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AIRCRAFT DESIGN

Aircraft Design explores the conceptual phase of a fixed-wing aircraft design project. Designing an aircraft is a complex, multifaceted process that embraces many technical challenges in a multidisciplinary environment. By definition, the topic requires intelligent use of aerodynamic knowledge to configure aircraft geometry suited specifically to a customer's demands. It involves configuring aircraft shape, estimating its weight and drag, and computing the available thrust from the matched engine. The methodology includes formal sizing of the aircraft, engine matching, and substantiating performance to comply with a customer's demands and government regulatory standards. Associated topics include safety issues; environmental issues; material choice; structural layout; and understanding the flight deck, avionics, and systems (for both civil and military aircraft). Cost estimation and manufacturing considerations also are discussed. The chapters are arranged to optimize understanding of industrial approaches to aircraft-design methodology. Example exercises based on the author's industrial experience with typical aircraft design are included. Additional sections specific to military aircraft highlighted with an asterisk are available on the Web at www.cambridge.org/Kundu

Ajoy Kumar Kundu was educated in India (Jadavpur University), the United Kingdom (Cranfield University and Queen's University Belfast), and the United States (University of Michigan and Stanford University). His experience spans nearly thirty years in the aircraft industry and fifteen years in academia. In India, he was Professor at the Indian Institute of Technology, Kharagpur; and Chief Aircraft Designer at Hindustan Aeronautics Ltd., Bangalore. In North America, he was Research Engineer for the Boeing Aircraft Company, Renton, and Intermediate Engineer for Canadair Ltd., Montreal. He began his aeronautical career in the United Kingdom with Short Brothers and Harland Ltd., retiring from Bombardier Aerospace-Shorts, Belfast, as Chief Assistant Aerodynamicist. He is currently associated with Queen's University Belfast. He held British, Indian, and Canadian private pilot licenses. He is a Fellow of the Royal Aeronautical Society and the Institute of Mechanical Engineers and an Associate Fellow of the American Institute of Aeronautics and Astronautics.

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Symbols and Abbreviations

Symbols

A	area
A_1	intake highlight area
A_{th}	throat area
APR	augmented power rating
AR	aspect ratio
A_W	wetted area
a	speed of sound; acceleration
ā	average acceleration at 0.7 V_2
ac	aerodynamic center
B	breadth, width
b	span
C_R, C_B	root chord
C_D	drag coefficient
C_{Di}	induced drag coefficient
C_{Dp}	parasitic drag coefficient
C_{Dpmin}	minimum parasitic drag coefficient
C_{Dw}	wave drag coefficient
C_v	specific heat at constant volume
C_F	overall skin friction coefficient; force coefficient
C_f	local skin friction coefficient; coefficient of friction
C_L	lift coefficient
C_l	sectional lift coefficient; rolling moment coefficient
C_{Li}	integrated design lift coefficient
$C_{L\alpha}$	lift curve slope
$C_{L\beta}$	sideslip curve slope
C_m	pitching-moment coefficient
C_n	yawing-moment coefficient
C_p	pressure coefficient; power coefficient; specific heat at constant pressure
C_T	thrust coefficient
C_{HT}	horizontal tail volume coefficient

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C_{VT}	vertical tail volume coefficient
C_{xxxx}	cost, with subscript identifying parts assembly
C'_{xxxx}	cost, heading for the type
CC	combustion chamber
CG	center of gravity
c	chord
c_{root}	root chord
c_{tip}	tip chord
cp	center of pressure
D	drag; diameter
D_{skin}	skin friction drag
D_{press}	pressure drag
d	diameter
E	modulus of elasticity
e	Oswald's factor
F	force
f	flat-plate equivalent of drag; wing span
f_c	ratio of speed of sound (altitude to sea level)
F_{ca}	aft-fuselage closure angle
F_{cf}	front-fuselage closure angle
F_B	body axis
F_I	inertia axis
F_W	wind axis
F_{xxx}	component mass fraction; subscript identifies the item (see Section 8.8)
F/m_a	specific thrust
FR	fineness ratio
g	acceleration due to gravity
H	height
h	vertical distance; height
J	advance ratio
k	constant (sometimes with subscript for each application)
L	length; lift
L_{FB}	nacelle forebody length
L_{HT}	horizontal tail arm
L_N	nacelle length
L_{VT}	vertical tail arm
L	length
M	mass; moment
M_f	fuel mass
M_i	component group mass; subscript identifies the item (see Section 8.6)
M_{xxx}	component item mass; subscript identifies the item (see Section 8.6)
$\dot{m}_a$	airmass flow rate
$\dot{m}_f$	fuel mass flow rate

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$\dot{m}_p$	primary (hot) airmass flow rate (turbofan)
$\dot{m}_s$	secondary (cold) airmass flow rate (turbofan)
N	revolutions per minute; number of blades; normal force
N_e	number of engines
n	load factor
ng	load factor × acceleration due to gravity
P, p	static pressure; angular velocity about *X*-axis
p_e	exit plane static pressure
p_∞	atmospheric (ambient) pressure
P_t, p_t	total pressure
Q	heat energy of the system
q	dynamic head; heat energy per unit mass; angular velocity about *Y*-axis
R	gas constant; reaction
Re	Reynolds number
Re_{crit}	critical Reynolds number
r	radius; angular velocity about *X*-axis
S	area (usually with the subscript identifying the component)
S_H	horizontal tail reference area
S_n	maximum cross-sectional area
S_W	wing reference area
S_V	vertical tail reference area
sfc	specific fuel consumption
T	temperature; thrust; time
T_C	nondimensional thrust
T_F	nondimensional force (for torque)
T_{SLS}	sea-level static thrust at takeoff rating
T/W	thrust loading
t/c	thickness-to-chord ratio
tf	turbofan
U_g	vertical gust velocity
U_∞	freestream velocity
u	local velocity along *X*-axis
V	freestream velocity
V_A	aircraft stall speed at limit load
V_B	aircraft speed at upward gust
V_C	aircraft maximum design speed
V_D	aircraft maximum dive speed
V_S	aircraft stall speed
V_e	exit plane velocity (turbofan)
V_{ep}	primary (hot) exit plane velocity (turbofan)
V_{es}	secondary (cold) exit plane velocity (turbofan)
W	weight; width
W_A	useful work done on aircraft
W_E	mechanical work produced by engine
W/S_w	wing; loading

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X	distance along X-axis
y	distance along Y-axis
z	vertical distance

Greek Symbols

α	angle of attack
β	CG angle with vertical at main wheel; blade pitch angle; sideslip angle
Γ	dihedral angle; circulation
γ	ratio of specific heat; fuselage clearance angle
Δ	increment measure
δ	deflection
ε	downwash angle
η_t	thermal efficiency
η_p	propulsive efficiency
η_o	overall efficiency
θ	angle
Λ	wing sweep (subscript indicates the chord line)
λ	taper ratio
μ	friction coefficient; wing mass
Σ	summation
ρ	density
θ	fuselage upsweep angle
π	pi
σ	atmospheric density ratio
τ	thickness parameter
ω	angular velocity

Subscripts

(In many cases, subscripts are spelled out and are not listed here.)

a	aft
ave	average
ep	primary exit plane
es	secondary exit plane
f	front; fuselage
f_b	blockage factor for drag
f_h	drag factor for nacelle profile drag (propeller-driven)
fus	fuselage
HT	horizontal tail
M	middle
N, nac	nacelle
o	freestream condition
p	primary (hot) flow
s	stall; secondary (cold) flow
t, tot	total

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w	wing
VT	vertical tail
∞	freestream condition

Abbreviations

AB	afterburning
ACAS	advanced close air support
ACN	aircraft classification number
ACT	active control technology
AEA	Association of European Airlines
AEW	airborne early warning
AF	activity factor
AGARD	Advisory Group for Aerospace Research and Department
AGS	aircraft general supply
AIAA	American Institute for Aeronautics and Astronautics
AIP	Aeronautical Information Publication
AJT	advanced jet trainer
AMPR	Aeronautical Manufacturer's Planning Report
APR	augmented power rating
APU	auxiliary power unit
AST	Air Staff Target
ATA	Aircraft Transport Association
ATC	air traffic control
ATF	advanced tactical support
AVGAS	aviation gasoline (petrol)
AVTUR	aviation turbine fuel
BAS	Bombardier Aerospace–Shorts
BFL	balanced field length
BOM	bill of material
BPR	bypass ratio
BRM	brake release mass
BVR	beyond visual range
BWB	blended wing body
CAA	Civil Aviation Authority
CAD	computer-aided design
CAE	computer-aided engineering
CAM	computer-aided manufacture
CAPP	computer-aided process planning
CAS	close air support; control augmentation system; calibrated air speed
CAT	clear air turbulence
CBR	California bearing ratio
CCV	control configured vehicle
CFD	computational fluid dynamics
CFL	critical field length

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CG	center of gravity
CRT	cathode ray tube
CV	control volume
DBT	design-build team
DCPR	Design Controller's Planning Report
DES	detached eddy simulation
DFFS	Design for Six Sigma
DFM/A	design for manufacture and assembly
DNS	direct numerical simulation
DOC	direct operating cost
DTLCC	design to life cycle cost
EAS	equivalent air speed
EASA	European Aviation Safety Agency
EBU	engine-build unit
ECS	environment control system
EDP	engine-driven pump
EFIS	electronic flight information system
EGT	exhaust gas temperature
EI	emission index
EPA	U.S. Environmental Protection Agency
EPNL	effective perceived noise level
EPR	exhaust–pressure ratio
ESDU	Engineering Sciences Data Unit
ESHP	equivalent SHP
ESWL	equivalent single wheel load
ETOPS	extended twin operations
EW	electronic warfare
FAA	Federal Aviation Administration
FADEC	full authority digital electronic control
FAR	Federal Aviation Regulations (U.S.)
FBW	fly-by-wire
FEM	finite element method
FPS	foot, pound, second
FS	factor of safety
GAW	Global Atmosphere Watch
HAL	Hindustan Aeronautics Ltd.
HMD	helmet-mounted display
HOTAS	hands-on throttle and stick
HP	horse power; high pressure
HSC	high-speed cruise
HST	hypersonic transport
H-tail	horizontal tail
HUD	head-up display
IAS	indicated air speed
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IIT	Indian Institute of Technology

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IMC	instrument meteorological conditions
INCOSE	International Council of Systems Engineering
IOC	indirect operational cost
IPPD	Integrated Product and Process Development
ISA	International Standard Atmosphere
ISRO	Indian Space Research Organization
JAA	Joint Aviation Authority
JAR	Joint Airworthiness Regulation
JPT	jet pipe temperature
JUCAS	Joint Unmanned Combat Air System
KE	kinetic energy
KEAS	knots equivalent air speed
km	kilometer
LA	light aircraft
LAM	lean and agile manufacturing
LCA	light combat aircraft
LCC	life cycle cost
LCD	liquid crystal display
LCG	load classification group
LCN	load classification number
LCR	lip contraction ratio
LD, L/D	lift-to-drag (ratio)
LE	leading edge
LES	large eddy simulation
LF	load factor
LFL	landing field length
LOH	liquid hydrogen
LP	low pressure
LPO	long-period oscillation
LRC	long-range cruise
LRU	line replacement unit
MAC	mean aerodynamic chord
MDA	multidisciplinary analysis
MDO	multidisciplinary optimization
MEM (W)	manufacturer's empty mass (weight)
MFD	multifunctional display
MFR	mass flow rate
MoD	Ministry of Defense
MOGAS	motor gasoline (petrol)
MP	minor parts
mph	miles per hour
MPM	manufacturing process management
MRM	maximum ramp mass
m/s	meters per second
MTM	maximum taxi mass
MTOM (W)	maximum take off mass (weight)
NACA	National Advisory Committee for Aeronautics

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NASA	National Aeronautics and Space Administration
NBAA	National Business Aircraft Association
NC	numerically controlled
NHA	negative high angle of attack
NIA	negative intermediate angle of attack
NLA	negative low angle of attack
nm	nautical miles
NP	neutral point
NRC	non-recurring cost
NTC	normal training configuration
OC	operational cost
OEM (W)	operator's empty mass (weight)
OEMF	operational empty mass fraction
OEWF	operational empty weight fraction
PAX	passenger
PCN	pavement classification number
PCU	power control unit
PE	potential energy
PFD	primary flight display
PHA	positive high angle of attack
PIA	positive intermediate angle of attack
PLA	positive low angle of attack
PLM	product life cycle management
PNdB	perceived noise decibel
PNL	perceived noise level
PPR	product, process, and resource
PRSOV	pressure-reducing shutoff valve
psfc	power-specific fuel consumption
psi	pounds per square inch
PTU	power transfer unit
QFD	quality function deployment
QUB	The Queen's University Belfast
RAE	Royal Aircraft Establishment
RAeS	Royal Aeronautical Society
RANS	Reynolds Average Navier–Stokes
RAT	ram air turbine
RC	rate of climb, recurring cost
RCS	radar cross-section signature
RD&D	research, design, and development
RDDMC	research, design, development, manufacture, and cost
RDD&T	research, design, development, and test
RFP	Request for Proposal
RJ	regional jet
R&M	reliability and maintainability
rpm	revolutions per minute; revenue passenger mile
rps	revolutions per second
RPV	remotely piloted vehicle

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SAS	stability augmentation system
SATS	Small Aircraft Transportation System
SAWE	Society of Allied Weights Engineers
SEP	specific excess power
sfc	specific fuel consumption
SHP	shaft horsepower
SI	system international
SOV	shutoff valve
SPL	sound pressure level
SPO	short-period oscillation
SST	supersonic transport
STOL	short takeoff and landing
STR	structures
TAF	total activity factor
TAS	true air speed
TBO	time between overhauls
t/c	thickness to chord
TET	turbine entry temperature
TGT	turbine guide vane temperature
TOC	total operating cost
TOFL	takeoff field length
TP	thrust power
TQM	Total Quality Management
TR	thrust reverser
TTOM	typical takeoff mass (military)
T&E	training and evaluation
UAV	unmanned air vehicle
UCA	unmanned combat aircraft
UHBPR	ultra-high BPR
UHC	unburned hydrocarbons
ULD	unit load device
USDOT	U.S. Department of Transportation
VOC	voice-operated control
VPI	Virginia Polytechnic Institute
V-tail	vertical tail
VTOL	vertical takeoff and landing
ZFM (W)	zero fuel mass (weight)

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Preface

This book is about the conceptual phase of a fixed-winged aircraft design project. It is primarily concerned with commercial aircraft design, although it does not ignore military aircraft design considerations. The level of sophistication of the latter is such that were I to discuss advanced military aircraft design, I would quickly deviate from the objective of this book, which is for introductory but extensive coursework and which provides a text for those in the industry who wish to broaden their knowledge. The practicing aircraft design engineer also will find the book helpful. However, this book is primarily meant for intensive undergraduate and introductory postgraduate coursework.

A hundred years after the first controlled flight of a manned, heavier-than-air vehicle, we can look back with admiration at the phenomenal progress that has been made in aerospace science and technology. In terms of hardware, it is second to none; furthermore, integration with software has made possible almost anything imaginable. Orville and Wilbur Wright and their contemporaries would certainly be proud of their progenies. Hidden in every mind is the excitement of participating in such feats, whether as operator (pilot) or creator (designer): I have enjoyed both no less than the Wright brothers.

The advancement of aerospace science and technology has contributed most powerfully to the shaping of society, regardless to which part of the world one refers. Sadly, of course, World War II was a catalyst for much of what has been achieved in the past six decades. My career spans the 1960s to the beginning of the twenty-first century, possibly the "golden age" of aeronautics! In that period, investment in the aerospace sector by both government and private organizations led to rapid changes in the acquisition, application, and management of resources. Aerospace design and manufacturing practices were transformed into their present manifestation.

The continuous changes in aircraft design and manufacturing procedures and methodologies have resulted in leaner aerospace infrastructure (sometimes to an "anorexic" level). New graduate-level engineers are expected to contribute to the system almost immediately, with minimal supervision, and to "do it right the first time." The route to the design office through apprentice training is not open to as many as it once was. Life is now more stressful for both employers and employees than it was the day I started my career: Organizational survivability and consequent loyalty are not what they used to be. The singular aim of this book is to

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