DOE/NASA/20320-75
NASA TM-100802

N-44
135699
14P.

Comparison of Pressure Distributions on Model and Full-Scale NACA 64-621 Airfoils With Ailerons for Wind Turbine Application

G.M. Gregorek and R.J. Kuniega
Ohio State University

and

T.W. Nyland
National Aeronautics and Space Administration
Lewis Research Center

(NASA-TM-100802) COMPARISON OF PRESSURE DISTRIBUTIONS ON MODEL AND FULL-SCALE NACA 64-621 AIRFOILS WITH AILERONS FOR WIND TURBINE APPLICATION Final Report (NASA) 14 p CSCL 10B G3/44 N88-21593 Unclas 0135699

April 1988

Prepared for

U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Wind/Ocean Technology Division

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes[1]
Printed copy: A02
Microfiche copy: A01

[1]Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication, NTIS-PR-360 available from NTIS at the above address.

DOE/NASA/20320-75
NASA TM-100802

Comparison of Pressure Distributions on Model and Full-Scale NACA 64-621 Airfoils With Ailerons for Wind Turbine Application

G.M. Gregorek and R.J. Kuniega
Ohio State University
Columbus, Ohio 43210

and

T.W. Nyland
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

April 1988

Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Wind/Ocean Technology Division
Washington, D.C. 20545
Under Interagency Agreement DE-AI01-76ET20320

COMPARISON OF PRESSURE DISTRIBUTIONS ON MODEL AND FULL-SCALE NACA 64-621 AIRFOILS WITH AILERONS FOR WIND TURBINE APPLICATION

G.M. Gregorek and R.J. Kuniega
Ohio State University
Columbus, Ohio

and

T.W. Nyland
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

The aerodynamic similarity between a small (4-in. chord) wind tunnel model and a full-scale wind turbine blade (24-ft tip section with a 36-in. chord) was evaluated by comparing selected pressure distributions around the geometrically similar cross sections. The airfoils were NACA 64-621 sections, including trailing-edge ailerons with a width equal to 38 percent of the airfoil chord. The model airfoil was tested in the OSU 6- by 12-In. High Reynolds Number Wind Tunnel; the full-scale blade section was tested in the NASA Langley Research Center 30- by 60-Ft Subsonic Wind Tunnel. The model airfoil contained 61 pressure taps connected by embedded tubes to pressure transducers. A belt containing 29 pressure taps was fixed to the full-scale section at midspan to obtain surface pressure data.

Lift coefficients were obtained by integrating pressures, and corrections were made for the three-dimensional effects of blade twist and downwash in the blade tip section. Good correlation was obtained between the results of the two different experimental methods for angles of attack from -4° to 36° and aileron deflections from 0° to 90°.

E-3982

INTRODUCTION

Aerodynamic pressures on an NACA 64-621 airfoil equipped with a plain aileron with a width equal to 38 percent of the chord have been measured in two previous studies. The first (ref. 1) dealt with the pressure distributions on this airfoil obtained from a small two-dimensional model with a 4-in. chord tested in the Ohio State University Aeronautical and Astronautical Research Laboratory's (AARL) 6- by 12-In. High Reynolds Number Wind Tunnel. In the second study (ref. 2) surface pressures were measured by means of a pressure belt mounted at midspan on a full-scale, 24-ft-long outboard section of a 200-kW wind turbine blade, tested in NASA Langley Research Center's 30- by 60-Ft Subsonic Wind Tunnel.

The opportunity to compare aerodynamic pressure distributions over the same airfoil shape in these two very different experimental facilities on models differing in size by an order of magnitude presented a true test of model similarity rules. Both sets of data were subsonic, although Mach and Reynolds numbers differed somewhat: $M = 0.25$ and $Re = 5 \times 10^6$ for the pressurized OSU tunnel, and $M = 0.10$ and $Re = 1.5 \times 10^6$ for the NASA atmospheric-pressure facility. The two Reynolds numbers were based on the 4-in. chord of the OSU model and the 3-ft chord at the pressure belt station of the rotor blade.

The aerodynamic similarity between a small wind-tunnel model and a full-scale wind turbine blade were evaluated by comparing selected pressure distributions in the disparate environments of the two facilities. Of special interest were the potential limits of good quality data at high angles of attack and high angles of aileron deflection in the small OSU facility in contrast to the large unconstrained flow of the NASA full-scale tunnel. Also of interest was the quality of pressure belt information, which is economically obtained on full-scale components but suffers potential errors from the simplified installation method.

EXPERIMENTAL PROCEDURES

Model Testing in OSU 6- by 12-In. High Reynolds Number Wind Tunnel

The wind tunnel and the model are shown schematically in figures 1 to 3. Normalized coordinates of the surfaces of an NACA 64-621 airfoil are listed in table I. The 4-in.-chord model was manufactured of an epoxy-aluminum material. Thirty-four pressure taps were formed into the main airfoil, and 27 pressure taps were formed into the aileron of this two-element, two-dimensional model. Plastic tubes were led from the pressure taps through the model and out through the rectangular end blocks to a pressure-scanning system. As shown in figure 3 the end blocks fit into circular mounting plates that fit flush with the tunnel walls and can be rotated to alter the angle of attack. The aileron was set into its own mounting plate, allowing rotation from 0° deflection to 100° (trailing edge up). Further details of the model installation and test procedure are given in references 1 and 3.

Full-Scale Testing in NASA Langley 30- by 60-Ft Subsonic Wind Tunnel

A section of a Mod-0 wind turbine blade was mounted vertically on a plate in the tunnel floor, as shown in figure 4. This plate was supported by a load-balance system and could be rotated about a vertical axis to change the airfoil angle of attack. Key dimensions of the installation are shown in figure 5. A pressure-measuring belt was fixed near midspan and 12.3 ft from the tip. The sensing end of the pressure-measuring system illustrated in figure 6 consisted of a belt comprising twenty-nine 0.125-in.-o.d. by 0.040-in.-i.d. plastic tubes. The wall of each tube was bored with a single static pressure tap 0.040 in. in diameter. The tap locations were selected so that a chordwise pressure distribution could be measured completely around the airfoil. The pressure belt was attached to the blade section with a silastic rubber cement. The pressure belt tubing and all auxiliary wiring then passed through the blade skin and down the inside of the blade through the tunnel floor to the control room below. A microprocessor was set up to digitize and format the data and then send them to a cassette tape recorder. Details of the design and operation of the pressure belt system can be obtained from reference 4.

RESULTS AND DISCUSSION

A direct comparison of the results from the two different tests was hampered by the fact that the model data were taken at 3° increments in angle of attack but the full-scale data were taken at 2° increments. In addition, the full-scale blade was twisted so that the nominal or geometric angle of attack at the tip differed by about 1° from the angle of attack at the station at which the pressure belt was mounted. Furthermore, the full-scale section had a downwash from the tip, but the two-dimensional model had no downwash. Nevertheless, with these cautions in mind, it was still possible to extract valuable comparative information from the two test methods.

Chordwise Pressure Distributions

Typical pressure distributions along the airfoil chords are presented in figure 7 for a nominally 0° aileron deflection. At modest angles of attack (fig. 7(a)) the flow was fully attached to both test airfoils. Lift coefficients obtained by integrating the surface pressures were approximately 0.4 for both the model and the full-scale airfoil. With the exception of the upper surface pressures at $x/c < 0.1$, local pressures from the two tests were in reasonable agreement. Note that the gap flow at $x/c = 0.6$ is well represented in both pressure distributions. Nominal angles of attack, however, were somewhat different at the two test sections. The full-scale section had an angle of attack of 4°; the model data are for a 0° angle of attack.

At a partially stalled condition (fig. 7(b)) both pressure distributions exhibited the flow pressure plateau representative of separated flow aft of the aileron gap on the upper surface. This agreement between the two pressure distributions is encouraging. The continuing concern that wind tunnel data, which are nominally two dimensional, may not be representative of "real" three-dimensional wind turbine rotors is eased somewhat by this agreement. Again, the nominal angle of attack of the full-scale airfoil was somewhat larger than that of the model airfoil. In this case the difference was 2°.

Figure 8 compares two data sets at 0° angle of attack. In one set (fig. 8(a)) the aileron was undeflected; in the other (fig. 8(b)) the aileron was deflected 90° (trailing edge up) for maximum aerodynamic braking. In this extreme case the entire upper surface of each airfoil was near stagnation pressure while the lower surface was at very low pressure. The agreement of the back-side pressures on the aileron is remarkable considering that the model data were obtained on a two-dimensional 4-in. airfoil in a 6- by 12-in. test section and the full-scale pressures were measured on a three-dimensional rotor blade with a 3-ft chord in a 30- by 60-ft facility.

Even more interesting data are given in figure 9 for 90° of aileron deflection. In both the model and full-scale tests pressure distributions were observed to change drastically between 18° and 36° angles of attack. At 18° the upper surfaces were in a high-pressure region and the lower surfaces were in a low-pressure zone, yielding negative lift coefficients. However, when the angle of attack was increased to 36°, the upper surface pressures showed separation and were at an essentially constant low pressure, but the lower surfaces were then acted upon by relatively high pressures. The net result was a positive lift coefficient. In other words, the braking effect of the deflected aileron was overcome and the airfoil could produce power.

When these reverse pressure distributions were first obtained on models in the OSU facility, there was some concern that the test section walls were contributing to these extreme pressure changes. The excellent agreement shown in figures 10 and 11 between the subscale and full-scale pressure distributions has relieved these concerns.

Lift Coefficients

Surface pressures were integrated to determine lift coefficients for selected cases. The OSU model was designed specifically for this pressure integration procedure and had 34 pressure taps on the main element plus 27 pressure taps on the aileron. Integration of pressures from this large number of orifices can be expected to produce stable, repeatable lift and drag coefficients. Only 29 pressure orifices were available from the pressure belt. Although this is sufficient to define the force normal to the airfoil, integration of pressures from this limited number of taps will not produce accurate chordwise forces. Therefore only lift coefficients are presented in this study.

As shown in figure 10, at 0° aileron deflection the model NACA 64-621 had a zero-lift angle of -4°, a lift curve slope of 0.091 per degree, and a maximum lift coefficient of 1.2. By comparison, the full-scale blade section had a zero-lift angle of -2°, a lift curve slope of 0.074 per degree, and a maximum lift coefficient of 1.1.

The difference in zero-lift angle was attributed to the twist of the full-scale blade, and the discrepancy in the lift curve slope was probably caused by a combination of downwash in the full-scale blade and differences in Reynolds number (5×10^6 for the model and 1.5×10^6 for the full-scale airfoil). The difference between the maximum lift coefficients was similarly attributed to a Reynolds number mismatch compounded by a small deflection of the full-scale aileron under load. At high angles of attack and small aileron deflections the full-scale aileron deflected about 1.5° (trailing edge up), decambering the airfoil. Because of this small aileron deflection the 0° angle of attack point for the full-scale test data is shown in parenthesis, and the lift coefficient has been lowered by 0.06 to account for a difference in aileron deflection at this angle of attack from the rest of the data at this aileron setting.

Aileron deflection angles of 10° and 90° (trailing edge up) are also presented in figure 10 as functions of angle of attack. The 10° deflection demonstrated the same behavior as the nominal 0° deflection, with a linearly increasing lift coefficient followed by a gentle stall. For this deflection the maximum lift coefficients for both the model and full-scale airfoils were nearly identical at 0.95. At 0° angle of attack the changes in lift per degree of aileron deflection were 0.055 and 0.060 for the model and full-scale tests, respectively. When the aileron was deflected to 90°, the integrated pressures yielded a nonlinear variation with angle of attack, and remarkably good agreement was obtained between the two data sets, considering the extreme aileron deflection and the large angles of attack.

The lift data from the full-scale three-dimensional test were scaled to two-dimensional form, taking into account the -2.2° twist of the rotor at the pressure belt station and the corresponding induced angle of attack. Figure 11 shows the results of this scaling, again compared with the two-dimensional model data. At 0° aileron deflection the scaled three-dimensional data yielded a zero-lift angle of -4.4°, a lift curve slope of 0.082 per degree, and a maximum lift coefficient of 1.1. Scaling brought the zero-lift angles and lift curve slopes into closer agreement but did not affect the maximum lift coefficient difference of 0.1.

Scaled three-dimensional lift data for aileron settings of 10° and 90° (trailing edge up) are also compared with two-dimensional data in figure 11. For the 10° deflection the OSU two-dimensional data corresponded almost identically to the scaled Langley data, with lift curve slopes of 0.090 and 0.093 per degree, respectively. At an aileron setting of 90° the Langley scaled data and the OSU data followed the same nonlinear variation with increasing angle of attack. However, the lift coefficient for the full-scale airfoil was 0.1 to 0.3 higher than that measured with the OSU model airfoil. This was primarily due to the different Reynolds numbers for the two tests.

CONCLUSIONS

Surface pressures were measured in two very different wind tunnels on a model and a full-scale NACA 64-621 airfoil equipped with a 0.38-chord aileron. The model, a two-dimensional configuration with a 4-in. chord and flush pressure taps, was tested in the pressurized OSU 6- by 12-In. High Reynolds Number Wind Tunnel. The full-scale airfoil, which was an actual tip section of a Mod-0 200-kW wind turbine rotor of riveted aluminum construction, was tested in the NASA Langley Research Center 30- by 60-Ft Subsonic Wind Tunnel. A 29-port pressure belt was used to obtain the pressure distributions near the midspan of the full-scale airfoil, at a station with a 3-ft chord.

Based on a comparison of the data from these two tests at very different scales and using different testing procedures, the following conclusions were drawn:

1. When corrections were made for the effects of blade twist and downwash in the full-scale airfoil, surface pressures from both tests were essentially in agreement.

2. In the poststall regime two-dimensional aerodynamic properties obtained in the small-scale OSU facility agreed with the pressure and lift data measured on the three-dimensional rotor in the large-scale NASA wind tunnel.

3. Using pressure belts on the full-scale rotor section was an economical method of obtaining surface pressures. Integration of the surface pressures produced lift coefficients of acceptable engineering precision.

4. When the aileron section of the airfoil was deflected 90°, the rapid change from negative to positive lift coefficient, which was noted in the OSU two-dimensional tests as the angle of attack increased from 18° to 36°, was duplicated in the full-scale test. This observation relieves earlier concerns

that the OSU wind tunnel might in some way be influencing the lift data and causing the rapid change.

REFERENCES

1. Gregorek, G.M.: Comparative Wind Tunnel Tests at High Reynolds Numbers of NACA 64-621 Airfoils With Two Aileron Configurations. Presented at 1984 DOE/NASA Workshop on Horizontal-Axis Wind Turbine Technology, 1988.

2. Savino, J.M., et al.: Wind Tunnel Tests of a Full-Scale Wind Turbine Blade Tip With NACA 64-XXX Series Airfoil Sections and Aileron Control Surfaces. Presented at 1984 DOE/NASA Workshop on Horizontal-Axis Wind Turbine Technology, 1988.

3. Law, S.P.; and Gregorek, G.M.: Wind Tunnel Evaluation of a Truncated NACA 64-621 Airfoil for Wind Turbine Applications. DOE/NASA/0330-2, NASA CR-180803, 1987.

4. Nyland, T.W.: Surface Pressure Measurements on the Blade of an Operating Mod-2 Wind Turbine With and Without Vortex Generators. DOE/NASA/20320-72, NASA TM-89903, 1987.

TABLE I. - NACA 64-621 AIRFOIL COORDINATES

[Coordinates normalized to airfoil chord dimension c.]

Upper surface		Lower surface	
x/c, percent	y/c, percent	x/c, percent	y/c, percent
-0.085	0.768	-0.085	0.768
-.038	1.223	0	0
.083	1.696	.459	-.954
.581	2.573	1.569	-2.006
1.197	3.298	3.096	-2.851
7.045	7.260	8.455	-4.657
9.294	8.277	10.706	-5.173
15.343	10.401	13.688	-5.741
21.432	11.907	19.616	-6.577
24.486	12.475	25.514	-7.105
30.606	13.276	31.394	-7.364
39.798	13.623	40.202	-7.196
48.982	12.840	49.018	-6.223
58.124	11.296	60.841	-4.268
70.224	8.446	69.776	-2.612
79.221	5.944	78.779	-1.037
88.152	3.353	87.848	.151
94.076	1.665	93.924	.502
100.000	0	100.000	0

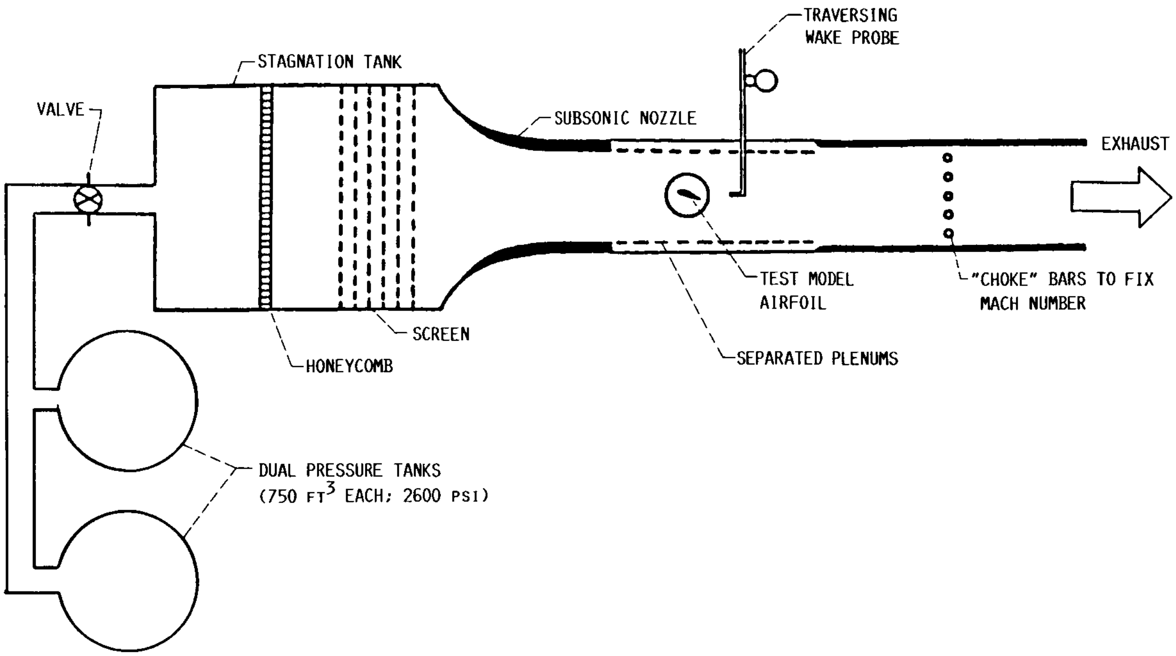


FIGURE 1. - SCHEMATIC VIEW OF OSU AARL 6- BY 12-IN. HIGH REYNOLDS NUMBER WIND TUNNEL, OPERATED BY THE PRESSURIZED/BLOWDOWN PROCEDURE.

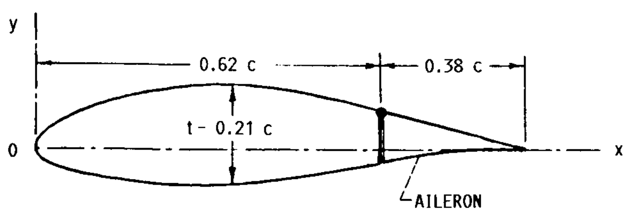
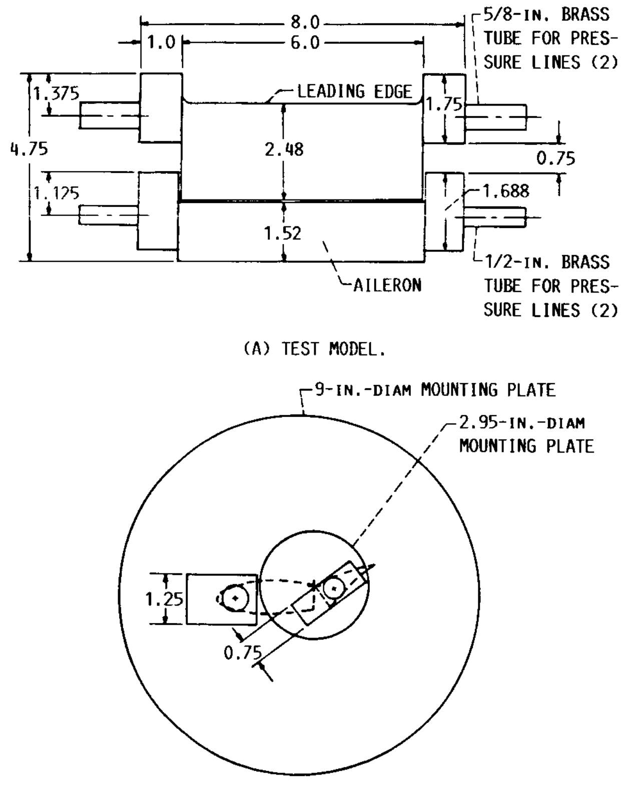


FIGURE 2. - NACA 64-621 AIRFOIL SECTION (COORDINATES IN TABLE I).



(A) TEST MODEL.

(B) MOUNTING PLATES.

FIGURE 3. - DIAGRAMS OF OSU TEST MODEL AND MOUNTING PLATES. (ALL DIMENSIONS ARE IN INCHES.)

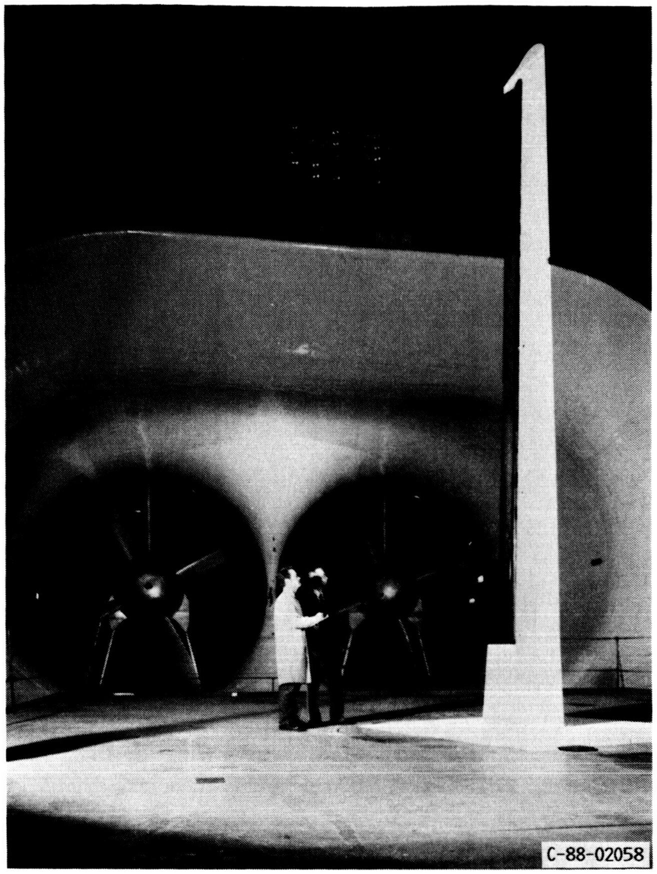


FIGURE 4. - FULL-SCALE BLADE TIP SECTION MOUNTED IN NASA LANGLEY 30- BY 30-FT SUBSONIC WIND TUNNEL.

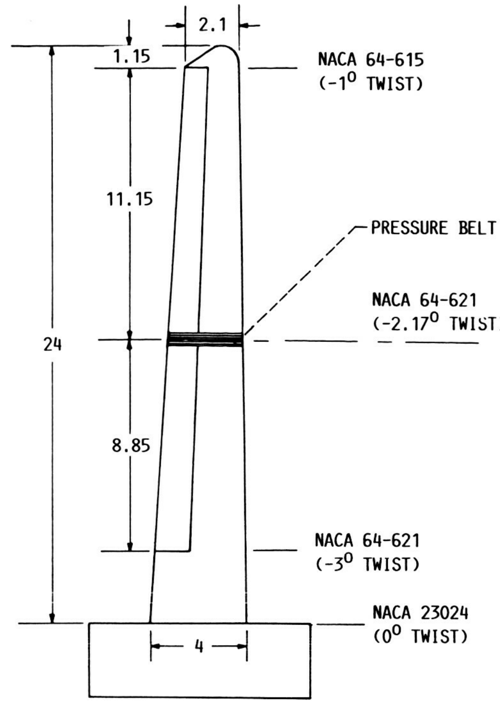


FIGURE 5. - PRINCIPAL DIMENSIONS OF FULL-SCALE TEST AIRFOIL, SHOWING LOCATION OF PRESSURE BELT. (ALL DIMENSIONS ARE IN FEET.)

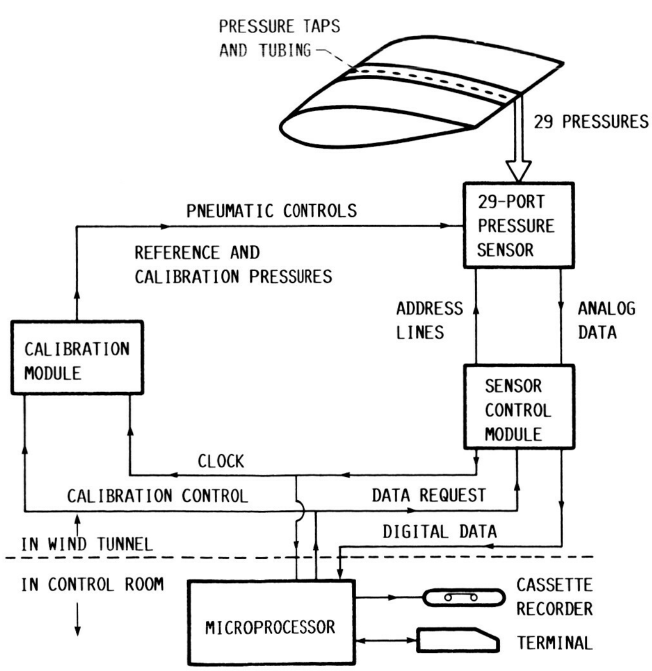
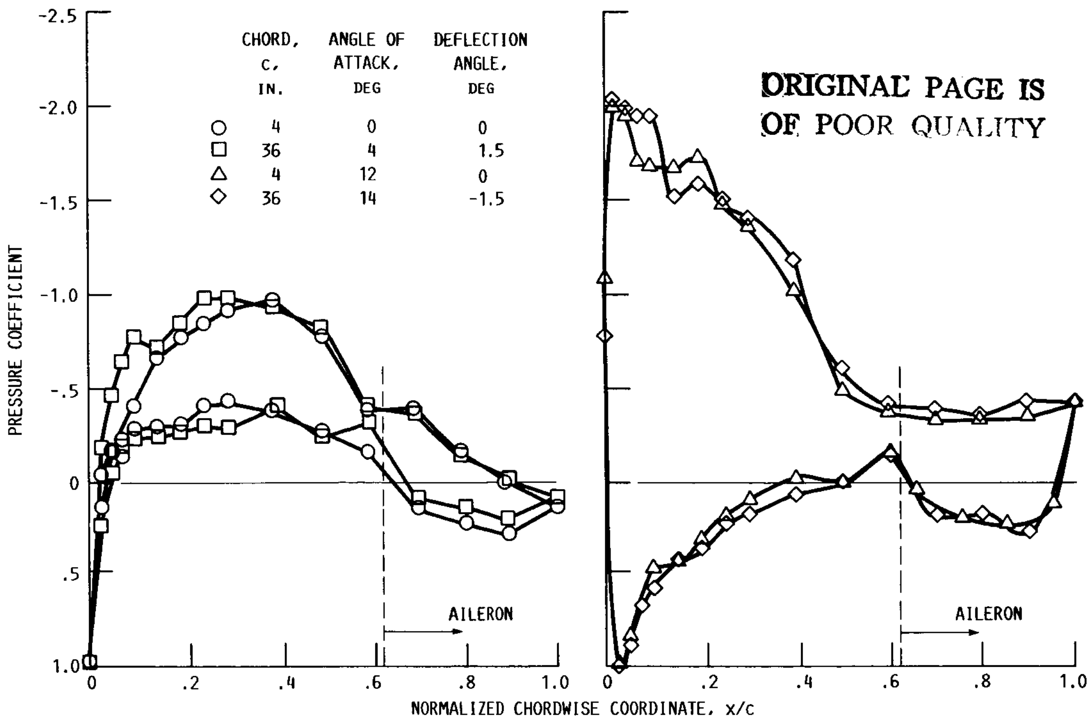


FIGURE 6. - SCHEMATIC DIAGRAM OF PRESSURE BELT DATA ACQUISITION SYSTEM.

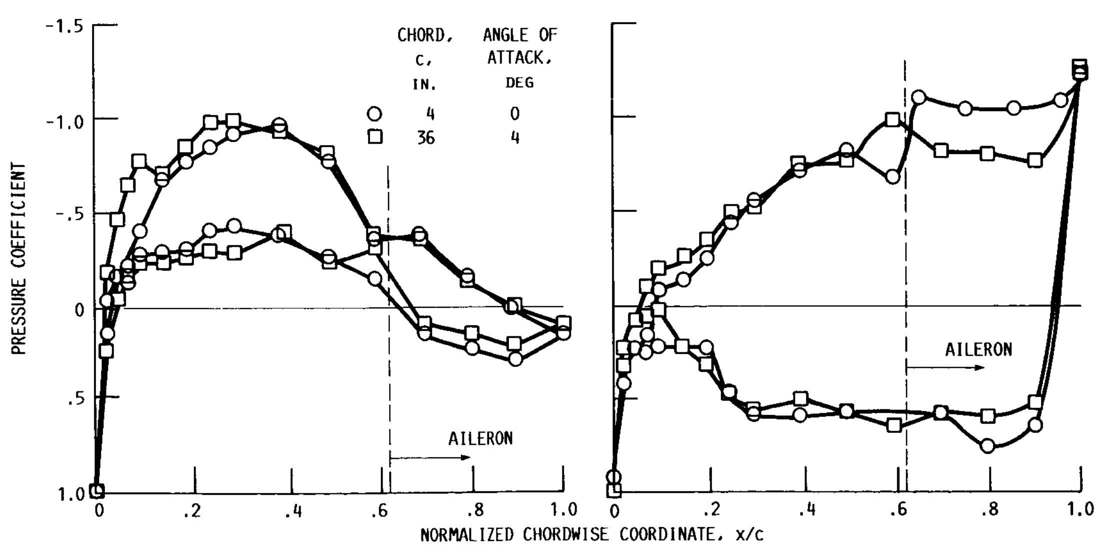


ORIGINAL PAGE IS OF POOR QUALITY

(A) FULLY ATTACHED FLOW.

(B) FLOW NEAR STALL.

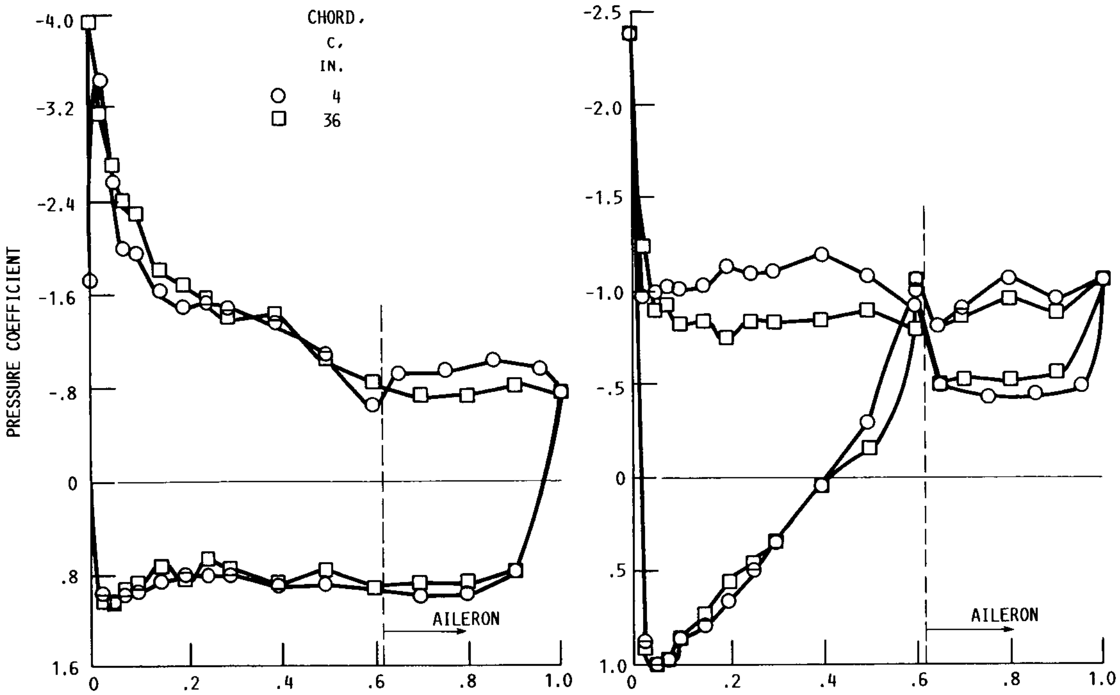
FIGURE 7. - COMPARISON OF CHORDWISE PRESSURE DISTRIBUTIONS WITH FLOW FULLY ATTACHED AND NEAR STALL.



(A) AILERON DEFLECTION ANGLE, NEAR 0^{o}.

(B) AILERON DEFLECTION ANGLE, 90^{o}.

FIGURE 8. - EFFECT OF AILERON DEFLECTION ON CHORDWISE PRESSURE DISTRIBUTION.



(A) ANGLE OF ATTACK, 18°.

(B) ANGLE OF ATTACK, 36°.

FIGURE 9. - CHANGE IN CHORDWISE PRESSURE DISTRIBUTION WITH INCREASING ANGLE OF ATTACK, WHEN AILERON DEFLECTION ANGLE IS 90°.

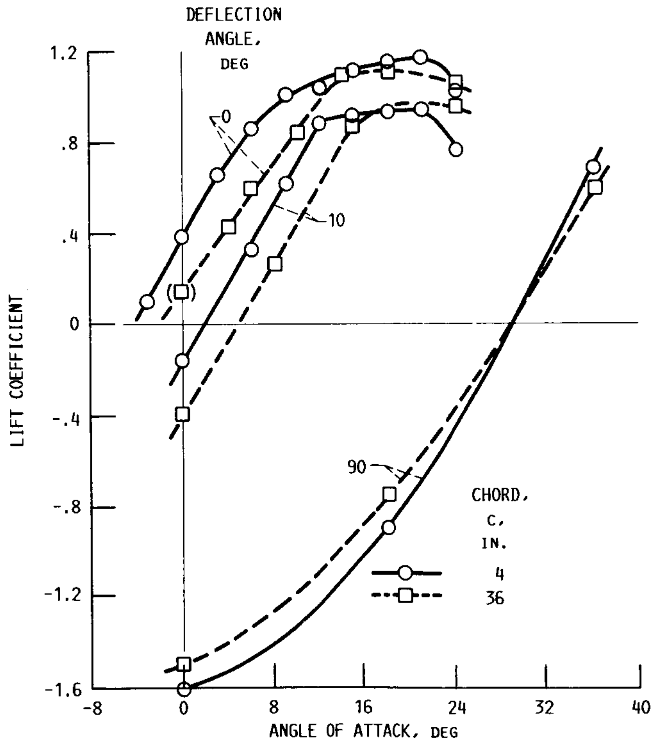


FIGURE 10. - COMPARISON OF LIFT COEFFICIENTS BEFORE SCALING DATA FOR LARGER AIRFOIL.

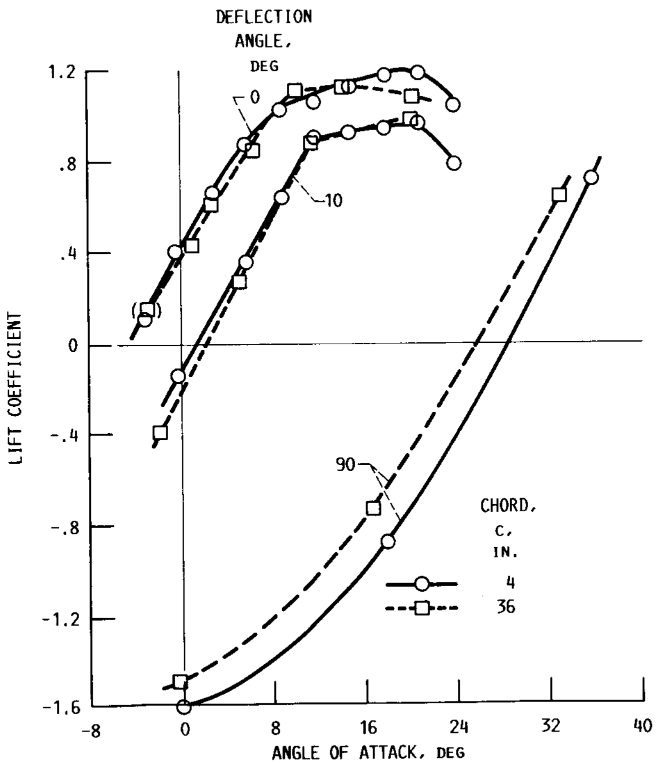


FIGURE 11. - COMPARISON OF LIFT COEFFICIENTS AFTER SCALING DATA FOR LARGER AIRFOIL.

Report Documentation Page

NASA — National Aeronautics and Space Administration

1. Report No. NASA TM-100802	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle: Comparison of Pressure Distributions on Model and Full-Scale NACA 64-621 Airfoils With Ailerons for Wind Turbine Application		5. Report Date: April 1988
		6. Performing Organization Code
7. Author(s): G.M. Gregorek, R.J. Kuniega, and T.W. Nyland		8. Performing Organization Report No.: E-3982
		10. Work Unit No.: 776-33-41
9. Performing Organization Name and Address: National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio 44135-3191		11. Contract or Grant No.
		13. Type of Report and Period Covered: Technical Memorandum
12. Sponsoring Agency Name and Address: U.S. Department of Energy, Wind/Ocean Technology Division, Washington, D.C. 20546-0001		14. Sponsoring Agency Report No.: DOE/NASA/20320-75

15. Supplementary Notes

Final Report. Prepared under Interagency Agreement DE-AI01-76ET20320.
G.M. Gregorek and R.J. Kuniega, Ohio State University, Columbus, Ohio, and T.W. Nyland, Lewis Research Center.

16. Abstract

The aerodynamic similarity between a small (4-in. chord) wind tunnel model and a full-scale wind turbine blade (24-ft tip section with a 36-in. chord) was evaluated by comparing selected pressure distributions around the geometrically similar cross sections. The airfoils were NACA 64-621 sections, including trailing-edge ailerons with a width equal to 38 percent of the airfoil chord. The model airfoil was tested in the OSU 6- by 12-In. High Reynolds Number Wind Tunnel; the full-scale blade section was tested in the NASA Langley Research Center 30- by 60-Ft Subsonic Wind Tunnel. The model airfoil contained 61 pressure taps connected by embedded tubes to pressure transducers. A belt containing 29 pressure taps was fixed to the full-scale section at midspan to obtain surface pressure data. Lift coefficients were obtained by integrating pressures, and corrections were made for the three-dimensional effects of blade twist and downwash in the blade tip section. The results of the two different experimental methods correlated well for angles of attack from -4° to 36° and aileron deflections from 0° to 90°.

17. Key Words (Suggested by Author(s)): Windpower utilization; Wind turbines; Airfoils; Aerodynamics; Aerodynamic drag; Aerodynamic similarity; Ailerons		18. Distribution Statement: Unclassified - Unlimited; Subject Category 44; DOE Category UC-60	
19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No of pages: 12	22. Price*: A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161