Fundamentals of

AIRCRAFT DESIGN

FUNDAMENTALS OF AIRCRAFT DESIGN

Leland M. Nicolai
Aerospace Engineering
University of Dayton
Dayton, Ohio

Book distributed by the School of Engineering, University of Dayton, Dayton, Ohio 45469

Printed in the United States of America
E.P. Domicone Printing Services • Fairborn, Ohio

AUTHOR'S PREFACE

This text is aimed at upper level undergraduate and graduate students, and practicing engineers. It has a comprehensive treatment of the conceptual design phase, treating civil and military aircraft equally. The book covers the entire phase of conceptual design from consideration of the mission needs to the decision to iterate the design "One More Time". The book is complete in that the reader should not have to go outside the text for additional information.

The text is structured to lead the reader through one iteration of the conceptual design cycle loop. It can also be used as a convenient reference book for practicing engineers to give them up-to-date methodology in aerodynamics, performance, propulsion systems, material selection, weights, stability and control and life cycle costing. It can also be used by technical managers to better understand and appreciate the fundamental parameters driving the design of an aircraft and their interplay.

The main theme of the text is that the aircraft design process is a compromise of all the engineering disciplines. An effective design is the integration of aerodynamics, propulsion, flight control, structures and materials, avionics and subsystems; blended in just the right way to give a synergistic effect. The text emphasizes this theme throughout its 25 chapters.

The book emphasizes the responsibility of the aircraft designer to design for low cost, low fuel consumption and low environmental pollution, i.e., "Design for Mankind". Guidelines are presented for designing for low life cycle cost and fuel consumption. Chapter 24 discusses life cycle cost and presents a methodology for estimating these costs.

The chapter on material selection discusses the typical metal systems and the new promising advanced composite material system and low fabrication cost materials, such as fiberglass, ABS plastic and wood. The weight estimate chapter is complete, giving methodology for estimating the component weights for high and low performance aircraft fabricated out of metals and advanced composites.

Many people have influenced the writing of this text. My many students who struggled through early sets of notes and versions of this text were most helpful in their critique. Fellow faculty members were invaluable in their suggestions and encouragement, especially Dr. Jay Pinson of the University of Dayton. Major Thomas Pilsch of the USAF Academy was a colleague in much of the preparation of the text and contributed Chapter 18 and part of Chapter 10. The aircraft industry was very generous in providing ideas, aircraft information and pictures, especially Mr. Bud Nelson of Boeing Aerospace Company, Seattle, Washington.

My sincerest appreciation goes to my family; my wife Carolyn, son Jeff and daughter Debra. Their encouragement, understanding and providing the proper home environment made the book possible. I dedicate this book to them.

Leland M. Nicolai

Dayton, Ohio
June 1975

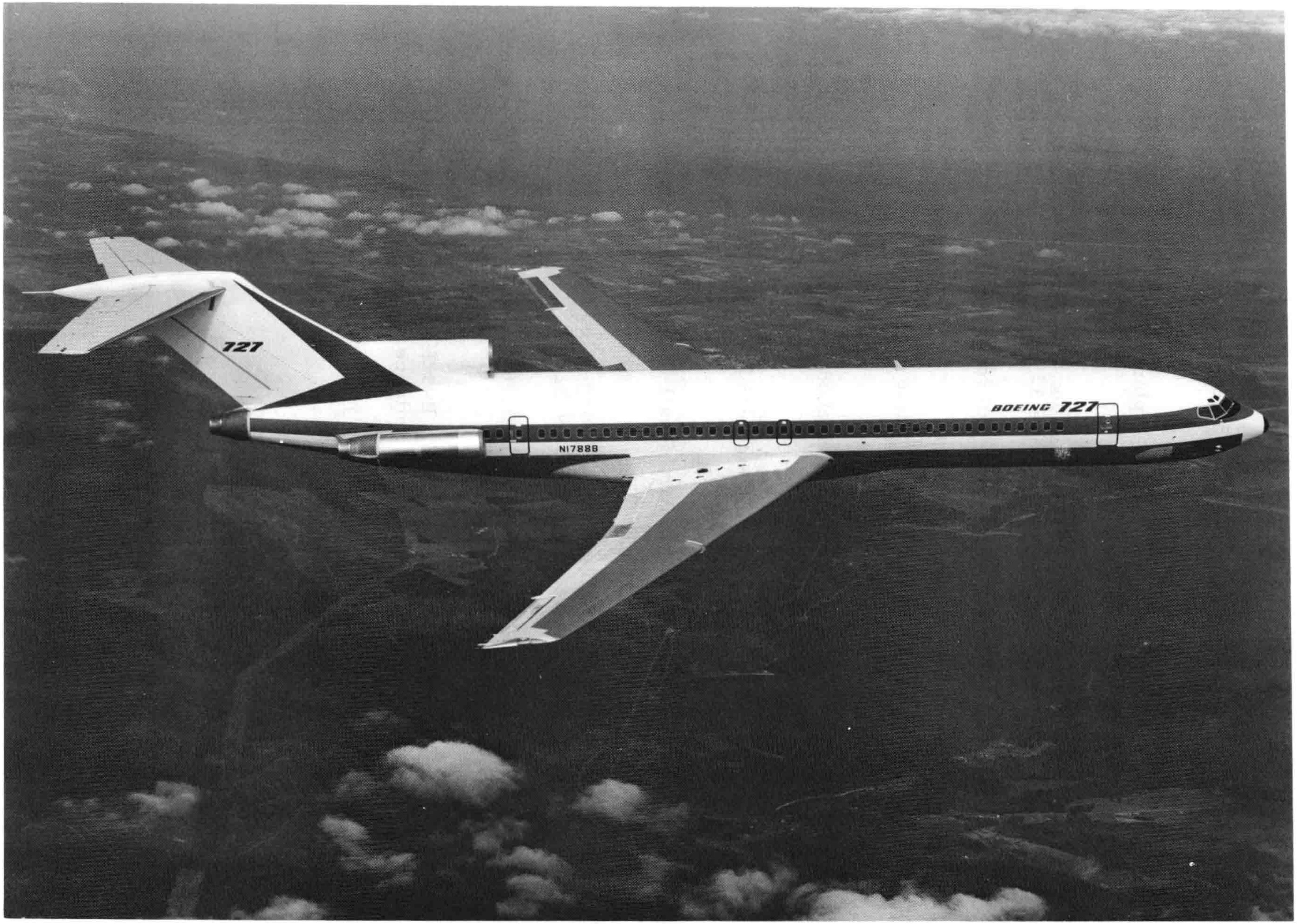

Plate I. Boeing 727 Medium Haul Subsonic Jetliner

TABLE OF CONTENTS

Chapter

1	Introduction
2	Review of Aerodynamics
3	Aircraft Performance Methods
4	Aircraft Operating Envelope
5	Preliminary Estimate of Take-Off Weight
6	Estimating the Take-Off Wing Loading
7	Selecting the Planform and Airfoil Section
8	Preliminary Fuselage Sizing and Design
9	High Lift Devices
10	Take-Off and Landing Analysis
11	Estimating Wing-Body Aerodynamics
12	Preliminary Sizing of the Vertical and Horizontal Tails
13	Transonic and Supersonic Wing-Body Drag (Area Ruling)
14	Turbine Engine Fundamentals
15	Turbine Engine Sizing
16	Turbine Engine Inlet Design
17	Corrections to Propulsion System Data
18	Propeller Propulsion Systems
19	Material Selection
20	Refined Weight Estimate
21	Static Stability and Control
22	Trim Drags and Maneuvering Flight
23	Control Surface Sizing Criteria
24	Design for Mankind
25	One More Time

Appendix

A	Characteristics of the Standard Atmosphere
B	One-Dimensional Isentropic Compressible Flow Functions for a Perfect Gas with Constant Specific Heat and Molecular Weight, $\gamma = 1.4$
C	One-Dimensional Normal Shock Functions for a Perfect Gas with Constant Specific Heat and Molecular Weight, $\gamma = 1.4$
D	Plane Oblique and Conical Shocks for a Perfect Gas with Constant Heat and Molecular Wright, $\gamma = 1.4$
E	Useful Design Charts and Tables
F	Aerodynamics of Low Aspect Ratio Wing-Body Combinations
G	NACA Airfoil Nomenclature and Characteristics

LIST OF TABLES

Table		Page
1.1	Characteristics of the USAF T-39	1-7
1.2	Documents in the DOD Specification and Standards System	1-8
1.3	Partial Listing of Military Specifications and Standards for Aircraft Design	1-9
1.4	The Three Phases of Levels of Aircraft Design	1-11
2.1	Section Parameters for Wave Drag	2-27
3.1	Composite Lightweight Fighter Aerodynamic Data for Figure 3.7	3-12
4.1	Inlet Static Pressures for Different Dynamic Pressure Condition	4-5
4.2	Properties of Metals at Room Temperature	4-7
5.1	Information on 747 and C-5 Aircraft	5-23
6.1	Take-off Wing Loading Trends	6-2
8.1	Avionics Equipment	8-3
8.2	Statistical Methods for Estimating Avionics System Weights and Volumes	8-4
9.1	Summary Chart of Maximum Lift Coefficient Obtained with Various Types of High Lift Devices	9-7
9.2	Typical High Lift Device Data	9-8
10.1	Summary of CTOL Take-Off Rules	10-2
10.2	Summary of CTOL Landing Rules	10-2
10.3	Coefficient of Friction Values	10-7
11.1	Roughness Height Values	11-14
11.2	Values for t/c	11-16
12.1	Values of C_{VT} for Fighter Aircraft	12-2
12.2	Values of C_{HT} (Aft Tailplane) for Fighter Aircraft	12-3
12.3	Values of C_c for Canard Aircraft	12-4
14.1	Gas Turbine Engines	14-6
14.2	Pratt and Whitney F-100-PW-100 Afterburning Turbofan Characteristics	14-12

Table		Page
14.3	General Electric TF-39-GE-1 Turbofan	14-21
15.1	Take-Off T/W Trends	15-2
16.1	Total Pressure Recovery Data for Inlet of Figure 16.14	16-13
16.2	Typical Secondary Airflows	16-21
16.3	Demand Capture Area for PW-F100	16-27
17.1	Incremental Afterbody Drag	17-19
19.1	Properties of Some Typical Material Systems	19-8
19.2	Composition of Aluminum Alloys	19-9
19.3	Relative Ranging of Candidate Material Systems	19-19
19.4	Materials Applicability for Specific Mission Requirements	19-20
19.5	Structural Materials as Percent of Structural Weight	19-21
23.1	Typical Aircraft Stability and Control Data	23-3
23.2	MIL-F-8785B Roll Performance Requirements	23-13
24.1	Crew Ratio for LCC Planning	24-20
24.2	LCC Planning Data	24-21
24.3	Aviation Fuel Costs Per Gallon	24-28
24.4	Properties of Some Candidate Fuels	24-32
24.5	Comparison of JP4 and H_2 Fueled Designs	24-33
24.6	Influence of Hydrogen Fuel on Aircraft Design	24-33
B.1	One-Dimensional Isentropic Compressible-Flow Functions, for a Perfect Gas with Constant Specific Heat and Molecular Weight, $\gamma = 1.4$ Molecular Weight = 28.97	B-2
C.1	One-Dimensional Normal Shock Functions, for a Perfect Gas with Constant Specific Heat and Molecular Weight, $\gamma = 1.4$	C-2
E.1	Fighter Aircraft	E-8
E.2	Long Range Transport Aircraft	E-9
E.3	Short and Intermediate Range Transport Aircraft	E-10
E.4	Light Utility Aircraft	E-11
G.1	Low Speed Data on Airfoil Sections $R_e = 9 \times 10^6$	G-3

LIST OF SYMBOLS

English Symbols

A	Aspect ratio, b^2/S
A	AMPR weight for cost estimating
A_c	Inlet capture area
A_e	Exit area
A_T	Throat area
A^*	Area at station where Mach number is one
A_∞	Free-Stream capture area
AF	Propeller blade activity factor
AR	Aspect ratio
a	Speed of sound, $\sqrt{\gamma R \theta}$
B	Propeller tip loss factor
B	Factor for sharp-nosed airfoils
BP	Bypass conditions
b	Wing span
C	Chord force
C	Thrust specific fuel consumption
$\overline{C}$	Mean aerodynamic chord or average chord
C_B	Bleed correction factor
C_c	Chord force coefficient
C_c	Canard volume coefficient
C_D	Three dimensional drag coefficient, $D/q\ S_{Ref}$
C_{D_A}	Additive drag coefficient
$C_{D_{Add}}$	Theoretical additive drag coefficient
C_{D_B}	Base pressure coefficient
C_{D_F}, C_{D_f}	Skin friction drag coefficient
$C_{D_{L_i}}$	Wing drag due-to-lift coefficient due to finite span
$C_{D_{LS}}$	Cowl lip suction term

$C_{D_{L_V}}$	Wing drag-due-to-life coefficient due to viscous separation
C_{D_o}	Three-dimensional zero lift drag coefficient
$C_{DP_{min}}$	Pressure drag due to viscous separation
C_d	Section drag coefficient, $D/q\overline{C}$
C_{d_o}	Section zero lift drag coefficient
c_{d_w}	Section wave drag coefficient
C_F, C_f	Skin friction coefficient
C_{HT}	Horizontal tail volume coefficient
C_j	Jet coefficient
C_L	Three dimensional lift coefficient, L/qS_{Ref}
C_{L_B}	Break C_L
C_{L_G}	Ground run C_L (in ground effect)
$C_{L_{Max}}$	Maximum lift coefficient
$C_{L_{Min}}$	C_L at minimum drag
$C_{L_{opt}}$	Optimum C_L, C_L for maximum L/D or minimum drag
C_{L_α}	Lift curve slope, $dC_L/d\alpha$
C_ℓ	Section lift coefficient, $L/q\overline{C}$
C_{ℓ_P}	Damping in roll coefficient, $dC_\ell/d(Pb/2V)$
C_{ℓ_β}	Static lateral stability derivative, $dC_\ell/d\beta$
$C_{\ell_{\delta_a}}$	Aileron control power derivative, dC_ℓ, $d\delta a$
C_M	Three dimensional moment coefficient, $M_A/qS_{Ref}\overline{C}$
C_{M_o}	Moment coefficient at zero angle-of-attack
C_{M_α}	Static longitudinal stability derivative, $dC_M/d\alpha$
$C_{M_{\alpha_c}}$	Canard control power, $dC_M/d\alpha_c$
C_{M_δ}	Horizontal tail power, $dC_M/d\delta_e$
C_m	Section moment coefficient, $M_A/q\overline{C}^2$
C_{m_q}	Damping in pitch derivative, $dC_M/d(q\overline{C}/2V)$

C_N	Normal force coefficient
C_{N_α}	Normal force curve slope
C_{n_β}	Directional stability derivative, dC_n/d_β
$C_{n_{\delta_r}}$	Rudder control power, $dC_n/d\delta_r$
C_P	Propeller power coefficient
C_p	Pressure coefficient, $(P - P_\infty)/q$
C_{p_B}	Base pressure coefficient
C_T	Thrust coefficient
C_{VT}	Vertical tail volume coefficient
C_1	Non-linear lift factor
C_2	Non-linear moment factor
C_μ	Blowing coefficient
D	Drag
d	Diameter
d_e	Exit diameter
E	Endurance
e	Wing planform efficiency factor
F	Wing-body lift interference factor
g	Acceleration of gravity
H_T	Throat height
h	Altitude
h_e	Specific energy
I_{sp}	Specific impulse
I_{xx}, I_{yy}, I_{zz}, I_{xy}	Moments of inertia
i_T	Thrust vector angle
J	Advance ratio
K	Wing drag-due-to-lift factor for uncambered wing
K'	Wing drag-due-to-lift factor due to finite span
K''	Wing drag-due-to-lift factor due to viscous separation

K_{Add}	Additive drag correction factor
K_B	Break drag-due-to-lift factor
K_D	Flow distortion parameter
k''	Section separation drag-due-to-lift factor
L	Lift
L_D	Diffuser length
ℓ	Length
M	Mach number
M_A	Moment about point A
M_{CR}	Critical Mach number
M_D	Divergence Mach number
M_N	Normal Mach number
M_S	Mach number on surface
m	Mass
m	Three-dimensional lift curve slope
$\dot{m}$	Mass flow rate
m_o	Section lift curve slope
N	Normal force
N	Moment about vertical axis (see Figure 20.2)
n	Load factor, L/W
n	Exponent for engine scaling
P	Static pressure
P	Roll rate
P_B	Base pressure
P_i	Induced power
P_R	Power required
P_S	Excess specific power
Q	$Q_D + Q_P$
Q_D	Number of flight test aircraft
Q_P	Number of production aircraft
q	Dynamic pressure, $\frac{1}{2}\rho V_\infty^2$

$\dot{q}$	Heating rate
R	Range
R'	Characteristic gas constant
R	Lifting surface correlation factor
R_e	Reynolds number
R_o	Nose radius
r_{LE}	Radius of leading edge
S	Maximum speed at best altitude (for cost estimating)
S_A	Air distance during landing
S_B	Base area
S_B	Braking distance
S_c	Canard area
S_e	Exposed planform area
S_G	Ground distance
S_{Ref}	Reference area for aerodynamic derivatives, usually total planform area
S_T	Horizontal tail area
S_W	Total planform area of wing
SM	Static margin
s	Distance between twin nozzle centerlines
T	Thrust
T_A	Available thrust
T_R	Required thrust
t	Time
t	Thickness
V	Velocity
$\overline{V}$	Tail volume coefficient
$\overline{V}_c$	Canard volume coefficient
V_{FR}	Engine failure recognition speed
V_R	Rotation speed
V_{stall}	Stall speed

V_{TD}	Speed at touchdown during landing
V_{TO}	Take-off or lift off speed
V_{50}	Speed over 50 foot obstacle
V_∞	Free-stream velocity
W	Weight
W_{empty}	Empty weight
W_L	Landing weight, usually W_{TO} - 1/2 fuel
W_{TO}	Take-off weight
w	Wing downwash velocity
X_w	Distance between c.g. and wing a.c.
z_T	Distance between c.g. and engine thrust line
x, y, z	Orthogonal axis system, see Figure 20.2

Greek Symbols

α	Angle-of-attack, angle between free-stream velocity and wing chord line
α_c	Canard angle-of-attack
α_i	Induced angle-of-attack or angle of incidence
α_{OL}	Angle for zero lift
β	Shock wave angle
β	Upwash angle into inlet
β	Sideslip angle
β	Propeller geometric pitch angle
β	Boattail angle
β	$\sqrt{\lvert 1\ M_\infty^2 - 1 \rvert}$
Γ	Dihedral
γ	Flight path angle, angle between V_∞ and horizontal reference
γ, γ'	Ratio of specific heats
Λ	Wing sweep
ΔN	Leading edge suction parameter

δ	Correction factor for non-elliptic lift distribution
δ_e	Elevator deflection angle
δ_f	Flap deflection
δ_{LEF}	Leading edge flap deflection
δ_r	Rudder deflection angle
δ_T	Turbulent boundary layer thickness
ϵ	Wing downwash angle
ϵ	Diffuser loss coefficient
ϵ	Surface emissivity
η	Propulsive efficiency
η_i	Ideal efficiency
η_R	Total pressure recovery of inlet
η_T	Tail efficiency factor $q_{\infty T}/q_{\infty}$
θ	Temperature
θ_w	Equilibrium wall temperature
θ	Flow deflection angle
θ_{BLD}	Boundary layer diverter compression ramp angle
θ_c	Cone semi-vertex angle
θ_{CL}	Climb flight angle
λ	Taper ratio, C_T/C_R
μ	Mach angle, arc sin $(\frac{1}{M_\infty})$
μ	Coefficient of viscosity
μ	Coefficient of friction
ν_{SB}	Stephan-Boltzman constant, $.481 \times 10^{-2} \frac{BTU}{ft^2\text{-sec-}^oR}$
ρ	Density
σ	Density ratio, ρ/ρ_{SL}
σ	Ground influence coefficient
σ	Sidewash angle
τ	Correction factor for non-elliptic lift distribution
τ	Rudder effectiveness, $d\alpha_{OL}/d\delta_r$

Φ	Roll angle for Mach plane determination
ϕ	Propeller effective pitch angle
ϕ	Bank angle, arc cos $(\frac{1}{n})$
$\dot{\psi}$	Turn rate
Ω	Rotational speed

Subscripts

B	Bleed conditions
BLB	Boundary layer bleed conditions
c	Conditions at compressor face
e	Exit
jet	Conditions in jet
MS	Maximum sustained
o	Total properties
T, t	Conditions at throat
TO	Conditions at take-off
∞	Free-stream quantities

Abbreviations

a.c.	Aerodynamic center
AMPR	Aeronautical Manufacturers Planning Report, aircraft weight for cost estimating
c.g. or C.G.	Center of gravity
CTOL	Conventional take-off and landing
DT&E	Development, test and evaluation
EPNdb	Effective perceived noise level in decibels
FAR	Federal Aviation Regulation
L/D	Lift to drag ratio
LCC	Life cycle cost
LWF	Lightweight fighter
MAC	Mean aerodynamic chord
MFP	Mass flow parameter