PRINCIPLES OF AERODYNAMICS

BY

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PREFACE

Principles of Aerodynamics is an outgrowth of six years' development of a set of printed lecture notes used by the author in undergraduate classes at the University of Washington. The purpose of the book is to present an introduction to some of the more important theoretical and practical aspects of aerodynamics.

In order to provide flexibility in teaching, many chapters have been designed as independent units. Thus, for instance, any of Chaps. 4, 7, 8, 9, 10, 12, and 15 may be omitted without destroying the continuity of the text.

While the assistance of all the scientists and engineers whose work has made this volume possible can scarcely be acknowledged separately, the author takes pleasure in thanking particularly the National Advisory Committee for Aeronautics, the Aeronautical Research Council, and the University of Washington Aeronautical Laboratories for permission to use some of the great wealth of material available in their reports. He wishes also to express his gratitude to his colleagues at the University of Washington and to Prof. F. S. Eastman, Prof. V. M. Ganzer, Prof. A. V. Hall, Dr. Alexander Klemin, and Prof. V. J. Martin for their helpful criticisms during the preparation of the manuscript.

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ABBREVIATIONS

AAL	Ames Aeronautical Laboratory, Moffett Field, Calif.
ACR	Advanced Confidential Report (of the NACA)
ARC	Aeronautical Research Council, England
ASME	American Society of Mechanical Engineers
CAA	Civil Aeronautics Administration, United States
DVL	Deutsche Versuchsanstalt für Luftfahrtforschung (German Institute for Aeronautical Research), Berlin and Göttingen, Germany
FRA	Fuselage reference axis
GALCIT	Guggenheim Aeronautical Laboratory, California Institute of Technology
JAS	Journal of the Aeronautical Sciences, United States
JRAS	Journal of the Royal Aeronautical Society, England
LDT	Two-Dimensional Low-Turbulence Pressure Tunnel (of the NACA)
LMAL	Langley Memorial Aeronautical Laboratory, Langley Field, Va.
LTT	Two-Dimensional Low-Turbulence Tunnel (of the NACA)
MIT	Massachusetts Institute of Technology
NACA	National Advisory Committee for Aeronautics, United States
NPL	National Physical Laboratory, Teddington, England
RAE	Royal Aeronautical Establishment, Farnborough, England
R&M	Reports and Memoranda (of the ARC). See the Bibliography for list of *R&M* used in this text.
SAE	Society of Automotive Engineers
TM	Technical Memorandum (of the NACA). See the Bibliography for list of *TM* used in this text.
TN	Technical Note (of the NACA). See the Bibliography for list of *TN* used in this text.
TR	Technical Report (of the NACA). See the Bibliography for list of *TR* used in this text.
UWAL	University of Washington Aeronautical Laboratories
VDT	Variable-Density Tunnel (of the NACA)
WR	Wartime Report (of the NACA). See the Bibliography for list of *WR* used in this text.

ENGLISH-LETTER NOMENCLATURE

a an area, sq ft or sq in.
speed of sound, fps or mph
slope of lift curve, $dC_L/d\alpha$, per deg (see m)
factor denoting fractional increase in velocity through propeller disk, $b/2$, dimensionless
equivalent flat-plate area, $D_p/1.28q$, sq ft
acceleration, fps per sec
area downswept by wing, $(\pi b^2/4) + bG$, sq ft

ac aerodynamic center, fraction of chord from leading edge

A cross-sectional area of stream tube, wind tunnel, jet, etc., sq ft
propeller disk area, $\pi D^2/4$, sq ft
aspect ratio, b^2/S, dimensionless

A_t tail aspect ratio, dimensionless

AF activity factor, $(100{,}000/16) \int_{0.2}^{1.0} (r/R)^3 (b/D)\, d(r/R)$, dimensionless

b factor denoting fractional increase in velocity behind propeller, $2a$, dimensionless
wing span, ft or in.
propeller blade width, ft or in.

bhp engine brake horsepower

B number of blades of propeller

c a constant
chord, ft or in.
specific fuel consumption, lb per bhp-hr (see w)

c_d section drag coefficient, D/qS, positive aft, dimensionless

c_l section lift coefficient, L/qS, positive up, dimensionless

c_m section pitching moment coefficient, M/qSc, positive for climbing moment, dimensionless

c_r wing-root chord, ft or in.

c_t wing-tip chord, ft or in.

cp center of pressure, positive aft of leading edge, fraction of chord

cg center of gravity, frequently expressed as fraction of chord from leading edge

C a constant
chordwise force, positive aft, lb

C degrees centigrade

C_D drag coefficient of wing or airplane, D/qS, positive aft, dimensionless
C_{D_i} induced drag coefficient, $C_L^2/\pi A$, dimensionless
C_{D_0} profile drag coefficient = wing drag coefficient for infinite aspect ratio, $C_D - C_{D_i}$, dimensionless
C_{D_p} parasite drag coefficient, $C_{D_0} + C_{D_r}$ or $C_D - C_{D_i}$, dimensionless
$C_{D_{p_e}}$ "effective" parasite drag coefficient at $C_L = 0$ for representative parabolic polar curve, dimensionless
C_{D_r} residual drag coefficient, $C_{D_p} - C_{D_0}$, dimensionless
C_{D_π} proper drag coefficient, dimensionless
C_F general force coefficient, F/qA, dimensionless
C_h rate of climb $(P_a - P_r)(33{,}000/W)$, fpm
C_H hinge moment coefficient, H/qSc, where Sc is based on surface aft of hinge line, positive when an applied aerodynamic torque on the hinge tends to increase the deflection of a positively deflected flap, dimensionless
C_l rolling moment coefficient, L/qSb, positive clockwise viewed from rear, dimensionless
C_L lift coefficient, L/qS, positive up, dimensionless
C_m pitching moment coefficient, M/qSc, positive for climbing moment, dimensionless
C_n yawing moment coefficient, N/qSb, positive clockwise viewed from above, dimensionless
C_N normal coefficient, N/qS, positive up, dimensionless
C_p pressure coefficient, $\Delta P/q$, dimensionless
C_{p_s} stagnation pressure coefficient, dimensionless
C_P power coefficient, $p/\rho n^3 D^5$, or $10^{11} P/2\sigma N^3 D^5$, dimensionless
C_s speed-power coefficient, $\rho v/\sqrt[5]{pn^2}$, or $0.638 V\sigma/\sqrt[5]{PN^2}$, dimensionless
C_T thrust coefficient, $T/\rho n^2 D^4$, or $10^7 T/6.61\sigma N^2 D^4$, dimensionless
C_Y side force coefficient, Y/Sq, positive right viewed from rear, dimensionless
d diameter, ft or in.
D diameter (propeller, sphere, cylinder, etc.), ft or in.
drag, $C_D Sq$, lb (see coefficient definitions above for subscript definitions)
e Oswald's airplane efficiency factor, $\dfrac{dC_{D_i}/dC_L^2}{dC_D/dC_L^2}$, dimensionless
Naperian logarithm base
e_w wing efficiency factor corresponding to e for an airplane, dimensionless
E modulus of elasticity (solid or fluid), psi or psf
endurance, hr

f	equivalent parasite area, D_p/q, sq ft (in performance equations, parasite drag is that at zero lift)
fhp	friction horsepower
F	degrees Fahrenheit
F	force, lb
	friction force, lb
	torque force, lb
F_η	tip-speed correction factor for propeller efficiency, dimensionless
FRA	fuselage reference axis
g	acceleration of gravity, 32.2 fps per sec
G	biplane gap, ft
	Froude Number, v^2/lg, dimensionless
h	height, ft or in.
	altitude, ft
H	absolute ceiling, ft
	total pressure, psf
	hinge moment, $C_H qSc$, lb-in. (see definition of C_H)
H_s	service ceiling, ft
i_w	wing incidence angle usually measured from fuselage reference axis, deg
i_s	stabilizer angle usually measured from either fuselage reference axis or wing chord, deg
ihp	indicated horsepower, bhp + fhp
J	propeller advance ratio, v/nD or $88V/ND$, dimensionless
k	constant
K	constant
	control-surface effectiveness factor, $(\partial\alpha/\partial\delta)_{C_N}$, dimensionless
l	length, ft or in.
l_t	tail length measured from airplane center of gravity to tail aerodynamic center, ft or in.
l_w	wing loading, W/S, psf
L	length, ft or in.
	lift, $C_L Sq$, positive up, lb
	rolling moment, $C_l qSb$, positive clockwise viewed from rear, lb-in.
m	mass, W/g, slug
	slope of lift curve, $dC_L/d\alpha$, per radian (see a)
M	mass flow of fluid, slug per sec
	Mach number, v/a, dimensionless
	pitching moment, $C_m qSc$, positive for climbing moment, lb-in.
M_{cr}	critical Mach number, dimensionless
n	revolutions per sec
	distance from leading edge, positive rearward, fraction of chord
N	revolutions per minute

N yawing moment, $C_n qSb$, positive clockwise when viewed from above, lb-in.
normal force $C_N qS$, positive up, lb
p power, ft-lb per sec
static pressure, psf
p_s stagnation pressure, psf
P engine bhp
P_a thrust horsepower available
P_{i_w} P_a or P_r adjusted for altitude and weight, hp
P_r airplane horsepower required
q dynamic pressure, $\frac{1}{2}\rho v^2$, or $V^2\sigma/391$, psf
Q torque, lb-ft
r radius, ft or in.
R radius, ft or in.
rolling moment, $C_l qSb$, positive clockwise viewed from rear, lb-in.
range, miles
resultant force, lb
test Reynolds number; also frequently used for effective Reynolds number R_e, $\rho vl/\mu$, dimensionless (l is arbitrary characteristic length that is chosen as chord for airfoil and diameter for cylinder, sphere, etc.)
resistance force during take-off, $F + D$, lb
R_e effective Reynolds number, simulating free air conditions, (R)(TF), dimensionless
s distance, ft or in.
distance along the surface of a body, commonly measured either from front stagnation point or from leading edge of chord, ft or in.
sg specific gravity, dimensionless
S wing area, sq ft
S_f wing area defined by flap span, sq ft
S_π proper area (maximum projected frontal area), sq ft
t thickness, ft, in., or fraction of chord
time, sec, min, or hr
temperature, °F (see T)
thp thrust horsepower, $Tv/550$ or $TV/375$
T thrust, $C_T\rho n^2D^4$ or $(6.61 \times 10^{-7})C_T\sigma N^2D^4$, lb
time, sec, min, or hr
minimum time to climb, min
temperature, $459.4 + t$, °F abs, (see t)
T_c thrust coefficient, $T/\rho v^2D^2$, dimensionless
TF turbulence factor, R_e/R, dimensionless
u velocity within boundary layer, fps

U velocity just outside boundary layer, fps
v velocity, fps
true air speed, fps (see V)
v_i indicated velocity, $v\sqrt{\sigma}$, fps
v_l landing velocity, fps
v_0 remote velocity, fps
v_s slip-stream velocity, $v(1 + b)$, fps
stalling speed, fps
v_t take-off velocity, fps
tangential velocity, fps
v_v sinking speed, fps
v_W wind speed, fps
V_{i_w} air speed adjusted for weight and altitude, mph
V velocity, mph (see v for subscript definitions)
true air speed, mph (see v)
volume, cu ft
specific volume, cu ft per lb
w density, lb per cu ft
down-wash velocity, fps
velocity introduced by circulation, fps
width, ft or in.
fuel consumption, lb fuel per hr per lb thrust (see c)
W weight, lb
width, ft or in.
W_a air flow, lb per sec
W_f fuel flow, lb per hr
x distance from aerodynamic center measured parallel to zero-lift chord, positive aft, dimensionless
horizontal distance, ft or in.
y distance perpendicular to surface for boundary-layer measurement, ft or in.
Y side force, C_YqS, positive right when viewed from rear, lb
z distance perpendicular to zero-lift chord, positive up, dimensionless

GREEK-LETTER NOMENCLATURE

alpha α	angle of attack measured between chord line and remote velocity, positive for trailing edge down, deg or radians
α_i	induced angle of attack, $C_L/\pi A$, radians, or $18.24 C_L/A$, deg
α_0	angle of attack for infinite aspect ratio, deg or radians
α_{l_0}	section angle of zero lift, deg or radians
α_{L_0}	angle of zero lift, deg or radians
beta β	propeller-blade angle between plane of rotation and chord line, deg (usually measured at three-quarter radius)
	deflection angle of streamlines in passing through a shock wave, deg
gamma γ	ratio of specific heats (1.4 for dry air), dimensionless
	angle between airfoil resultant and lift, deg
Gamma Γ	dihedral angle, positive for wing tips up, deg
	circulation, sq ft per sec
delta δ	control-surface deflection, positive deflection causes positive lift or side force, deg (subscript designates surface considered; *i.e.*, δ_e for elevator, δ_a for aileron, etc.)
	induced drag correction factor for taper and aspect ratio, dimensionless
	boundary-layer thickness defined where 99 per cent of local velocity is attained, ft or in.
Delta Δ	prefix meaning "increment;" *e.g.*, ΔP means "pressure increment"
epsilon ϵ	down-wash angle, deg or radians
	exchange coefficient in turbulent flow, slug per ft-sec
eta η	propeller efficiency, dimensionless
η_t	tail efficiency factor, proportional to the ratio of dynamic pressure at tail to the remote dynamic pressure, dimensionless
theta θ	an angle, deg or radians
	angle of pitch, positive for climbing moment, deg
	glide angle, deg
	climb angle, deg
	shock wave angle, deg
lambda λ	wing-taper ratio, tip chord/root chord, dimensionless
Lambda Λ	sweepback angle, deg

mu μ	coefficient of viscosity, $\frac{\tau_L}{dv/dy}$, slug per ft-sec
	coefficient of friction, dimensionless
	Mach angle, deg
nu ν	kinematic coefficient of viscosity, μ/ρ, sq ft per sec
	frequency, per sec
xi ξ	camber, fraction of chord, dimensionless
pi π	a constant, 3.14
rho ρ	mass density, w/g, slug per cu ft
sigma σ	ratio of any mass density to standard sea-level mass density of air, ρ/ρ_0, dimensionless
tau τ	shearing stress, subscripts L and T refer to laminar and turbulent, respectively, psf
	induced angle of attack correction for taper and aspect ratio, dimensionless
phi ϕ	propeller helix angle, $\beta - \alpha$, deg
	angle of roll, positive clockwise viewed from rear, deg
psi ψ	angle of yaw, positive clockwise viewed from above, deg

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CHAPTER 1

INTRODUCTION

Aerodynamics is a branch of fluid mechanics that deals with the particular fluid, air. The laws that govern fluid mechanics are fundamentally identical to those used in the usual mechanical studies, but they frequently appear in an unfamiliar or extended form, giving the impression of novelty. In this introductory chapter, some of the general laws of fluid mechanics will be discussed, with particular reference to applications in aerodynamics. It is thought advisable to generalize the discussion wherever possible, to prevent creating the impression that the relations are peculiar to aerodynamics.

1·1 Newton's Laws of Motion. From an engineering standpoint, the most important laws governing both solid and fluid mechanics are those encompassed by the laws[1] of Sir Isaac Newton:

1. Every body continues in a state of rest or uniform motion in a straight line unless acted upon by some external force.
2. An acceleration, which is proportional to the force, will be produced in the direction of the force.
3. Action and reaction are equal and opposite.

The meaning of the first and third laws is evident from physical experience. The implications contained in the second law are not apparent without study. According to the statement of the law,

$$F \propto a \tag{1·1}$$

where F is force

a is acceleration

There is no statement as to the size of the acceleration, but only that one will be produced if there is an unbalanced force on the body. In the form of an equality,

$$F = ma \tag{1·2}$$

where m is a constant called *mass*. Mass is a physical character-

[1] The laws are not stated exactly as originally proposed. They are reworded, without reservation, for simplicity of presentation.

istic of the body that may be regarded as a measure of its material content or "how much matter" it has. By this is meant that the mass of a body is constant if no molecules are added to or subtracted from the body, even though it may undergo changes in state. This definition does not describe all the properties of mass, but has an advantage of giving to it a degree of tangibility.

Mass may be considered from another viewpoint. Let a stationary body be suspended in a vacuum from an infinite string. If a horizontal force is applied for a short time and is then removed, the body attains a constant linear velocity in accordance with Newton's first law. If the force is applied continuously, the velocity increases linearly with time; hence the acceleration is constant. Now let the experiment be repeated on half the body (half the mass). With the same force, the resultant acceleration must be double, in accordance with Newton's second law. Therefore, mass may be regarded as a measure of the *inertia*, or "resistance to acceleration," of a body.

The character of mass has been described; its magnitude will next be discussed. One of the most elementary of algebraic processes is that involved in determining a constant of proportionality in an equation such as

$$x = ky \tag{1·3}$$

where x and y are variables and k is a constant. The procedure is to substitute any known value of x and its corresponding value of y. For instance, if $x = 6$ when $y = 3$, substitution shows that $k = 2$. This constant, once determined, is fixed for all values of x and y within the meaning of the equation. Similarly, Eq. (1·2) may be regarded as an equation involving two variables, F and a, and a constant, m. If *any* force and its corresponding acceleration are known for the body, the constant of proportionality, m, may be found in a manner similar to that described above. One such combination may be chosen if the body is allowed to fall freely in a vacuum, where the force is the weight and the acceleration is that due to gravity, thus

$$m = \frac{W}{g} \tag{1·4}$$

The *magnitude* of mass may be obtained from Eq. (1·4) by use of the standard acceleration of gravity, 32.2 fps per sec.

Mass is a scalar quantity, while weight is a vector quantity. The relation between them is seen to arise only from experimental convenience.

If W is the weight in pounds and g is the acceleration in feet per second per second, the dimensions of mass may be obtained from Eq. (1·4):

$$m \approx \frac{\text{lb-sec}^2}{\text{ft}} \tag{1·5}$$

This unwieldy combination of terms is combined to form the engineering unit of mass called a *slug;* hence,

1 lb force = (1 slug mass) (1 fps per sec acceleration)

Equation (1·2) may be written in several forms dependent upon convenience. For instance,

$$F = ma = m\frac{dv}{dt}$$
$$F\,dt = m\,dv \tag{1·6}$$

If F is independent of time and m is independent of velocity, integration of Eq. (1·6) gives

$$Ft = m(v_f - v_i) \tag{1·7}$$
$$= m\,\Delta v \tag{1·8}$$
$$= mv_f - mv_i \tag{1·9}$$
$$F = \frac{m}{t}(v_f - v_i) \tag{1·10}$$
$$F = M\,\Delta v \tag{1·11}$$

where F is force, lb
- m is mass, slug
- a is acceleration, fps per sec
- v is velocity, with subscript f indicating final and subscript i indicating initial, fps
- t is time, sec
- Ft is impulse, lb-sec
- mv is momentum, slug-ft per sec
- M is mass per unit time, slug per sec
- Δv is change in velocity, fps