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Abstract

This paper reviews design procedures for wind-axis turbine rotors. An "on-design" routine for rotor blade design is presented as well as an "off-design" performance calculation program. Resulting from this review are analyses of desirable characteristics of airfoil sections and of types of data which rotor designers need. Included in the paper are airfoil characteristics for candidate blade sections including 360 degree data for GA(W)-1 and GA(W)-2 airfoils.

1. INTRODUCTION

This paper reviews design procedures for 2- and 3-bladed wind axis turbine rotors. The purpose of this review is to summarize desirable characteristics and limitations of airfoil sections which can be used as turbine blade sections. The large wind-axis (horizontal-axis) turbines being constructed have been designed using airfoil sections originally designed for aircraft wings and/or helicopter rotor blades. By analyzing turbine blade requirements, it is possible to choose more appropriate blade sections.

2. SYMBOLS

A	Area swept by rotor, $\pi d^2/4$	sq.ft.
a	Wind speed retardation factor	
a	Air swirl factor	
B	Number of blades	
c	Blade chord	ft.
c_d	Section (2-D) drag coefficient, D/qdS	
c_ℓ	Section lift coefficient, L/qdS	
c_x	Force coefficient in rotor plane, F_Q/qdS	
c_y	Thrust force coefficient, F_T/qdS	
D	Drag	lb.
d	Turbine rotor diameter	ft.
dr	Radial length of blade element	ft.
dS	Area of blade element	sq.ft.
F_Q	Force on blade in plane of rotation	lb.
F_T	Force on blade normal to plane of rotation	lb.
L	Lift	lb.
n	Rotational speed	r.p.s.
P	Power = $2\pi nQ$	ft.-lb./sec.
Q	Torque = $\int r dF_Q$	
q	Dynamic pressure = $\frac{1}{2}\rho V_{res}^2$	p.s.f.
r	Radial distance	ft.
Re	Reynolds number = $\rho Vc/\mu$	
T	Thrust force = $\int dF_T$	lb.
V_a	Ambient wind velocity	ft./sec.
V_1	Axial velocity through turbine rotor	ft./sec.
V_2	Downstream wind velocity	ft./sec.
V_{res}	Velocity relative to blade section	ft./sec.
X	Tip speed ratio = $\pi nd/V_a$	
α	Airfoil angle of attack	deg.

β	Blade angle	deg.
ϕ	Wind helix angle	deg.
μ	Air viscosity	slug/ft.-sec.
ρ	Air density	slug/cu.ft.

3. DESIGN OF WIND-AXIS TURBINE

3.1 DESIGN PARAMETERS

Momentum considerations permit calculation of induced velocities resulting from extraction of energy from the air stream. Speed of air approaching the wind turbine

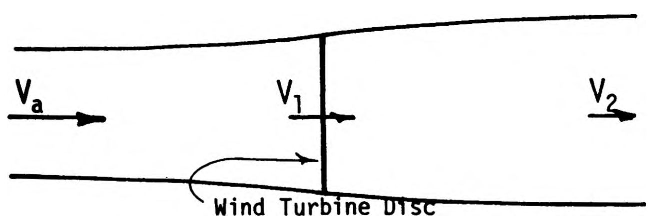


Figure 1. Streamtube of Air Passing Through Wind Turbine Disc.

is reduced from ambient velocity, V_a, to speed through the rotor disc, V_1.

$$V_1 = V_a(1 - a)$$

Extraction of torque from the airstream produces swirling of the airstream, i.e., velocity is induced in the plane of rotation of the turbine rotor. Relative wind velocity at a section of the rotor blade is shown in figure 2(b).

Designers have airfoil data available which permit prediction of lift and drag coefficients as functions of section angle of attack, α. For design purposes it is necessary to resolve blade forces into force components in the plane of rotation (which produce torque) and forces in the direction of the shaft (which must be resisted by supporting structure).

$$C_x = \frac{dF_Q}{q\,dS} = C_l \sin\phi - C_d \cos\phi$$

$$C_y = \frac{dF_T}{q\,dS} = C_l \cos\phi + C_d \sin\phi$$

where

$$q = \tfrac{1}{2}\rho V_{res}^2 \quad \& \quad dS = c\,dr$$

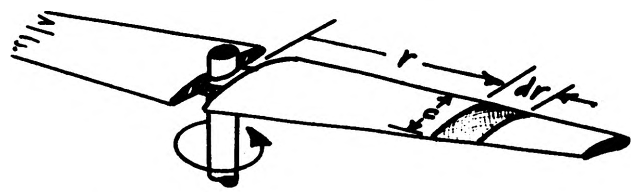
The torque produced by B blades is:

$$\text{Torque} = Q = \int r\,dF_Q = B\int C_x\, r\, q\, dS$$

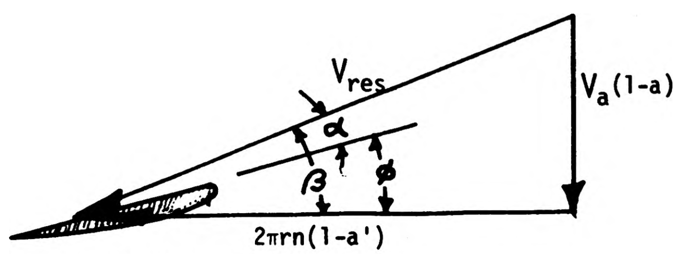
$$= \tfrac{1}{2}\rho B\int_{r_1}^{r_2} C_x V_{res}^2\, r\, c\, dr$$

The thrust (i.e., the force tending to blow the tower over) is:

$$\text{Thrust} = T = \int dT = \tfrac{1}{2}\rho B\int_{r_1}^{r_2} C_y\, c\, V_{res}^2\, dr$$



(a) Turbine Rotor



(b) Blade Section

Figure 2. Velocities at Turbine Rotor Blade.

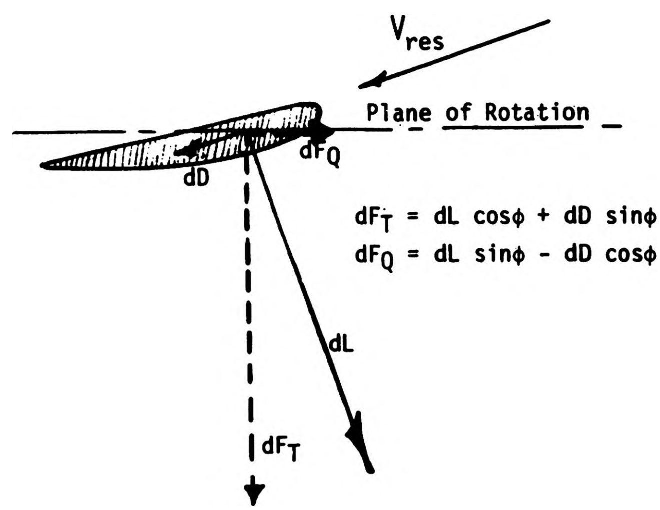


Figure 3. Forces Acting on Blade Element.

Power extracted from the airstream is:

$$\text{Power} = P = 2\pi nQ$$

A coefficient of power is defined as the power extracted by the rotor expressed as a fraction of the power of the air in the streamtube intercepted by the rotor.

$$C_p \equiv \frac{P}{\frac{1}{2}\rho V_a^3 A} = \frac{8}{\pi} \frac{P}{\rho V_a^3 d^2}$$

The theoretical (Betz) limit to the power coefficient is $C_{p_{max}} = .593$. Attainable power coefficients are functions of tip speed ratio $= X = \frac{\text{Tip Speed}}{\text{Wind Speed}} = \frac{\pi n d}{V_a}$. Typical values of C_p are shown in figure 4.

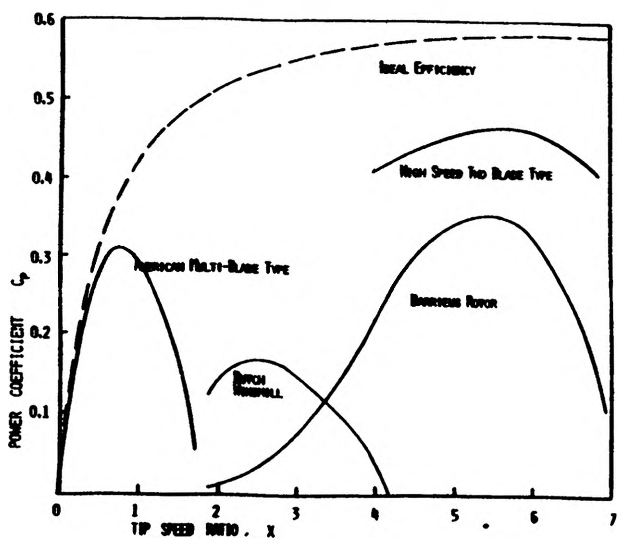


Figure 4. Wind Turbine Power Coefficients.

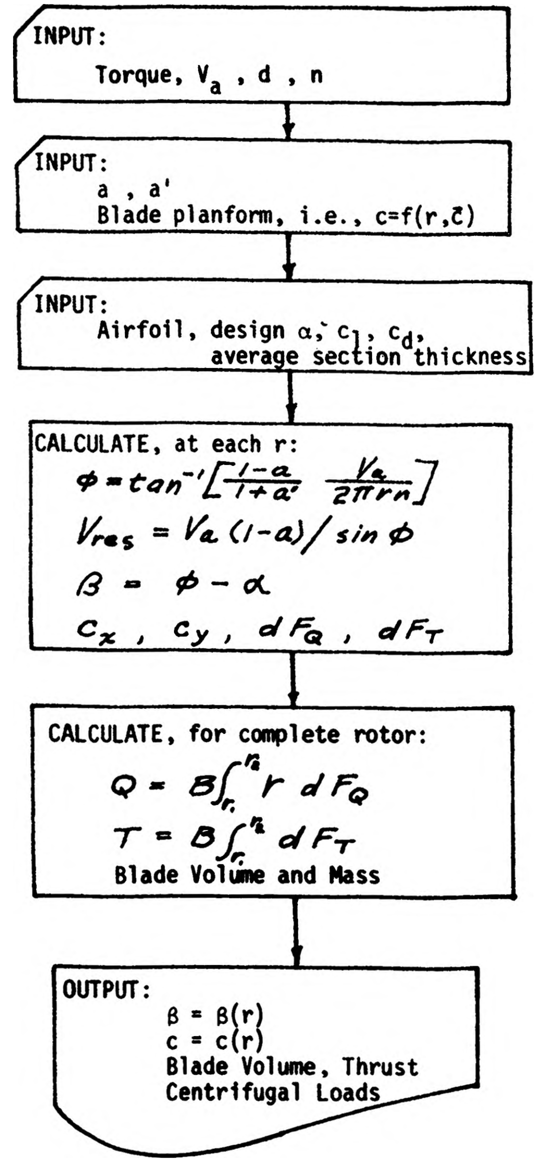


Figure 5. "On - Design" Program.

3.2 ON-DESIGN PROGRAM

Using these relations it is possible to devise a design routine which may be computerized so that a large number of airfoil sections may be explored in arriving at a given design. A flow diagram for the "On-Design" program is shown in figure 5.

Design values of torque (Q), rotational speed (n), wind speed (V_a), and rotor diameter (d) are based on the generator size, local wind characteristics and expected C_p vs X curve. Knowing design V_a and required power, d and n are varied to obtain the design point at the top of the expected C_p vs X curve.

Ideal value of a is 1/3, but a = .15 is a more practical value. a' will be about a/10. Various blade planforms may be explored; the most popular planform appears to be a straight taper with tip chord about one-half of root chord. The design airfoil angle of attack should be that for $c_{l_{max}}$ (for reasons detailed later in this paper).

Output of this design program is the local blade angle (β) and chord (c) at all stations along the blade. Also, blade volume, centrifugal loads, blade weight and thrust are obtained. Design may be optimized on any of these factors. The author has chosen to base his design on the parameters which provide minimum blade volume (and mass) because this reduces size and cost of the support structure as well as the rotor.

This criterion is important to the airfoil section chosen and to the design angle of attack. In the early stages of the design of the Wichita State University wind turbine, comparison was made between rotors using various airfoil sections. (Design values are 150 rpm, torque = 155.0 ft-lb, X = 5.23, power = 3.3 kW, d = 18 ft). Results were:

Planform	Airfoil	Design α (degrees)	Blade Volume (cu.ft.)
	Clark-Y	11	1.398
Straight taper	0015	10	0.863
$c_{tip} = 2 c_{root}$	23012	10.5	0.520
	GA(W)-1	10	0.412

Recently, a design study was made to determine effect of design angle of attack on resulting blade volume. (This is essentially the same rotor: d = 18 ft, planform is constant except for tapered inboard one-fourth, power = 3.3 kW.) Results of this study are shown in figure 6.

A series of "paper airfoils" were devised based on the GA(W)-1. Design angle of attack was 16 deg. (c_ℓ = 1.425) but c_{d_o} was varied from .0038 to .00608 so that L/D varied from 234.4 to 375. Results are shown in figure 7.

It may be concluded that blade sections should be designed at, or near, $c_{\ell_{max}}$, that high $c_{\ell_{max}}$ is very desirable, and that high L/D is desirable.

3.3 OFF-DESIGN PERFORMANCE CALCULATION

Having determined the design of the blades, it is desirable to calculate rotor performance at "off-design" conditions, i.e., at all of the various wind speeds, rotational speeds, and blade angles (if the rotor is variable pitch) at which it may operate. An "off-design" computer program may be written based on the same basic relations.

Any systematic exploration of effects of varying wind speeds, rotational speeds, and blade angle results in wide ranges of

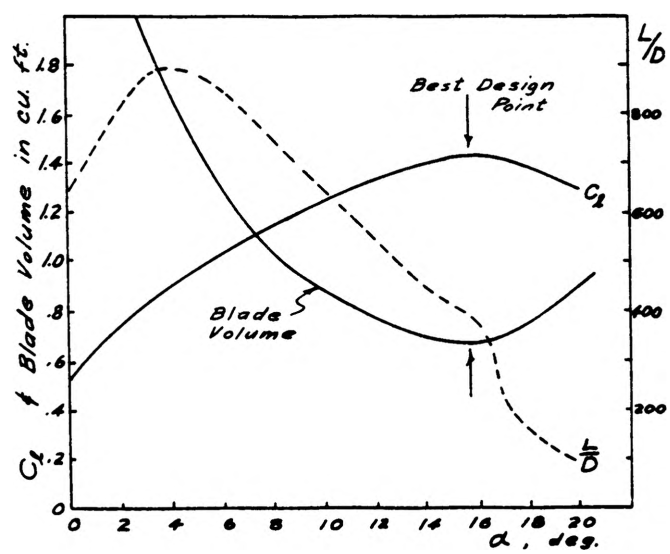


Figure 6. Effect of design angle of attack on blade size.

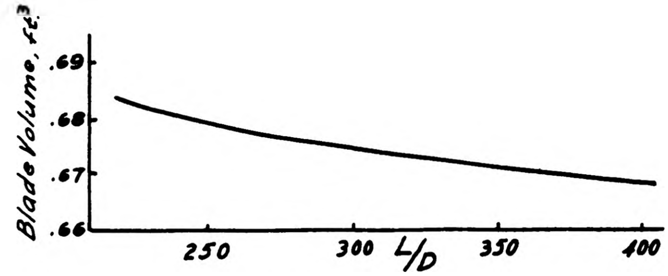


Figure 7. Effect of L/D on blade size.

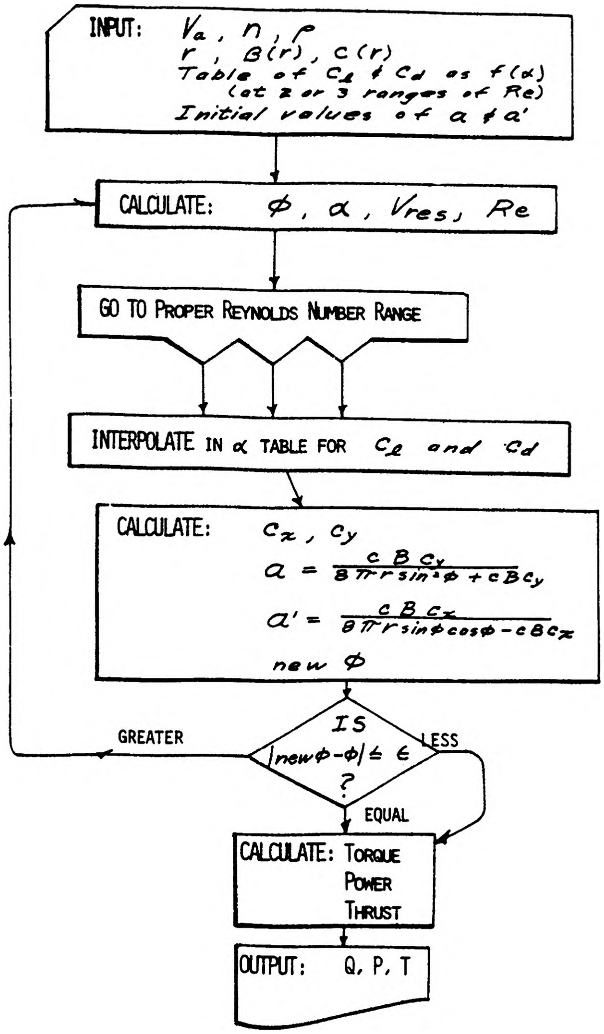


Figure 8. Off-Design Performance Program.

angles of attack at various radial stations on the blades--more than ±90 degrees! Also, Reynolds numbers vary widely and are, in general, lower than those of most modern wind tunnel tests. For example, on the W.S.U. 18-ft. rotor, design Reynolds number varies from 18,000 to 620,000. On the NASA Mod 0 (125 ft. rotor), Reynolds number varies from about 0.53×10^6 to 1.76×10^6.

Requirements for airfoil data for wind turbine designers include airfoil data at low Reynolds numbers and for high ranges of angle of attack. It is desirable that airfoil sections produce as high c_ℓ as possible with reasonably good L/D at $c_{\ell_{max}}$.

4. AIRFOIL SECTION DATA

One of the problems posed by the listed requirements is the relationship of $c_{\ell_{max}}$ to Reynolds number. Reference 1 reports characteristics of NACA 4412 airfoil at Reynolds numbers from 20,000 to 250,000. Figures 9 and 10 are reproduced from reference 1.

Most published airfoil data at Reynolds numbers less than 1 million date back to the 1920's and early thirties. Much of these data are unusable because turbulence factors of the test facilities were large, but unknown, so that the effective Reynolds numbers of the tests were considerably greater than the reported Reynolds numbers.

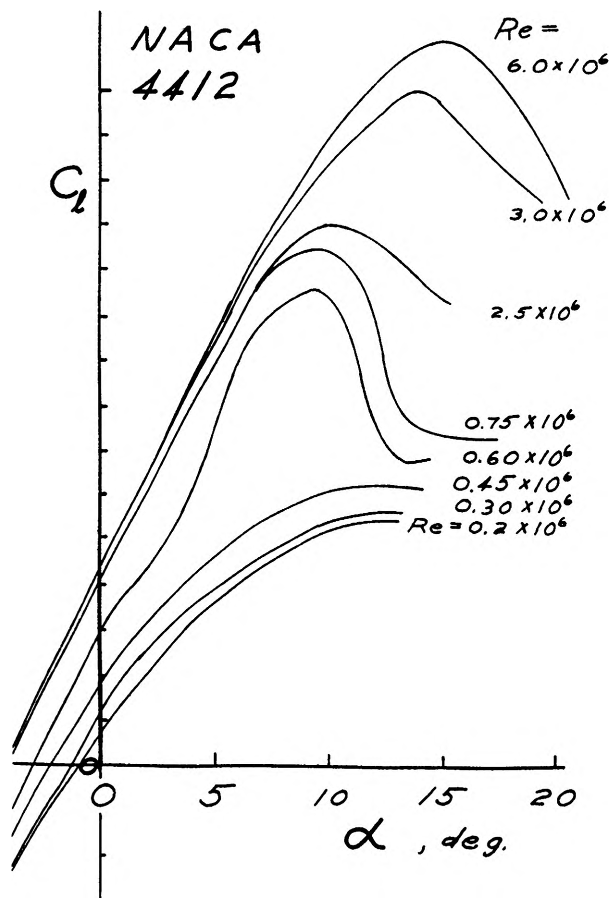


Figure 9. Effect of Reynolds Number on Lift Coefficient.

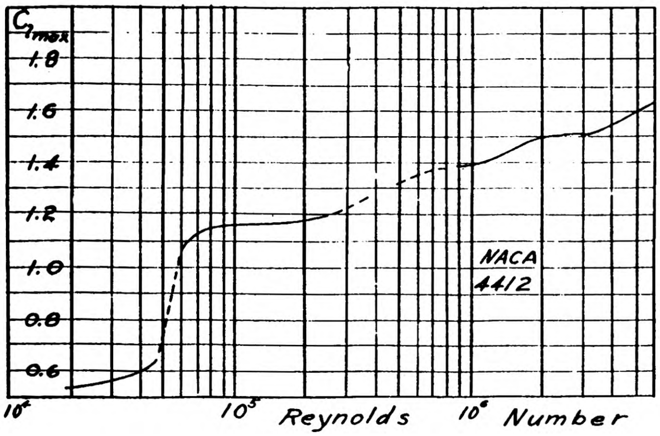


Figure 10. Maximum Lift Coefficient is a Function of Reynolds Number.

Reference 2 presents wide range angle of attack information for the NACA 0012 airfoil. Figure 11 is reproduced from reference 2. Note the hysterisis immediately after stall, and that Reynolds number is 1.8×10^6.

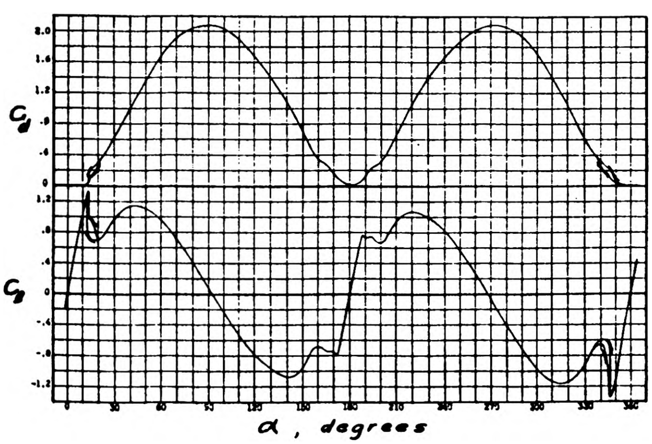


Figure 11. NACA 0012 Section Characteristics, Re = 1.8×10^6.

In an effort to produce additional data, wide range angle of attack tests of short chord 2-D models were conducted at Wichita State University. Test results were reported in reference 3, and figures 12 through 18 are taken from that reference.

In addition to a high $c_{\ell_{max}}$ it would be highly desirable that the stall be "gentle," i.e., with only a slow drop off of c_ℓ per degree beyond stall and

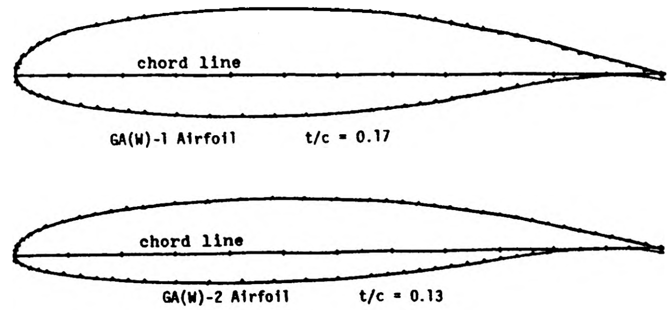


Figure 12. General Aviation Airfoil Profiles.

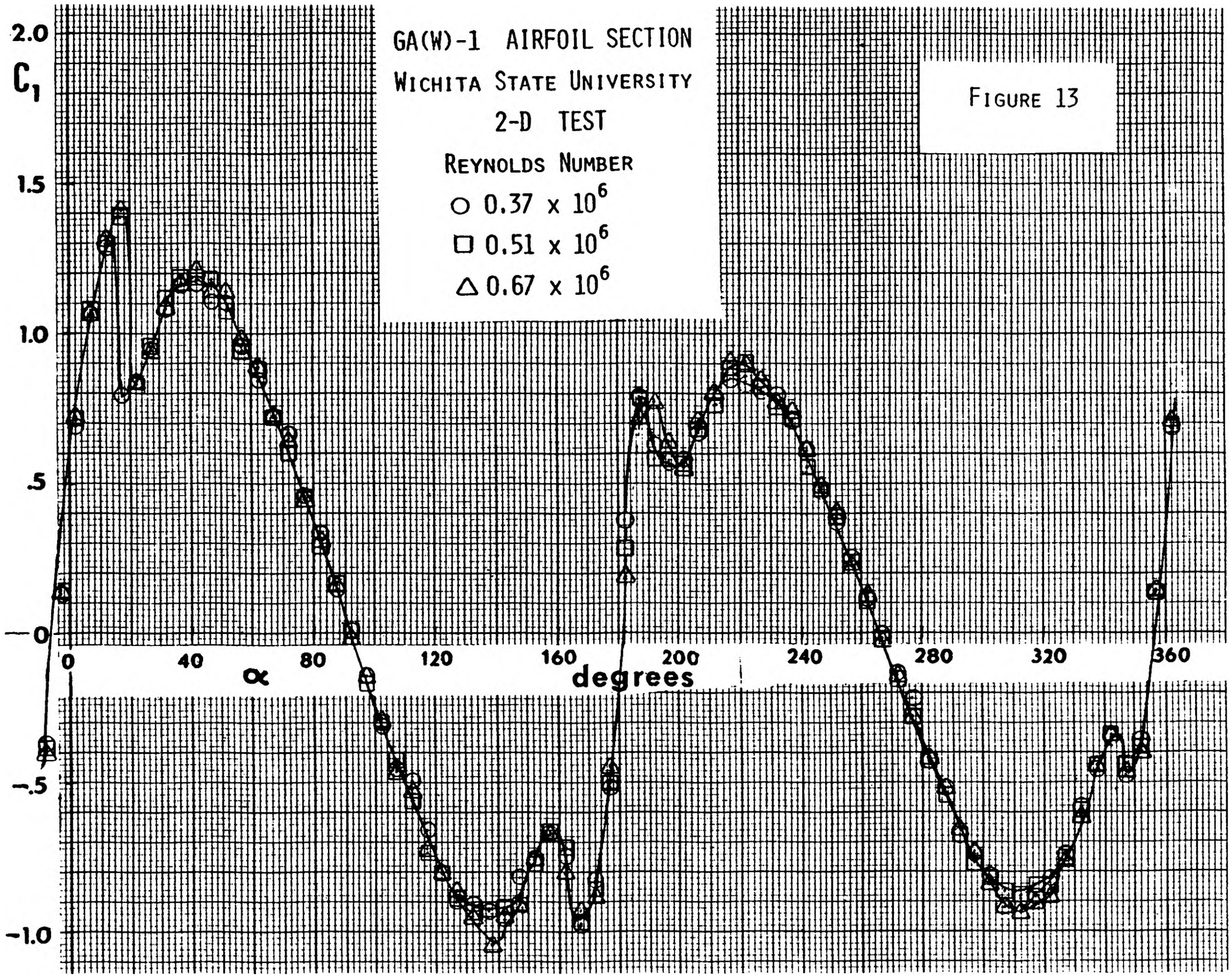
with small hysterisis. A general-aviation type airfoil tested at Wichita State recently shows that it is possible to design airfoils with this type of stall as shown in figure 19. Information about this airfoil is restricted by NASA to "Early Dissemination" rules; persons desiring additional information may write to Dr. W. H. Wentz, Jr., Wichita State University.

Another source of new airfoils for turbine rotors can be those designed for gliders and sailplanes. In general, these airfoils are marked by high camber, high lift coefficient at relatively low Reynolds numbers, and a very gentle stall. The high camber may complicate fabrication, but the flat topped c_ℓ curve will justify the extra work.

5. SUMMARY

Optimum rotor design may be chosen from the "on-design" program based on minimum blade size or on minimum thrust. Alternately, performance may be used as the basis of optimization.

Designing the blade to operate at maximum c_ℓ produces minimum blade size and weight. Lift-drag ratio is of secondary importance. New airfoil sections, such as GA(W)-1, produce smaller blades than do such standard sections as Clark-Y. Blade section Reynolds numbers may vary from 1.8×10^4 to 1.8×10^6. In exercising the "off-design" performance program,


GA(W)-1 AIRFOIL SECTION
WICHITA STATE UNIVERSITY
2-D TEST
REYNOLDS NUMBER
○ 0.37 x 10^6
□ 0.51 x 10^6
△ 0.67 x 10^6
FIGURE 13
C1
2.0
1.5
1.0
.5
0
-.5
-1.0
0
40
80
120
160
200
240
280
320
360
α
degrees

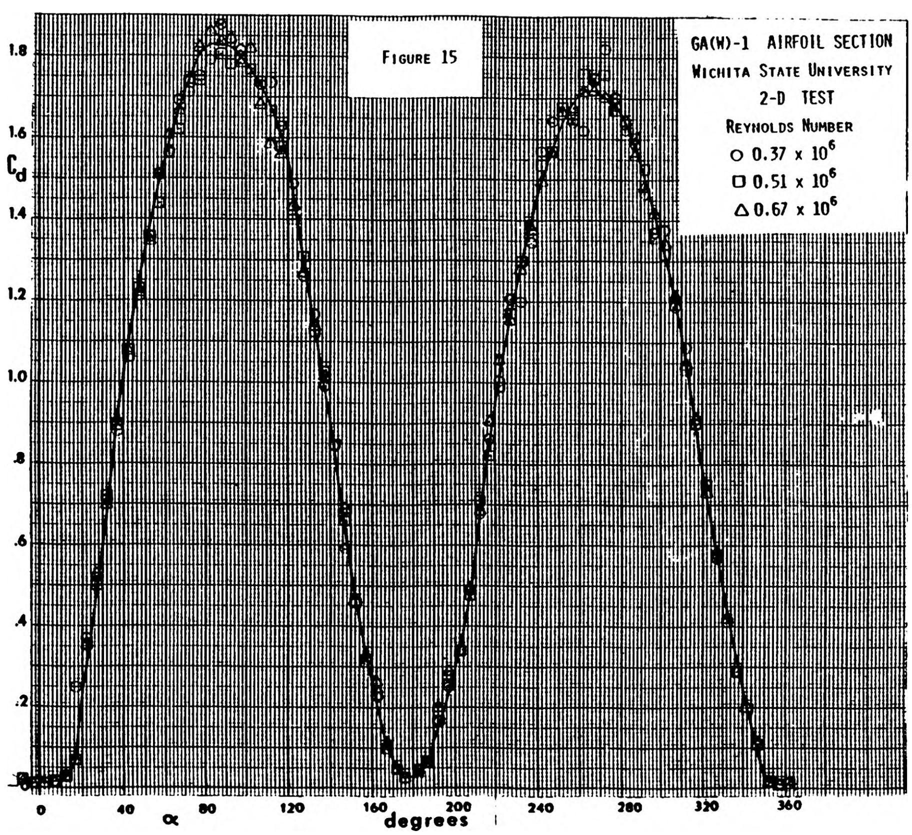
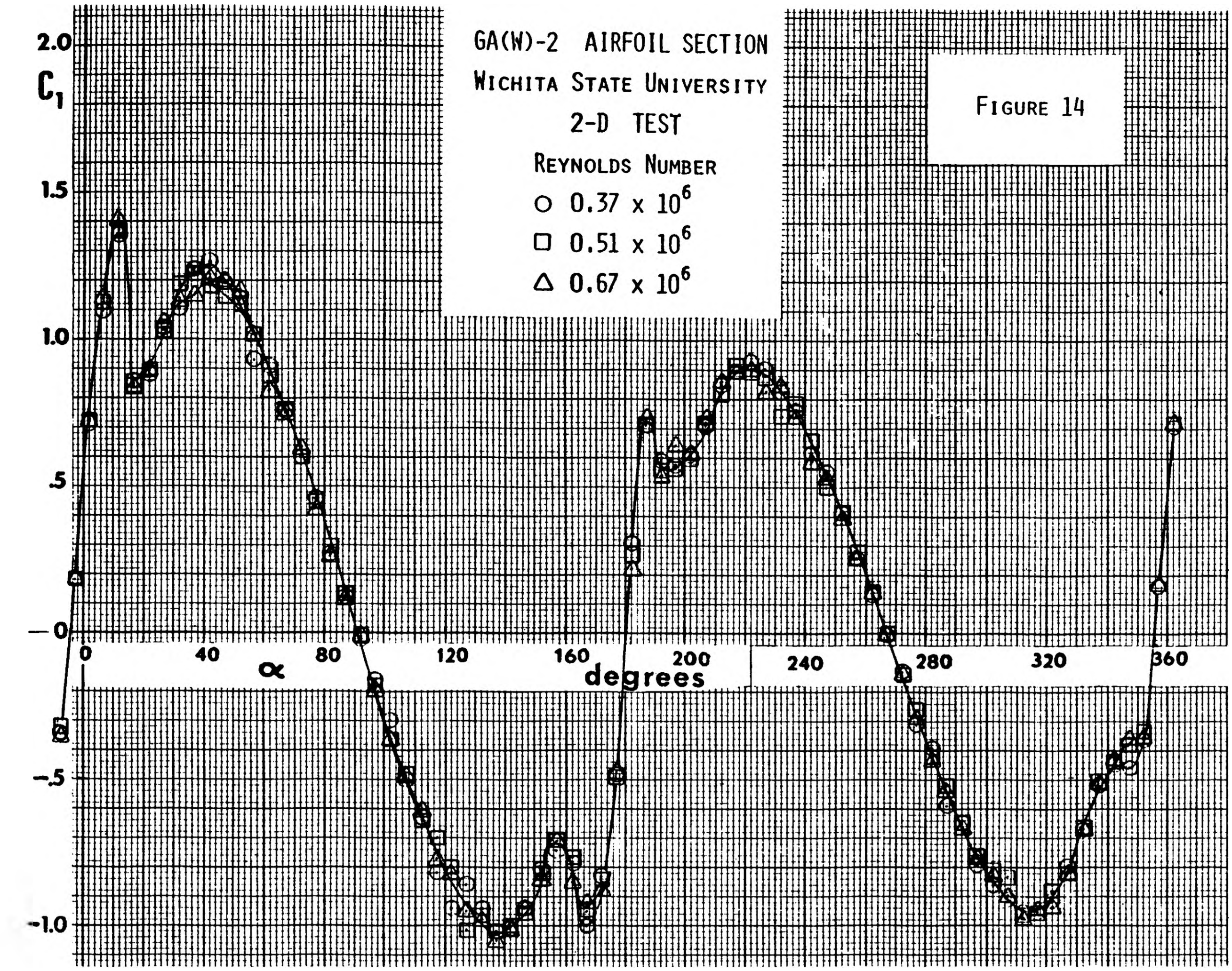
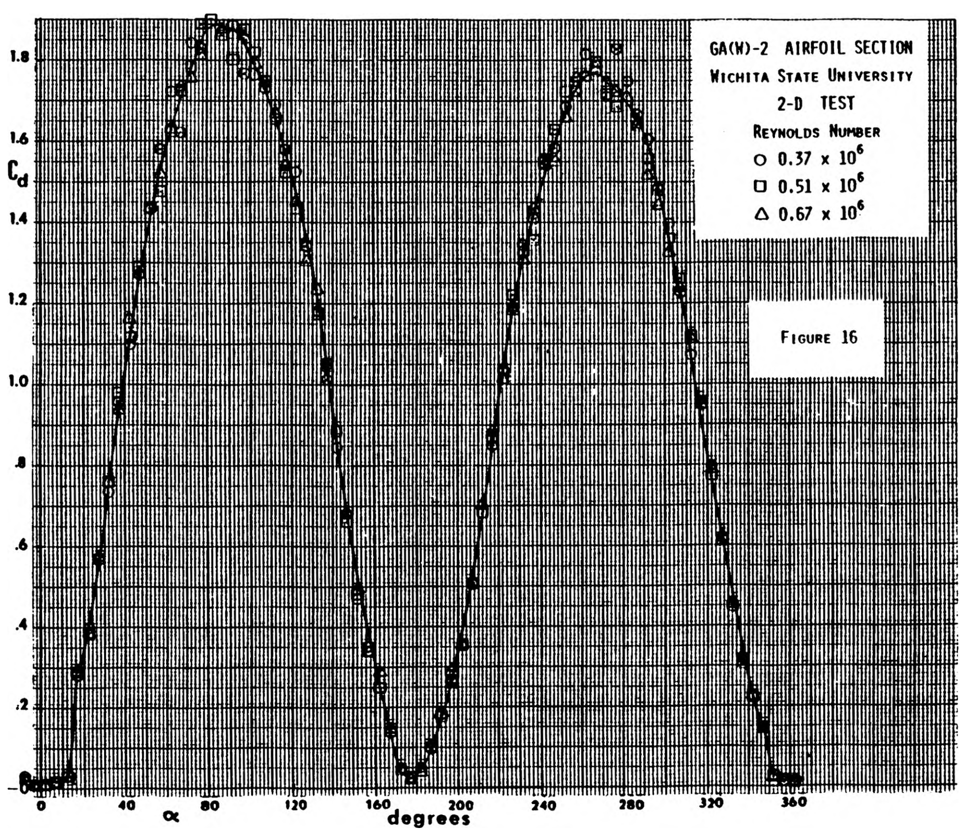


FIGURE 15
GA(W)-1 AIRFOIL SECTION
WICHITA STATE UNIVERSITY
2-D TEST
REYNOLDS NUMBER
○ 0.37 x 10^6
□ 0.51 x 10^6
△ 0.67 x 10^6
Cd
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
0
40
80
120
160
200
240
280
320
360
α
degrees


GA(W)-2 AIRFOIL SECTION
WICHITA STATE UNIVERSITY
2-D TEST
REYNOLDS NUMBER
○ 0.37 x 10^6
□ 0.51 x 10^6
△ 0.67 x 10^6
FIGURE 14
C_l
2.0
1.5
1.0
.5
0
-.5
-1.0
0
40
80
120
160
200
240
280
320
360
α
degrees


GA(W)-2 AIRFOIL SECTION
WICHITA STATE UNIVERSITY
2-D TEST
REYNOLDS NUMBER
○ 0.37 x 10^6
□ 0.51 x 10^6
△ 0.67 x 10^6
FIGURE 16
C_d
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
0
40
80
120
160
200
240
280
320
360
α
degrees

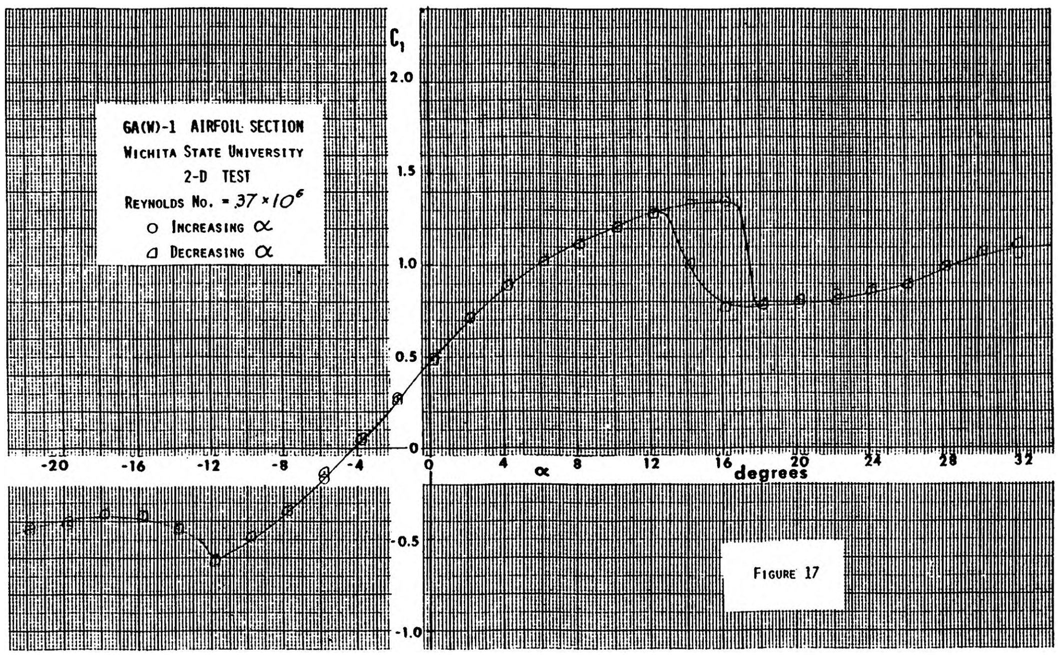


FIGURE 17

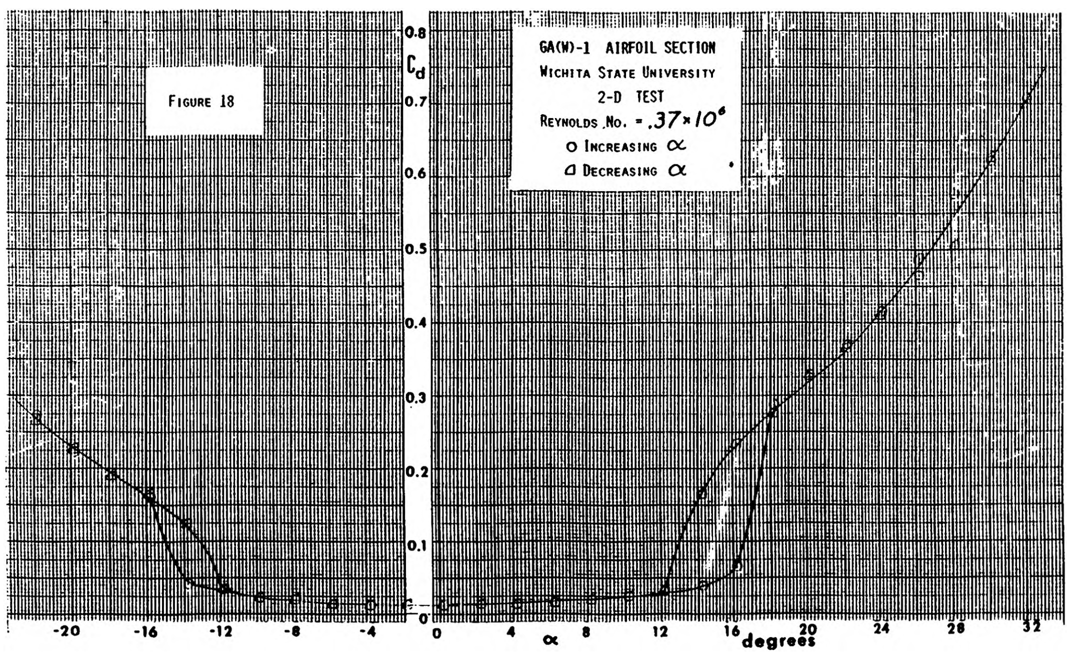


FIGURE 18

local α may be varied by more than ±90 degrees.

The following blade section data are important:

a. High maximum c_ℓ
b. Very flat top to c_ℓ curve
c. Good L/D at $c_{\ell_{max}}$
d. Characteristics for a wide range of α need to be known
e. Characteristics at low Reynolds numbers are needed

The NASA-sponsored general aviation airfoil design effort and sailplane airfoil design efforts are producing new sections which will be quite useful in wind turbine rotor design.

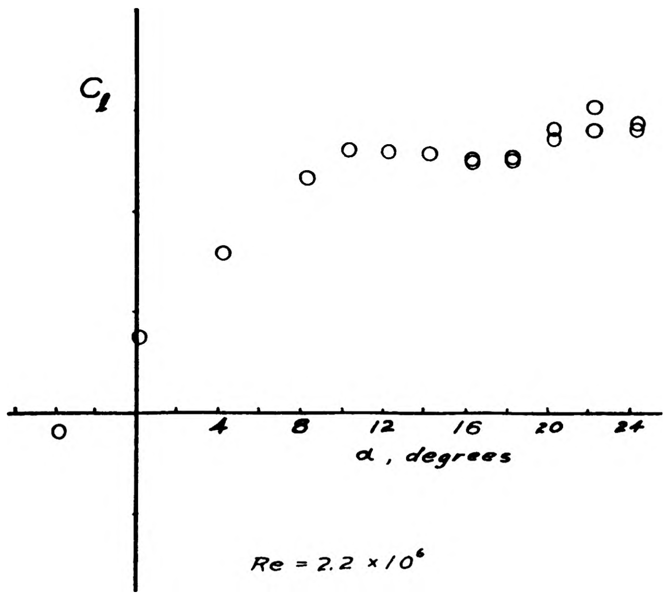


Figure 19. Lift Coefficient, General Aviation Airfoil.

6. REFERENCES

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3. Satran, Dale; and Snyder, M.H.: Two-Dimensional Tests of GA(W)-1 and GA(W)-2 Airfoils at Angles-of-Attack from 0 to 360 Degrees; WER-1, Wind Energy Laboratory, Wichita State University, Wichita, Kansas, Jan. 1977.

4. Dunn, C.H.; and Snyder, M.H.: A Prototype Wind Generator System Supplying Energy to the Electric Utility Grid; University of Missouri-Rolla Energy Conference, Rolla, MO, October 1975.