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.

JAMES H. DWINNELL

SEATTLE, WASH. July, 1949

ABBREVIATIONS

AAL	Ames	Aeronautical	Laboratory,	Moffett	Field.	Calif.
			V)		- verget	CONTINO

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

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, Dp/1.28q, sq ft acceleration, fps per sec area downswept by wing, $(\pi b^2/4) + bG$, so ft

aerodynamic center, fraction of chord from leading edge

cross-sectional area of stream tube, wind tunnel, jet, etc., sq ft propeller disk area, $\pi D^2/4$, sq ft aspect ratio, b2/S, dimensionless

tail aspect ratio, dimensionless At

activity factor, (100,000/16) $\int_{0.2}^{1.5} (r/R)^3 (b/D) d(r/R)$, dimensionless AF factor denoting fractional increase in velocity behind propeller, 2a, dimensionless wing span, ft or in. propeller blade width, ft or in.

engine brake horsepower

bhp number of blades of propeller B

a constant chord, ft or in.

specific fuel consumption, lb per bhp-hr (see w)

section drag coefficient, D/qS, positive aft, dimensionless Ca section lift coefficient, L/qS, positive up, dimensionless Cz

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

wing-root chord, ft or in.

wing-tip chord, ft or in.

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

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

a constant

chordwise force, positive aft, lb

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, $C_D C_{D_U}$ dimensionless
- C_{D_p} parasite drag coefficient, $C_{D_0} + C_{D_r}$ or $C_D C_{D_U}$ dimensionless
- $C_{D_{p_e}}$ "effective" parasite drag coefficient at $C_L = 0$ for representative parabolic polar curve, dimensionless
 - C_{D_7} residual drag coefficient, $C_{D_p} C_{D_0}$, dimensionless
- CD, 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
 - C₁ 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/qSe, 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
- Cps stagnation pressure coefficient, dimensionless
- C_P power coefficient, p/on³D⁵, or 10¹¹P/2σN³D⁵, 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, $\frac{dC_{D4}/dC_L^2}{dC_D/dC_L^2}$, dimensionless Naperian logarithm base
- e. 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, 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, v²/lg, dimensionless

h height, ft or in.
altitude, ft

H absolute ceiling, ft total pressure, psf hinge moment, C_HqSc , lb-in. (see definition of C_H)

H. service ceiling, ft

iw wing incidence angle usually measured from fuselage reference axis, deg

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_i tail length measured from airplane center of gravity to tail aerodynamic center, ft or in.

lw wing loading, W/S, psf

L length, ft or in.

lift, CLSq, positive up, lb

rolling moment, CiqSb, 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_mqSc , positive for climbing moment, lb-in.

Mer 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_nqSb, positive clockwise when viewed from above, lb-in.

Les la velocial, tos

gal Lyderdie v elemen

normal force C_NqS, positive up, lb

p power, ft-lb per sec static pressure, psf

p_s stagnation pressure, psf

P engine bhp

Pa thrust horsepower available

 P_{i_w} P_a or P_r adjusted for altitude and weight, hp

Pr 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, $C_t qSb$, positive clockwise viewed from rear, lb-in. range, miles

resultant force, lb

test Reynolds number; also frequently used for effective Reynolds number R_* , $\rho v l/\mu$, 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_{\bullet} 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, wing area defined by flap span, sq ft

S_r 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, $C_T \rho n^2 D^4$ or $(6.61 \times 10^{-7}) C_T \sigma N^2 D^4$, lb time, sec, min, or hr minimum time to climb, min temperature, 459.4 + t, °F abs, (see t)

 T_c thrust coefficient, $T/\rho v^2 D^2$, dimensionless

TF turbulence factor, Re/R, dimensionless

u velocity within boundary layer, fps

velocity just outside boundary layer, fps

2 velocity, fps

velocity, fps true air speed, fps (see V)

Vi indicated velocity, $v \sqrt{\sigma}$, fps

22 landing velocity, fps

220 remote velocity. fps

slip-stream velocity, v(1+b), fps The Minimo town stalling speed, fps

take-off velocity, fps tangential velocity, fps sinking speed, fps

wind speed, fps e w

air speed adjusted for weight and altitude, mph

velocity, mph (see v for subscript definitions) true air speed, mph (see v)

volume, cu ft

specific volume, cu ft per lb

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)

weight, lb width, ft or in.

air flow, lb per sec

W, fuel flow, lb per hr

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.

side force, CyqS, positive right when viewed from rear, lb

distance perpendicular to zero-lift chord, positive up, dimensionless

GREEK-LETTER NOMENCLATURE

alpha a angle of attack measured between chord line and remote velocity, positive for trailing edge down, deg or radians

induced angle of attack, $C_L/\pi A$, radians, or $18.24C_L/A$, deg

α0 angle of attack for infinite aspect ratio, deg or radians

x10 section angle of zero lift, deg or radians

αLo angle of zero lift, deg or radians

beta \$\beta\$ 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 r dihedral angle, positive for wing tips up, deg circulation, sq ft per sec

delta 5 control-surface deflection, positive deflection causes positive lift or side force, deg (subscript designates surface considered; i.e., 5. for elevator, 5. 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 down-wash angle, deg or radians exchange coefficient in turbulent flow, slug per ft-sec

eta n / propeller efficiency, dimensionless

n, 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 \(\) wing-taper ratio, tip chord/root chord, dimensionless

Lambda A sweepback angle, deg

coefficient of viscosity, $\frac{\tau_L}{dr/du}$, slug per ft-sec mu u coefficient of friction, dimensionless Mach angle, deg

kinematic coefficient of viscosity, μ/ρ , sq ft per sec nu p frequency, per sec

camber, fraction of chord, dimensionless xi £

ρίπ a constant, 3.14

mass density, w/g, slug per cu ft rhop

ratio of any mass density to standard sea-level mass density sigma o of air, ρ/ρ_0 , dimensionless

shearing stress, subscripts L and T refer to laminar and turbulent, respectively, psf induced angle of attack correction for taper and aspect ratio, dimensionless

propeller helix angle, $\beta - \alpha$, deg angle of roll, positive clockwise viewed from rear, deg

psi & 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 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,

$$F \propto a$$
 (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,

$$F = ma ag{1.2}$$

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

$$\dot{x} = ky \tag{1.3}$$

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):

$$m \approx \frac{\text{lb-sec}^2}{\text{ft}}$$
 (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,

$$F = ma = m \frac{dv}{dt}$$

$$F dt = m dv$$
(1.6)

If F is independent of time and m is independent of velocity, integration of Eq. (1.6) gives

$$Ft = m(v_f - v_t) \tag{1.7}$$

$$= m \Delta v \tag{1.8}$$

$$= mv_f - mv_t {1.9}$$

$$F = \frac{m}{t} \left(v_f - v_i \right) \tag{1.10}$$

$$F = M \Delta v \tag{1.11}$$

where F is force, Ib

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