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**LOW SPEED WIND TUNNEL TESTS OF SEVERAL
AIRFOIL SECTIONS THROUGH 360° ANGLE OF ATTACK**

James F. Reed

ABSTRACT

A series of two-dimensional airfoils were run through a complete 360° angle of attack range to determine their low-speed force characteristics. The airfoils were chosen in an attempt to vary as many parameters (such as thickness, camber, thickness distribution, etc.) as possible with the limited number of shapes that time permitted. All airfoils tested had lift curves with two distinct stalls and quite similar drag curves between 0° and 90° angle of attack. The highly cambered sections developed peculiar characteristics in the inverted and trailing edge forward positions, as might be expected. The effective test Reynolds number was 0.81×10^6 based on the model chord of one foot.

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October 14, 1954

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LOW SPEED WIND TUNNEL TESTS OF SEVERAL AIRFOIL SECTIONS THROUGH 360° ANGLE OF ATTACK

INTRODUCTION

To obtain some knowledge on force coefficients of various airfoil sections through these large angle-of-attack variations, tests were performed by Sandia Corporation at the Municipal University of Wichita 7 x 10 foot Low Speed Wind Tunnel on the following airfoil sections:

Flat Plate
NACA 0015
NACA 0015 (Modified - See Figure 3)
NACA 63015
NACA 64021
St. Ae. 27a
NACA 6712

The models were of laminated mahogany with one-foot chord and spanned the four-foot dimension of the University of Wichita 7 x 4 foot two-dimensional test section. The forces measured were lift, drag, and pitching moment about the model one-quarter chord.

SYMBOLS

c_l = section lift coefficient, $\frac{L}{qS}$

c_d = section drag coefficient, $\frac{D}{qS}$

$c_{m\frac{c}{4}}$ = section pitching moment coefficient about the 1/4 chord, $\frac{M_{\frac{c}{4}}}{qSc}$

$c_{m\frac{3c}{4}}$ = section pitching moment coefficient about the 3/4 chord, $\frac{M_{\frac{3}{4}c}}{qSc}$

α = angle of attack, degrees

D/L = drag to lift ratio = $\frac{c_d}{c_l}$

S = wing area, $ft^2 = 4 ft^2$

c = wing chord, $ft = 1 ft$

q = dynamic pressure, $1/2\rho V^2$, lb/ft^2

Subscripts

c = tunnel test data as corrected for boundary effects

u = uncorrected tunnel test data

MODELS AND APPARATUS

The models were constructed of laminated mahogany and were finished to contour, sprayed with lacquer, and rubbed to a smooth surface. The model chord was one foot and the span was four feet. The University of Wichita 7 x 10 foot low speed wind tunnel was modified by two vertical walls to a 7 x 4 foot two-dimensional test section as shown in Figure 1.

The airfoil sections investigated may be seen in Figure 2. The models were mounted on the University of Wichita pyramidal-type balance through which the forces were read. The end plates on the models were rigidly attached to the ends of the airfoils and consisted of 20-inch diameter disks of plywood. Approximately 1/2-inch of clearance was allowed between the end plate and the tunnel wall at the downstream edge and about 1/4-inch at the upstream edge. The large amount of clearance was necessary because of excessive deflection of the balance system under the high drag loads imposed at large angles of attack. It is recognized that such deflections produce errors in the drag and moment data.

Due to a build-up of pressure on the upstream face of an airfoil near 90° and a resultant low pressure on the downstream face, the end sealing problem was quite serious. Some experimentation with two types of seals, see Figure 3, showed no difference in the data. Since time did not permit further investigation, the labyrinth type seal was employed during practically all of the test.

In order to correlate the low angle of attack drag coefficient with NACA data and thus determine Δc_d due to end plates, a wake survey rake was installed as shown in Figure 5. The pressures were read on a 60° inclined water manometer to achieve accuracy, and were photographed.

The angle of attack was varied remotely from the console using a 24-volt motor with a drum attached, and a cable which was wrapped around a large disc. See Figure 6. The angle was read from the console by means of a telescope. The entire angle-of-attack mechanism was mounted on the balance so as to alleviate the necessity for a tare due to cable tension. The models were located on the end plates by dowel pins and rigidly fastened to the end plates by machine screws. The only method of aligning the end plates was by shims under the airfoil tips (this proved to be the major fault of this mounting system). The end plates had a tendency to crush slightly under the stress of the screws necessitating additional shimming. Finally, a steel plate was inserted in the end plate and this procedure helped immensely. However, bending in the thin airfoils allowed the end plates to toe in at the high angles of attack and it is felt that either more rigid models should be employed or a rigid mount be constructed for each end plate if future two-dimensional tests of this type are required. Figure 7 shows a typical model installation.

METHODS AND PROCEDURES

The tests were run at constant indicated velocity of 125.3 ft/sec. The angle of attack was then varied from below zero lift to 90° while the lift, drag, and pitching moment were read. For consistency the angle of attack was always varied in such a manner as to allow the airfoil to stall normally, that is, 0° to 90° , 180° to 90° , 180° to 270° , and 360° to 270° , instead of merely rotating the airfoil through the four quadrants. The test dynamic pressure was limited to 16.85 psf, corresponding to the above velocity, by model bending and vibration at high angles. The models were rotated about the one-quarter chord and the forces and moments were resolved about this point. The pitching moment data was resolved about the model one-quarter chord and no corrections have been made for the trailing edge first data. This means that, for the trailing edge first runs, the pitching moments were resolved about the effective three-quarter chord.

The wake rake for drag correlation was mounted one chord length downstream from the model trailing edge and the pressure data was reduced to drag coefficient form by the method outlined in Reference 1, pp 165-168. A pitot-static tube was mounted near the tunnel ceiling to obtain the tunnel dynamic pressure during this run.

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RESULTS AND DISCUSSION

The force and moment coefficients and the drag-to-lift ratio are plotted versus angle of attack and presented as data in Figures 8 through 31. On each graph is a small sketch showing effective angle-of-attack variation.

The data was taken on the U.W. pyramidal-type balance and then corrected for tunnel wall effects by the method as shown in Appendix I. Since the airfoils were not inverted so as always to read positive lift and correct pitching moments, the following additional changes in sign had to be applied:

First quadrant,

The data was plotted as taken.

Second quadrant,

The data was plotted as taken except that the plotted

$$\alpha = 180^\circ - \alpha_c$$

$$c_1 = -c_{1c}$$

Third quadrant,

The data was plotted as taken except that the plotted

$$\alpha = \alpha_c - 180^\circ$$

Fourth quadrant,

The data was plotted as taken except that the plotted

$$\alpha = 360^\circ - \alpha$$

$$c_1 = -c_{1c}$$

$$D/L = -\left(\frac{D}{L}\right)_c$$

Note that in the above outlined corrections, the only changes were in sign, that is, the pitching moments were not transferred to the 1/4-chord in the trailing edge first configurations.

Comparative plots showing the effect of various parameters such as thickness, thickness distribution, camber, etc. are presented as Figures 32 through 37.

Figure 32 shows the effect of leading edge shape on the force coefficients of a flat plate. The ever present "second stall" is very predominate on this shape; in fact, in the leading edge forward configuration, the airfoil hardly can be said to have a first stall at all.

On Figure 33 can be seen the difference in lift and drag on an airfoil with and without a spanwise slot. Of special interest is the fact that the slot hardly effects the lift curve at all below the first stall leading to the theory that the second stall is caused simply by pressure build-up on the upstream face even though the downstream face of the airfoil is still badly stalled.

The tremendous effect of the "drooped snoot" and camber on the first stall of the NACA 63015 as compared to the NACA 0015 can be seen from Figure 34. Note that the lift and drag curves above 35° are practically identical for both airfoils.

Figures 35, 36, and 37 show the effect of reverse flow on an uncambered and a cambered airfoil. The stall is quite abrupt on all the trailing edge first lift data, most noticeably on the NACA 0015. The very high camber of the St. Ae. 27a shape makes the trailing edge first lift curves stall at very low angles of attack. The high angle-of-attack drag curves are all very similar except for the increase in maximum drag coefficient due to the airfoil camber in the second and third quadrants.

The angle-of-zero lift was determined for all sections and compared to published information as can be seen from Figure 39. In the case of the uncambered airfoils, the angles agreed fairly well; but for the cambered airfoils, NACA 64021 and NACA 63015, there was some discrepancy (in the order of .5 degree). This discrepancy is as yet unexplained but is possibly due to model inaccuracies since the agreement in all other cases is less than .25 degree. Also, subsequent testing has indicated a slight flow inclination in the U.W. 2-dimensional throat, but the magnitude of this inclination is not precisely determined.

A run was made after the completion of the program to determine the buoyancy correction, if any, required by the build-up of boundary layer. No measurable static pressure gradient could be found, so no buoyancy corrections were applied to the data.

Since the primary objective of this test was to obtain data at angles of attack above the first stall, no great effort was made to correlate the minimum drag coefficients with published data. The wake survey run (No. 165) was made to find the minimum drag of the NACA 0015 airfoil so as to determine the tare drag of the end plates. A wake rake with $1/8$ -inch spacing on the tubes was utilized with the pressures being read on a 60° inclined water manometer. The manometer was photographed and the drag coefficients for the low angles of attack were computed using the method outlined in Reference 1, pp 165-168. The results, uncorrected for Reynolds number effect, are shown as Figure 38.

The minimum drag coefficient as determined by the wake momentum method was computed as .0081 as compared to .0086 from Reference 4 corrected to the same effective Reynolds number ($.81 \times 10^6$).

In order to compare the maximum lift coefficients of the data obtained in this test with that in Reference 4, corrections must be applied for the effect of Reynolds number. The method described in Reference 5, pp 387-411 was used to correct from the effective Reynolds number on the reference data of approximately 8,000,000 to the U.W. test Reynolds number of 810,000. The following chart shows the results of this correction:

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<u>Airfoil</u>	<u>$C_{1\max}$ from Ref. 5 ($RN = .8 \times 10^6$)</u>	<u>$C_{1\max}$ U.W.</u>	<u>Difference in $C_{1\max}$</u>
0015	1.12	.96	- .16
6712	1.55	1.41	- .14
63015	1.82	1.49	- .33
St. Ae. 27a	1.92	1.79	- .13

The $\Delta C_{1\max}$ noted is probably due to poor end sealing. The corrections were not available on the 64021 and the Flat Plate.

As an example of the effect of turbulence factor on $C_{1\max}$, take the NACA 0015 and assume a turbulence factor of 1.00.

<u>Ref. 5 $C_{1\max}$ from $RN = .66 \times 10^6$</u>	<u>$C_{1\max}$ U.W.</u>	<u>Diff. in $C_{1\max}$</u>
1.03	.96	- .07

This compares to a $\Delta C_{1\max}$ of -.16 using $.81 \times 10^6$ as RN_e . No further corrections will be applied, however, since the 1.21 factor was obtained by standard methods using a turbulence sphere.

CONCLUDING REMARKS

Since the object of this report is to present the data obtained and give a few estimates as to the accuracy of some of the points, there are few conclusions that can be drawn. Most of the inaccuracies present were due to the crudity of equipment available and could not have been avoided without major changes to the tunnel balance and support system. It is felt that the lift and drag data above the first stall are better than indicated by the maximum lift errors above, since the leakage through the end seals would decrease with the rise in pressure on the back face of the airfoil due to the stall.

JAMES F. REED - 5142

Case No. 637.0
October 14, 1954

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Figure 1.- 4 foot by 7-foot Two-dimensional auxiliary throat.

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Figure 2.- Airfoil sections investigated.

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FIGURE 3.
TWO TYPES OF END PLATE SEALS

14

$\frac{1}{6}$ SCALE
ALL DIMENSIONS IN INCHES
UNLESS NOTED

SECTION AA, TYPICAL SECTION

Figure 4.- Modification slots of the NACA 0015 airfoil section model.

Figure 5 -- Front view of model and wake survey rake as positioned in auxiliary throat.

Figure 6 -- Angle of attack mechanism, outside of auxiliary throat.

Figure 7 -- Front view of typical model mounted in auxiliary throat.

303 016

302 018

FIGURE 9

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SANDIA 2-DIM. MODELS
FLAT PLATE
2ND QUADRANT
 $Re = 8.20 \times 10^5$

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FIGURE 11

26

303 021

28

29

30

32

FIGURE 151

302 C24

25

33

34

FIGURE 16

36

SANDIA 2-DIM MODELS
NACA G3015
2ND QUADRANT
 $Re = 8.20 \times 10^5$

302 026

FIGURE 17

38

39

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302 028

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gm 6-22-54

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202 030

31

45

46

FIGURE 22

47

303 031

FIGURE 23

50

FIGURE 24

303 033

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308 034

35

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303 035

FIGURE 26

56

57

60

UNIVERSITY OF WICHITA
SCHOOL OF ENGINEERING
SANDIA 2-DIM. MODELS
NACA 6712
2ND QUADRANT
 $Re = 8.25 \times 10^5$

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FIGURE 29

303 038

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303 039

FIGURE 30

63

070 806

FIGURE 31

UNIVERSITY OF WICHITA
SCHOOL OF ENGINEERING
SANDIA 2-DIM. MODELS
NACA 6712
4TH QUADRANT
 $Re = 6.20 \times 10^5$

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66

COMPARISON OF TWO LEADING EDGE SHAPES ON LIFT AND DRAG COEFFICIENTS OF A FLAT PLATE

KEY

○ } LIFT COEFFICIENT
□ } DRAG COEFFICIENT

SANDIA 2-DIM. MODELS
FLAT PLATE
 $Re = 8.2 \times 10^6$

FIGURE 32

503 041

67

68

EFFECT OF SLOTS ON FORCE CHARACTERISTICS OF AN NACA 0015 AIRFOIL SECTION

KEY

- NACA 0015 - C_l
- NACA 0015, MOD. - C_l
- NACA 0015 - C_d
- NACA 0015, MOD. - C_d

FIGURE 33

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COMPARISON OF FORCE CHARACTERISTICS OF THE NACA 0015 & NACA 63015 AIRFOIL SECTIONS

KEY

○ NACA 0015, c_l
△ NACA 63015, c_l

○ NACA 0015, c_d
△ NACA 63015, c_d

SANDIA 2-DIM. MODELS
NACA 0015 & NACA 63015

1st QUADRANT
 $Re = 8.2 \times 10^6$

FIGURE 34

803 043

71

COMPARISON OF NACA 0015 SECTION FORCE CHARACTERISTICS LEADING EDGE FIRST AND TRAILING EDGE FIRST

KEY

- LEADING EDGE FIRST
- TRAILING EDGE FIRST
- } LIFT COEFFICIENT
- } LIFT COEFFICIENT
- } DRAG COEFFICIENT
- } DRAG COEFFICIENT

SANDIA 2-DIM. MODELS
NACA 0015

$$Re = 8.2 \times 10^6$$

FIGURE 35

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COMPARISON OF St Ae 27A SECTION LIFT COEFFICIENT THROUGH ALL FOUR QUADRANTS

SANDIA 2-DIM MODELS

St Ae 27A

$R_e = 8.2 \times 10^6$

303 045

FIGURE 36

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75

COMPARISON OF St Ae 27A SECTION DRAG COEFFICIENT THROUGH ALL FOUR QUADRANTS

308 668

FIGURE 37

78

508 047

FIGURE 38

48

79

FIGURE 39

302 048

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APPENDIX I

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JET BOUNDARY CORRECTIONS

1. Solid Blocking, ϵ_{sb}

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

Where: Λ = Model shape factor dependent on thickness ratio from Figure 1A.

$$\sigma = \frac{\pi^2}{48} \left(\frac{c}{h} \right)^2 = .00411$$

2. Wake Blocking, ϵ_{wb}

$$\epsilon_{wb} = \tau c_{d_u}$$

Where: $\tau = \frac{1}{4} \times \frac{c}{h} = .035714$

3. Application of Corrections

$$V_c = V_u \left(1 + \Lambda \sigma + \tau c_{d_u} \right)$$

$$q_c = q_u \left(1 + 2\Lambda \sigma + 2\tau c_{d_u} \right)$$

$$a_c = a_u + \frac{57.3\sigma}{2\pi} \left(c_{l_u} + 4c_m \frac{1}{4_u} \right)$$

$$c_{l_c} = c_{l_u} \left(1 - \sigma - 2\Lambda \sigma - 2\tau c_{d_u} \right)$$

$$c_m \frac{1}{4_c} = c_m \frac{1}{4_u} \left(1 - 2\Lambda \sigma - 2\tau c_{d_u} \right) + \frac{\sigma c_{l_u}}{4}$$

$$c_{d_c} = c_{d_u} \left(1 - 3\Lambda \sigma - 2\tau c_{d_u} \right)$$

VALUES OF Δ FOR SEVERAL THICKNESS
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