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Effects of Grit Roughness and Pitch Oscillations on the S812 Airfoil

Airfoil Performance Report, Revised (12/99)

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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 turbine operating in yawed, stall or turbulent conditions. Little dynamic stall data exists for the airfoils of interest to a wind turbine designer. In summary, very little airfoil performance data exits 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 included 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 which have been or will be used for horizontal axis wind turbines. The purpose is to investigate the effect of pitch oscillations and leading edge grit roughness 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 which account for unsteady behavior and also aid in the design of new airfoils for wind turbines. The application of leading edge grit roughness (LEGR) simulates surface irregularities that occur on wind turbines. These irregularities on the blades are due to the accumulation of insect debris, ice, and/or the aging process and can significantly reduce the output of the horizontal axis wind turbines. The experimental results from the application of leading edge grit roughness will help develop airfoils that are less sensitive to roughness.

The present work was made possible by the efforts and financial support of the National Renewable Energy Laboratory who provided major funding and technical monitoring. The staff of The Ohio State University Aeronautical and Astronautical Research Laboratory appreciate the contributions made by personnel from that organization. In addition, the authors would like to recognize the efforts of the following graduate and undergraduate student research assistants, Jolanta M. Janiszewska, Fernando Falasca, and Mònica Angelats i Coll.

Summary

A NREL S812 airfoil model was tested in The Ohio State University Aeronautical and Astronautical Research Laboratory 3×5 subsonic wind tunnel under steady state and unsteady conditions. The test defined baseline conditions for steady state angles of attack from -20° to +40° and examined unsteady behavior by oscillating the model about its quarter chord pitch axis for three mean angles, three frequencies, and two amplitudes. For all oscillating cases, Reynolds numbers of 0.75, 1, 1.25 and 1.5 million were used. In addition, the above conditions were repeated after the application of leading edge grit roughness (LEGR) to determine contamination effects on the airfoil performance.

Typical steady state results of the S812 testing showed a baseline maximum lift coefficient of 1.12 at 16.2° angle of attack for 1 million Reynolds number. The application of LEGR reduced the maximum lift coefficient by 13% and increased the 0.0073 minimum drag coefficient value by over 91%. The zero lift pitching moment coefficient of -0.0607 showed a 28% reduction in magnitude to -0.0435 with LEGR applied.

Data were also obtained for two pitch oscillation amplitudes, ±5.5° and ±10°. The larger amplitude consistently gave a higher maximum lift coefficient than the smaller amplitude and both sets of 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, the hysteresis behavior persisted into lower angles of attack than with the clean case.

In general, the unsteady maximum lift coefficient was up to 92% higher than the steady state maximum lift coefficient, and variation in the quarter chord pitching moment coefficient magnitude was from 16% to over 350% larger than the steady state values at high angles of attack. These findings indicate the importance of considering the unsteady flow behavior occurring in wind turbine operation because use of steady values could result in inaccurate loads.

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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 (0.305 used)
π	3.1416
σ	Tunnel solid wall correction parameter
ω_{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 design of new rotor airfoils. The rotors also experience performance degradation due to surface roughness. These surface irregularities are due to 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 also be used to validate analytical computer codes.

A NREL S812 airfoil model was tested in The Ohio State University Aeronautical and Astronautical Research Laboratory (OSU/AARL) 3×5 subsonic wind tunnel (3×5) under steady flow with stationary model conditions, and 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 -20° to +40°. While the model underwent pitch oscillations, data was 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 model was in pitch oscillation.

Experimental Facility

Wind Tunnel

The OSU/AARL 3×5 was used to conduct tests on the S812 airfoil section. Schematics of the top and side views of the tunnel are shown in Figure 1 and Figure 2. 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. 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. A steel tube through the quarter chord of the model was used to attach 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.

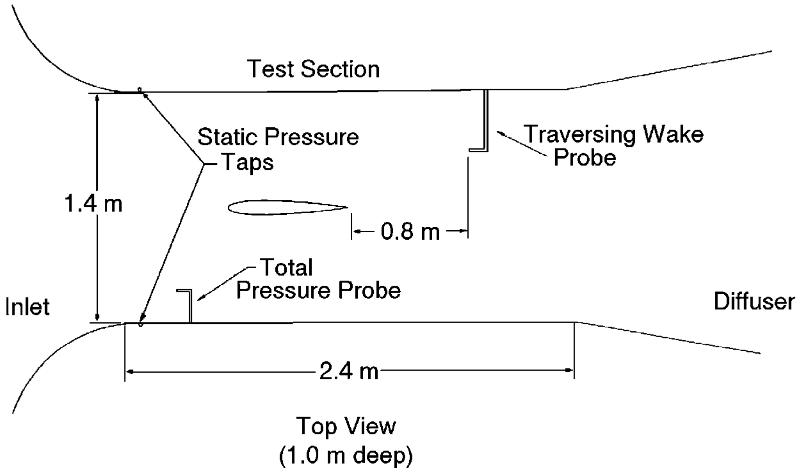

Figure 1. 3×5 subsonic wind tunnel, top view.

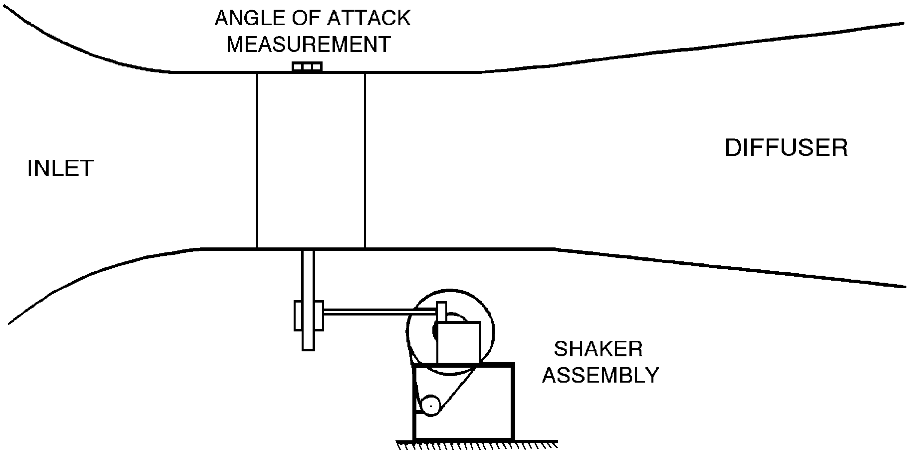

Figure 2. 3×5 subsonic wind tunnel, side view.

Oscillation System

Portions of the testing required the use of a reliable model 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, Figure 3. The choice of cam governed the type and amplitude of the wave form produced. Sine wave forms having amplitudes of ±5.5° and ±10° 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 a.c. motor with a 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.

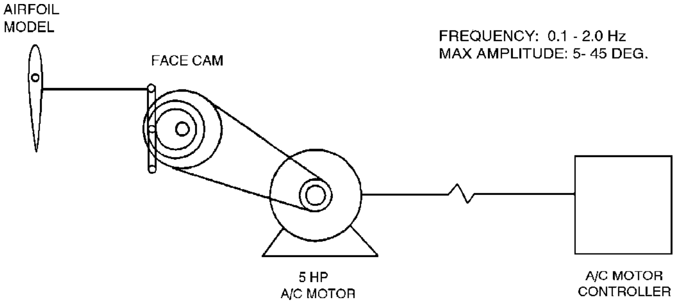

Figure 3. 3×5 wind tunnel oscillation system.

Model Details

A 457-mm (18-in) constant chord S812 airfoil model was designed and manufactured for the 3x5 wind tunnel test program. Figure 4 shows the airfoil section (Tangler, 1995). The model coordinates are not presented in tabular form, since they are proprietary to NREL. The model trailing edge was thickened to 1.25-mm (0.05-in) for fabrication purposes. The model was made of a nine layer composite lay up of alternating fiberglass and carbon fiber over ribs. The main load 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 filled, painted and wet sanded to attain given coordinates within a requested tolerance of ±0.25 mm (±0.01 inches). The completed model was measured at three spanwise locations using a Sheffield-Cordax coordinate measurement machine. Measurements were made in English units and later converted to metric. Figure 5 shows the results of comparing measured-to-desired coordinates by calculating differences normal to the profiled surface at three stations on the model. The "spikes" showing near the trailing edge and at the leading edge are due to the numerical methods and are not real. Although a small portion of the model lower surface near the leading edge was not within tolerance, this model was accepted because the discrepancy was small and over a narrow range.

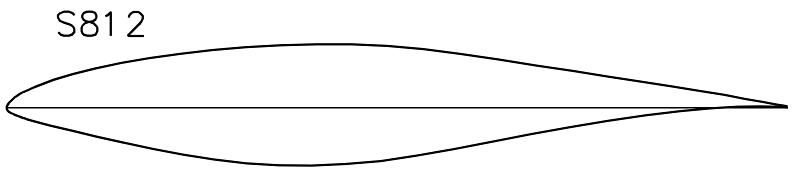

Figure 4. S812 airfoil section.

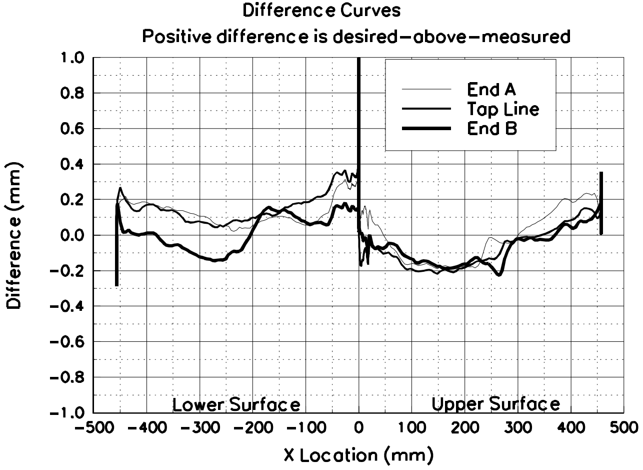

Figure 5. Measured-to-desired model coordinates difference curves.

To minimize pressure response times, which is important for the unsteady testing, the lengths of surface pressure tap lead-out lines had to be as short as possible. Consequently, a compartment was built into the model and the pressure scanning modules were 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 roughness pattern developed for the National Renewable Energy Laboratory airfoil test program was employed. The pattern was generated using a molded insect pattern taken from a wind turbine in the field. 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 grain 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.

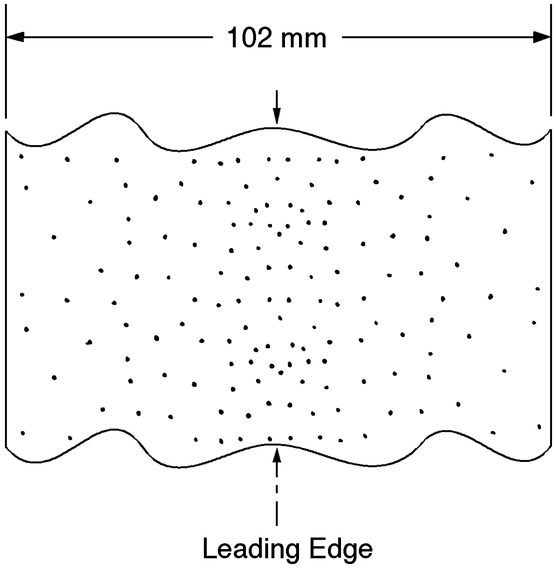

Figure 6. Roughness pattern.

To use the template, 102-mm (4-in) wide double-sided 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 allows 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 shows the schematic of the data acquisition system.

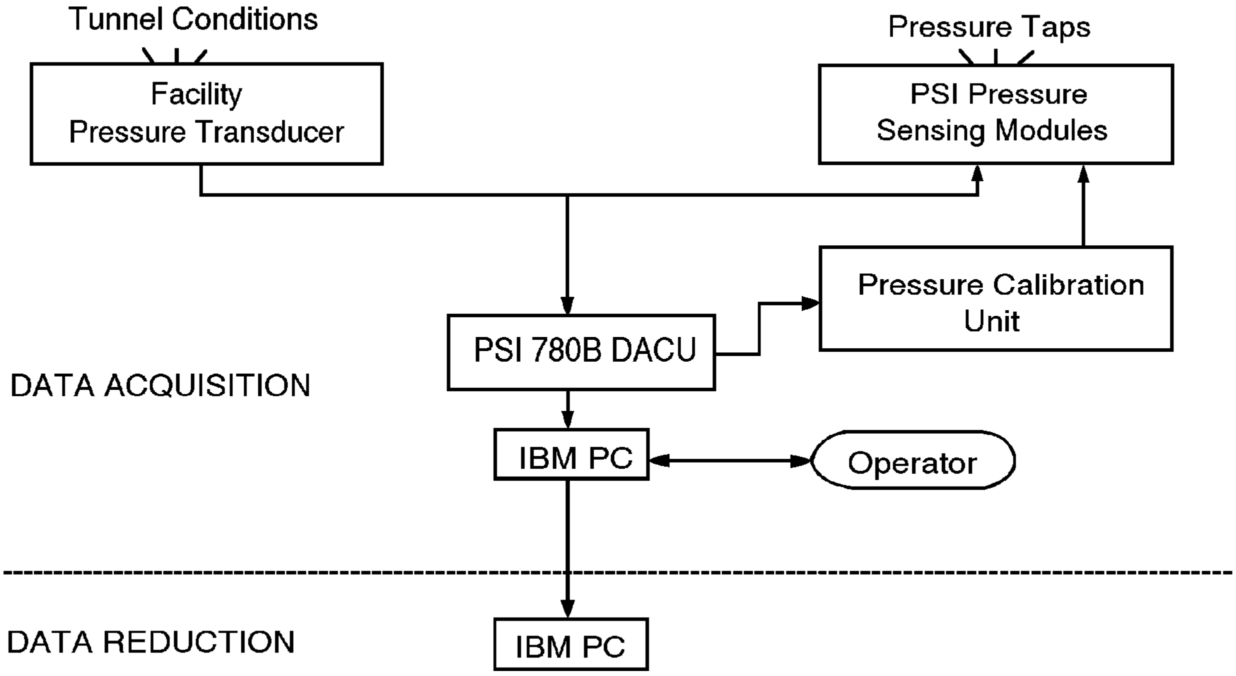

Figure 7. Data acquisition schematic.

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 ±0.25° 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 by 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 was set to an angle of attack and the tunnel conditions 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 0° to -20° then from 0° to +40°.

For model oscillating cases, the tunnel conditions were set while the model was stationary at the desired mean angle of attack. The "shaker" was started, the model was allowed to oscillate through at least five cycles to establish the flow field, and then 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 insure 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, as well as 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 data 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 coefficient (C_p, C_l, $C_{m\frac{1}{4}}$, and C_{dp}) using the measured surface pressure voltages, calibration coefficients, tap locations and wind tunnel conditions. Then, all scan sets for a given condition were ensemble averaged to provide one data set and that data set was then corrected for the effects of solid tunnel walls. All data was 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 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

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

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

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

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

Model wake data were taken for steady state cases when the wake could be completely traversed. Pressures were acquired from a pitot-static probe which 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. There was no calibration available 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; thereby giving near 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 $-20° < \alpha < +10°$ or $+20° < \alpha < +40°$ and one degree when $+10° < \alpha < +20°$. Wake surveys were conducted to find total airfoil drag over an approximate angle of attack range of -10° to +10°. Unsteady data were taken for Reynolds numbers of 0.75, 1, 1.25, and 1.5 million. Sine wave cams having amplitudes ±5.5° and ±10° 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 Hz, 1.2 Hz and 1.8 Hz. All data points for the unsteady cases were acquired for both clean and LEGR cases.

Results and Discussion

An S812 airfoil model was tested under steady state and pitch oscillation conditions. A brief discussion of the results follows, including a comparison of experimental data and computational predictions, steady state results, and unsteady results.

Comparison With Theory

The wind tunnel steady state data were compared with the 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 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, shows adequate agreement for angles of attack from -2° to +6°. The pressure distributions shown in Figure 10 and Figure 11 are for angles of attack of 0.1° and 6.1°, respectively, and include clean wind tunnel data as compared to computed free transition pressure

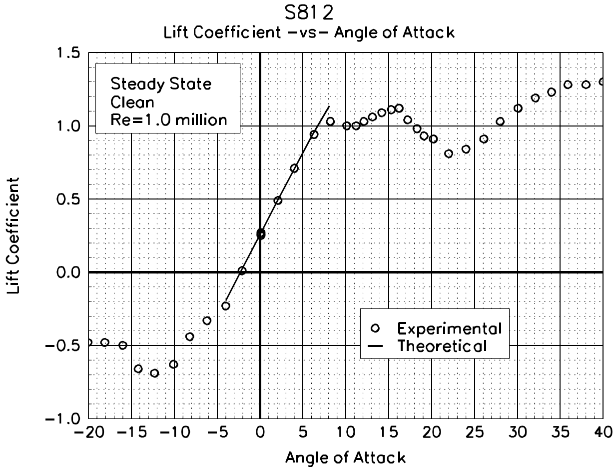

Figure 8. Comparison with theory, C_l vs α.

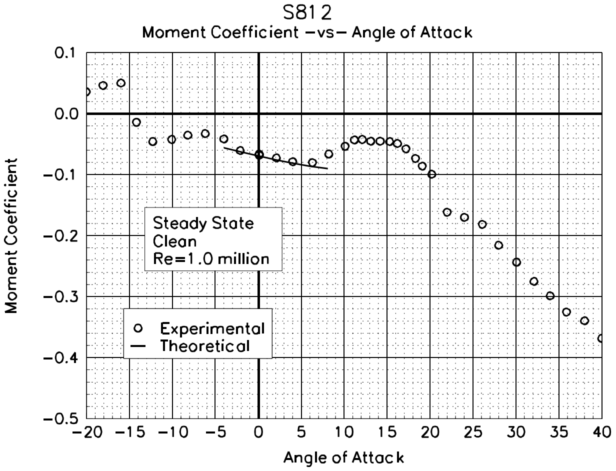

Figure 9. Comparison with theory, C_m vs α.

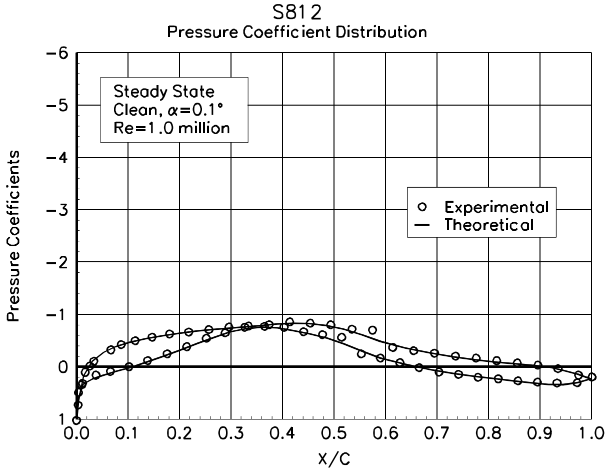

Figure 10. Comparison with theory, C_p vs x/c, α=0.1°.

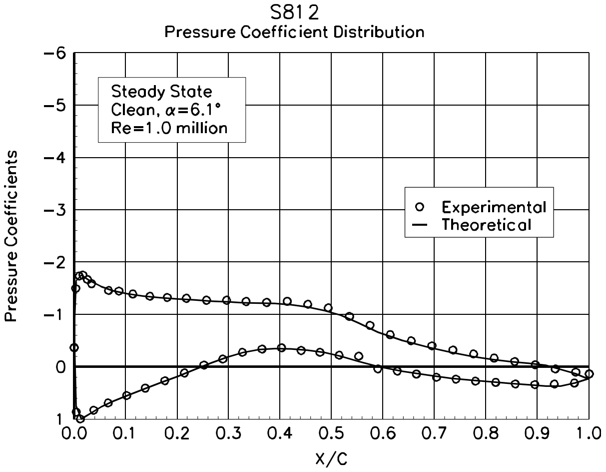

Figure 11. Comparison with theory, C_p vs x/c, α=6.3°.

distributions. For both angles of attack, there is excellent correlation between the experimental and predicted values.

Steady State Data

The S812 airfoil model was tested at four Reynolds numbers at nominal angles of attack from -20° to +40°. Figure 12 and Figure 13 show lift coefficients for all the test Reynolds numbers both for model clean and with LEGR applied, respectively. The maximum positive lift coefficient, found at 1.5 million Reynolds number, for the clean cases is 1.13 and 0.98 for the LEGR cases, a 13% reduction. The clean cases have a positive stall at 15.2° while the LEGR cases stall at 14.2° angle of attack. The clean data show an initial break in the lift curve at 8°, a short recovery, then C_{lmax} is achieved. The LEGR data show a similar trend but the break in the lift curve is not as severe. The average lift curve slope through 0° angle of attack for clean data is about 0.114 and about 0.098 for the LEGR case. The associated average lift coefficients at zero angle of attack are for the clean case 0.26 and 0.19 for the LEGR case.

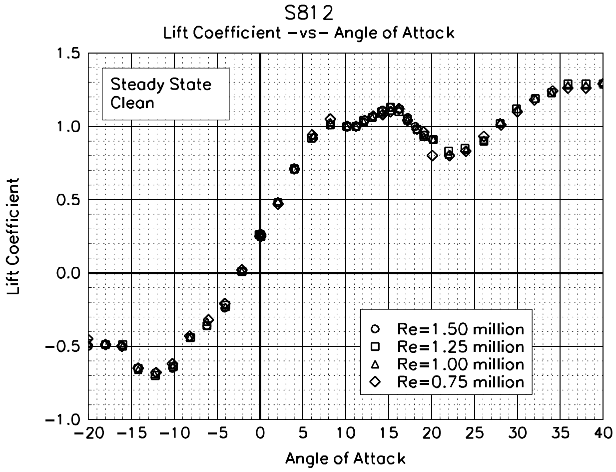

Figure 12. C_l vs α, clean.

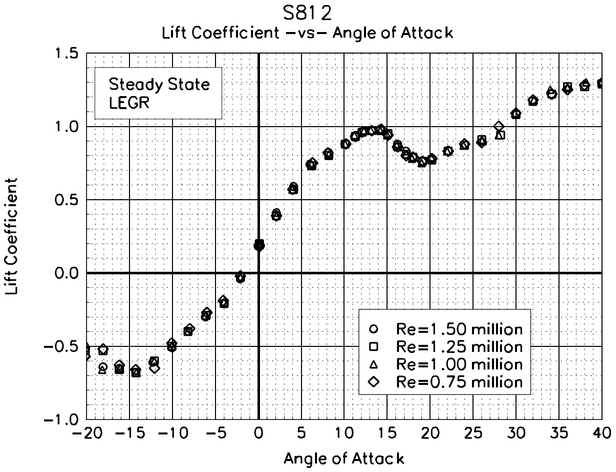

Figure 13. C_l vs α, LEGR, k/c=0.0019.

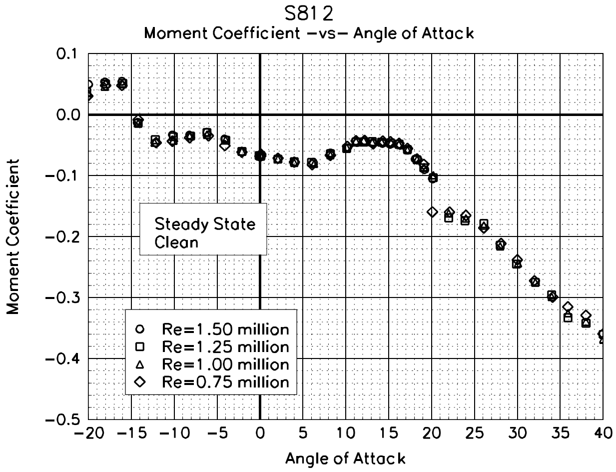

Figure 14. C_m vs α, clean.

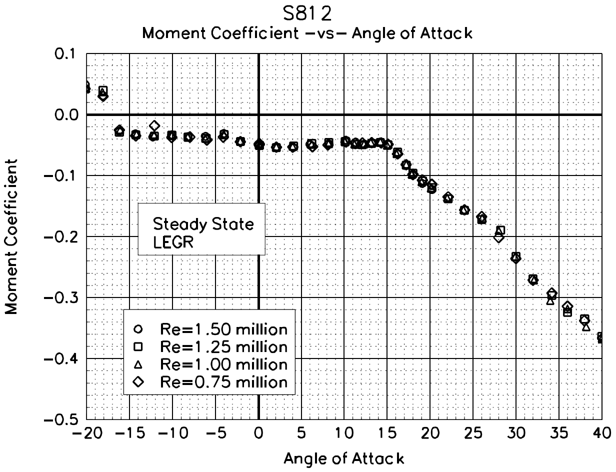

Figure 15. C_m vs α, LEGR, k/c=0.0019.

Figure 14 shows the pitching moment about the quarter chord for the clean cases and Figure 15 shows the LEGR cases. The magnitude of the zero lift pitching moment is 28% higher for the clean case than for the LEGR case. The zero lift pitching moment coefficient about the quarter chord for the 1 million Reynolds number, clean case is -0.0607 and -0.0435 for the LEGR case. For moderate angles of attack -15° to +15° the pitching moment is nearly constant for the LEGR cases but varies between -0.013 to -0.080 for the clean cases.

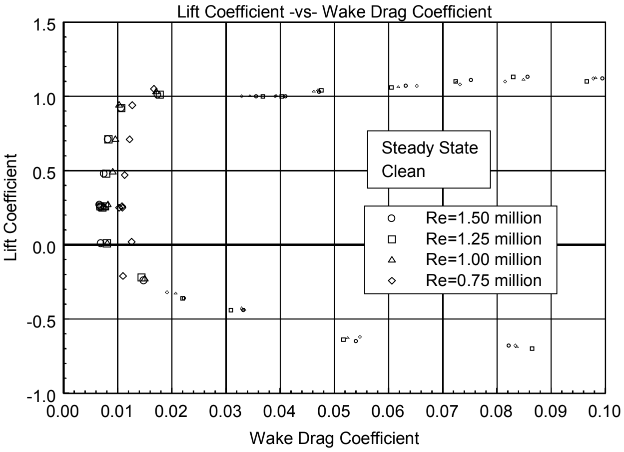

Figure 16. Clean, drag polar.

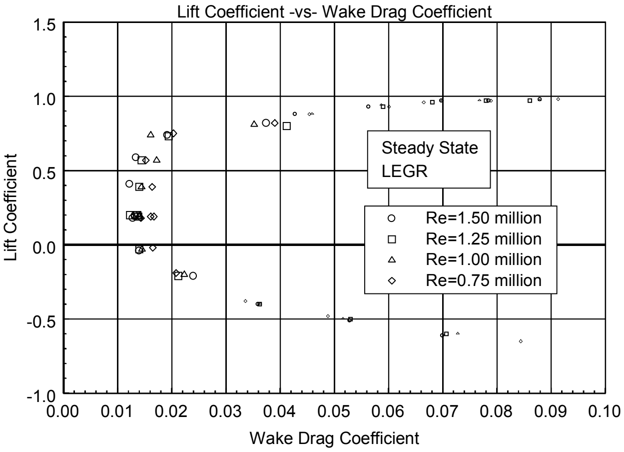

Figure 17. LEGR, drag polar.

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 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 0.0073, and 0.0140 for LEGR; an 92% increase. The general effect of LEGR is to increase drag consistently through most angles of attack and narrow the drag bucket.

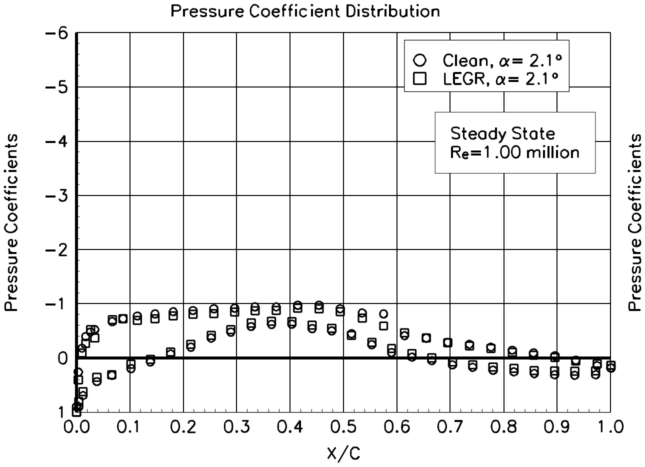

Figure 18. Pressure distribution, α=2.1°.

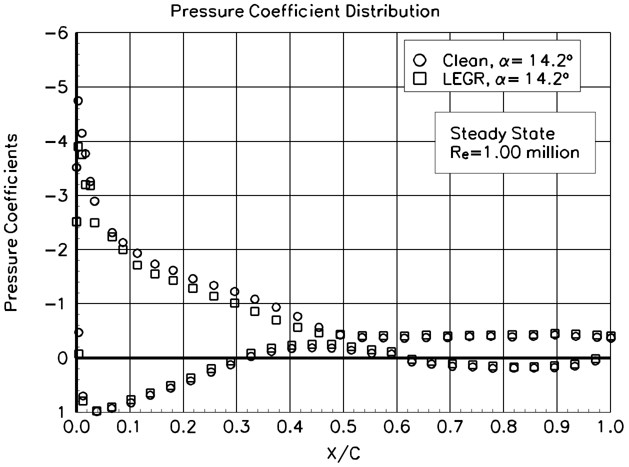

Figure 19. Pressure distribution, α=14.2°.

Two examples of the surface pressure distributions are shown in Figure 18 and Figure 19 for 2.1° and 14.2°, respectively, for 1 million Reynolds number. At angles of attack close to zero degrees, the effect of LEGR does not appear to significantly affect the pressure distribution in comparison with the clean case distribution; however, the effect is apparent in the lift coefficient where for the LEGR case it is 0.39 and 0.49 for the clean case at 2.1°. For the higher angle of attack case, Figure 19, the effect of LEGR is to reduce the magnitude of the pressure peak from -4.7 to -3.9, increase the pressures on the upper (suction) surface over the forward 45% of the chord. The net effect is a reduction in lift coefficient from 1.09 to 0.97, a 11% decrease.

Unsteady Data

Unsteady experimental data were obtained for the S812 airfoil model undergoing sinusoidal pitch oscillations. As mentioned earlier, no calibration was available 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. A comprehensive set of test conditions was used to describe unsteady behavior of the airfoil including: two angle of attack amplitudes, ±5.5° and ±10°; 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°.

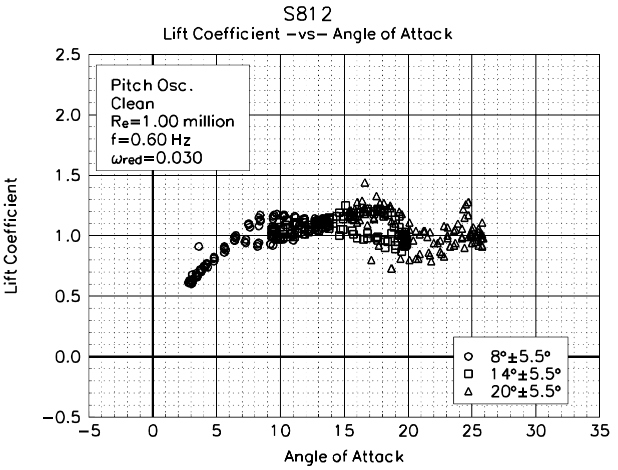

Figure 20. Clean, C_l vs α, ω_{red}=0.030, ±5.5°.

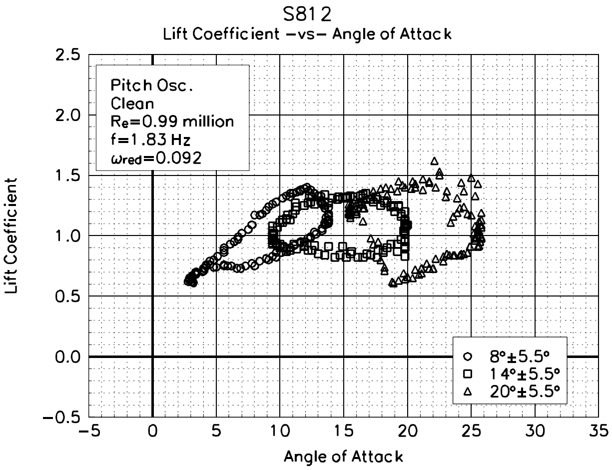

Figure 21. Clean, C_l vs α, ω_{red}=0.092, ±5.5°.

Figure 20 shows the lift coefficient versus angle of attack for the ±5.5° amplitude model clean case, at reduced frequency of 0.030 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 1.18 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 of the unsteady data. In order 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 0.97, an 18% decrease from the 1.18 unsteady maximum value. In comparison, the steady state maximum lift coefficient is 1.12. At higher reduced frequency of 0.092, the hysteresis behavior is more pronounced as seen in Figure 21. In addition to greater hysteresis, the maximum lift coefficient is increased to about 1.40, which is a 25% increase over the steady state value. The corresponding hysteresis lift coefficient is 0.98. This difference between steady state behavior and unsteady hysteresis behavior demonstrates the need for unsteady testing of airfoils used in wind turbine applications.

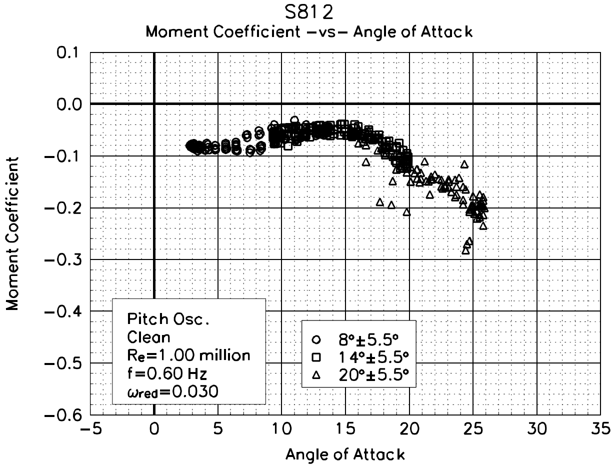

Figure 22. Clean, C_m vs α, ω_{red}=0.030, ±5.5°.

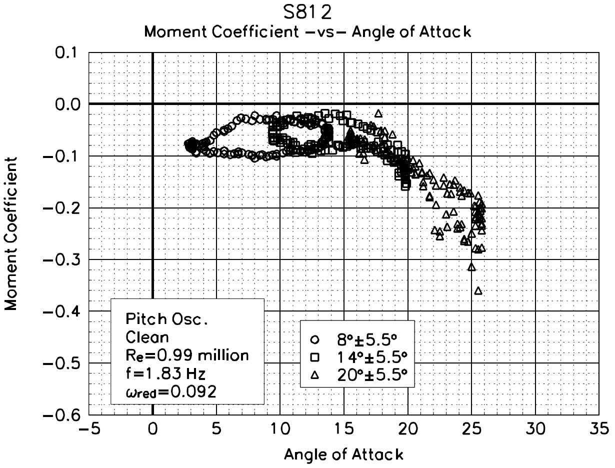

Figure 23. Clean, C_m vs α, ω_{red}=0.092, ±5.5°.

The pitching moment in Figure 22 and Figure 23 corresponds to the same conditions as the two lift coefficient plots previously discussed. There is an indication that the hysteresis behavior is present but it is not as apparent as in the lift coefficient plots; but the higher reduced frequency case does show hysteresis more than the lower reduced frequency case. For reference, the steady state maximum lift occurs near 16° angle of attack and the steady state pitching moment at this maximum lift point is -0.0491. In comparison, when the airfoil is undergoing pitch oscillation for the lower frequency, pitching moment varies from -0.0761 to -0.0487 (at the angle of attack where maximum lift occurs), up to a 55% increase 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.

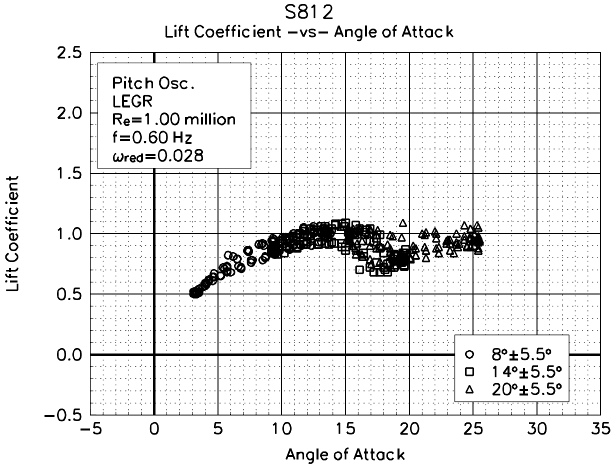

Figure 24. LEGR, C_l vs α, ω_{red}=0.028, ±5.5°.

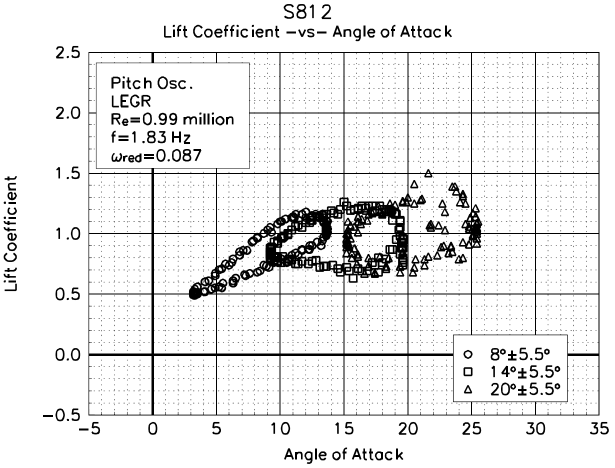

Figure 25. LEGR, C_l vs α, ω_{red}=0.087, ±5.5°.

In comparison 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 in Figure 25. Both correspond to the same run conditions which were described earlier for the clean cases. For the lower reduced frequency, the maximum unsteady lift coefficient is reduced to 1.09 from the corresponding clean case of 1.18, an 8% decrease. Hysteresis behavior is apparent at this frequency but it is of slightly smaller order than the clean case; the corresponding hysteresis lift coefficient is 0.89 when LEGR is applied. In contrast, the higher frequency LEGR case has a maximum lift coefficient of 1.20 while the model is increasing in angle of attack and the corresponding decreasing angle of attack lift coefficient is 0.68. Again, the application of LEGR slightly reduces the hysteresis loop behavior for larger angles of attack in comparison with the clean case.

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 -0.0682 to -0.0506, while the steady state LEGR pitching moment is -0.0444 at the steady state stall angle of attack (14.2°). The higher reduced frequency of 0.087 with LEGR application is shown in Figure 27. As was seen with the lift coefficient, pitching moment hysteresis is more apparent at the higher reduced frequency than the corresponding low reduced frequency case. Unsteady maximum lift angle of attack for this reduced frequency occurs at 14.7° and the pitching moment ranges from -0.0776 to -0.0269 at that angle. Throughout the higher angle of attack range, the magnitude of the unsteady pitching moment can be very different than the steady state clean case (steady state pitching moment at maximum lift is -0.0444). These differences can have an impact on the fatigue life predictions of a wind turbine system.

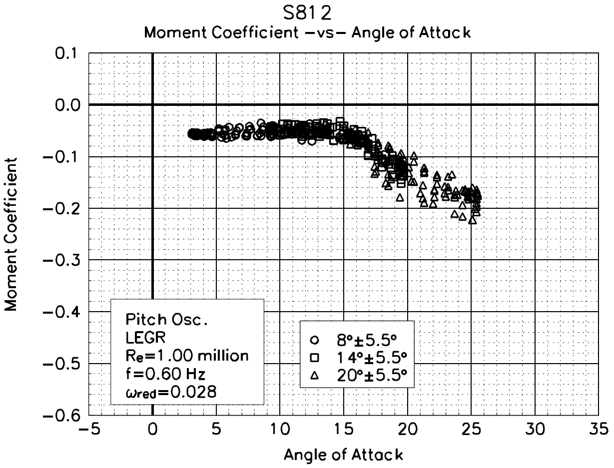

Figure 26. LEGR, C_m vs α, ω_{red}=0.028, ±5.5°.

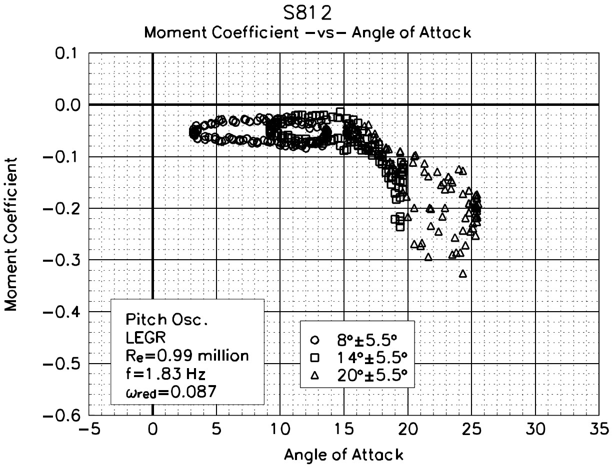

Figure 27. LEGR, C_m vs α, ω_{red}=0.087, ±5.5°.

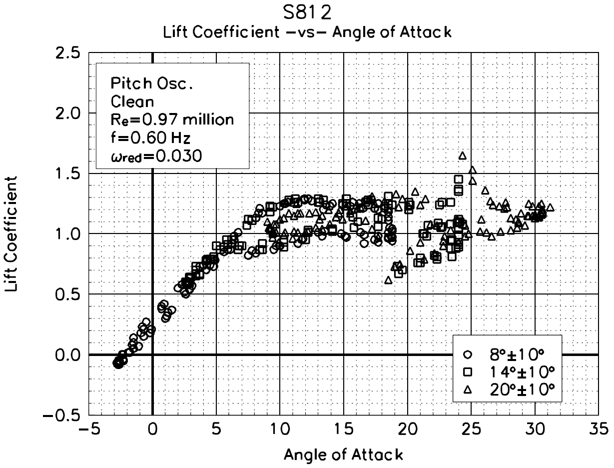

Figure 28. Clean, C_l vs α, ω_{red}=0.030, ±10°.

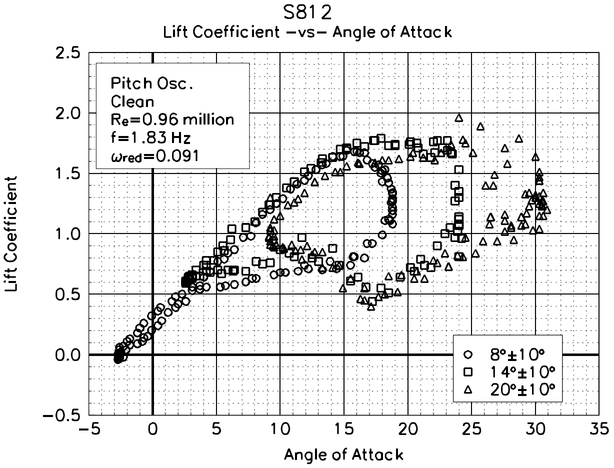

Figure 29. Clean, C_l vs α, ω_{red}=0.091, ±10°.

In addition to the ±5.5° unsteady experimental data, ±10° 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 ±10°, unsteady, clean, lift coefficient for the reduced frequencies of 0.030 and 0.091, respectively. The maximum lift coefficient for the lower frequency is 1.29 and occurs, as expected, when the airfoil is traveling through increasing angle of attack. The hysteresis lift coefficient (at 12.2°) is 0.96. At the higher reduced frequency, the maximum lift coefficient occurs at a higher angle of attack, 17.9°, and is 1.79. The corresponding hysteresis lift coefficient is 0.55. 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 1.12; therefore, the unsteady behavior created lift coefficients up to 60% higher than the steady state conditions.

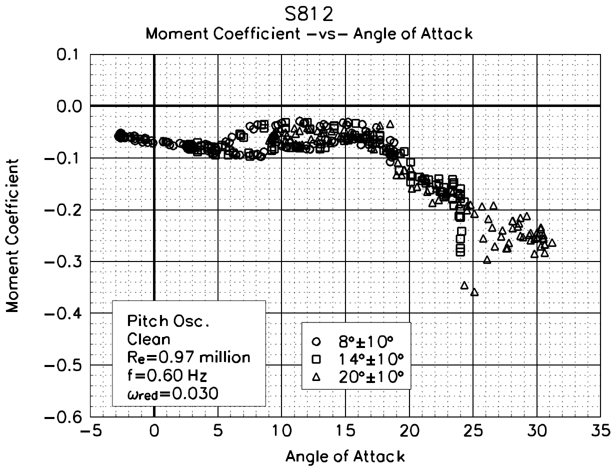

Figure 30. Clean, C_m vs α, ω_{red}=0.030, ±10°.

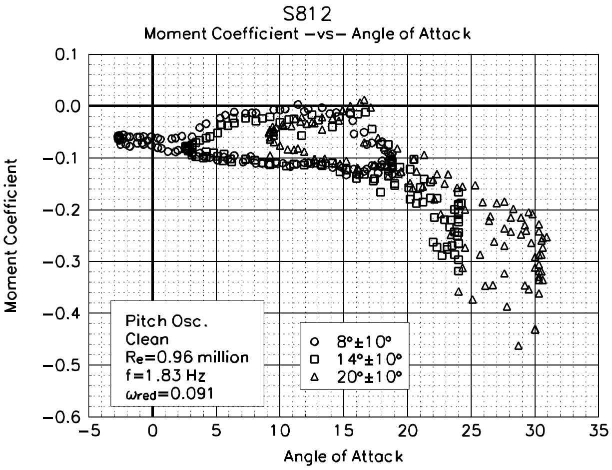

Figure 31. Clean, C_m vs α, ω_{red}=0.091, ±10°.

The quarter chord pitching moments having 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 reflected in this pitching moment data. Near the maximum lift angle, 12.2° for the lower frequency, the pitching moment coefficient ranges from -0.0838 to -0.0319; whereas the 0.091 reduced frequency case has maximum lift near 17.9° and pitching moment ranges from -0.1667 to -0.0739. In comparison, the steady state pitching moment is -0.0491 near the steady state maximum lift coefficient angle of attack of 16.2°. The higher reduced frequency again shows large hysteresis loops for all three mean angles of attack.

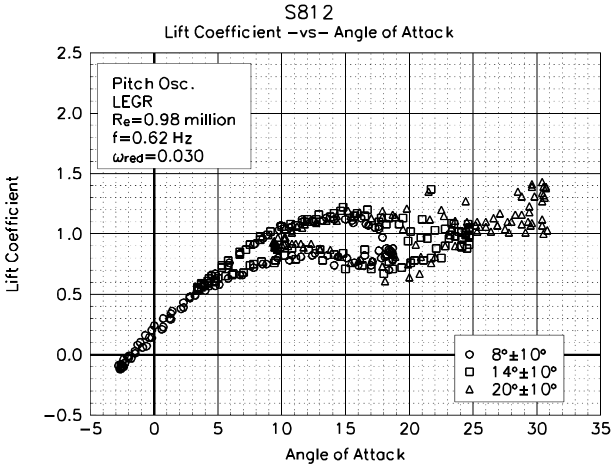

Figure 32. LEGR, C_l vs α, ω_{red}=0.030, ±10°.

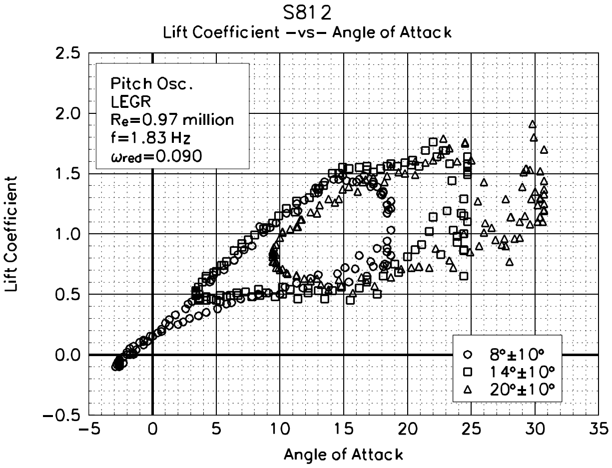

Figure 33. LEGR, C_l vs α, ω_{red}=0.090, ±10°.

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 0.030 and 0.090 are shown in Figure 32 and Figure 33, respectively. The maximum lift coefficient is reduced to 1.22 from 1.29 for the low frequency clean case. Although there is a reduction, this value is still higher than the LEGR steady state case which has a maximum lift coefficient of 0.97 at 14.2° angle of attack. The higher reduced frequency has a maximum lift coefficient of 1.55 which occurs near 15° angle of attack. The corresponding lift coefficient at 15.3° for the airfoil traveling with decreasing angle of attack is 0.55, a 65% reduction from the maximum.

Figure 34 and Figure 35 show the corresponding pitching moment coefficients for the reduced frequencies of 0.030 and 0.090. For the 0.030 reduced frequency case, the pitching moment varies from -0.0887 to -0.0344 at 14.8° (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 15.3° is from -0.1130 to -0.0304. These values can then be compared to the steady state LEGR value of -0.0444.

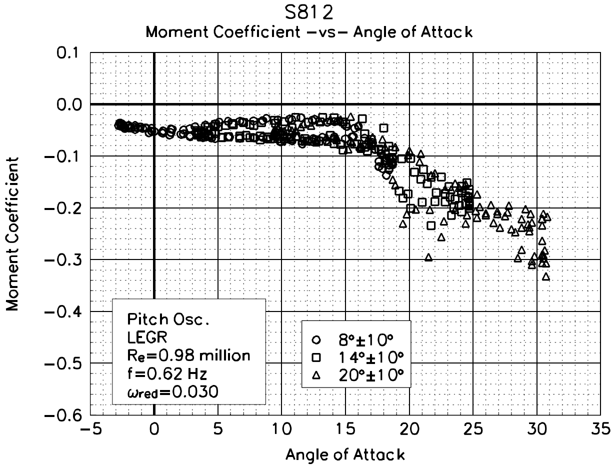

Figure 34. LEGR, C_m vs α, ω_{red}=0.030, ±10°.

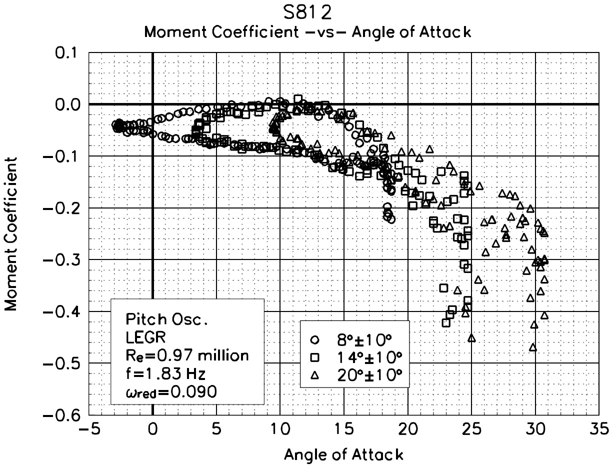

Figure 35. LEGR, C_m vs α, ω_{red}=0.090, ±10°.

Although all the unsteady data were not discussed here, the previous discussion included typical examples of the wind tunnel data. The remaining cases of the ±5.5° and ±10° oscillation data for all the Reynolds numbers are included in Appendix C.

The following unsteady pressure distributions show examples of the data used to calculate the lift, pressure drag, and the pitching moment coefficients. Figure 36 shows the distribution for a clean model, with a reduced frequency of 0.059, a mean angle of attack of 14°, and a ±5.5° pitch oscillation. For plotting clarity, the model pressures were "unwrapped" about the trailing edge. The upper surface pressures are depicted on the right of the surface plot, lower surface values on the left. The trailing edge is then at the midpoint of the x-axis with the leading edge at each extreme. Additionally, the pressure coefficients were linearly interpolated to make an evenly spaced grid. The time scale corresponds to angle of attack. For this case, the negative pressure peak is at approximately -5. Figure 37 shows the LEGR case for the same test conditions as the previous figure. The application of LEGR reduces the pressure peak to -3. Separated flow is defined as the irregular, "rough" areas on the upper surface, that are more noticeable for the LEGR case than for the clean case. Also note that the lower surface stays attached through the airfoil travel.

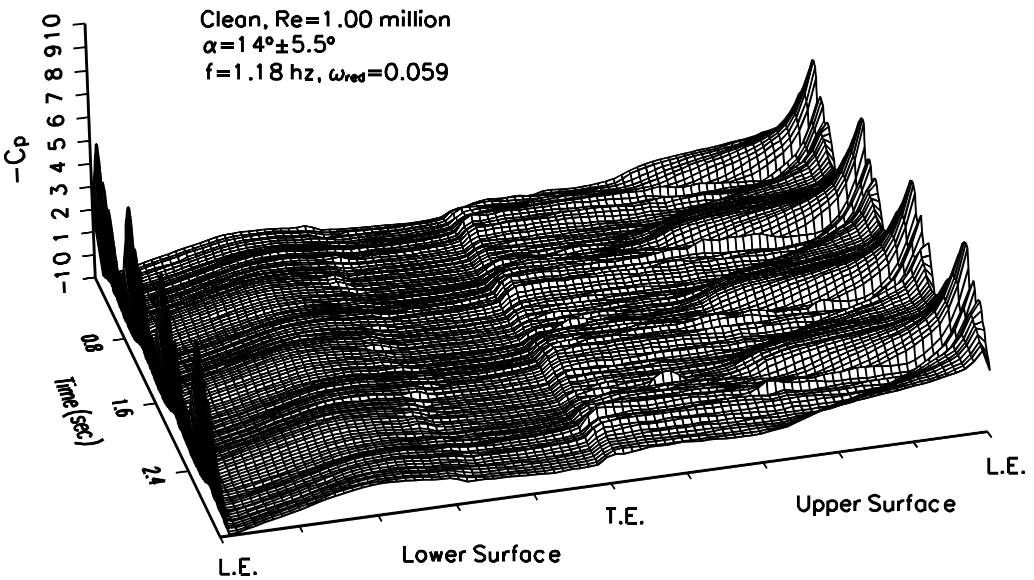

Figure 36. Unsteady pressure distribution, clean, ω_{red}=0.059, 14±5.5°.

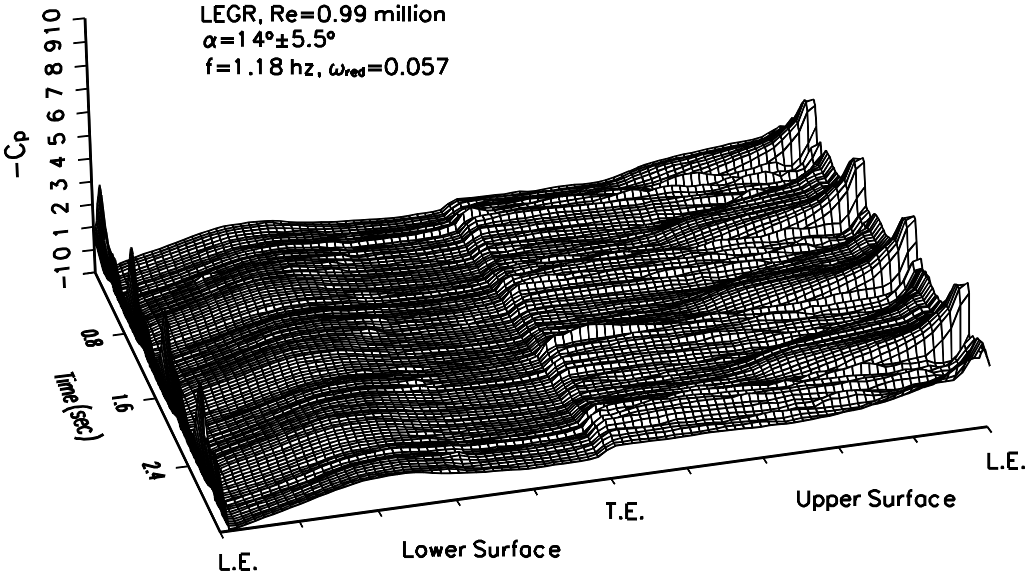

Figure 37. Unsteady pressure distribution, LEGR, ω_{red}=0.057, 14±5.5°.

Figure 38 shows the same clean run conditions as above except with the ±10° amplitude oscillation. This case is characterized by significant portions of the upper surface in stall and high pressure peaks. The negative pressure coefficient peaks are about -6 for this case while it was near -5 for the previous clean, 14° mean angle of attack case. The secondary peaks apparent on the upper surface correspond to a region of partial stall recovery while the model is traveling through decreasing angle of attack.

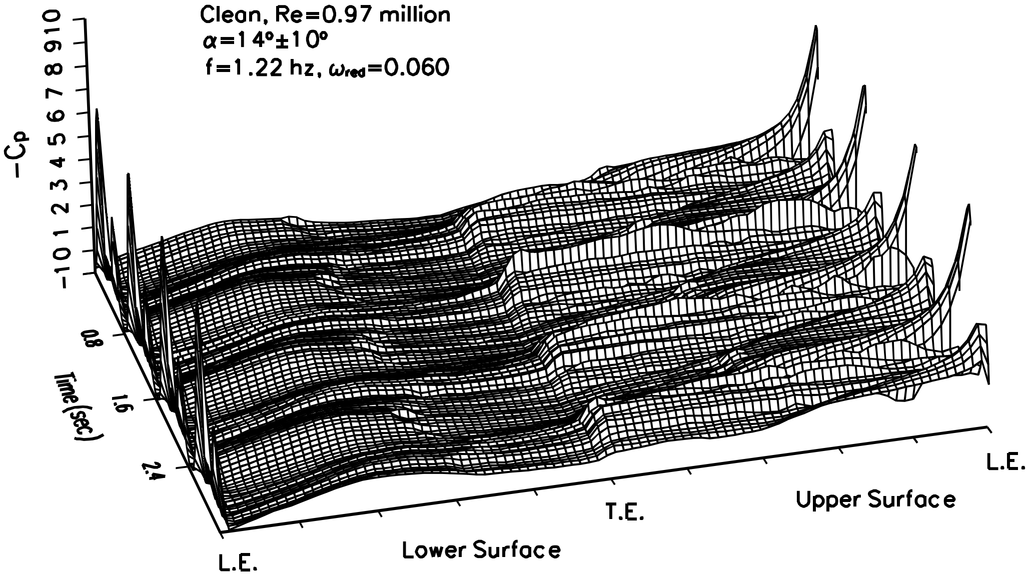

Figure 38. Unsteady pressure distribution, clean, ω_{red}=0.060, 14±10°.

Summary of Results

An S812 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 leading edge grit roughness (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 14% and the minimum drag coefficient increased in some cases more than 91%. The zero lift pitching moment coefficient was also affected by application of LEGR which reduced the magnitude an average of 28%.

Table 1. S812 Steady State Parameters Summary

Grit Pattern	Re x 10^{-6}	C_{lmax}	C_{dmin}	C_{mo}
Clean	0.75	1.12 @ 16.2°	0.0103	-0.0618
k/c=0.0019	0.75	0.98 @ 14.3°	0.0143	-0.0446
Clean	1.00	1.12 @ 16.2°	0.0073	-0.0607
k/c=0.0019	1.00	0.97 @ 14.2°	0.0140	-0.0435
Clean	1.25	1.13 @ 15.2°	0.0068	-0.0606
k/c=0.0019	1.25	0.97 @ 14.2°	0.0123	-0.0443
Clean	1.50	1.13 @ 15.2°	0.0067	-0.0617
k/c=0.0019	1.50	0.98 @ 14.2°	0.0122	-0.0439

Table 2. S812, Unsteady, Clean, ±5.5°

ω_{red}	Re x 10^{-6}	f	C_{lmax}	α_{max}	$C_{l\ dec}$	$C_{m\ inc}$	$C_{m\ dec}$
0.039	0.76	0.60	1.23	10.2	0.94	-0.0725	-0.0403
0.079	0.75	1.19	1.36	11.9	0.97	-0.0836	-0.0385
0.121	0.76	1.83	1.48	15.7	0.84	-0.1089	-0.0225
0.030	1.00	0.60	1.18	9.7	0.97	-0.0761	-0.0487
0.060	1.00	1.21	1.29	10.0	0.92	-0.0902	-0.0398
0.092	0.99	1.83	1.40	12.1	0.98	-0.0896	-0.0382
0.024	1.24	0.61	1.15	10.0	0.96	-0.0732	-0.0463
0.049	1.24	1.22	1.25	10.3	0.94	-0.0821	-0.0406
0.073	1.23	1.81	1.32	11.6	0.97	-0.0871	-0.0424
0.020	1.48	0.61	1.13	9.7	0.95	-0.0686	-0.0522
0.041	1.48	1.21	1.22	10.5	0.96	-0.0781	-0.0426
0.062	1.48	1.85	1.29	11.6	0.97	-0.0812	-0.0420

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 some parameters are in Tables 2, 3, 4, and 5. Looking at the reduced frequency, which takes oscillation and tunnel speed into account, and as this value increases, the maximum lift coefficient also increases. The increase in maximum lift coefficient with reduced frequency is linear for all of the test cases as shown in Figure 39 and Figure 40. In addition, the hysteresis behavior becomes increasingly apparent with increased reduced frequency.

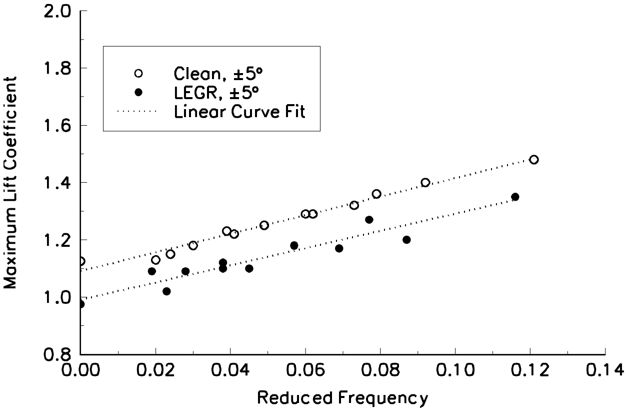

Figure 39. ±5.5°, unsteady C_{lmax} vs ω_{red}.

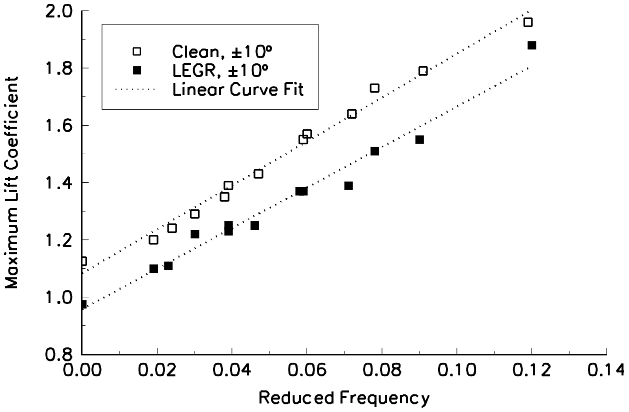

Figure 40. ±10°, unsteady C_{lmax} vs ω_{red}.

Table 3. S812, Unsteady, LEGR, ±5.5°

ω_{red}	Re x 10^{-6}	f	C_{lmax}	α_{max}	$C_{l\,dec}$	$C_{m\,inc}$	$C_{m\,dec}$
0.038	0.75	0.60	1.10	13.6	0.87	-0.0680	-0.0349
0.077	0.74	1.21	1.27	16.4	0.72	-0.0928	-0.0526
0.116	0.75	1.83	1.35	16.3	0.66	-0.1035	-0.0585
0.028	1.00	0.60	1.09	15.0	0.89	-0.0682	-0.0506
0.057	0.99	1.19	1.18	15.2	0.69	-0.0703	-0.0382
0.087	0.99	1.83	1.20	14.7	0.68	-0.0776	-0.0269
0.023	1.25	0.60	1.02	13.4	1.00	-0.0531	-0.0530
0.045	1.24	1.19	1.10	14.5	0.72	-0.0636	-0.0385
0.069	1.24	1.83	1.17	15.2	0.74	-0.0836	-0.0306
0.019	1.49	0.61	1.09	15.3	0.89	-0.0592	-0.0424
0.038	1.49	1.21	1.12	14.7	0.82	-0.0670	-0.0348
0.057	1.49	1.79	1.18	15.8	0.74	-0.0821	-0.0454

As expected, the application of LEGR reduces the aerodynamic performance of the airfoil. The unsteady maximum lift coefficient is reduced from 4% to 15% for both the ±5.5° case and the ±10° case. As well as 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 do the clean cases. Overall, the unsteady wind tunnel data shows hysteresis behavior that becomes more apparent with increased, reduced frequency. The maximum unsteady lift coefficient can be up to 37% higher for the ±5.5° amplitude and up to 92% higher for the ±10° amplitude than the steady state maximum lift coefficient. In addition, variation in the quarter chord pitching moment coefficient can be over 350% greater than that indicated by steady state results. These findings indicate that it is very important to consider the unsteady loading that will occur in wind turbine operation because use of steady state results can greatly underestimate the forces.

Table 4. S812, Unsteady, Clean, ±10°

ω_{red}	Re x 10^{-6}	f	C_{lmax}	α_{max}	$C_{l\ dec}$	$C_{m\ inc}$	$C_{m\ dec}$
0.038	0.75	0.60	1.35	13.0	0.99	-0.0951	-0.0325
0.078	0.74	1.21	1.73	16.6	0.40	-0.1222	-0.0321
0.119	0.74	1.83	1.96	18.5	0.66	-0.1739	-0.1104
0.030	0.97	0.60	1.29	12.2	0.96	-0.0838	-0.0319
0.059	0.97	1.19	1.55	15.2	1.07	-0.1027	-0.0305
0.091	0.96	1.83	1.79	17.9	0.55	-0.1667	-0.0739
0.024	1.23	0.61	1.24	11.4	0.94	-0.0803	-0.0425
0.047	1.22	1.21	1.43	13.9	0.90	-0.1033	-0.0203
0.072	1.22	1.81	1.64	15.2	0.91	-0.1228	-0.0204
0.019	1.47	0.60	1.20	10.3	0.95	-0.0745	-0.0440
0.039	1.46	1.19	1.39	13.0	1.05	-0.0916	-0.0495
0.060	1.46	1.83	1.57	15.5	0.90	-0.1125	-0.0475

Table 5. S812, Unsteady, LEGR, ±10°

ω_{red}	Re x 10^{-6}	ω	C_{lmax}	α_{max}	$C_{l\ dec}$	$C_{m\ inc}$	$C_{m\ dec}$
0.039	0.74	0.61	1.25	15.5	0.75	-0.0874	-0.0358
0.078	0.73	1.19	1.51	18.3	0.61	-0.1368	-0.0647
0.120	0.73	1.83	1.88	22.2	0.83	-0.2121	-0.1195
0.030	0.98	0.62	1.22	14.8	0.84	-0.0887	-0.0344
0.059	0.97	1.19	1.37	16.5	0.62	-0.1057	-0.0375
0.090	0.97	1.83	1.55	15.3	0.55	-0.1130	-0.0304
0.023	1.23	0.60	1.11	13.2	0.85	-0.0717	-0.0294
0.046	1.21	1.19	1.25	15.4	0.58	-0.0810	-0.0430
0.071	1.22	1.83	1.39	15.1	0.62	-0.1123	-0.0309
0.019	1.48	0.59	1.10	15.4	0.84	-0.0736	-0.0396
0.039	1.47	1.19	1.23	14.6	0.67	-0.0799	-0.0317
0.058	1.46	1.81	1.37	16.8	0.64	-0.0992	-0.0432

References

Pope, A.; Harper, J.J. 1966. *Low Speed Wind Tunnel Testing*. New York, NY: John Wiley & Sons, Inc.

Tangler, J. and Somers, D. 1995. *NREL Airfoil Families for HAWTs.* Windpower '95, Wahington D.C.

Schlichting, H. 1979. *Boundary Layer Theory*. New York, NY: McGraw-Hill Inc.

Smetana, F., Summey, D. et-al. 1975. *Light Aircraft Lift, Drag, and Moment Prediction - a Review and Analysis*. North Carolina State University. NASA CR-2523.

Appendix A: Surface Pressure Tap Coordinates

Table A1. S812 Surface Pressure Taps, Non-Diminsional Coordinates

Tap Number	Chord Station	Ordinate
1	1.0009	--
2	0.9715	--
3	0.9334	--
4	0.8951	--
5	0.8572	--
6	0.8187	--
7	0.7802	--
8	0.7418	--
9	0.7035	--
10	0.6650	--
11	0.6276	--
12	0.5899	--
13	0.5527	--
14	0.5153	--
15	0.4780	--
16	0.4407	--
17	0.4032	--
18	0.3652	--
19	0.3270	--
20	0.2893	--
21	0.2516	--
22	0.2135	--
23	0.1759	--
24	0.1383	--
25	0.1017	--
26	0.0657	--
27	0.0383	--
28	0.0119	--
29	0.0039	--
30	0.0000	--
31	0.0027	--
32	0.0097	--
33	0.0171	--
34	0.0255	--

Table A1. S812 Surface Pressure Taps, Non-Diminsional Coordinates

Tap Number	Chord Station	Ordinate
35	0.0340	--
36	0.0666	--
37	0.0870	--
38	0.1138	--
39	0.1474	--
40	0.1813	--
41	0.2183	--
42	0.2566	--
43	0.2955	--
44	0.3345	--
45	0.3740	--
46	0.4143	--
47	0.4539	--
48	0.4941	--
49	0.5348	--
50	0.5747	--
51	0.6144	--
52	0.6547	--
53	0.6953	--
54	0.7357	--
55	0.7757	--
56	0.8157	--
57	0.8563	--
58	0.8963	--
59	0.9353	--
60	0.9753	--
End of Table A1		

Appendix B: Steady State Data
Integrated Coefficients and Pressure Distributions

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Table B1. S812, Clean, Re = 0.75 x 10^6

RUN	AOA	C_l	C_{dp}	$C_{m¼}$	Re x 10^{-6}	C_{dw}
49	-20.1	-0.45	0.2910	0.0300	0.76	--
48	-18.0	-0.49	0.2787	0.0474	0.77	--
47	-16.1	-0.50	0.2504	0.0474	0.76	--
46	-14.2	-0.65	0.1573	-0.0088	0.75	--
45	-12.1	-0.68	0.0834	-0.0461	0.75	--
44	-10.2	-0.62	0.0547	-0.0437	0.75	--
43	-8.2	-0.43	0.0329	-0.0382	0.76	--
42	-6.0	-0.32	0.0191	-0.0352	0.76	0.0498
41	-4.1	-0.21	0.0073	-0.0509	0.75	0.0110
40	-2.1	0.02	0.0051	-0.0618	0.74	0.0126
76	0.0	0.25	0.0047	-0.0687	0.76	0.0109
39	0.1	0.25	0.0048	-0.0652	0.75	0.0103
50	0.1	0.26	0.0052	-0.0679	0.75	0.0108
51	2.1	0.47	0.0080	-0.0718	0.74	0.0113
52	4.0	0.71	0.0112	-0.0781	0.77	0.0122
53	6.1	0.94	0.0170	-0.0823	0.74	0.0127
54	8.2	1.05	0.0239	-0.0670	0.75	0.0167
55	10.2	1.00	0.0329	-0.0522	0.75	0.0763
56	11.2	1.00	0.0391	-0.0432	0.74	--
57	12.2	1.04	0.0470	-0.0425	0.75	--
58	13.2	1.07	0.0652	-0.0479	0.76	--
59	14.3	1.08	0.0732	-0.0435	0.74	--
60	15.2	1.10	0.0815	-0.0445	0.74	--
61	16.2	1.12	0.0978	-0.0474	0.75	--
62	17.2	1.04	0.1227	-0.0558	0.75	--
63	18.3	0.98	0.1563	-0.0728	0.76	--
64	19.1	0.96	0.1804	-0.0817	0.75	--
65	20.1	0.80	0.3675	-0.1598	0.76	--

Table B1. S812, Clean, Re = 0.75 x 10^6

RUN	AOA	C_l	C_{dp}	$C_{m1/4}$	Re x 10^{-6}	C_{dw}
66	22.1	0.80	0.4057	-0.1601	0.76	--
67	24.0	0.83	0.4515	-0.1655	0.76	--
68	26.1	0.93	0.5359	-0.1859	0.76	--
69	28.1	1.01	0.6230	-0.2116	0.76	--
70	30.0	1.10	0.7163	-0.2382	0.74	--
71	32.0	1.18	0.8263	-0.2726	0.74	--
72	34.1	1.24	0.9230	-0.2996	0.77	--
73	35.9	1.26	0.9987	-0.3153	0.74	--
74	38.0	1.26	1.0715	-0.3292	0.75	--
75	40.0	1.29	1.1744	-0.3596	0.74	--

End of Table B1

Table B2. S812, Clean, Re = 1 X 10^6

RUN	AOA	C_l	C_{dp}	$C_{m¼}$	Re x 10^{-6}	C_{dw}
11	-20.1	-0.48	0.3018	0.0355	1.01	--
10	-18.1	-0.48	0.2785	0.0459	1.00	--
9	-16.0	-0.50	0.2508	0.0498	1.01	--
8	-14.2	-0.66	0.1518	-0.0142	1.00	--
7	-12.3	-0.69	0.0837	-0.0458	1.00	--
6	-10.1	-0.63	0.0525	-0.0426	1.00	--
5	-8.2	-0.44	0.0334	-0.0355	1.00	--
4	-6.2	-0.33	0.0207	-0.0329	1.00	--
3	-4.0	-0.23	0.0102	-0.0416	1.00	0.0150
2	-2.1	0.01	0.0040	-0.0607	1.01	0.0081
1	0.1	0.26	0.0038	-0.0670	1.00	0.0073
12	0.1	0.27	0.0037	-0.0683	1.00	0.0082
38	0.1	0.25	0.0039	-0.0665	1.00	0.0077
13	2.1	0.49	0.0067	-0.0729	1.00	0.0091
14	4.0	0.71	0.0108	-0.0790	1.00	0.0096
15	6.3	0.94	0.0173	-0.0804	1.00	0.0103
16	8.2	1.03	0.0251	-0.0664	1.00	0.0171
17	10.1	1.00	0.0344	-0.0535	0.99	--
18	11.2	1.00	0.0393	-0.0434	1.00	--
19	12.1	1.03	0.0462	-0.0426	1.00	--
20	13.1	1.06	0.0618	-0.0454	1.00	--
21	14.2	1.09	0.0725	-0.0454	1.00	--
22	15.3	1.11	0.0849	-0.0459	0.99	--
23	16.2	1.12	0.0982	-0.0491	1.00	--
24	17.2	1.04	0.1219	-0.0579	1.00	--
25	18.3	0.98	0.1568	-0.0735	1.00	--
26	19.1	0.93	0.1865	-0.0864	1.00	--
27	20.2	0.91	0.2221	-0.0994	1.01	--

Table B2. S812, Clean, Re = 1 X 10^6

RUN	AOA	C_l	C_{dp}	$C_{m¼}$	Re x 10^{-6}	C_{dw}
28	22.0	0.81	0.4080	-0.1617	1.02	--
29	24.0	0.84	0.4589	-0.1703	1.00	--
30	26.1	0.91	0.5260	-0.1814	1.00	--
31	28.0	1.03	0.6286	-0.2158	1.00	--
32	30.1	1.12	0.7308	-0.2437	1.00	--
33	32.1	1.19	0.8341	-0.2752	0.99	--
34	34.0	1.23	0.9228	-0.2989	0.99	--
35	35.9	1.28	1.0198	-0.3254	1.00	--
36	38.0	1.28	1.0946	-0.3397	0.99	--
37	40.0	1.30	1.1902	-0.3685	0.98	--

End of Table B2

Table B3. S812, Clean, Re = 1.25 x 10^6

RUN	AOA	C_l	C_{dp}	$C_{m¼}$	Re x 10^{-6}	C_{dw}
115	-20.2	-0.48	0.3032	0.0367	1.26	--
114	-18.0	-0.49	0.2825	0.0502	1.27	--
113	-16.0	-0.49	0.2513	0.0513	1.27	--
112	-14.2	-0.65	0.1515	-0.0144	1.25	--
111	-12.2	-0.70	0.0865	-0.0415	1.26	--
110	-10.1	-0.64	0.0517	-0.0364	1.25	--
109	-8.1	-0.44	0.0309	-0.0353	1.25	--
108	-6.2	-0.36	0.0220	-0.0297	1.25	--
107	-4.0	-0.22	0.0098	-0.0421	1.25	0.0144
106	-2.1	0.01	0.0029	-0.0606	1.25	0.0080
105	-0.1	0.26	0.0031	-0.0674	1.24	0.0077
116	0.0	0.26	0.0039	-0.0684	1.25	0.0068
142	0.1	0.25	0.0039	-0.0673	1.25	0.0072
117	2.1	0.48	0.0074	-0.0733	1.25	0.0079
118	4.0	0.71	0.0093	-0.0777	1.26	0.0083
119	6.0	0.92	0.0130	-0.0784	1.25	0.0107
120	8.2	1.01	0.0255	-0.0644	1.25	0.0178
121	10.1	1.00	0.0368	-0.0560	1.25	--
122	11.2	1.00	0.0403	-0.0452	1.25	--
123	12.1	1.04	0.0476	-0.0450	1.25	--
124	13.1	1.06	0.0605	-0.0446	1.26	--
125	14.2	1.10	0.0724	-0.0454	1.26	--
126	15.2	1.13	0.0830	-0.0466	1.26	--
127	16.2	1.10	0.0966	-0.0484	1.25	--
128	17.2	1.05	0.1215	-0.0572	1.25	--
129	18.3	0.98	0.1574	-0.0744	1.25	--
130	19.1	0.94	0.1889	-0.0874	1.25	--
131	20.2	0.91	0.2278	-0.1037	1.25	--

Table B3. S812, Clean, Re = 1.25 x 10^6

RUN	AOA	C_l	C_{dp}	$C_{m¼}$	Re x 10^{-6}	C_{dw}
132	22.0	0.83	0.4166	-0.1693	1.26	--
133	23.9	0.85	0.4620	-0.1741	1.25	--
134	26.1	0.90	0.5213	-0.1788	1.24	--
135	28.0	1.02	0.6262	-0.2140	1.24	--
136	29.9	1.12	0.7272	-0.2450	1.24	--
137	32.1	1.19	0.8319	-0.2749	1.24	--
138	34.0	1.23	0.9165	-0.2957	1.23	--
139	35.9	1.29	1.0317	-0.3329	1.23	--
140	38.0	1.29	1.1002	-0.3423	1.23	--
141	40.0	1.29	1.1770	-0.3606	1.22	--

End of Table B3

Table B4. S812, Clean, Re = 1.5 x 10^6

RUN	AOA	C_l	C_{dp}	$C_{m1/4}$	Re x 10^{-6}	C_{dw}
167	-20.0	-0.50	0.3126	0.0493	1.46	--
166	-18.1	-0.49	0.2847	0.0533	1.48	--
165	-16.1	-0.50	0.2561	0.0540	1.50	--
164	-14.3	-0.65	0.1539	-0.0128	1.51	--
163	-12.2	-0.68	0.0822	-0.0464	1.52	--
162	-10.2	-0.65	0.0540	-0.0337	1.51	--
161	-8.2	-0.44	0.0332	-0.0338	1.50	--
160	-6.2	-0.36	0.0222	-0.0294	1.50	--
159	-4.1	-0.24	0.0098	-0.0401	1.51	0.0148
158	-2.1	0.01	0.0030	-0.0617	1.50	0.0069
157	0.0	0.25	0.0041	-0.0678	1.50	0.0068
184	0.0	0.26	0.0034	-0.0692	1.50	0.0069
168	0.1	0.27	0.0042	-0.0693	1.50	0.0067
169	2.1	0.48	0.0065	-0.0731	1.50	0.0075
170	4.1	0.71	0.0095	-0.0781	1.50	0.0082
171	6.2	0.92	0.0149	-0.0787	1.50	0.0107
172	8.2	1.01	0.0244	-0.0632	1.51	0.0174
173	10.2	1.00	0.0356	-0.0547	1.50	--
174	11.3	1.00	0.0410	-0.0459	1.50	--
175	12.1	1.03	0.0472	-0.0446	1.51	--
176	13.2	1.07	0.0632	-0.0468	1.50	--
177	14.3	1.11	0.0752	-0.0472	1.50	--
178	15.2	1.13	0.0857	-0.0487	1.50	--
179	16.3	1.12	0.0995	-0.0503	1.50	--
180	17.2	1.06	0.1216	-0.0586	1.49	--
181	18.1	1.00	0.1521	-0.0727	1.50	--
182	19.2	0.94	0.1934	-0.0904	1.50	--
183	20.1	0.91	0.2300	-0.1056	1.50	--

End of Table B4

Table B5. S812, LEGR, Re = 0.75 x 10^6

RUN	AOA	C_l	C_{dp}	$C_{m¼}$	Re x 10^{-6}	C_{dw}
373	-20.2	-0.57	0.3007	0.0419	0.75	--
372	-18.1	-0.52	0.2563	0.0299	0.76	--
371	-16.2	-0.63	0.1665	-0.0257	0.75	--
370	-14.3	-0.66	0.1108	-0.0349	0.75	--
369	-12.1	-0.65	0.0844	-0.0184	0.75	--
368	-10.1	-0.48	0.0488	-0.0374	0.75	0.0471
367	-8.0	-0.38	0.0336	-0.0370	0.75	0.0399
366	-6.0	-0.27	0.0180	-0.0417	0.75	0.0532
365	-4.1	-0.19	0.0120	-0.0373	0.75	0.0208
364	-2.1	-0.02	0.0067	-0.0446	0.75	0.0165
363	0.1	0.19	0.0058	-0.0496	0.75	0.0167
374	0.1	0.19	0.0049	-0.0492	0.74	0.0161
400	0.1	0.18	0.0046	-0.0477	0.75	0.0143
375	2.1	0.39	0.0074	-0.0536	0.74	0.0164
376	4.0	0.57	0.0100	-0.0534	0.75	0.0152
377	6.3	0.75	0.0199	-0.0528	0.74	0.0203
378	8.1	0.82	0.0313	-0.0499	0.75	0.0390
379	10.2	0.88	0.0454	-0.0451	0.75	0.0597
380	11.3	0.93	0.0601	-0.0474	0.75	--
381	12.1	0.96	0.0665	-0.0469	0.75	--
382	13.2	0.97	0.0789	-0.0463	0.75	--
383	14.3	0.98	0.0913	-0.0466	0.75	--
384	15.1	0.94	0.1039	-0.0487	0.75	--
385	16.2	0.86	0.1379	-0.0646	0.75	--
386	17.2	0.80	0.1791	-0.0824	0.75	--
387	18.0	0.79	0.2146	-0.0984	0.76	--
388	19.1	0.76	0.2519	-0.1076	0.76	--
389	20.2	0.78	0.2797	-0.1145	0.75	--

Table B5. S812, LEGR, Re = 0.75 x 10^6

RUN	AOA	C_l	C_{dp}	$C_{m¼}$	Re x 10^{-6}	C_{dw}
390	22.1	0.83	0.3473	-0.1351	0.75	--
391	24.0	0.88	0.4207	-0.1565	0.75	--
392	26.0	0.89	0.4824	-0.1676	0.75	--
393	28.0	1.00	0.5944	-0.2015	0.75	--
394	30.0	1.09	0.7089	-0.2361	0.74	--
395	32.0	1.18	0.8214	-0.2716	0.75	--
396	34.2	1.22	0.9144	-0.2928	0.73	--
397	36.0	1.25	0.9958	-0.3142	0.73	--
398	38.0	1.28	1.0863	-0.3381	0.75	--
399	40.1	1.30	1.1890	-0.3664	0.74	--

End of Table B5

Table B6. S812, LEGR, Re = 1 x 10^6

RUN	AOA	C_l	C_{dp}	$C_{m1/4}$	Re x 10^{-6}	C_{dw}
231	-20.1	-0.49	0.3006	0.0425	1.00	--
230	-18.2	-0.66	0.2699	0.0369	1.01	--
229	-16.1	-0.65	0.1618	-0.0250	1.00	--
228	-14.2	-0.68	0.1158	-0.0324	0.99	--
227	-12.1	-0.60	0.0728	-0.0326	1.00	0.0667
226	-10.1	-0.50	0.0516	-0.0347	1.00	0.0441
225	-8.2	-0.40	0.0363	-0.0368	1.00	0.0425
224	-6.2	-0.29	0.0223	-0.0391	1.00	0.0490
223	-4.0	-0.20	0.0135	-0.0336	1.00	0.0223
222	-2.1	-0.03	0.0073	-0.0435	1.00	0.0145
221	0.1	0.19	0.0060	-0.0502	1.00	0.0140
232	0.1	0.19	0.0059	-0.0499	1.00	0.0140
258	0.1	0.20	0.0056	-0.0504	1.00	0.0140
233	2.1	0.39	0.0075	-0.0524	1.00	0.0144
234	4.0	0.57	0.0106	-0.0519	1.00	0.0172
235	6.2	0.74	0.0176	-0.0488	0.99	0.0161
236	8.2	0.81	0.0310	-0.0478	1.01	0.0352
237	10.1	0.88	0.0459	-0.0447	1.00	--
238	11.2	0.94	0.0587	-0.0485	1.00	--
239	12.3	0.97	0.0699	-0.0485	1.00	--
240	13.1	0.97	0.0768	-0.0457	1.00	--
241	14.2	0.97	0.0879	-0.0444	1.00	--
242	15.0	0.94	0.1044	-0.0507	1.00	--
243	16.1	0.87	0.1365	-0.0642	1.00	--
244	17.2	0.81	0.1776	-0.0815	1.00	--
245	17.9	0.78	0.2167	-0.0981	1.00	--
246	19.0	0.75	0.2564	-0.1104	1.01	--
247	20.1	0.79	0.2889	-0.1205	1.00	--

Table B6. S812, LEGR, Re = 1 x 10^6

RUN	AOA	C_l	C_{dp}	$C_{m¼}$	Re x 10^{-6}	C_{dw}
248	22.0	0.83	0.3494	-0.1367	0.99	--
249	23.9	0.87	0.4203	-0.1561	0.99	--
250	26.1	0.90	0.4872	-0.1699	0.99	--
251	28.0	0.94	0.5651	-0.1900	1.00	--
252	29.9	1.09	0.7012	-0.2331	1.00	--
253	32.1	1.18	0.8249	-0.2716	0.99	--
254	34.0	1.25	0.9307	-0.3051	0.98	--
255	36.0	1.26	1.0013	-0.3187	0.99	--
256	38.2	1.30	1.1124	-0.3480	0.98	--
257	40.0	1.30	1.1852	-0.3674	0.98	--

End of Table B6

Table B7. S812, LEGR, Re = 1.25 x 10^6

RUN	AOA	C_l	C_{dp}	$C_{m¼}$	Re x 10^{-6}	C_{dw}
335	-20.2	-0.53	0.3009	0.0417	1.25	__
334	-18.1	-0.53	0.2666	0.0393	1.26	--
333	-16.2	-0.66	0.1527	-0.0291	1.25	--
332	-14.3	-0.68	0.1158	-0.0332	1.25	--
331	-12.1	-0.60	0.0707	-0.0357	1.25	--
330	-10.1	-0.50	0.0530	-0.0339	1.25	0.0439
329	-8.2	-0.40	0.0362	-0.0372	1.25	0.0449
328	-6.1	-0.29	0.0223	-0.0391	1.26	0.0455
327	-4.0	-0.21	0.0139	-0.0327	1.25	0.0212
326	-2.1	-0.03	0.0062	-0.0443	1.25	0.0140
325	0.1	0.20	0.0046	-0.0505	1.25	0.0123
336	0.1	0.19	0.0047	-0.0506	1.25	0.0138
362	0.1	0.20	0.0048	-0.0507	1.25	0.0136
337	2.1	0.39	0.0072	-0.0544	1.26	0.0140
338	4.1	0.57	0.0102	-0.0516	1.26	0.0144
339	6.2	0.73	0.0171	-0.0476	1.25	0.0194
340	8.2	0.80	0.0302	-0.0459	1.25	0.0412
341	10.1	0.88	0.0444	-0.0445	1.25	--
342	11.3	0.93	0.0590	-0.0488	1.25	--
343	12.1	0.96	0.0681	-0.0496	1.25	--
344	13.2	0.97	0.0780	-0.0475	1.25	--
345	14.2	0.97	0.0861	-0.0458	1.25	--
346	15.1	0.95	0.1022	-0.0493	1.25	--
347	16.2	0.86	0.1333	-0.0618	1.26	--
348	17.2	0.81	0.1786	-0.0832	1.26	--
349	18.0	0.79	0.2114	-0.0964	1.26	--
350	19.1	0.76	0.2515	-0.1090	1.25	--
351	20.2	0.77	0.2875	-0.1200	1.26	--

Table B7. S812, LEGR, Re = 1.25 x 10^6

RUN	AOA	C_l	C_{dp}	$C_{m¼}$	Re x 10^{-6}	C_{dw}
352	22.1	0.83	0.3502	-0.1382	1.25	--
353	24.0	0.87	0.4210	-0.1570	1.26	--
354	26.0	0.91	0.4890	-0.1724	1.24	--
355	28.2	0.94	0.5667	-0.1894	1.24	--
356	30.0	1.08	0.6968	-0.2328	1.25	--
357	32.0	1.17	0.8127	-0.2692	1.23	--
358	34.2	1.22	0.9151	-0.2969	1.24	--
359	36.0	1.27	1.0124	-0.3246	1.23	--
360	38.0	1.27	1.0759	-0.3351	1.23	--
361	40.0	1.29	1.1753	-0.3636	1.23	--

End of Table B7

Table B8. S812, LEGR, Re = 1.5 x 10^6

RUN	AOA	C_l	C_{dp}	$C_{m\frac{1}{4}}$	Re x 10^{-6}	C_{dw}
269	-20.2	-0.52	0.3104	0.0493	1.50	--
268	-18.1	-0.64	0.2606	0.0310	1.50	--
267	-16.2	-0.65	0.1546	-0.0278	1.50	--
266	-14.3	-0.68	0.1183	-0.0320	1.50	--
265	-12.3	-0.61	0.0699	-0.0368	1.51	--
264	-10.1	-0.51	0.0528	-0.0336	1.50	0.0486
263	-8.2	-0.40	0.0359	-0.0368	1.49	0.0472
262	-6.2	-0.30	0.0238	-0.0360	1.50	0.0484
261	-4.0	-0.21	0.0143	-0.0311	1.51	0.0240
260	-2.1	-0.04	0.0065	-0.0439	1.51	0.0140
259	0.0	0.18	0.0049	-0.0496	1.50	0.0128
270	0.1	0.20	0.0052	-0.0506	1.50	0.0132
286	0.1	0.19	0.0048	-0.0508	1.50	0.0132
271	2.1	0.41	0.0062	-0.0538	1.51	0.0122
272	4.1	0.59	0.0104	-0.0543	1.51	0.0134
273	6.0	0.74	0.0146	-0.0493	1.51	0.0192
274	8.2	0.82	0.0313	-0.0482	1.50	0.0374
275	10.2	0.88	0.0427	-0.0422	1.52	--
276	11.3	0.93	0.0563	-0.0457	1.51	--
277	12.3	0.97	0.0697	-0.0485	1.50	--
278	13.2	0.97	0.0785	-0.0474	1.50	--
279	14.2	0.98	0.0879	-0.0453	1.50	--
280	15.1	0.94	0.1021	-0.0490	1.50	--
281	16.2	0.88	0.1355	-0.0636	1.49	--
282	17.2	0.83	0.1775	-0.0823	1.50	--
283	18.0	0.79	0.2176	-0.0995	1.51	--
284	19.1	0.76	0.2589	-0.1128	1.51	--
285	20.2	0.78	0.2927	-0.1229	1.52	--

End of Table B8

S812

Pressure Distributions, Steady State, Re = 0.75 million

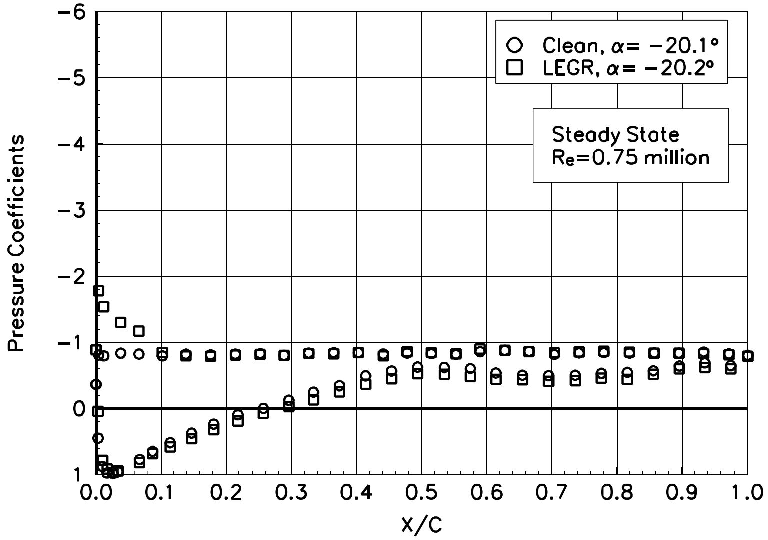

Figure 1. α = -20.1°

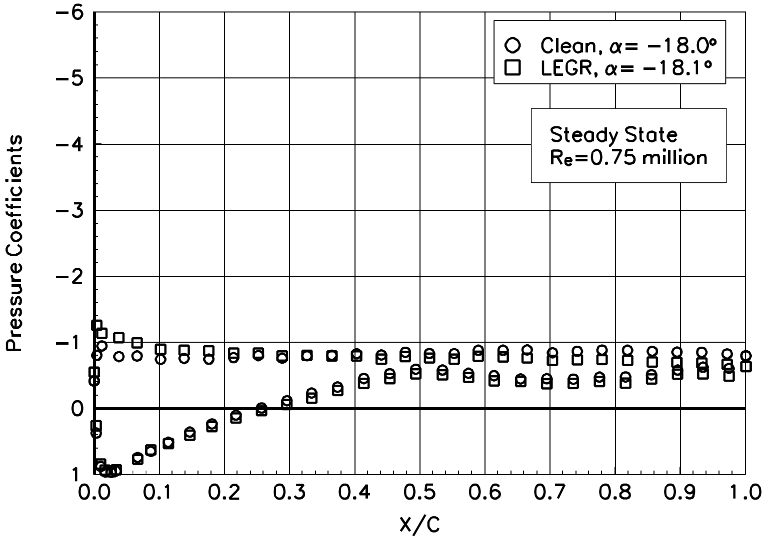

Figure 2. α = -18.0°

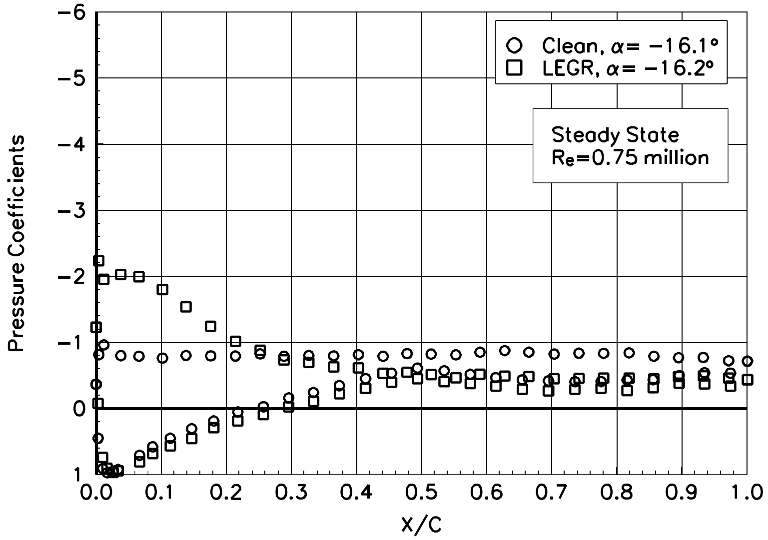

Figure 3. α = -16.1°

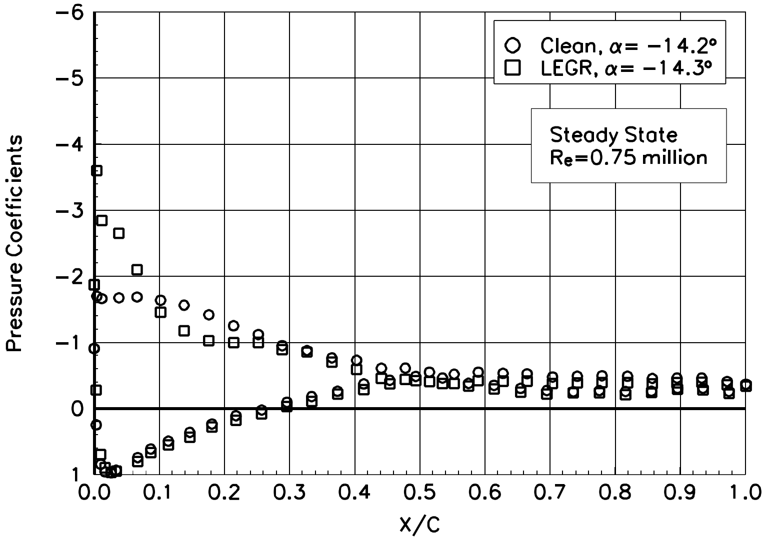

Figure 4. α = -14.2°

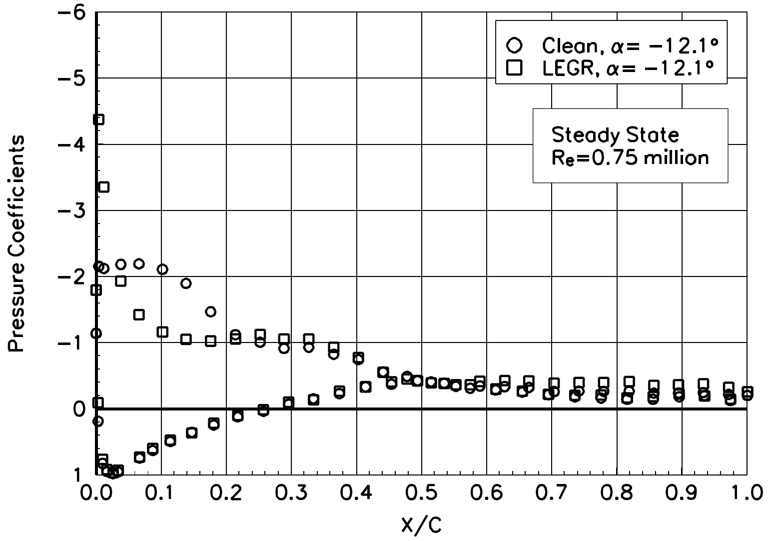

Figure 5. α = -12.1°

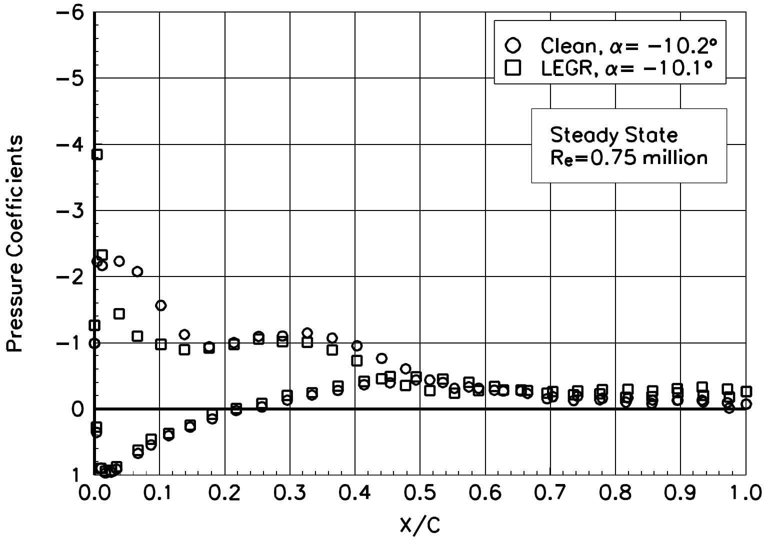

Figure 6. α = -10.2°

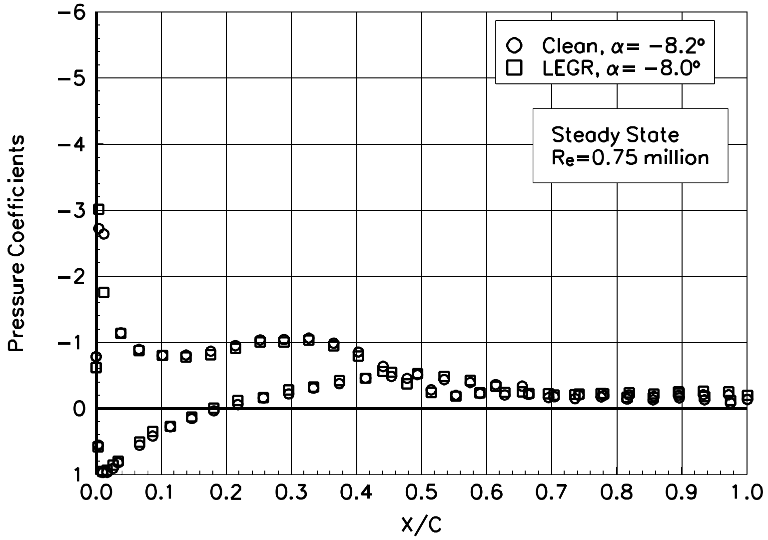

Figure 7. α = -8.2°

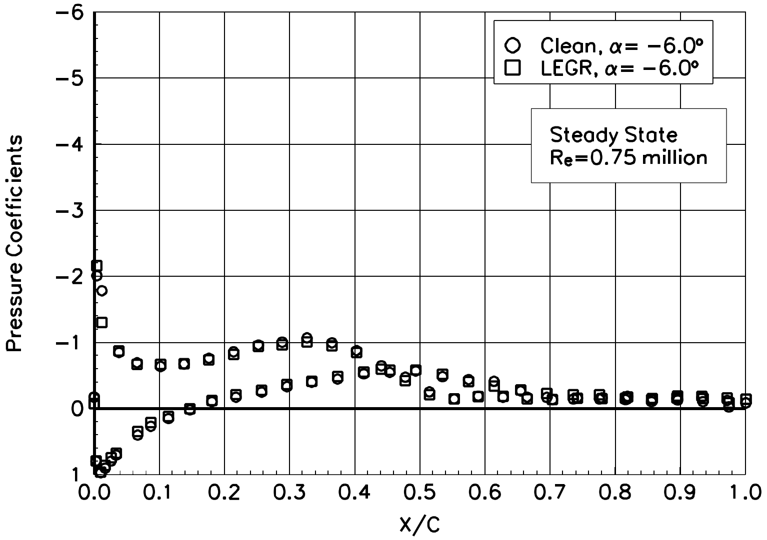

Figure 8. α = -6.0°

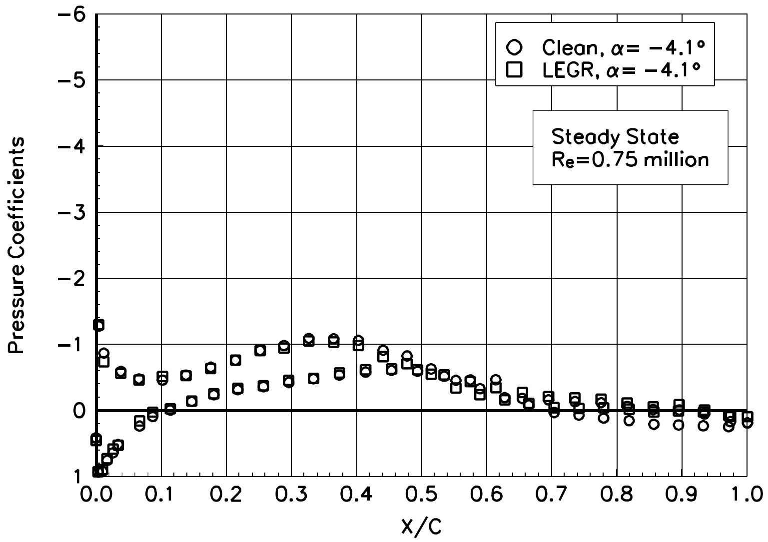

Figure 9. α = -4.1°

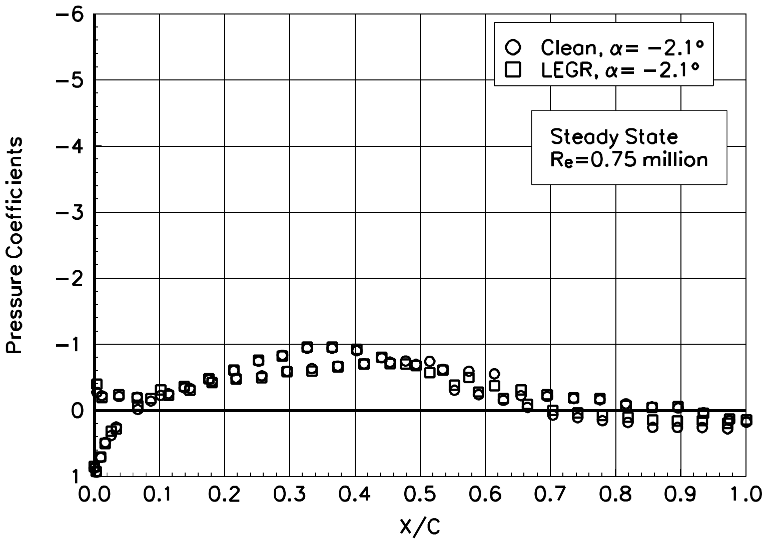

Figure 10. α = -2.1°

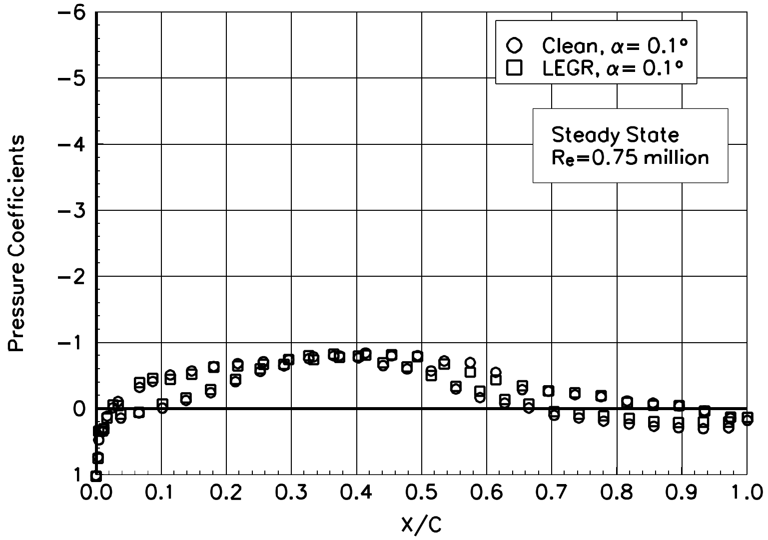

Figure 11. α = 0.1°

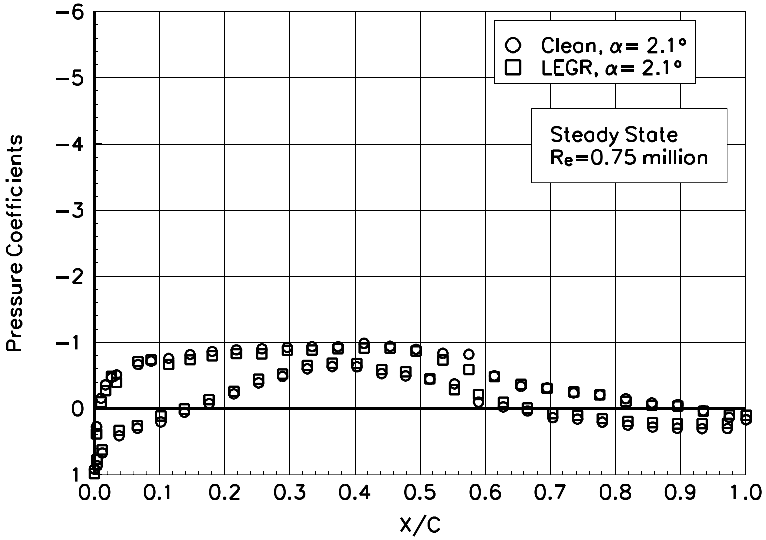

Figure 12. α = 2.1°

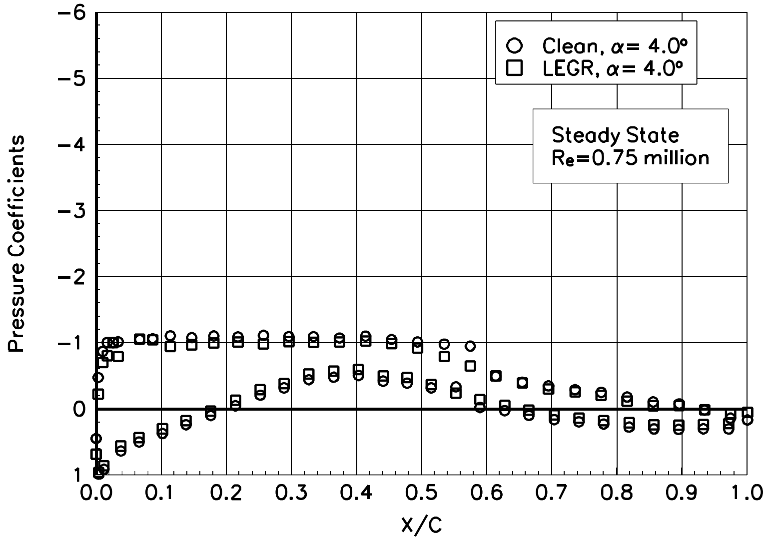

Figure 13. α = 4.0°

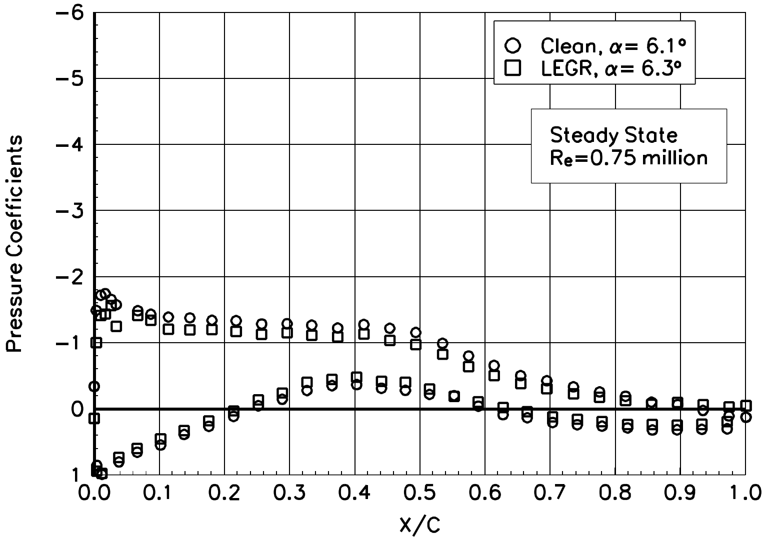

Figure 14. α = 6.1°

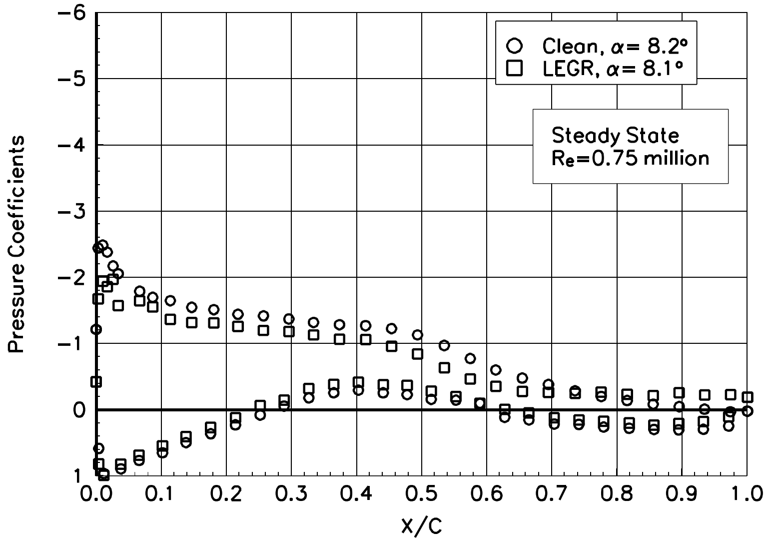

Figure 15. α = 8.2°

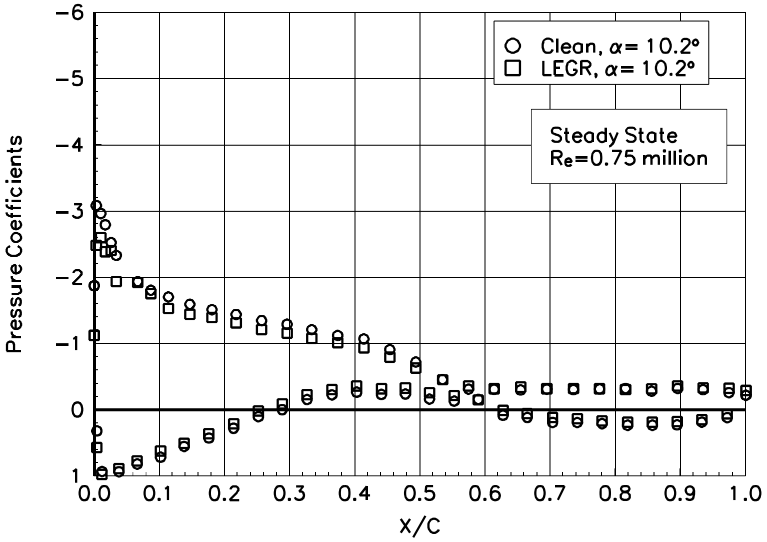

Figure 16. α = 10.2°

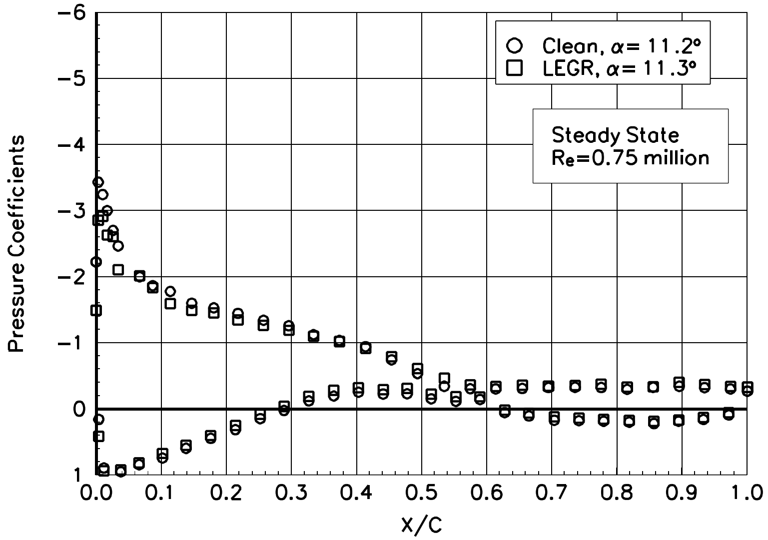

Figure 17. α = 11.2°

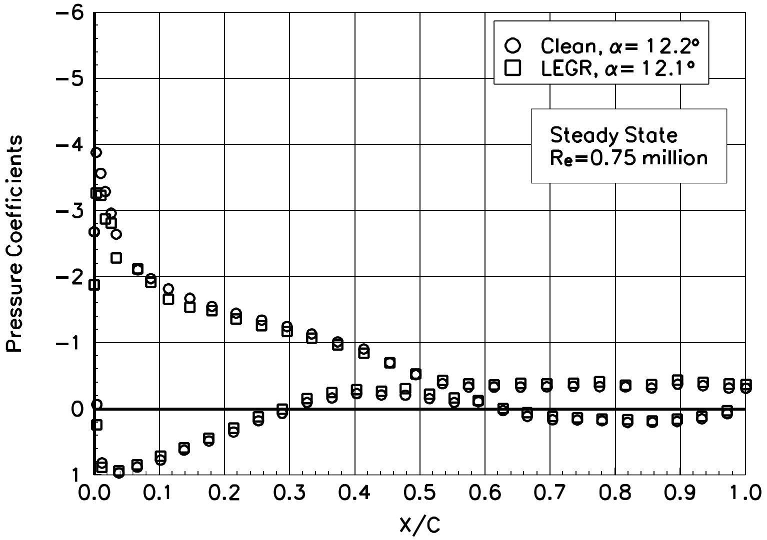

Figure 18. α = 12.2°

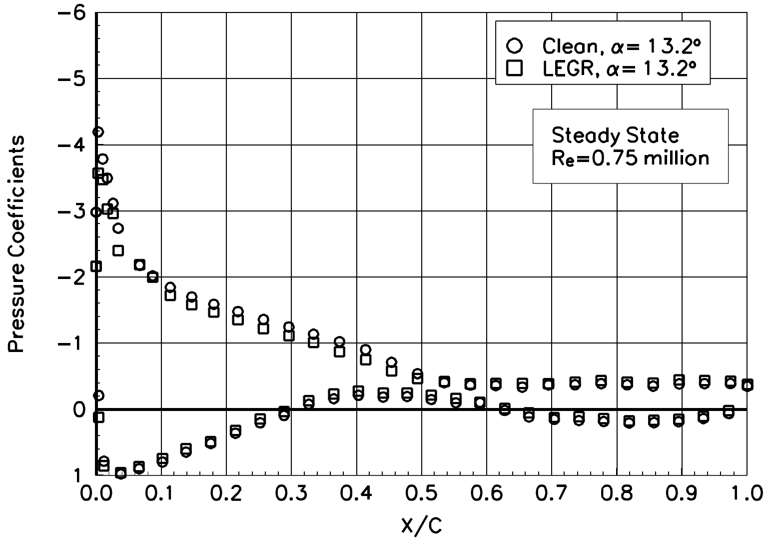

Figure 19. α = 13.2°

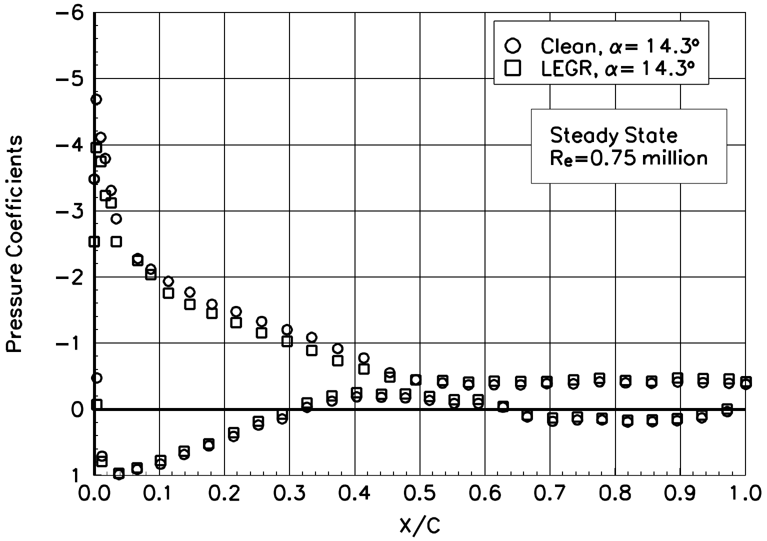

Figure 20. α = 14.3°

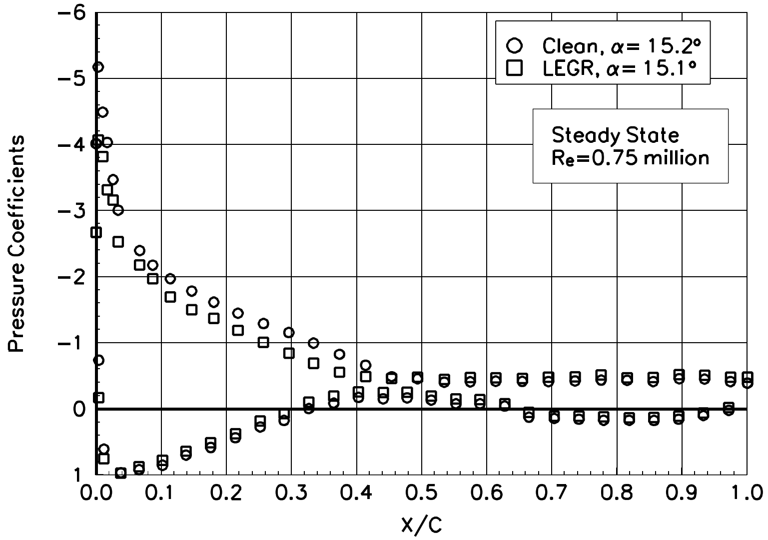

Figure 21. α = 15.2˙

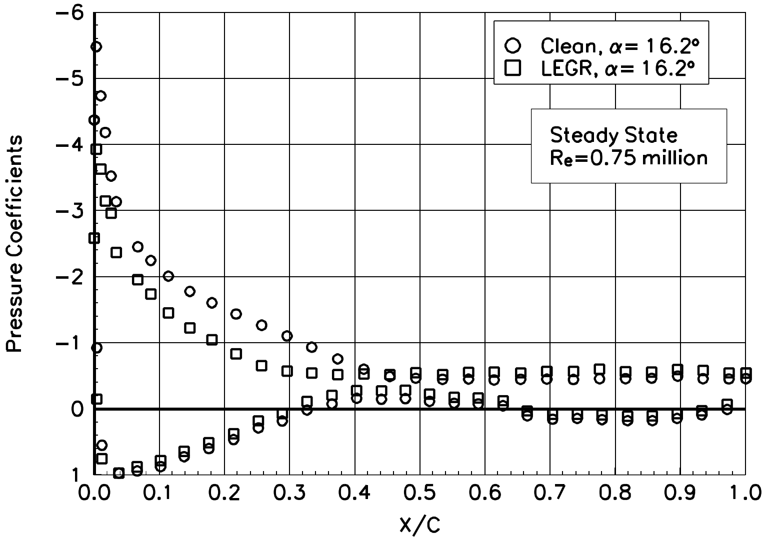

Figure 22. α = 16.2°

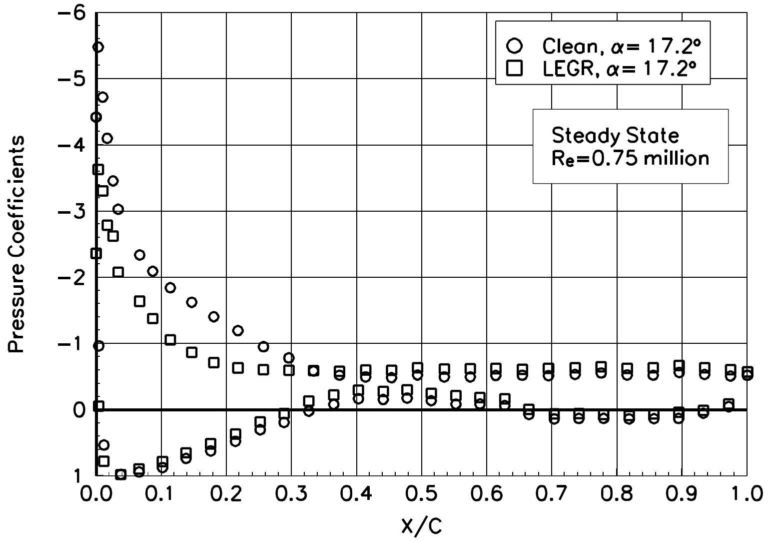

Figure 23. α = 17.2°

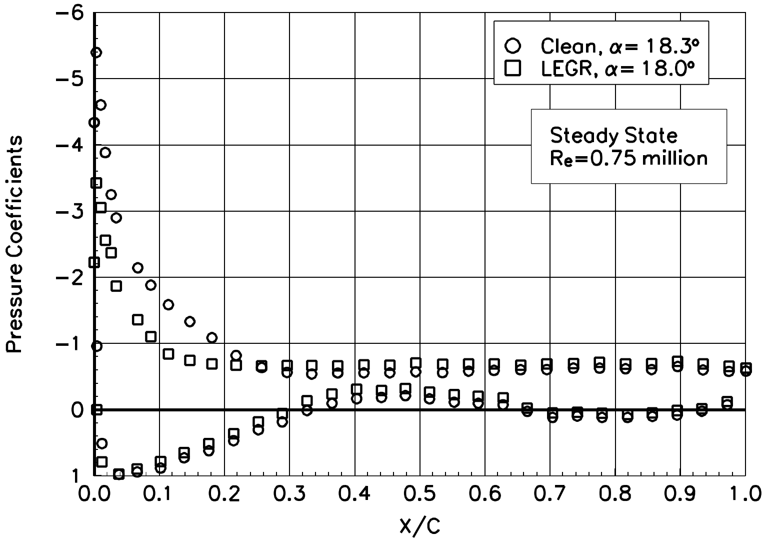

Figure 24. α = 18.3°

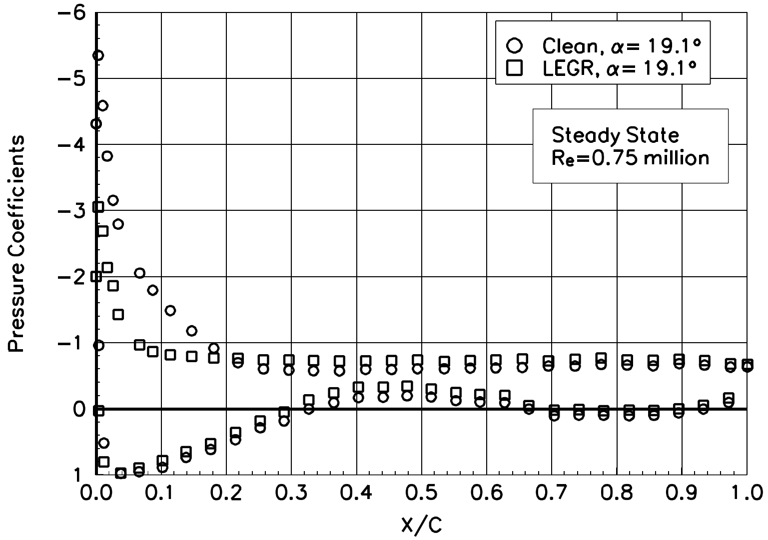

Figure 25. $\alpha = 19.1°$

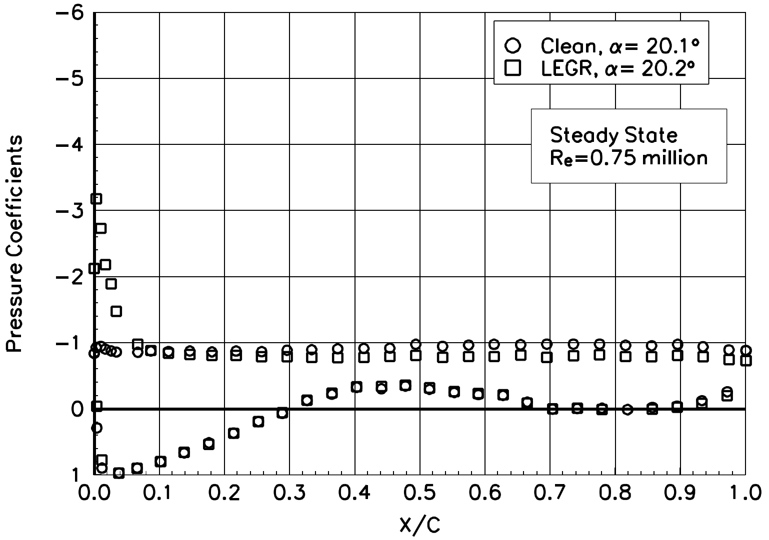

Figure 26. $\alpha = 20.1°$

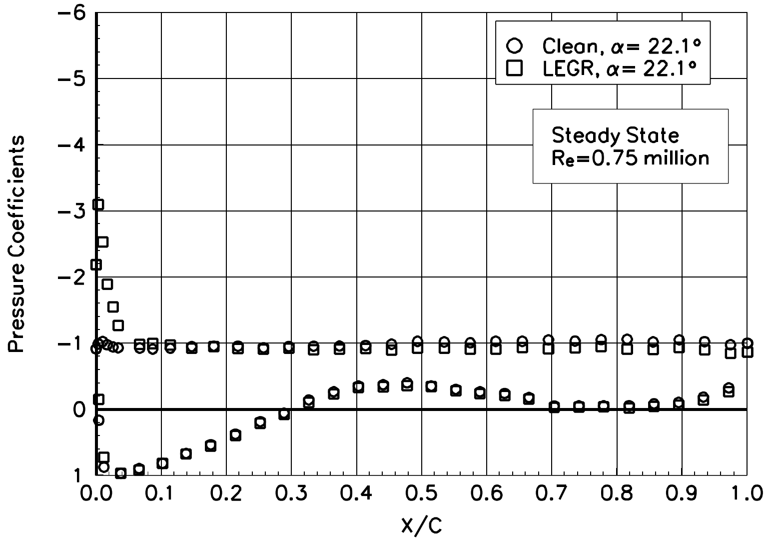

Figure 27. $\alpha = 22.1°$

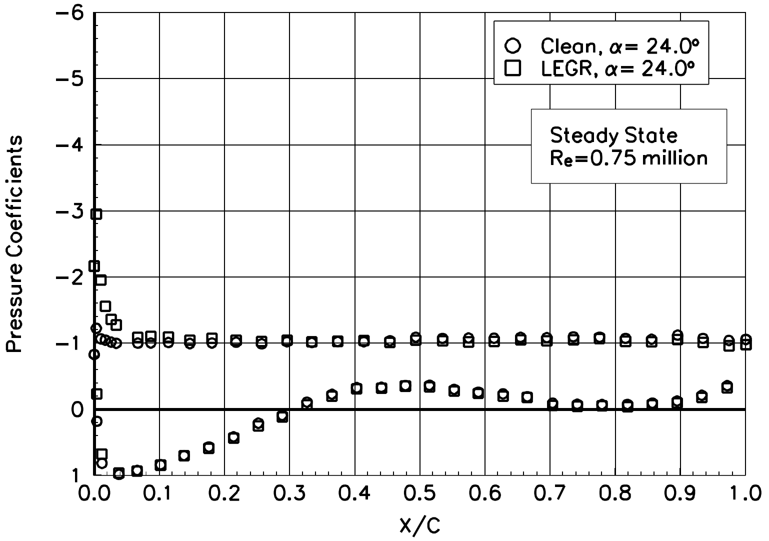

Figure 28. $\alpha = 24.0°$

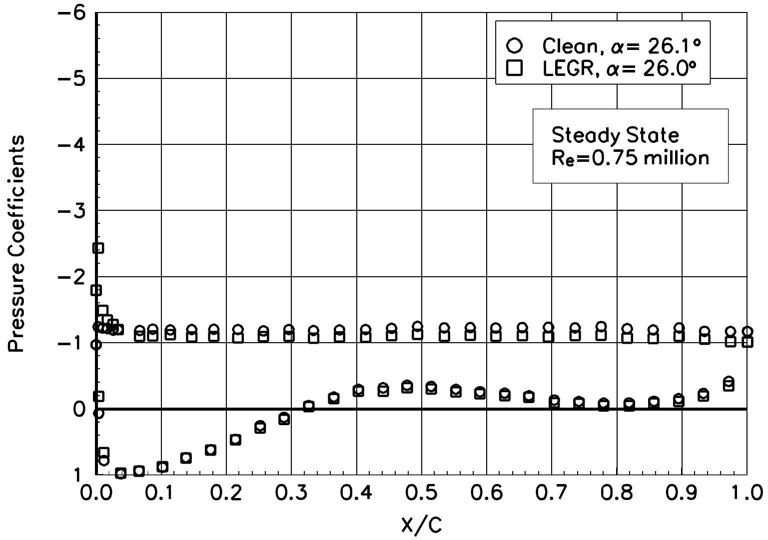

Figure 29. α = 26.1°

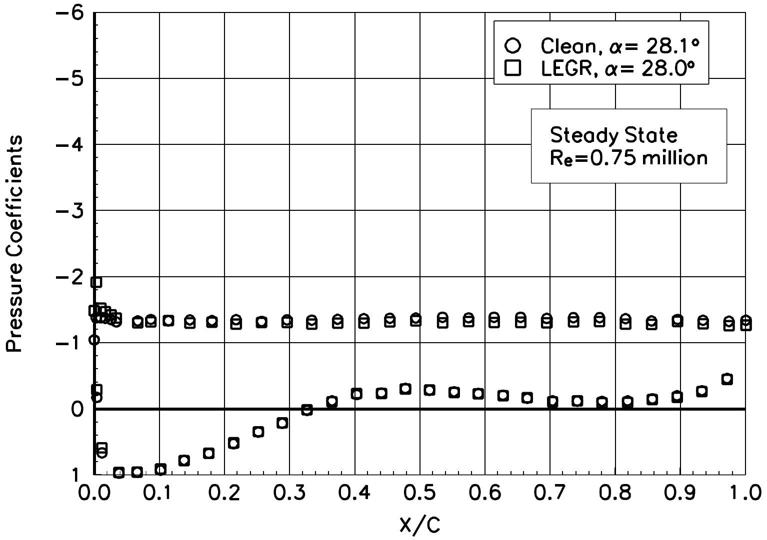

Figure 30. α = 28.1°

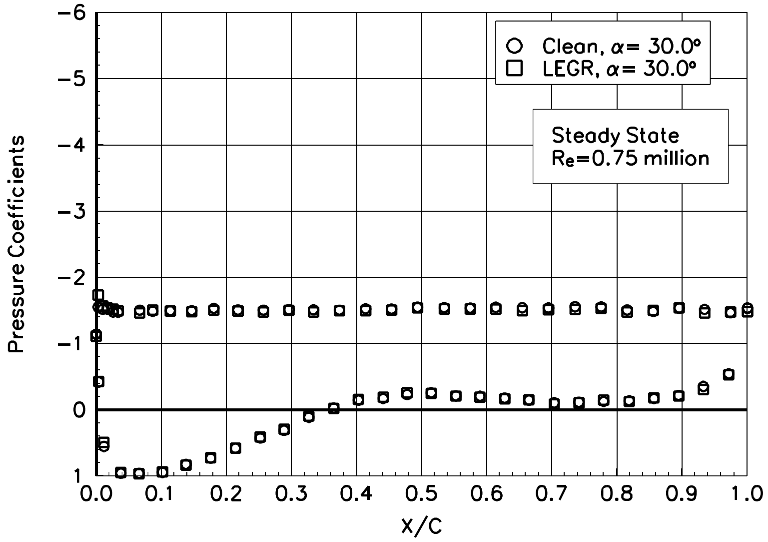

Figure 31. α = 30.0°

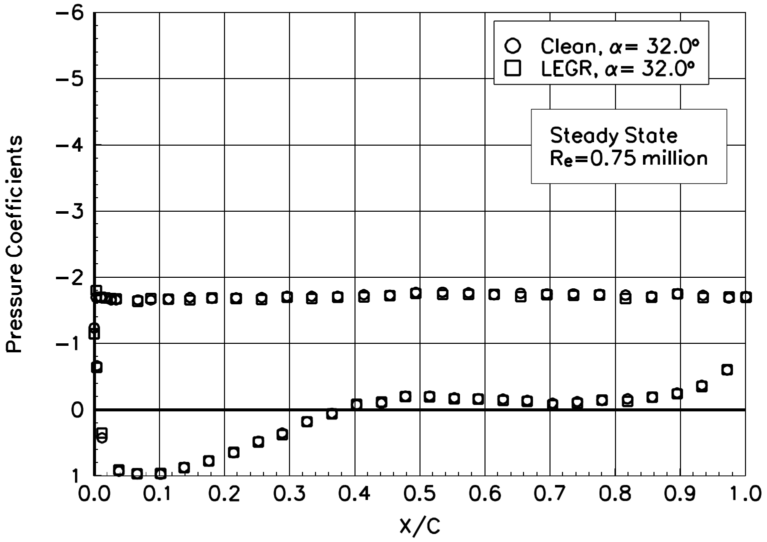

Figure 32. α = 32.0°

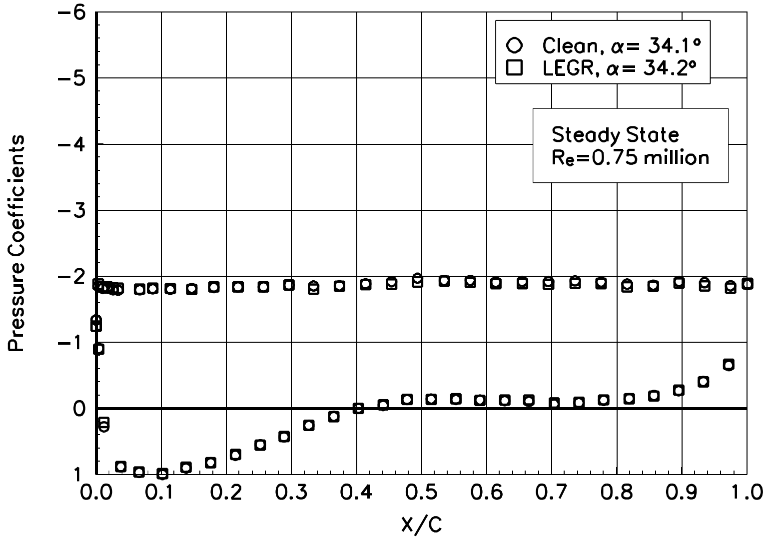

Figure 33. α = 34.1°

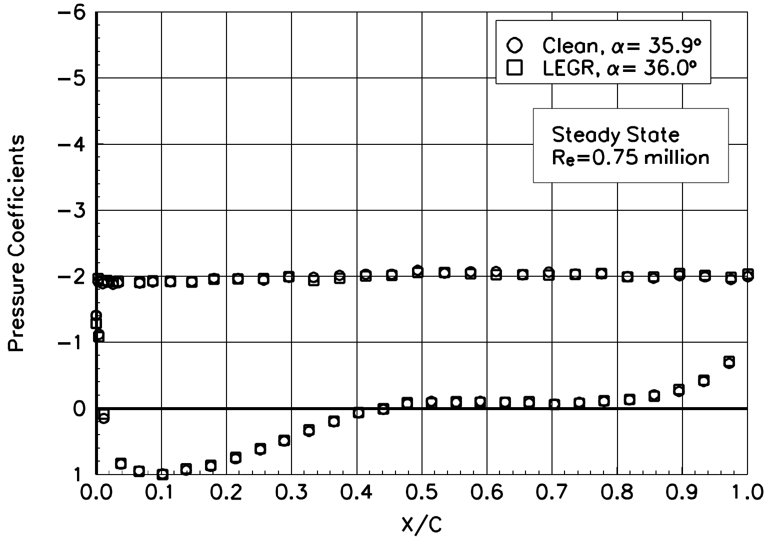

Figure 34. α = 35.9°

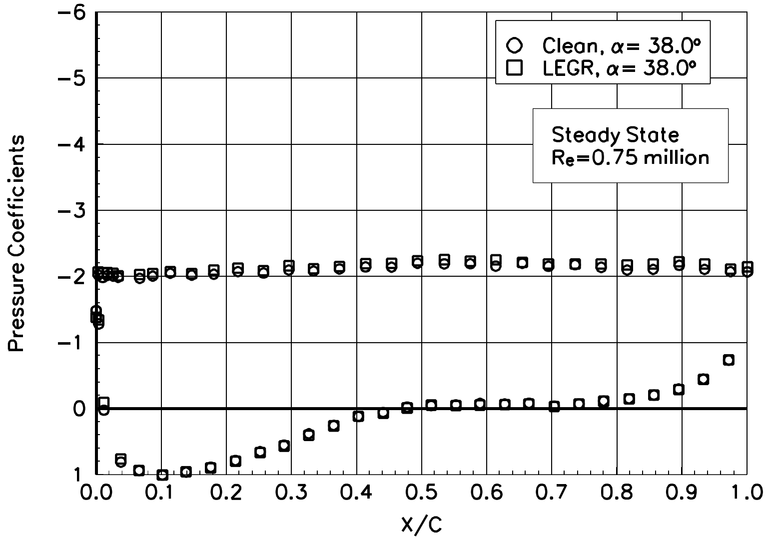

Figure 35. α = 38.0°

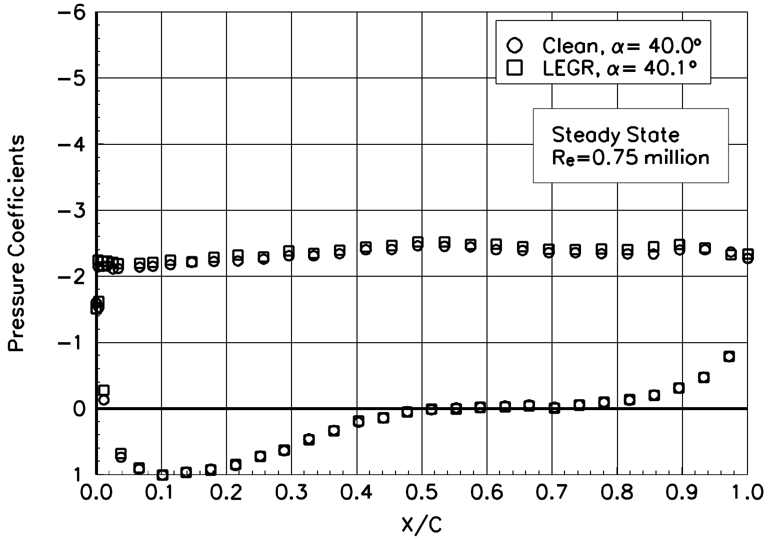

Figure 36. α = 40.0°

S812

Pressure Distributions, Steady State, Re = 1 million

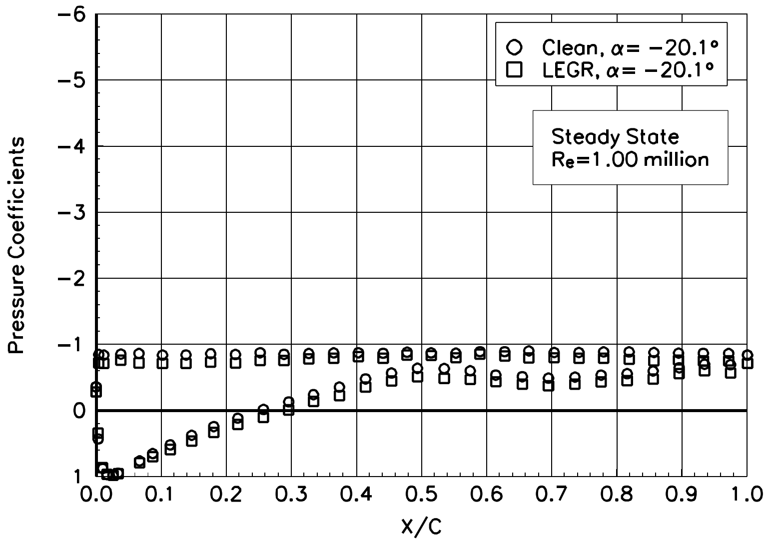

Figure 37. α = -20.1°

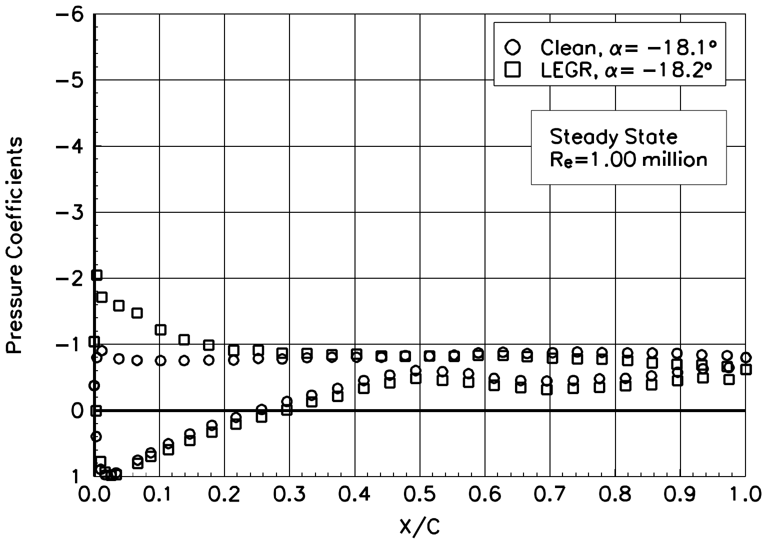

Figure 38. α = -18.1°

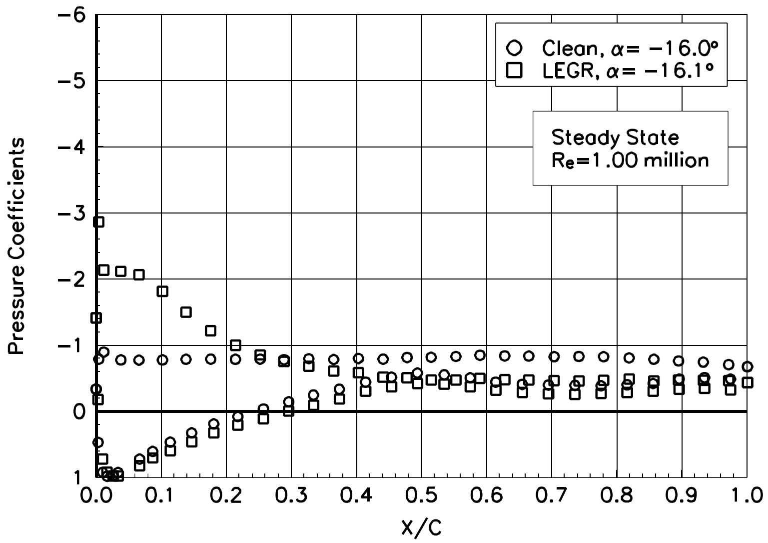

Figure 39. α = -16.0°

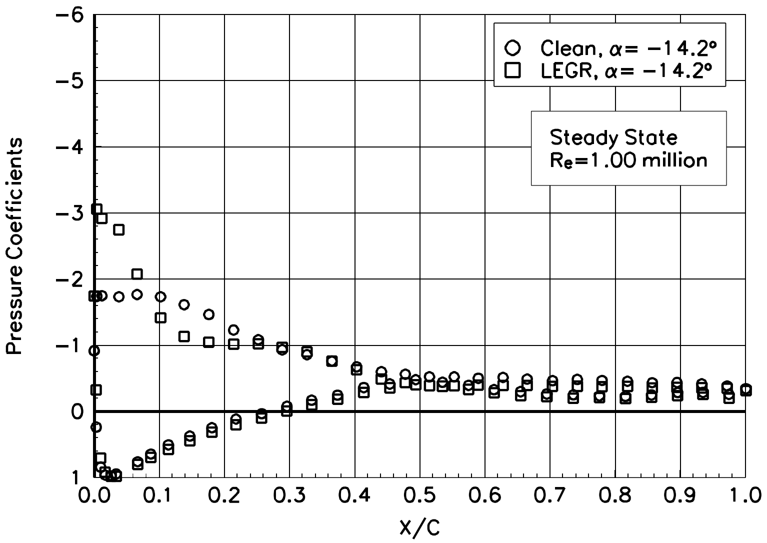

Figure 40. α = -14.2°

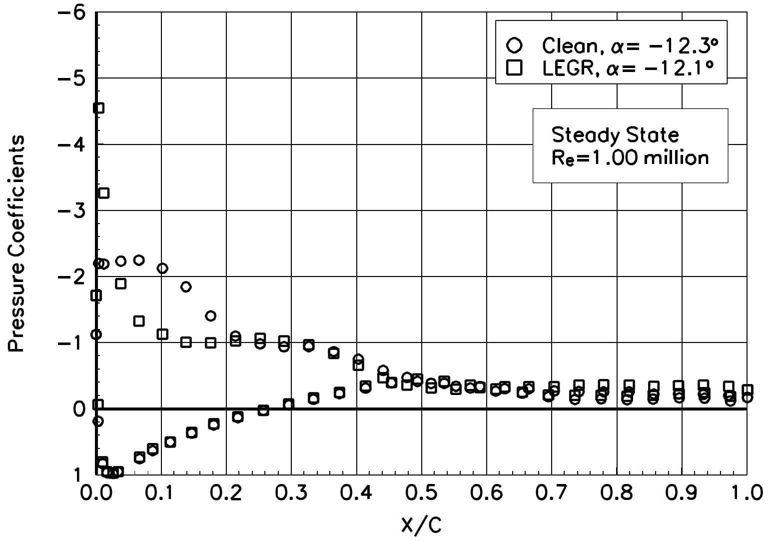

Figure 41. α = -12.3°

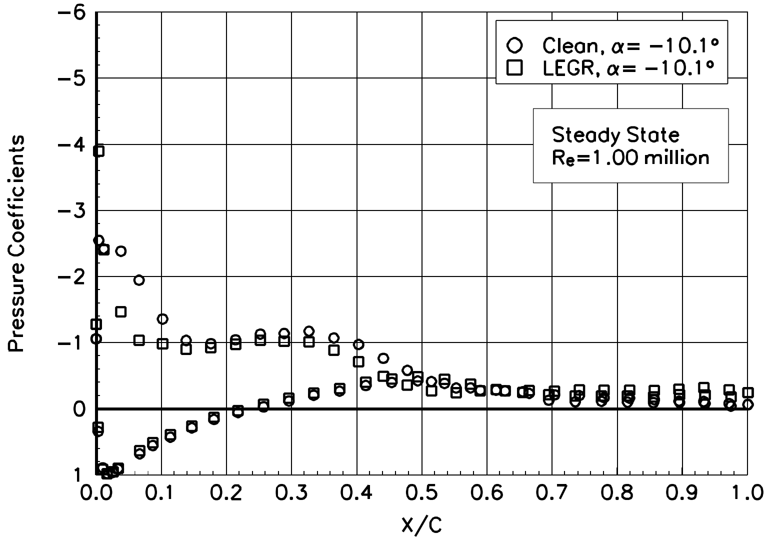

Figure 42. α = -10.1°

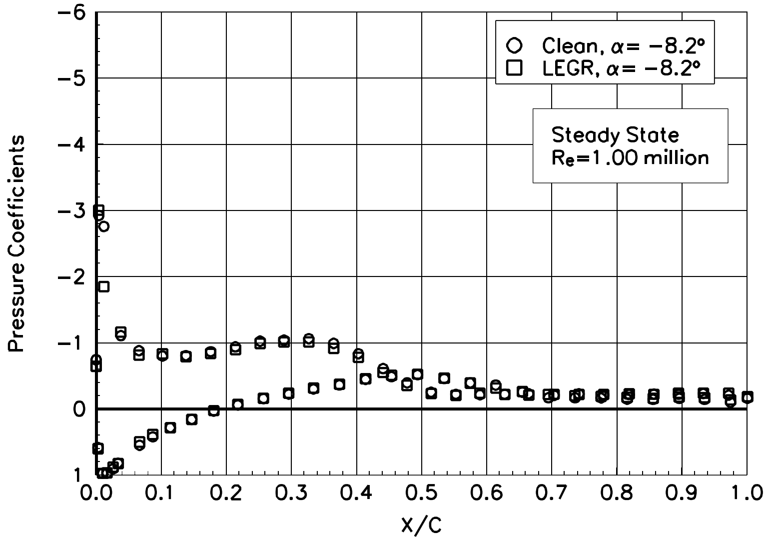

Figure 43. α = -8.2°

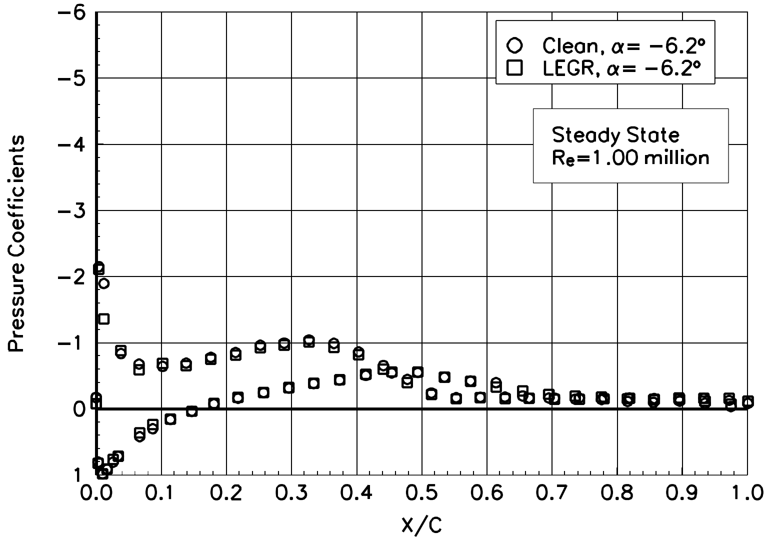

Figure 44. α = -6.2°

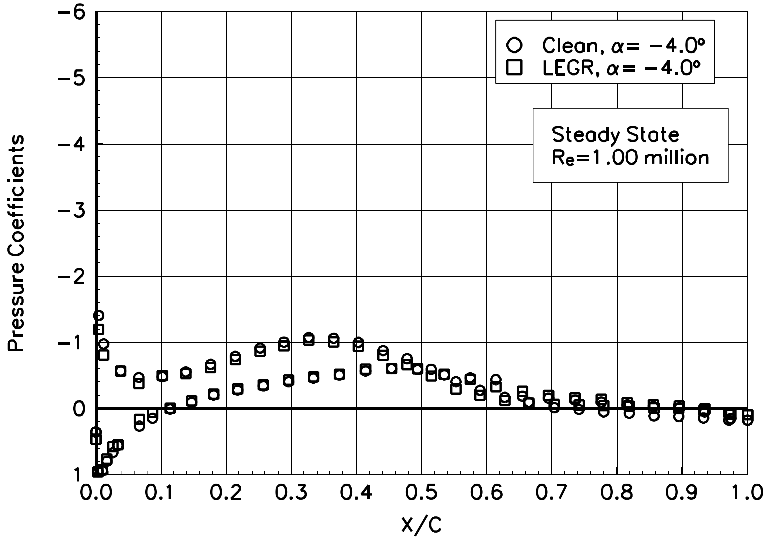

Figure 45. α = -4.0°

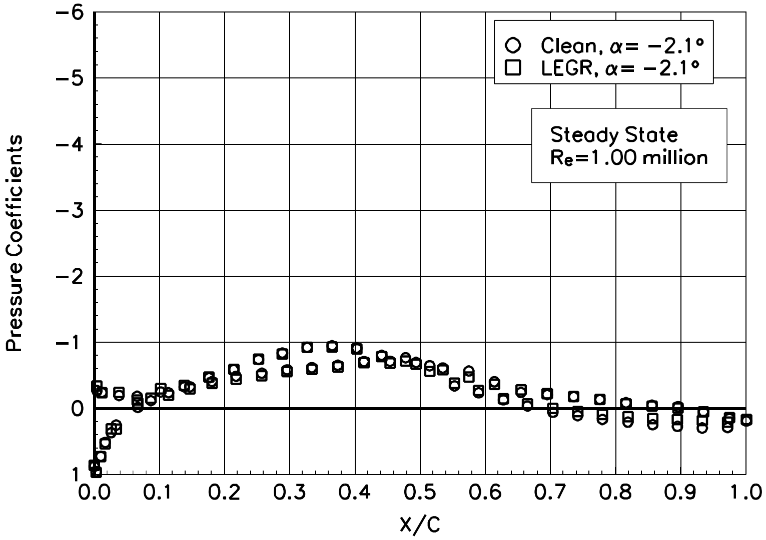

Figure 46. α = -2.1°

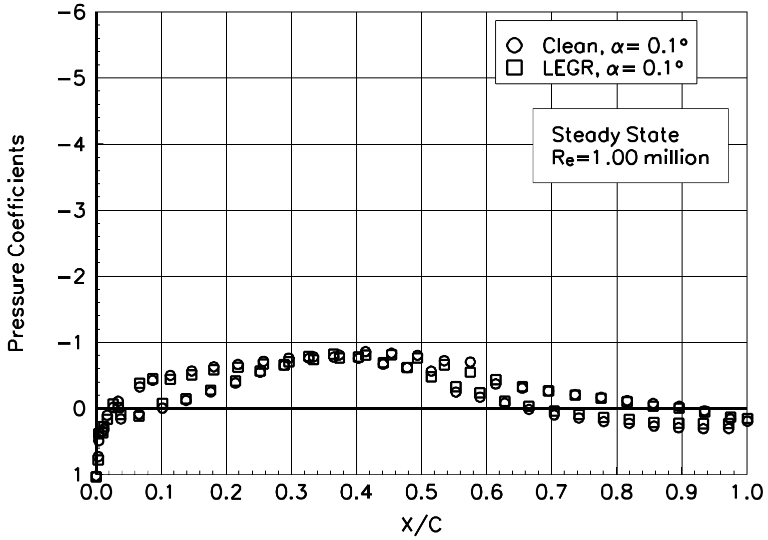

Figure 47. α = 0.1°

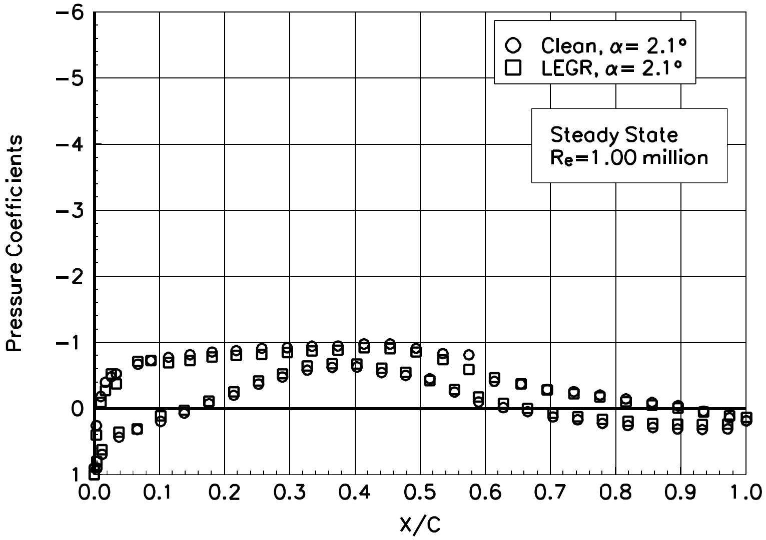

Figure 48. α = 2.1°

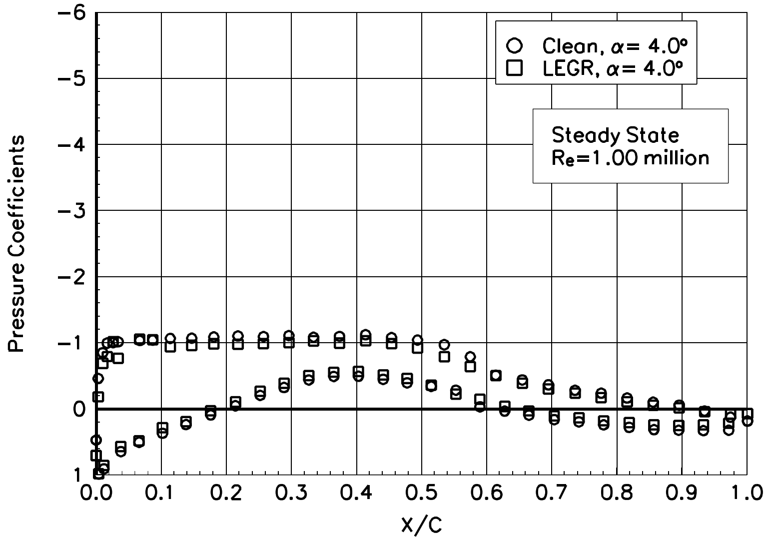

Figure 49. α = 4.0°

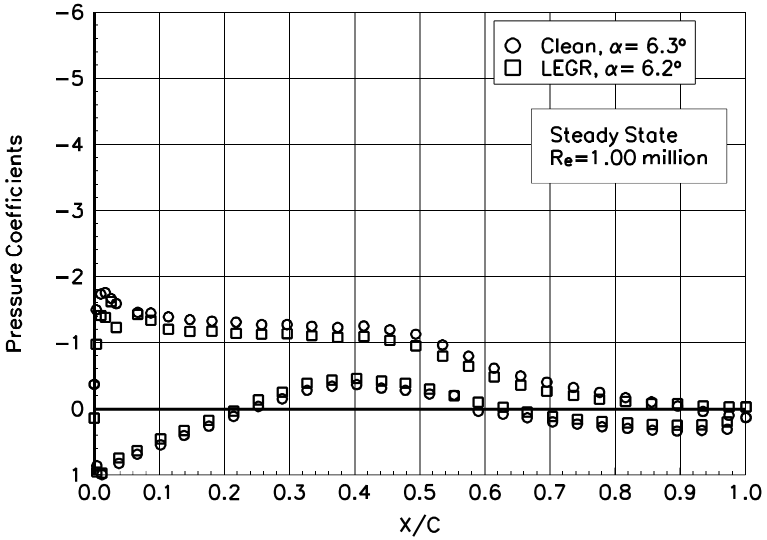

Figure 50. α = 6.3°

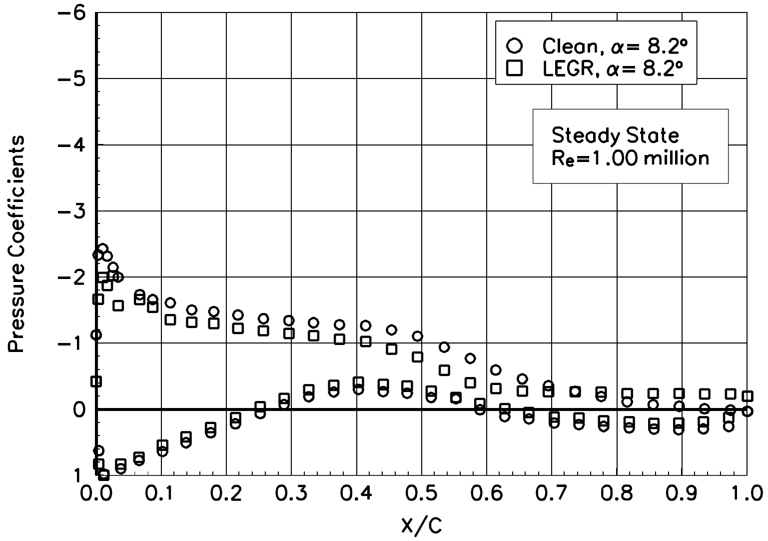

Figure 51. α = 8.2°

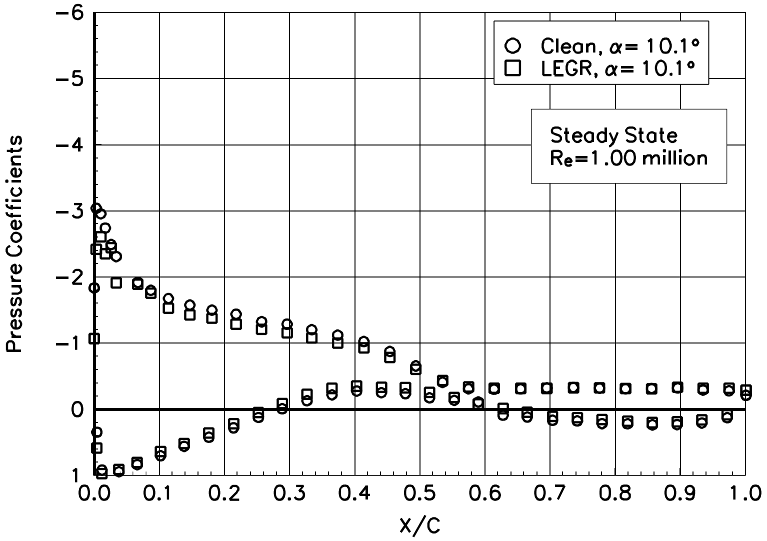

Figure 52. α = 10.1°

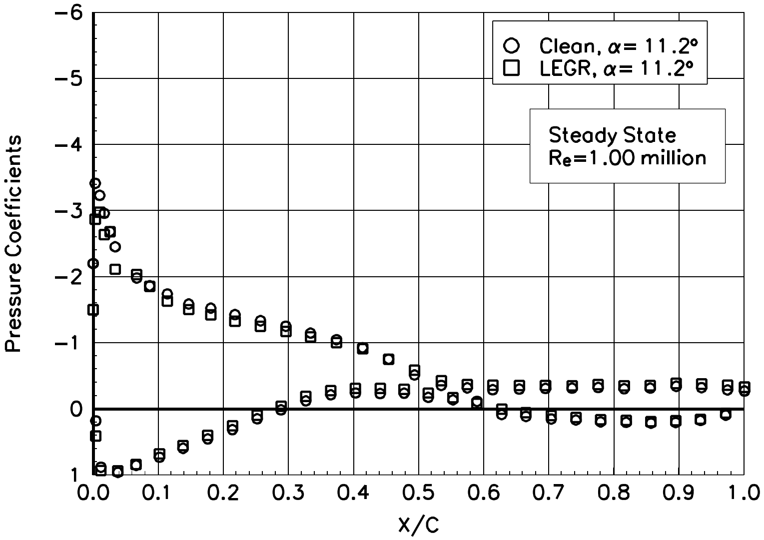

Figure 53. α = 11.2°

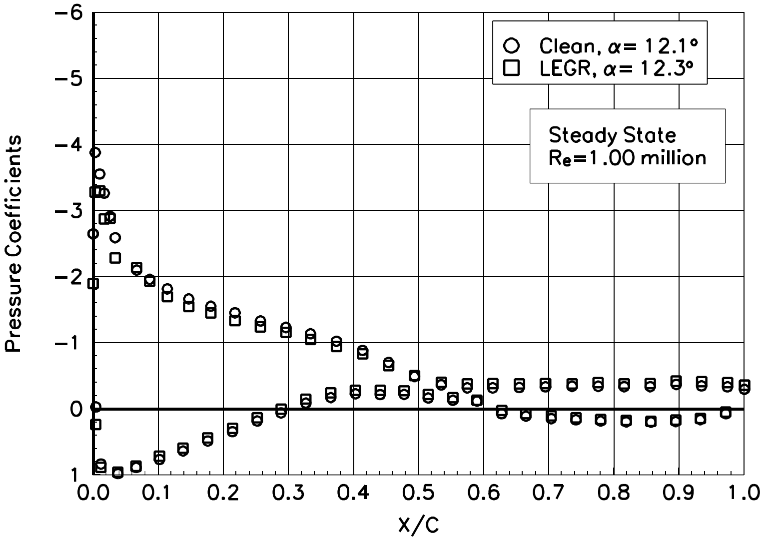

Figure 54. α = 12.1°

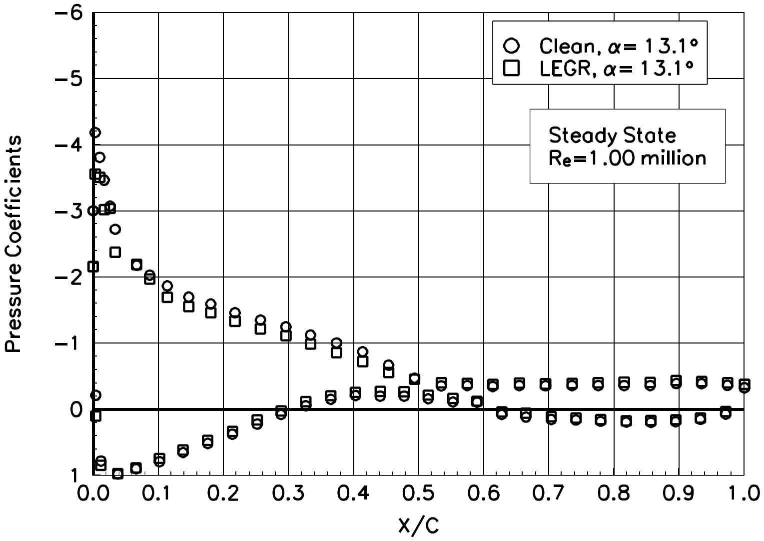

Figure 55. α = 13.1°

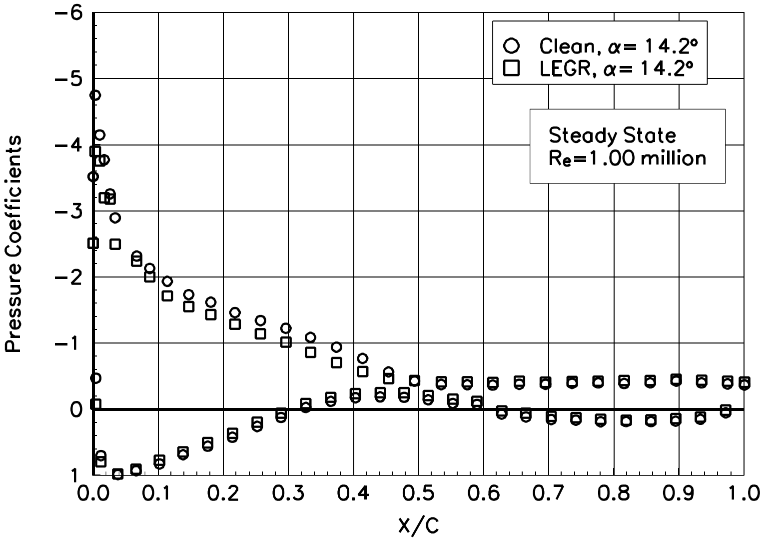

Figure 56. α = 14.2°

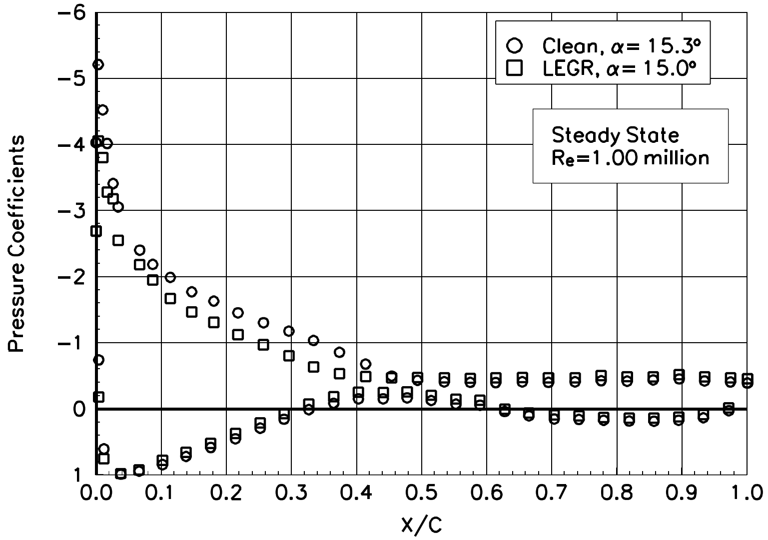

Figure 57. α = 15.3°

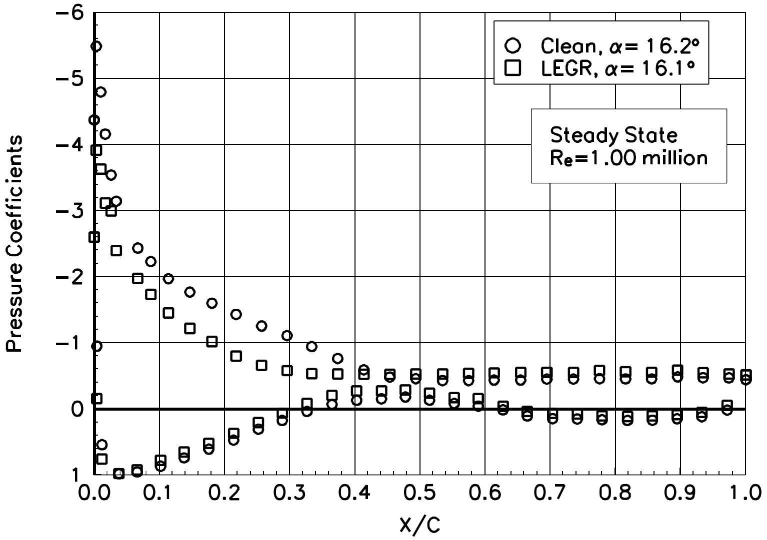

Figure 58. α = 16.2°

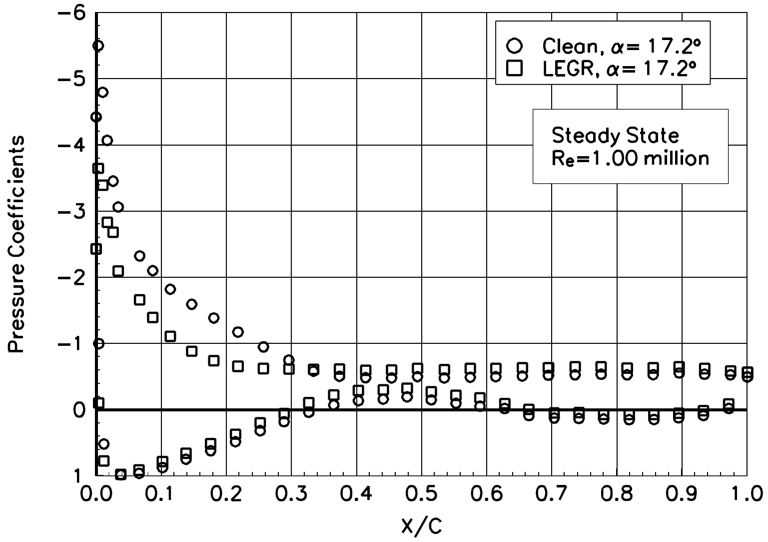

Figure 59. α = 17.2°

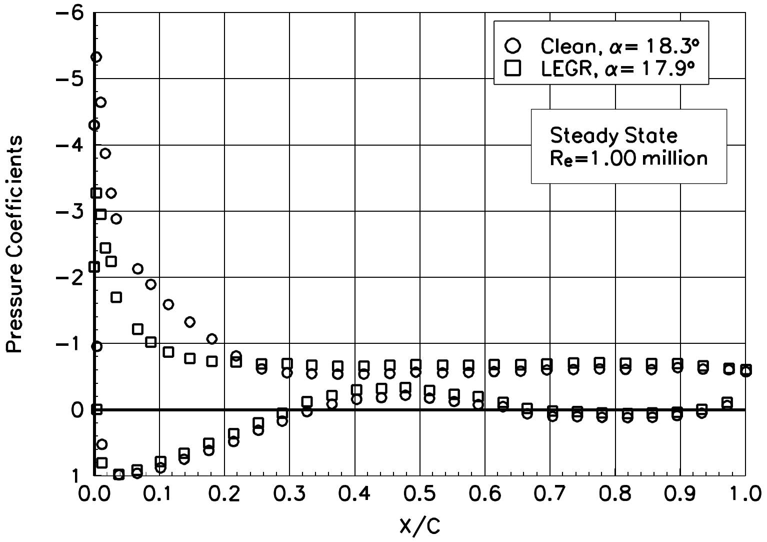

Figure 60. α = 18.3°

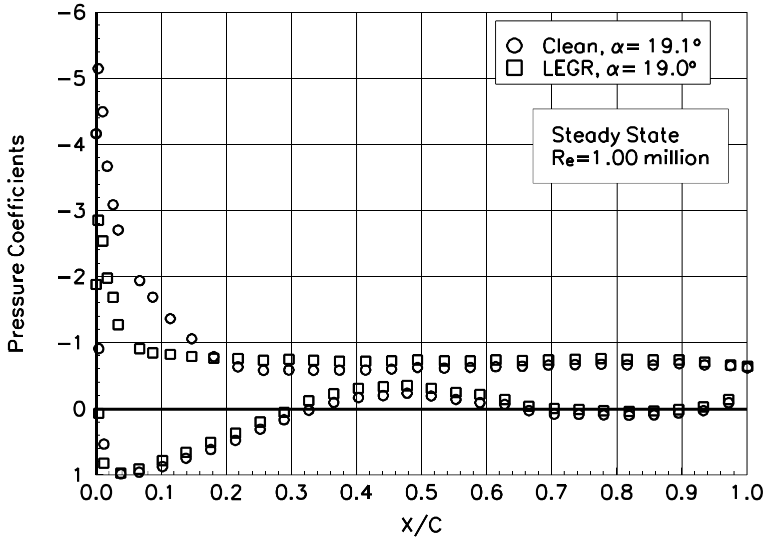

Figure 61. α = 19.1°

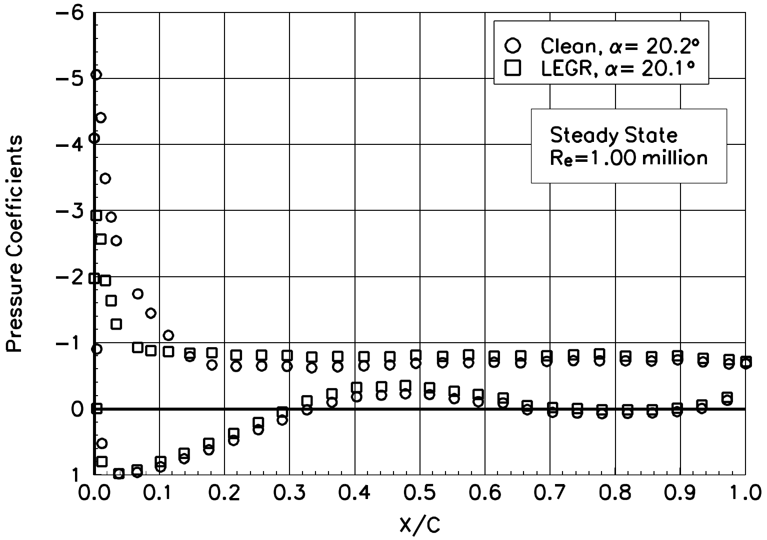

Figure 62. α = 20.2°

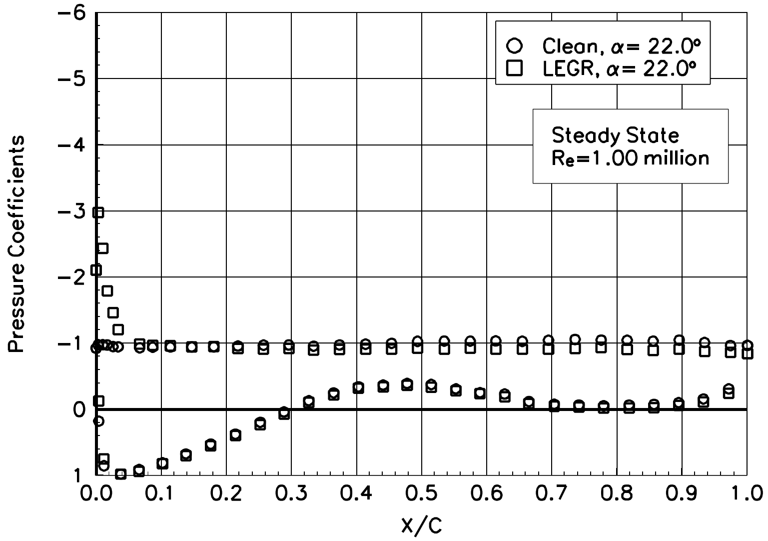

Figure 63. α = 22.0°

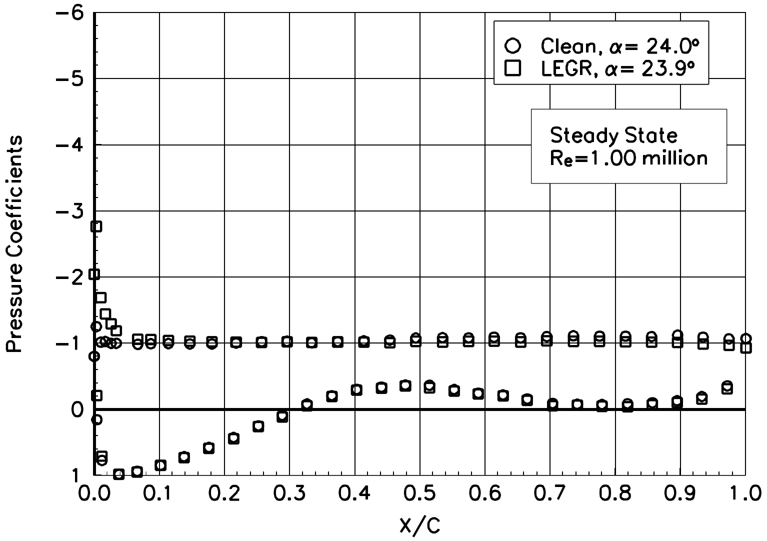

Figure 64. α = 24.0°

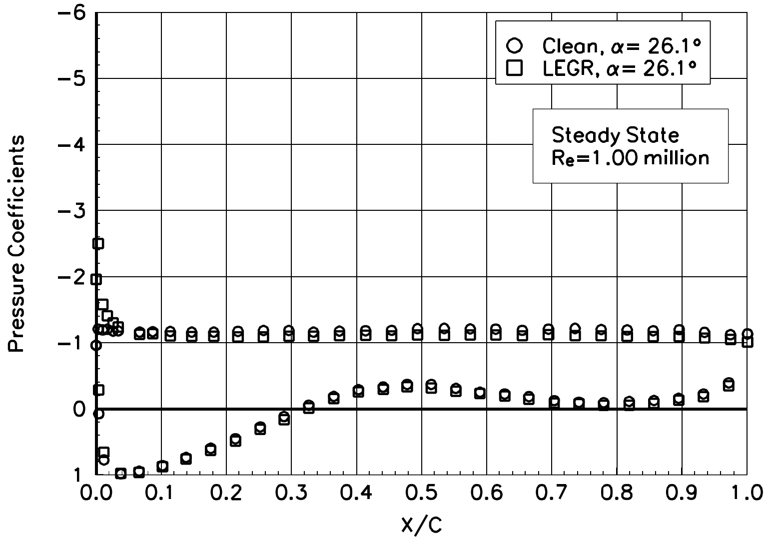

Figure 65. α = 26.1°

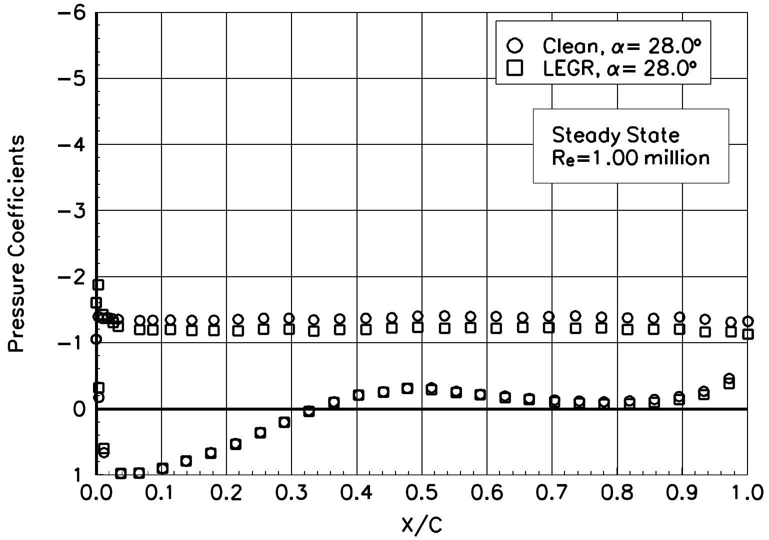

Figure 66. α = 28.0°

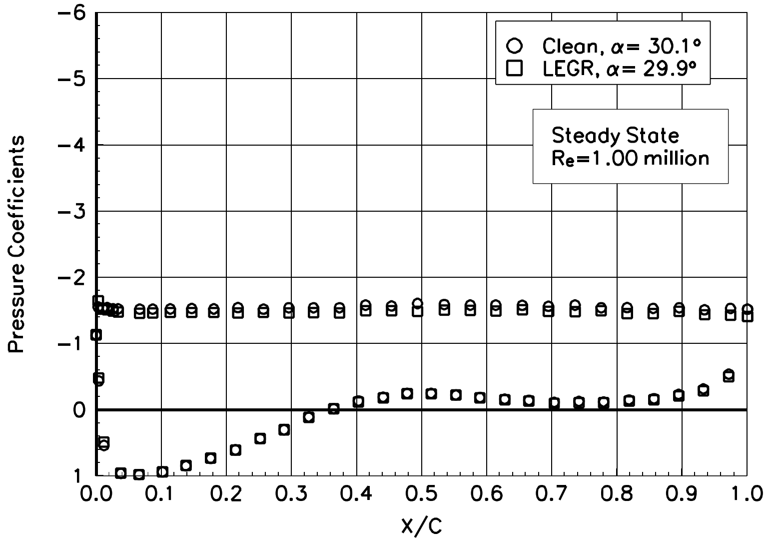

Figure 67. α = 30.1°

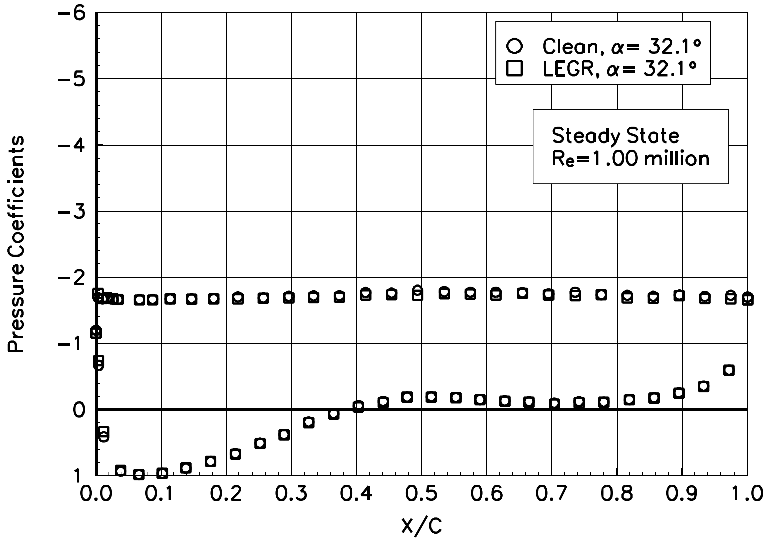

Figure 68. α = 32.1°

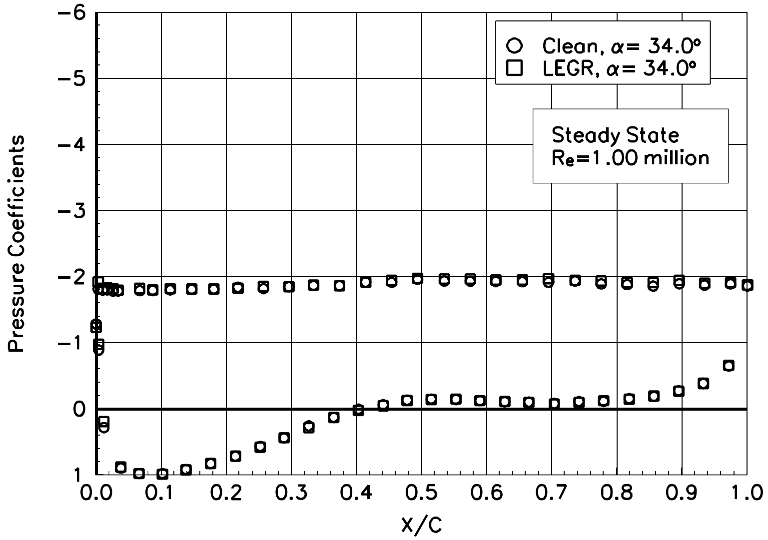

Figure 69. α = 34.0°

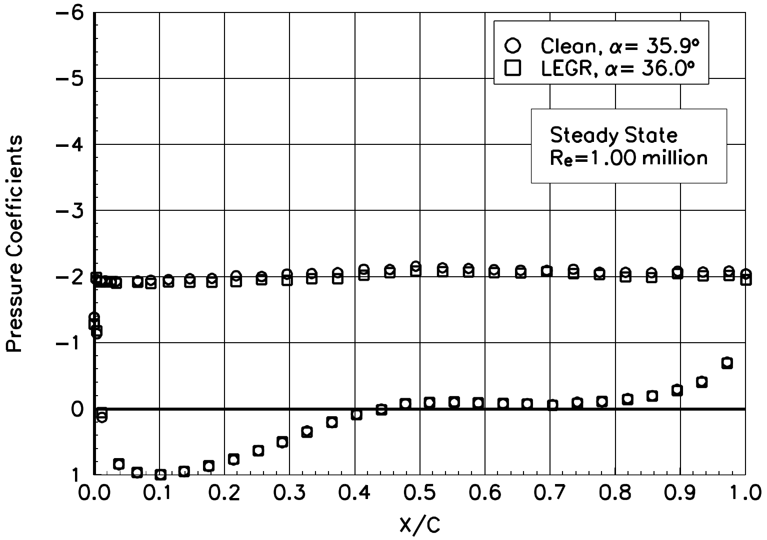

Figure 70. α = 35.9°

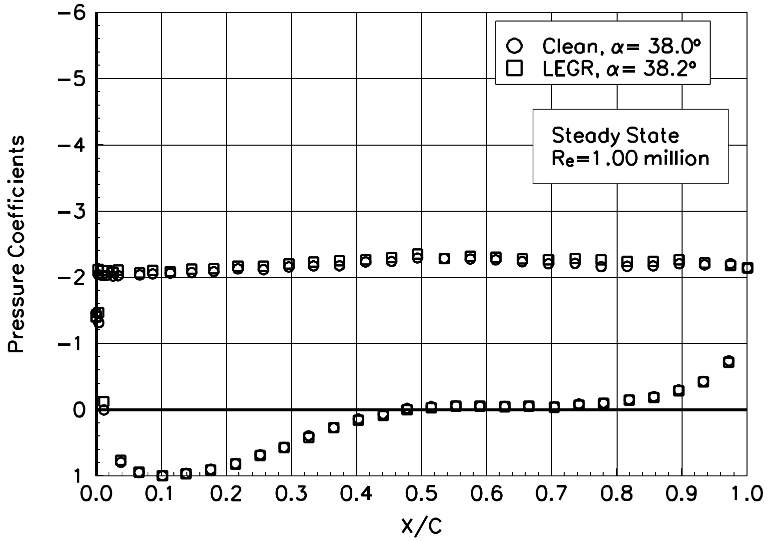

Figure 71. α = 38.0°

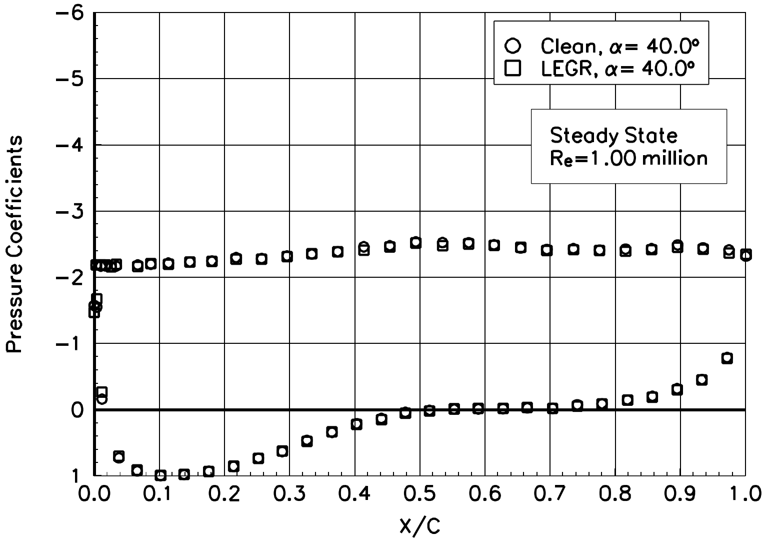

Figure 72. α = 40.0°

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Pressure Distributions, Steady State, Re = 1.25 million

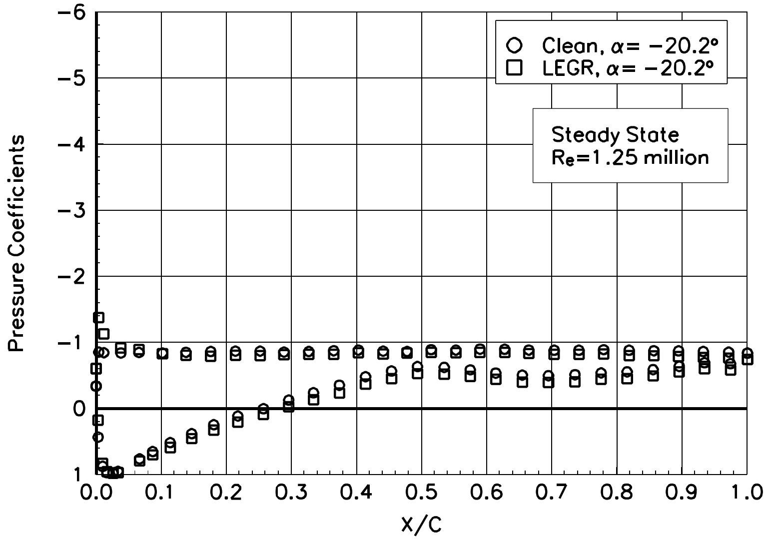

Figure 73. α = -20.2°

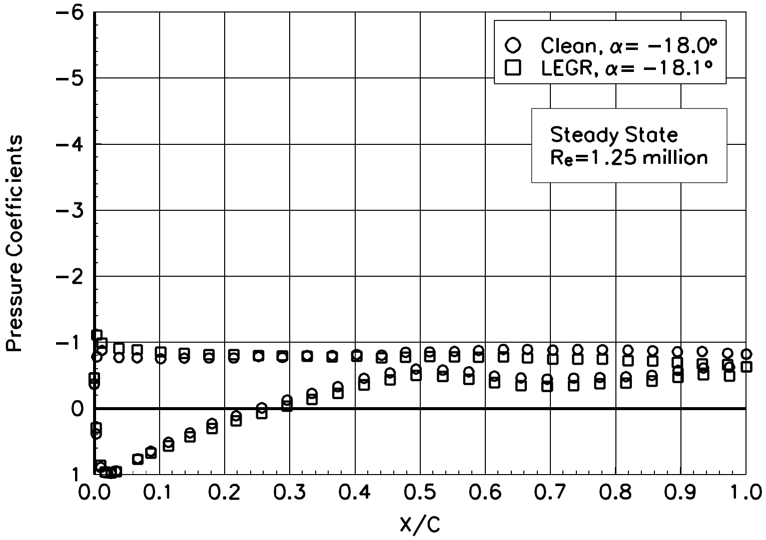

Figure 74. α = -18.0°

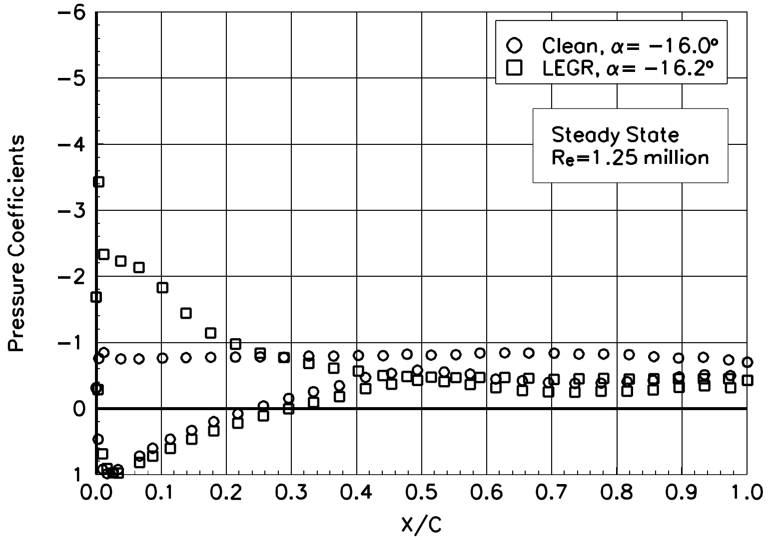

Figure 75. α = -16.0°

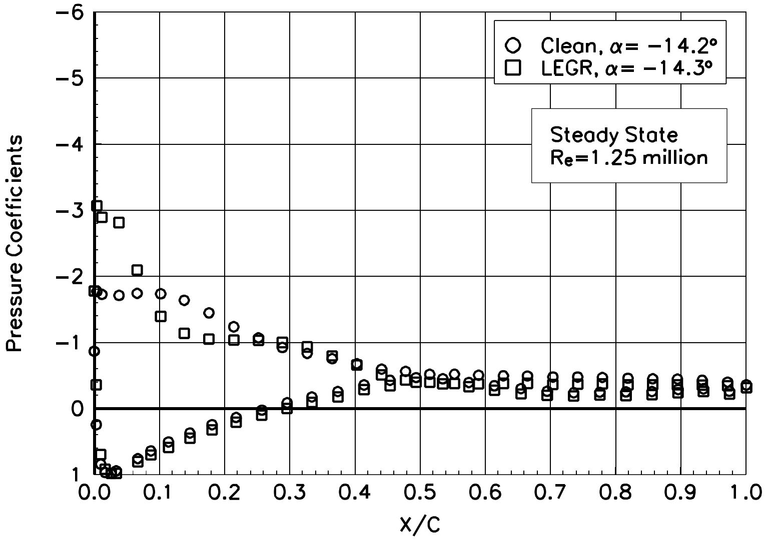

Figure 76. α = -14.2°

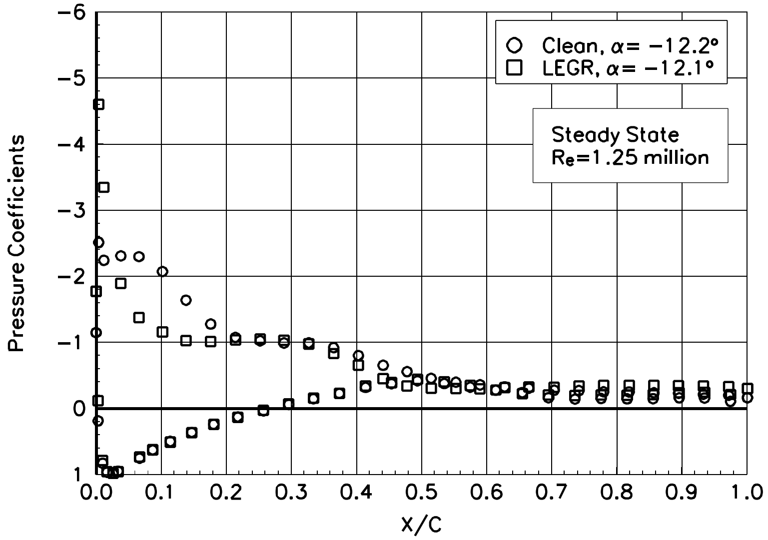

Figure 77. α = -12.2°

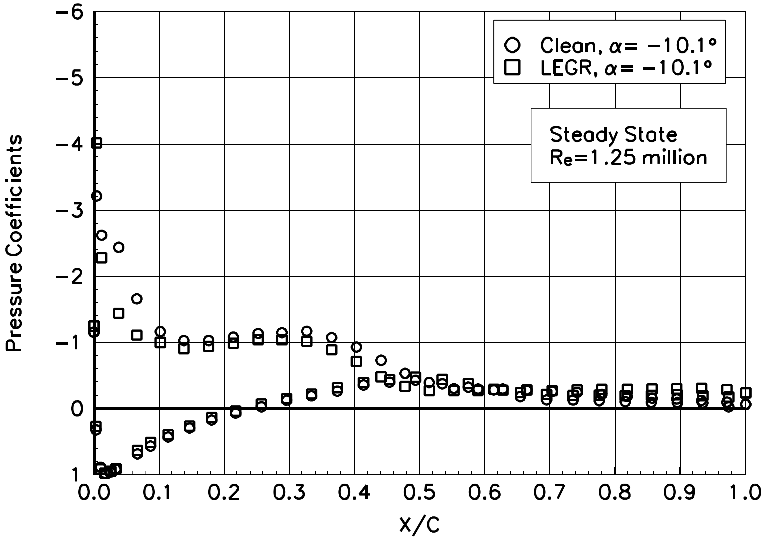

Figure 78. α = -10.1°

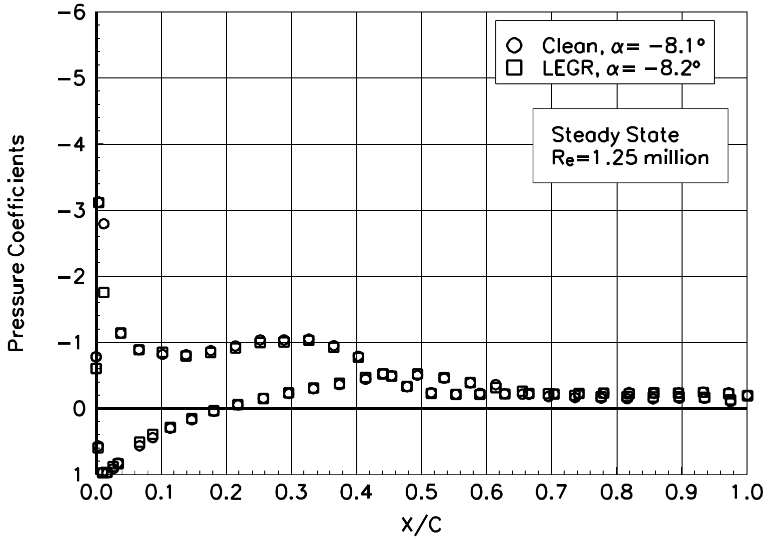

Figure 79. α = -8.1°

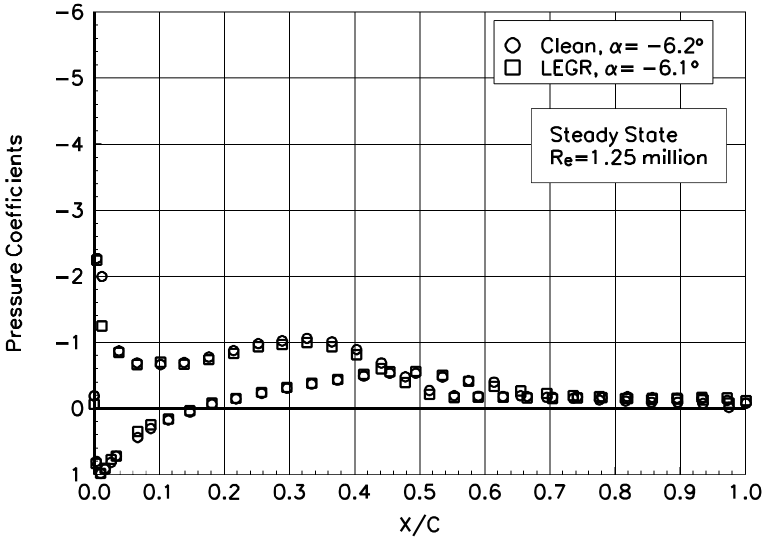

Figure 80. α = -6.2°

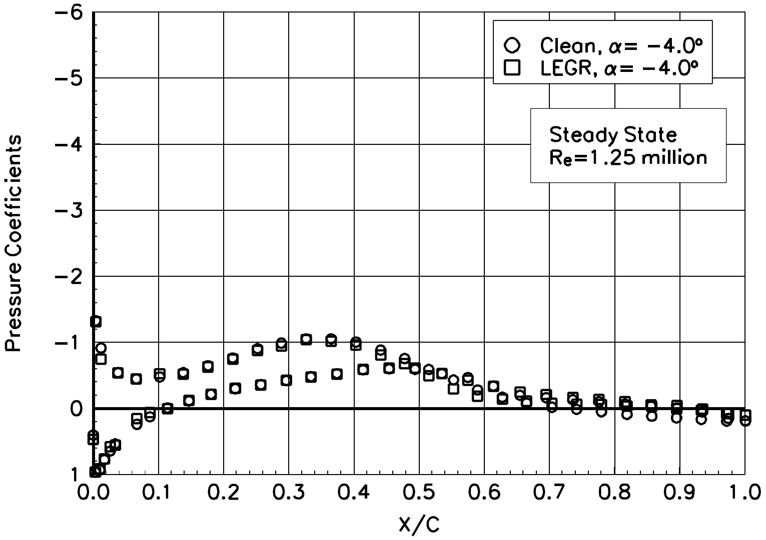

Figure 81. α = -4.0°

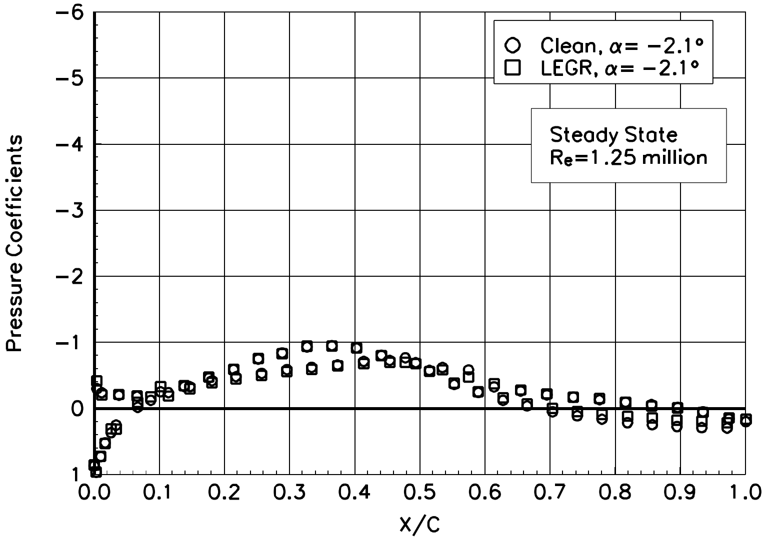

Figure 82. α = -2.1°

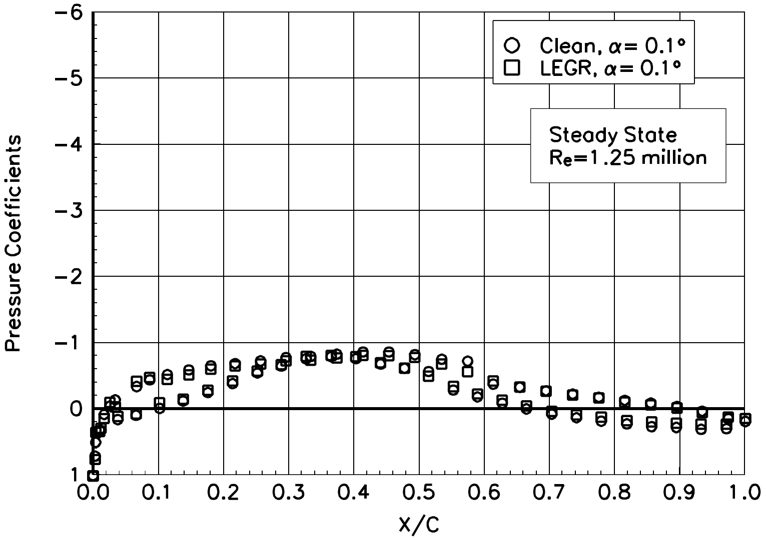

Figure 83. α = 0.1°

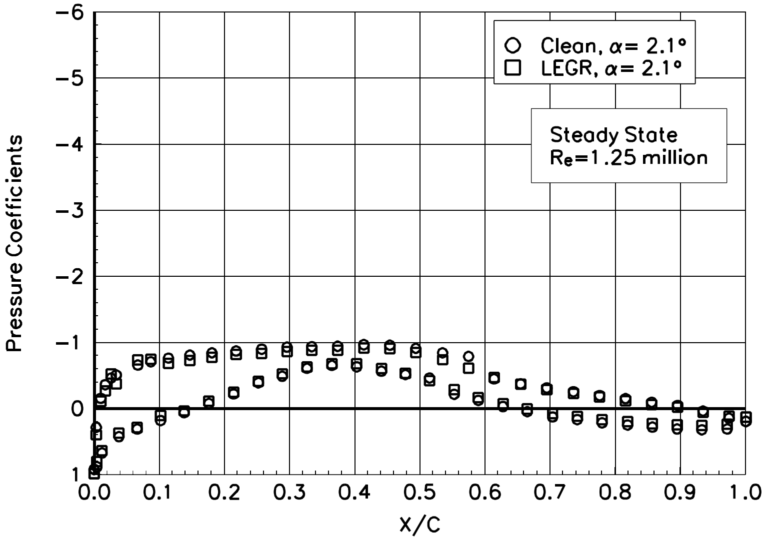

Figure 84. α = 2.1°

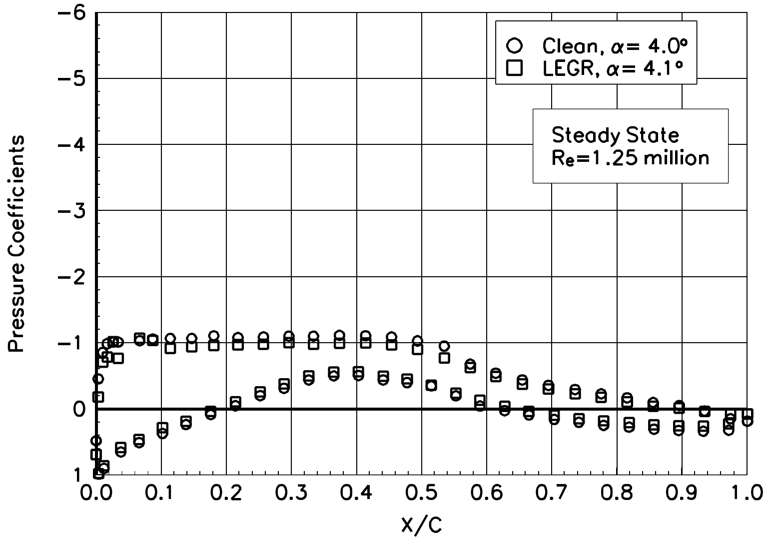

Figure 85. α = 4.0°

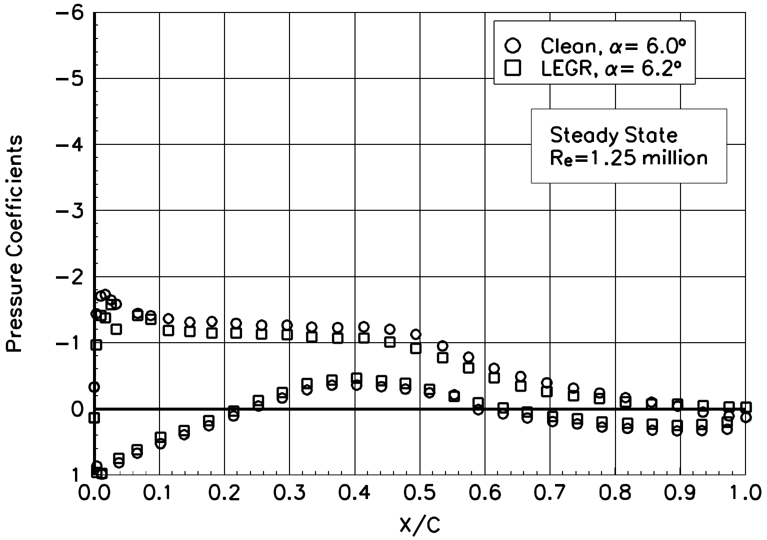

Figure 86. α = 6.0°

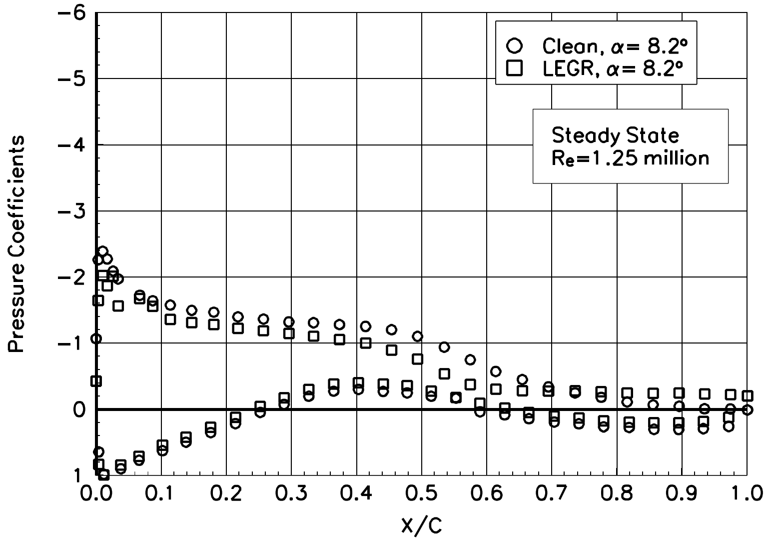

Figure 87. α = 8.2°

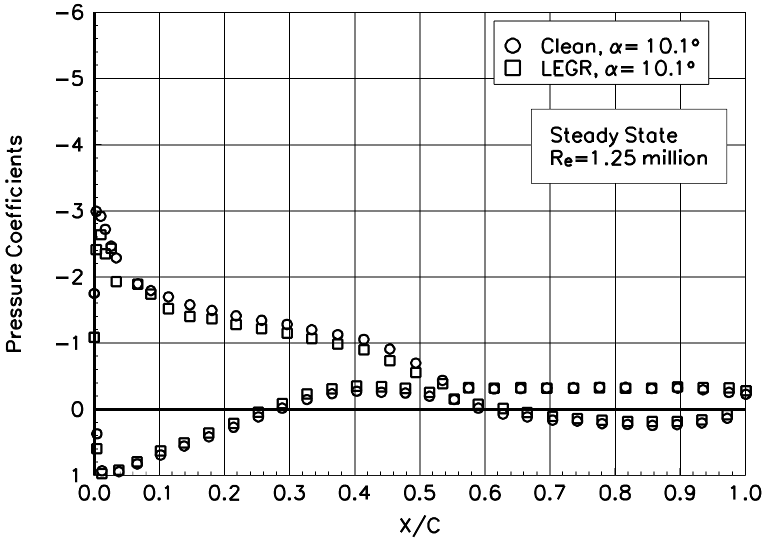

Figure 88. α = 10.1°

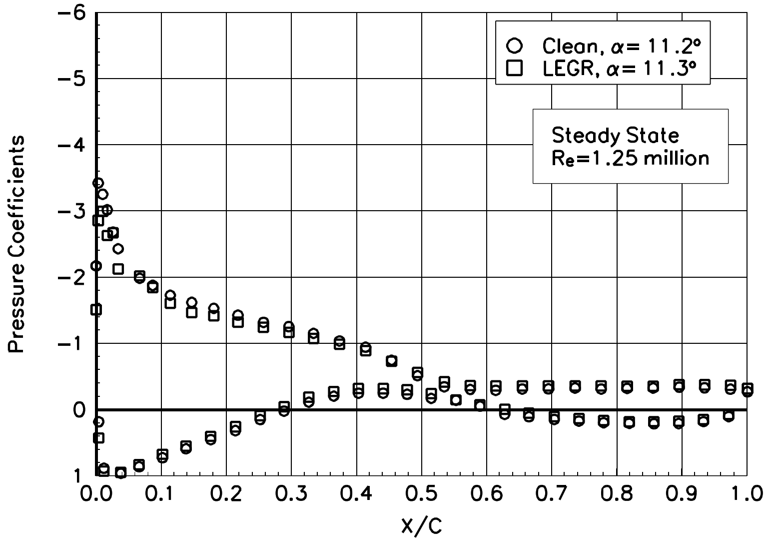

Figure 89. α = 11.2°

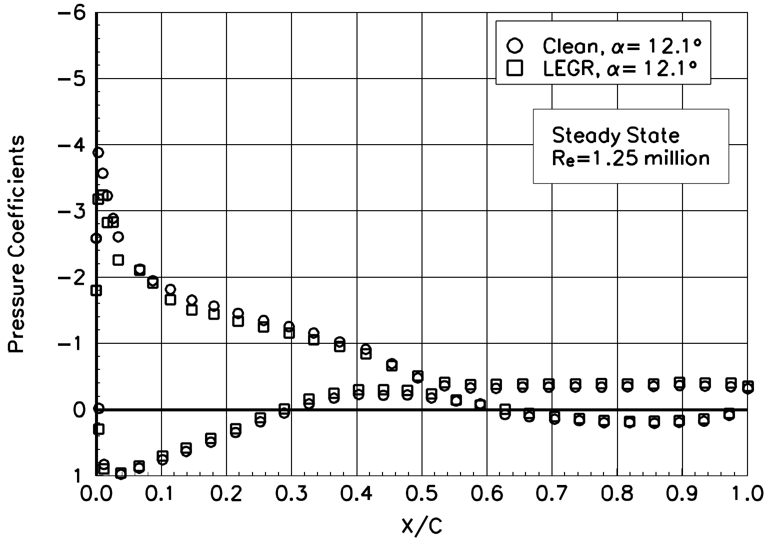

Figure 90. α = 12.1°

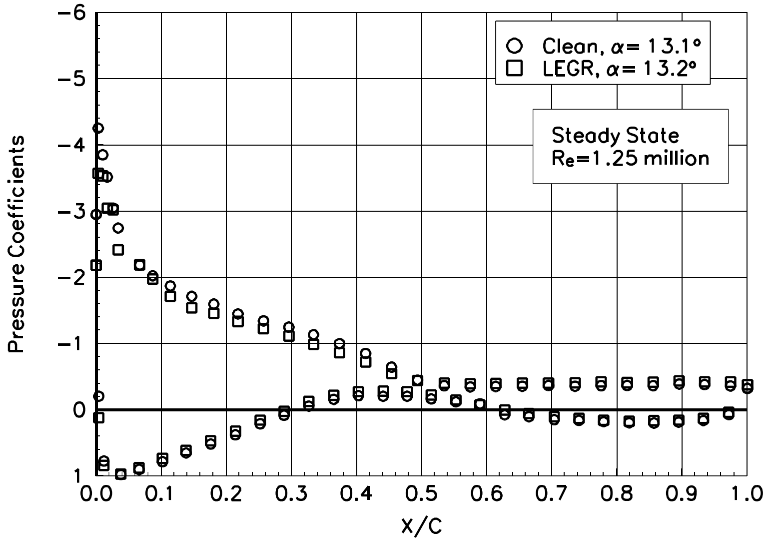

Figure 91. α = 13.1°

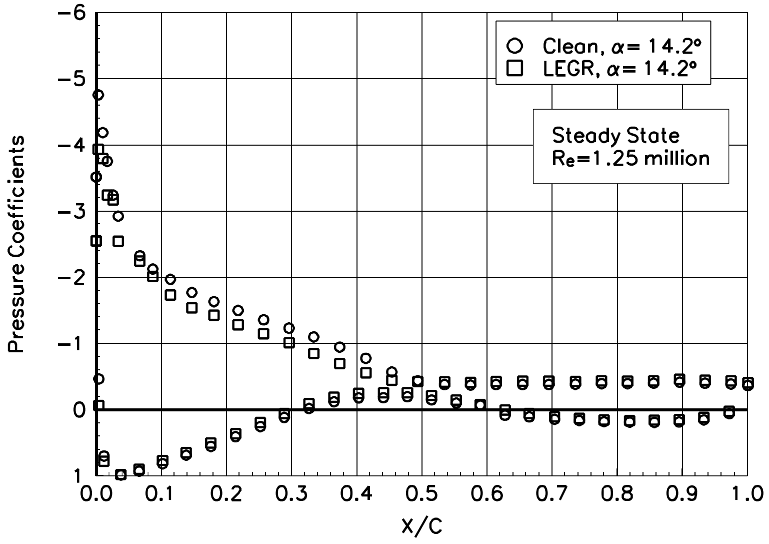

Figure 92. α = 14.2°

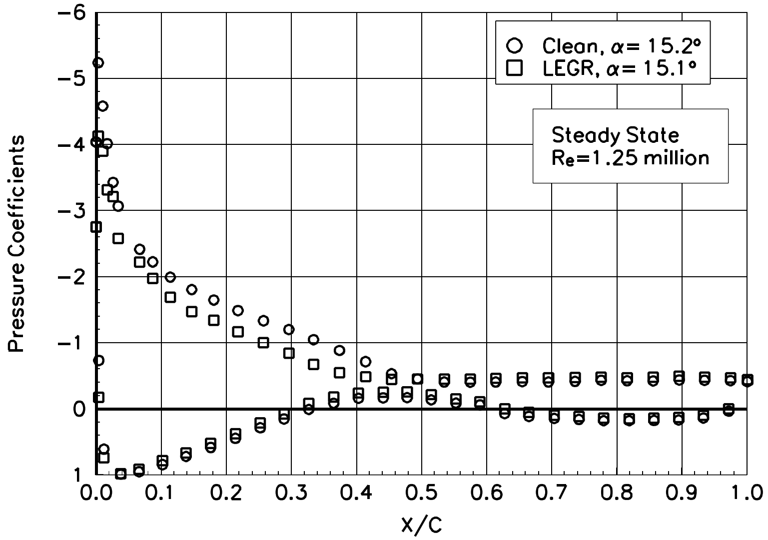

Figure 93. α = 15.2°

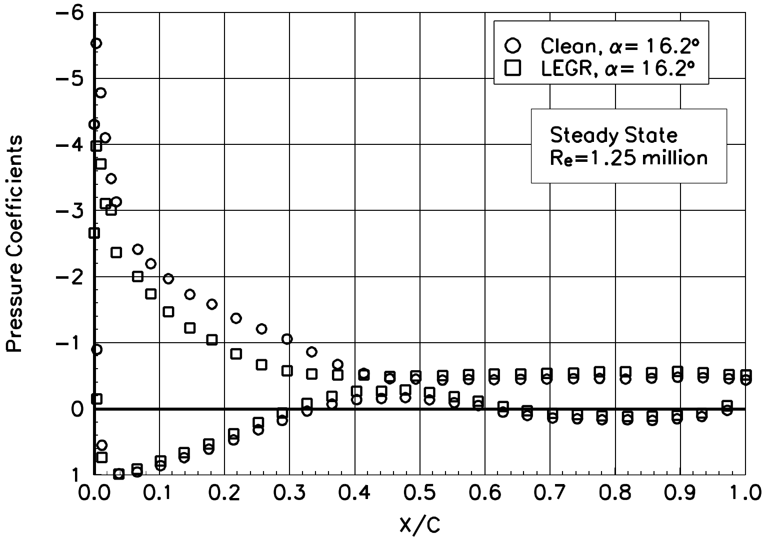

Figure 94. α = 16.2°

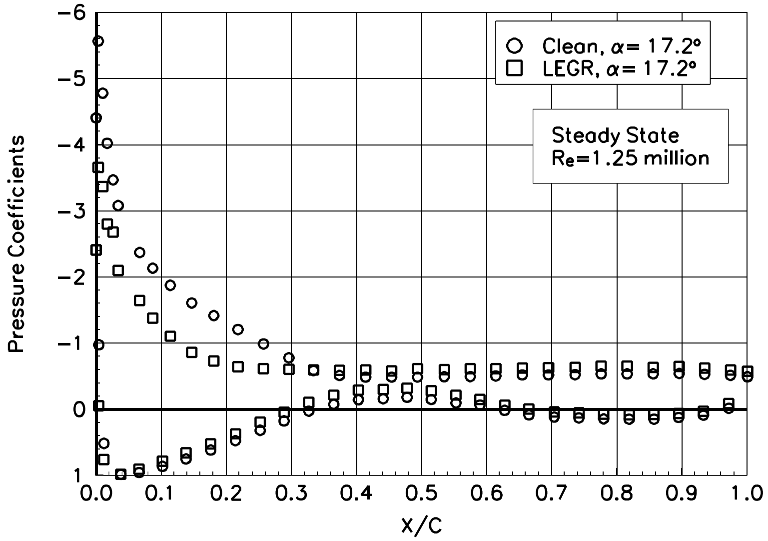

Figure 95. α = 17.2°

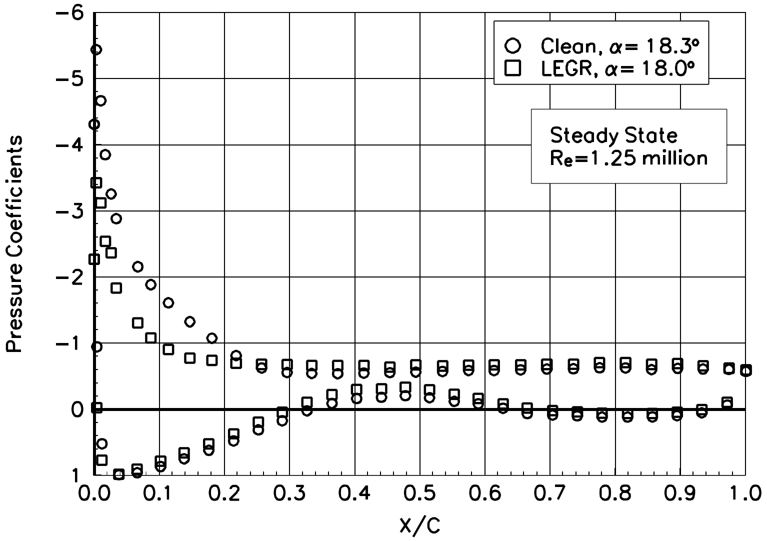

Figure 96. α = 18.3°

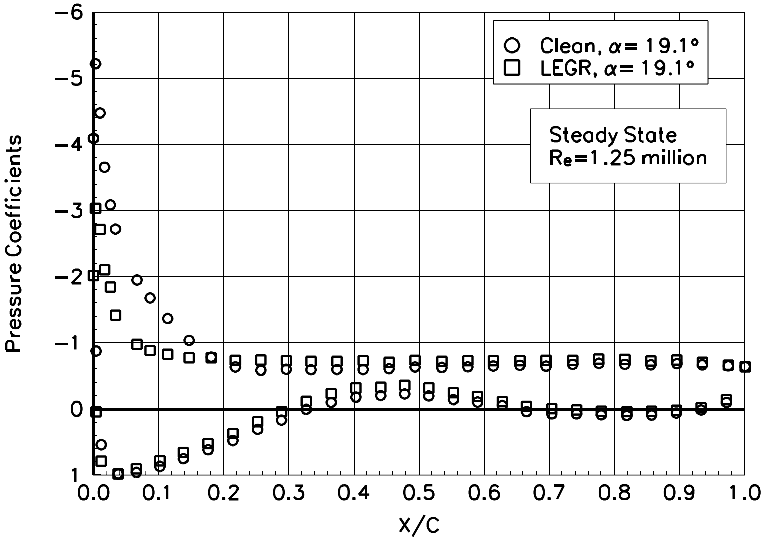

Figure 97. α **= 19.1°**

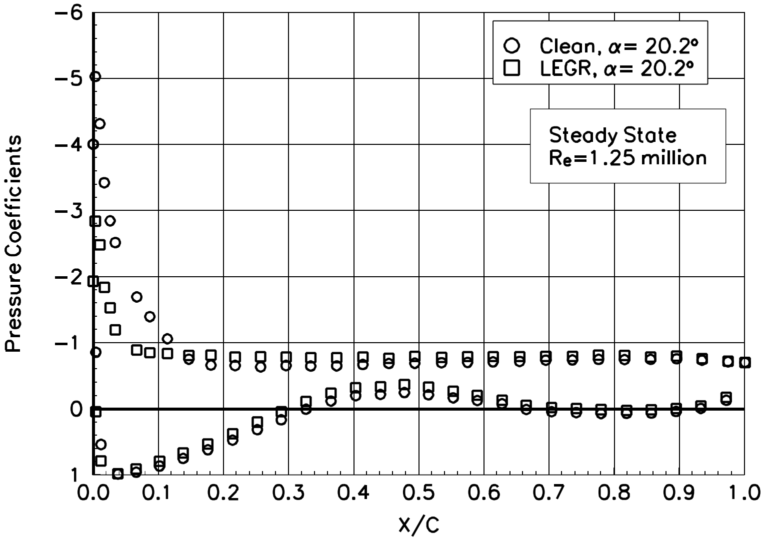

Figure 98. α **= 20.2°**

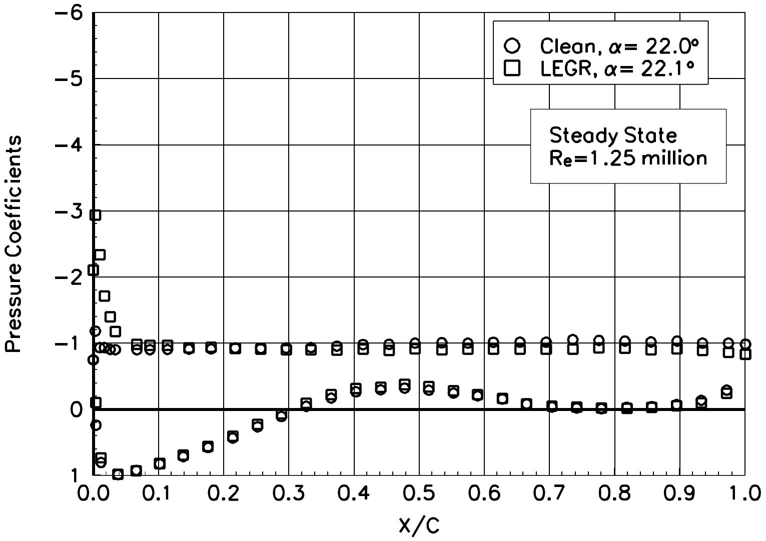

Figure 99. α **= 22.0°**

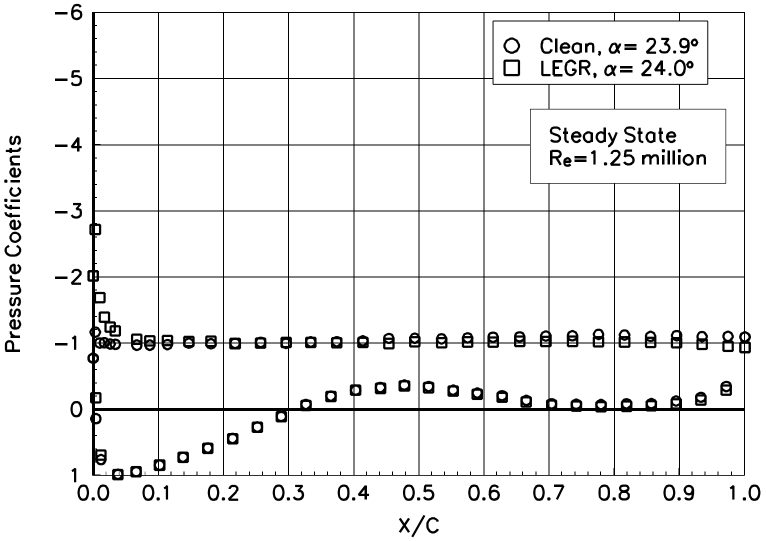

Figure 100. α **= 23.9°**

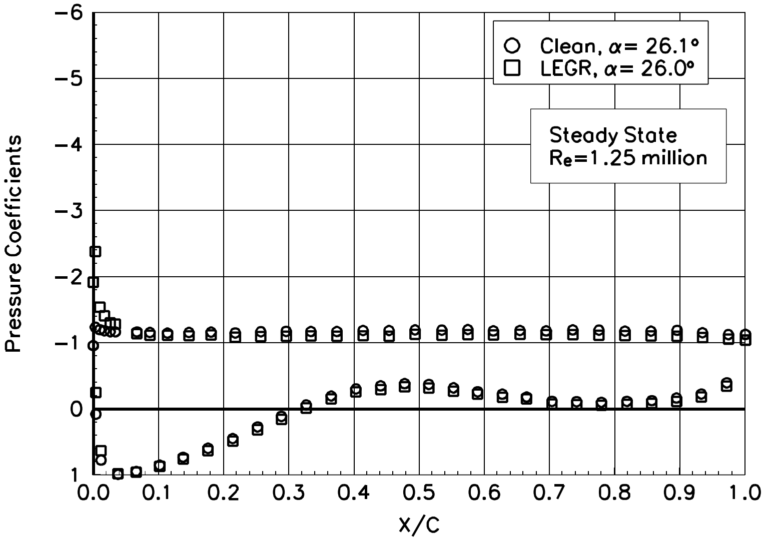

Figure 101. α = 26.1°

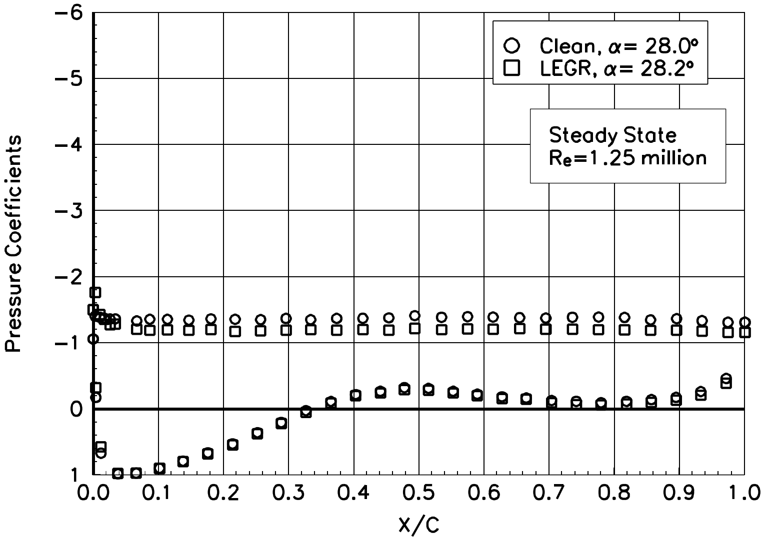

Figure 102. α = 28.0°

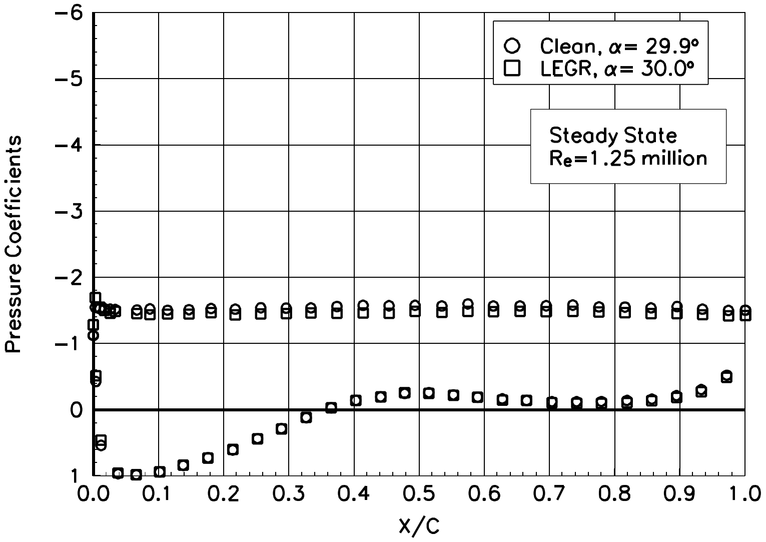

Figure 103. α = 29.9°

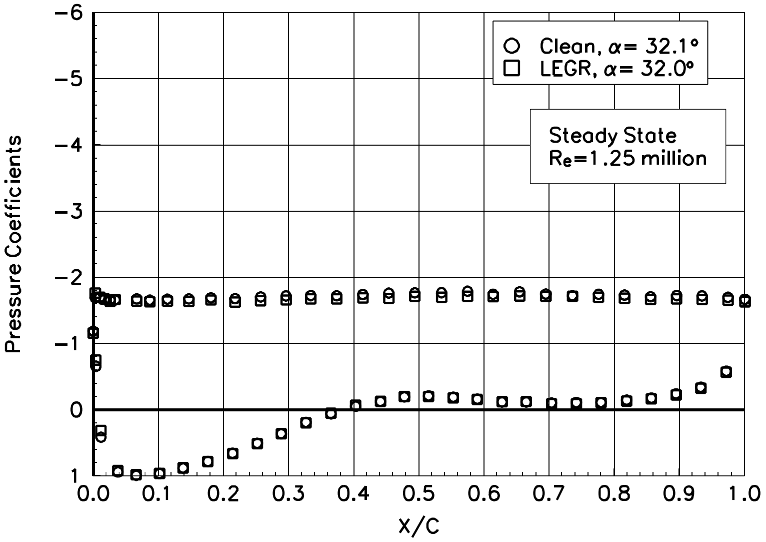

Figure 104. α = 32.1°

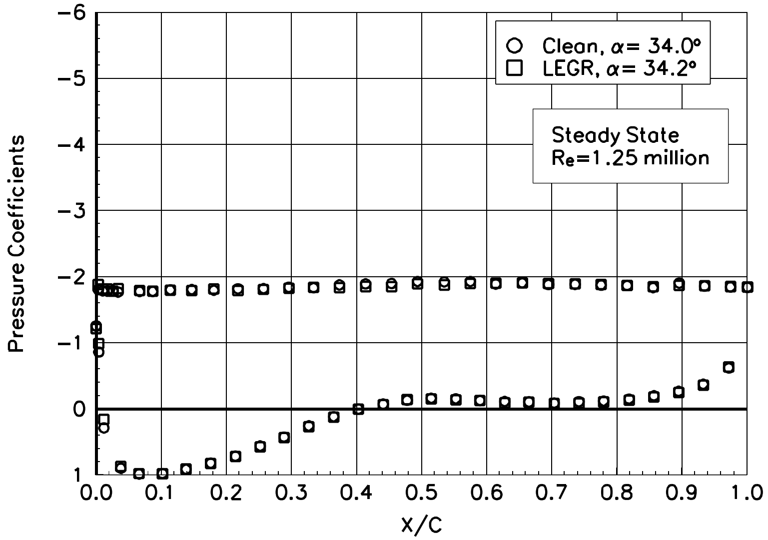

Figure 105. α = 34.0°

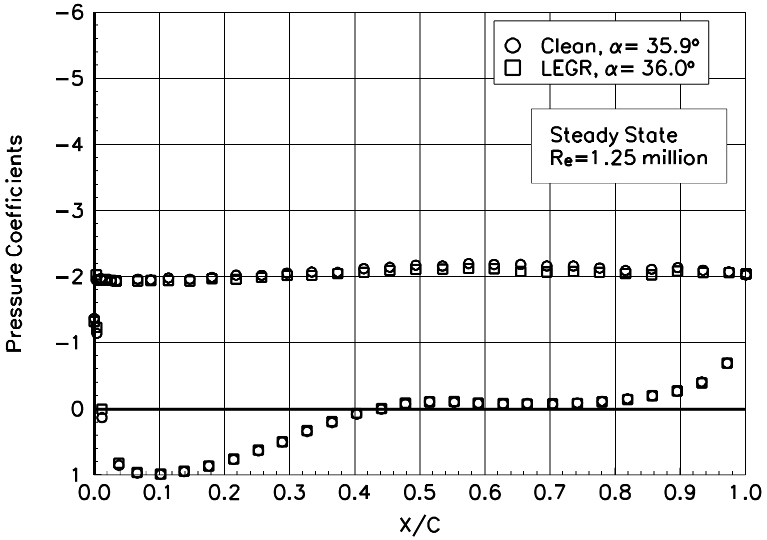

Figure 106. α = 35.9°

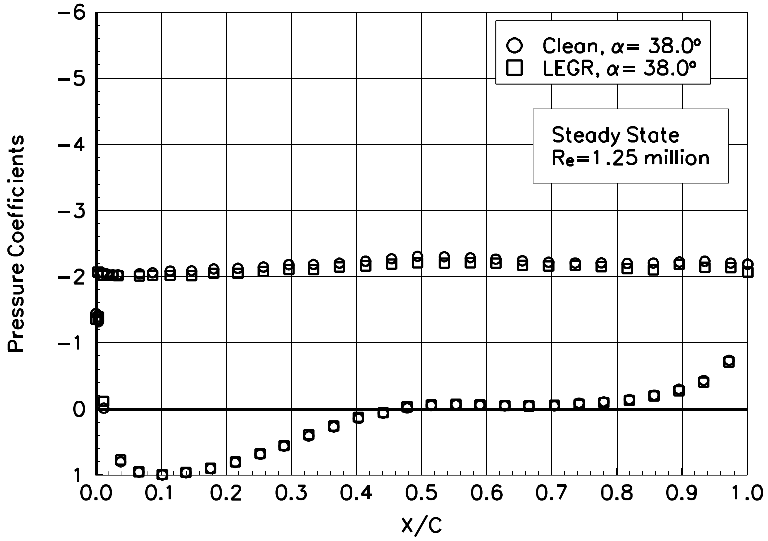

Figure 107. α = 38.0°

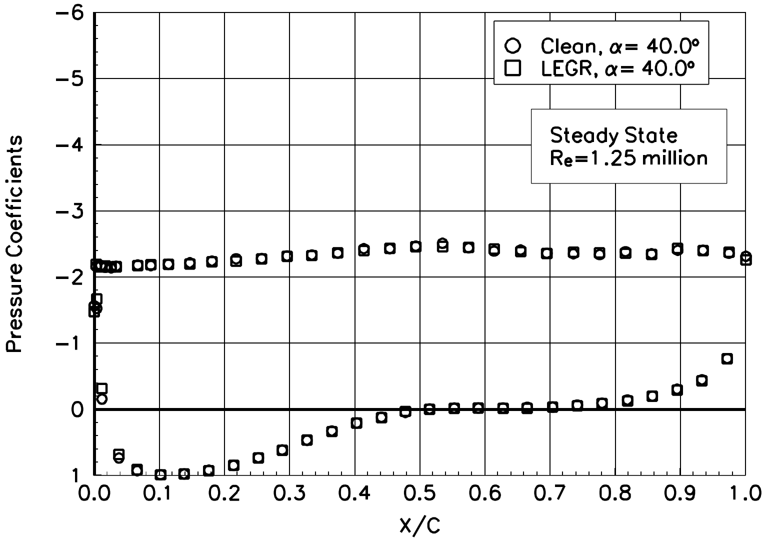

Figure 108. α = 40.0°

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Pressure Distributions, Steady State, Re = 1.5 million

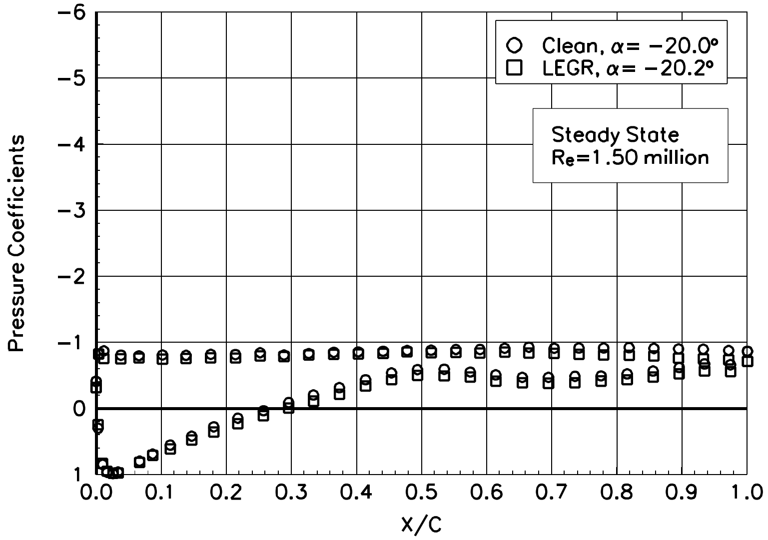

Figure 109. α = -20.0°

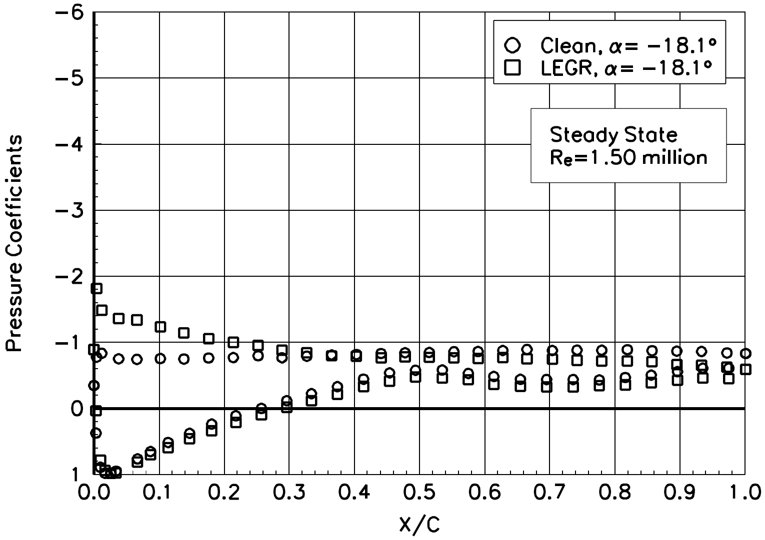

Figure 110. α = -18.1°

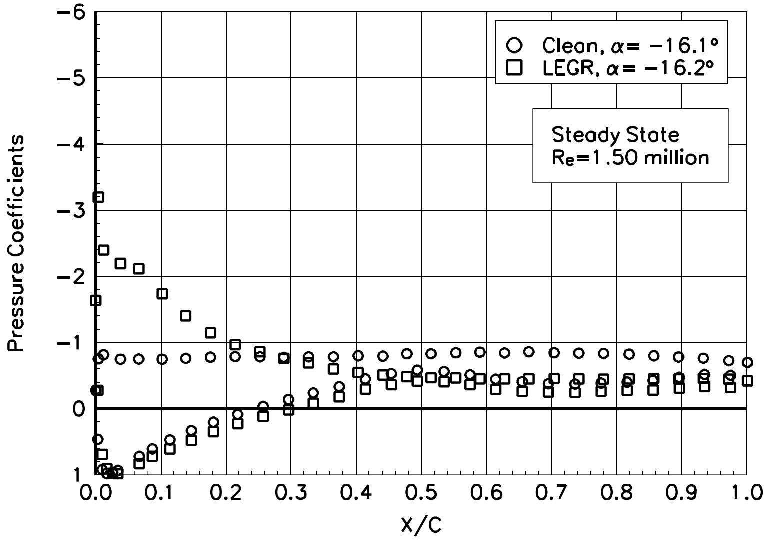

Figure 111. α = -16.1°

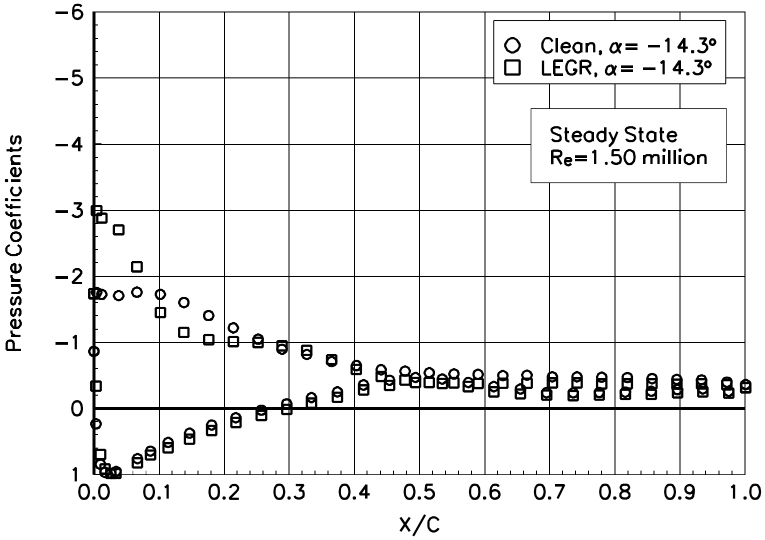

Figure 112. α = -14.3°

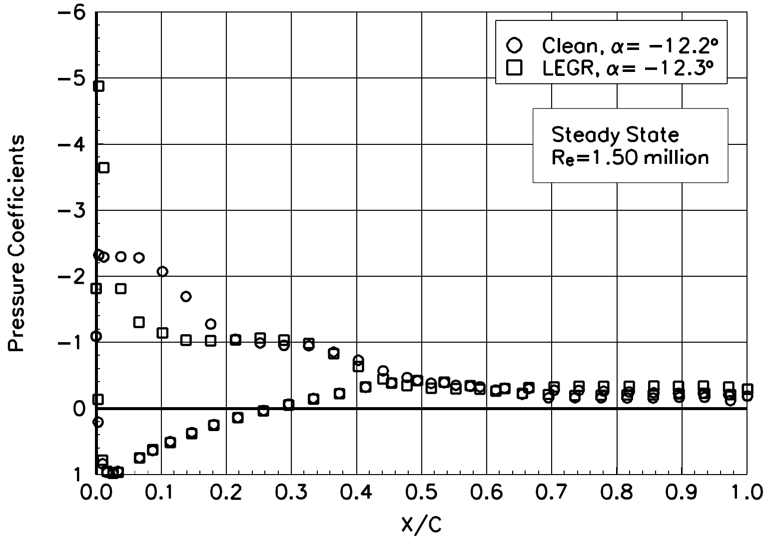

Figure 113. α = -12.2°

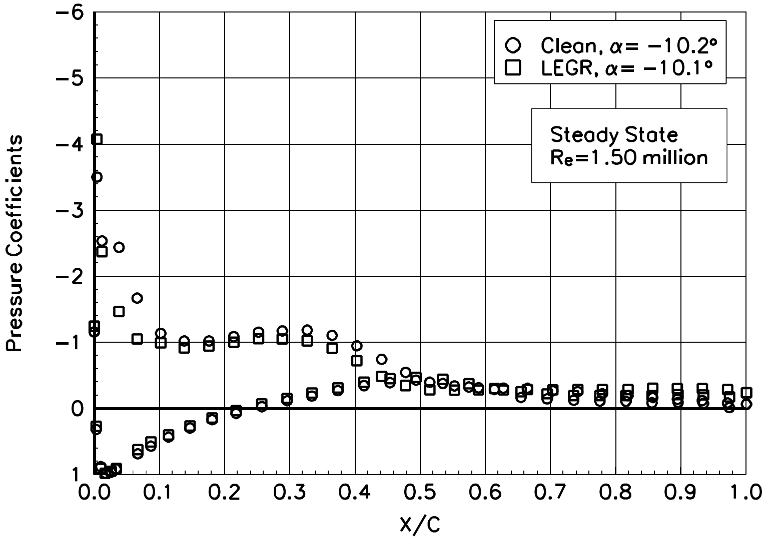

Figure 114. α = -10.2°

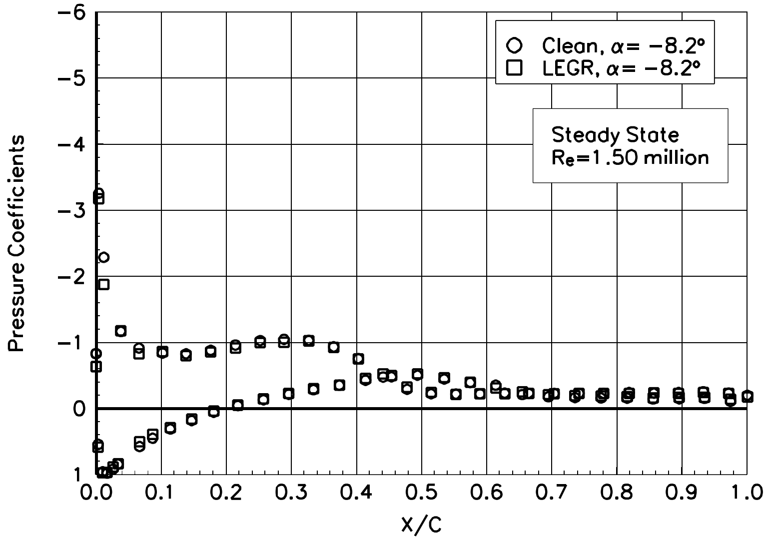

Figure 115. α = -8.2°

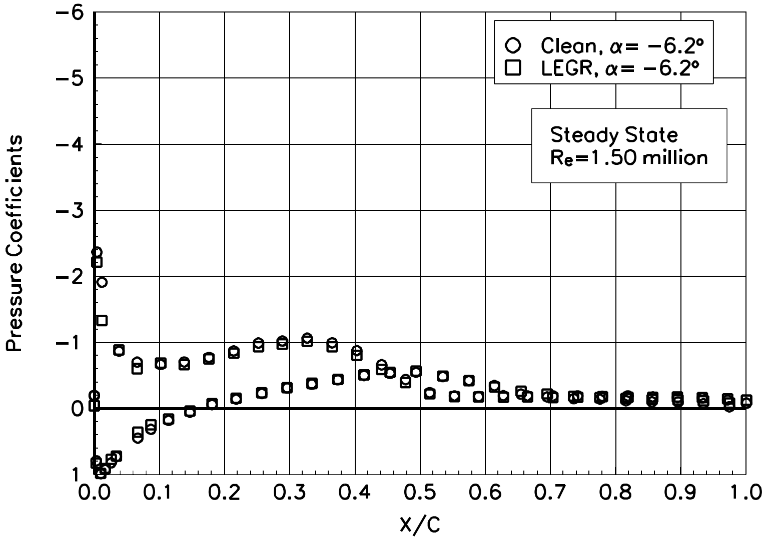

Figure 116. α = -6.2°

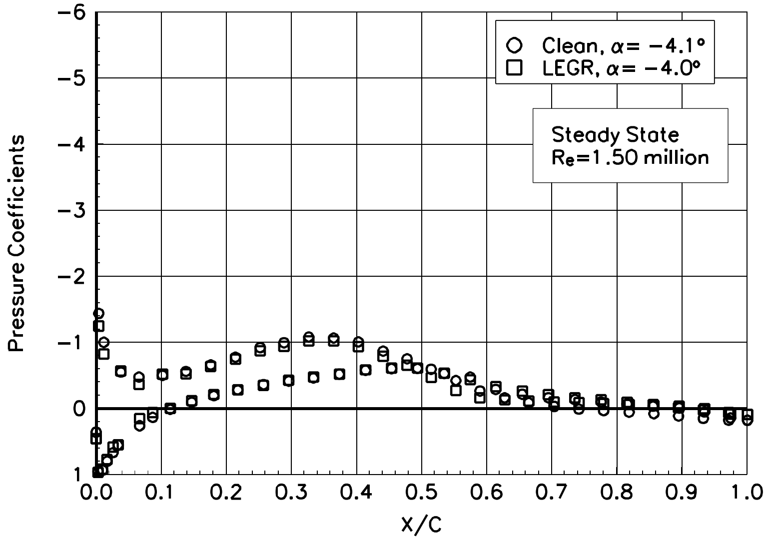

Figure 117. α = -4.1°

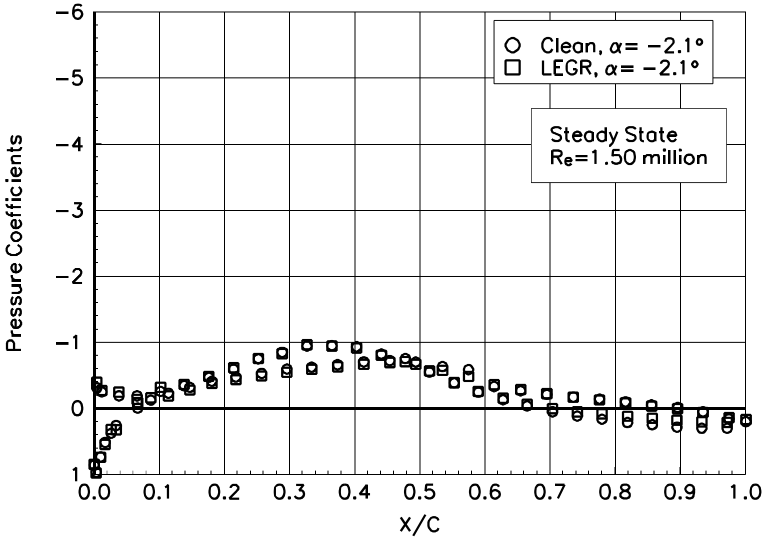

Figure 118. α = -2.1°

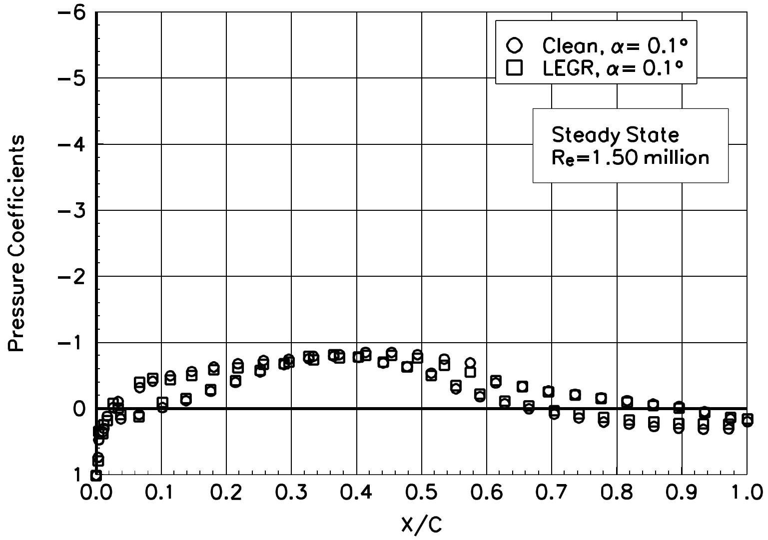

Figure 119. α = 0.1°

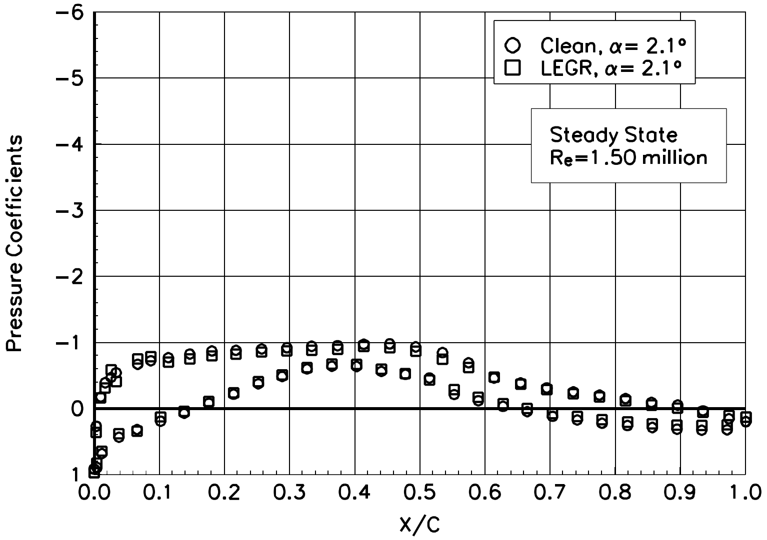

Figure 120. α = 2.1°

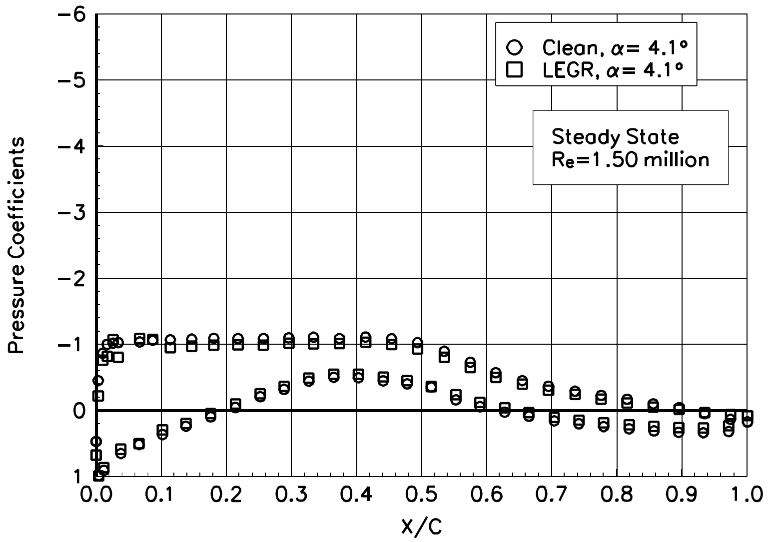

Figure 121. α = 4.1°

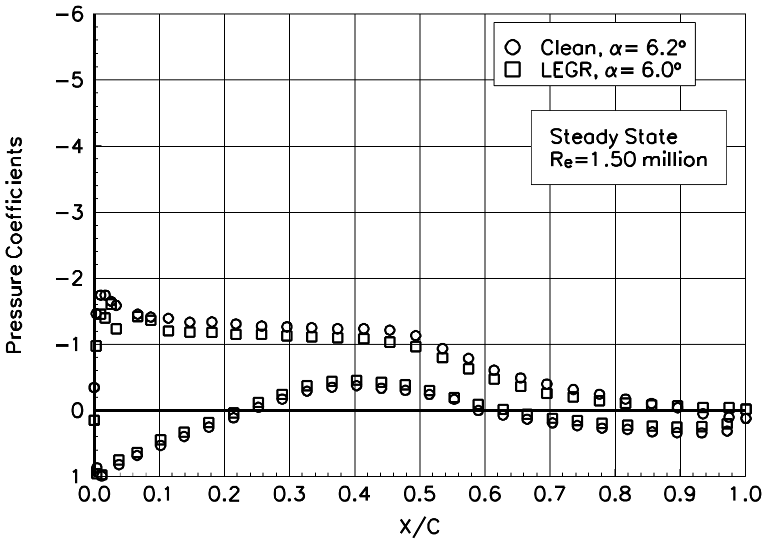

Figure 122. α = 6.2°

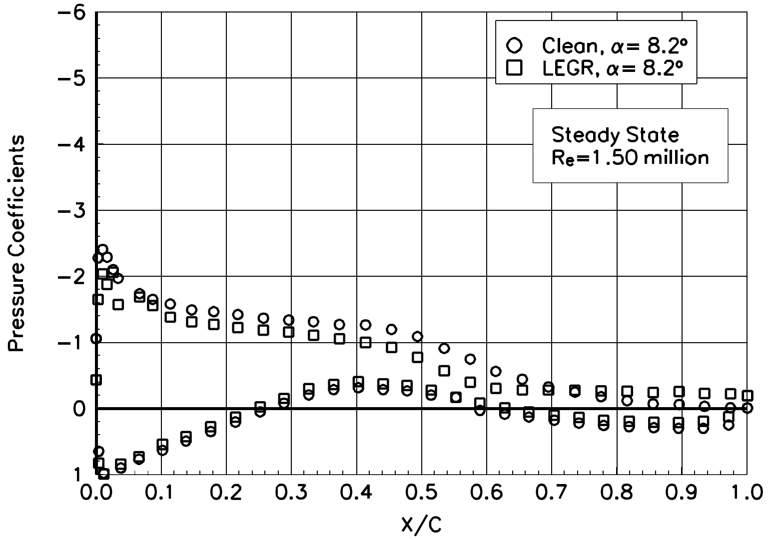

Figure 123. α = 8.2°

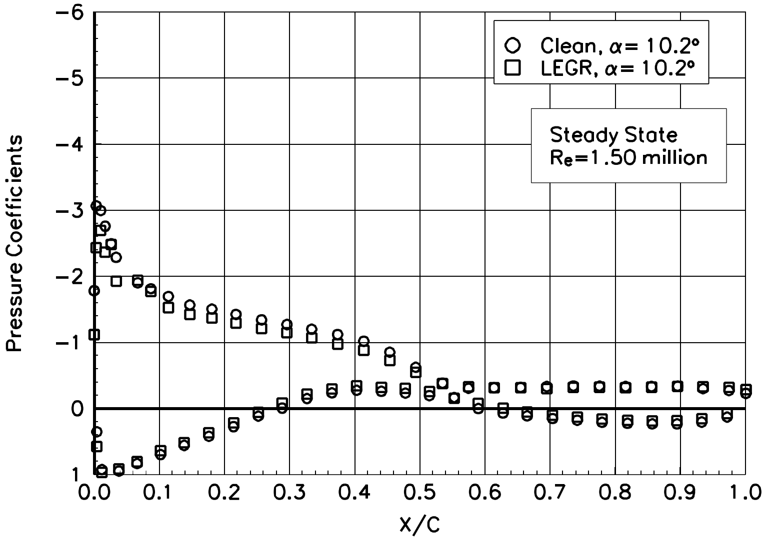

Figure 124. α = 10.2°

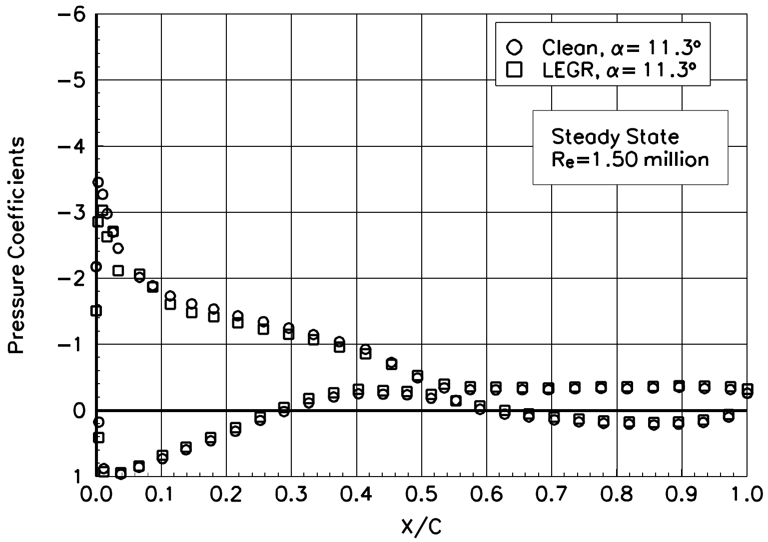

Figure 125. α = 11.3°

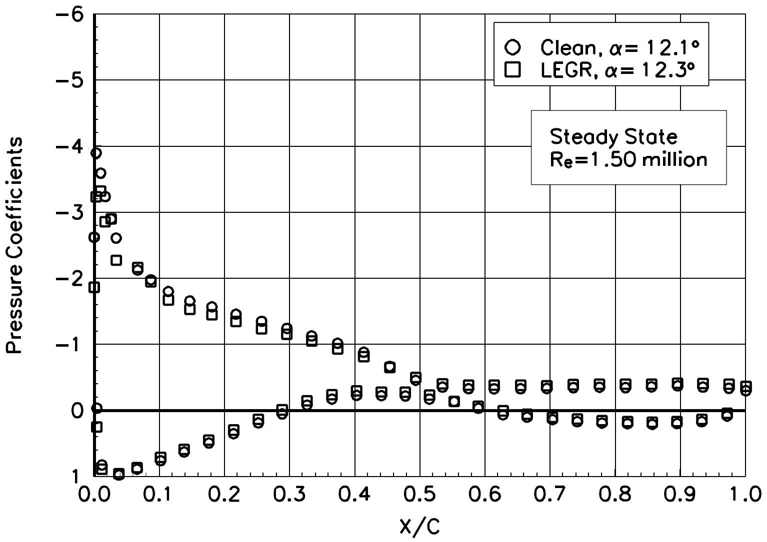

Figure 126. α = 12.1°

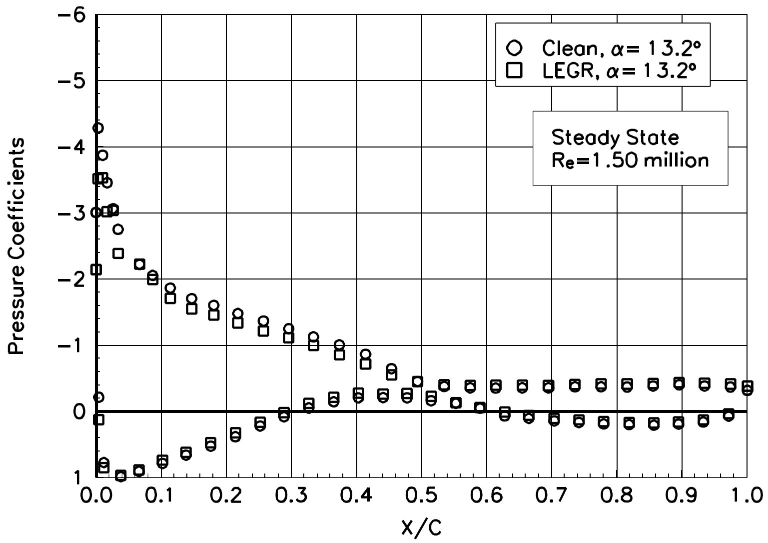

Figure 127. α = 13.2°

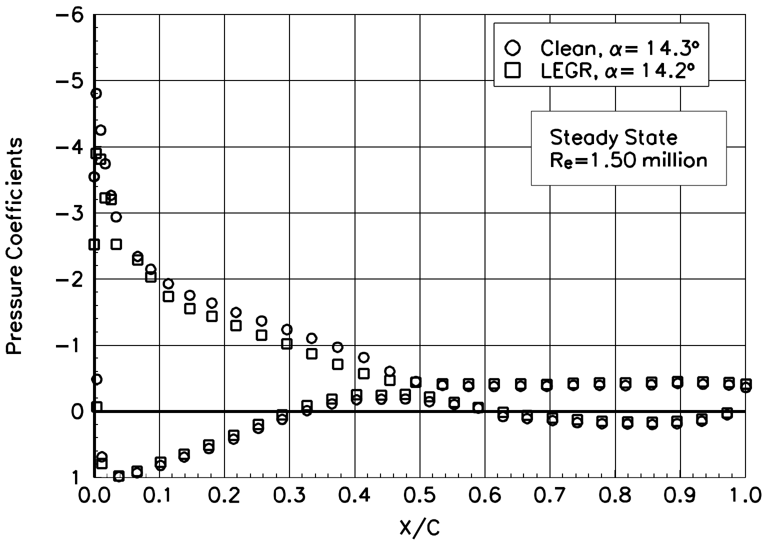

Figure 128. α = 14.3°

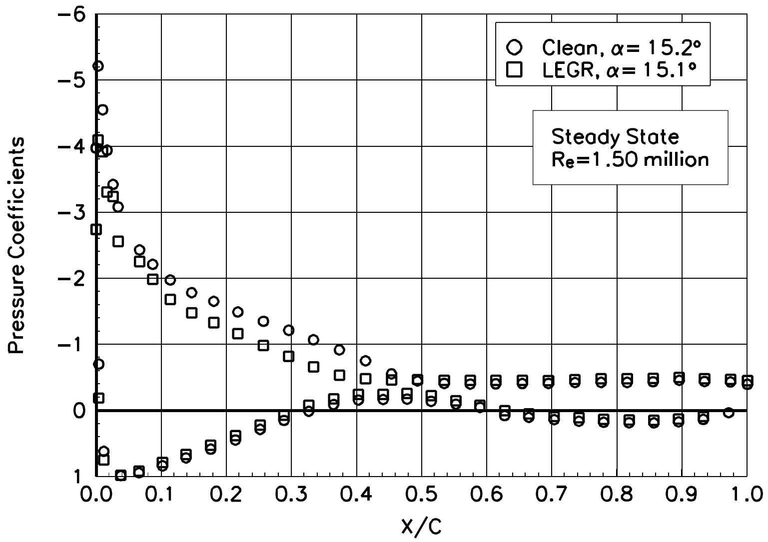

Figure 129. α = 15.2°

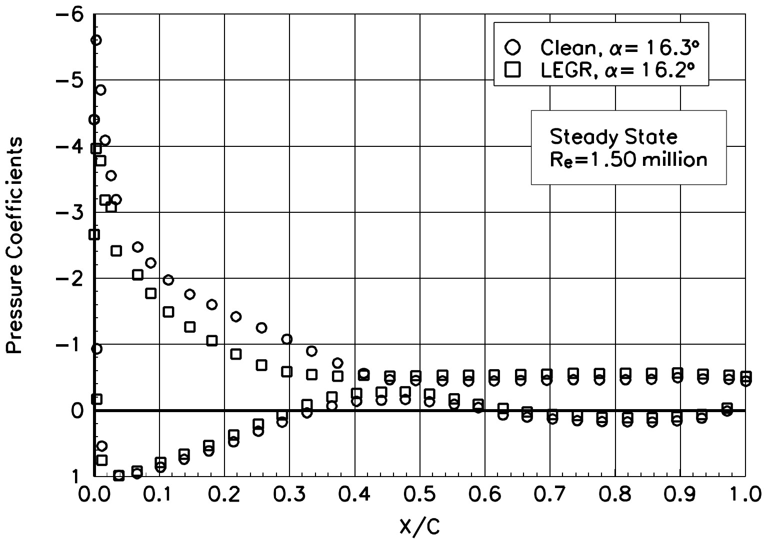

Figure 130. α = 16.3°

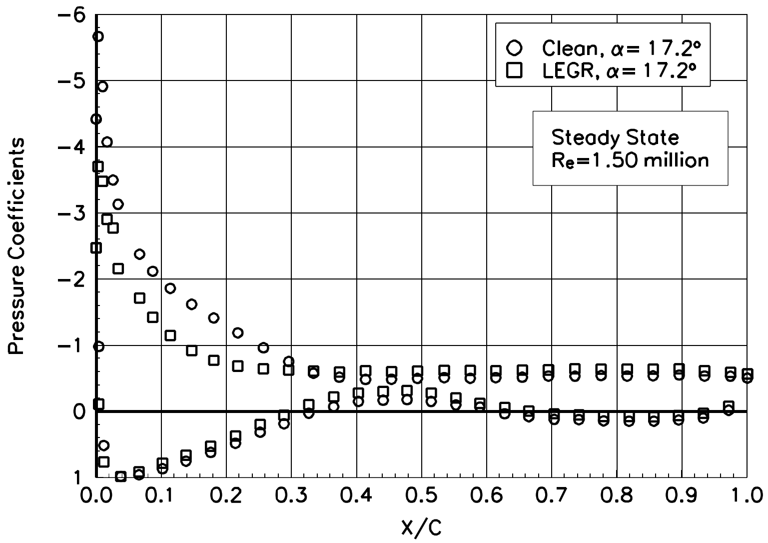

Figure 131. α = 17.2°

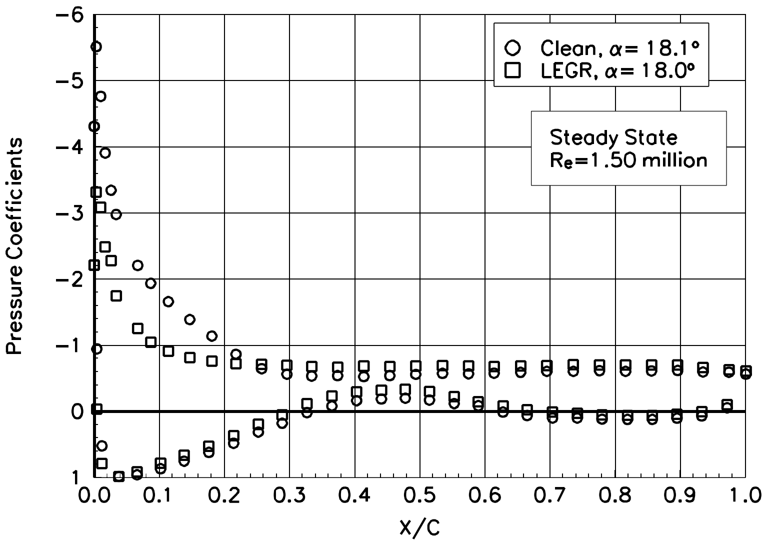

Figure 132. α = 18.1°

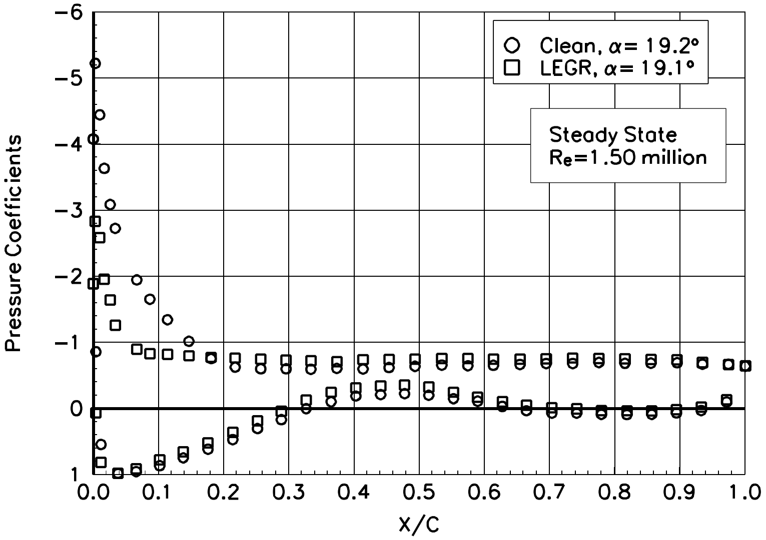

Figure 133. α = 19.2°

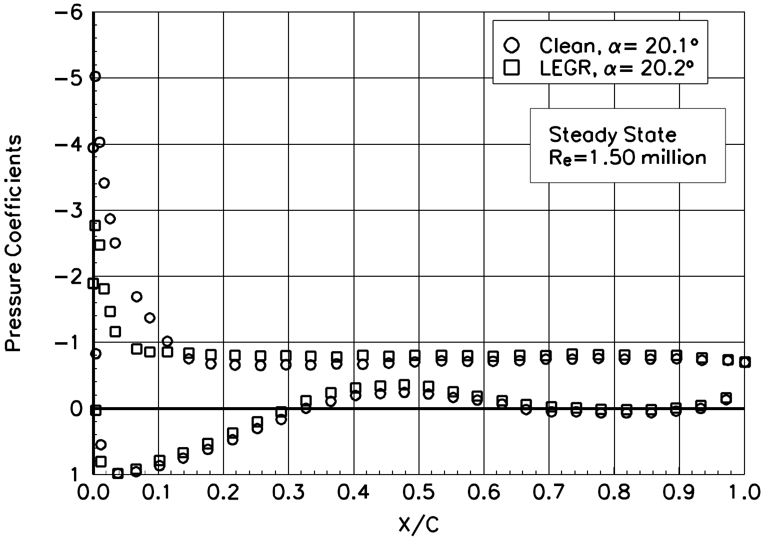

Figure 134. α = 20.1°

Appendix C: Unsteady Integrated Coefficients

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Unsteady Airfoil Characteristics

±5.5° Sine, Re = 0.75 million

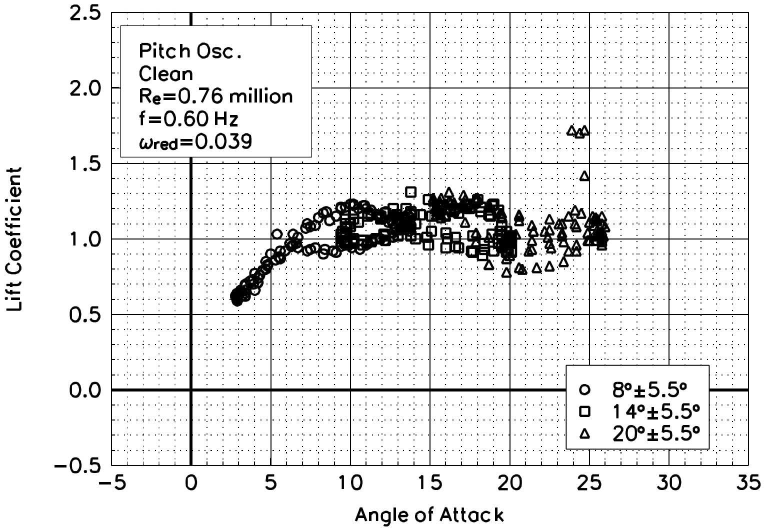

Figure C1. Lift coefficient vs α.

S812
Clean
Re=0.76 million
$\omega_{reduced}$=0.039

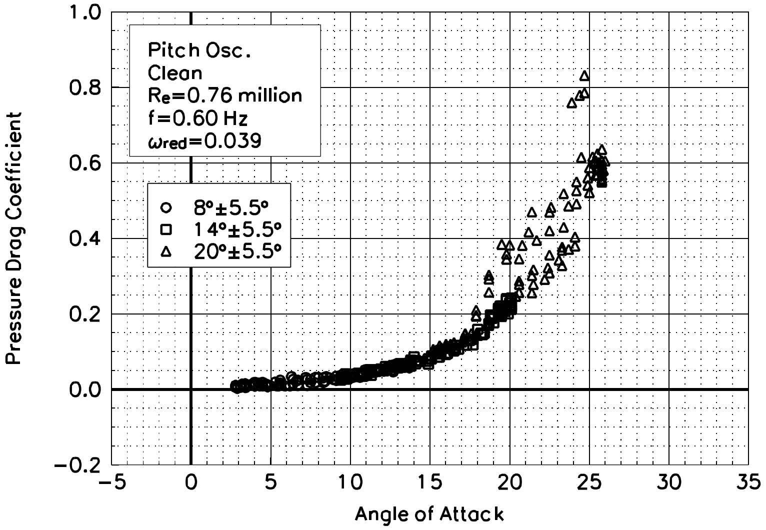

Figure C2. Pressure drag coefficient vs α.

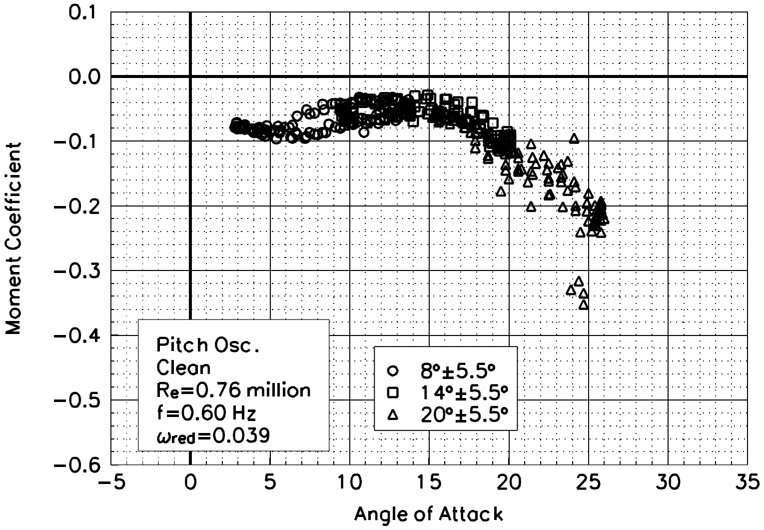

Figure C3. Moment coefficient vs α.

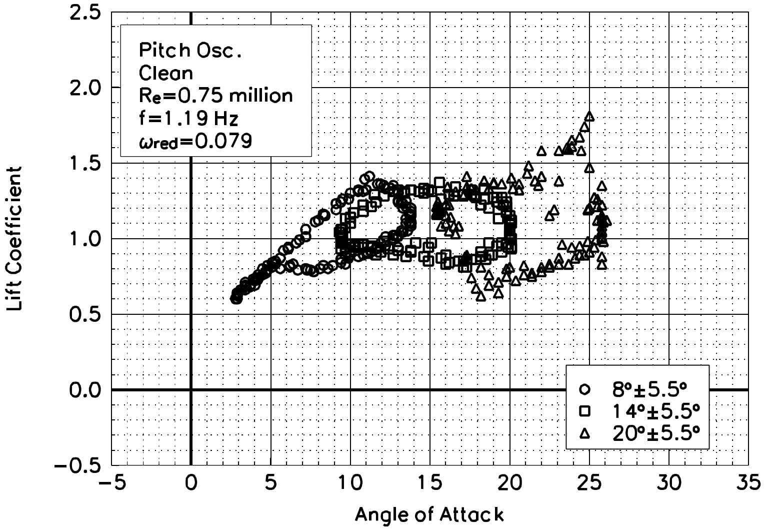

Figure C4. Lift coefficient vs α.

S812
Clean
Re=0.75 million
$\omega_{reduced}$=0.079

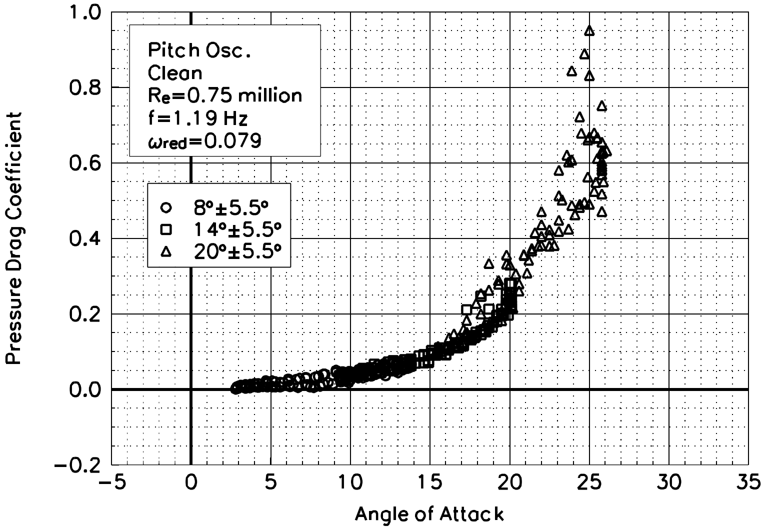

Figure C5. Pressure drag coefficient vs α.

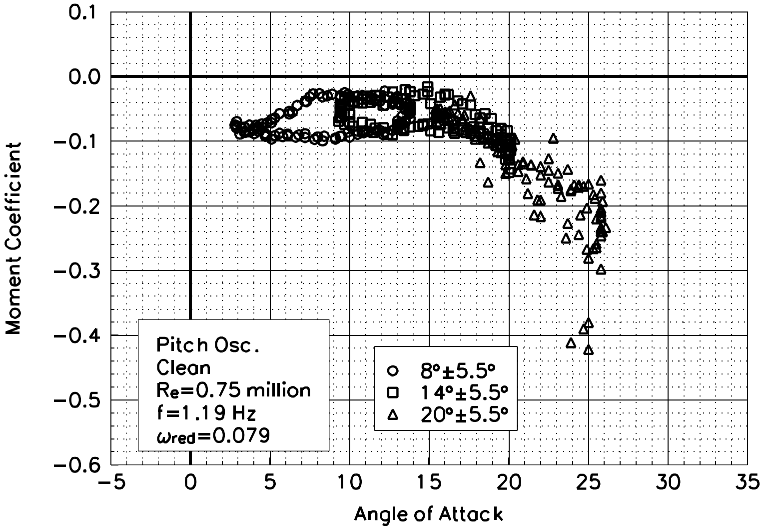

Figure C6. Moment coefficient vs α.

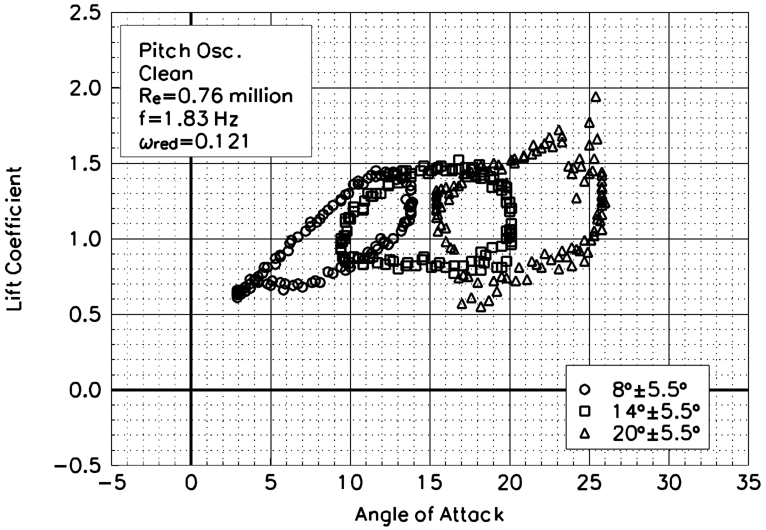

Figure C7. Lift coefficient vs α.

S812
Clean
Re=0.76 million
$\omega_{reduced}$=0.121

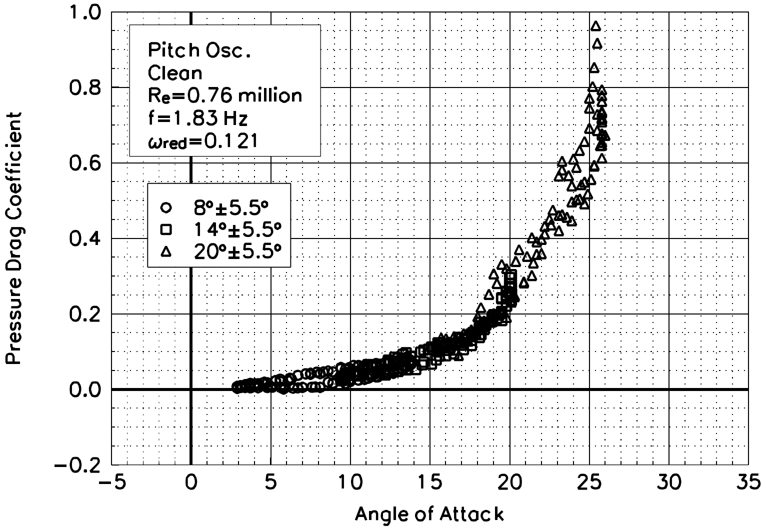

Figure C8. Pressure drag coefficient vs α.

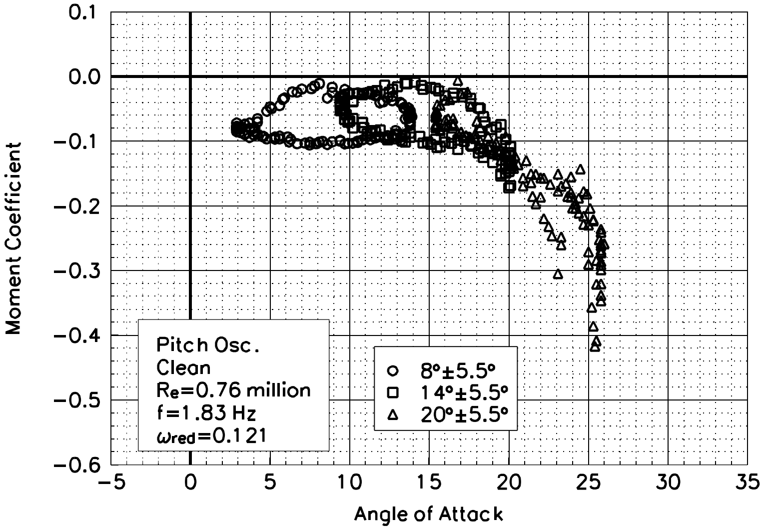

Figure C9. Moment coefficient vs α.

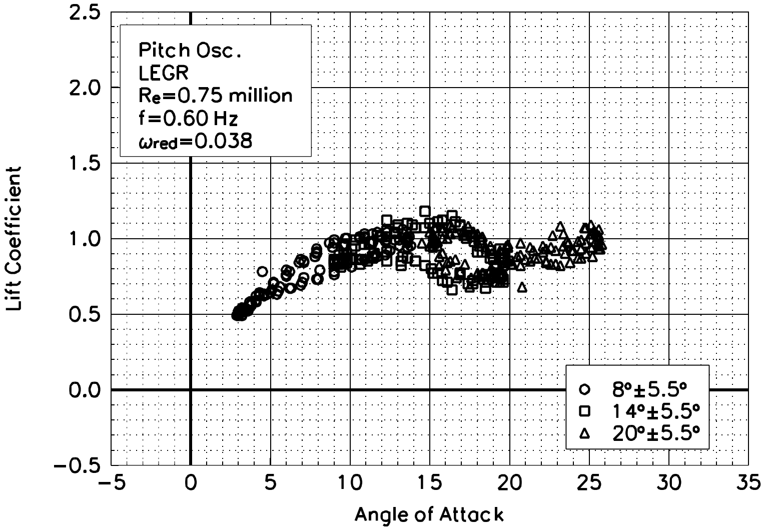

Figure C10. Lift coefficient vs α.

S812
LEGR
Re=0.75 million
$\omega_{reduced}$=0.038

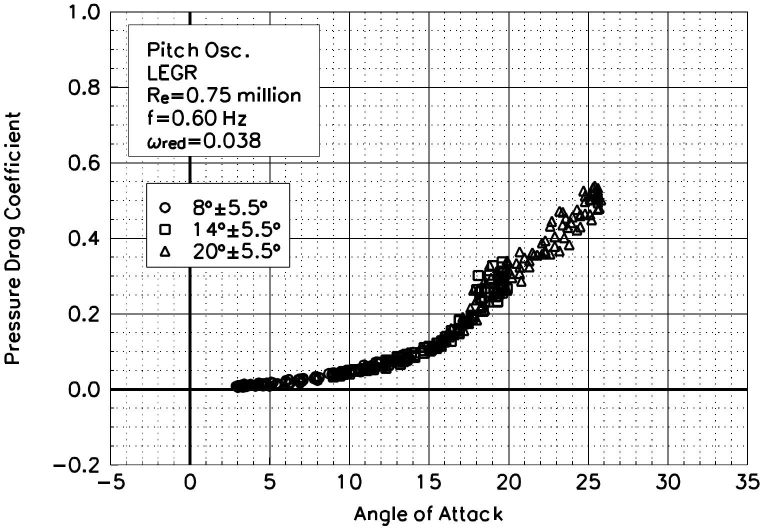

Figure C11. Pressure drag coefficient vs α.

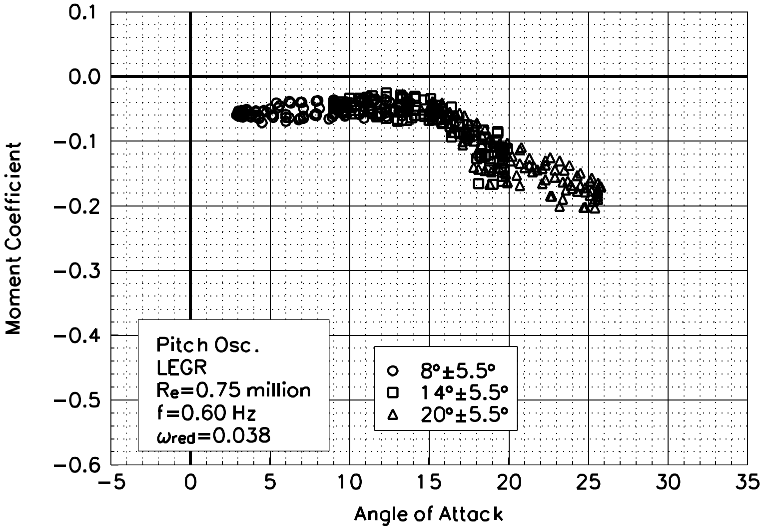

Figure C12. Moment coefficient vs α.

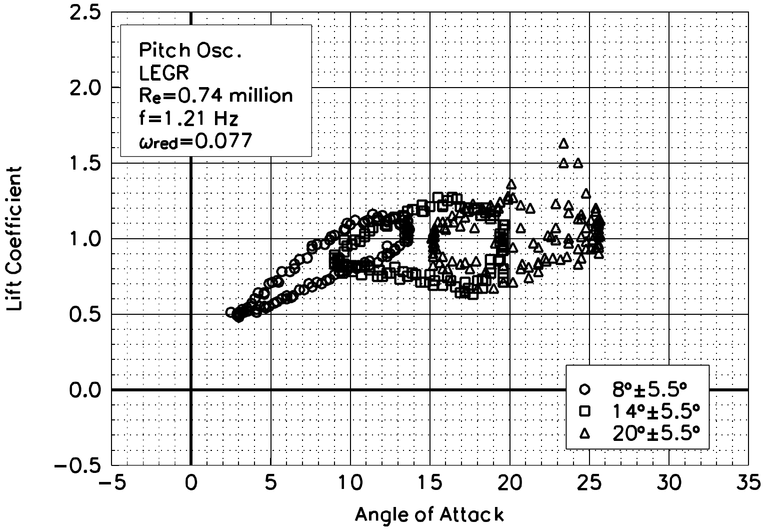

Figure C13. Lift coefficient vs α.

S812
LEGR
Re=0.74 million
$\omega_{reduced}$=0.077

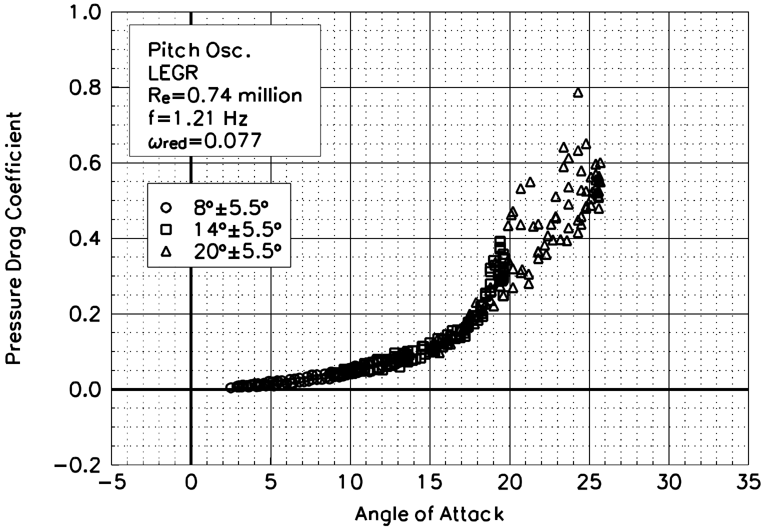

Figure C14. Pressure drag coefficient vs α.

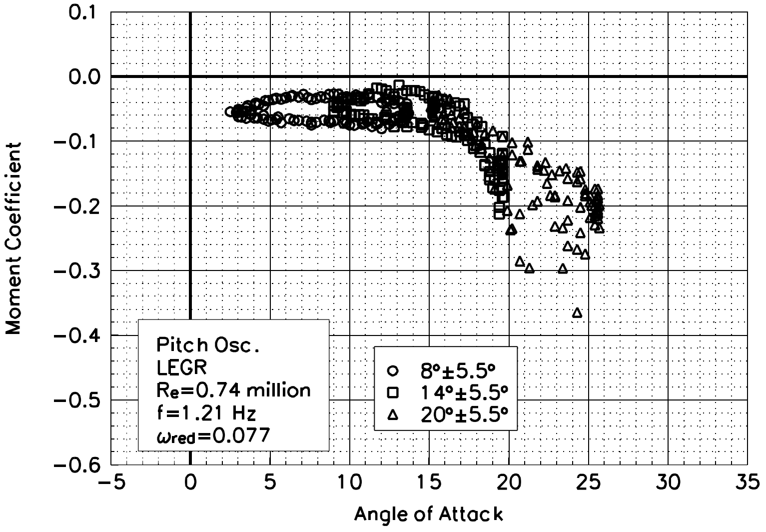

Figure C15. Moment coefficient vs α.

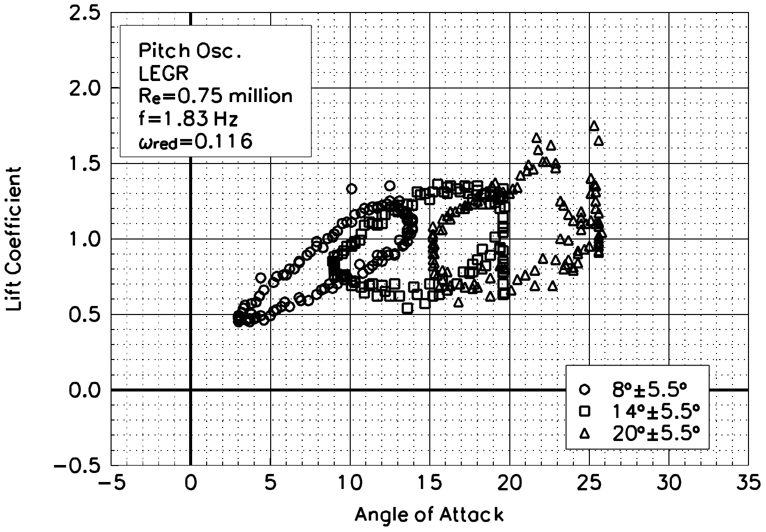

Figure C16. Lift coefficient vs α.

S812
LEGR
Re=0.75 million
$\omega_{reduced}$=0.116

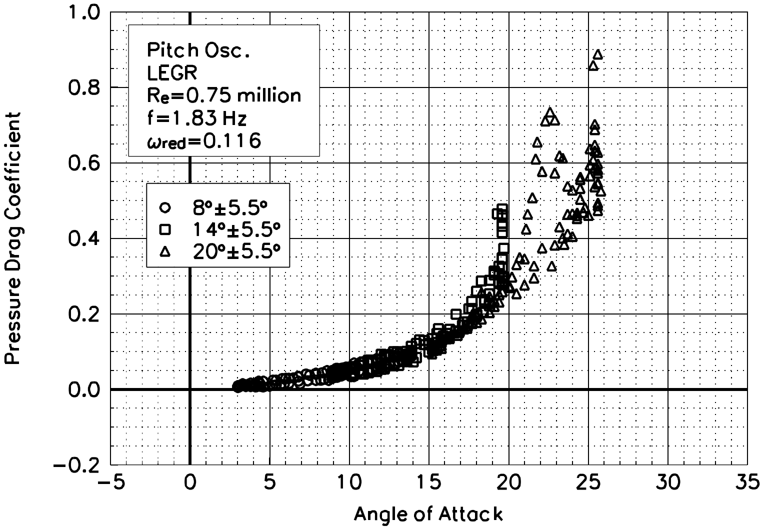

Figure C17. Pressure drag coefficient vs α.

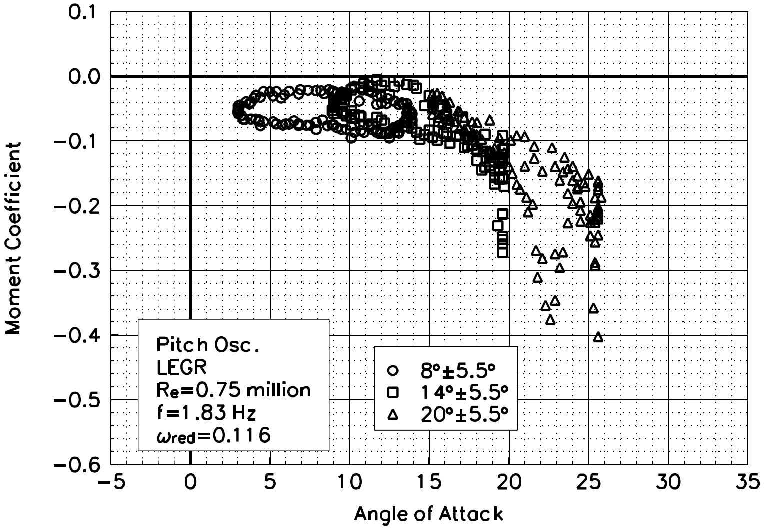

Figure C18. Moment coefficient vs α.

Unsteady Airfoil Characteristics

±5.5° Sine, Re = 1 million

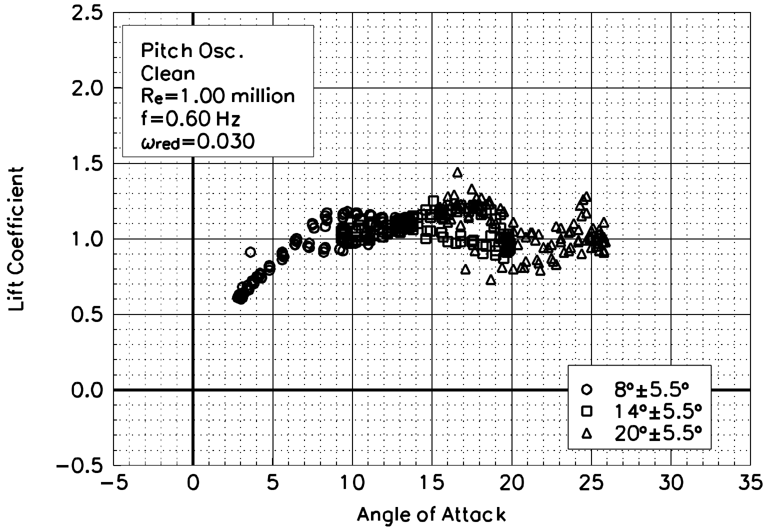

Figure C19. Lift coefficient vs α.

S812
Clean
Re=1.00 million
$\omega_{reduced}$=0.030

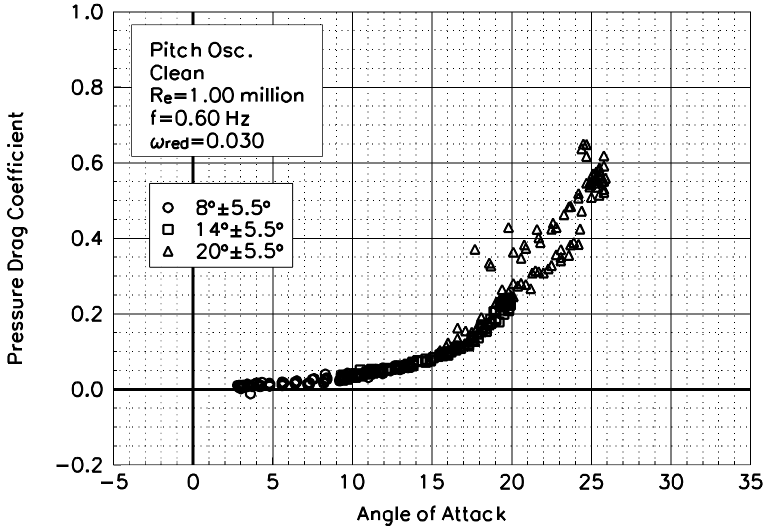

Figure C20. Pressure drag coefficient vs α.

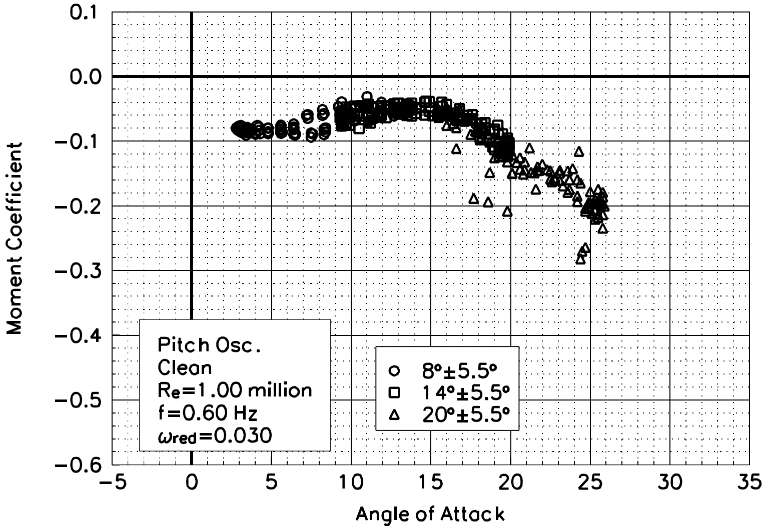

Figure C21. Moment coefficient vs α.

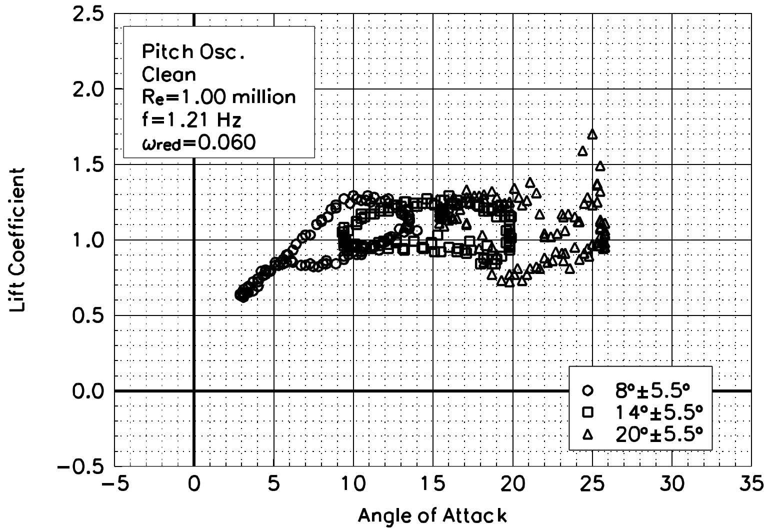

Figure C22. Lift coefficient vs α.

S812
Clean
Re=1.00 million
$\omega_{reduced}$=0.060

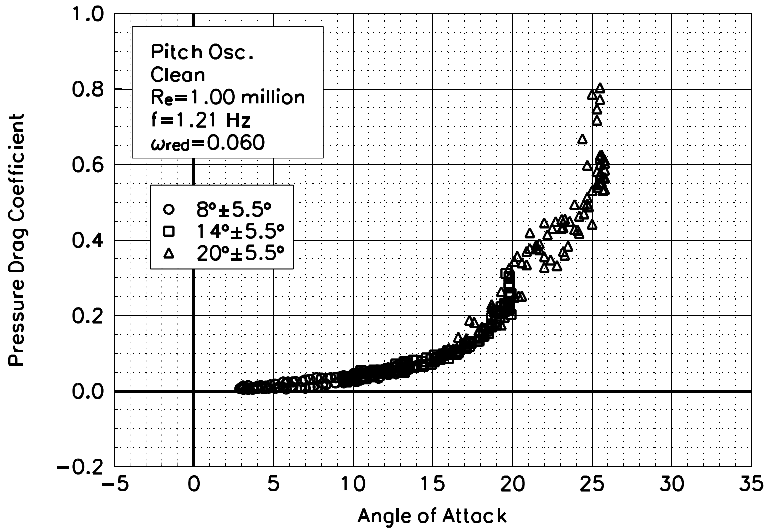

Figure C23. Pressure drag coefficient vs α.

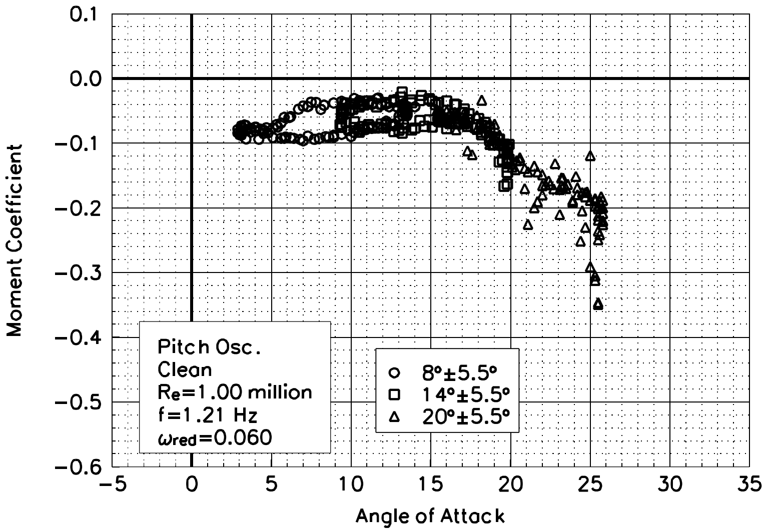

Figure C24. Moment coefficient vs α.

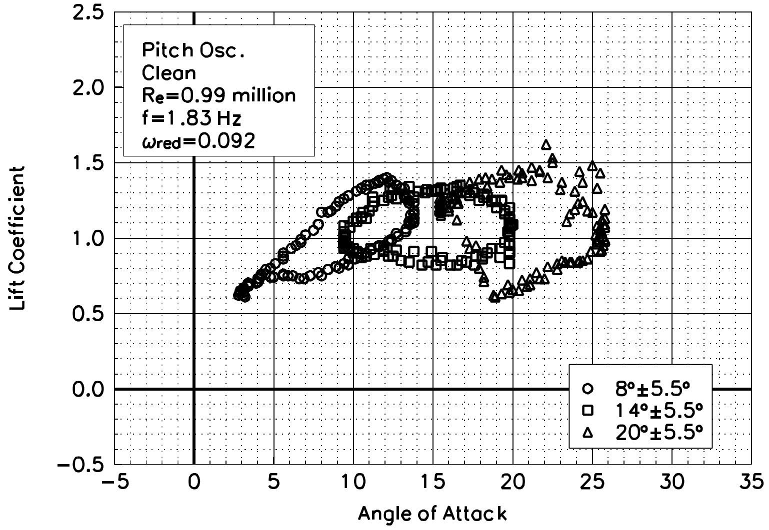

Figure C25. Lift coefficient vs α.

S812
Clean
Re=0.99 million
$\omega_{reduced}$=0.092

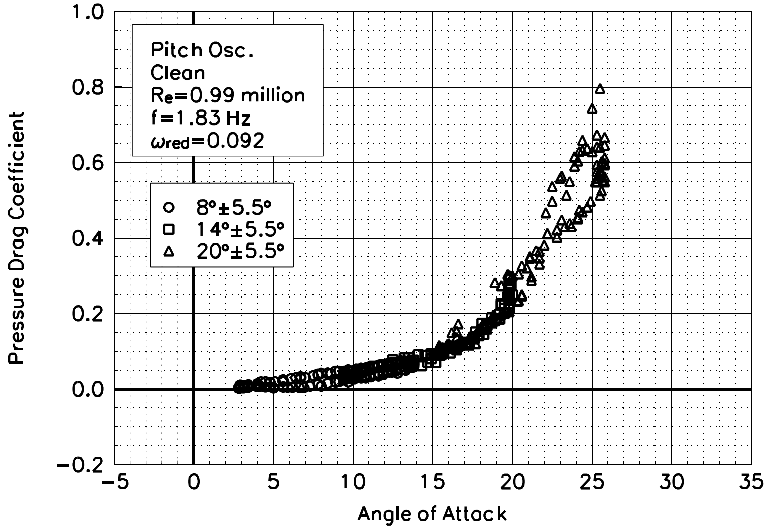

Figure C26. Pressure drag coefficient vs α.

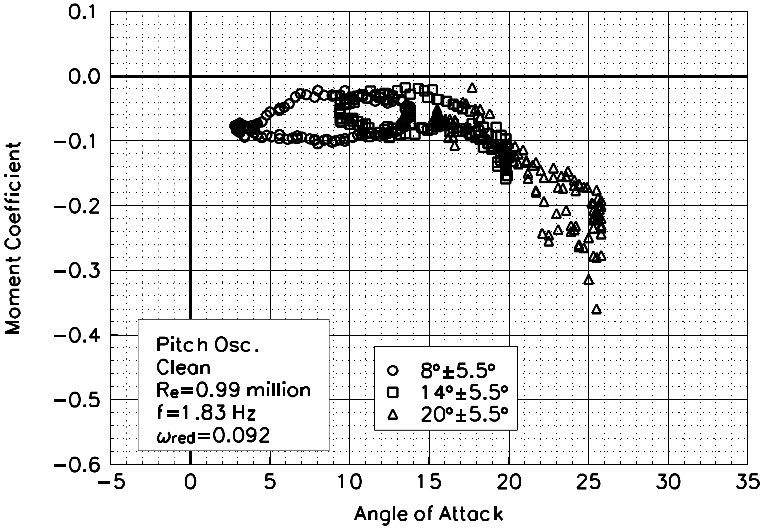

Figure C27. Moment coefficient vs α.

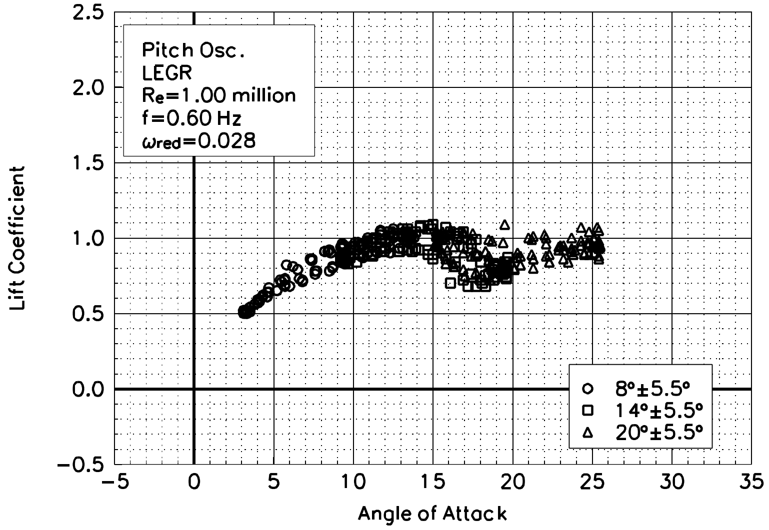

Figure C28. Lift coefficient vs α.

S812
LEGR
Re=1.00 million
$\omega_{reduced}$=0.028

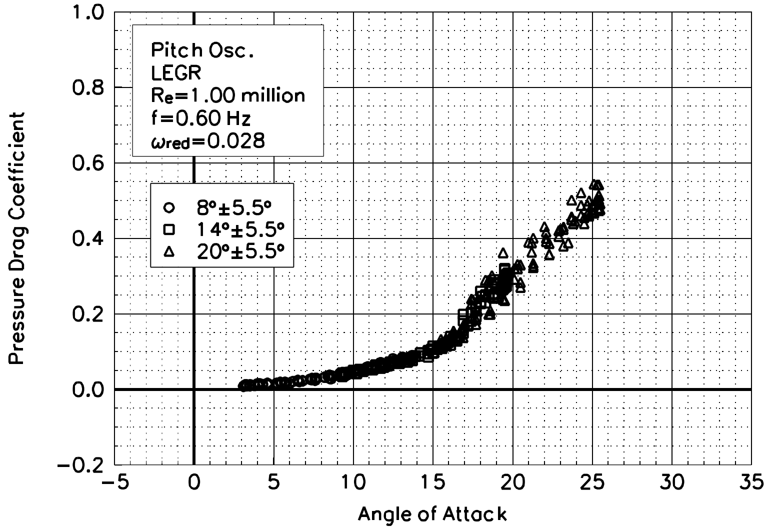

Figure C29. Pressure drag coefficient vs α.

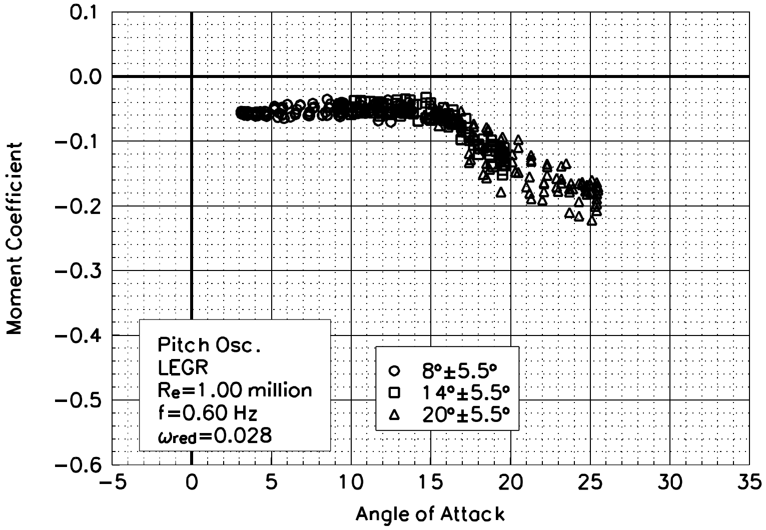

Figure C30. Moment coefficient vs α.

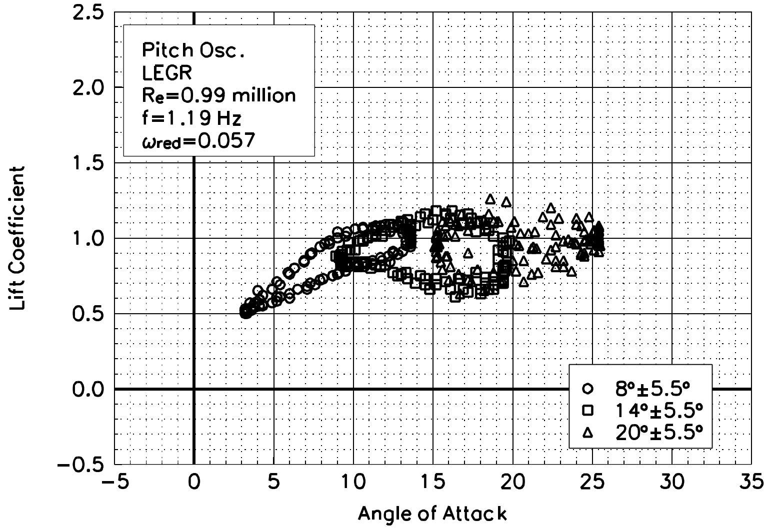

Figure C31. Lift coefficient vs α.

S812
LEGR
Re=0.99 million
$\omega_{reduced}$=0.057

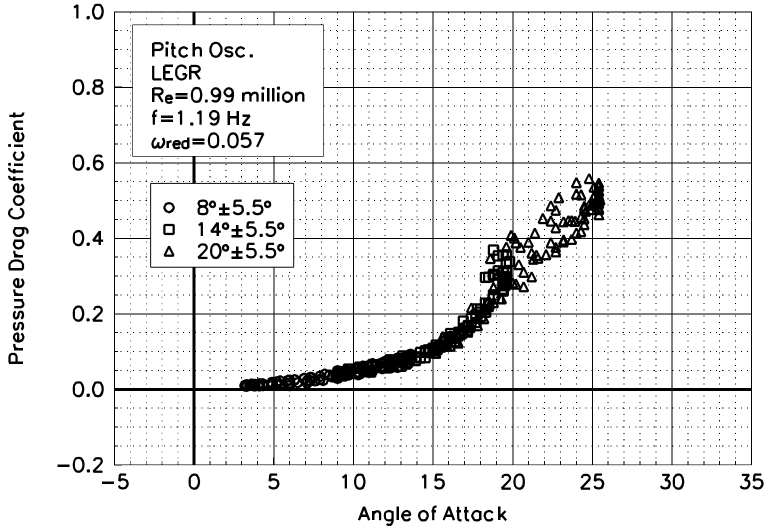

Figure C32. Pressure drag coefficient vs α.

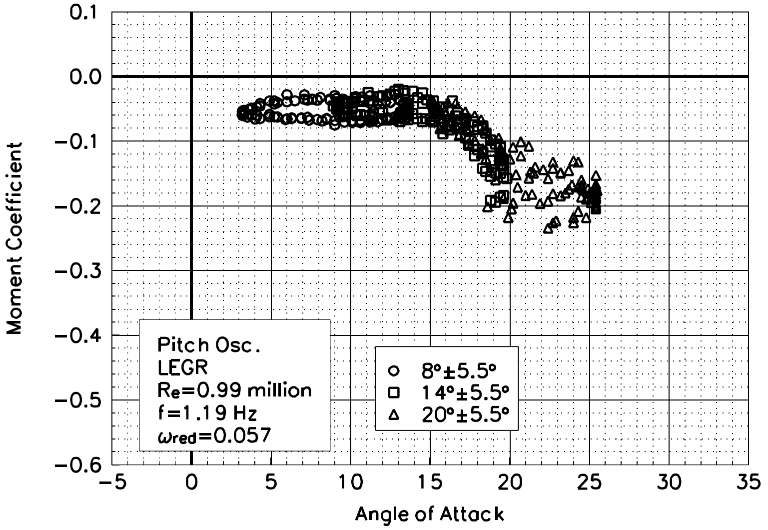

Figure C33. Moment coefficient vs α.

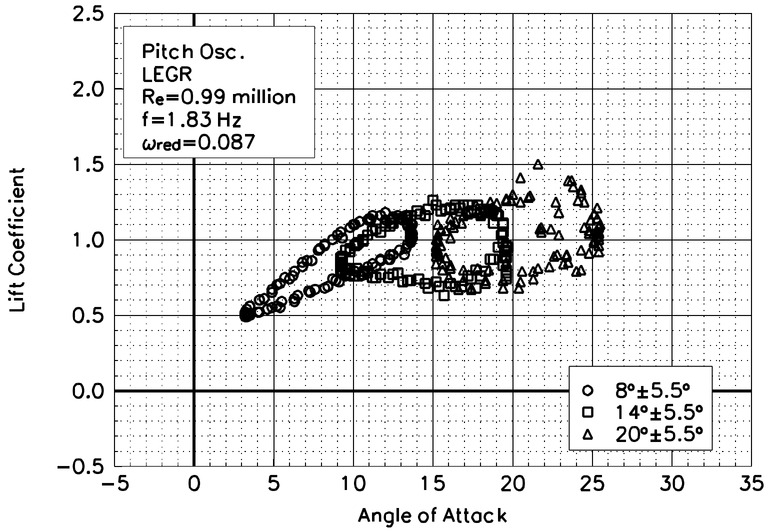

Figure C34. Lift coefficient vs α.

S812
LEGR
Re=0.99 million
$\omega_{reduced}$=0.087

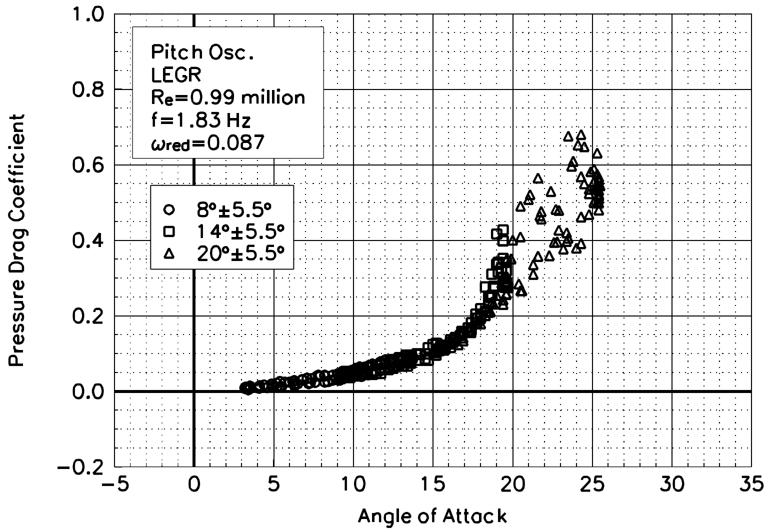

Figure C35. Pressure drag coefficient vs α.

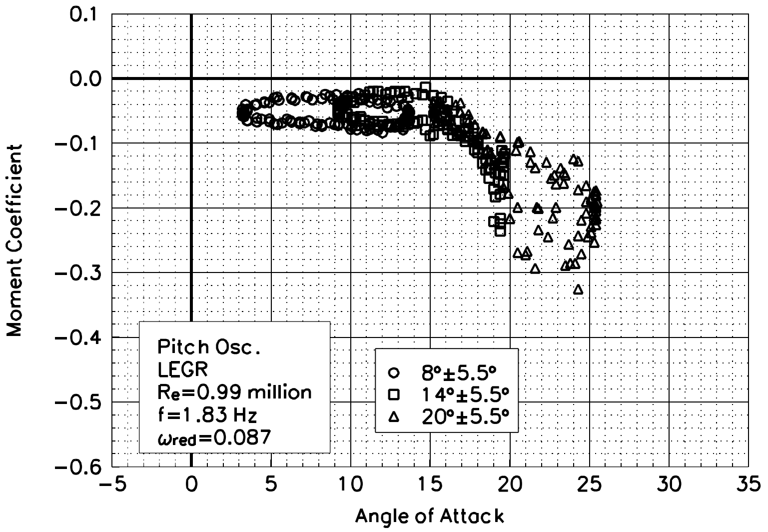

Figure C36. Moment coefficient vs α.

Unsteady Airfoil Characteristics

±5.5° Sine, Re= 1.25 million

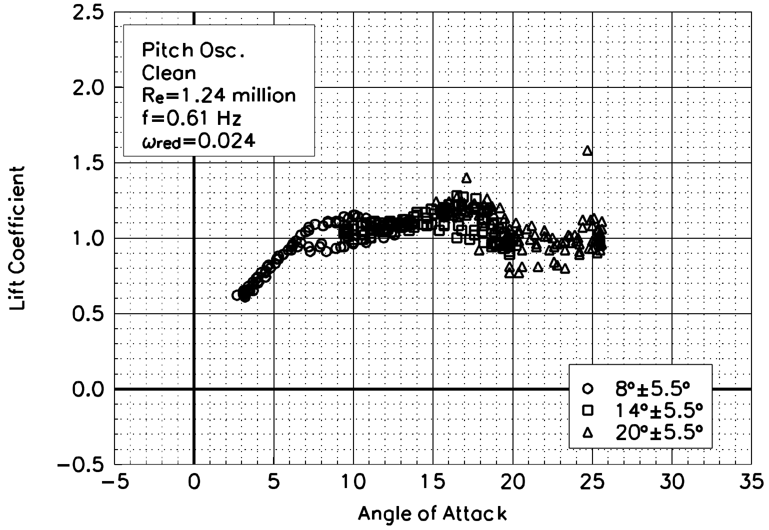

Figure C37. Lift coefficient vs α.

S812
Clean
Re=1.24 million
$\omega_{reduced}$=0.024

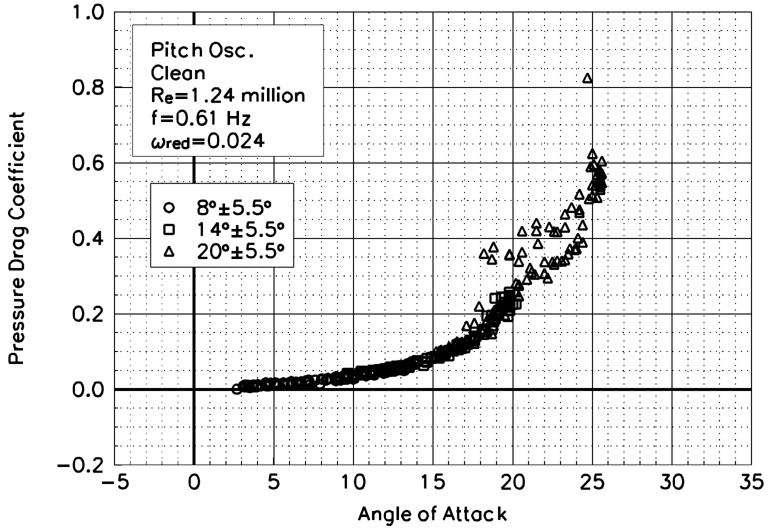

Figure C38. Pressure drag coefficient vs α.

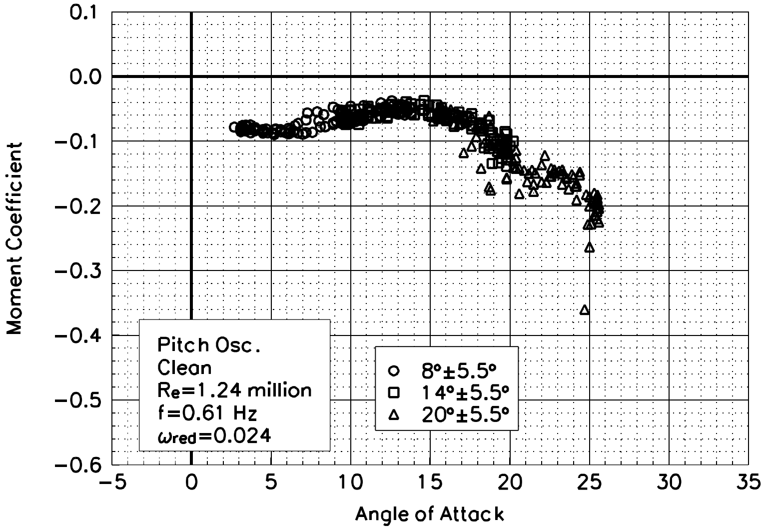

Figure C39. Moment coefficient vs α.

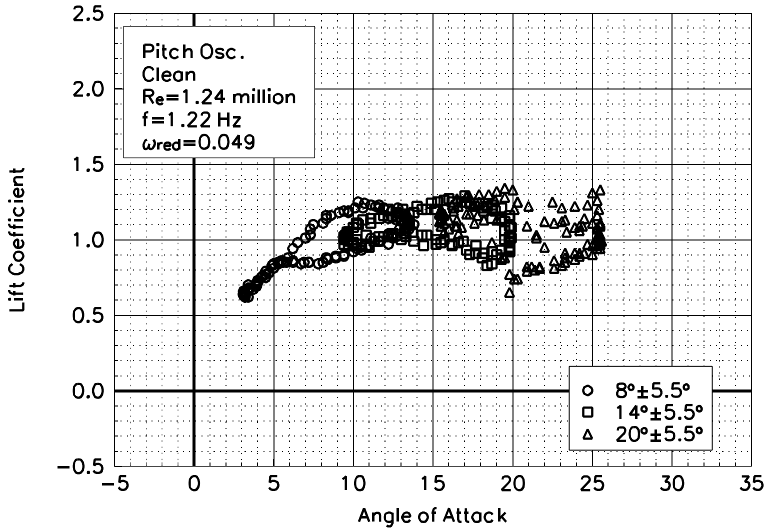

Figure C40. Lift coefficient vs α.

S812
Clean
Re=1.24 million
$\omega_{reduced}$=0.049

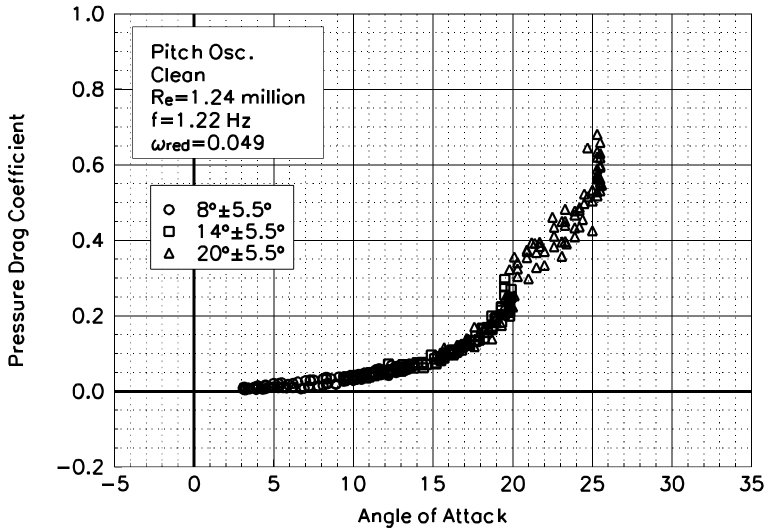

Figure C41. Pressure drag coefficient vs α.

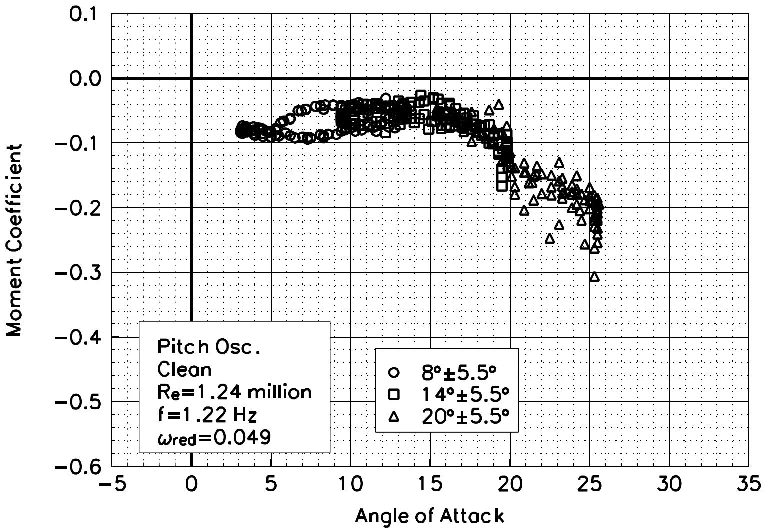

Figure C42. Moment coefficient vs α.

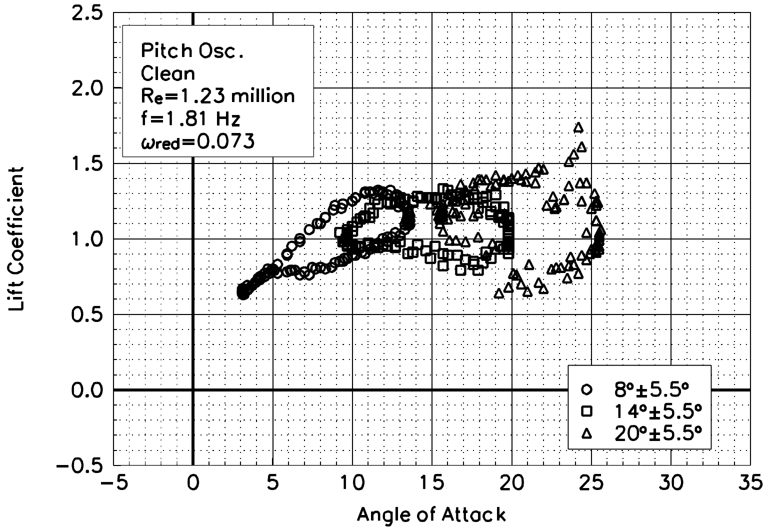

Figure C43. Lift coefficient vs α.

S812
Clean
Re=1.23 million
$\omega_{reduced}$=0.073

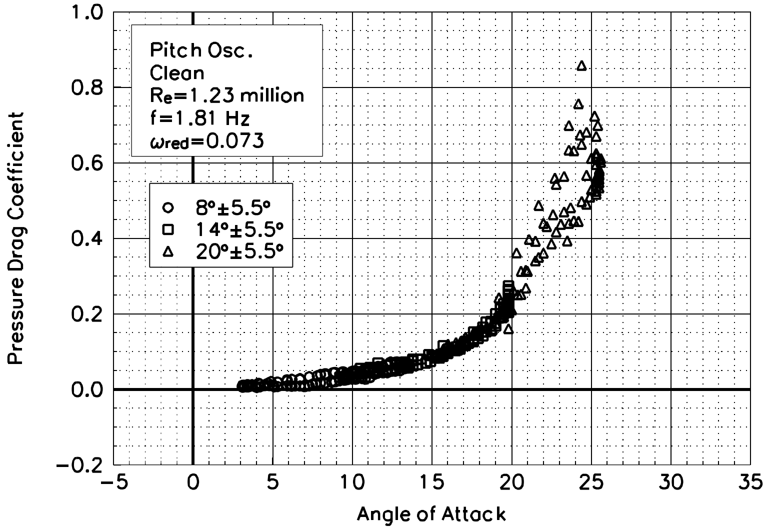

Figure C44. Pressure drag coefficient vs α.

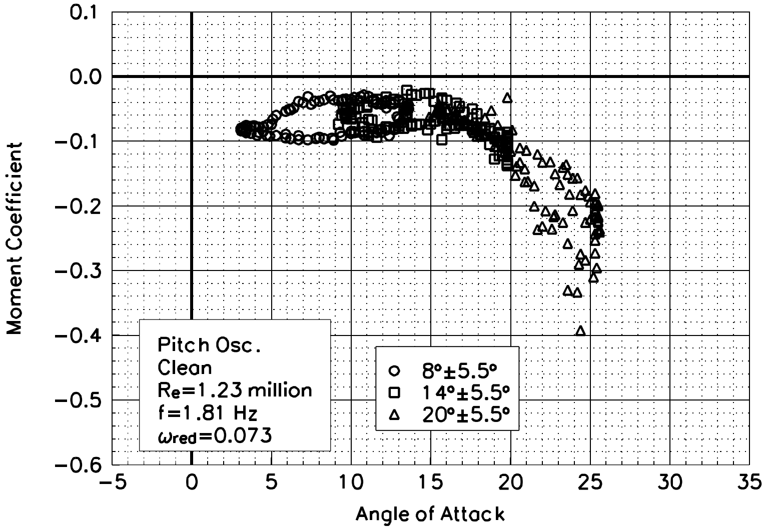

Figure C45. Moment coefficient vs α.

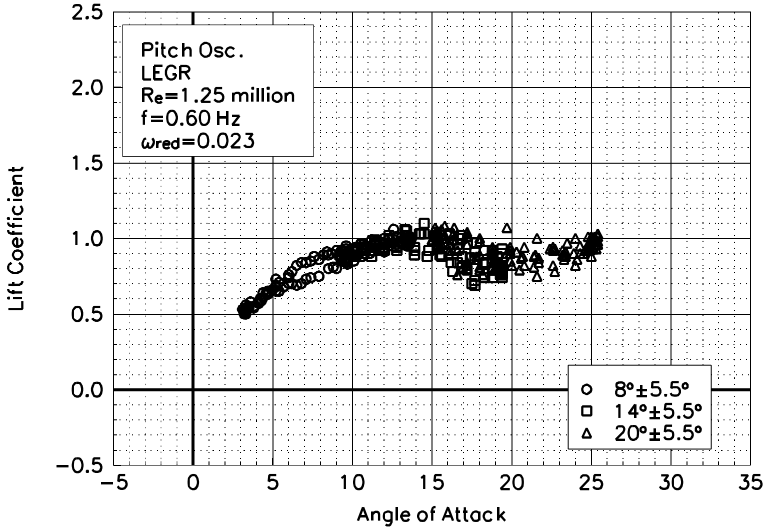

Figure C46. Lift coefficient vs α.

S812
LEGR
Re=1.25 million
$\omega_{reduced}$=0.023

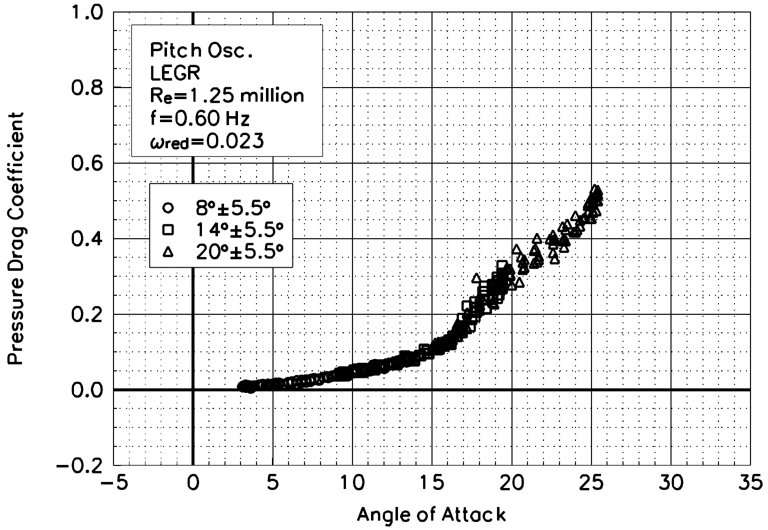

Figure C47. Pressure drag coefficient vs α.

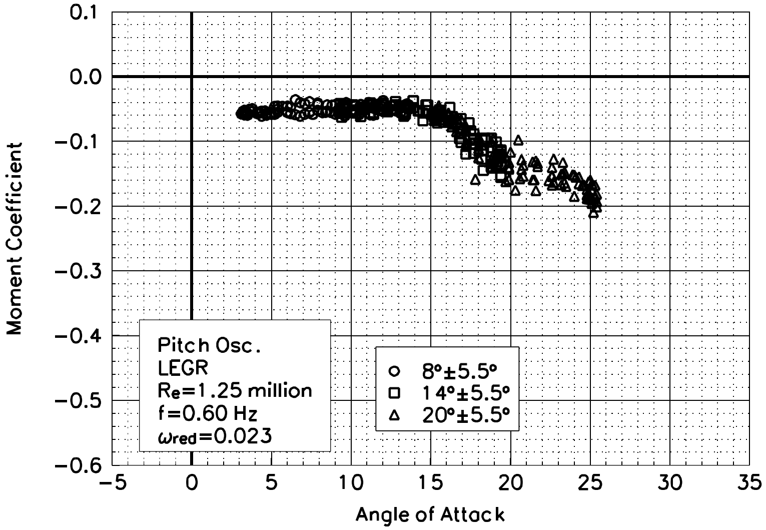

Figure C48. Moment coefficient vs α.

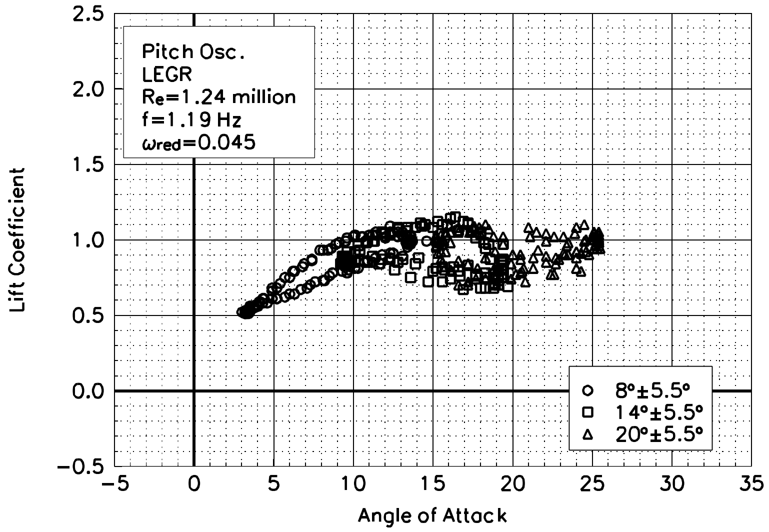

Figure C49. Lift coefficient vs α.

S812
LEGR
Re=1.24 million
$\omega_{reduced}$=0.045

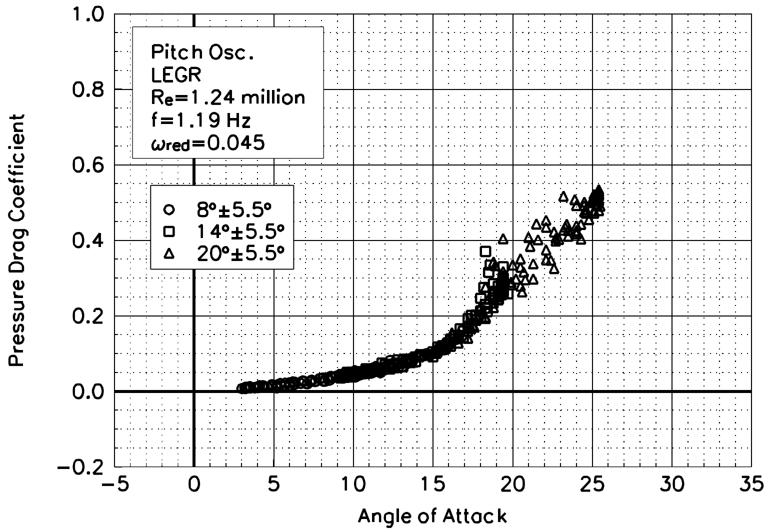

Figure C50. Pressure drag coefficient vs α.

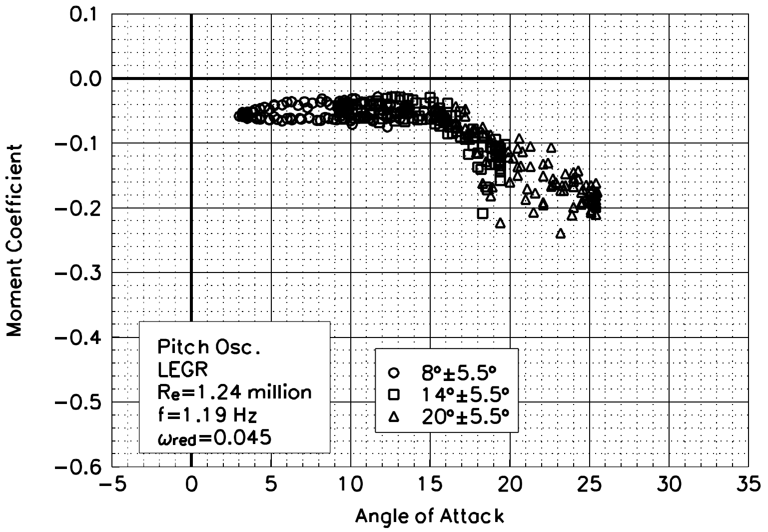

Figure C51. Moment coefficient vs α.

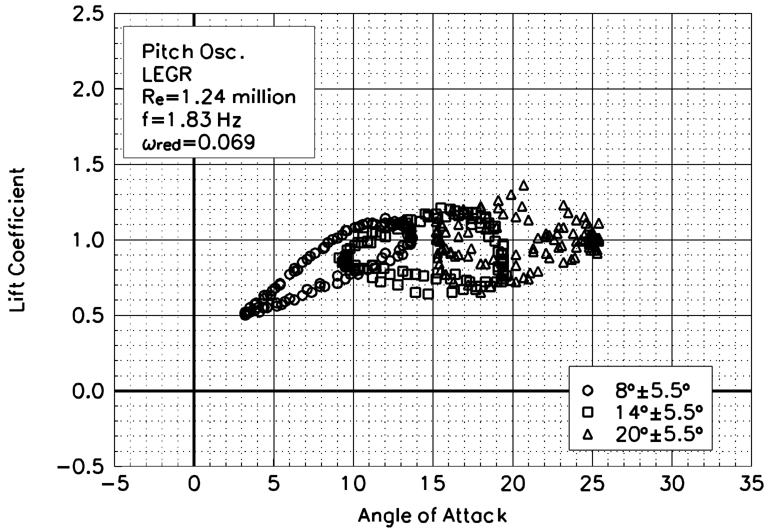

Figure C52. Lift coefficient vs α.

S812
LEGR
Re=1.24 million
$\omega_{reduced}$=0.069

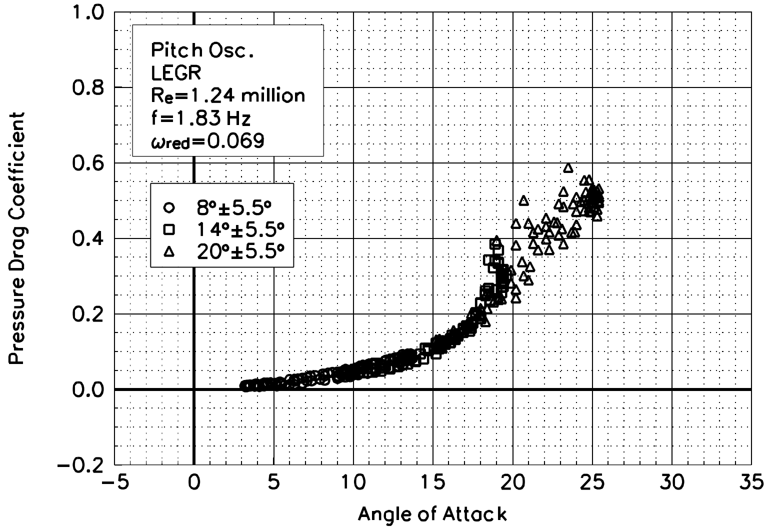

Figure C53. Pressure drag coefficient vs α.

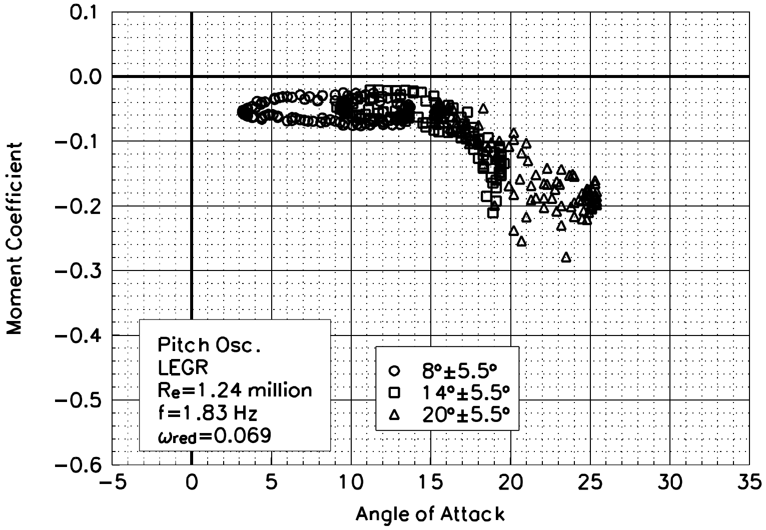

Figure C54. Moment coefficient vs α.

Unsteady Airfoil Characteristics

±5.5° Sine, Re = 1.5 million

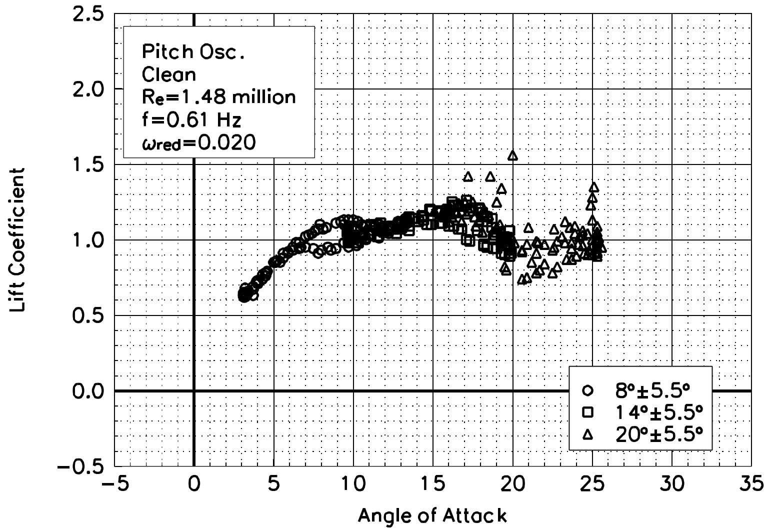

Figure C55. Lift coefficient vs α.

S812
Clean
Re=1.48 million
$\omega_{reduced}$=0.020

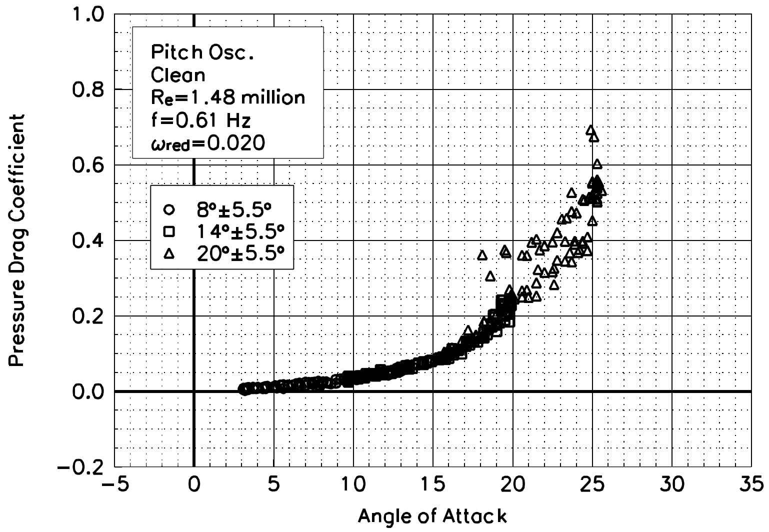

Figure C56. Pressure drag coefficient vs α.

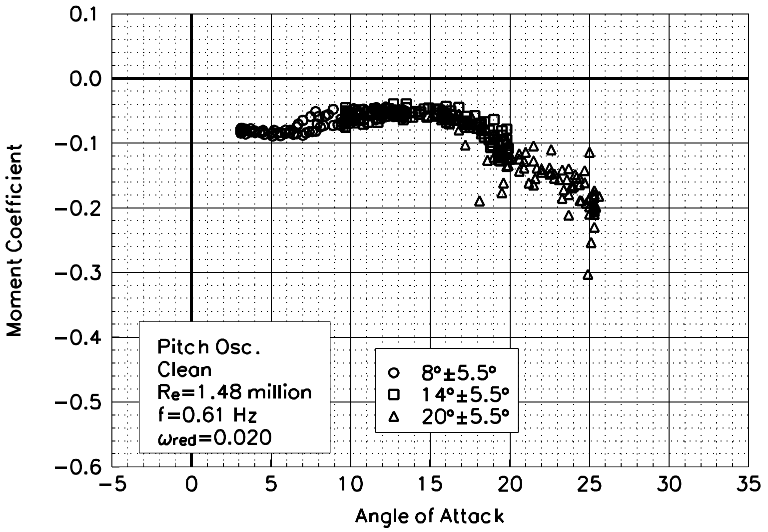

Figure C57. Moment coefficient vs α.

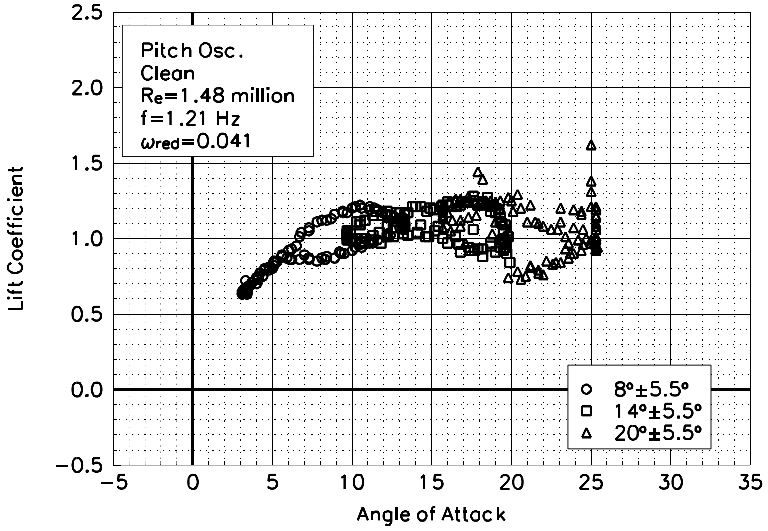

Figure C58. Lift coefficient vs α.

S812
Clean
Re=1.48 million
$\omega_{reduced}$=0.041

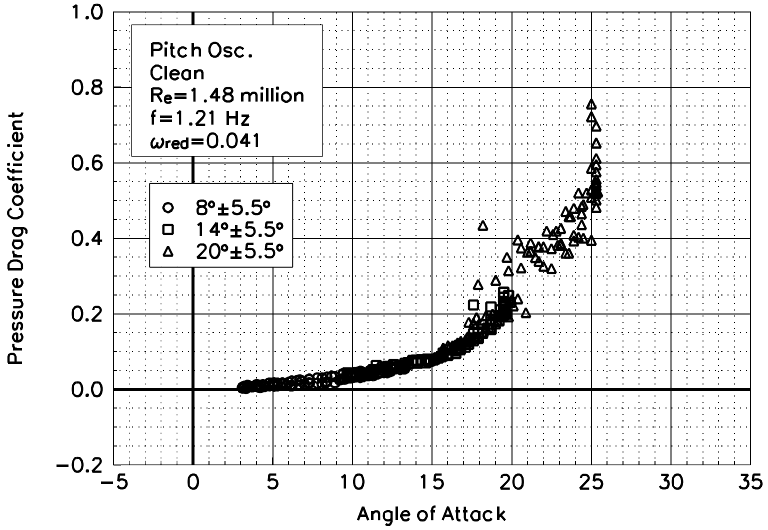

Figure C59. Pressure drag coefficient vs α.

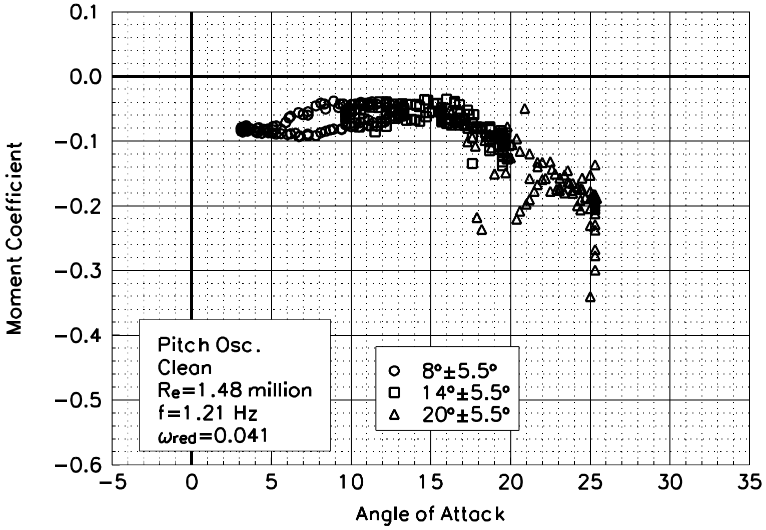

Figure C60. Moment coefficient vs α.

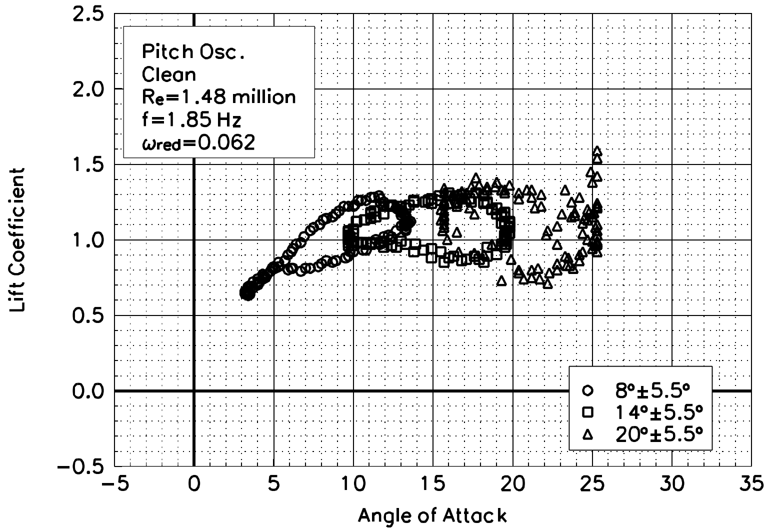

Figure C61. Lift coefficient vs α.

S812
Clean
Re=1.48 million
$\omega_{reduced}$=0.062

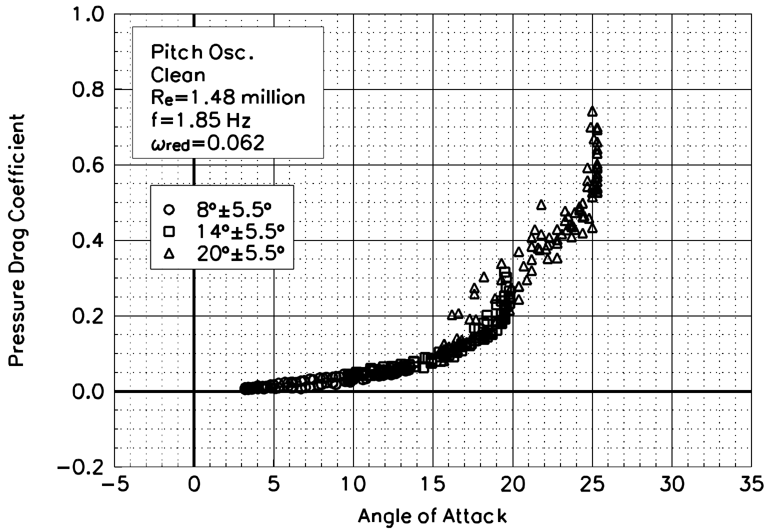

Figure C62. Pressure drag coefficient vs α.

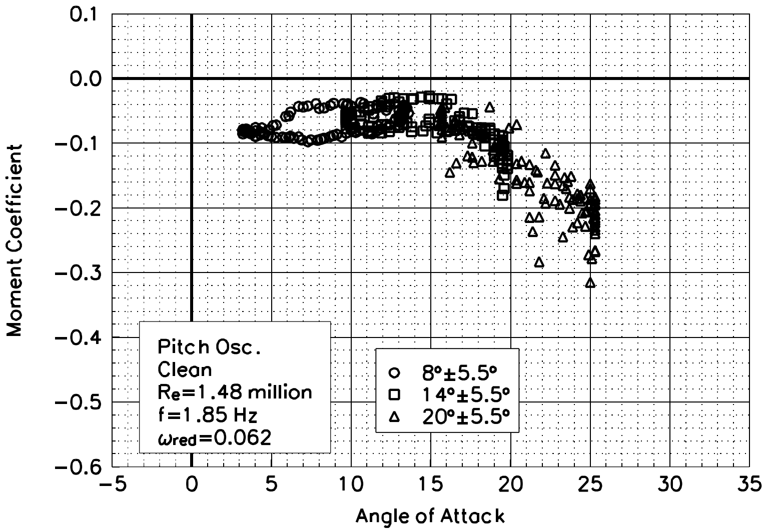

Figure C63. Moment coefficient vs α.

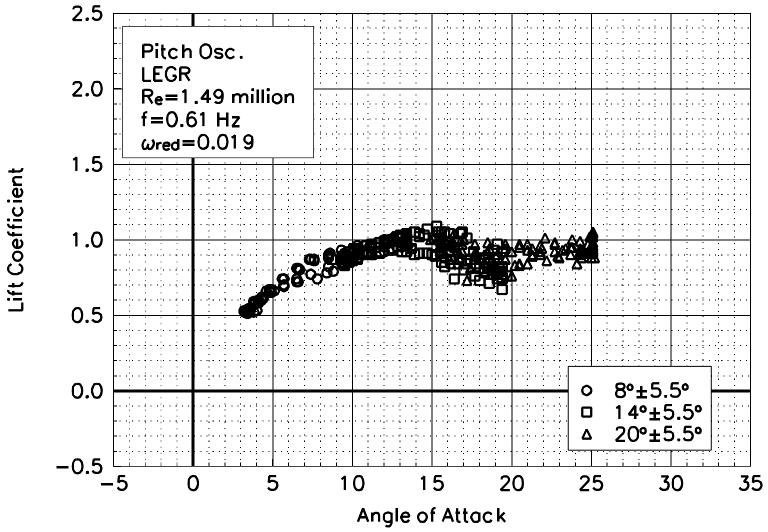

Figure C64. Lift coefficient vs α.

S812
LEGR
Re=1.49 million
$\omega_{reduced}$=0.019

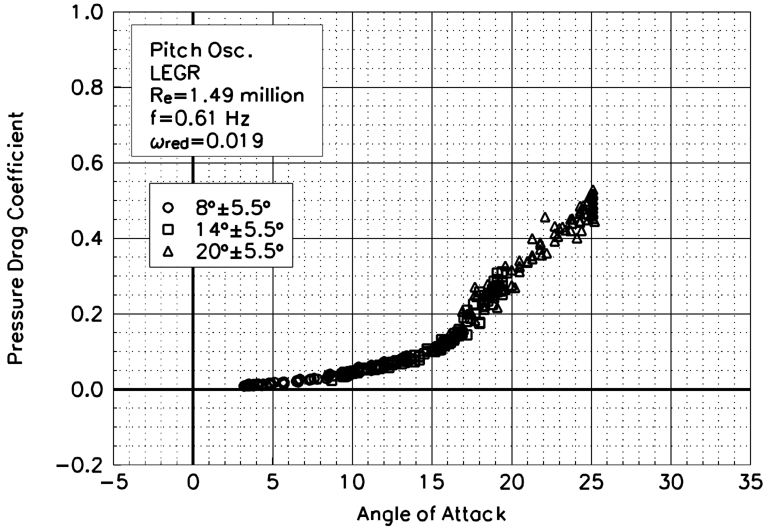

Figure C65. Pressure drag coefficient vs α.

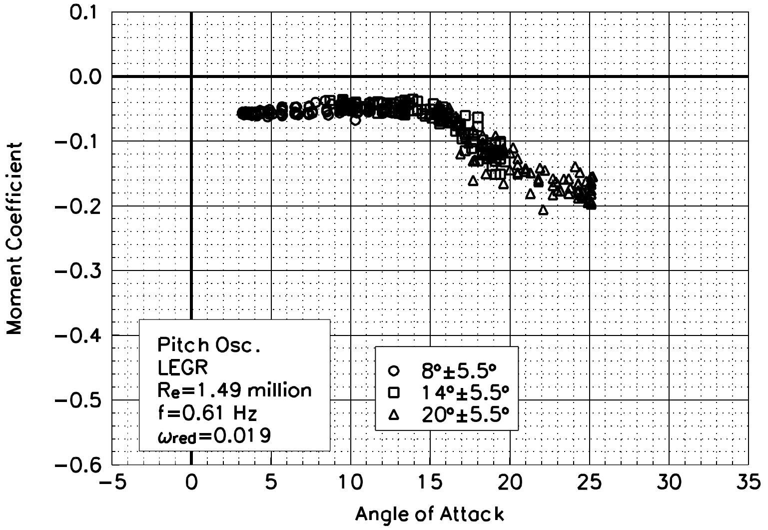

Figure C66. Moment coefficient vs α.

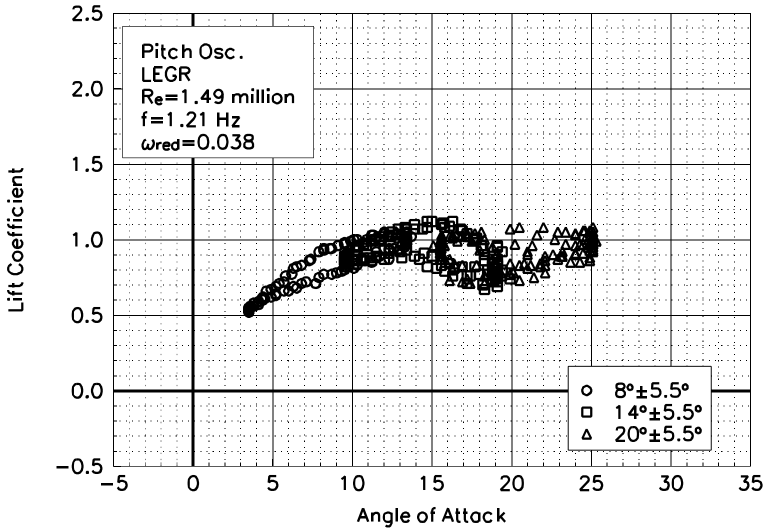

Figure C67. Lift coefficient vs α.

S812
LEGR
Re=1.49 million
$\omega_{reduced}$=0.038

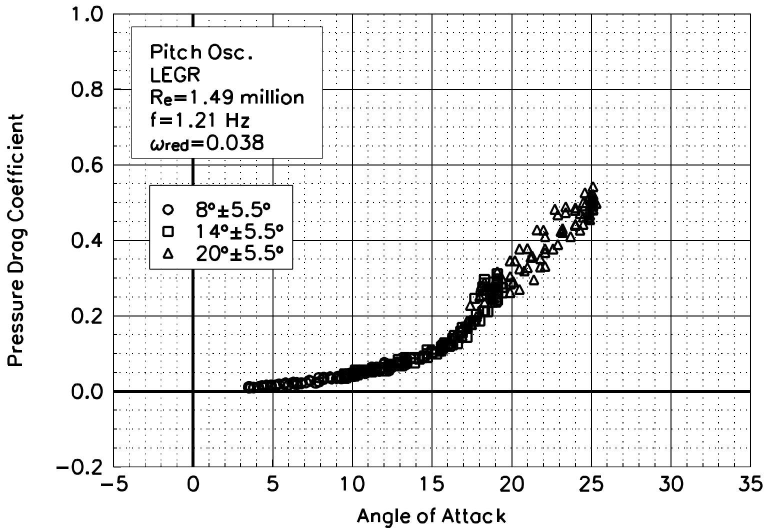

Figure C68. Pressure drag coefficient vs α.

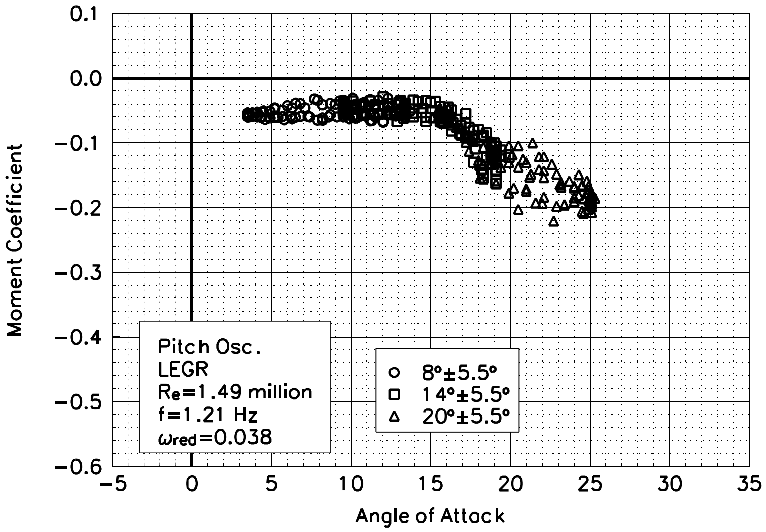

Figure C69. Moment coefficient vs α.

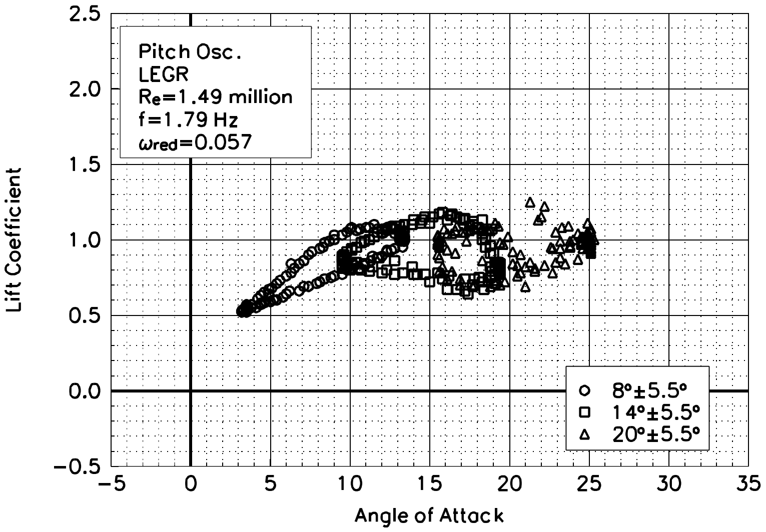

Figure C70. Lift coefficient vs α.

S812
LEGR
Re=1.49 million
$\omega_{reduced}$=0.057

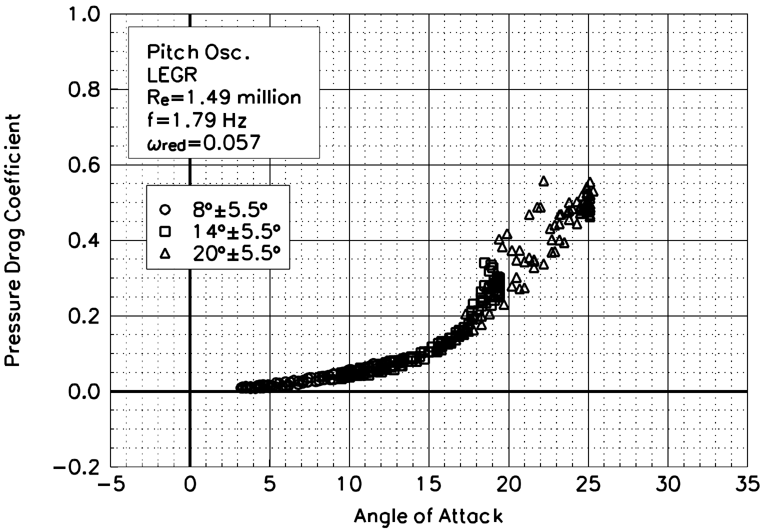

Figure C71. Pressure drag coefficient vs α.

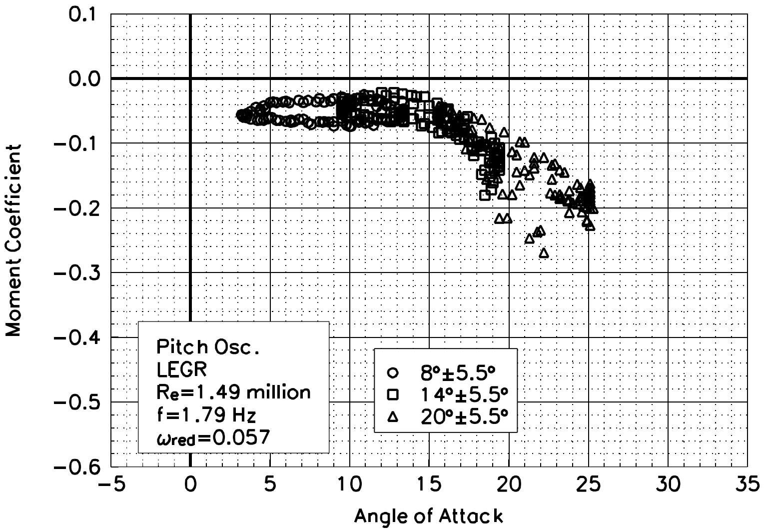

Figure C72. Moment coefficient vs α.

Unsteady Airfoil Characteristics

±10° Sine, Re = 0.75 million

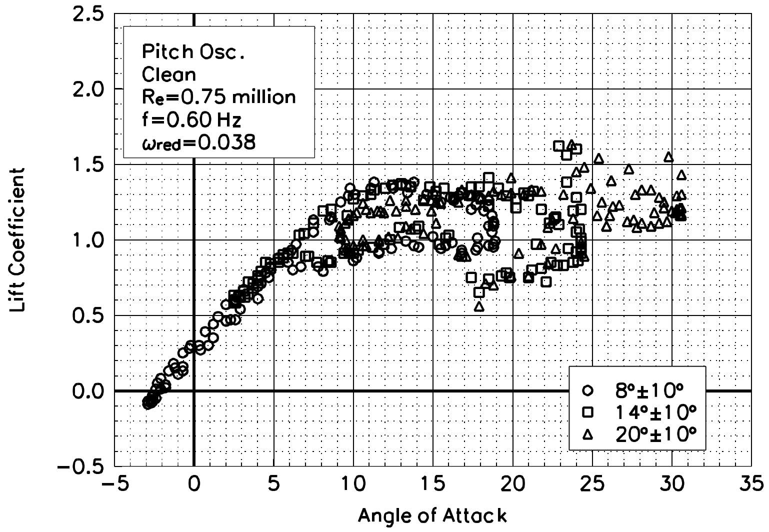

Figure C73. Lift coefficient vs α.

S812
Clean
Re=0.75 million
$\omega_{reduced}$=0.038

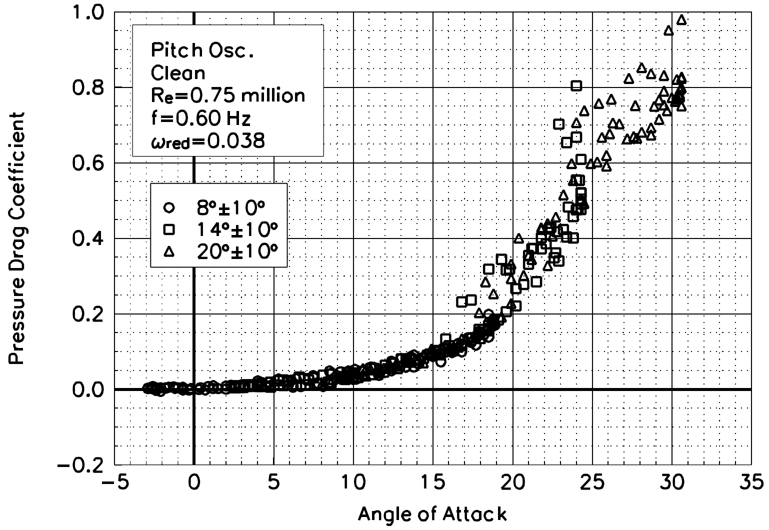

Figure C74. Pressure drag coefficient vs α.

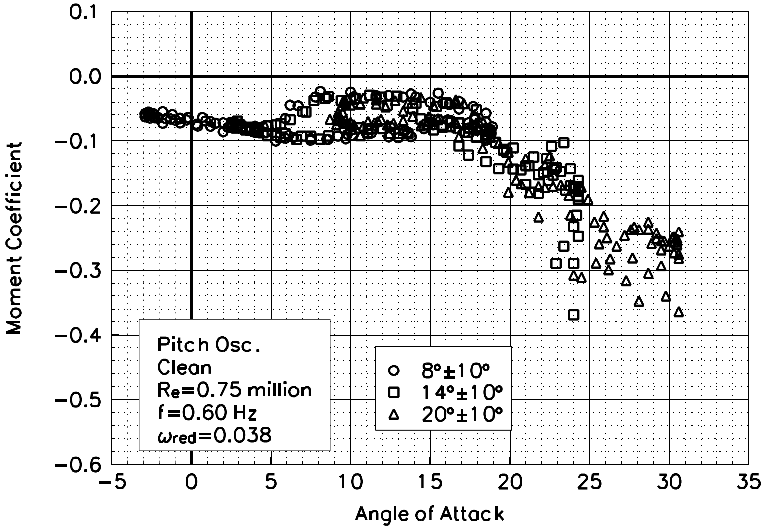

Figure C75. Moment coefficient vs α.

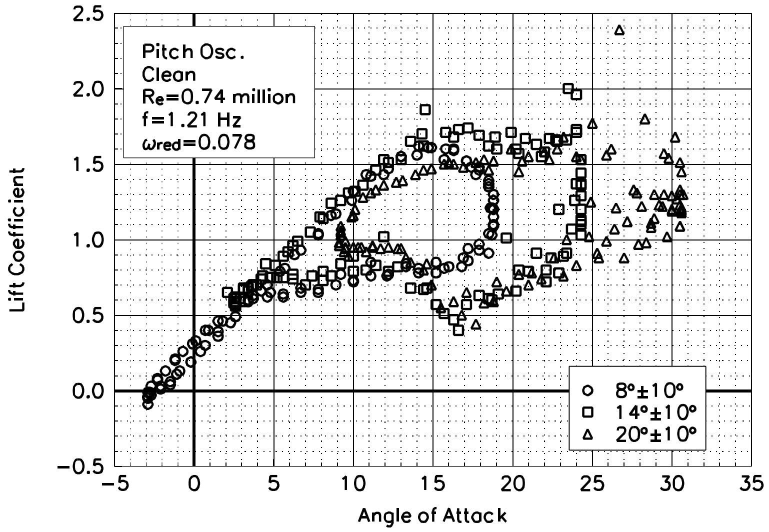

Figure C76. Lift coefficient vs α.

S812
Clean
Re=0.74 million
$\omega_{reduced}$=0.078

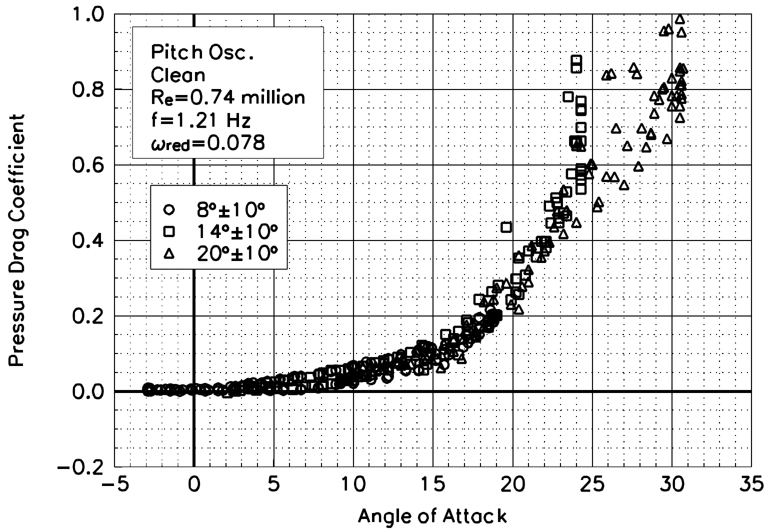

Figure C77. Pressure drag coefficient vs α.

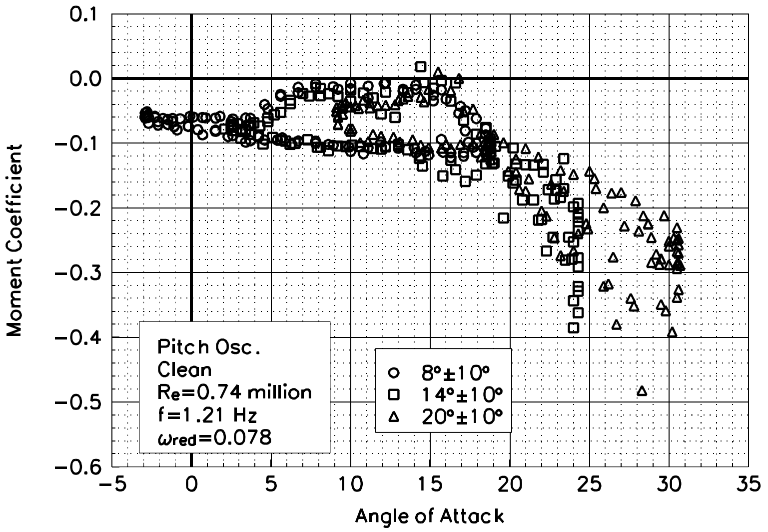

Figure C78. Moment coefficient vs α.

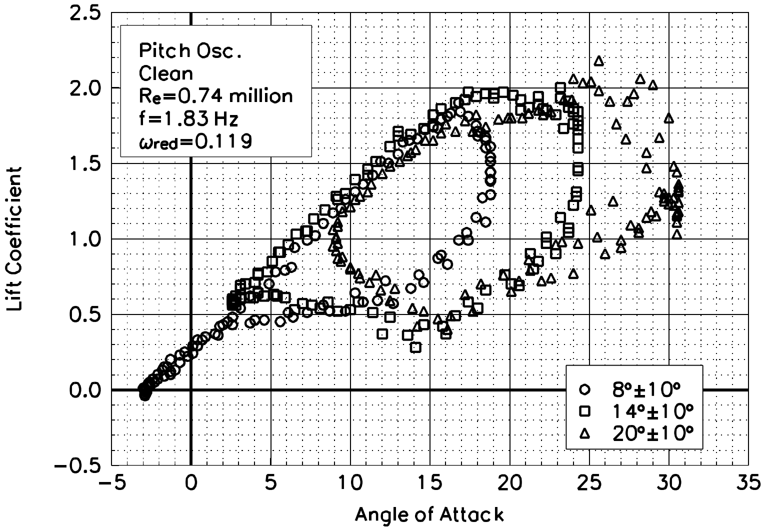

Figure C79. Lift coefficient vs α.

S812
Clean
Re=0.74 million
$\omega_{reduced}$=0.119

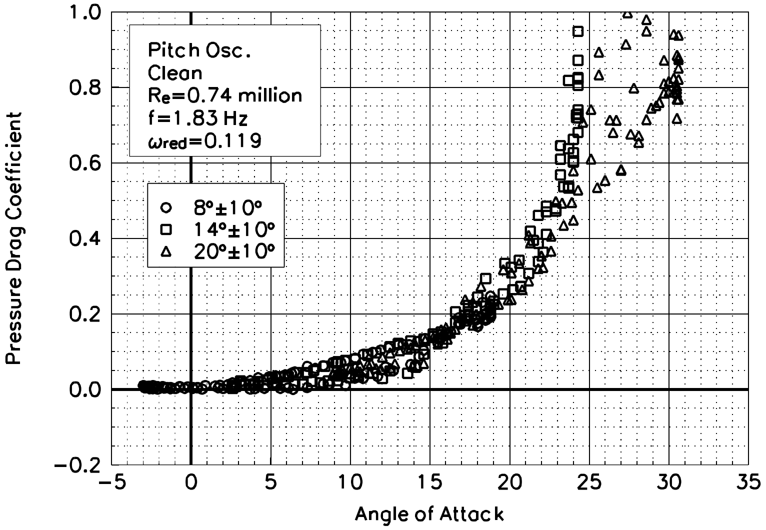

Figure C80. Pressure drag coefficient vs α.

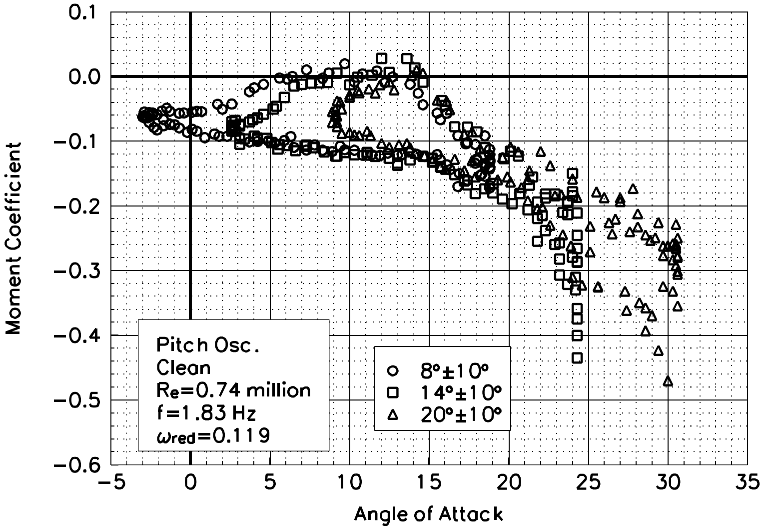

Figure C81. Moment coefficient vs α.

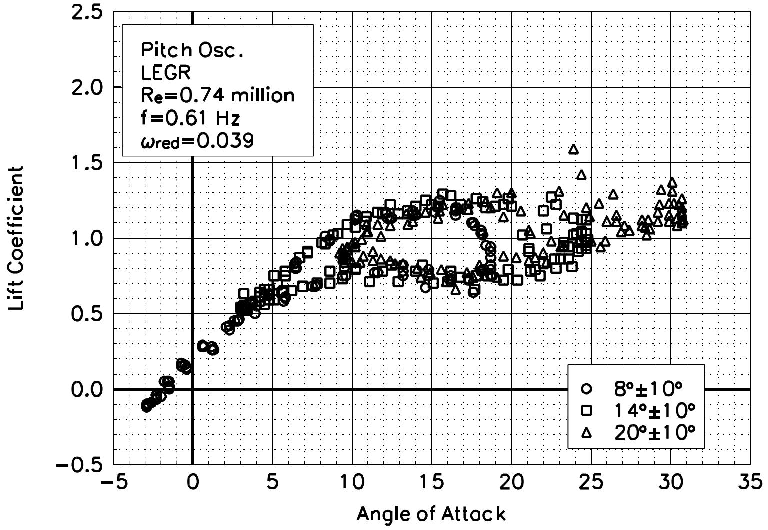

Figure C82. Lift coefficient vs α.

S812
LEGR
Re=0.74 million
$\omega_{reduced}$=0.039

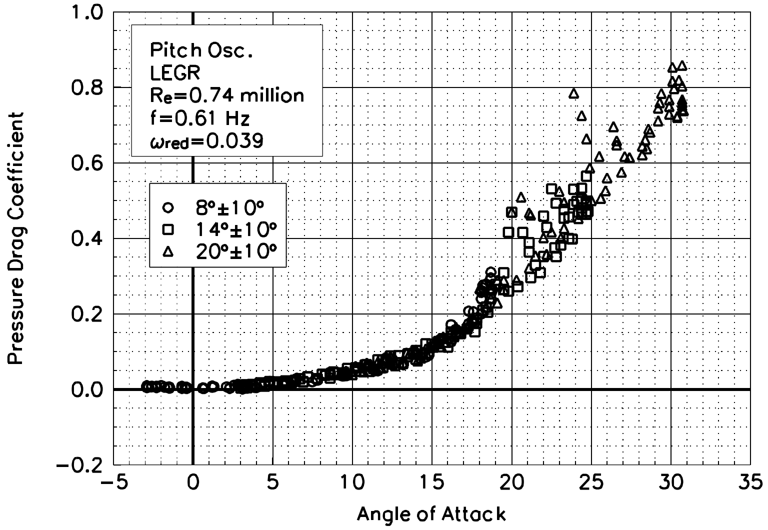

Figure C83. Pressure drag coefficient vs α.

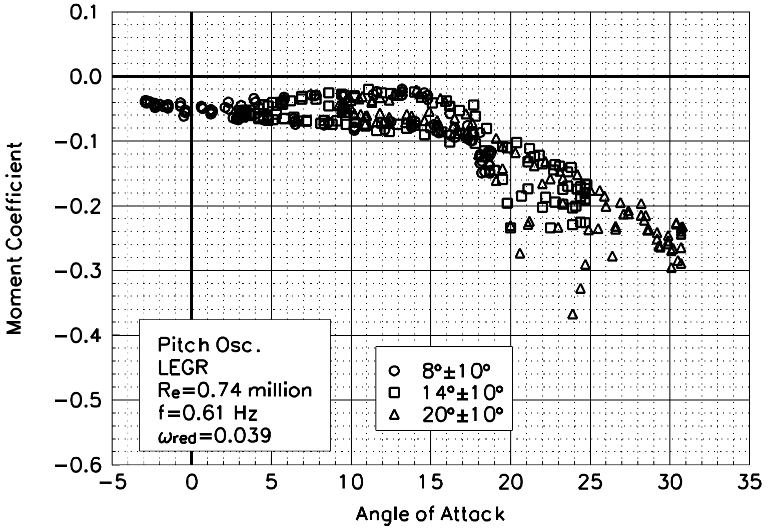

Figure C84. Moment coefficient vs α.

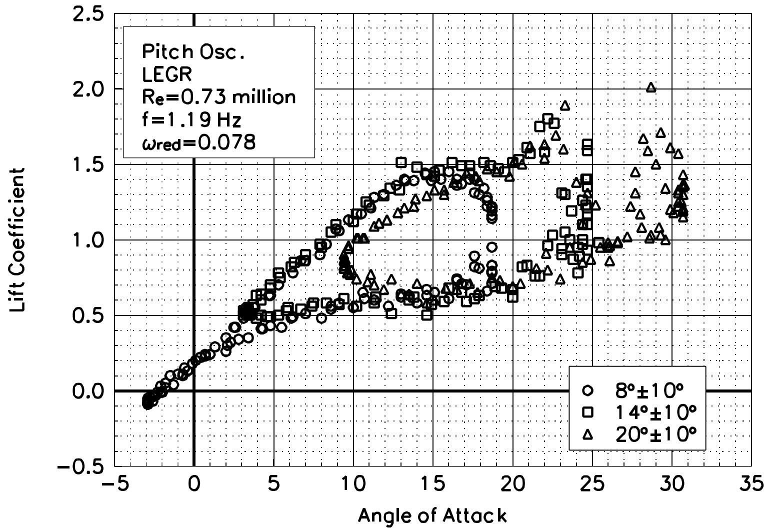

Figure C85. Lift coefficient vs α.

S812
LEGR
Re=0.73 million
$\omega_{reduced}$=0.078

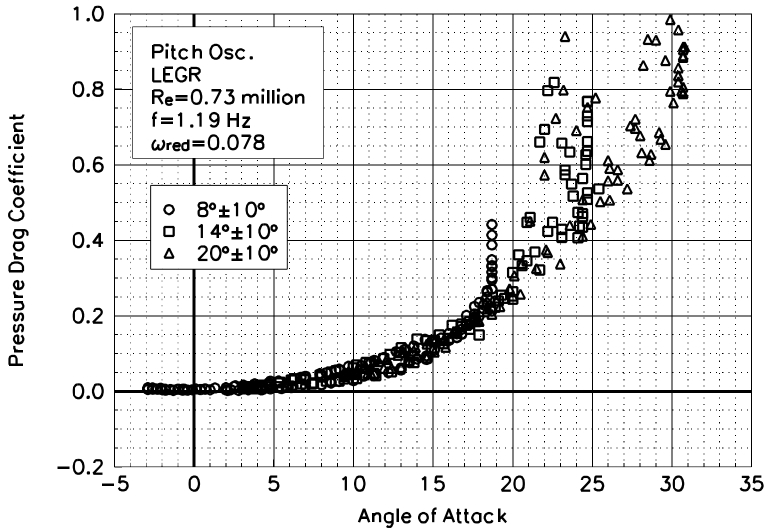

Figure C86. Pressure drag coefficient vs α.

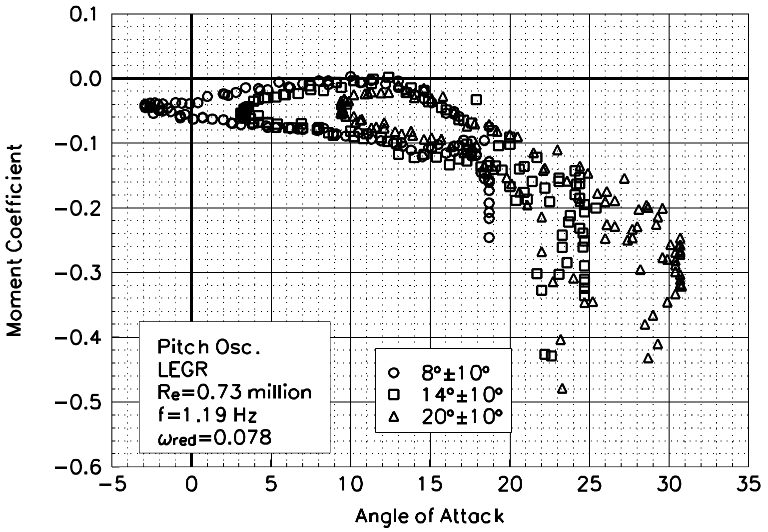

Figure C87. Moment coefficient vs α.

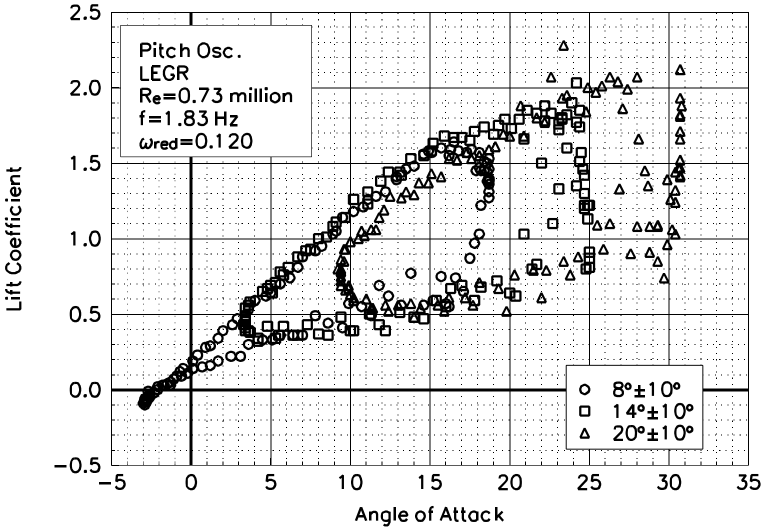

Figure C88. Lift coefficient vs α.

S812
LEGR
Re=0.73 million
$\omega_{reduced}$=0.120

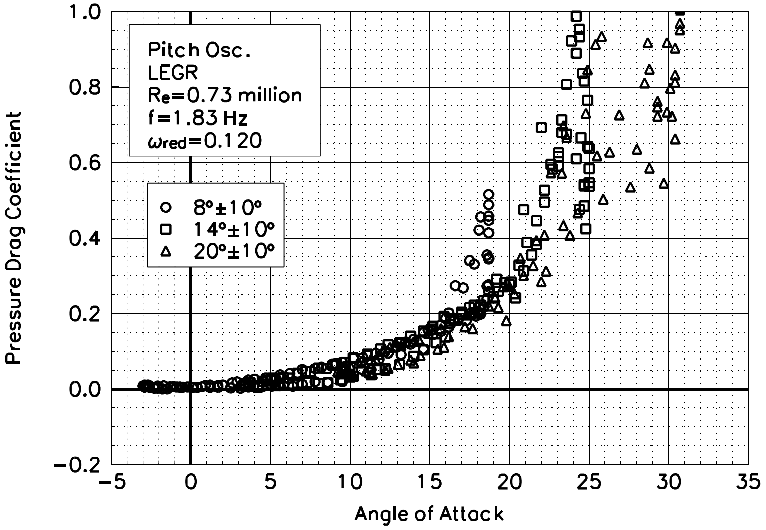

Figure C89. Pressure drag coefficient vs α.

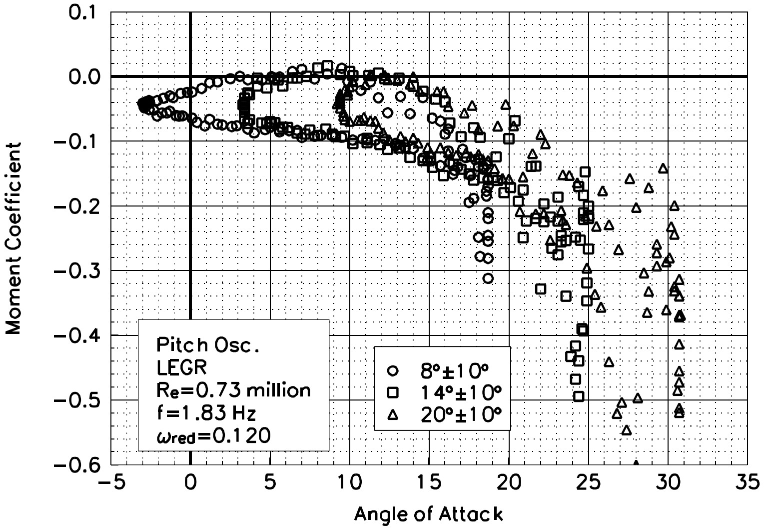

Figure C90. Moment coefficient vs α.

Unsteady Airfoil Characteristics

±10° Sine, Re = 1 million

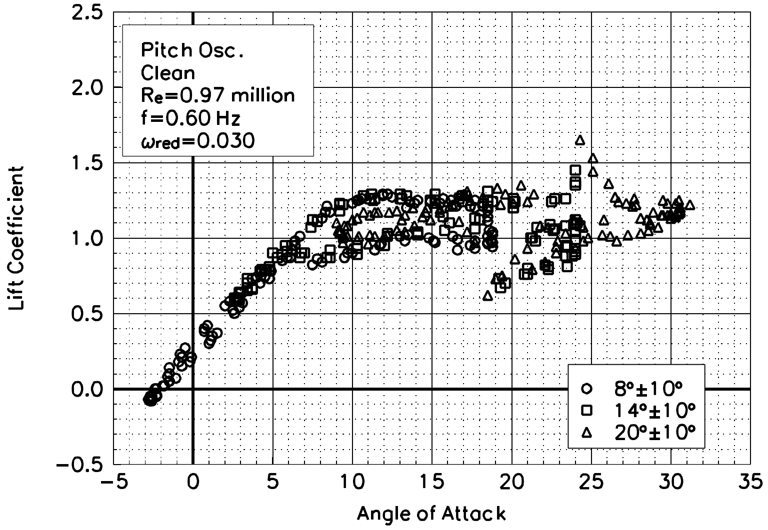

Figure C91. Lift coefficient vs α.

S812
Clean
Re=0.97 million
$\omega_{reduced}$=0.030

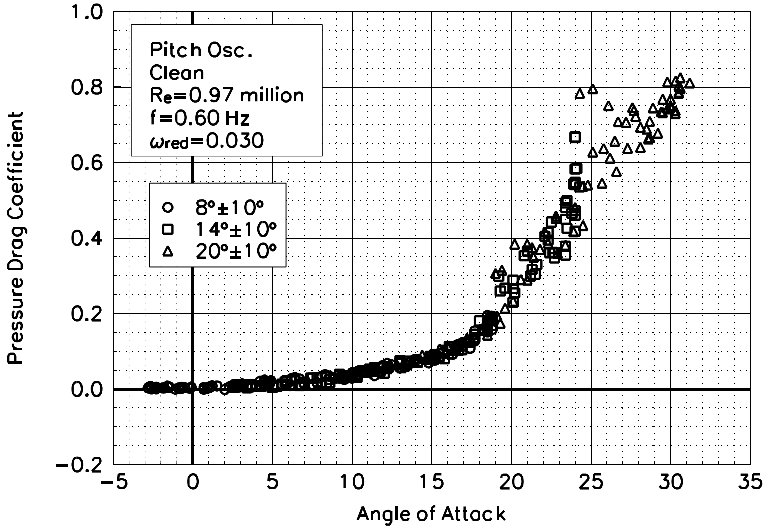

Figure C92. Pressure drag coefficient vs α.

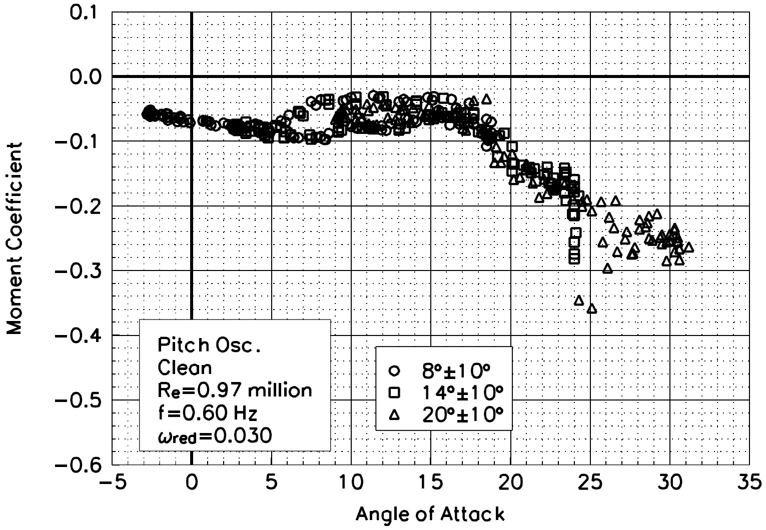

Figure C93. Moment coefficient vs α.

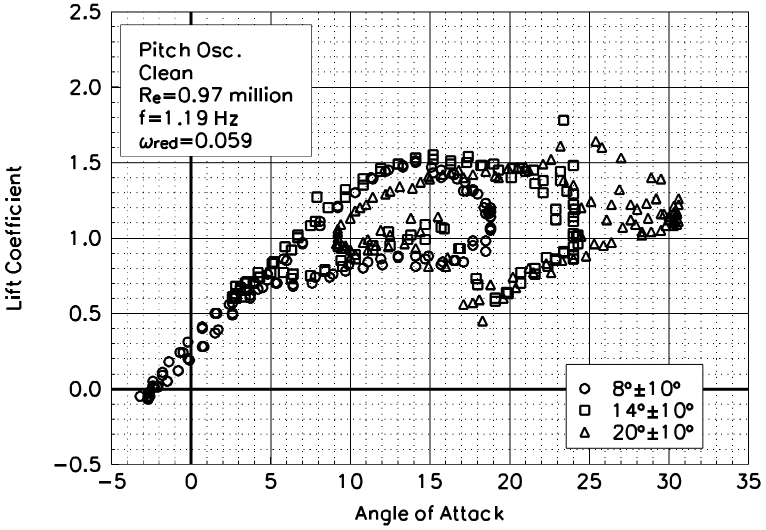

Figure C94. Lift coefficient vs α.

S812
Clean
Re=0.97 million
$\omega_{reduced}$=0.059

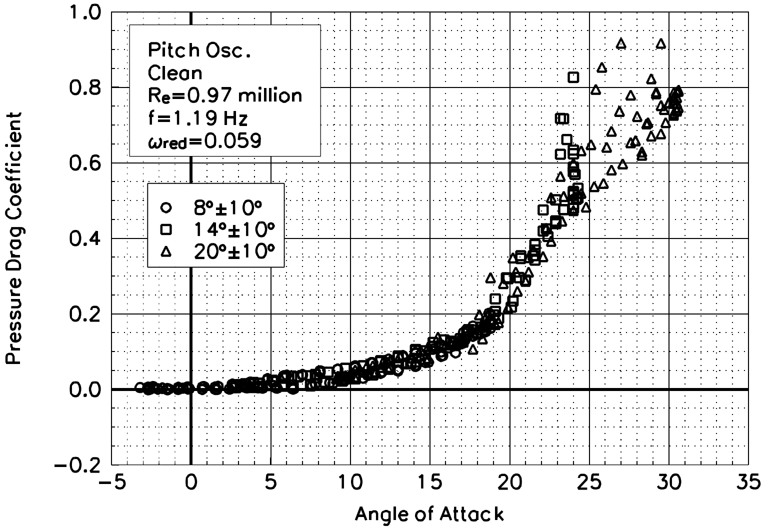

Figure C95. Pressure drag coefficient vs α.

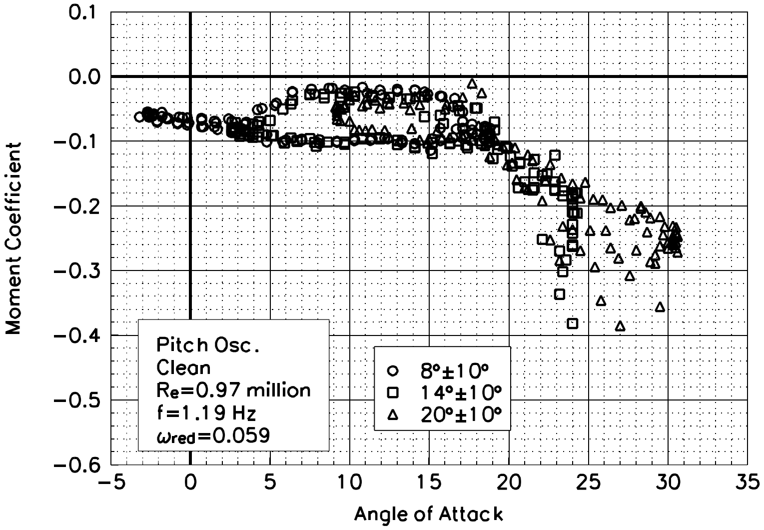

Figure C96. Moment coefficient vs α.

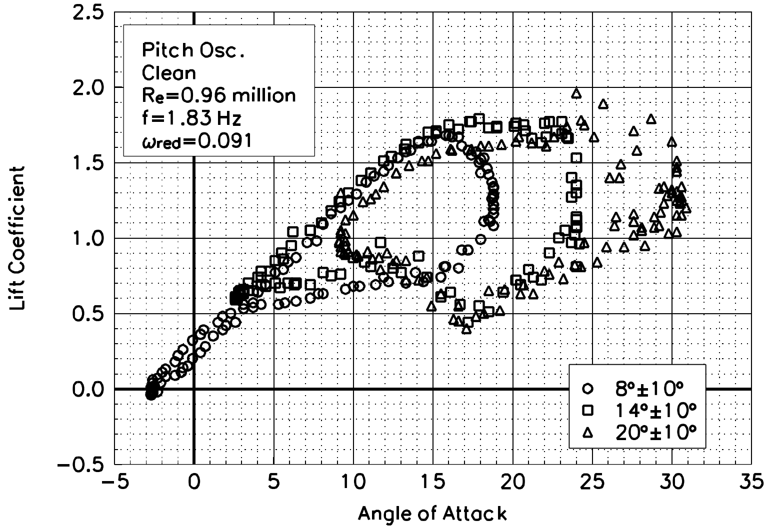

Figure C97. Lift coefficient vs α.

S812
Clean
Re=0.96 million
$\omega_{reduced}$=0.091

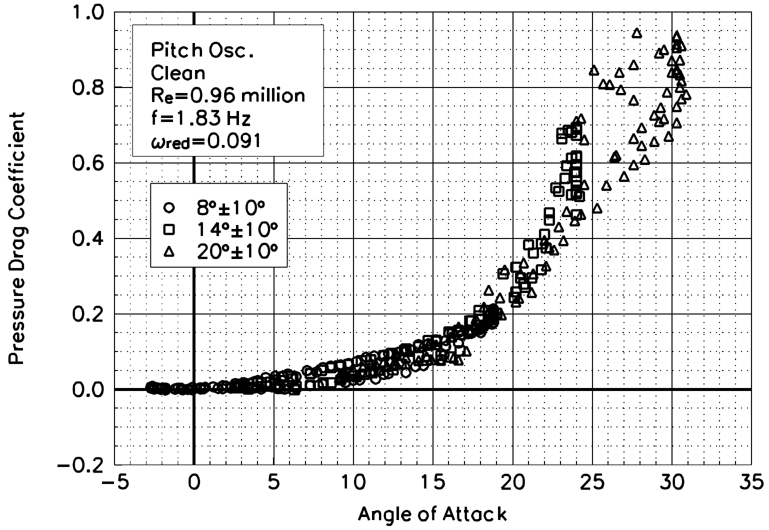

Figure C98. Pressure drag coefficient vs α.

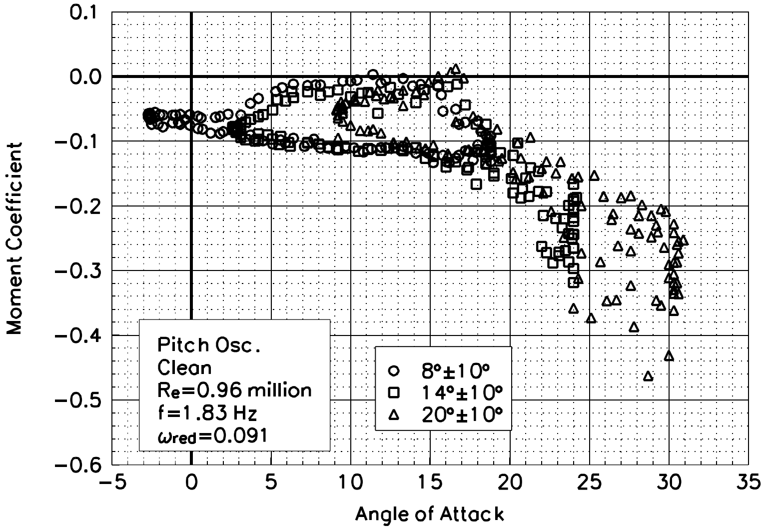

Figure C99. Moment coefficient vs α.

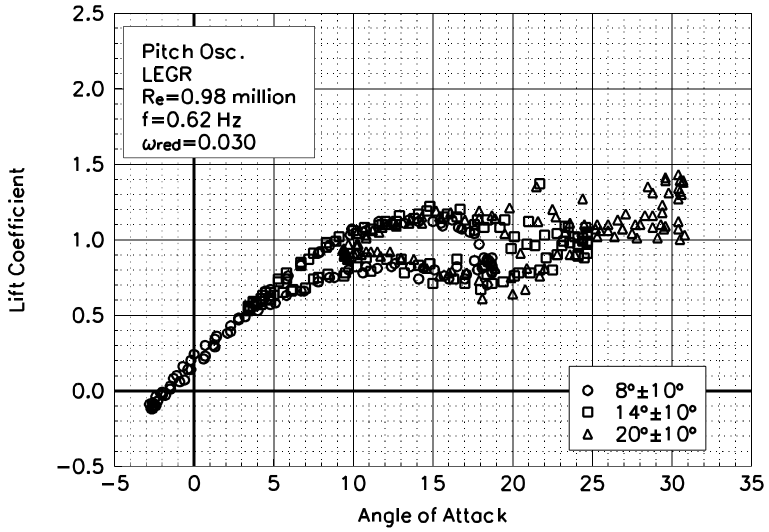

Figure C100. Lift coefficient vs α.

S812
LEGR
Re=0.98 million
$\omega_{reduced}$=0.030

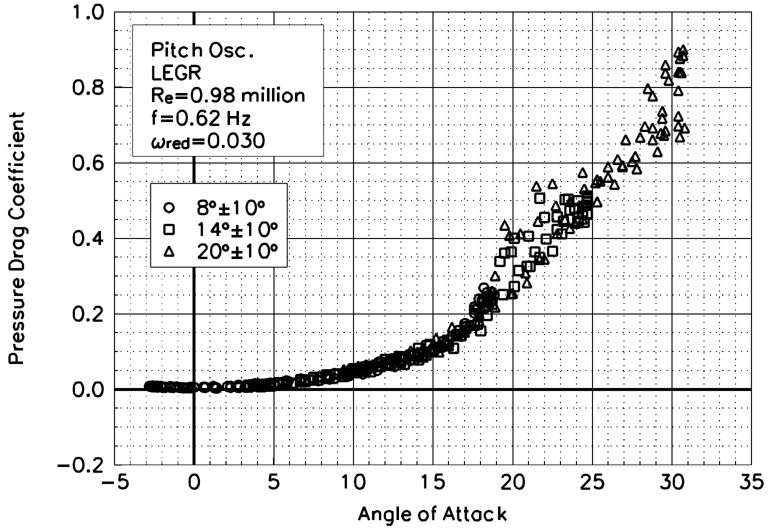

Figure C101. Pressure drag coefficient vs α.

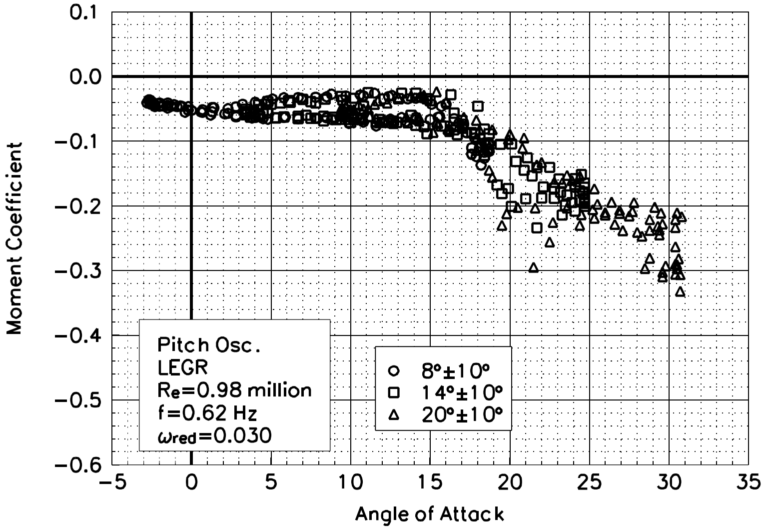

Figure C102. Moment coefficient vs α.

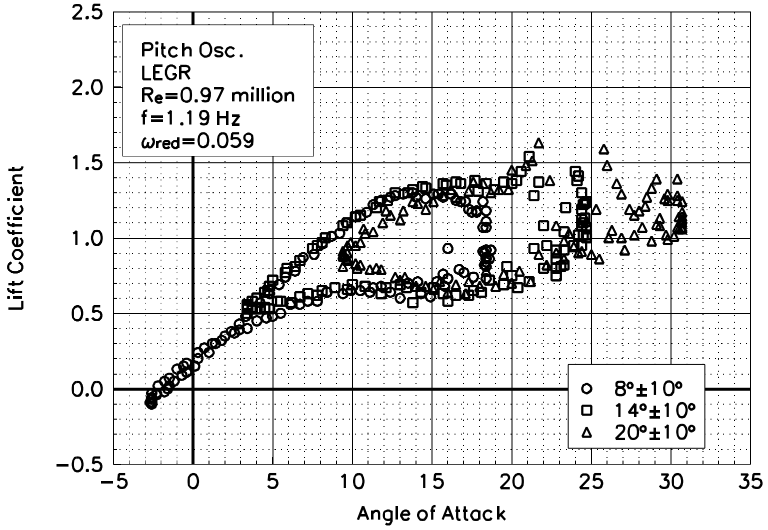

Figure C103. Lift coefficient vs α.

S812
LEGR
Re=0.97 million
$\omega_{reduced}$=0.059

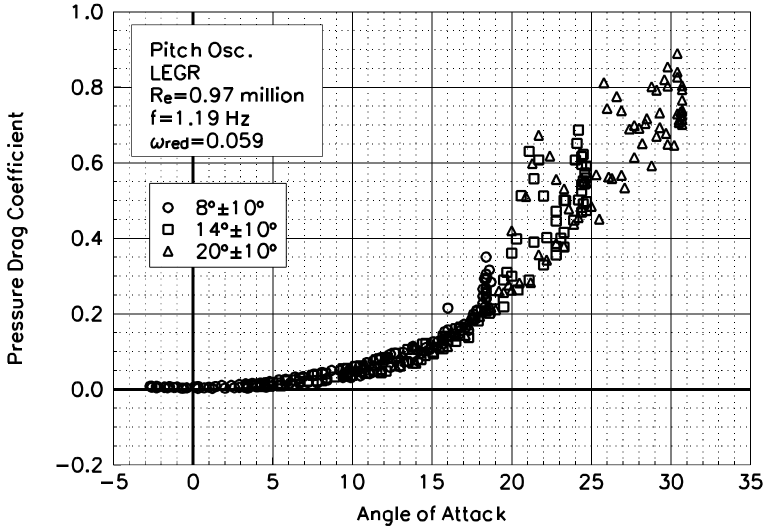

Figure C104. Pressure drag coefficient vs α.

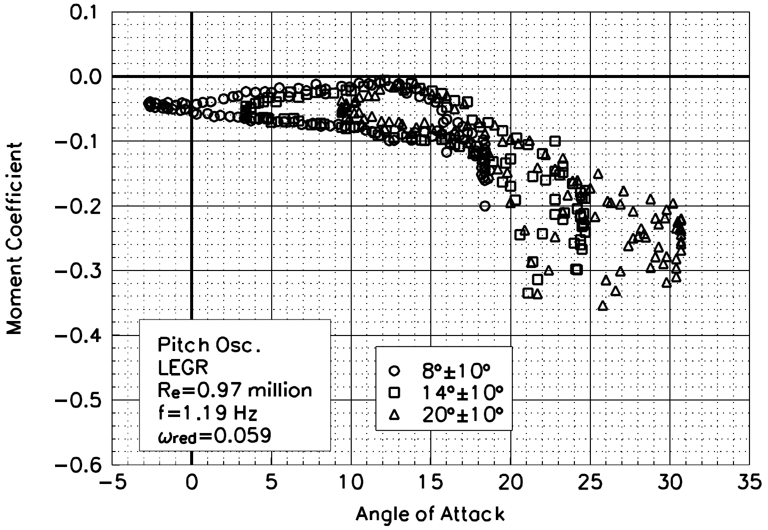

Figure C105. Moment coefficient vs α.

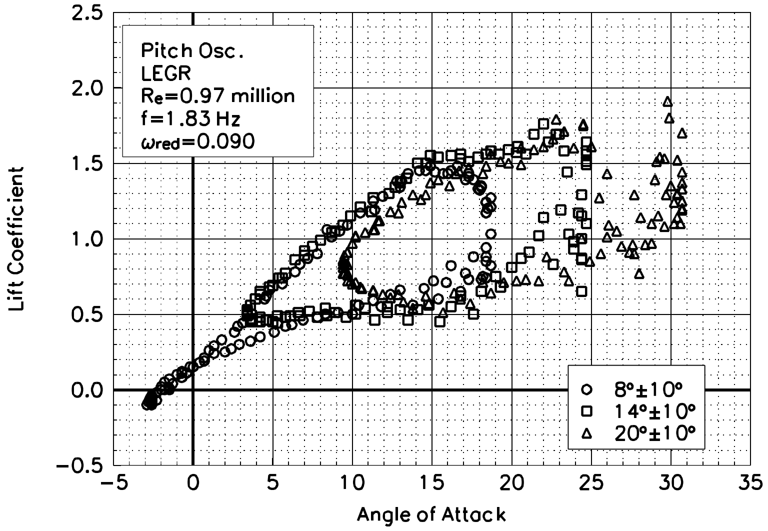

Figure C106. Lift coefficient vs α.

S812
LEGR
Re=0.97 million
$\omega_{reduced}$=0.090

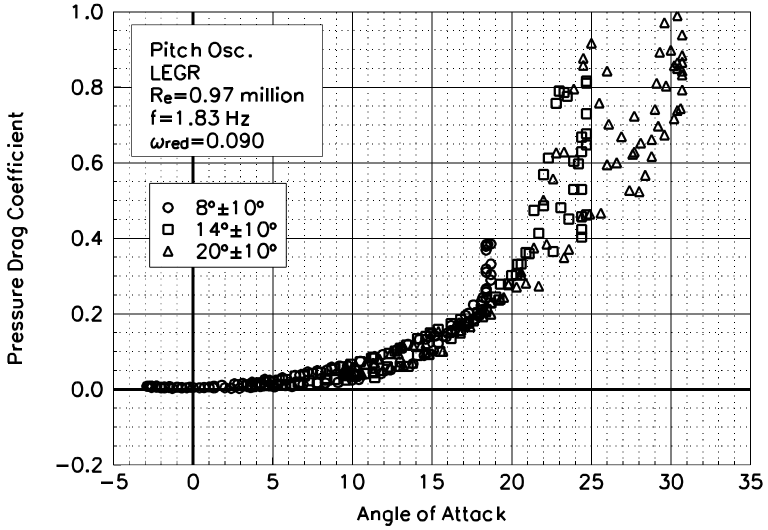

Figure C107. Pressure drag coefficient vs α.

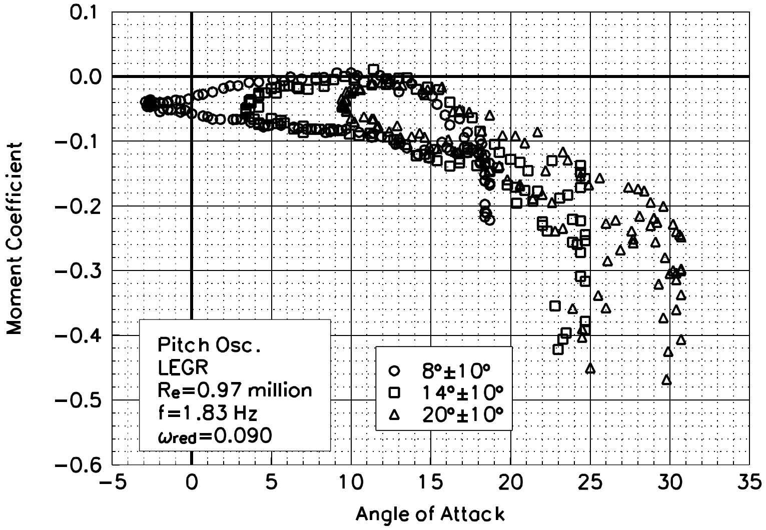

Figure C108. Moment coefficient vs α.

Unsteady Airfoil Characteristics

±10° Sine, Re = 1.25 million

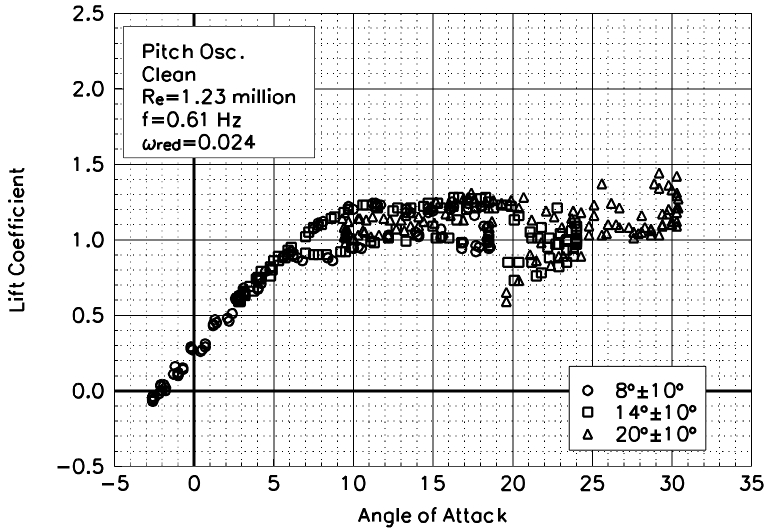

Figure C109. Lift coefficient vs α.

S812
Clean
Re=1.23 million
$\omega_{reduced}$=0.024

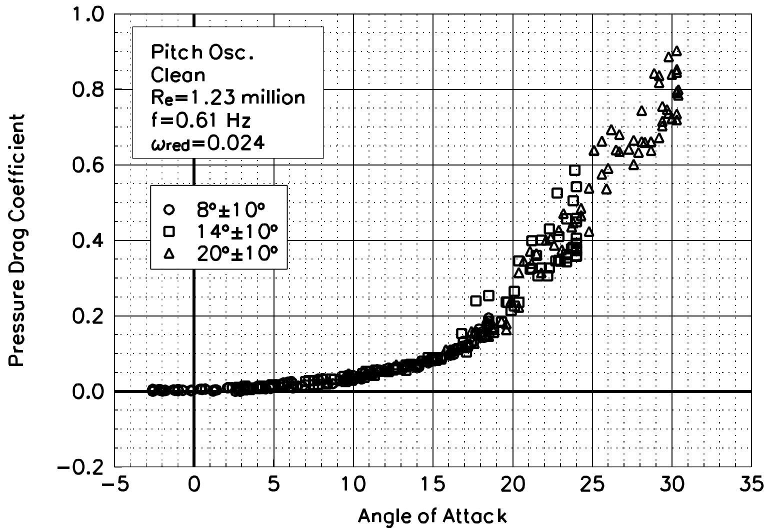

Figure C110. Pressure drag coefficient vs α.

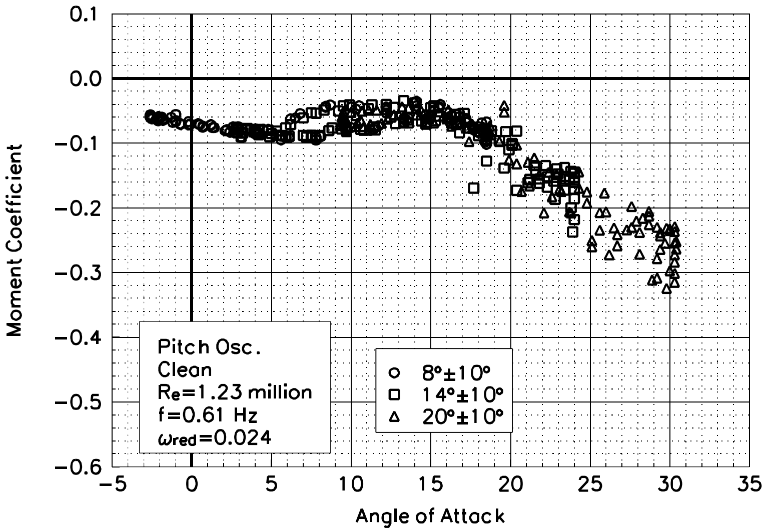

Figure C111. Moment coefficient vs α.

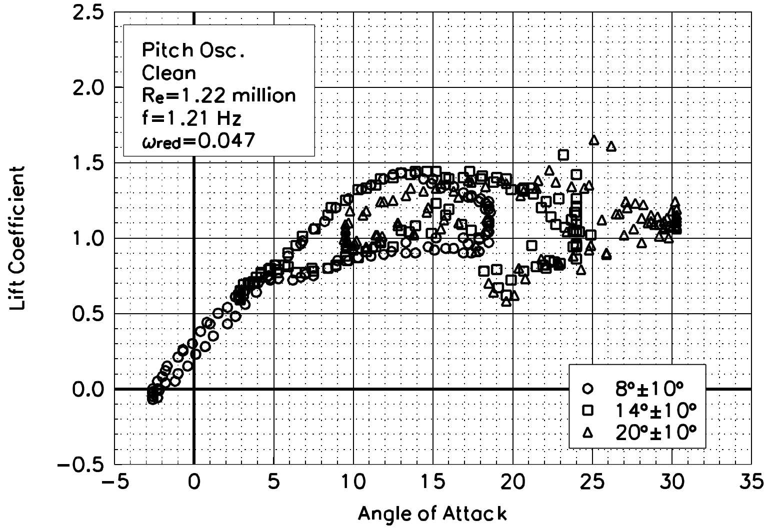

Figure C112. Lift coefficient vs α.

S812
Clean
Re=1.22 million
$\omega_{reduced}$=0.047

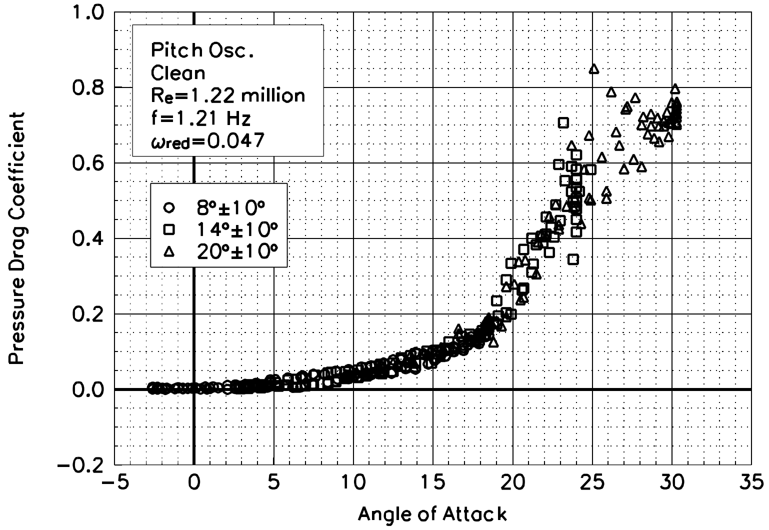

Figure C113. Pressure drag coefficient vs α.

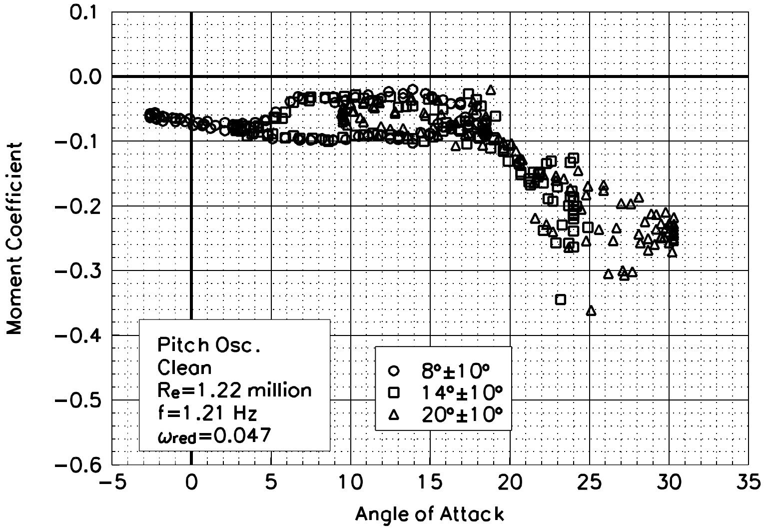

Figure C114. Moment coefficient vs α.

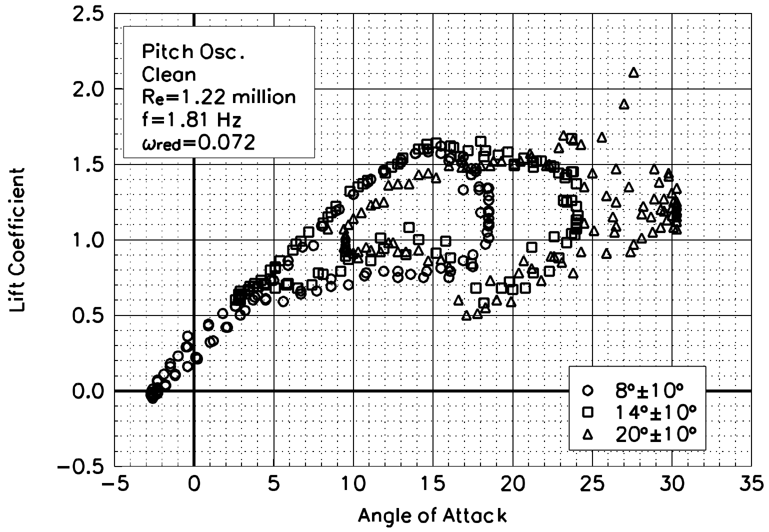

Figure C115. Lift coefficient vs α.

S812
Clean
Re=1.22 million
$\omega_{reduced}$=0.072

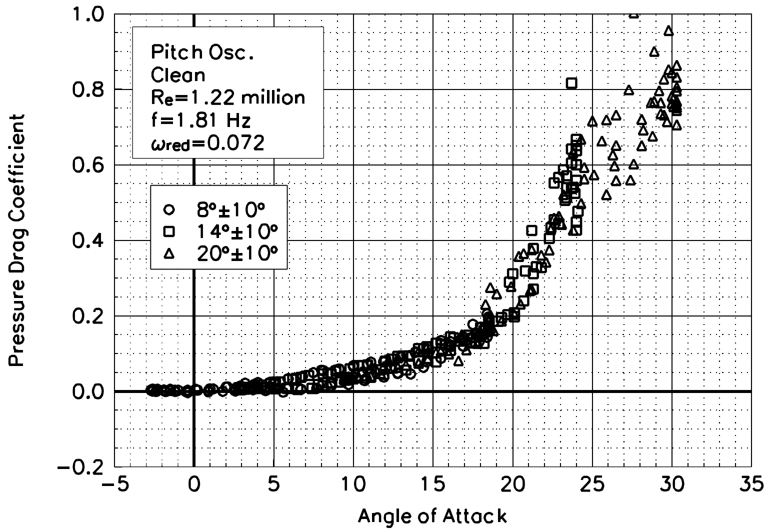

Figure C116. Pressure drag coefficient vs α.

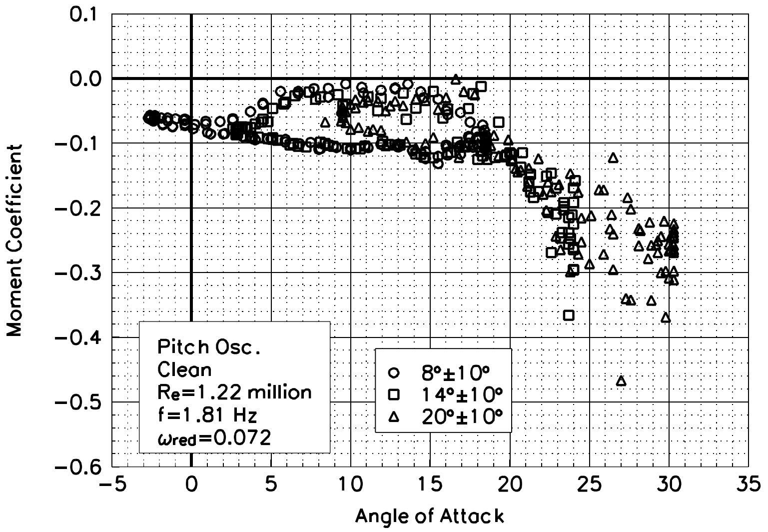

Figure C117. Moment coefficient vs α.

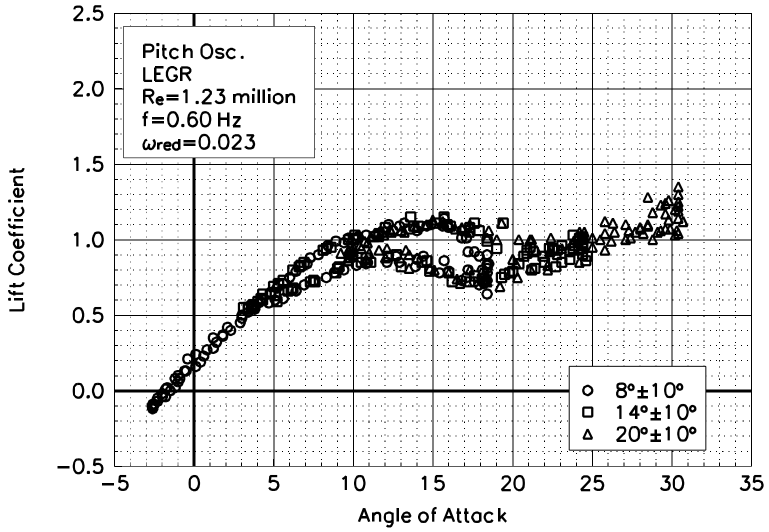

Figure C118. Lift coefficient vs α.

S812
LEGR
Re=1.23 million
$\omega_{reduced}$=0.023

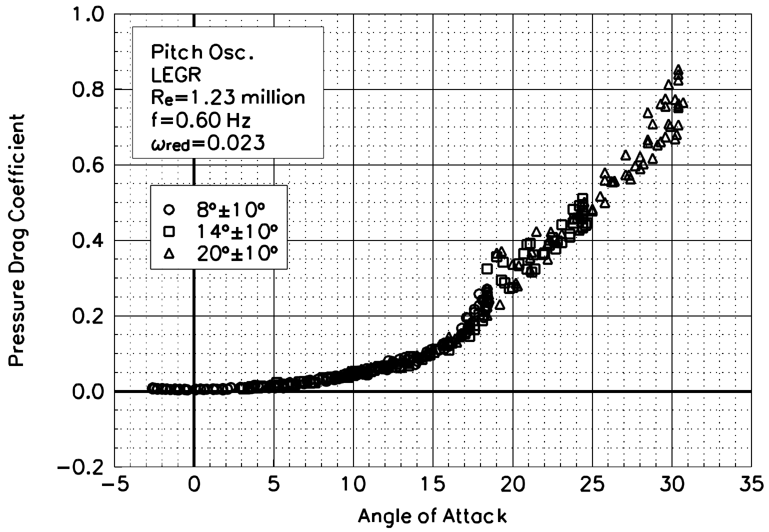

Figure C119. Pressure drag coefficient vs α.

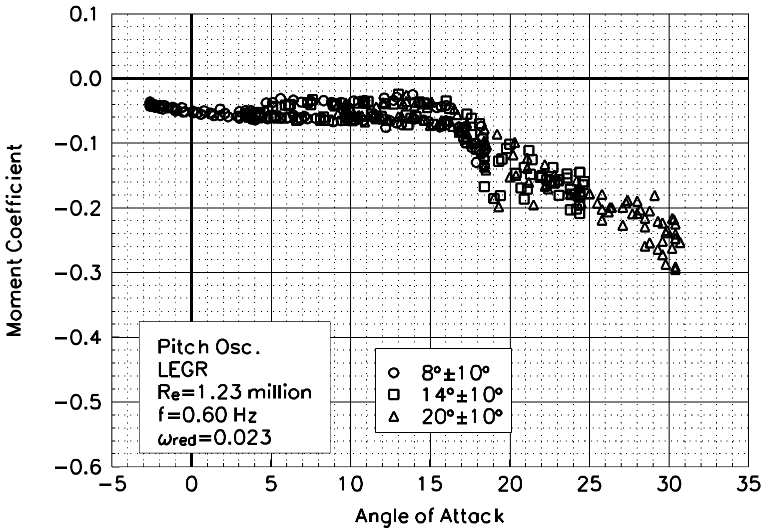

Figure C120. Moment coefficient vs α.

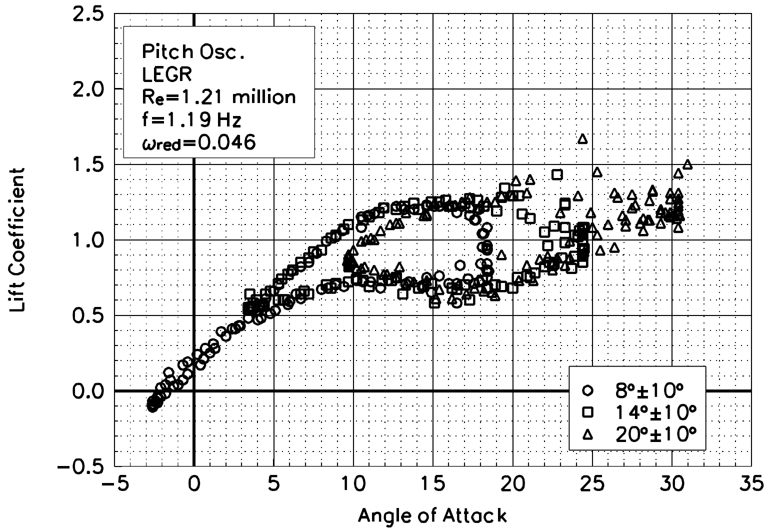

Figure C121. Lift coefficient vs α.

S812
LEGR
Re=1.21 million
$\omega_{reduced}$=0.046

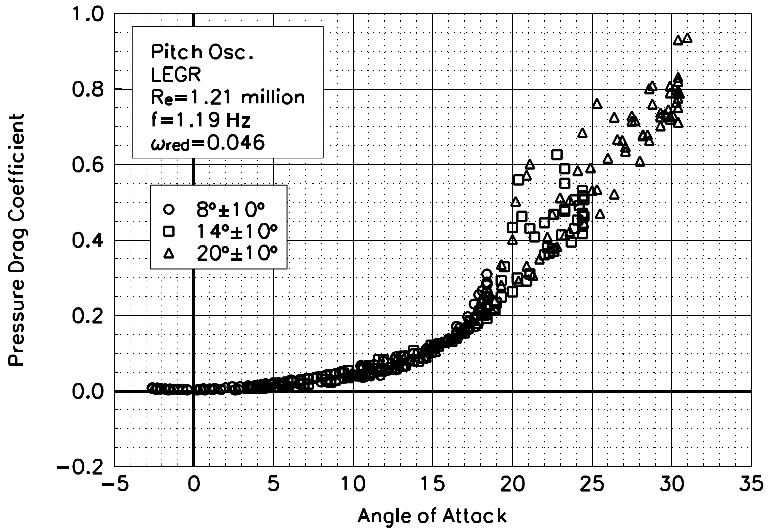

Figure C122. Pressure drag coefficient vs α.

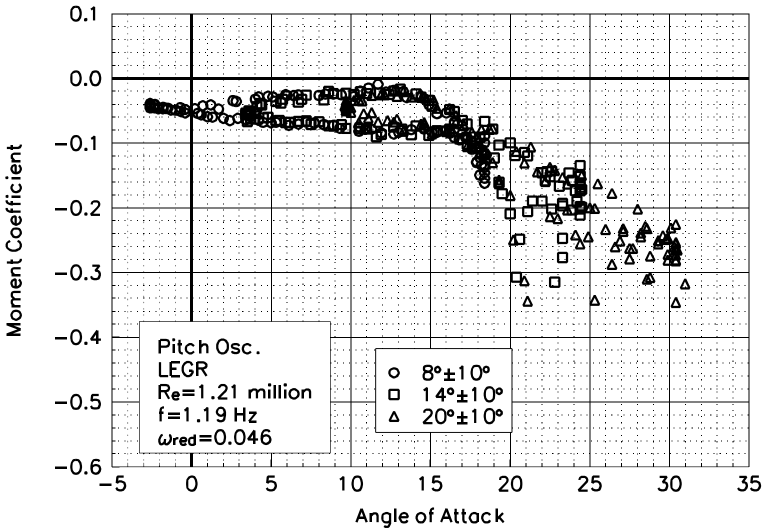

Figure C123. Moment coefficient vs α.

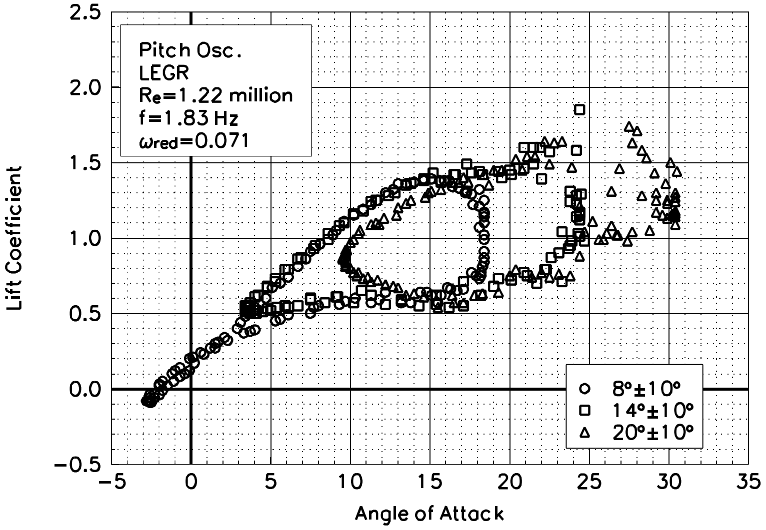

Figure C124. Lift coefficient vs α.

S812
LEGR
Re=1.22 million
$\omega_{reduced}$=0.071

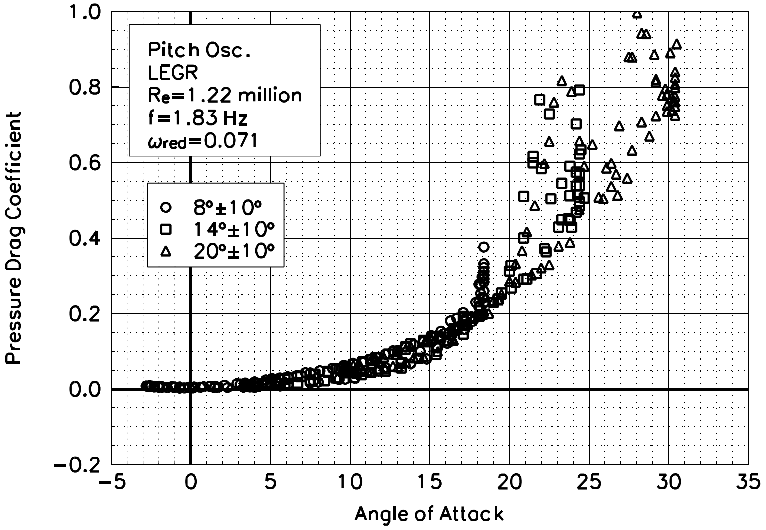

Figure C125. Pressure drag coefficient vs α.

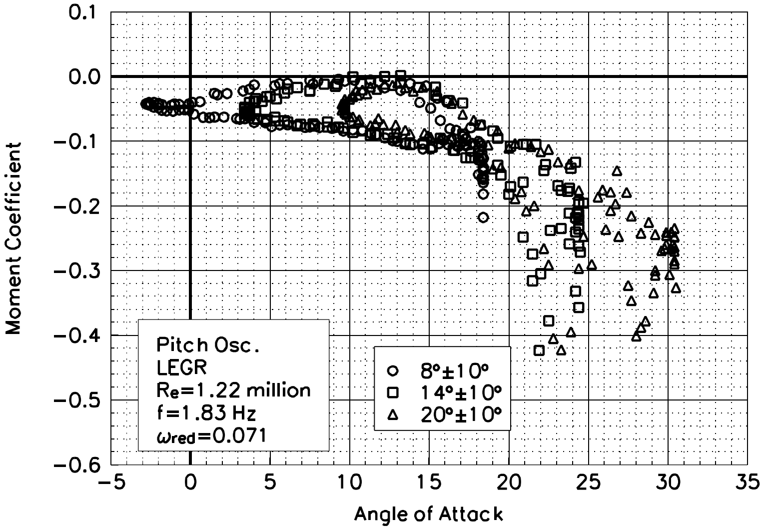

Figure C126. Moment coefficient vs α.

Unsteady Airfoil Characteristics

±10° Sine, Re = 1.5 million

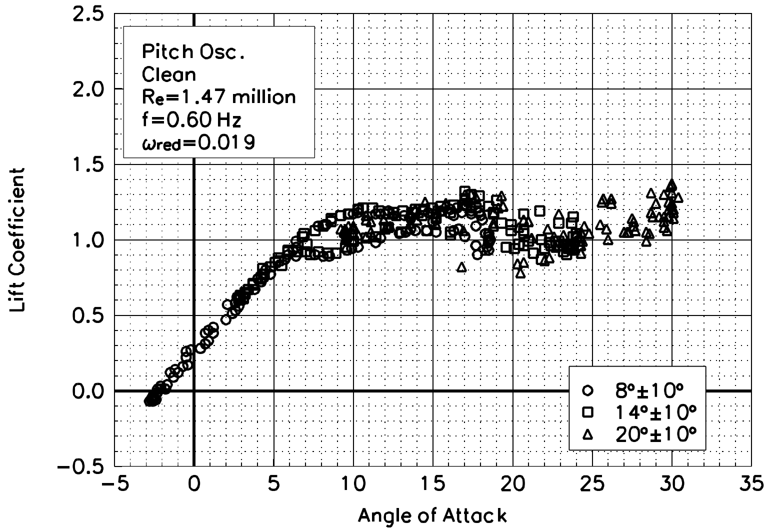

Figure C127. Lift coefficient vs α.

S812
Clean
Re=1.47 million
$\omega_{reduced}$=0.019

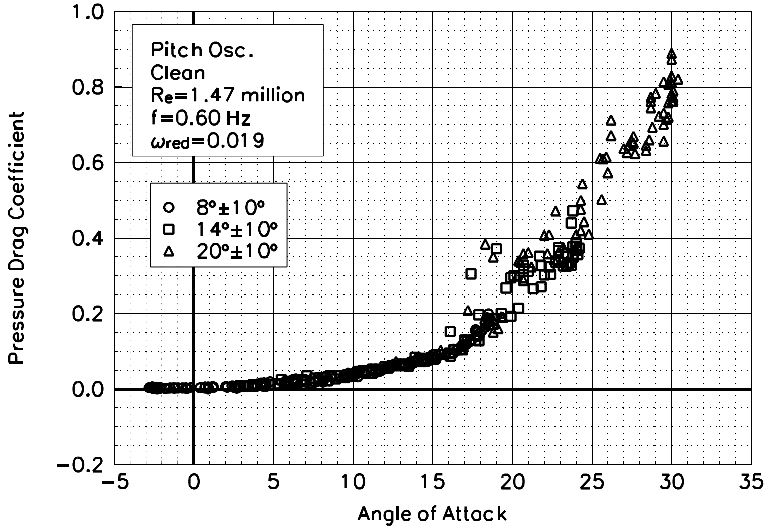

Figure C128. Pressure drag coefficient vs α.

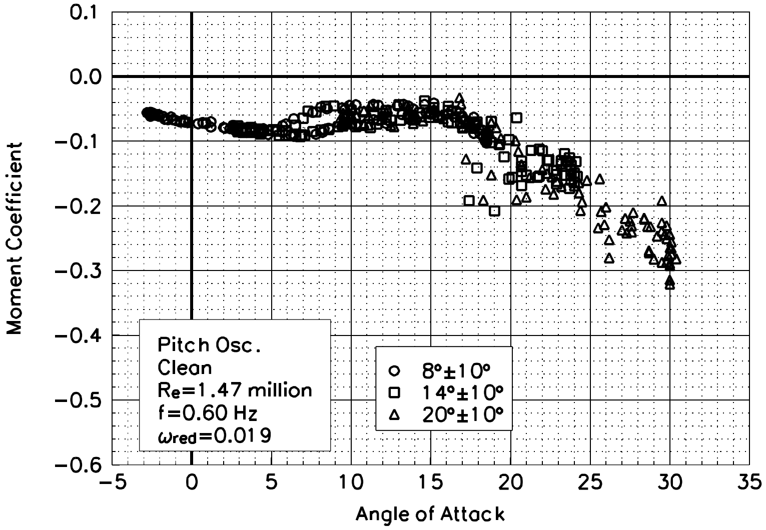

Figure C129. Moment coefficient vs α.

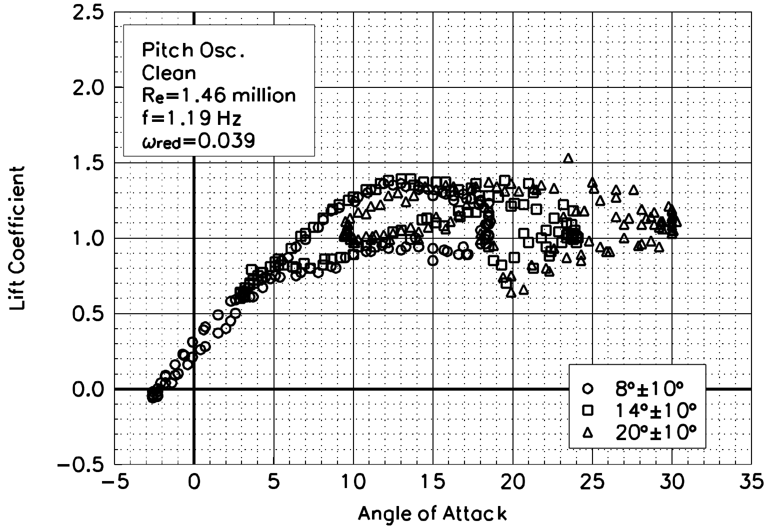

Figure C130. Lift coefficient vs α.

S812
Clean
Re=1.46 million
$\omega_{reduced}$=0.039

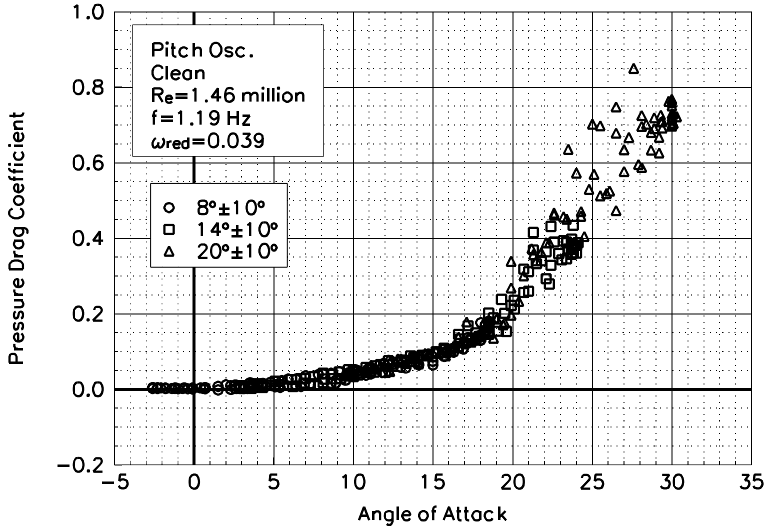

Figure C131. Pressure drag coefficient vs α.

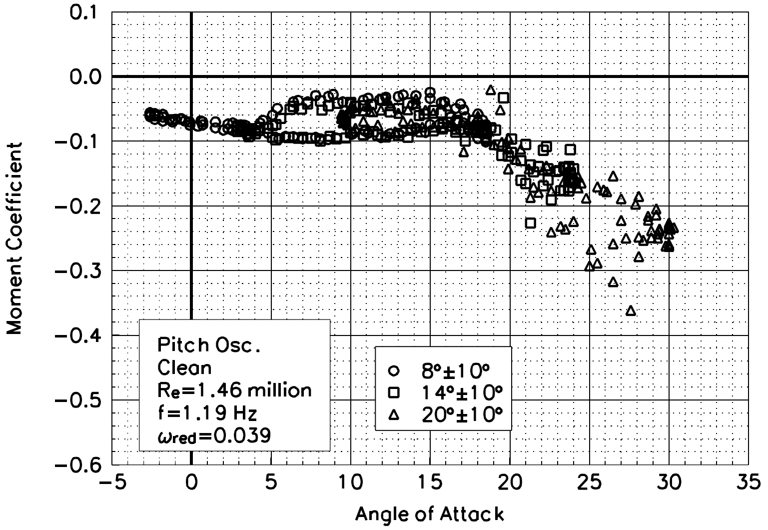

Figure C132. Moment coefficient vs α.

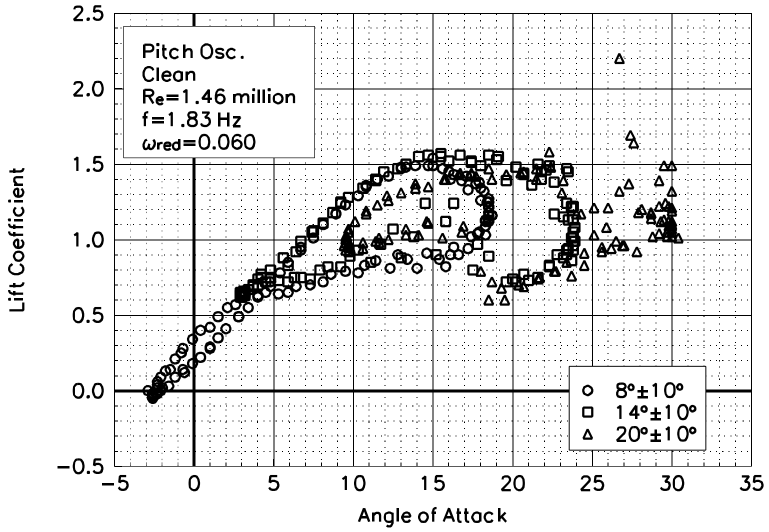

Figure C133. Lift coefficient vs α.

S812
Clean
Re=1.46 million
$\omega_{reduced}$=0.060

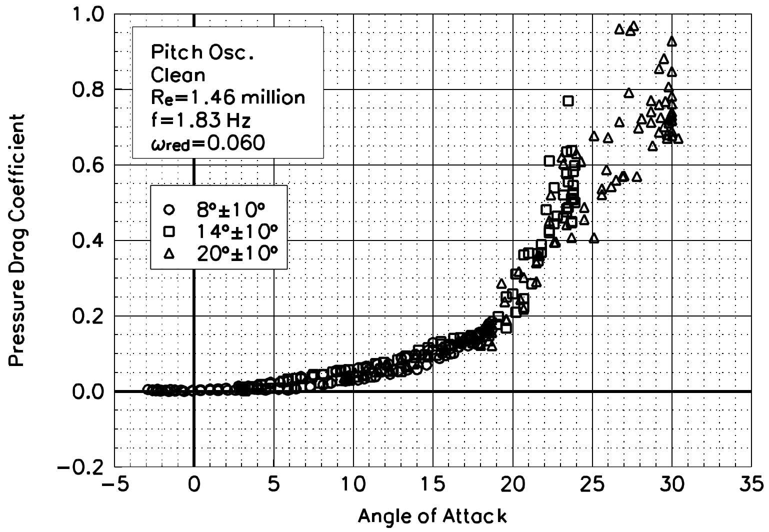

Figure C134. Pressure drag coefficient vs α.

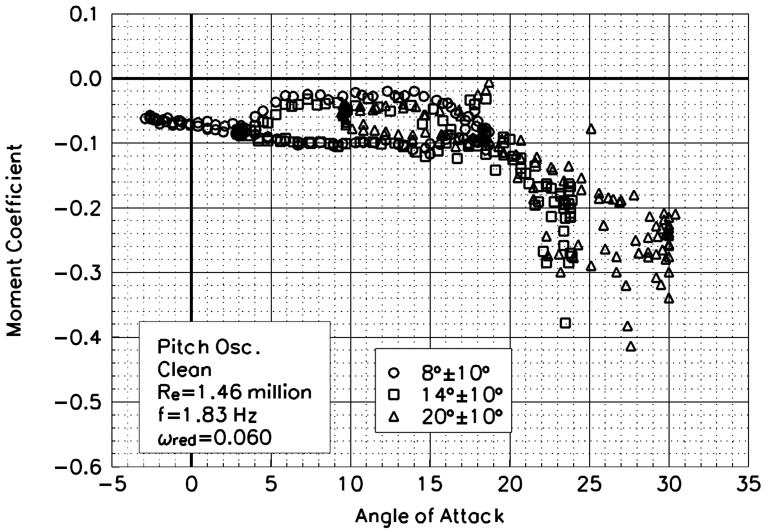

Figure C135. Moment coefficient vs α.

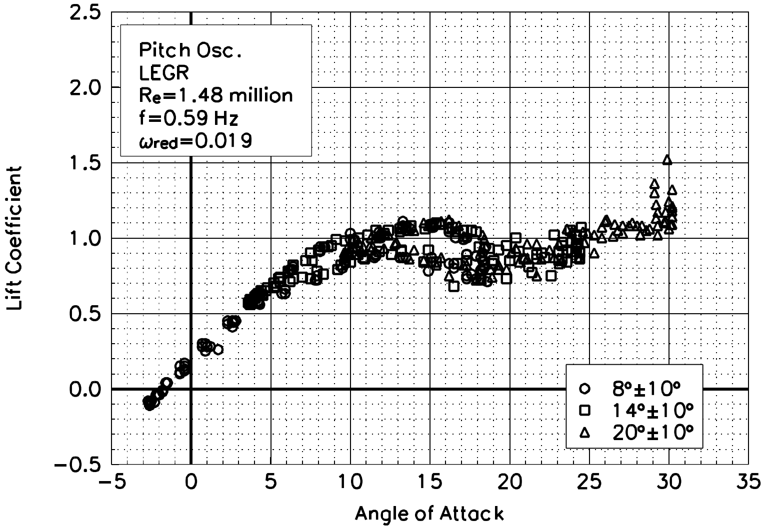

Figure C136. Lift coefficient vs α.

S812
LEGR
Re=1.48 million
$\omega_{reduced}$=0.019

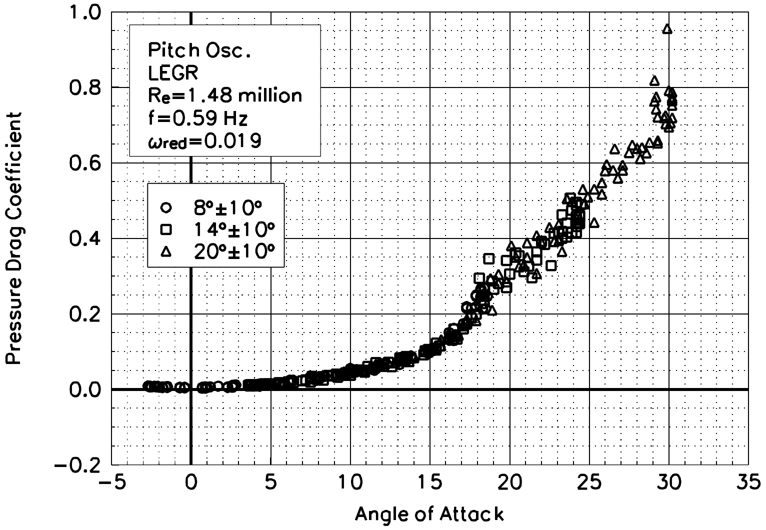

Figure C137. Pressure drag coefficient vs α.

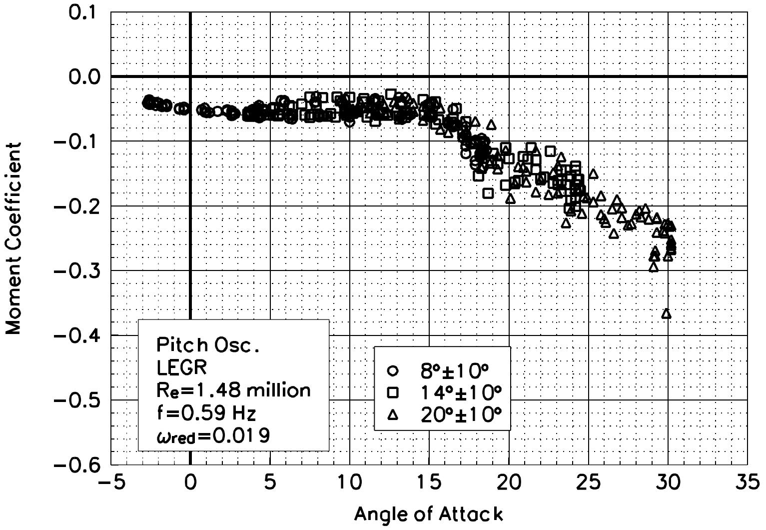

Figure C138. Moment coefficient vs α.

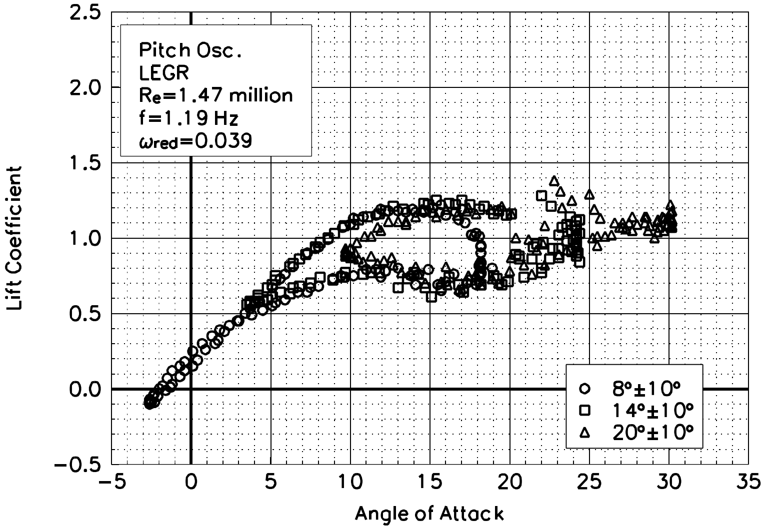

Figure C139. Lift coefficient vs α.

S812
LEGR
Re=1.47 million
$\omega_{reduced}$=0.039

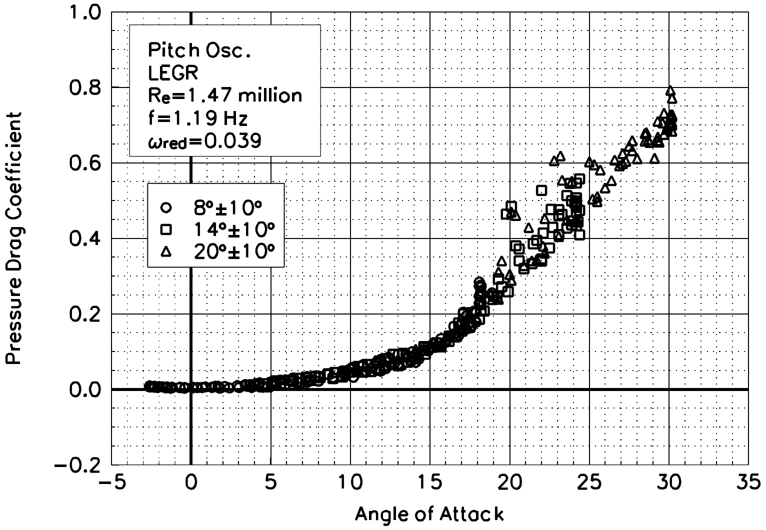

Figure C140. Pressure drag coefficient vs α.

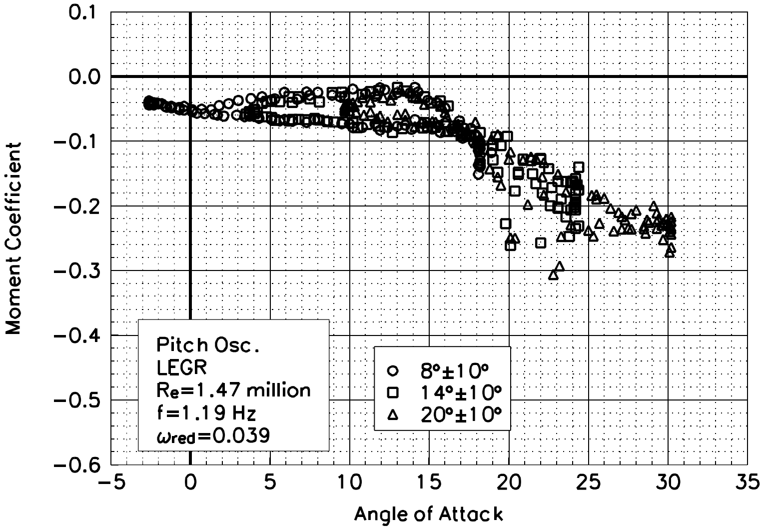

Figure C141. Moment coefficient vs α.

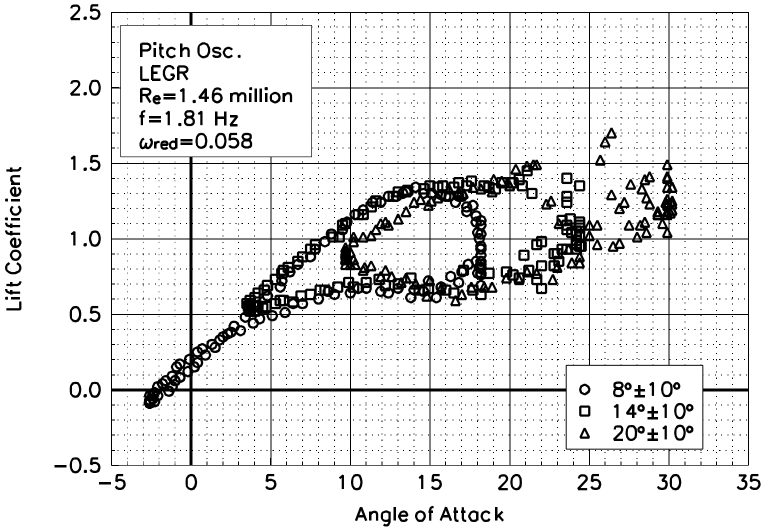

Figure C142. Lift coefficient vs α.

S812
LEGR
Re=1.46 million
$\omega_{reduced}$=0.058

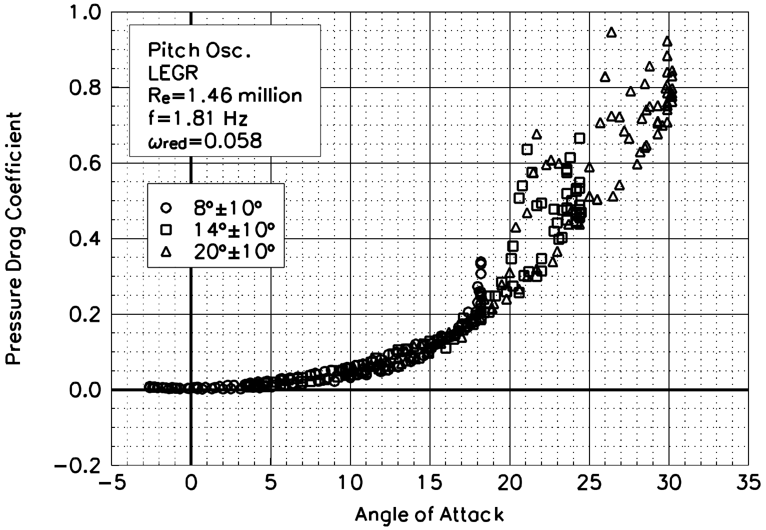

Figure C143. Pressure drag coefficient vs α.

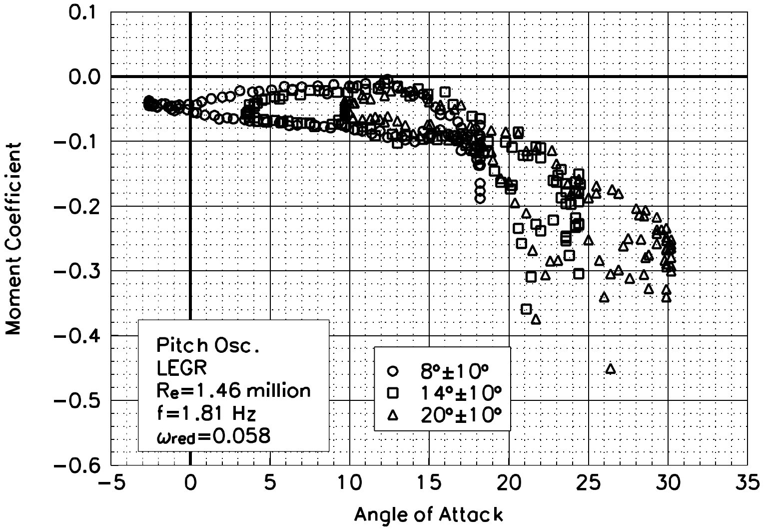

Figure C144. Moment coefficient vs α.