha = 34.1^\circ$

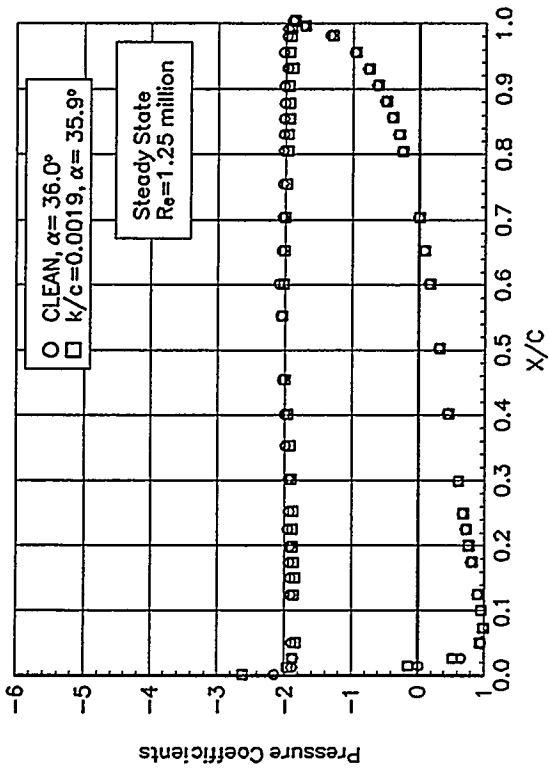


Figure B91. $\alpha = 36.0^\circ$

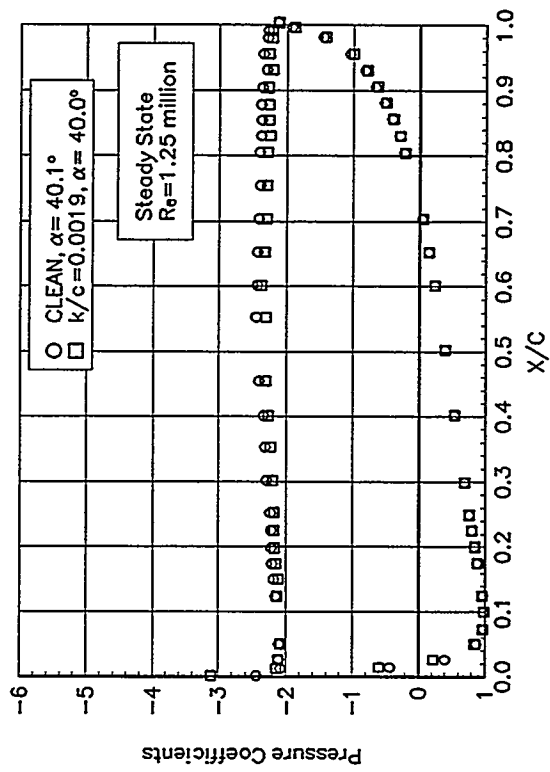


Figure B93. $\alpha = 40.1^\circ$

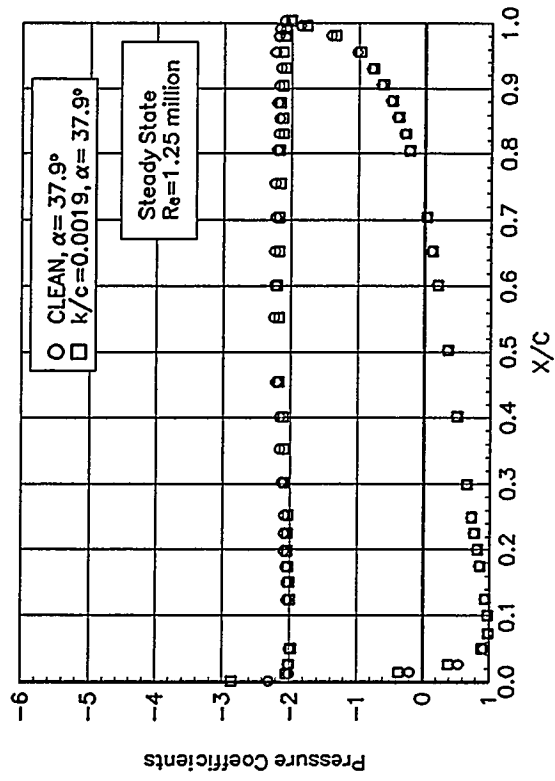


Figure B92. $\alpha = 37.9^\circ$

NACA 4415

Pressure Distributions, Steady State, $Re = 1.5$ million

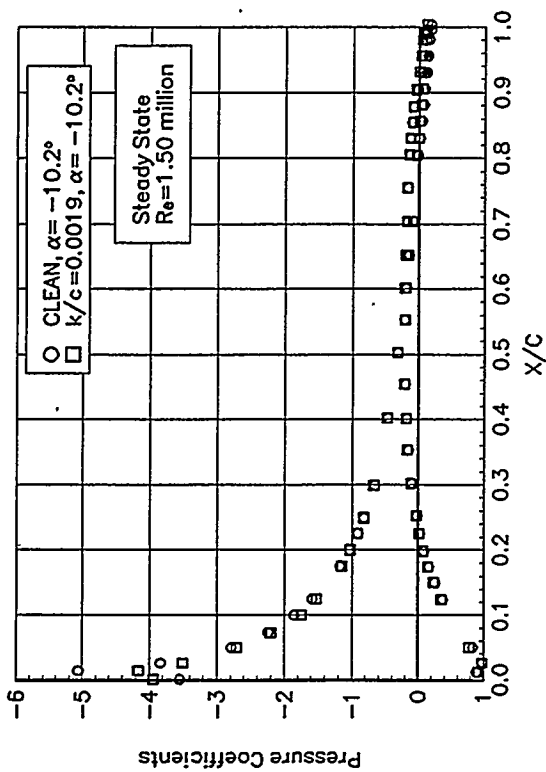


Figure B94. $\alpha = -10.2^\circ$

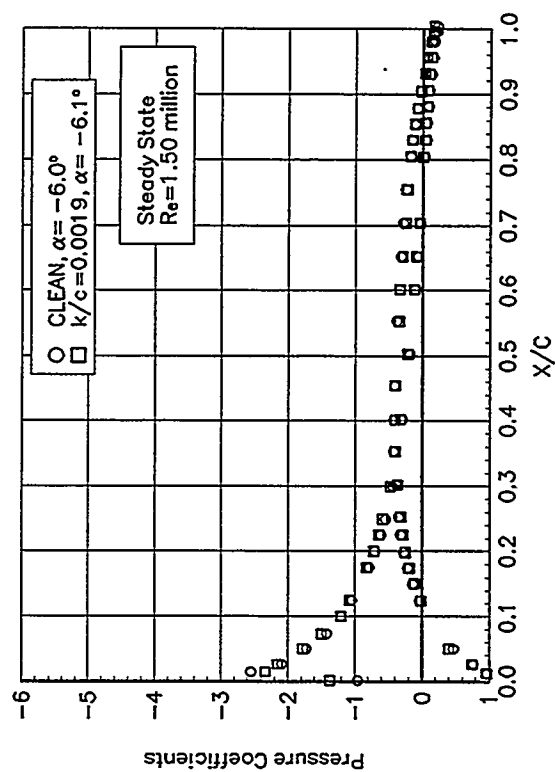


Figure B96. $\alpha = -6.0^\circ$

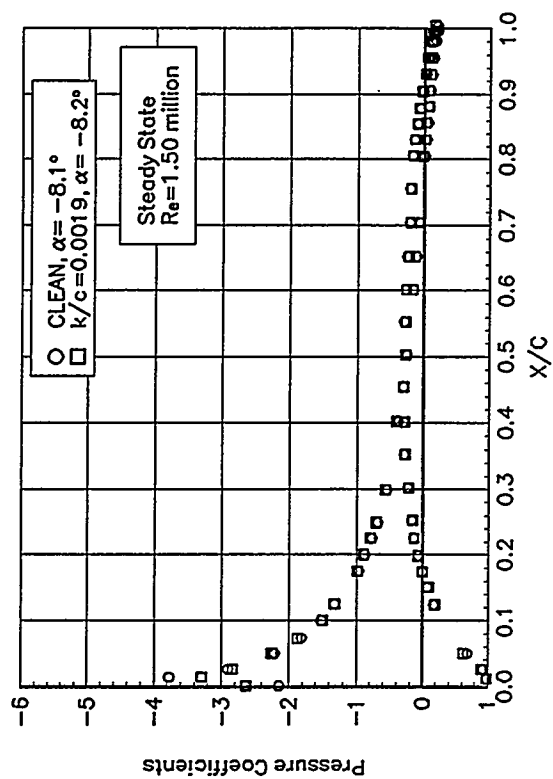


Figure B95. $\alpha = -8.1^\circ$

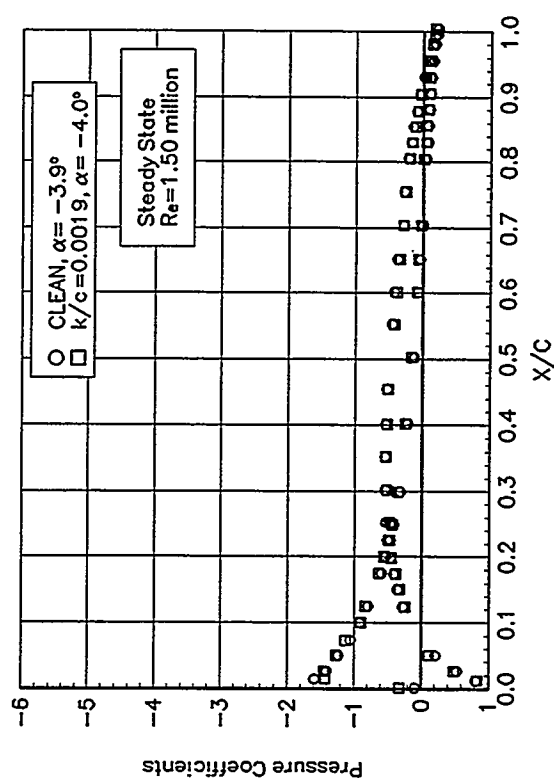


Figure B97. $\alpha = -3.9^\circ$

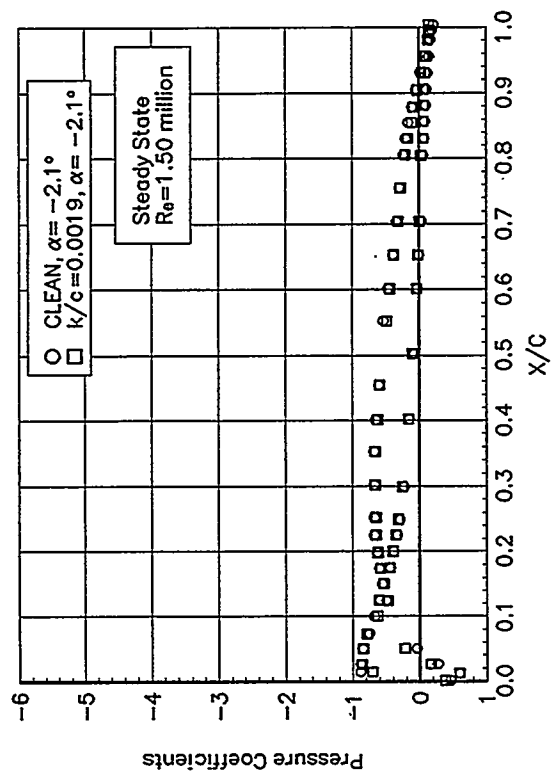


Figure B98. $\alpha = -2.1^\circ$

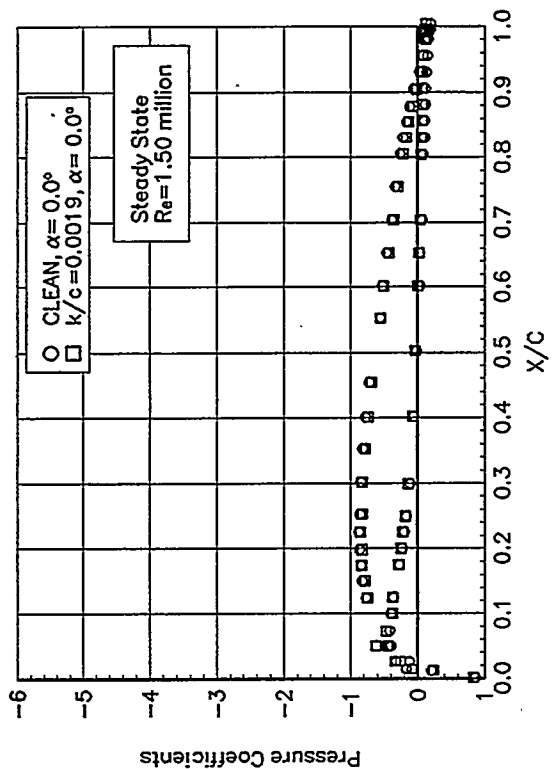


Figure B99. $\alpha = 0.0^\circ$

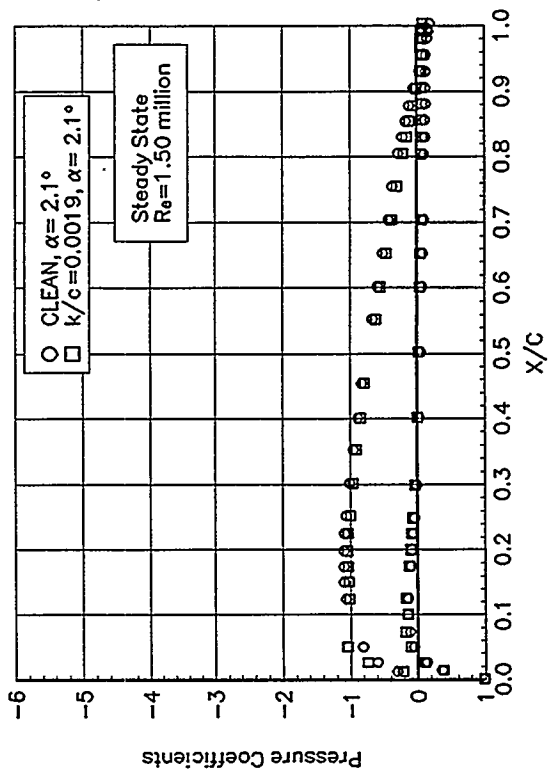


Figure B100. $\alpha = 2.1^\circ$

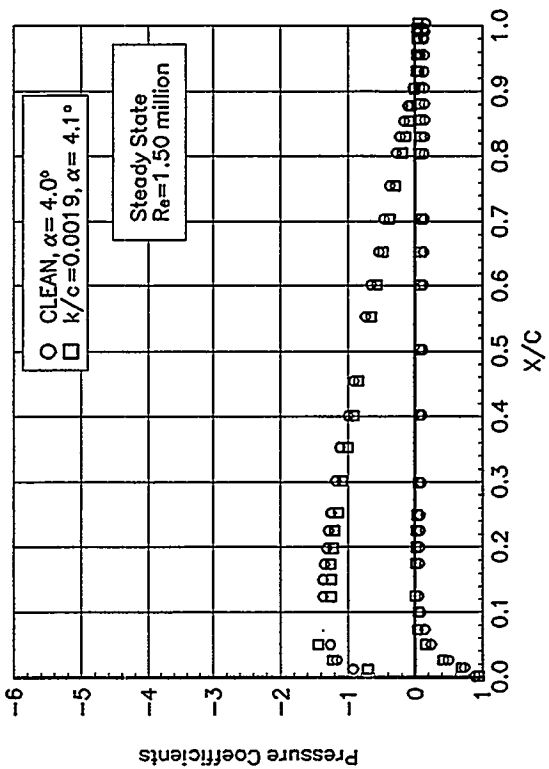


Figure B101. $\alpha = 4.0^\circ$

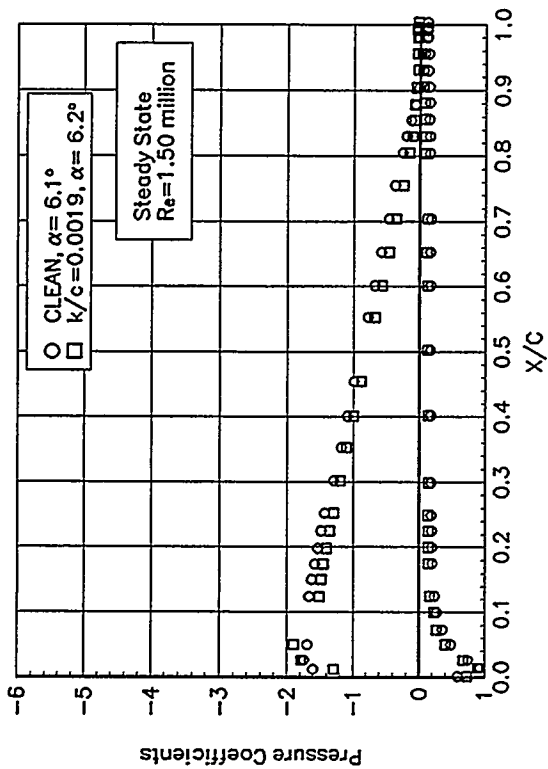


Figure B102. $\alpha = 6.1^\circ$

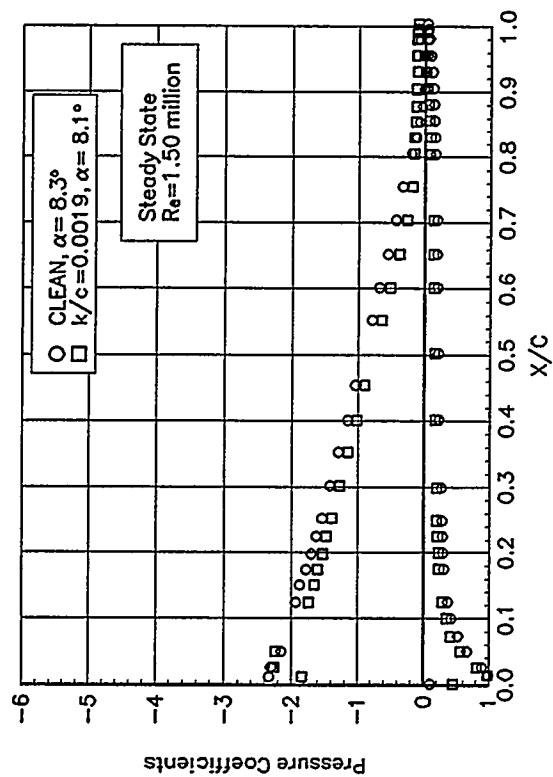


Figure B103. $\alpha = 8.3^\circ$

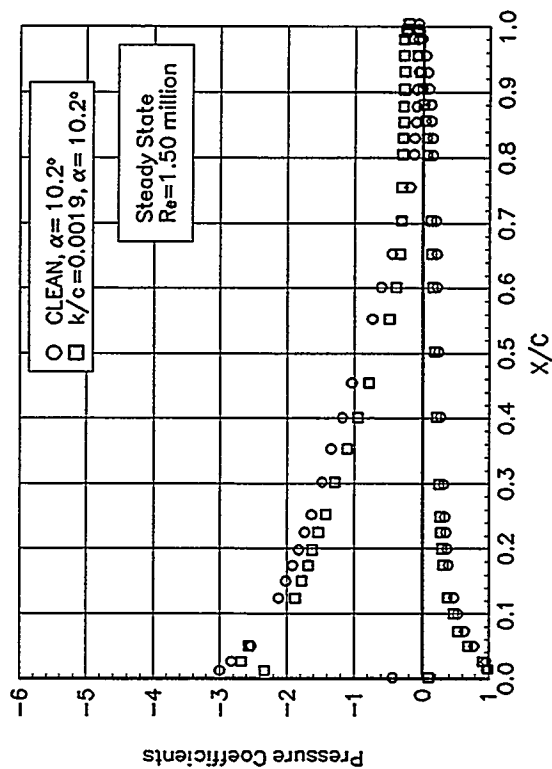


Figure B104. $\alpha = 10.2^\circ$

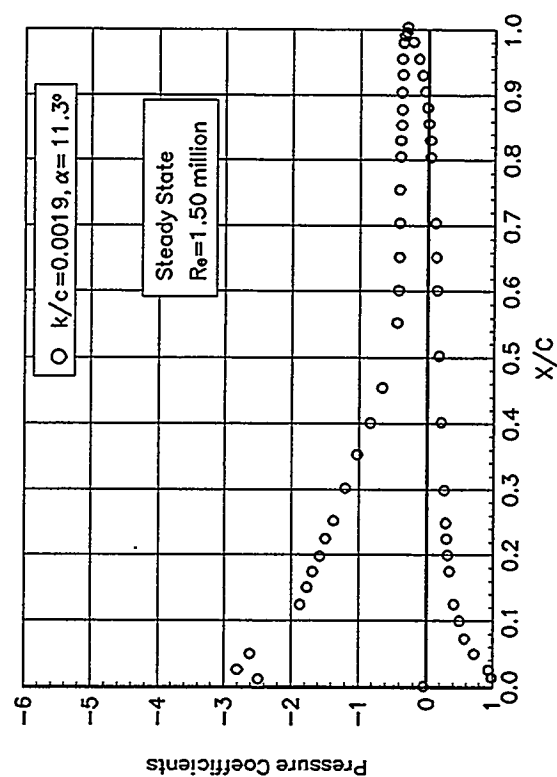


Figure B105. $\alpha = 11.3^\circ$

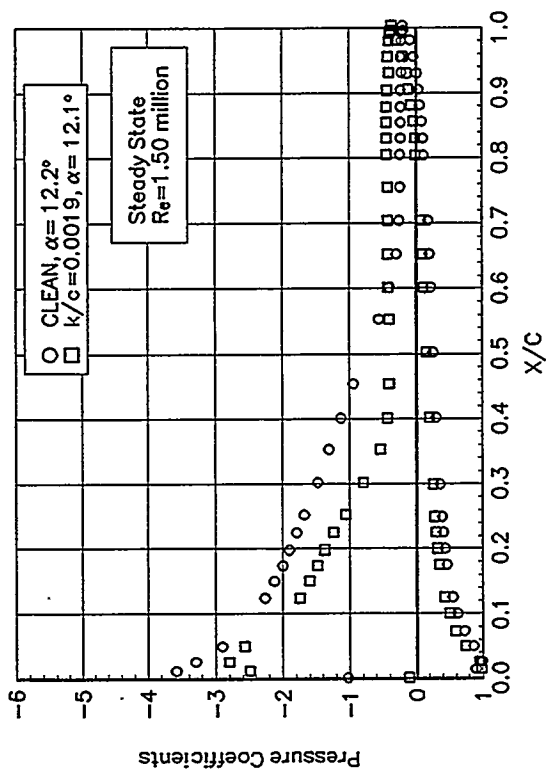


Figure B106. $\alpha = 12.1^\circ$

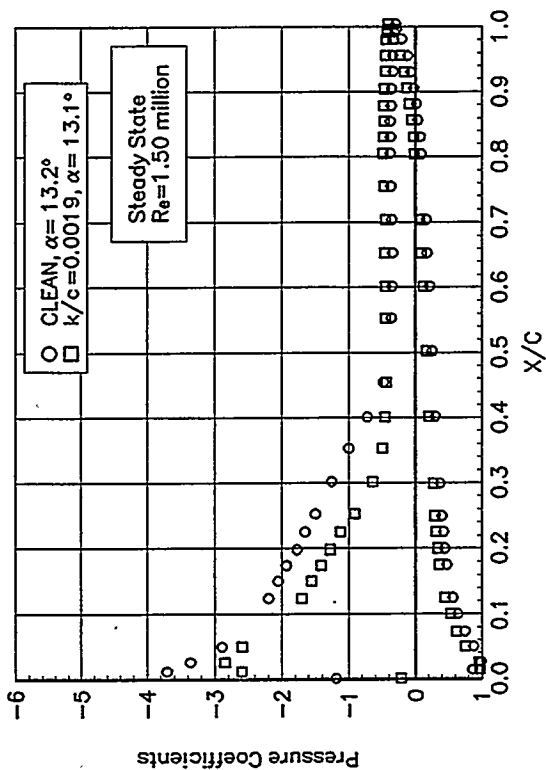


Figure B107. $\alpha = 13.1^\circ$

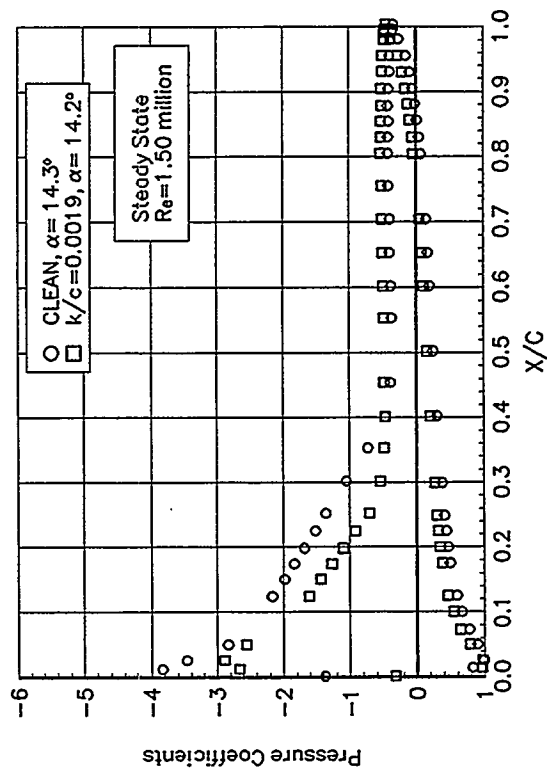


Figure B108. $\alpha = 14.2^\circ$

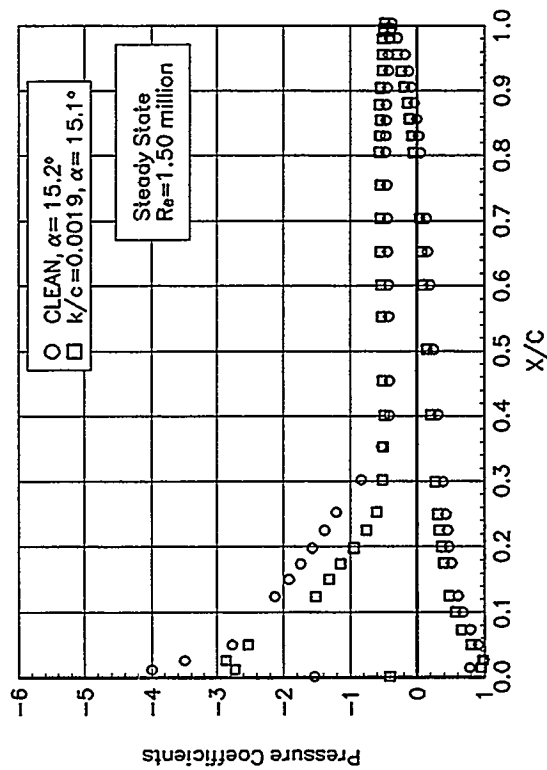


Figure B109. $\alpha = 15.1^\circ$

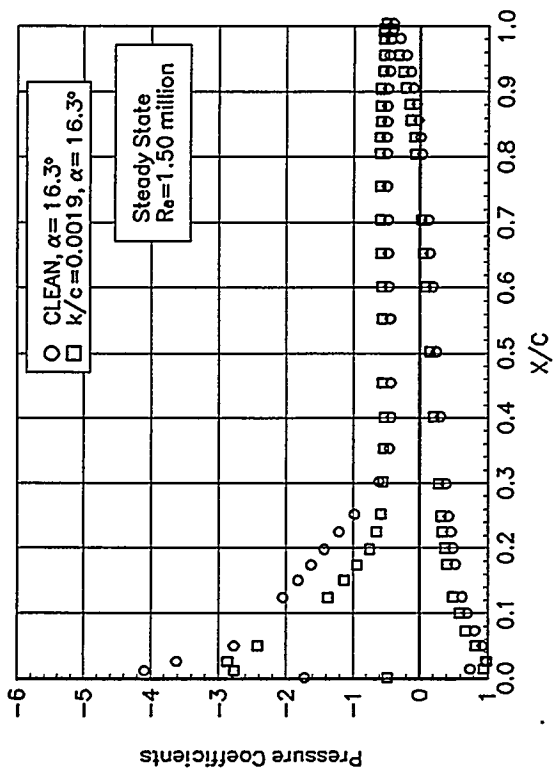


Figure B110. $\alpha = 16.3^\circ$

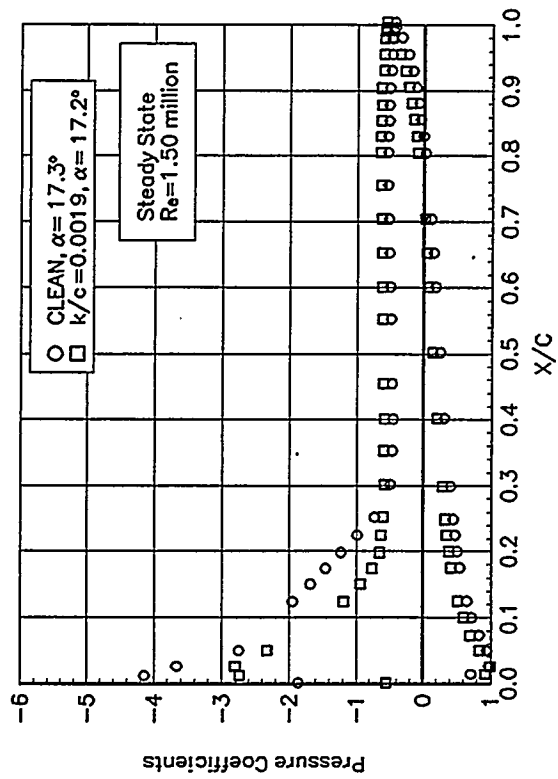


Figure B111. $\alpha = 17.2^\circ$

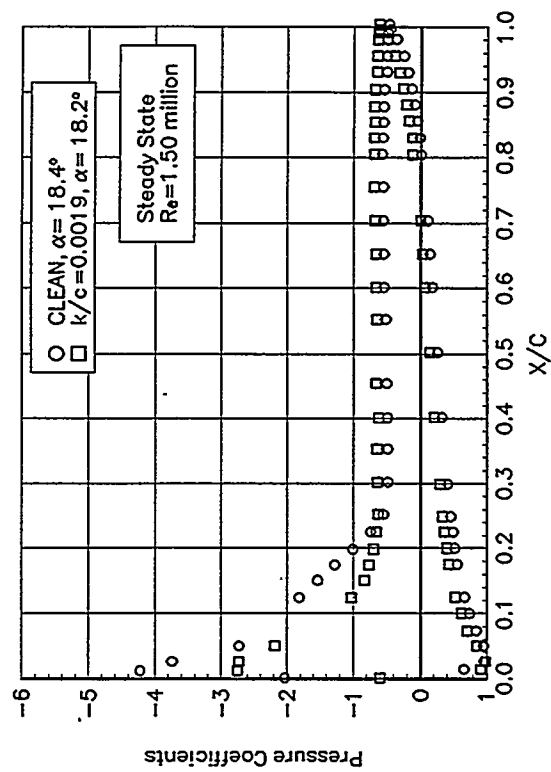


Figure B112. $\alpha = 18.2^\circ$

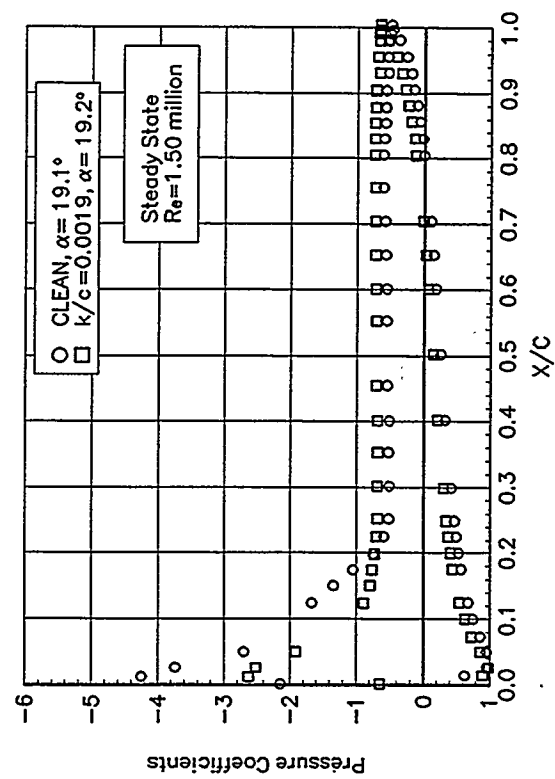


Figure B113. $\alpha = 19.2^\circ$

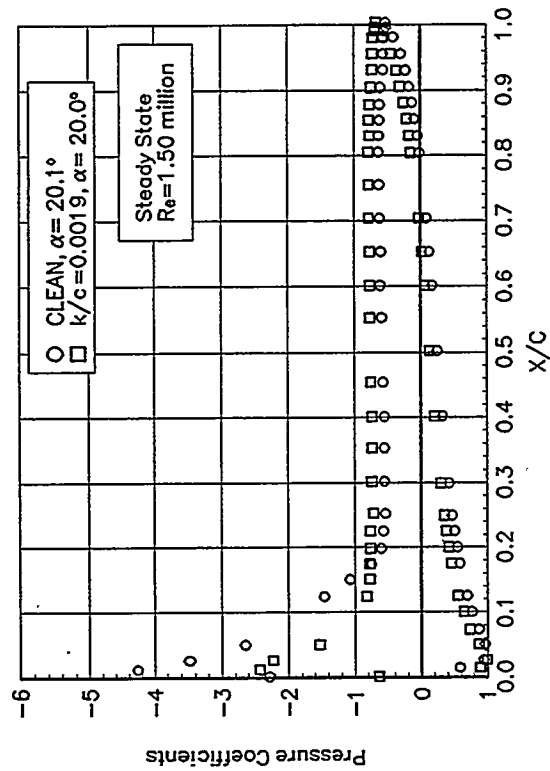


Figure B114. $\alpha = 20.0^\circ$

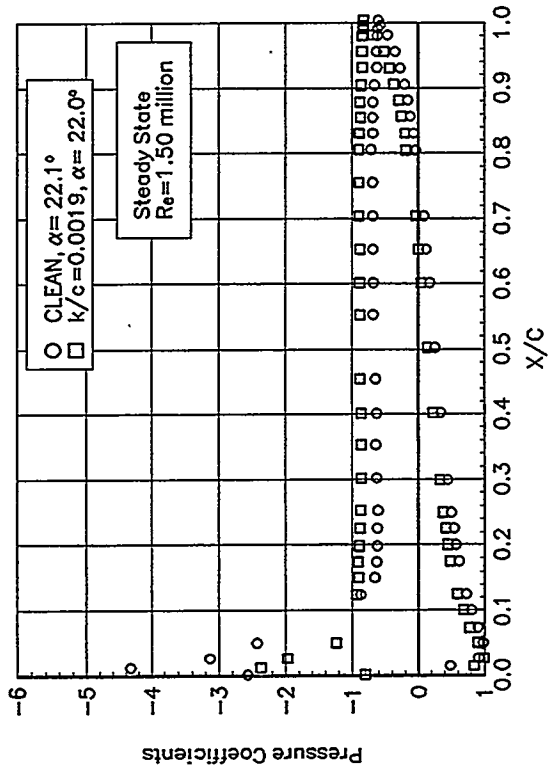


Figure B115. $\alpha = 22.0^\circ$

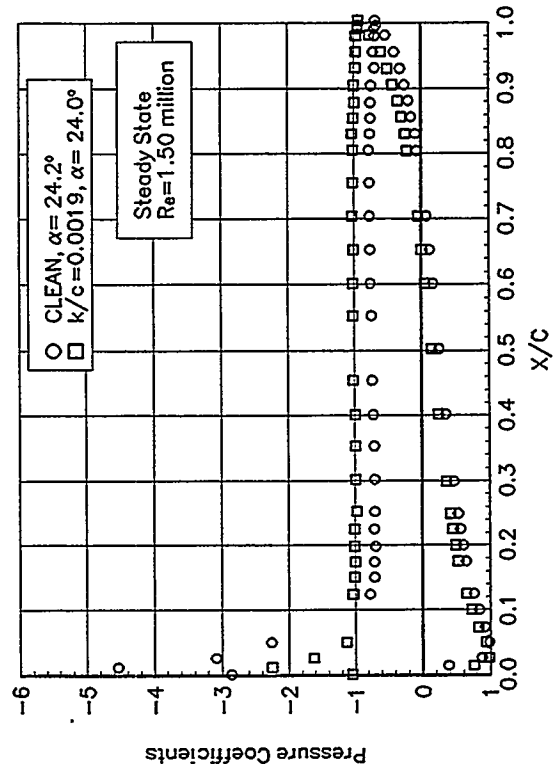


Figure B116. $\alpha = 24.0^\circ$

Appendix C: Unsteady Integrated Coefficients

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$\pm 5.5^\circ$ Sine, Re = 0.75 million	C-3
$\pm 5.5^\circ$ Sine, Re = 1 million	C-10
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Unsteady Airfoil Characteristics

$\pm 5.5^\circ$ Sine, Re = 0.75 million

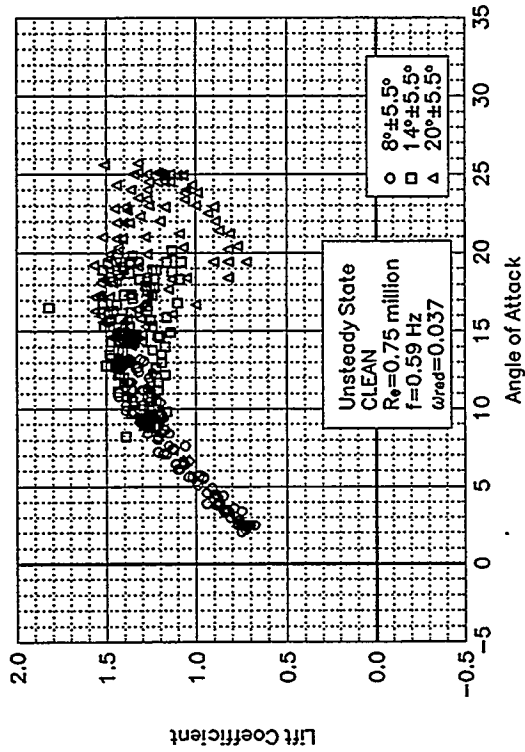


Figure C1. Lift coefficient vs α .

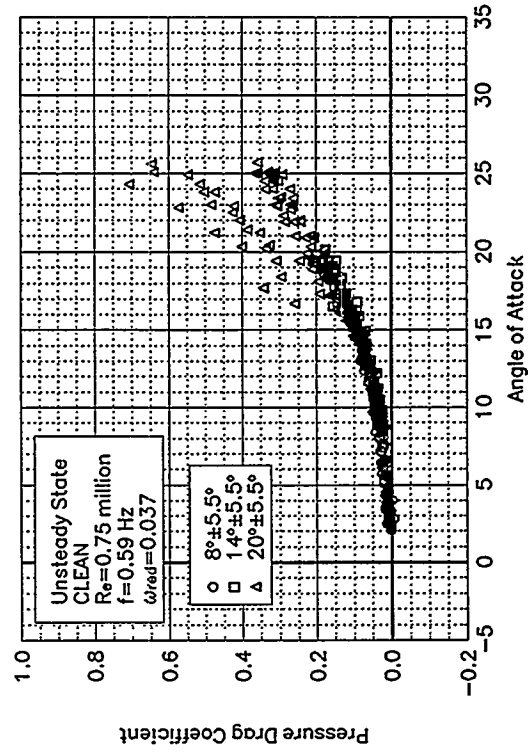


Figure C2. Pressure drag coefficient vs α .

NACA 4415
Clean
 $Re = 0.75$ million
 $\omega_{red} = 0.037$

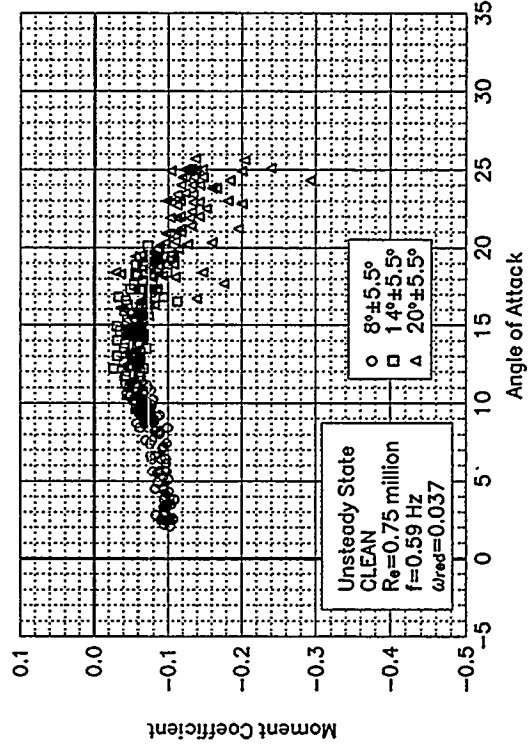


Figure C3. Moment coefficient vs α .

NACA 4415
Clean
 $Re = 0.75$ million
 $\omega_{reduced} = 0.076$

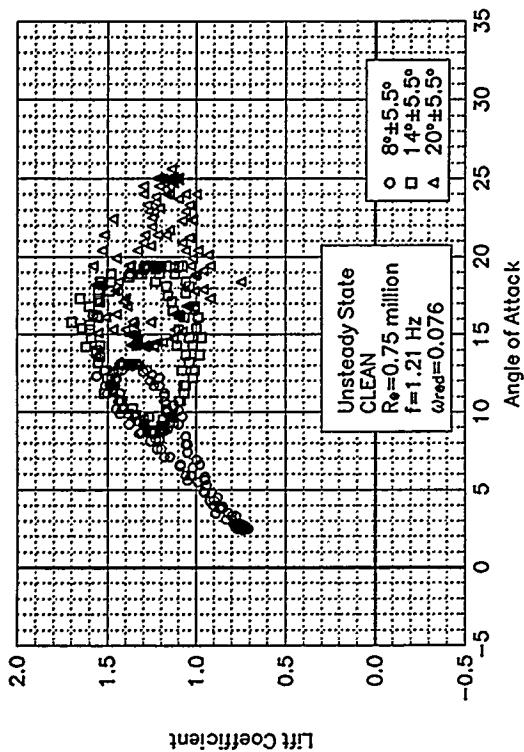


Figure C4. Lift coefficient vs α .

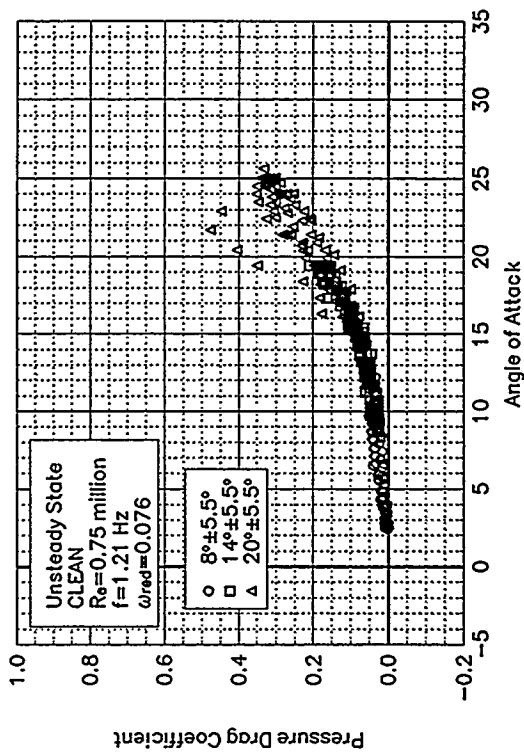


Figure C5. Pressure drag coefficient vs α .

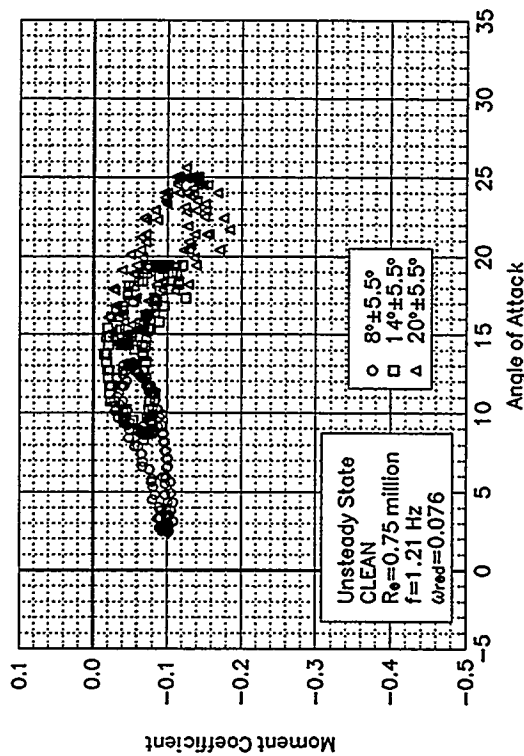


Figure C6. Moment coefficient vs α .

NACA 4415
Clean
 $Re = 0.75$ million
 $\omega_{\text{reduced}} = 0.116$

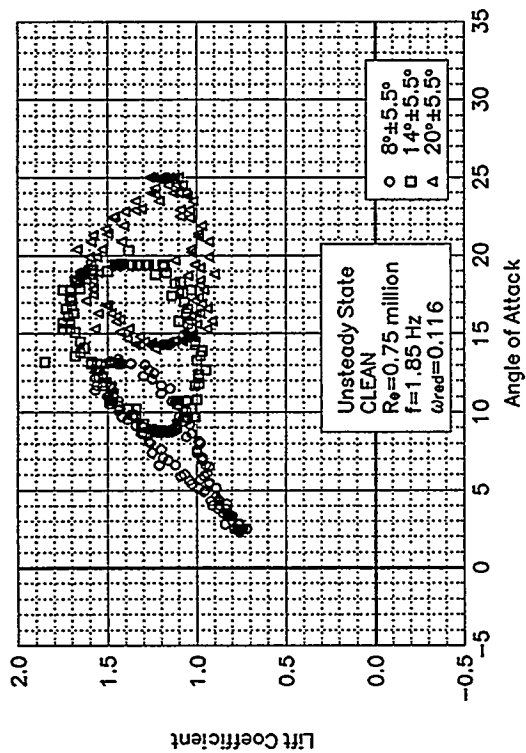


Figure C7. Lift coefficient vs α .

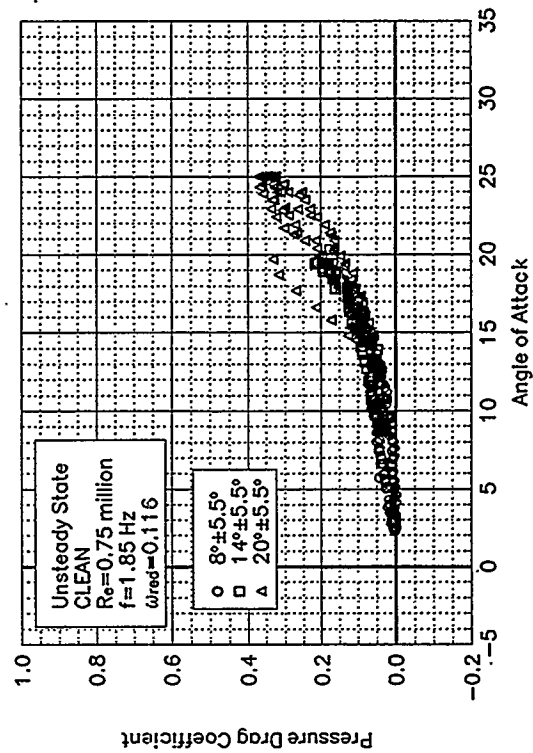


Figure C8. Pressure drag coefficient vs α .

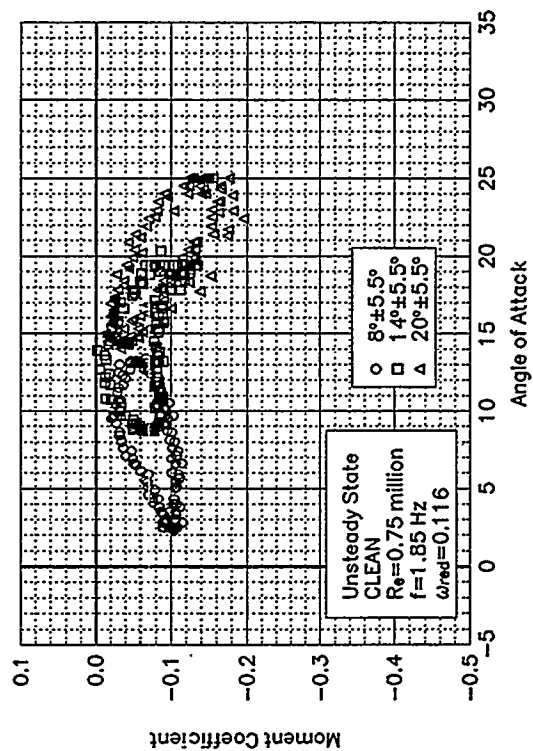


Figure C9. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 0.76$ million
 $\omega_{\text{reduced}} = 0.038$

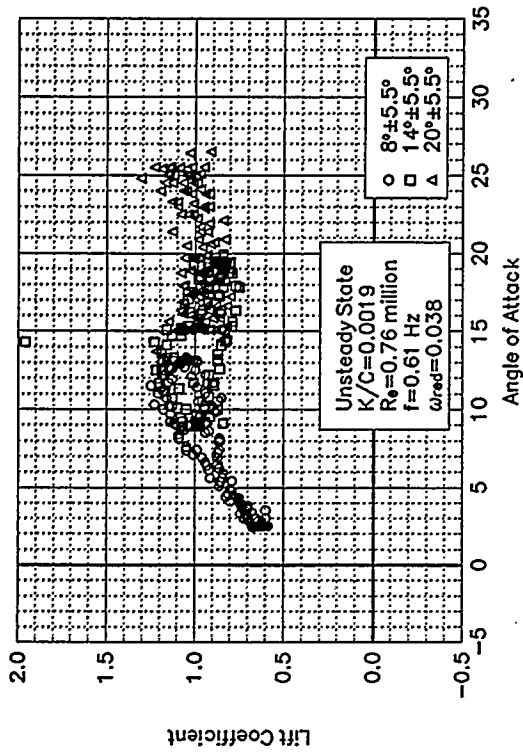


Figure C10. Lift coefficient vs α .

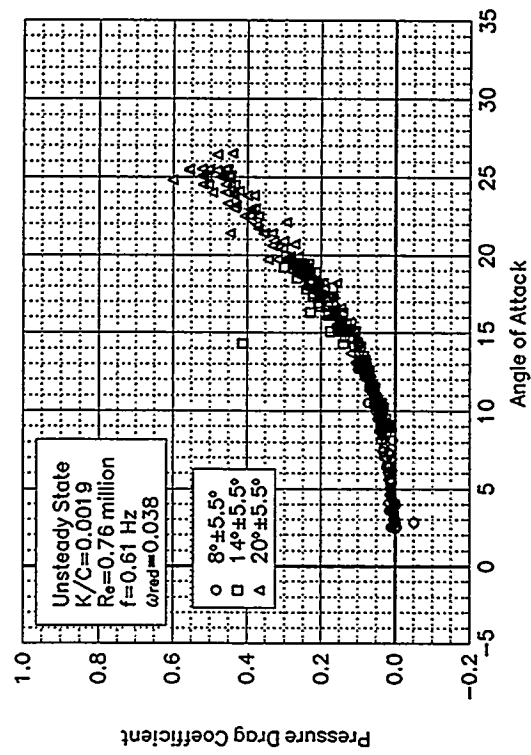


Figure C11. Pressure drag coefficient vs α .

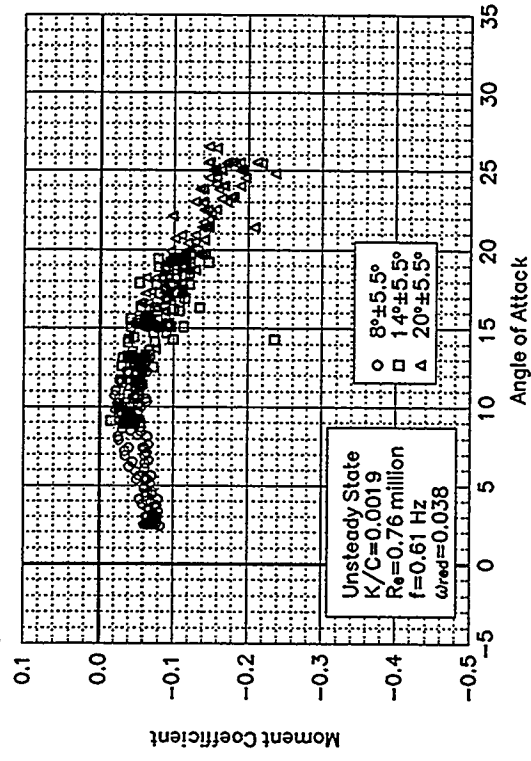


Figure C12. Moment coefficient vs α .

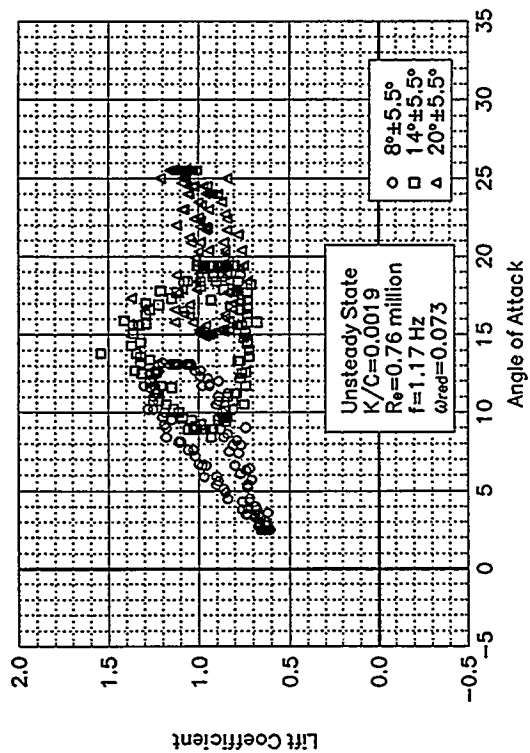


Figure C13. Lift coefficient vs α .

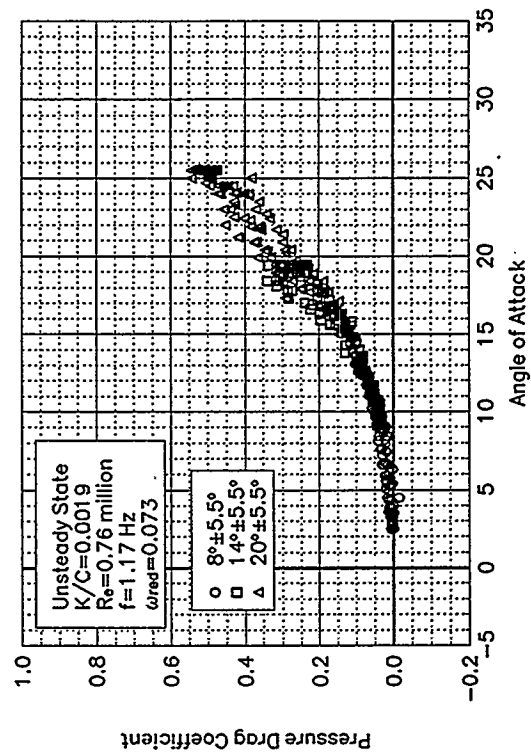


Figure C14. Pressure drag coefficient vs α .

NACA 4415
LEGR
 $Re = 0.76$ million
 $\omega_{reduced} = 0.073$

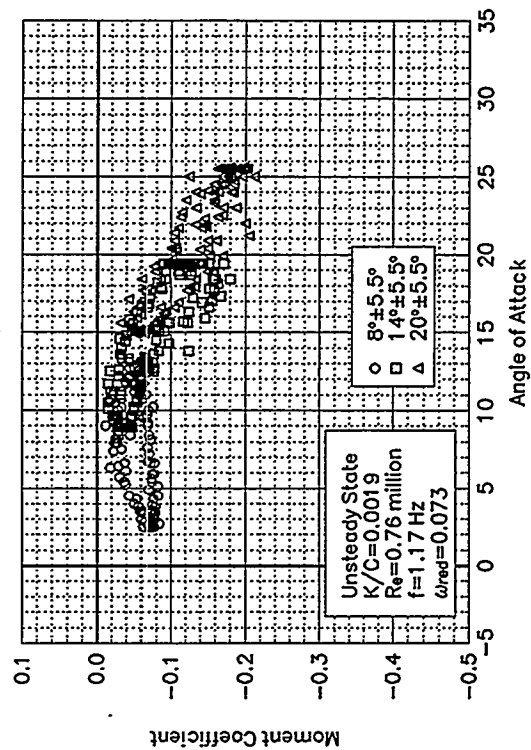


Figure C15. Moment coefficient vs α .

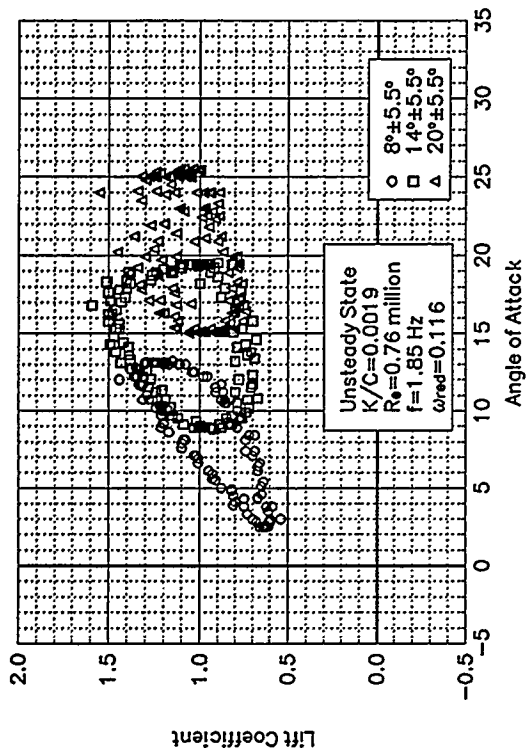


Figure C16. Lift coefficient vs α .

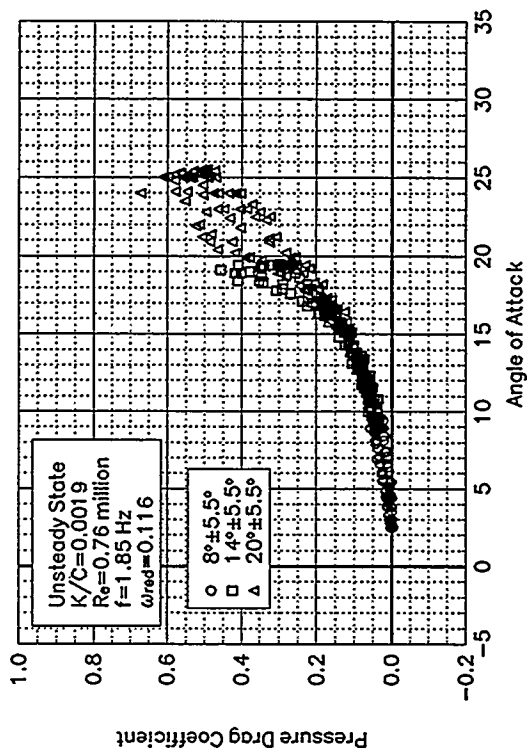


Figure C17. Pressure drag coefficient vs α .

NACA 4415
LEGR
 $Re = 0.76$ million
 $\omega_{reduced} = 0.116$

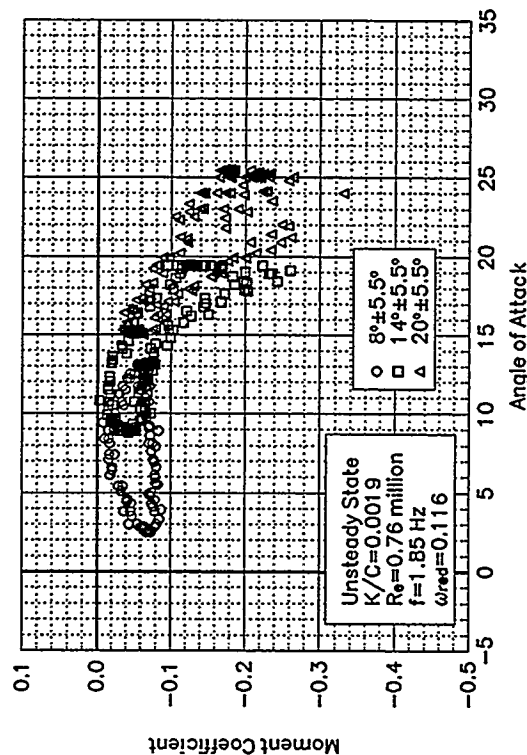


Figure C18. Moment coefficient vs α .

Unsteady Airfoil Characteristics

$\pm 5.5^\circ$ Sine, Re = 1 million

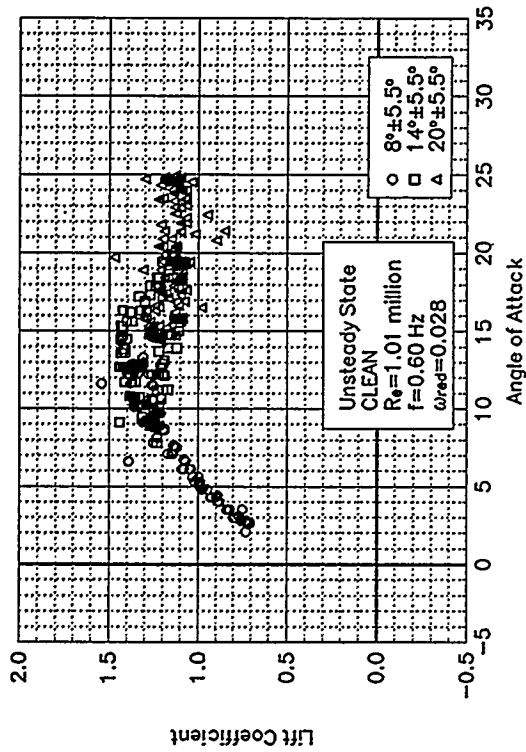


Figure C19. Lift coefficient vs α .

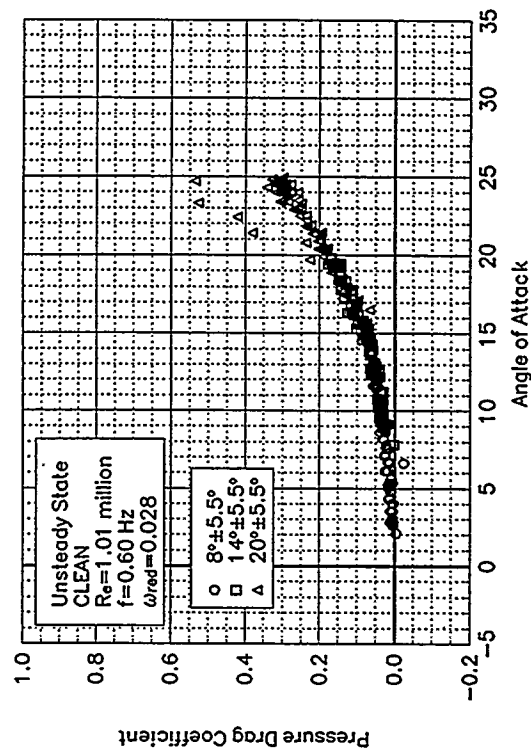


Figure C20. Pressure drag coefficient vs α .

NACA 4415
Clean
 $Re = 1.01$ million
 $\omega_{red} = 0.028$

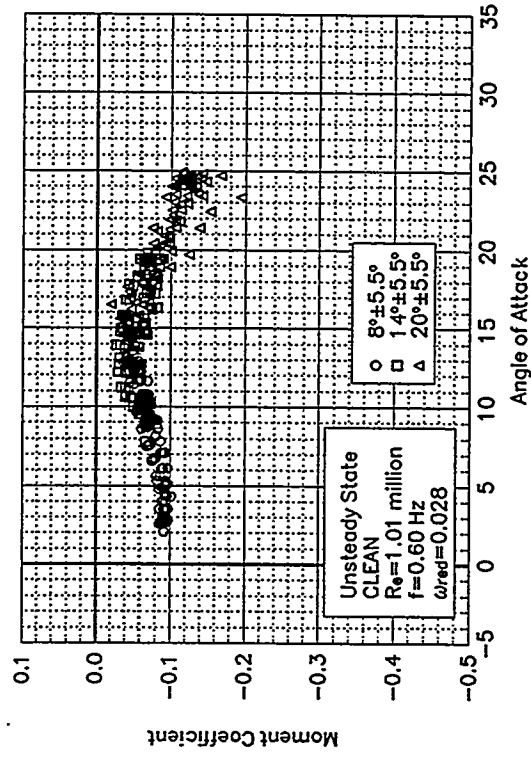


Figure C21. Moment coefficient vs α .

NACA 4415
Clean
 $Re = 1.01$ million
 $\omega_{reduced} = 0.056$

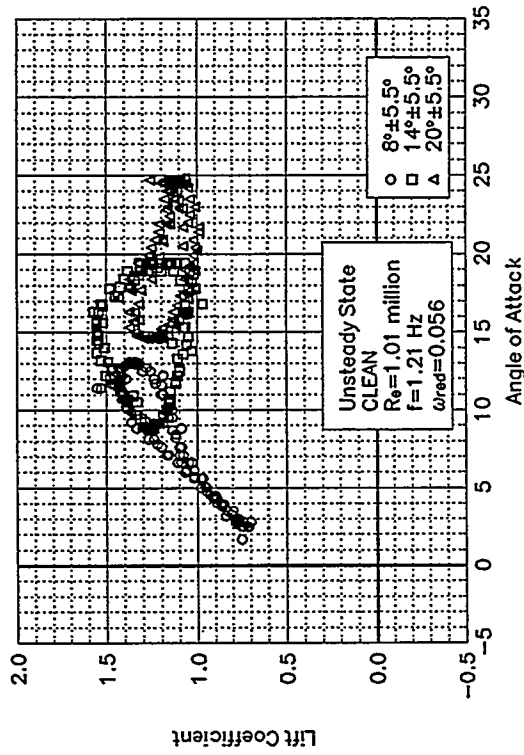


Figure C22. Lift coefficient vs α .

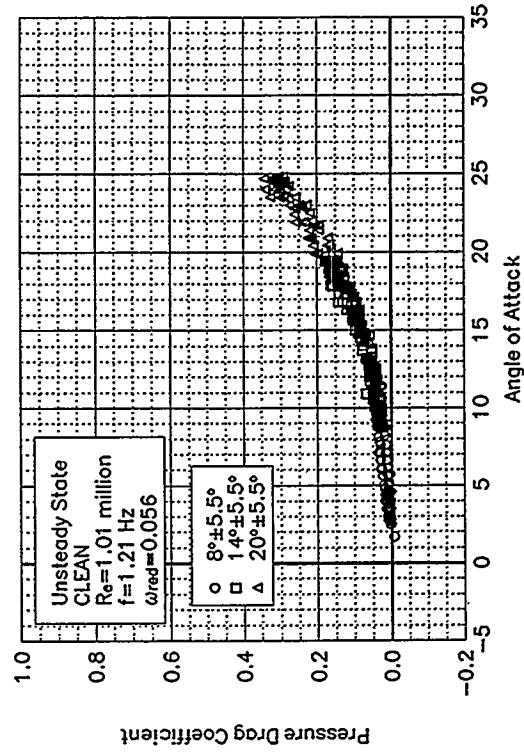


Figure C23. Pressure drag coefficient vs α .

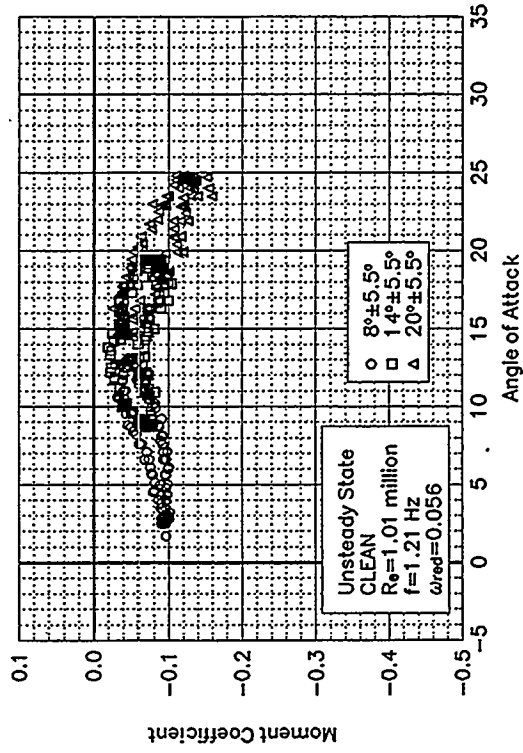


Figure C24. Moment coefficient vs α .

NACA 4415
Clean
 $Re = 1.01 \text{ million}$
 $\omega_{\text{reduced}} = 0.086$

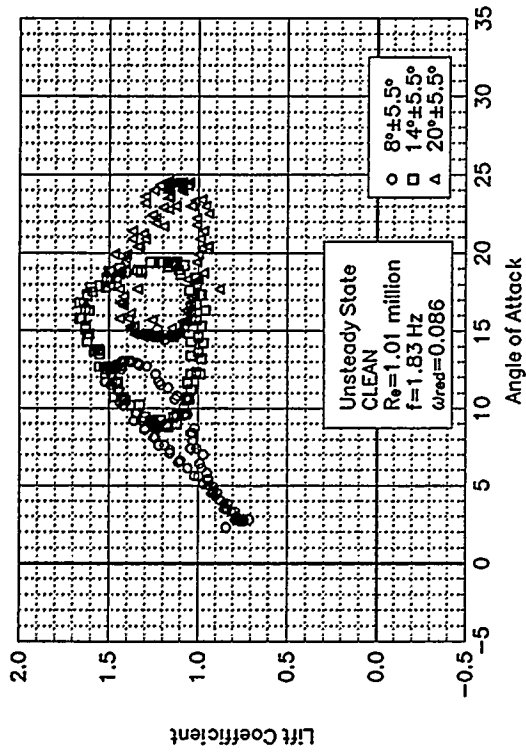


Figure C25. Lift coefficient vs α .

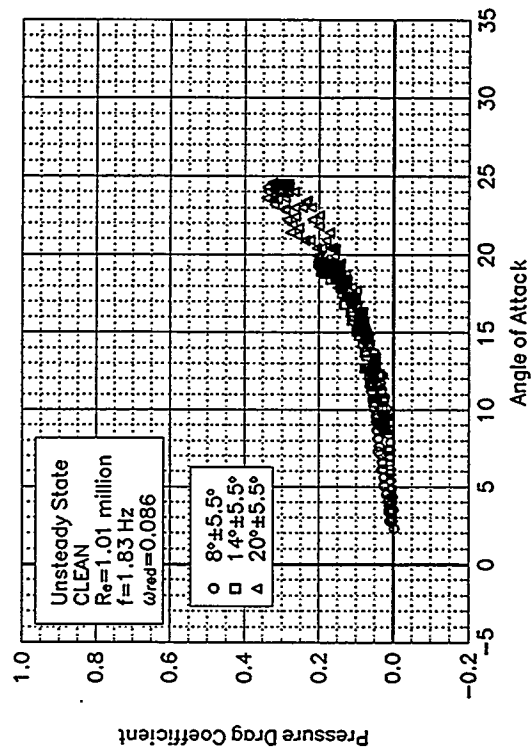


Figure C26. Pressure drag coefficient vs α .

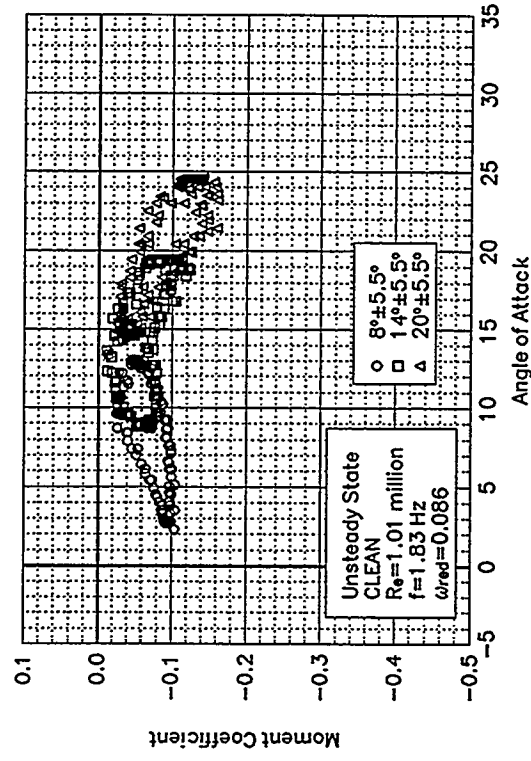


Figure C27. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 1.01 \text{ million}$
 $\omega_{\text{reduced}} = 0.028$

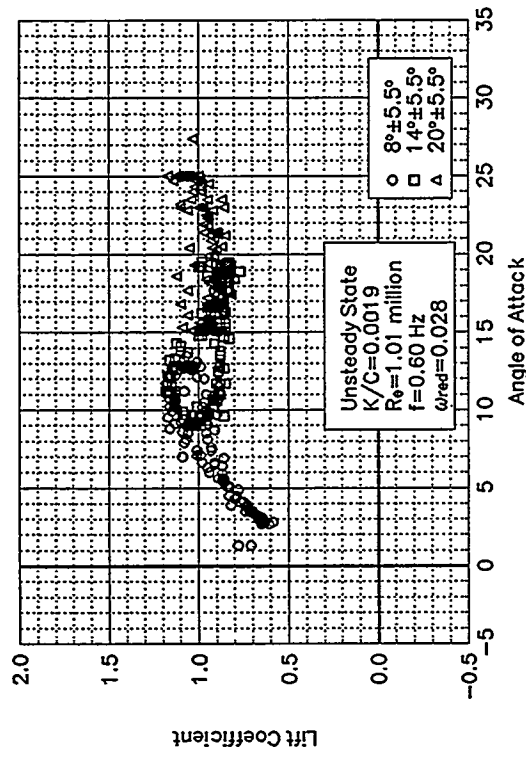


Figure C28. Lift coefficient vs α .

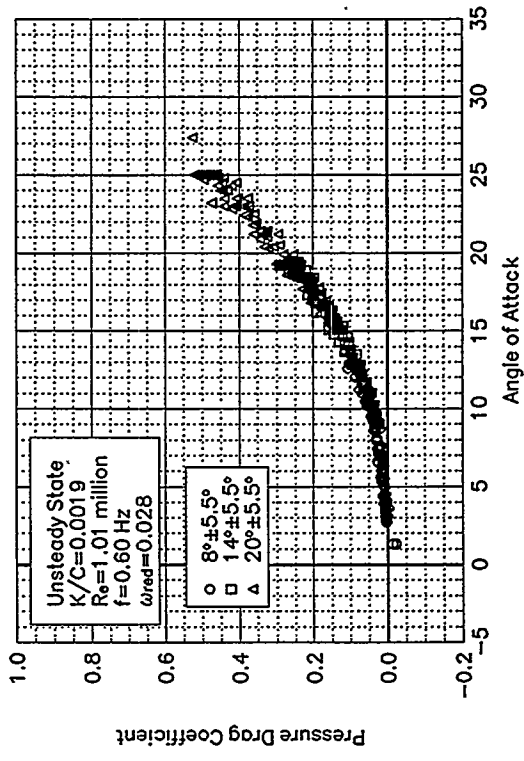


Figure C29. Pressure drag coefficient vs α .

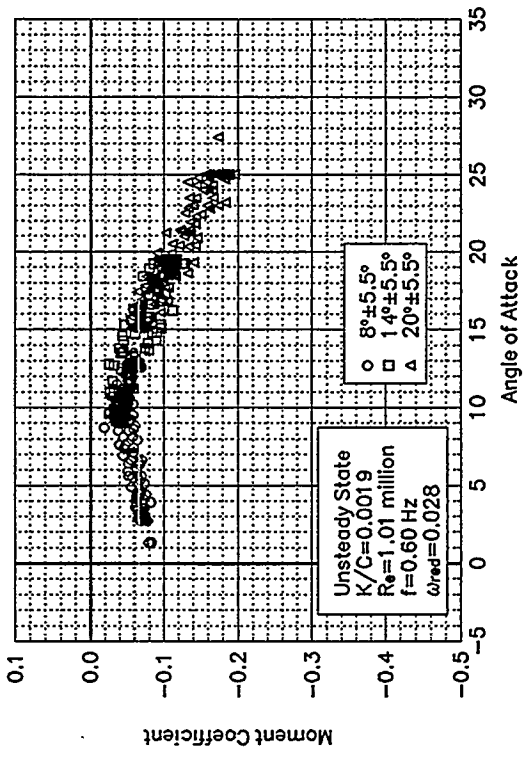


Figure C30. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 1.01 \text{ million}$
 $\omega_{\text{reduced}} = 0.056$

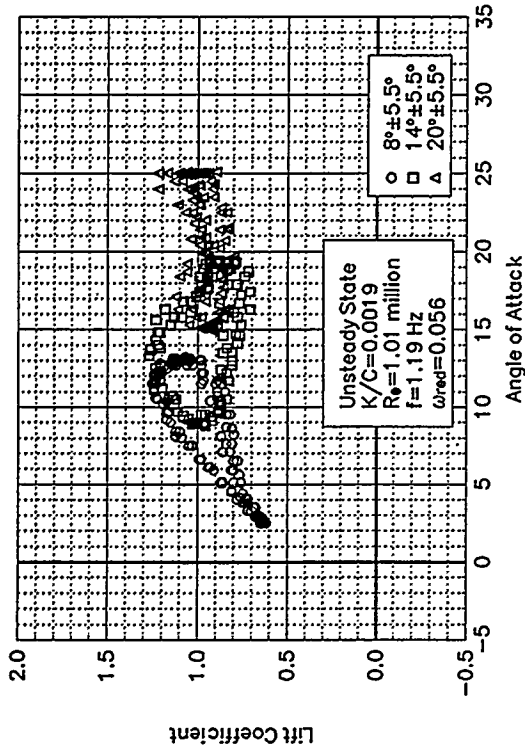


Figure C31. Lift coefficient vs α .

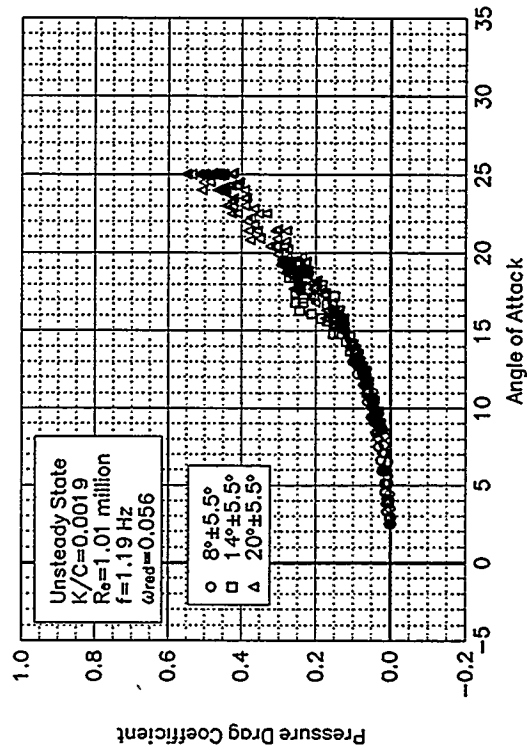


Figure C32. Pressure drag coefficient vs α .

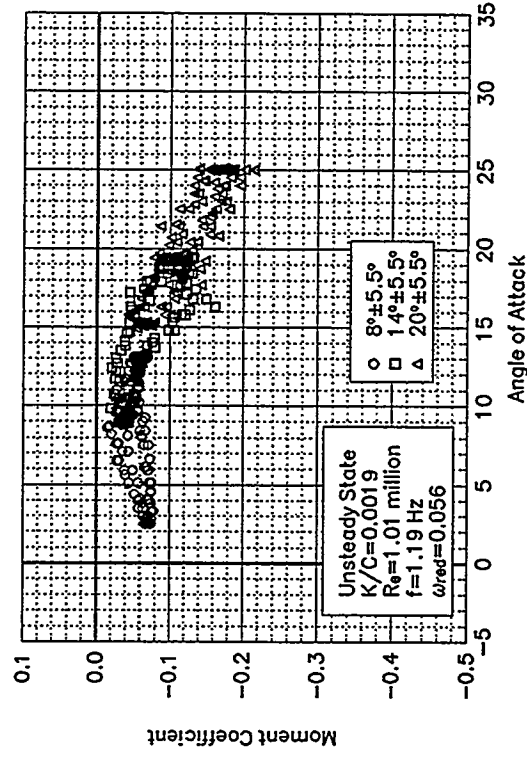


Figure C33. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 1.01$ million
 $\omega_{\text{reduced}} = 0.087$

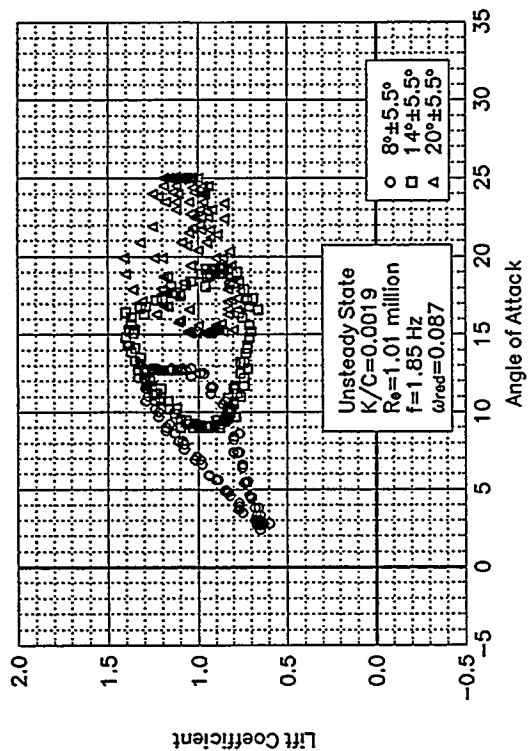


Figure C34. Lift coefficient vs α .

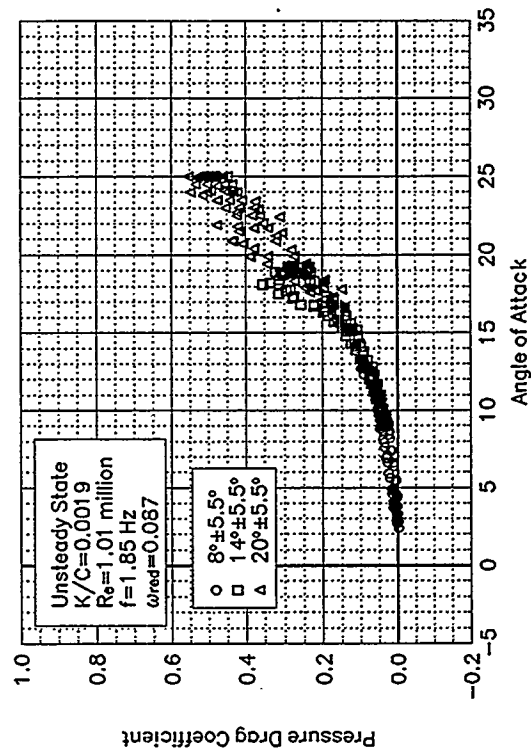


Figure C35. Pressure drag coefficient vs α .

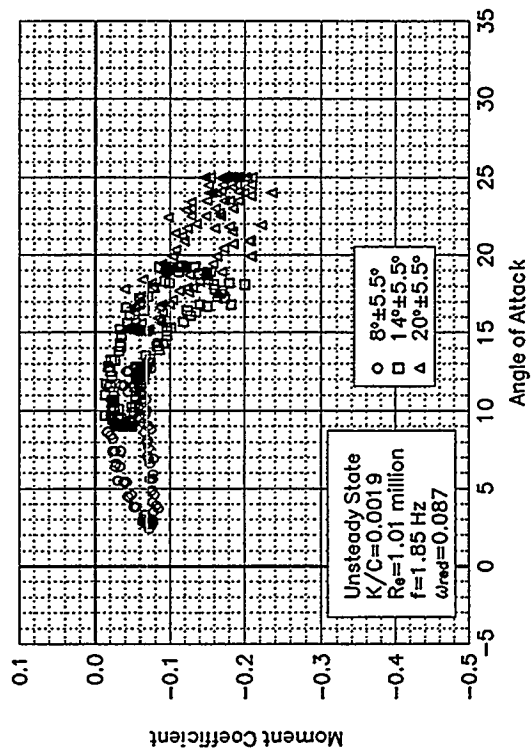


Figure C36. Moment coefficient vs α .

Unsteady Airfoil Characteristics

$\pm 5.5^\circ$ Sine, Re = 1.25 million

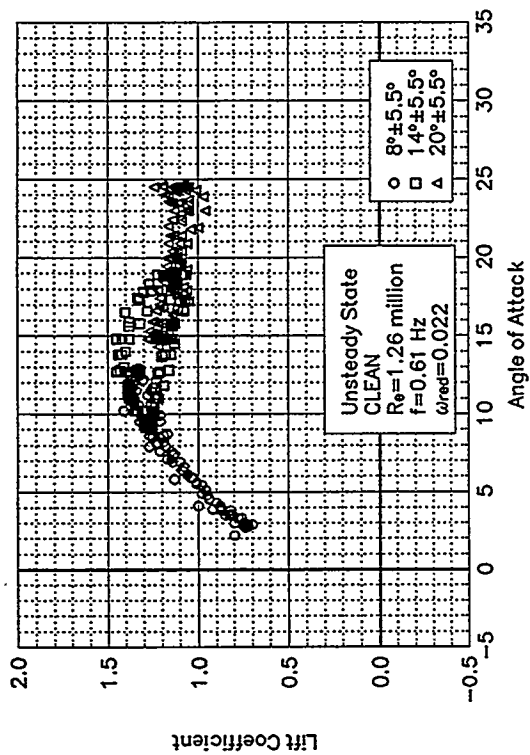


Figure C37. Lift coefficient vs α .

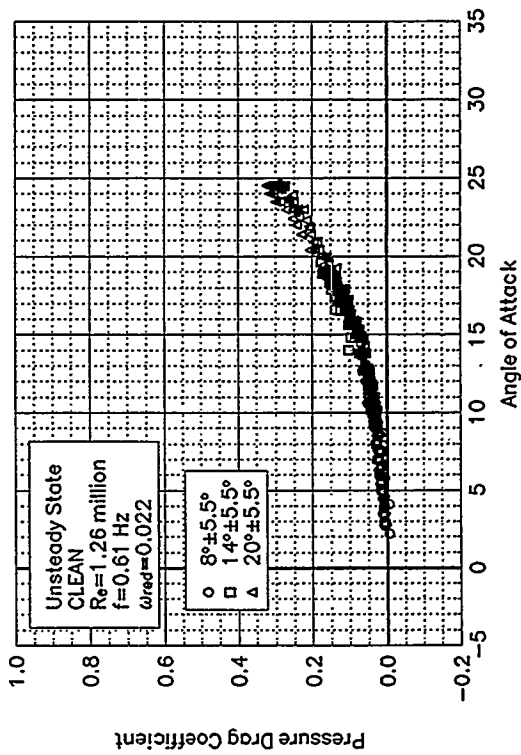


Figure C38. Pressure drag coefficient vs α .

NACA 4415
Clean
 $Re = 1.26$ million
 $\omega_{red} = 0.022$

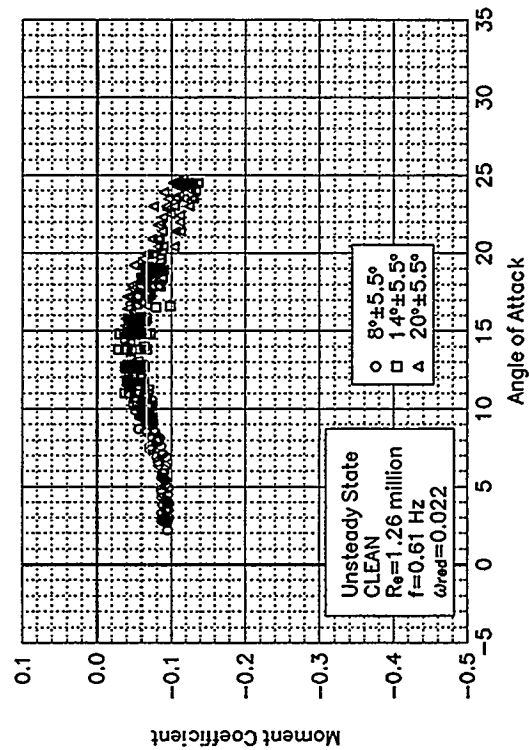


Figure C39. Moment coefficient vs α .

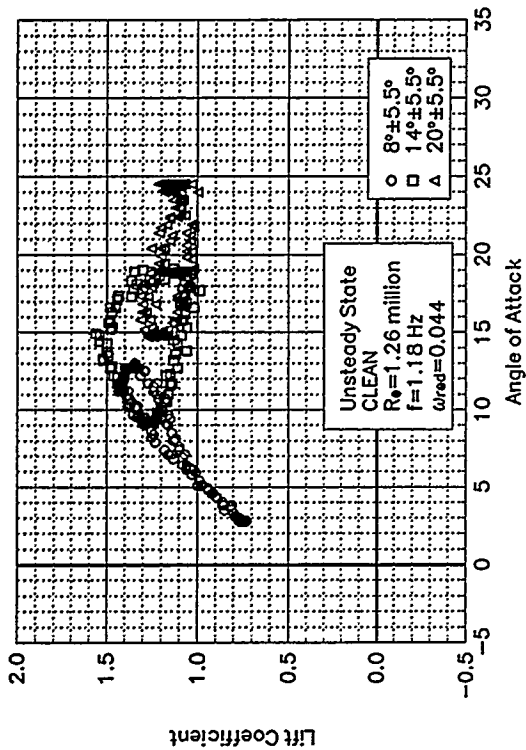


Figure C40. Lift coefficient vs α .

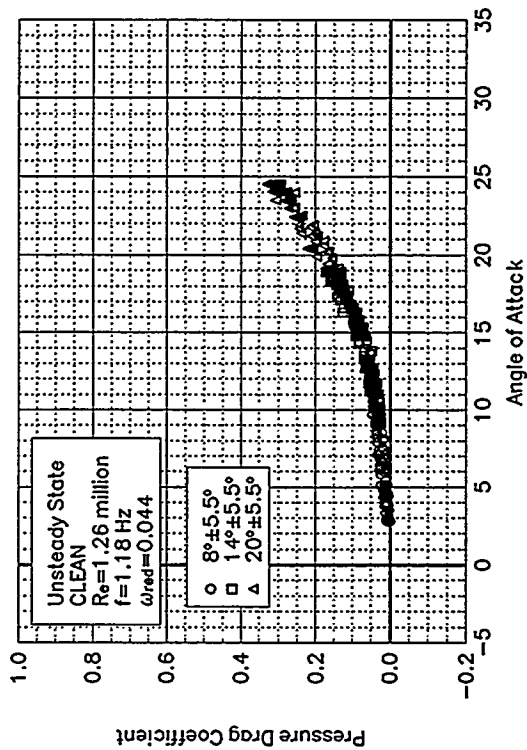


Figure C41. Pressure drag coefficient vs α .

NACA 4415
Clean
 $Re = 1.26$ million
 $\omega_{\text{reduced}} = 0.044$

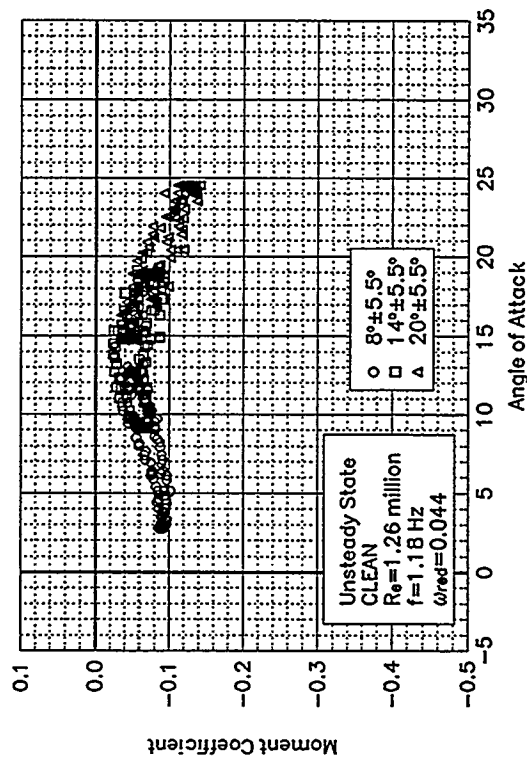


Figure C42. Moment coefficient vs α .

NACA 4415
Clean
 $Re = 1.26$ million
 $\omega_{\text{reduced}} = 0.069$

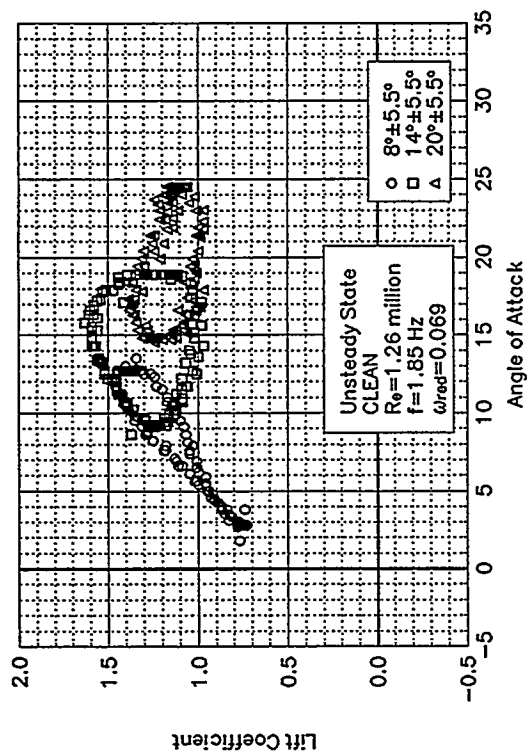


Figure C43. Lift coefficient vs α .

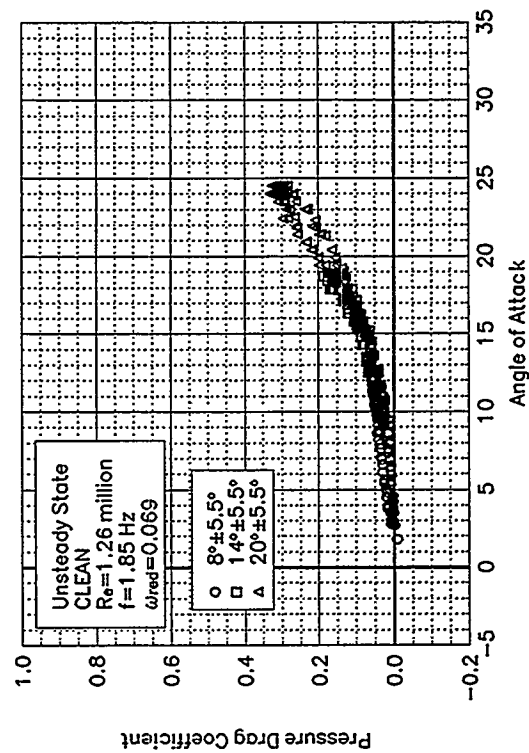


Figure C44. Pressure drag coefficient vs α .

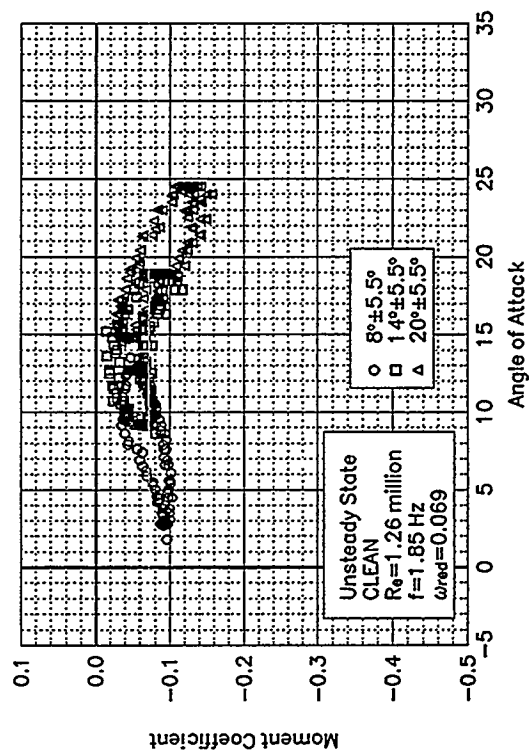


Figure C45. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 1.26 \text{ million}$
 $\omega_{\text{reduced}} = 0.023$

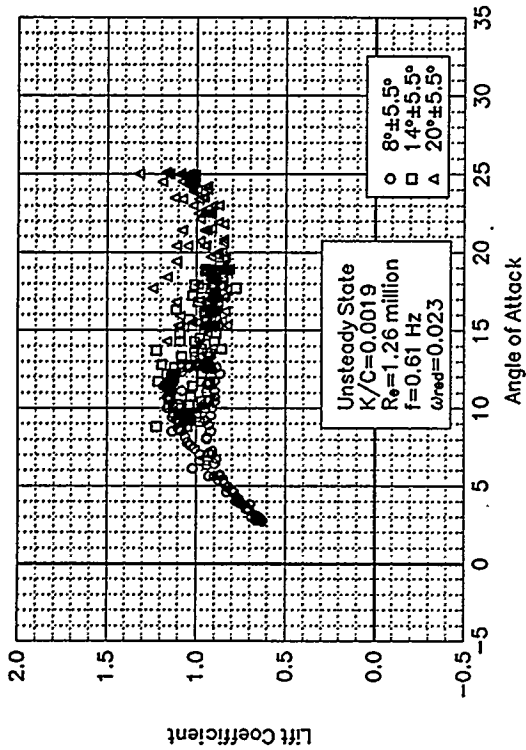


Figure C46. Lift coefficient vs α .

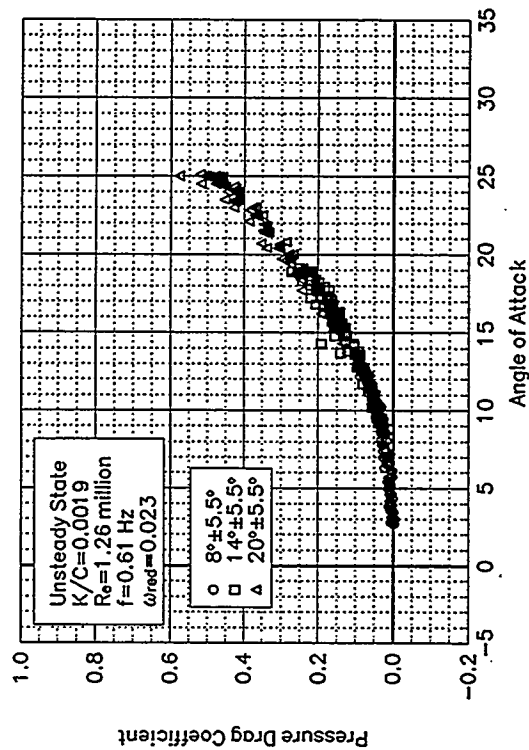


Figure C47. Pressure drag coefficient vs α .

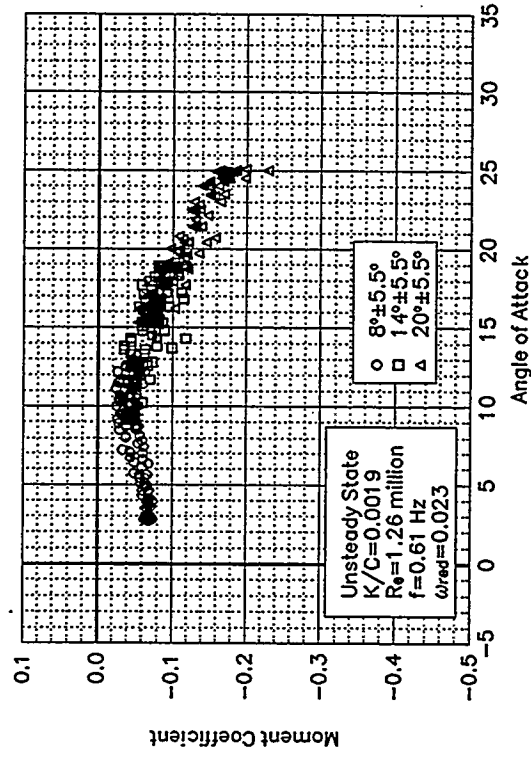


Figure C48. Moment coefficient vs α .

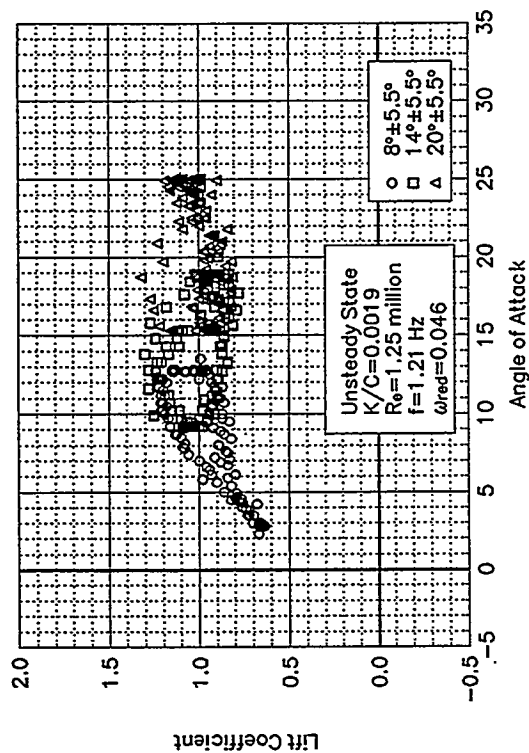


Figure C49. Lift coefficient vs α .

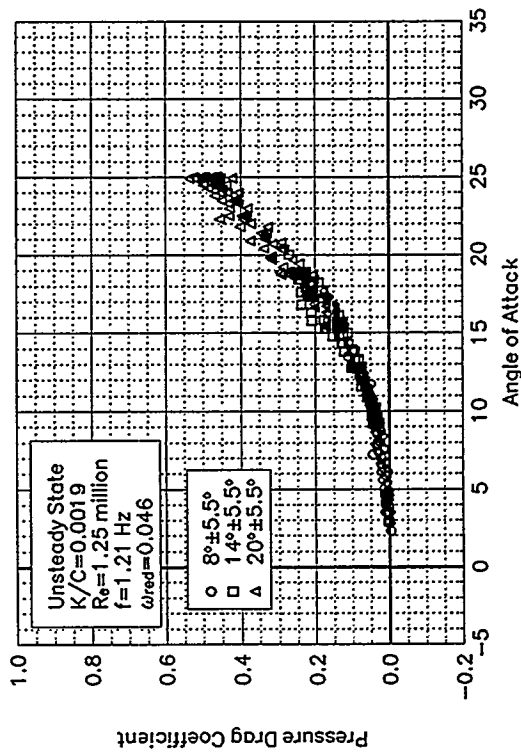


Figure C50. Pressure drag coefficient vs α .

NACA 4415
LEGR
 $Re = 1.25 \text{ million}$
 $\omega_{\text{reduced}} = 0.046$

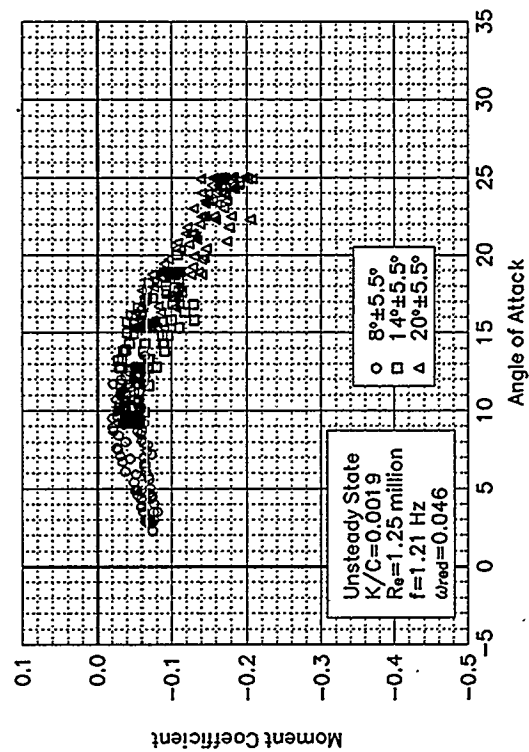


Figure C51. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 1.25$ million
 $\omega_{\text{reduced}} = 0.068$

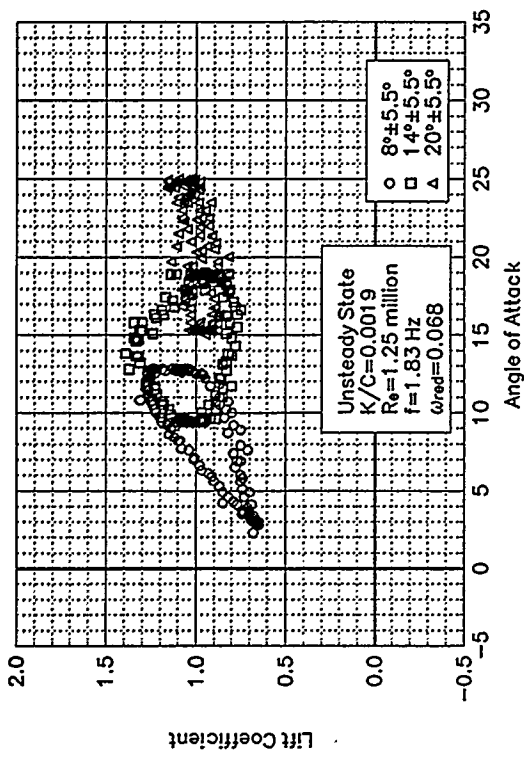


Figure C52. Lift coefficient vs α .

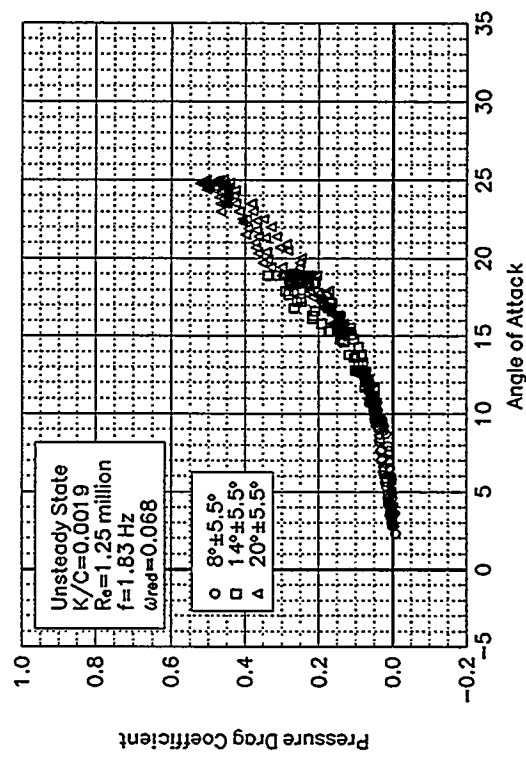


Figure C53. Pressure drag coefficient vs α .

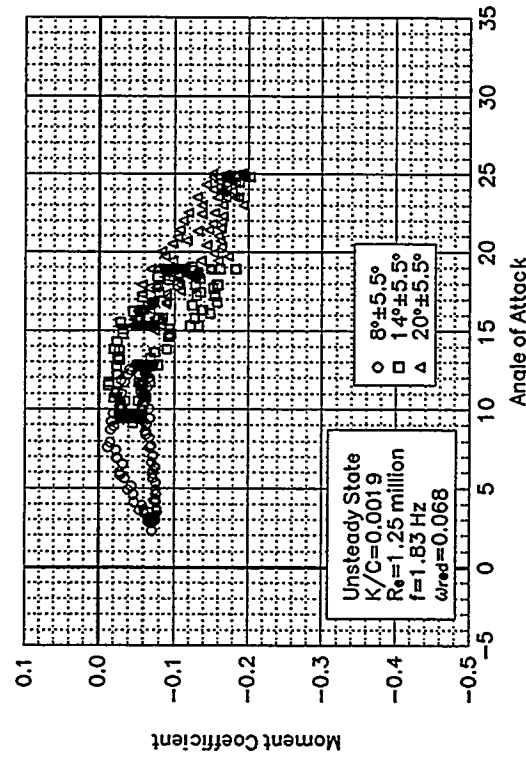


Figure C54. Moment coefficient vs α .

Unsteady Airfoil Characteristics

$\pm 5.5^\circ$ Sine, Re = 1.5 million

NACA 4415
Clean
 $Re = 1.51 \text{ million}$
 $\omega_{\text{reduced}} = 0.019$

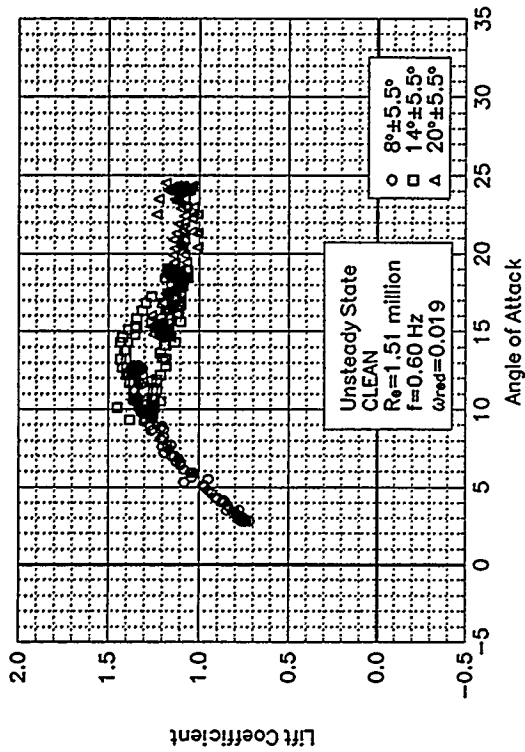


Figure C55. Lift coefficient vs α .

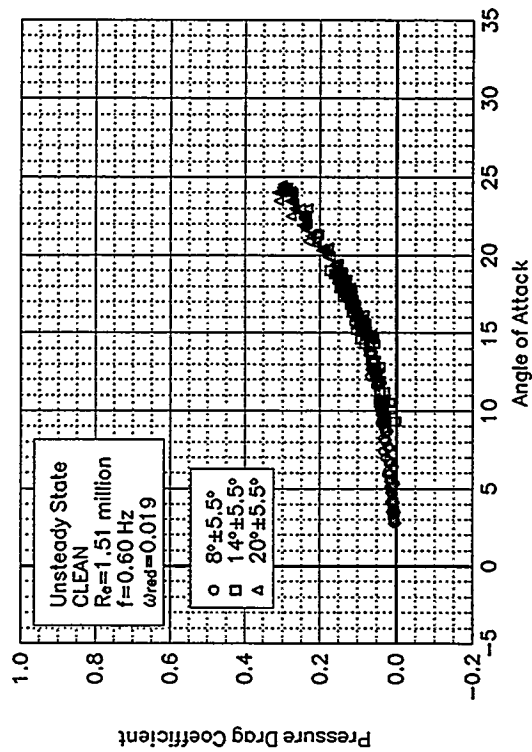


Figure C56. Pressure drag coefficient vs α .

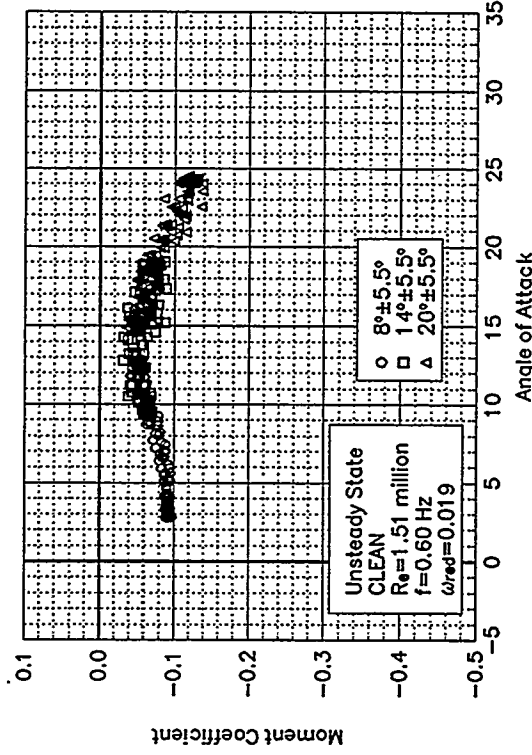


Figure C57. Moment coefficient vs α .

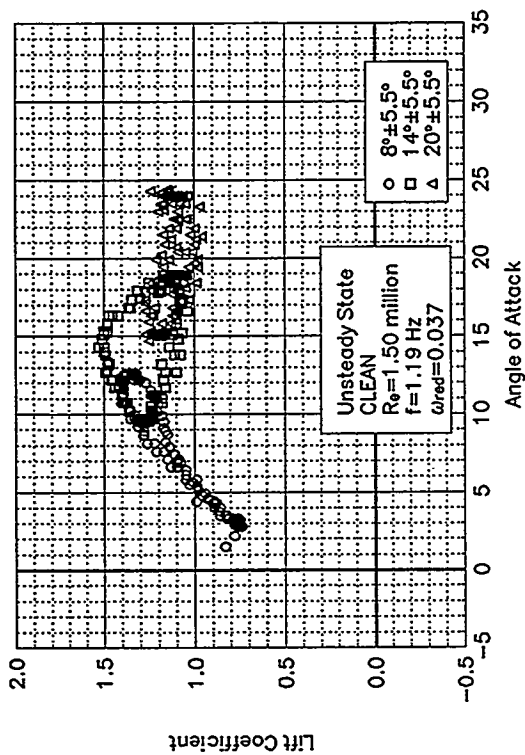


Figure C58. Lift coefficient vs α .

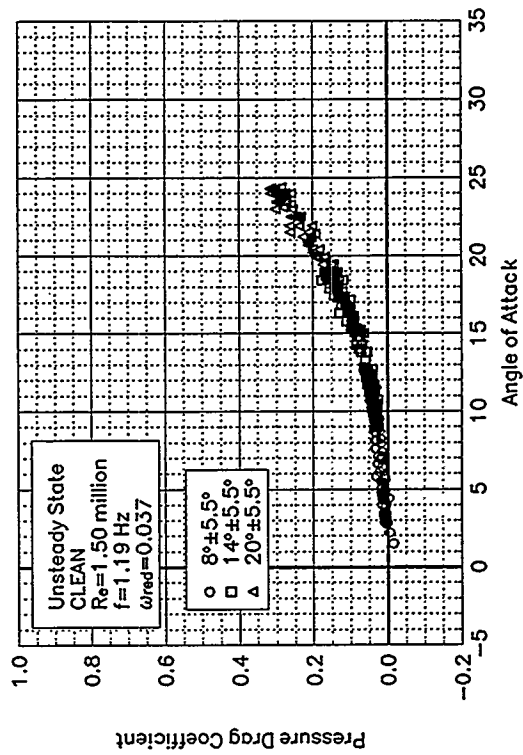


Figure C59. Pressure drag coefficient vs α .

NACA 4415
Clean
 $Re = 1.50$ million
 $\omega_{reduced} = 0.037$

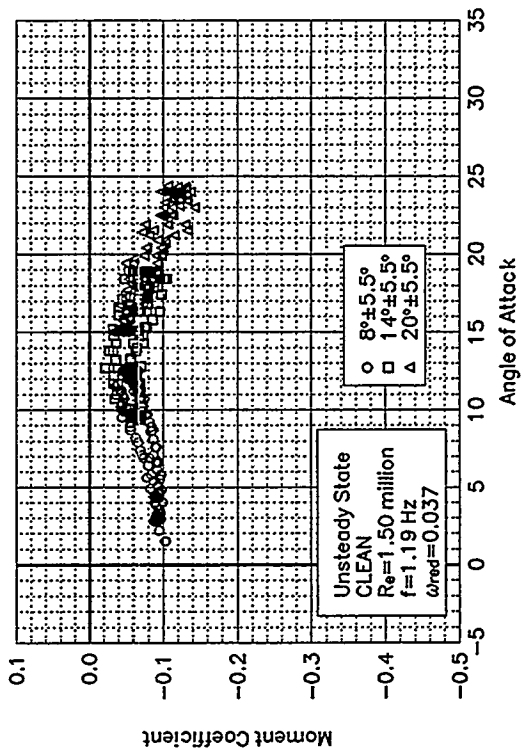


Figure C60. Moment coefficient vs α .

NACA 4415
Clean
 $Re = 1.51$ million
 $\omega_{\text{reduced}} = 0.056$

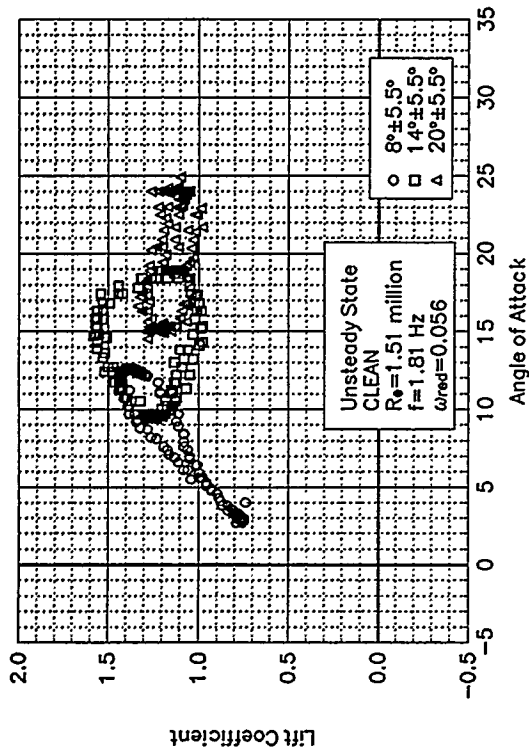


Figure C61. Lift coefficient vs α .

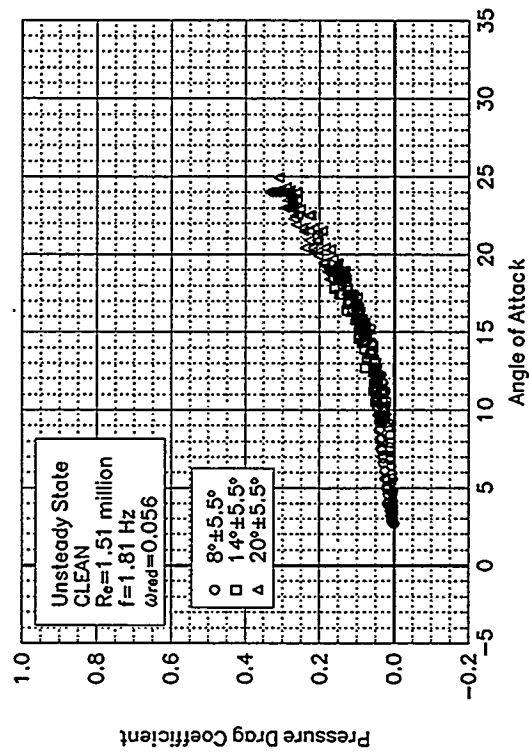


Figure C62. Pressure drag coefficient vs α .

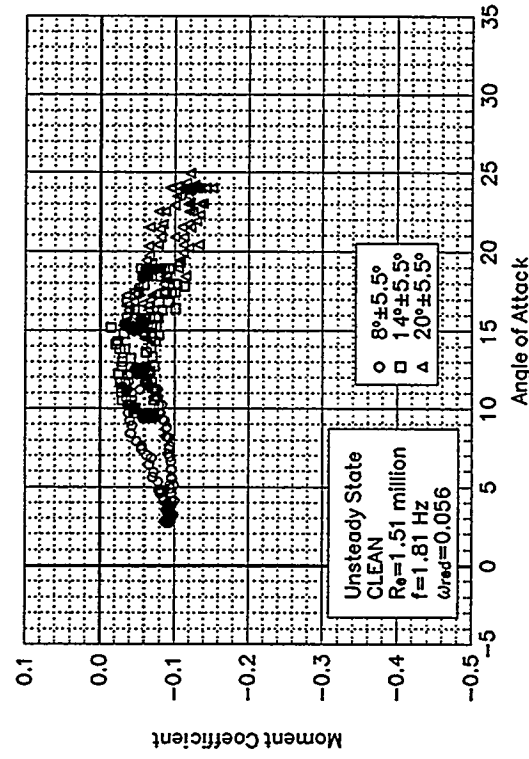


Figure C63. Moment coefficient vs α .

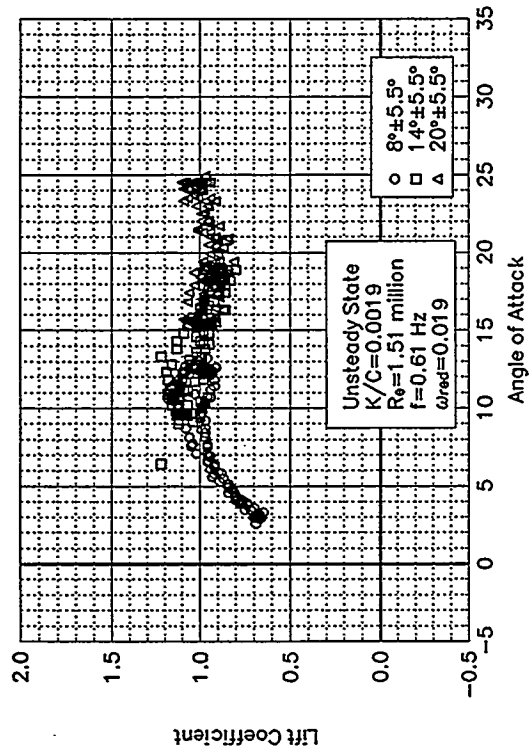


Figure C64. Lift coefficient vs α .

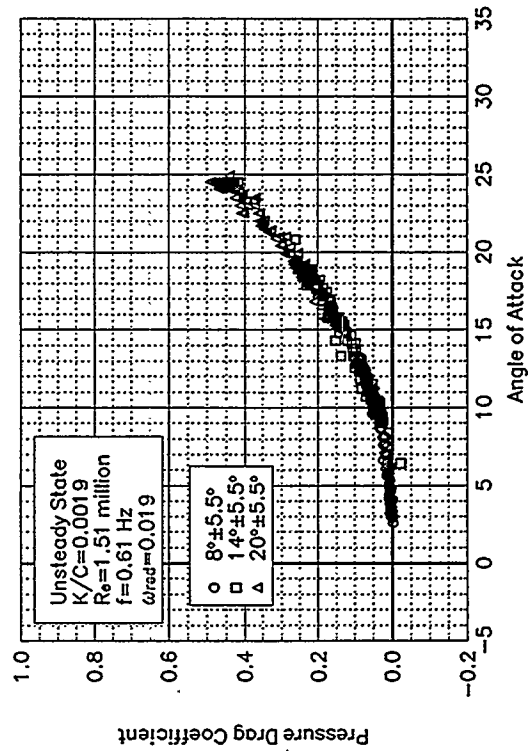


Figure C65. Pressure drag coefficient vs α .

NACA 4415
LEGR
 $Re = 1.51$ million
 $\omega_{reduced} = 0.019$

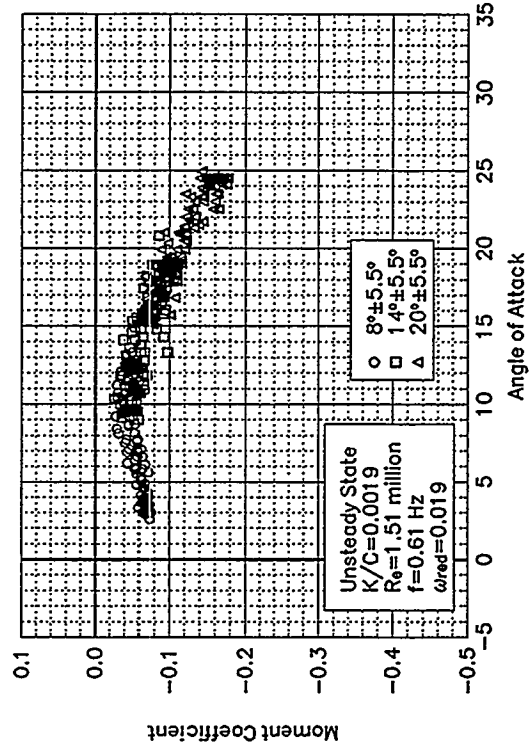


Figure C66. Moment coefficient vs α .

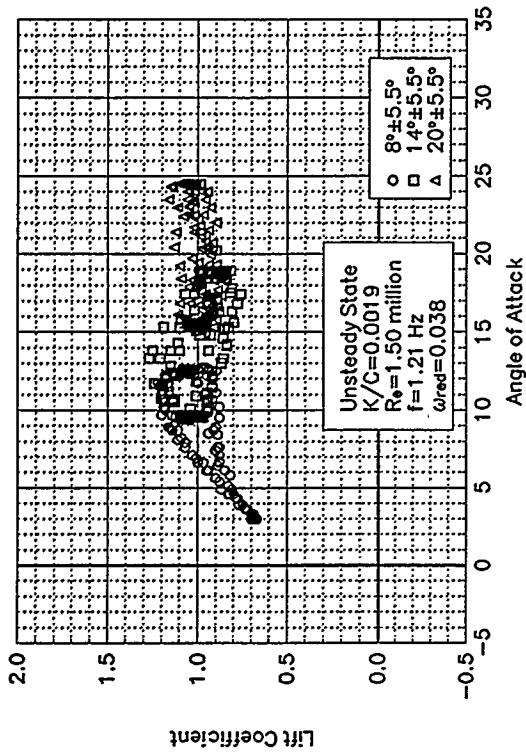


Figure C67. Lift coefficient vs α .

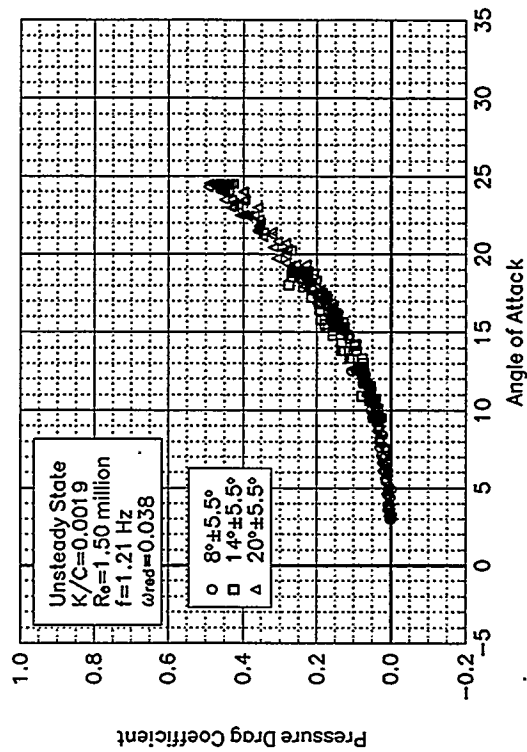


Figure C68. Pressure drag coefficient vs α .

NACA 4415
LEGR
 $Re = 1.50$ million
 $\omega_{reduced} = 0.038$

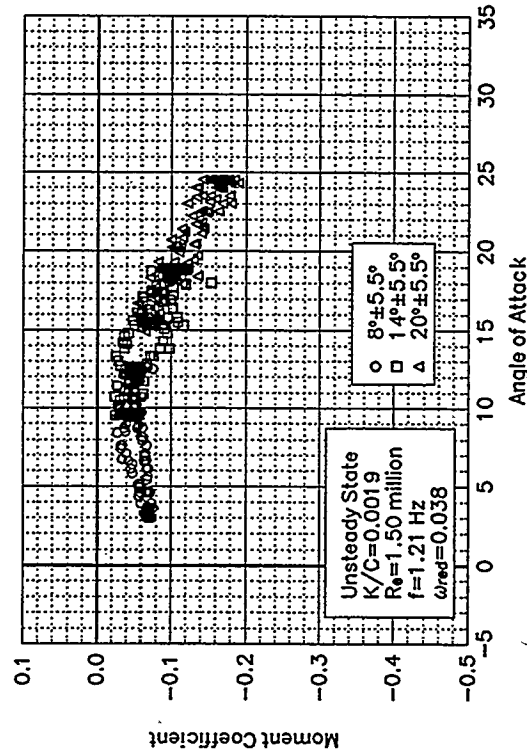


Figure C69. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 1.50 \text{ million}$
 $\omega_{\text{reduced}} = 0.057$

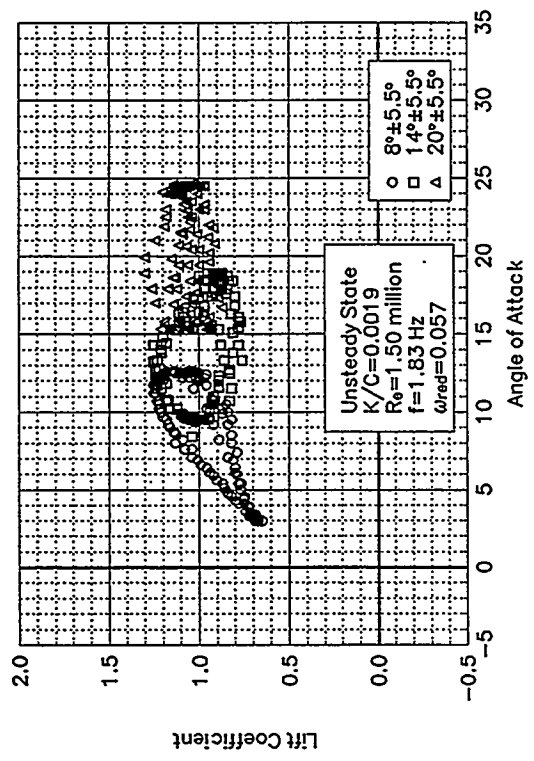


Figure C70. Lift coefficient vs α .

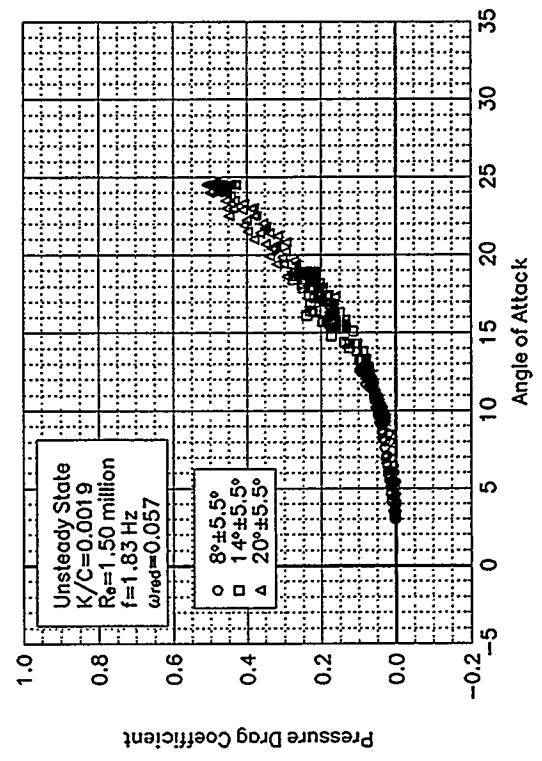


Figure C71. Pressure drag coefficient vs α .

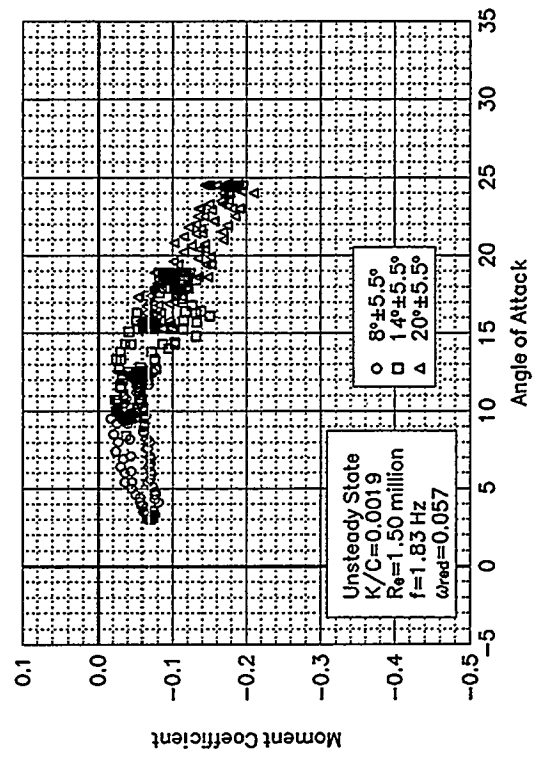


Figure C72. Moment coefficient vs α .

Unsteady Airfoil Characteristics

$\pm 10^\circ$ Sine, $Re = 0.75$ million

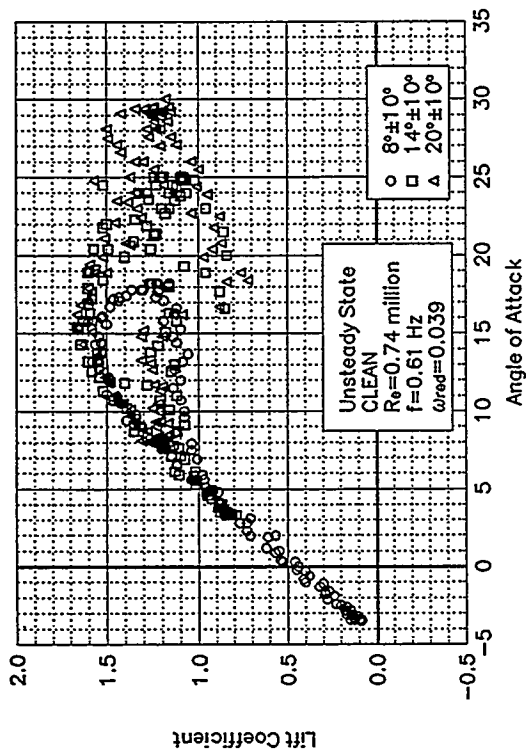


Figure C73. Lift coefficient vs α .

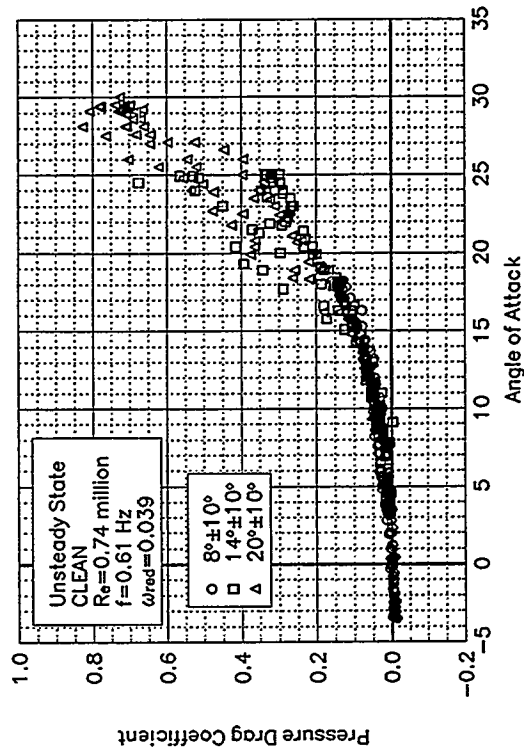


Figure C74. Pressure drag coefficient vs α .

NACA 4415
Clean
 $Re = 0.74$ million
 $\omega_{reduced} = 0.039$

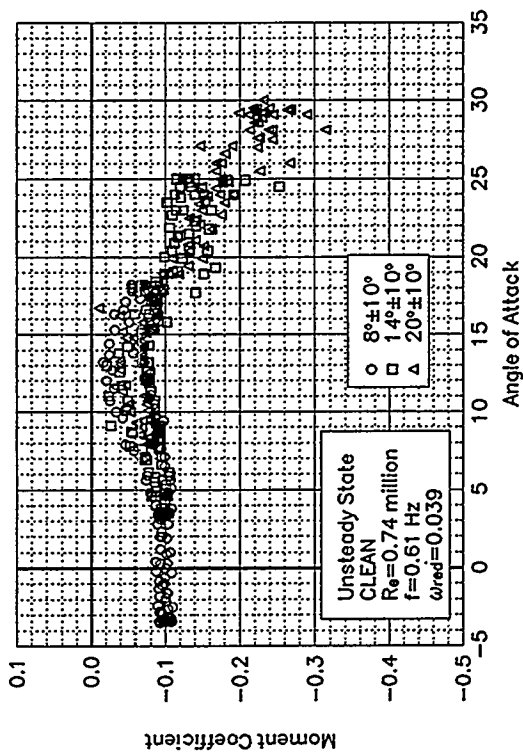


Figure C75. Moment coefficient vs α .

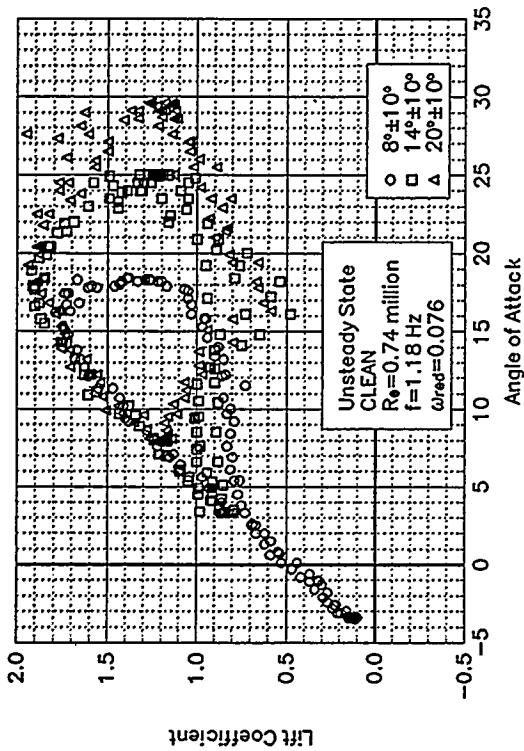


Figure C76. Lift coefficient vs α .

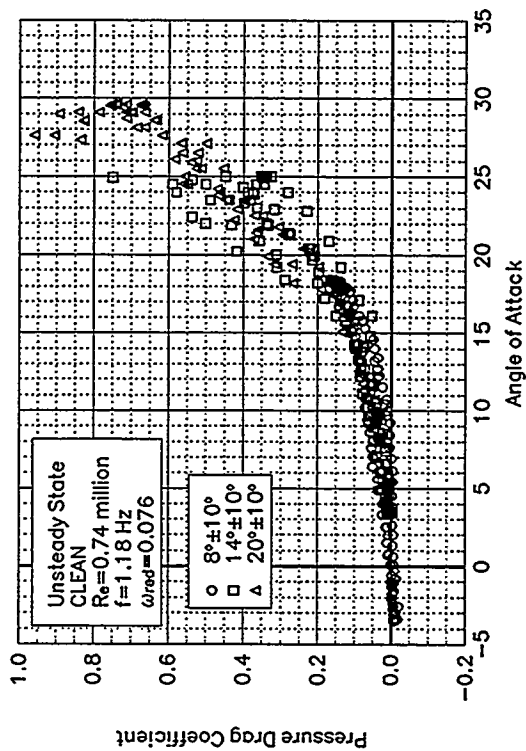


Figure C77. Pressure drag coefficient vs α .

NACA 4415
Clean
 $Re = 0.74$ million
 $\omega_{red} = 0.076$

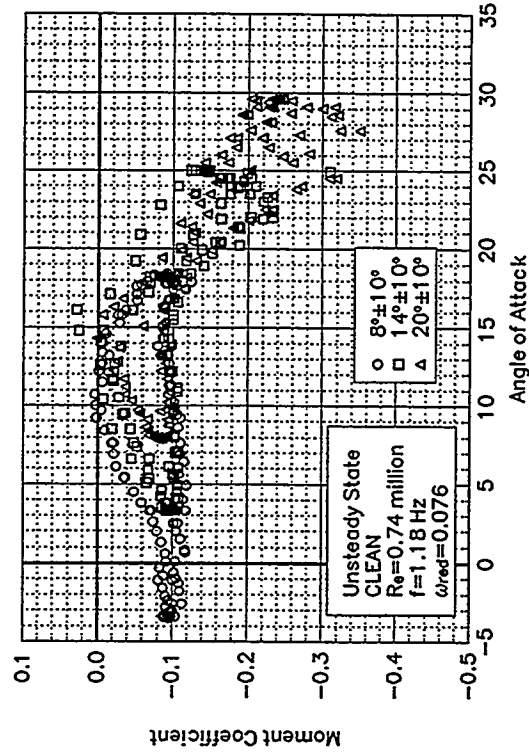


Figure C78. Moment coefficient vs α .

NACA 4415
Clean
 $Re = 0.74$ million
 $\omega_{reduced} = 0.118$

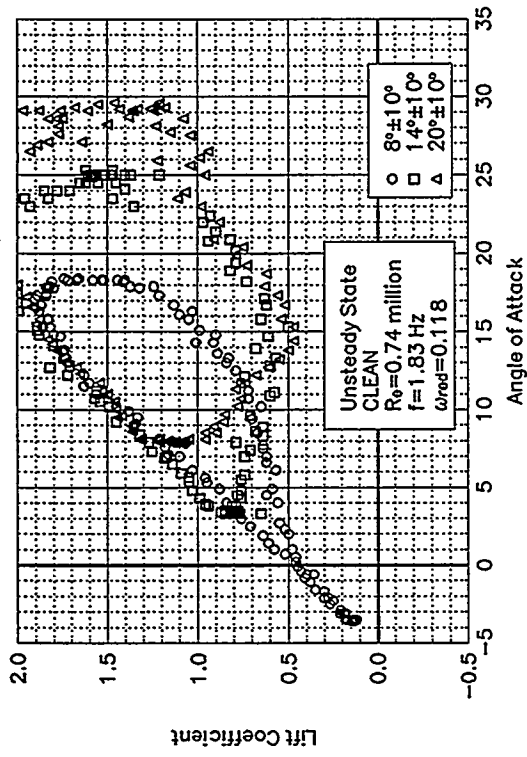


Figure C79. Lift coefficient vs α .

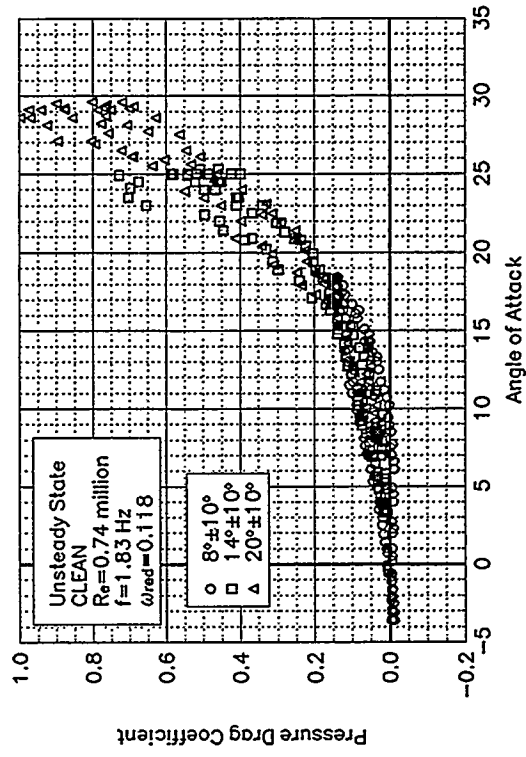


Figure C80. Pressure drag coefficient vs α .

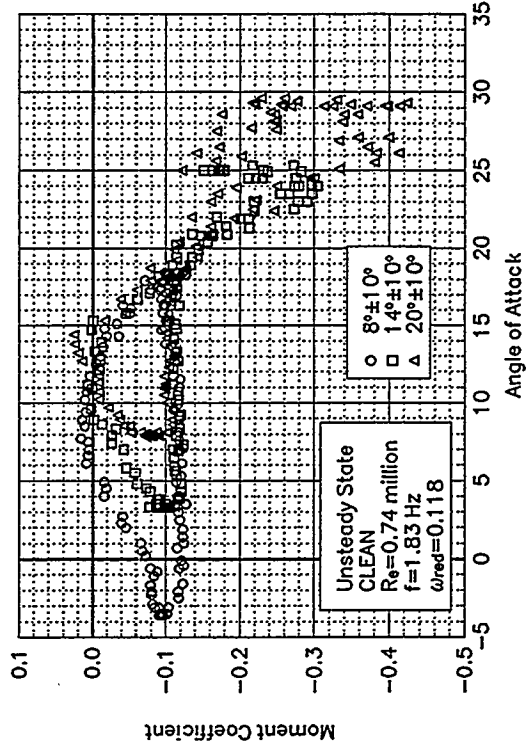


Figure C81. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 0.75$ million
 $\omega_{\text{reduced}} = 0.038$

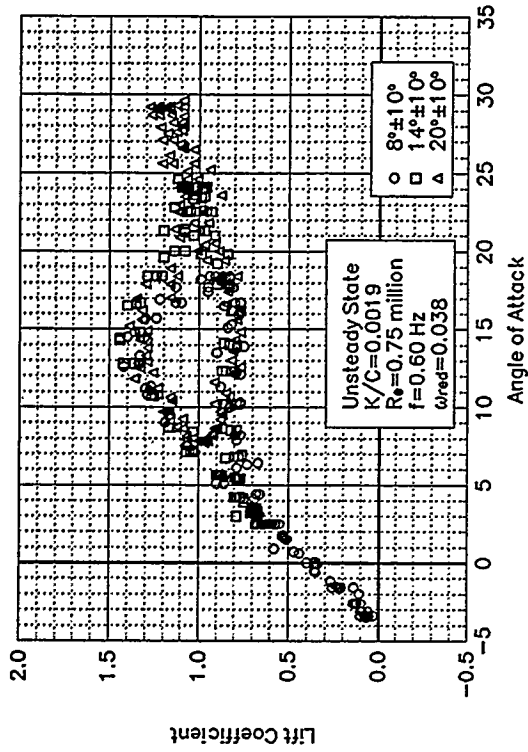


Figure C82. Lift coefficient vs α .

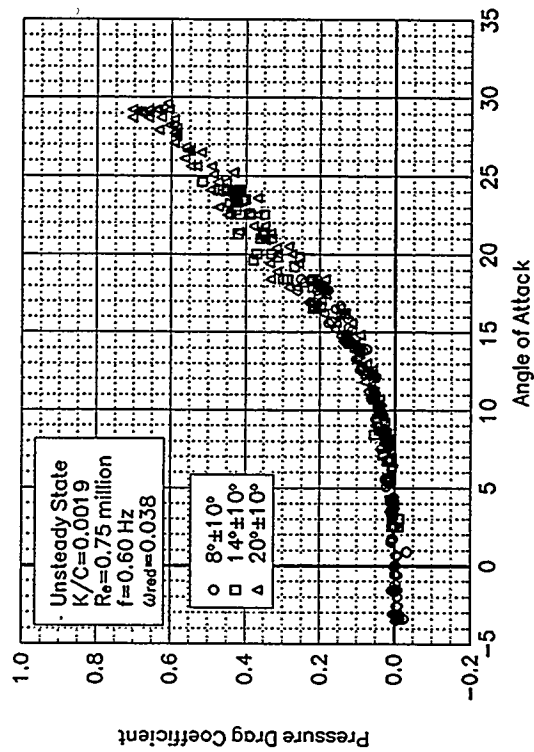


Figure C83. Pressure drag coefficient vs α .

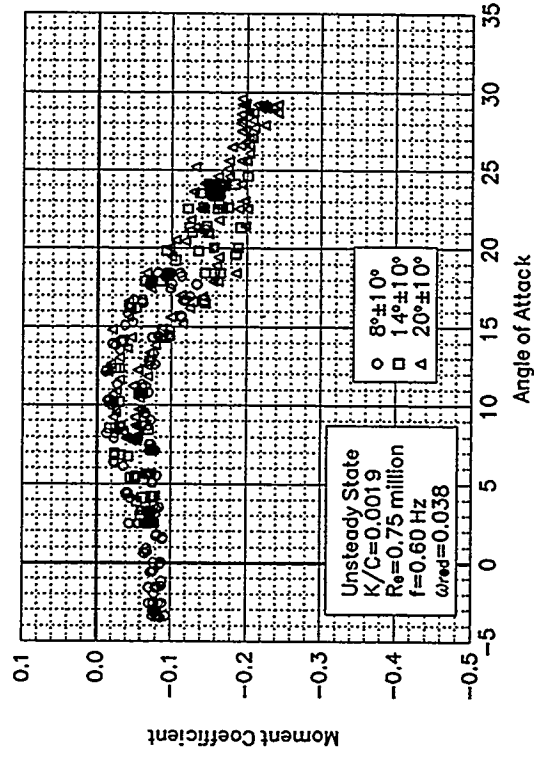


Figure C84. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 0.75$ million
 $\omega_{\text{reduced}} = 0.076$

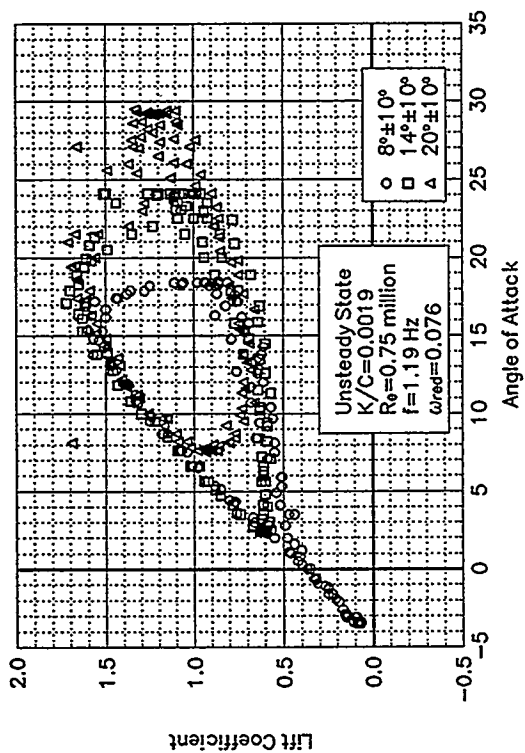


Figure C85. Lift coefficient vs α .

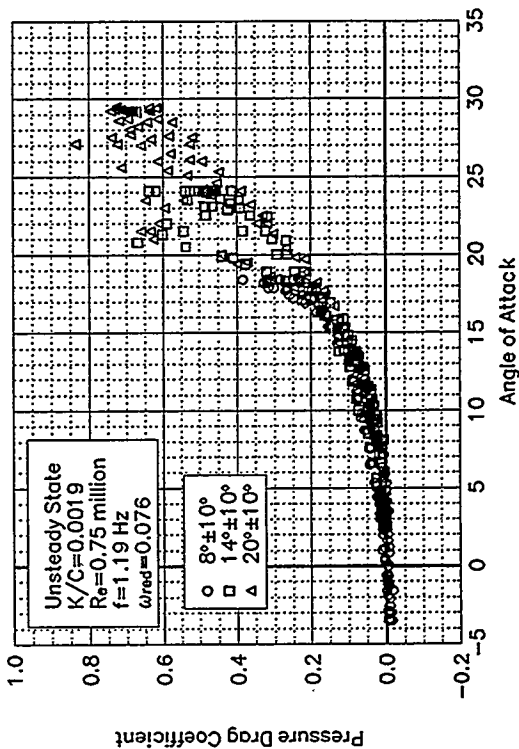


Figure C86. Pressure drag coefficient vs α .

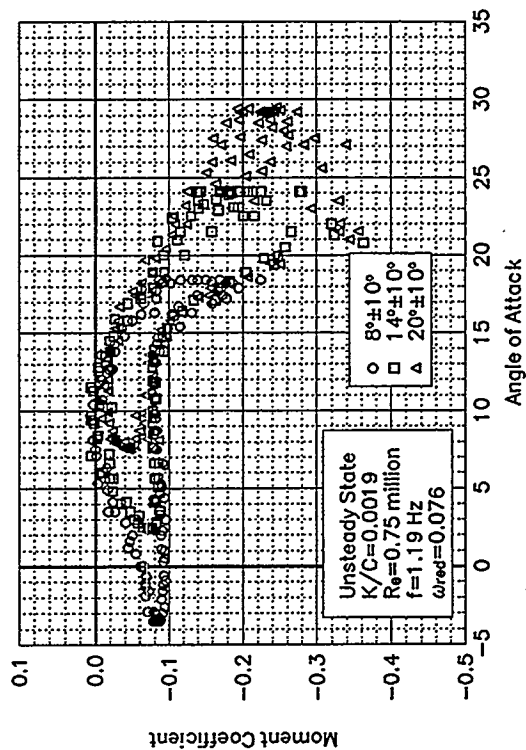


Figure C87. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 0.74$ million
 $\omega_{\text{reduced}} = 0.119$

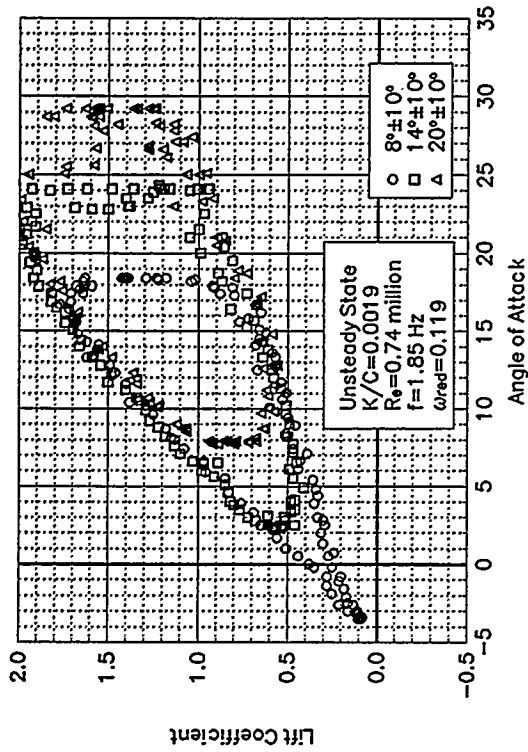


Figure C88. Lift coefficient vs α .

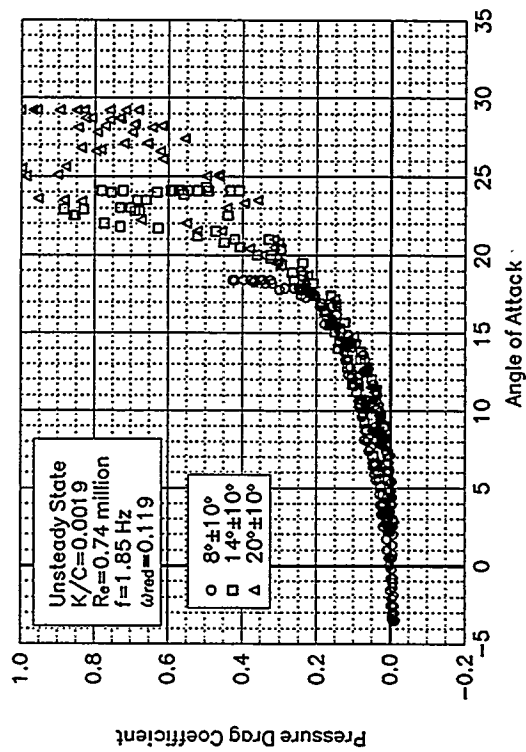


Figure C89. Pressure drag coefficient vs α .

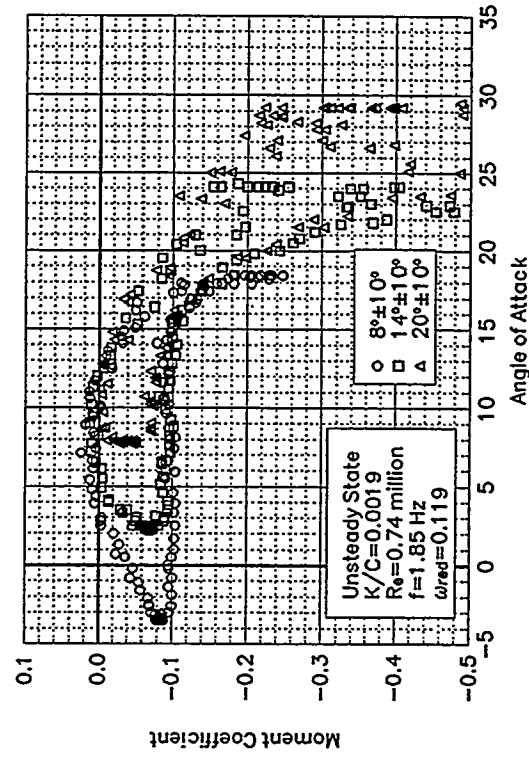


Figure C90. Moment coefficient vs α .

Unsteady Airfoil Characteristics

$\pm 10^\circ$ Sine, Re = 1 million

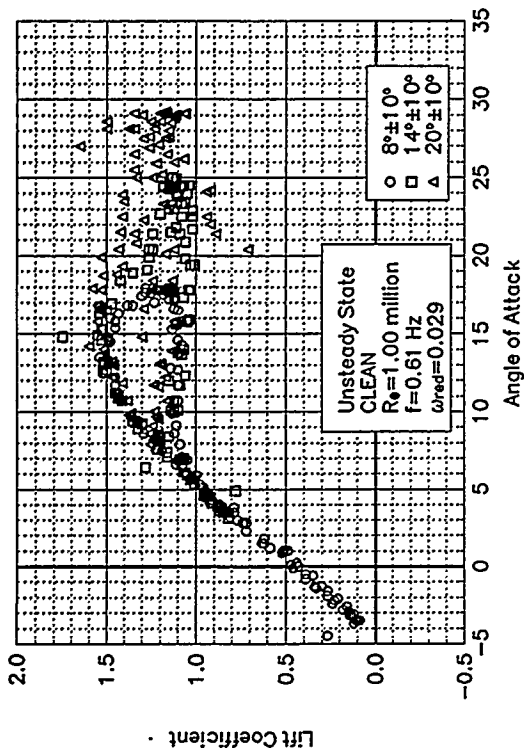


Figure C91. Lift coefficient vs α .

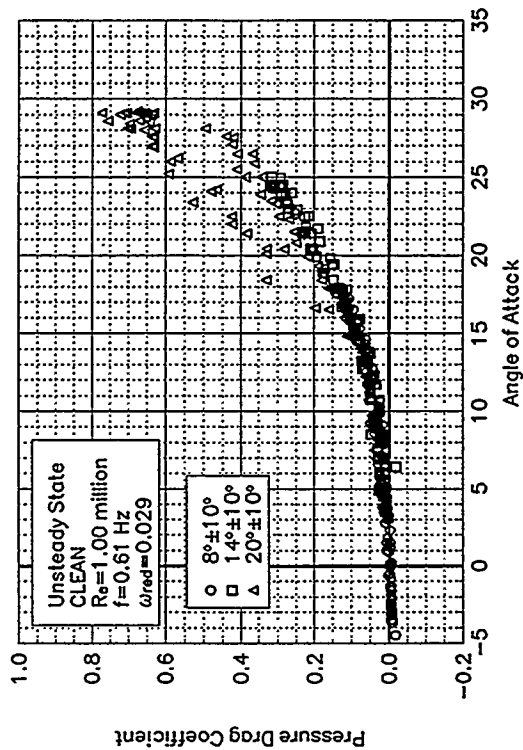


Figure C92. Pressure drag coefficient vs α .

NACA 4415
Clean
 $Re = 1.00$ million
 $\omega_{reduced} = 0.029$

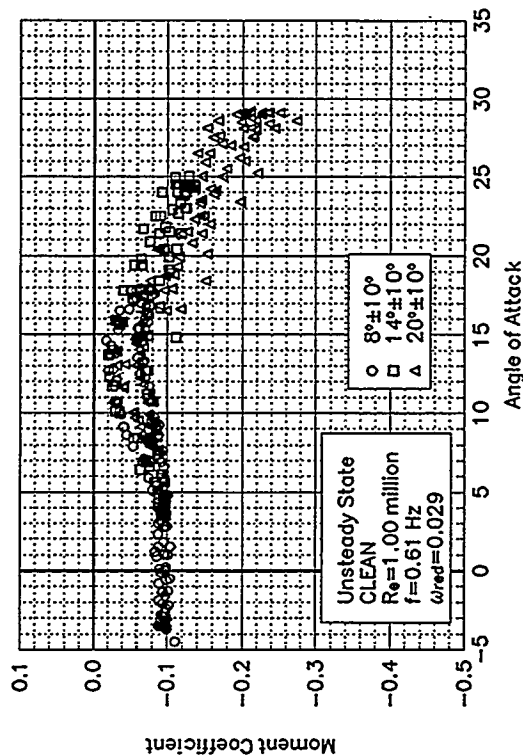


Figure C93. Moment coefficient vs α .

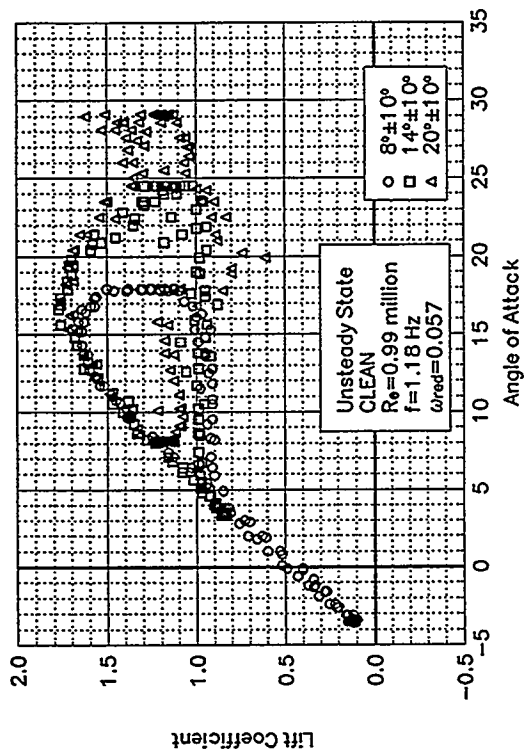


Figure C94. Lift coefficient vs α .

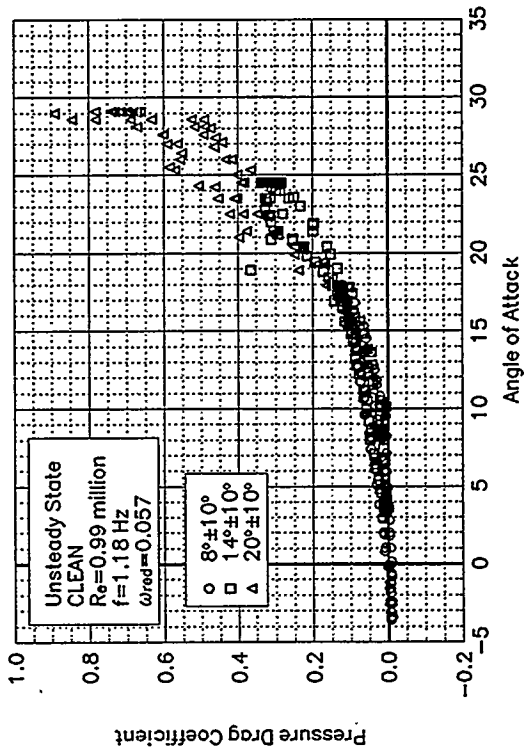


Figure C95. Pressure drag coefficient vs α .

NACA 4415
Clean
 $Re = 0.99$ million
 $\omega_{red} = 0.057$

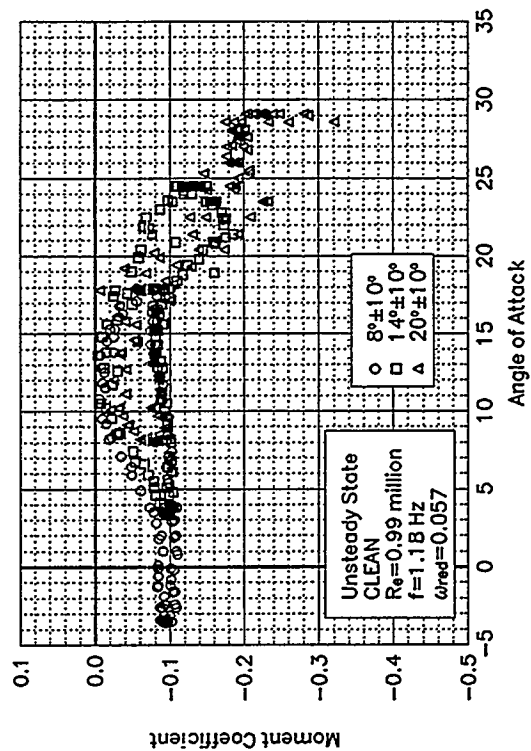


Figure C96. Moment coefficient vs α .

NACA 4415
Clean
 $Re = 0.99$ million
 $\omega_{\text{reduced}} = 0.089$

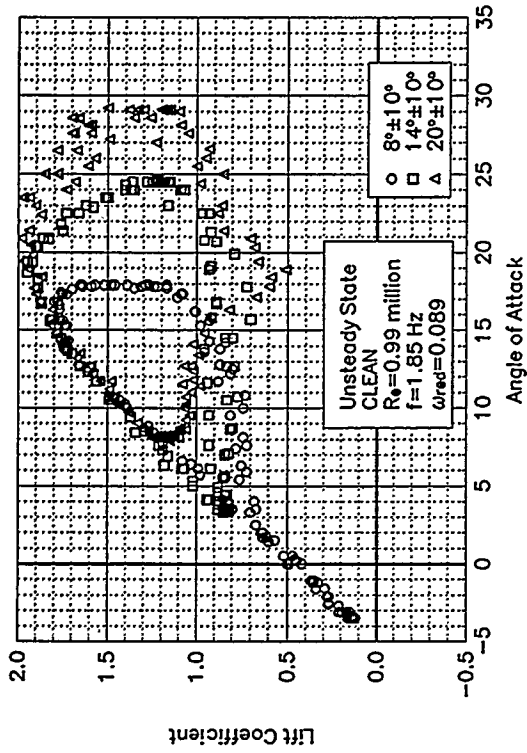


Figure C97. Lift coefficient vs α .

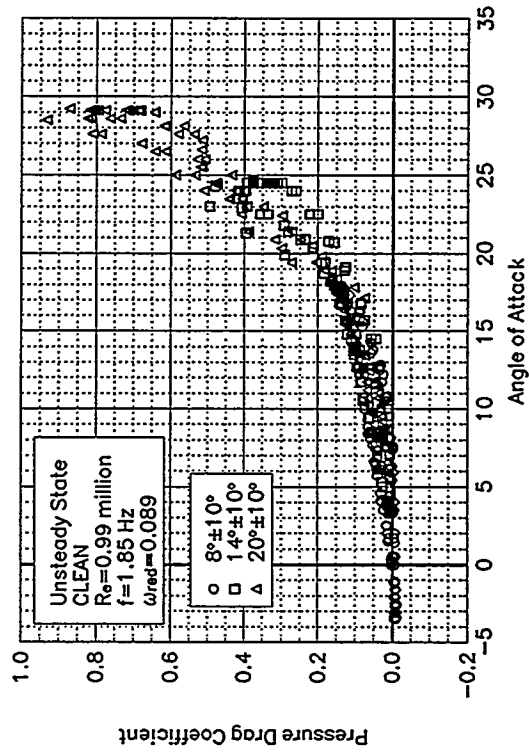


Figure C98. Pressure drag coefficient vs α .

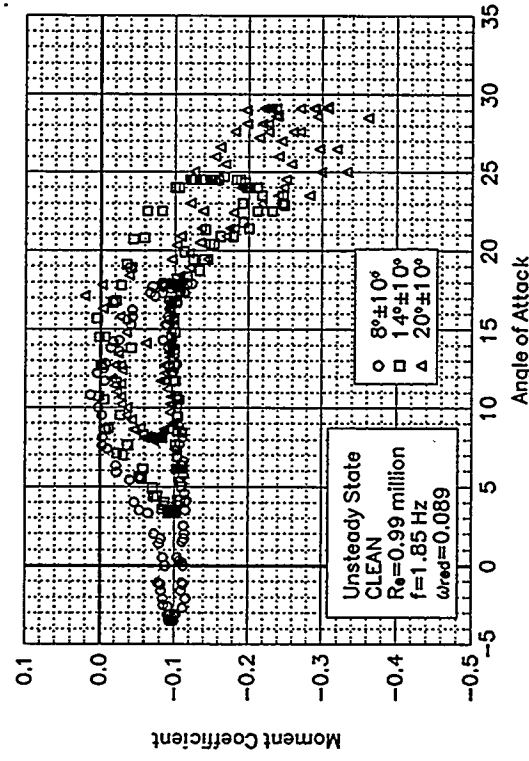


Figure C99. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 1.00 \text{ million}$
 $\omega_{\text{reduced}} = 0.028$

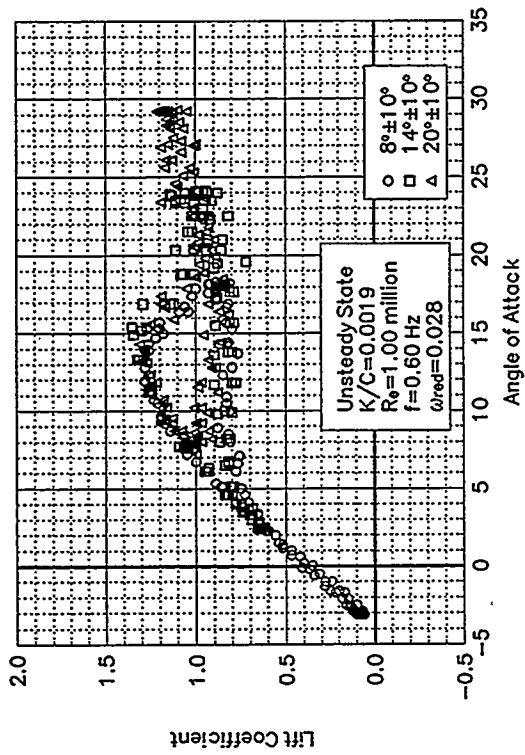


Figure C100. Lift coefficient vs α .

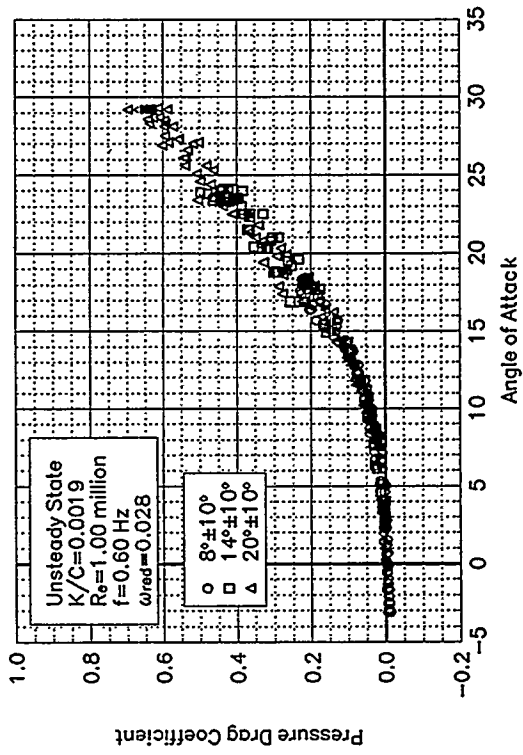


Figure C101. Pressure drag coefficient vs α .

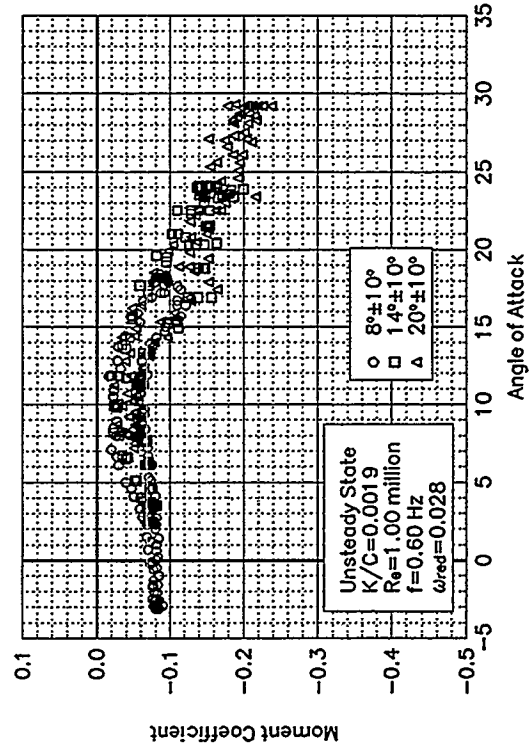


Figure C102. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 0.99 \text{ million}$
 $\omega_{\text{reduced}} = 0.058$

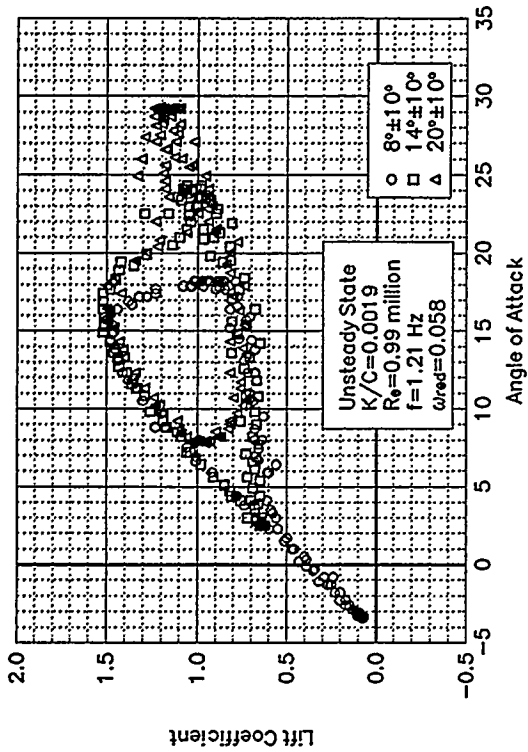


Figure C103. Lift coefficient vs α .

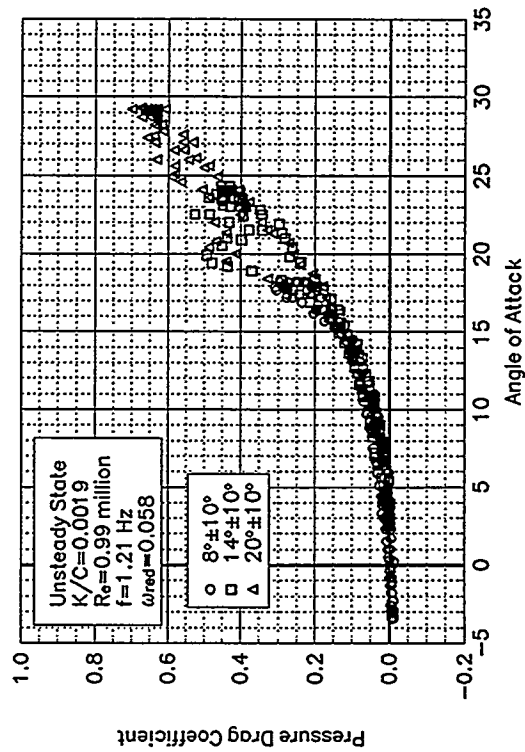


Figure C104. Pressure drag coefficient vs α .

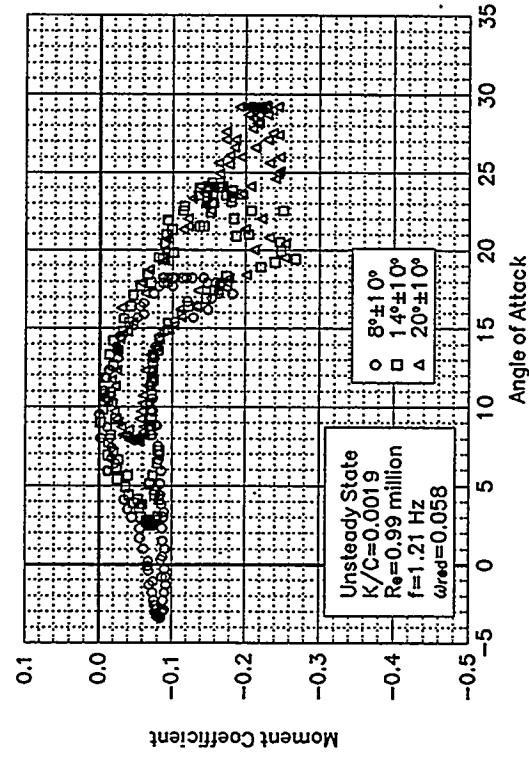


Figure C105. Moment coefficient vs α .

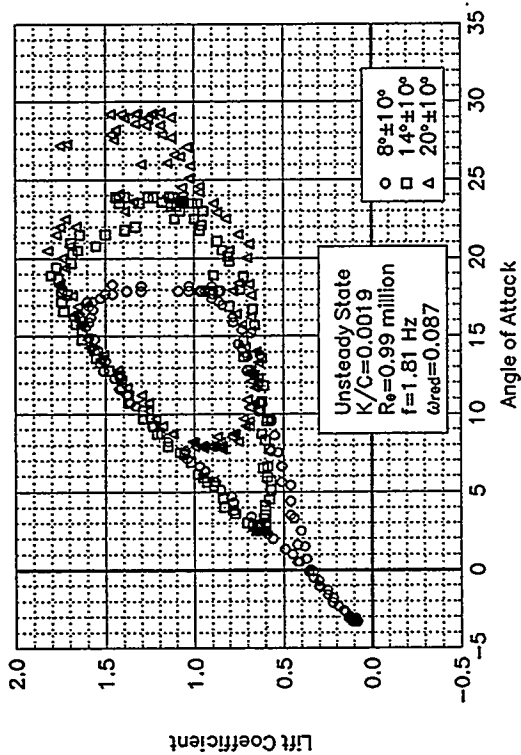


Figure C106. Lift coefficient vs α .

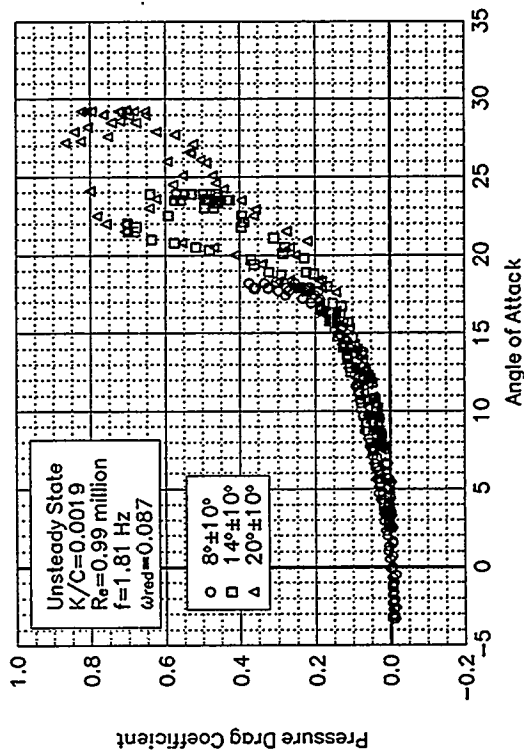


Figure C107. Pressure drag coefficient vs α .

NACA 4415
LEGR
 $Re = 0.99$ million
 $\omega_{\text{reduced}} = 0.087$

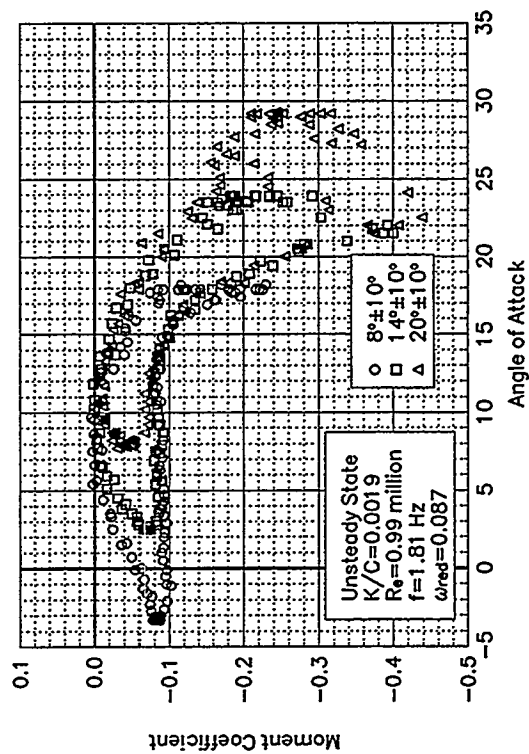


Figure C108. Moment coefficient vs α .

Unsteady Airfoil Characteristics

$\pm 10^\circ$ Sine, Re = 1.25 million

NACA 4415
Clean
 $Re = 1.24$ million
 $\omega_{\text{reduced}} = 0.023$

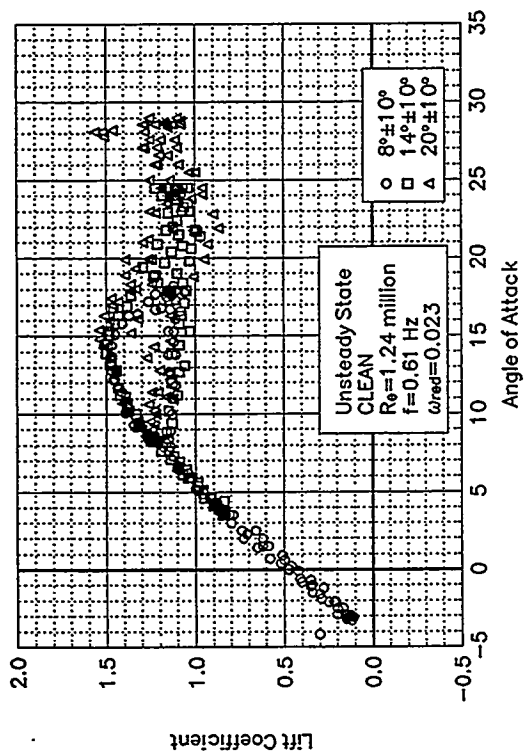


Figure C109. Lift coefficient vs α .

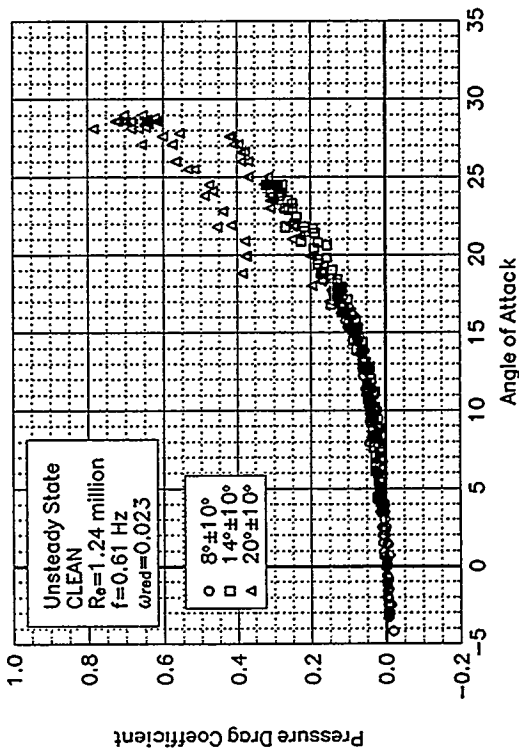


Figure C110. Pressure drag coefficient vs α .

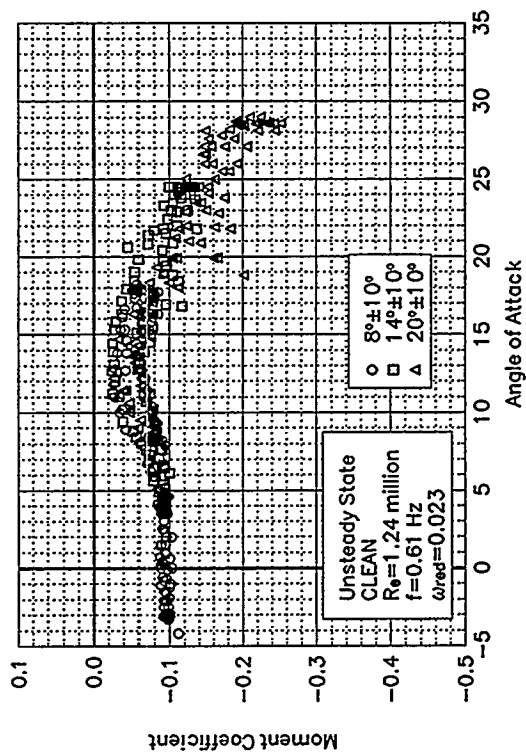


Figure C111. Moment coefficient vs α .

NACA 4415
Clean
 $Re = 1.24$ million
 $\omega_{reduced} = 0.046$

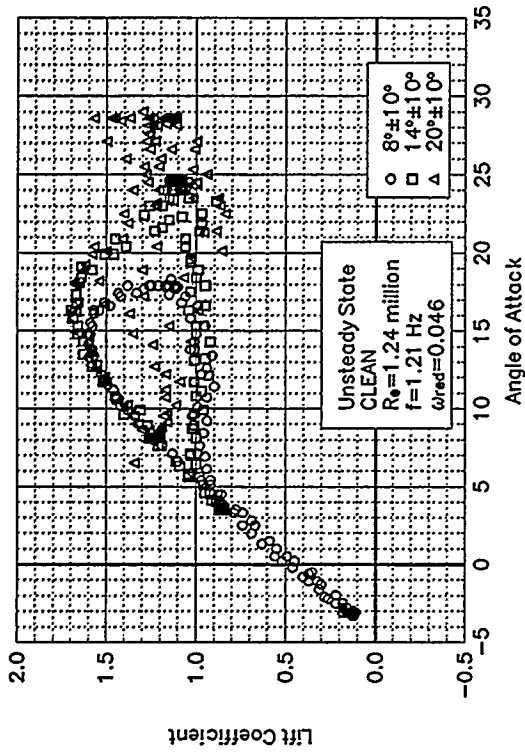


Figure C112. Lift coefficient vs α .

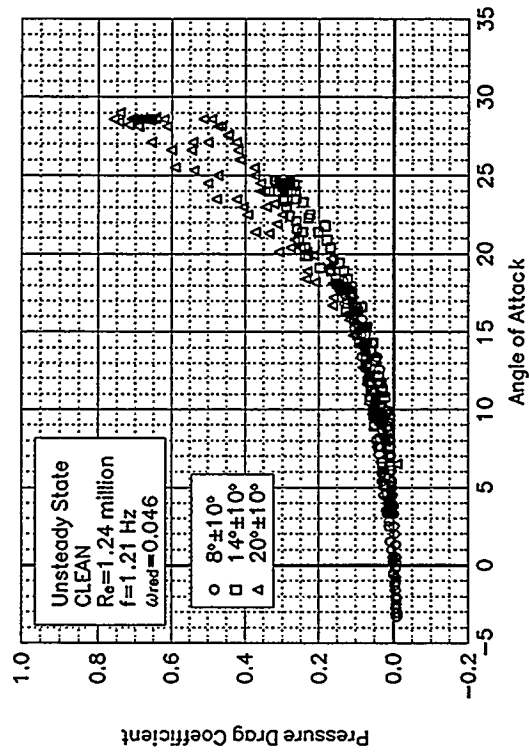


Figure C113. Pressure drag coefficient vs α .

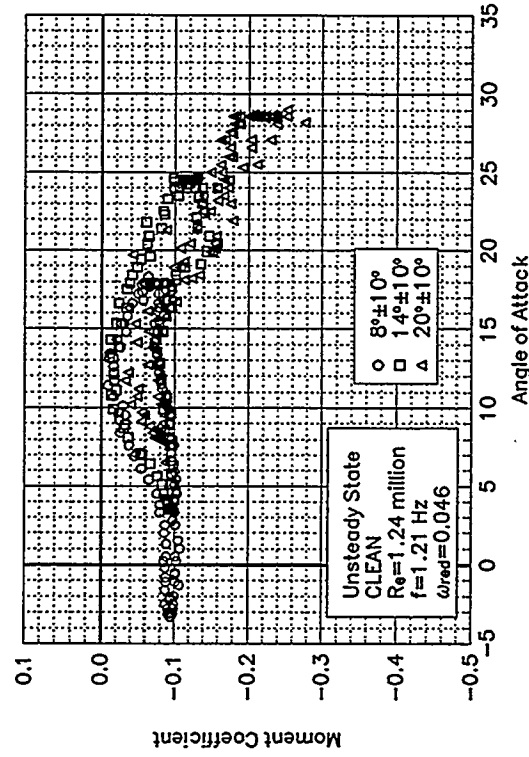


Figure C114. Moment coefficient vs α .

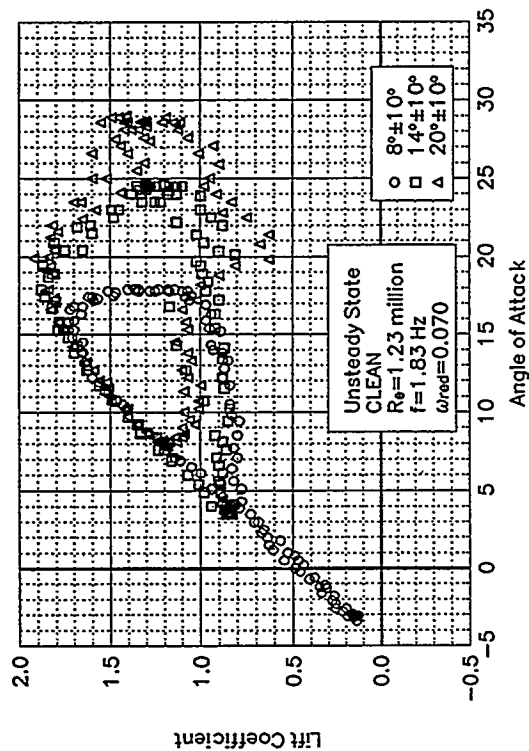


Figure C115. Lift coefficient vs α .

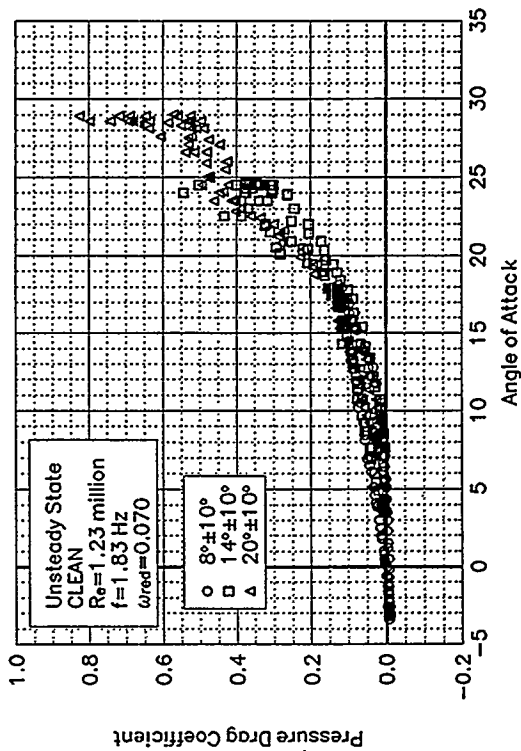


Figure C116. Pressure drag coefficient vs α .

NACA 4415
Clean
 $Re = 1.23$ million
 $\omega_{\text{reduced}} = 0.070$

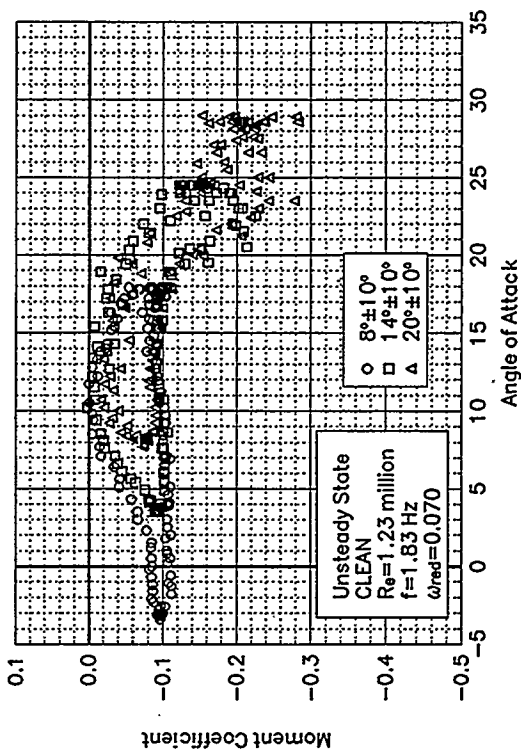


Figure C117. Moment coefficient vs α .

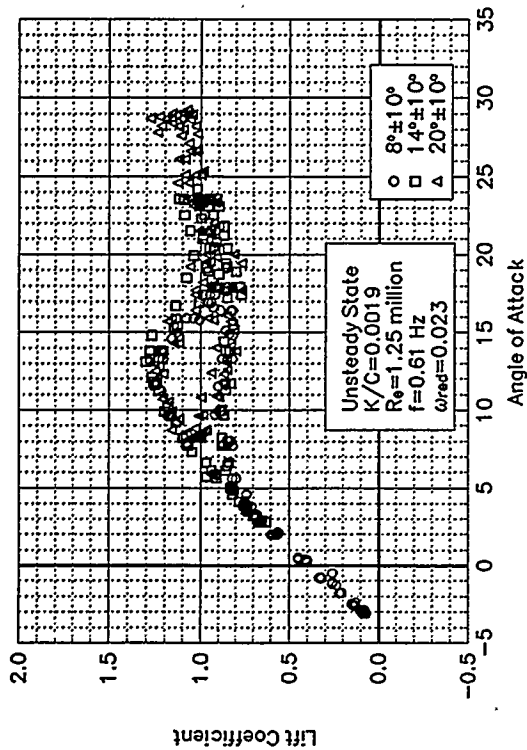


Figure C118. Lift coefficient vs α .

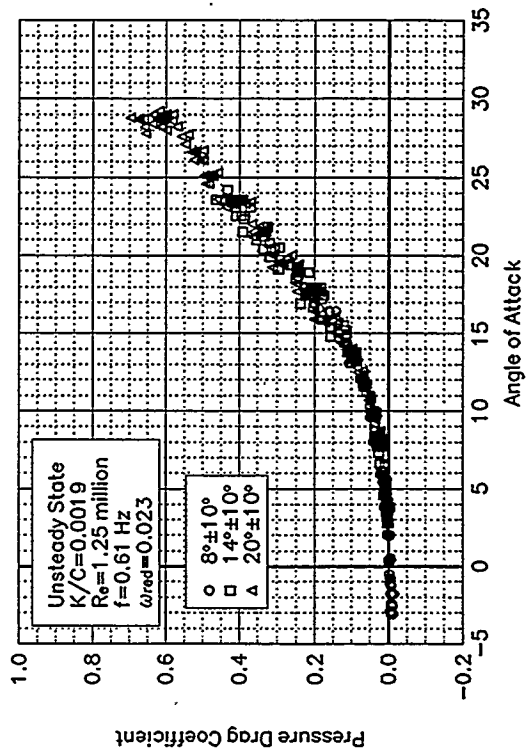


Figure C119. Pressure drag coefficient vs α .

NACA 4415
LEGR
 $Re = 1.25$ million
 $\omega_{reduced} = 0.023$

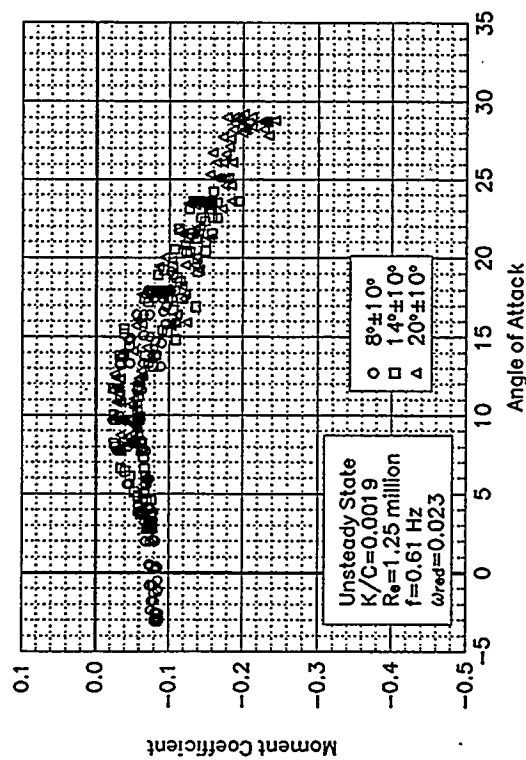


Figure C120. Moment coefficient vs α .

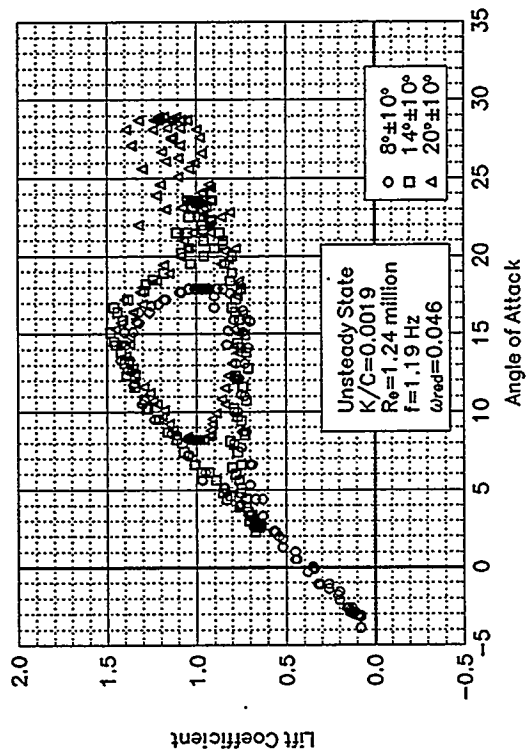


Figure C121. Lift coefficient vs α .

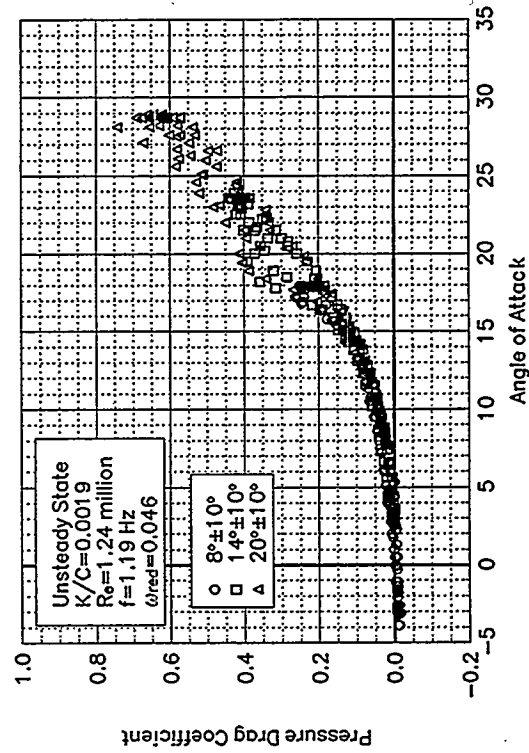


Figure C122. Pressure drag coefficient vs α .

NACA 4415
LEGR
 $Re = 1.24$ million
 $\omega_{reduced} = 0.046$

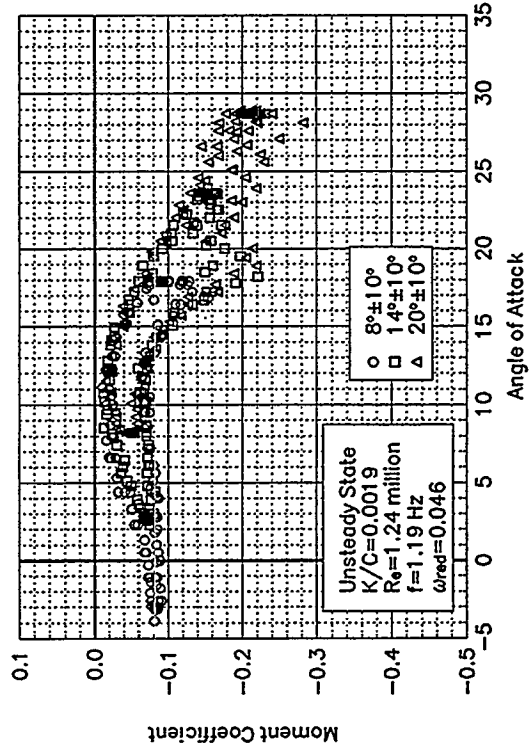


Figure C123. Moment coefficient vs α .

NACA 4415
LEGR
 $Re = 1.24$ million
 $\omega_{reduced} = 0.070$

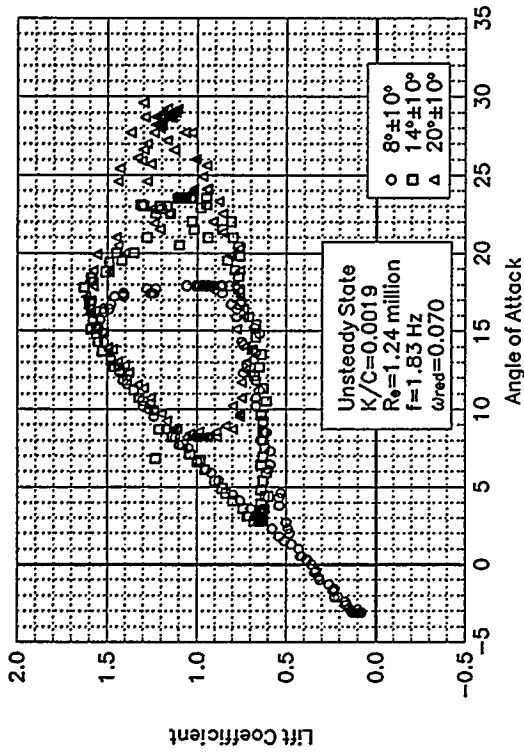


Figure C124. Lift coefficient vs α .

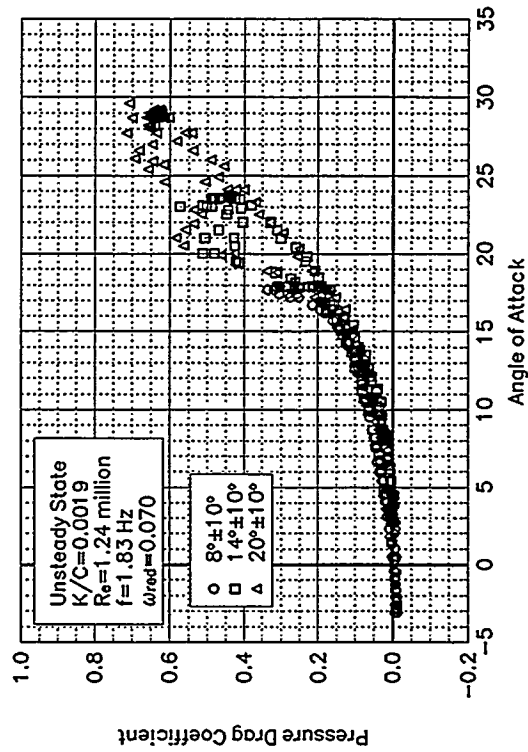


Figure C125. Pressure drag coefficient vs α .

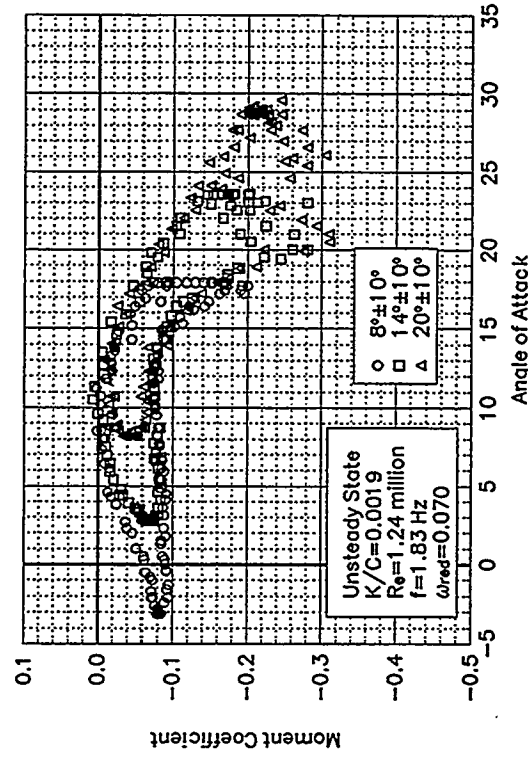


Figure C126. Moment coefficient vs α .

Unsteady Airfoil Characteristics

$\pm 10^\circ$ Sine, Re = 1.5 million

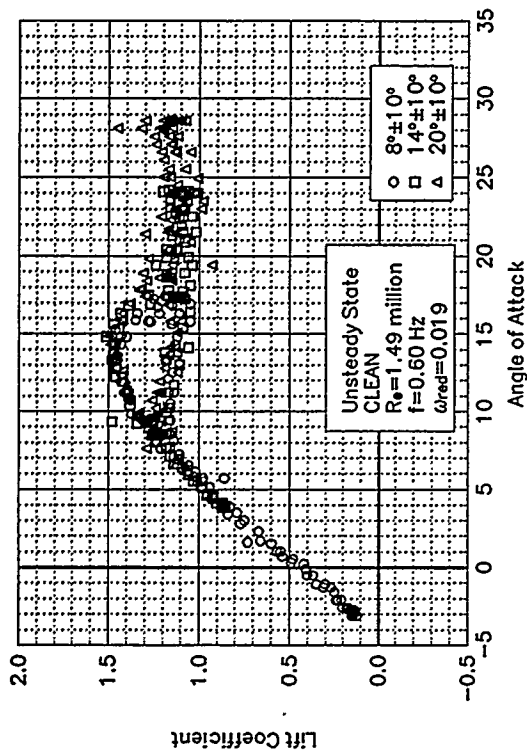


Figure C127. Lift coefficient vs α .

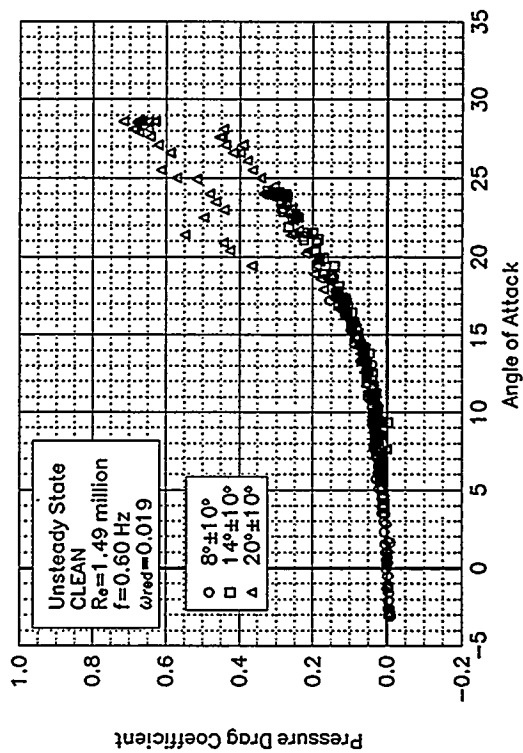


Figure C128. Pressure drag coefficient vs α .

NACA 4415
Clean
 $Re = 1.49$ million
 $\omega_{red} = 0.019$

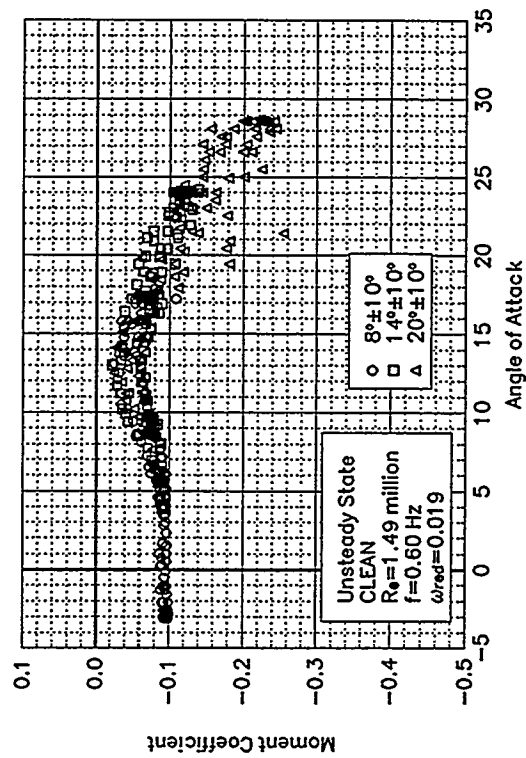


Figure C129. Moment coefficient vs α .

NACA 4415
Clean
 $Re = 1.49 \text{ million}$
 $\omega_{\text{reduced}} = 0.038$

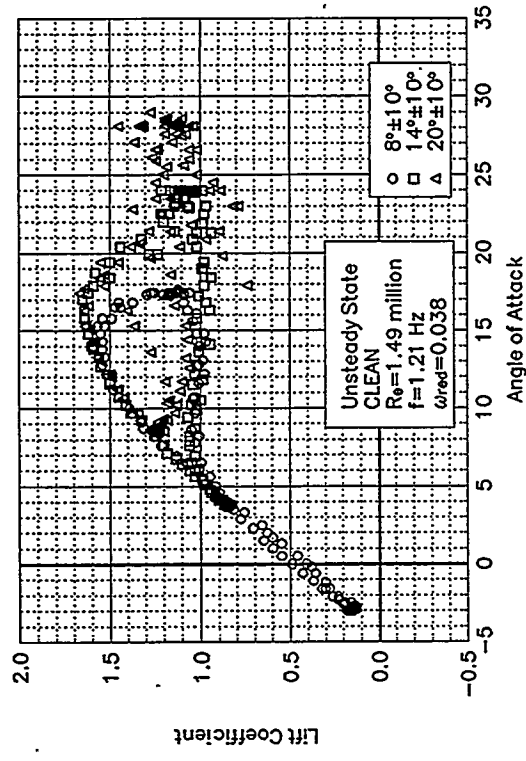


Figure C130. Lift coefficient vs α .

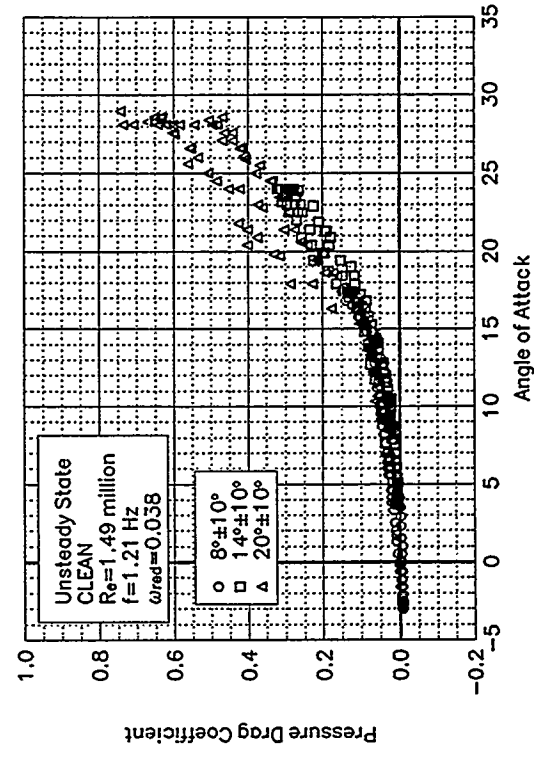


Figure C131. Pressure drag coefficient vs α .

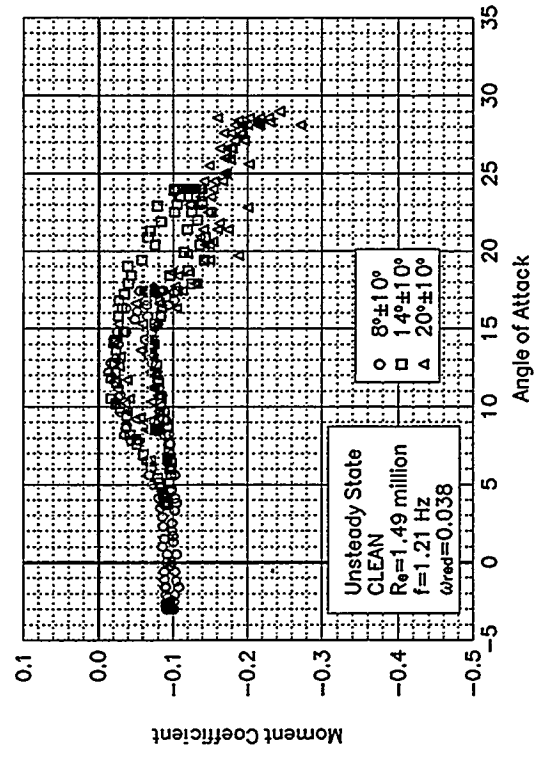


Figure C132. Moment coefficient vs α .

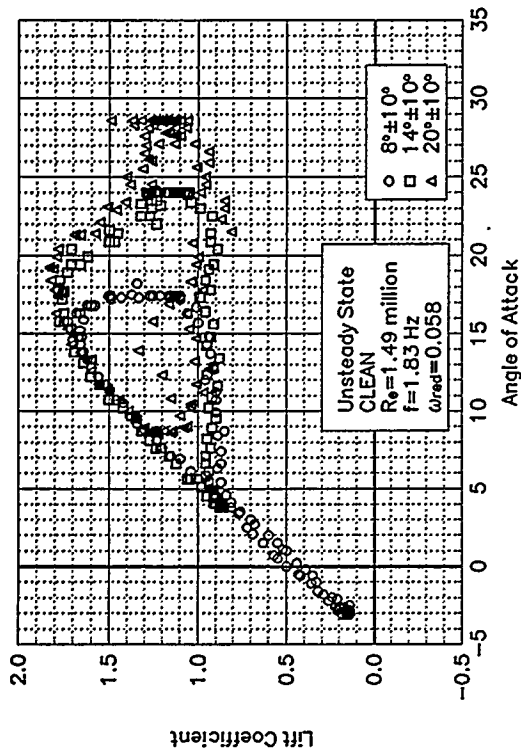


Figure C133. Lift coefficient vs α .

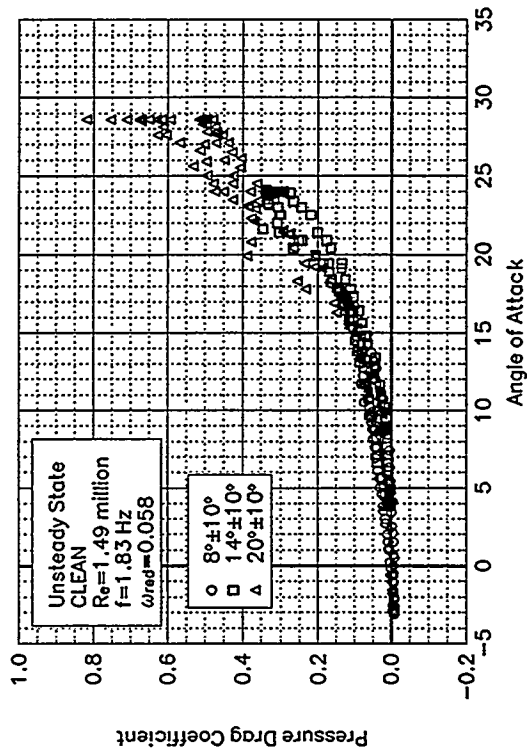


Figure C134. Pressure drag coefficient vs α .

NACA 4415
Clean
 $Re = 1.49$ million
 $\omega_{red} = 0.058$

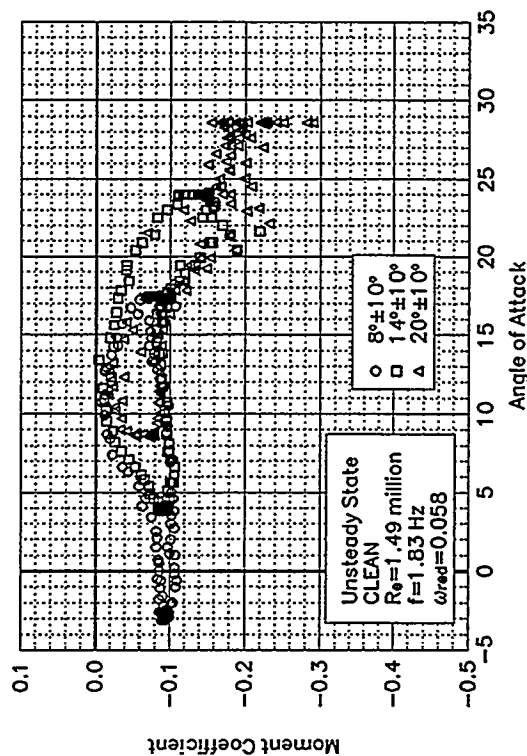


Figure C135. Moment coefficient vs α .

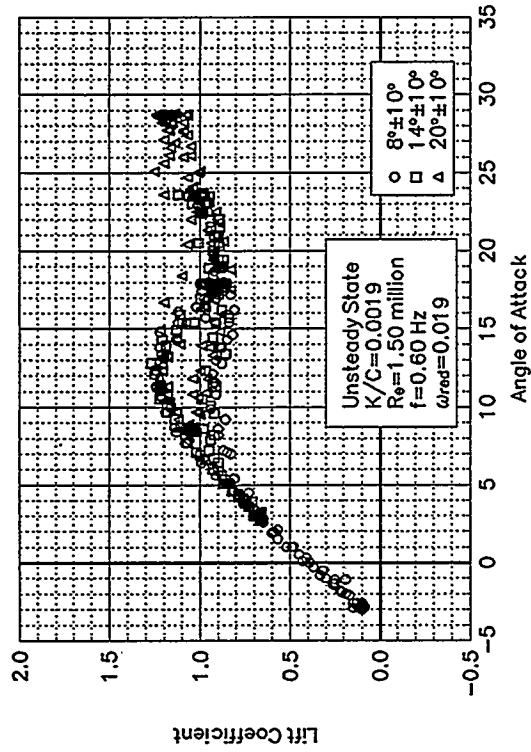


Figure C136. Lift coefficient vs α .

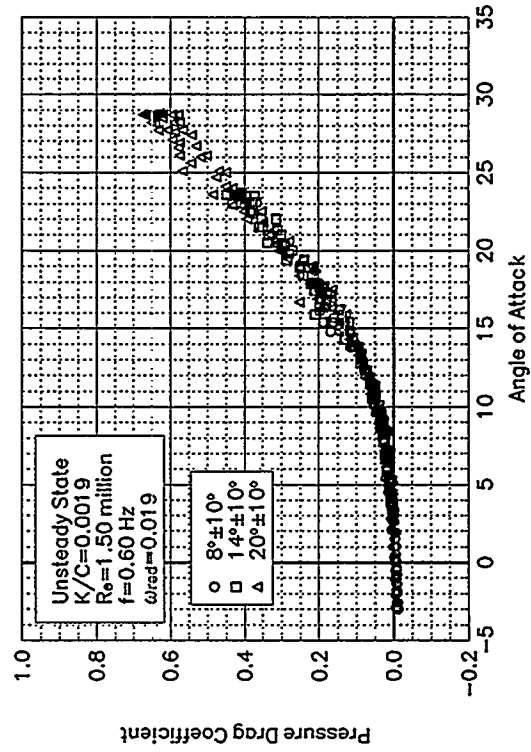


Figure C137. Pressure drag coefficient vs α .

NACA 4415
LEGR
 $Re = 1.50$ million
 $\omega_{red} = 0.019$

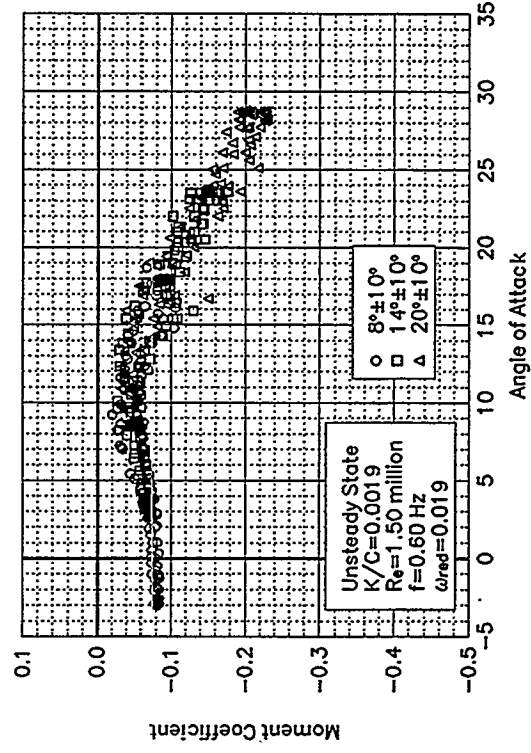


Figure C138. Moment coefficient vs α .

NACA 4415
LEGR
Re = 1.49 million
 $\omega_{\text{reduced}} = 0.037$

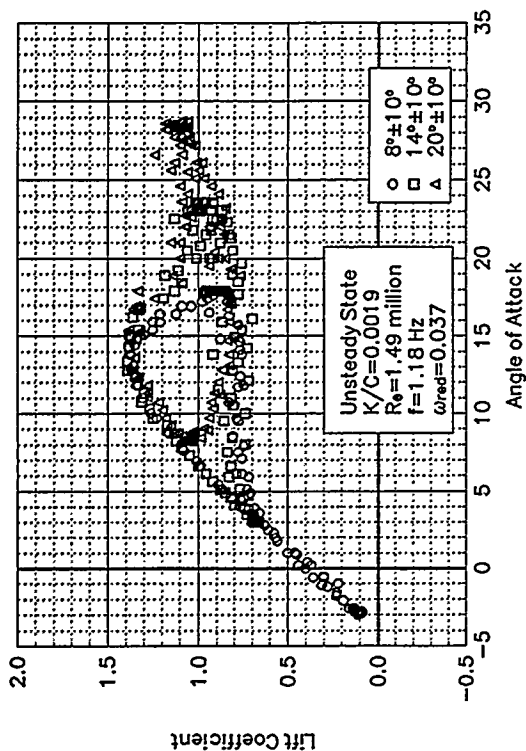


Figure C139. Lift coefficient vs α .

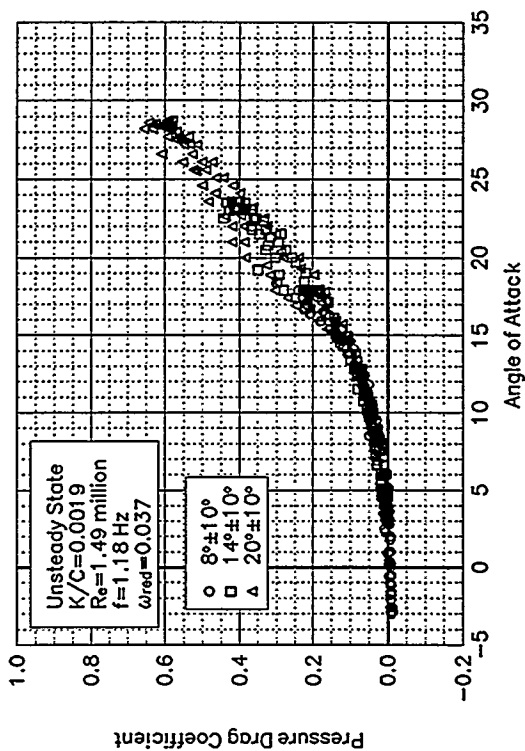


Figure C140. Pressure drag coefficient vs α .

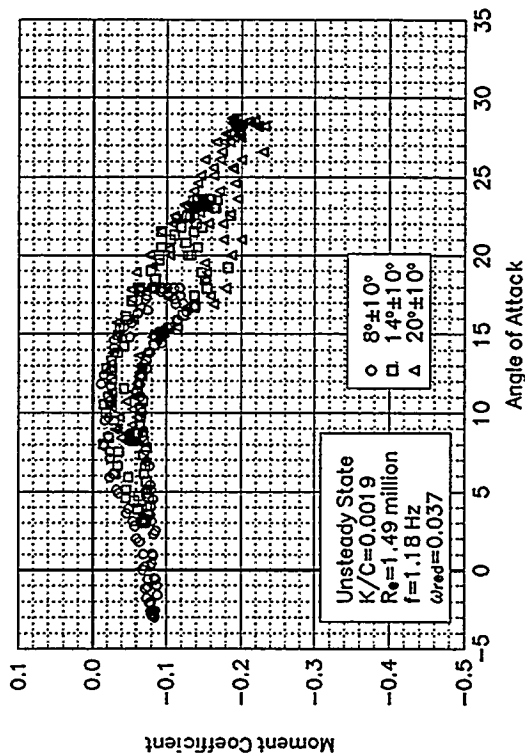


Figure C141. Moment coefficient vs α .

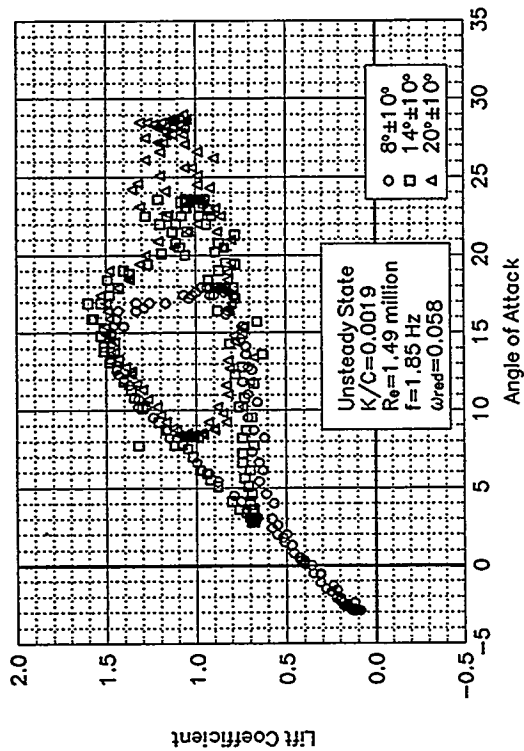


Figure C142. Lift coefficient vs α .

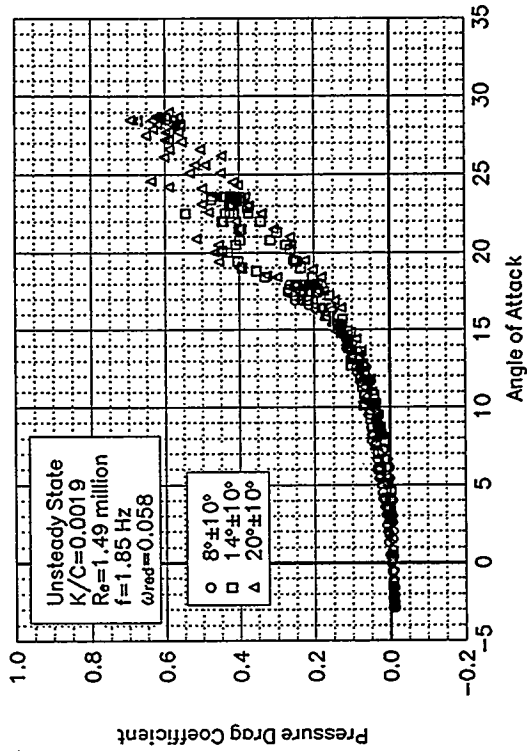


Figure C143. Pressure drag coefficient vs α .

NACA 4415
LEGR
 $Re = 1.49$ million
 $\omega_{\text{reduced}} = 0.058$

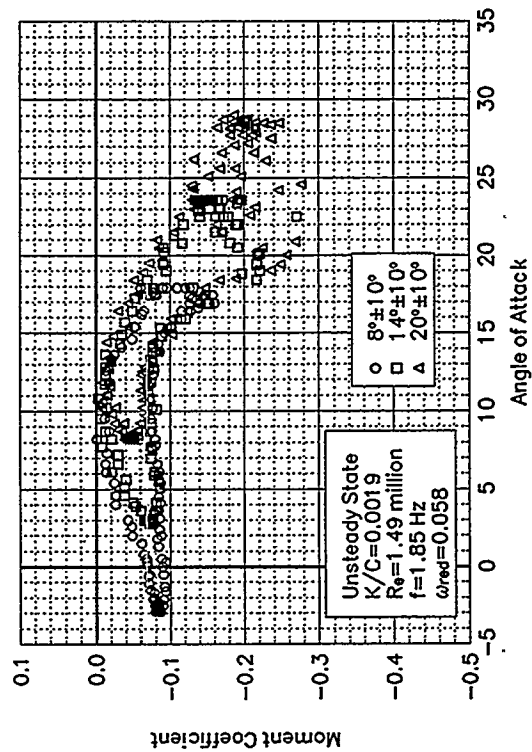


Figure C144. Moment coefficient vs α .

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words) Horizontal axis wind turbine rotors experience unsteady aerodynamics due to wind shear when the rotor is yawed, when rotor blades pass through the support tower wake, and when the wind is gusting. An understanding of this unsteady behavior is necessary to assist in the calculation of rotor performance and loads. The rotors also experience performance degradation due to surface roughness. These surface irregularities are caused by the accumulation of insect debris, ice, and the aging process. Wind tunnel studies that examine both the steady and unsteady behavior of airfoils can help define pertinent flow phenomena, and the resultant data can be used to validate analytical computer codes. A NACA 4415 airfoil model was tested in The Ohio State University Aeronautical and Astronautical Research Laboratory (OSU/AARL) 3x5 subsonic wind tunnel (3x5) under steady flow and stationary model conditions, as well as with the model undergoing pitch oscillations. To study the possible extent of performance loss due to surface roughness, a standard grit pattern (LEGR) was used to simulate leading edge contamination. After baseline cases were completed, the LEGR was applied for both steady state and model pitch oscillation cases. The Reynolds numbers for steady state conditions were 0.75, 1, 1.25, and 1.5 million, while the angle of attack ranged from -10° to +40°. With the model undergoing pitch oscillations, data were acquired at Reynolds numbers of 0.75, 1, 1.25, and 1.5 million, at frequencies of 0.6, 1.2, and 1.8 Hz. Two sine wave forcing functions were used, ±5.5° and ±10°, at mean angles of attack of 8°, 14°, and 20°. For purposes herein, any reference to unsteady conditions means the airfoil model was in pitch oscillation about the quarter chord.			
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