Aircraft Design: A Conceptual Approach

Sixth Edition

Daniel P. Raymer

Joseph A. Schetz
Editor-in-Chief

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Conceptual Research Corporation
Playa del Rey, California

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The cover shows a far-term tailless transport design developed by Dr. Raymer under contract to NASA-GRC. The use of advanced controls technologies permits the elimination of traditional tails, resulting in major savings in weight and drag. This exotic concept was designed and analyzed in the RDS-Professional aircraft design software and exported as a 3-D geometry file. The CAD rendering was done from that file by Alfredo Ramirez P. of the University of San Buenaventura, Bogota, Colombia, using the Blender 3D content creation suite and the YafaRay ray tracing program. Mr. Ramirez also created the colorful paint and marking scheme.

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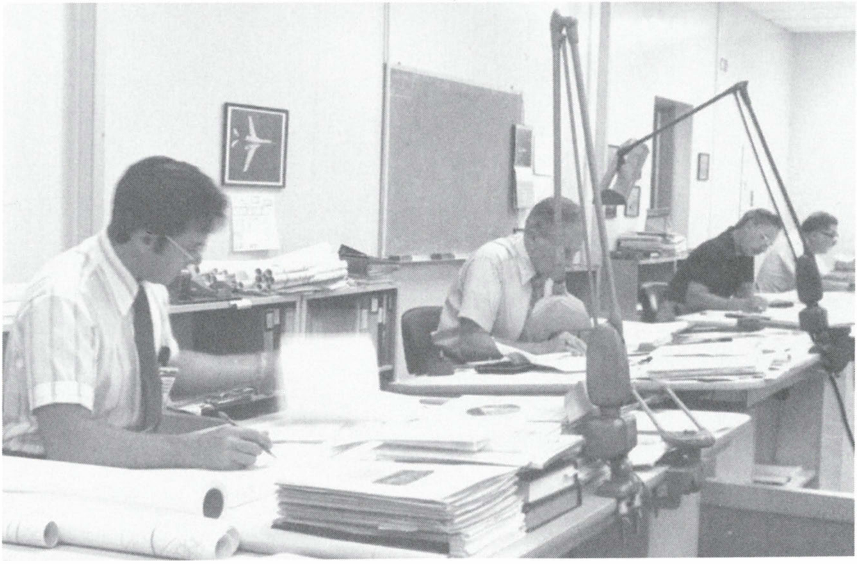
This book is dedicated to all who taught me, especially Lester Hendrix, Richard Hibma, Louis Hecq, Harry Scott, Richard Child, George Owl, Robert Maier, Ed McGachan, Doug Robinson, Steve White, Harvey Hoge, Michael Robinson, George Palmer, Henry Yang, Robert Swaim, C. T. Sun, David Schmidt, Bruce Reese, William Heiser, Tony Hays, Jess Sponable, and Gordon Raymer (test pilot, aeronautical engineer, and my father).

A special thanks, nearly 30 years after its initial publication, to the 60,000+ purchasers of this book and to the hundreds of readers who have sent letters of appreciation and suggestions for improvements. You too have taught me.

Thanks to Rockwell North American Aircraft Operations, Boeing, SAAB Aircraft, Composite Engineering, Mr. Alfredo Ramirez P., Mr. Lance Bradshaw, and Lockheed Martin for permission to use various illustrations. All other artwork is original, in the public domain, or copyrighted by AIAA.



Rockwell North American Aviation Advanced Design Department ~1980, Harry Scott at left, George Owl at far right. The author's drafting table was two rows in front of Harry's. (Photo courtesy of The Boeing Company.)

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Author with Paris Airshow display model of his Advanced Supercruise Fighter Concept.[20] (Photo courtesy of Rockwell International North American Aircraft.)

FOREWORD

The American Institute of Aeronautics and Astronautics is delighted to present another new edition of our bestselling textbook, *Aircraft Design: A Conceptual Approach* by AIAA Fellow Dr. Daniel P. Raymer. This is the standard textbook and reference throughout the world on the subject of aircraft conceptual design, and proudly sits in just about every design office on the planet. Most aeronautical engineers who've graduated in the last 25 years have used *AD:ACA* at some point in their education, and for most the book was a "keeper" even when the class was finished.

In this sixth edition Dr. Raymer has expanded and updated his presentation of fast-moving technologies, added lots of new material, and rewritten introductory material to make it even more "user-friendly." Given the ever-growing importance of electric propulsion, Raymer has added a whole new chapter entitled *Electric Aircraft*. This presents technologies, design-to guidance, and rules of thumb, and offers electric aircraft performance and sizing equations derived in a format familiar to those designing conventionally powered airplanes.

This encyclopedic book covers every topic necessary to the understanding of aircraft design. Preliminary sizing, aerodynamics, structures, stability and control, propulsion, configuration layout, performance, cost analysis, and much more are all presented starting from first principles and building to a set of tools allowing the reader to actually do a realistic job of aircraft conceptual design. All topics are presented from the point of view of the aircraft designer, not the specialist in any given topic area.

After 19 chapters detailing the way to design "normal" aircraft, Raymer concludes with four more chapters describing the design of more exotic flight vehicles including electric aircraft, helicopters, vertical takeoff jets, hypersonic aircraft, launch vehicles, airships, flying wings, forward-swept wings, asymmetric airplanes, and much more. Enjoy!

Daniel Raymer is uniquely qualified to write this book because of his broad expertise in the field. He actually is an aircraft conceptual designer, doing blank-sheet-of-paper designs for over 40 years for large and small aircraft companies. He also teaches aircraft design both in a university setting and in his famous design short courses, and is widely published with topics ranging from actual design studies, to design and CAD methodologies, to esoteric optimization methods as applied to aircraft design. His command of the material is excellent, and he is able to organize and present it in a very clear manner. 60,000+ purchasers seem to agree!

The AIAA Education Series is a premier provider of textbooks in the field of aerospace engineering. The Education Series covers a broad range of related topics and includes textbooks of basic theory, application, and design. Not just a "print house," the AIAA staff and working-engineer volunteers actively solicit submissions from world-renowned experts, then work with them to produce books which are suitable for both university usage and as archival sources of information for working engineers. A complete list of titles can be found at *www.aiaa.org*. Suggestions for new topics and new authors are always welcome.

Joseph A. Schetz
Editor-in-Chief
AIAA Education Series

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PREFACE

Aircraft Design is a challenging, rewarding, and fun career. There are dozens of different activities involved in creating a new air vehicle concept, different specialties ranging from initial configuration layout to system optimization and cost estimation. These activities can be grouped into two equally important aspects of aircraft design: *design layout* and *design analysis.* While some people do both, in most cases these differing aspects attract different types of people. Certain people love playing with numbers and computers, whereas others can't stop doodling on every piece of paper within reach.

This book offers a balanced overview of these two aspects of design, integrated together and presented in the manner typically seen in an aircraft design project at a major aerospace company. Whichever aspect you may lean towards, the book should help get you started and will provide a resource of material throughout your career.

Aircraft design depends on the reliable calculation of numbers but in the end, the only thing that actually gets built is the configuration concept shown on the drawing or CAD file. Its creation is not a trivial task of drafting based upon the analysis results, but rather it is a key element of the overall design process and ultimately determines the performance, weight, and cost of the aircraft. Bluntly stated, if you don't have a good drawing, you don't have an aircraft design. The "Conceptual Approach" mentioned in the book's title refers to a design process centered around a realistic concept layout.

It is difficult to visualize and draw a new aircraft that has a streamlined aerodynamic shape and an efficient internal layout and yet satisfies an incredible number of real-world constraints and design specifications. Aircraft conceptual design layout is a rare talent that takes years to cultivate. Although to some extent good designers are "born, not made," the proven methods and best practices of aircraft configuration layout can be taught and are covered here in the first half of this book. These apply equally to traditional drafting table drawings and to modern computer-aided design.

It is also true that a nice aircraft drawing is nothing without the analytical results to support it, and it will be a much better design if clever optimization methods are employed. So, a good designer or design team must find an appropriate balance between design layout and design analysis. The second half of this book covers analysis and optimization methods that will tell you if the design works, if it meets its design requirements, and how you can make it better in the next drawing.

Writing—and rewriting—this book has been an educating and humbling experience. It is my sincere wish that it helps aspiring aircraft designers to "learn the ropes" more quickly. My greatest pride in the previous editions has been the thanks from the students who've used the book in their design classes, and the designers of built-and-flown airplanes who've told me that they made extensive use of my book. Thanks—that means a lot.

Daniel P. Raymer
Los Angeles, California
June 2018

The author's Aircraft Conceptual Design Web site at www.aircraftdesign.com includes examination questions for the book, advice to students and would-be inventors, sample aircraft design layouts, free design software, tips for the use of the companion RDS-Student design software, and information on aircraft design short courses. It is free, and all are welcome!

Raymer's Reverse Installation Vectored Engine Thrust ("RIVET") supersonic VSTOL concept.[130]

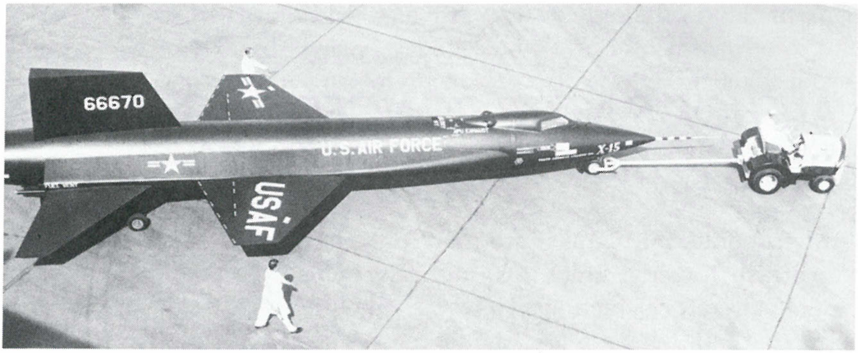
AUTHOR'S NOTE CONCERNING USE OF METRIC WEIGHT UNITS

Metric units (SI or mks) are more universal and technically consistent than British Imperial units (fps) and also reduce the possibility of stupid errors in aircraft calculations. However, one must still decide exactly which metric unit multipliers to use. Should masses be defined in grams or in kilograms? Should time be in seconds or in hours, or used as needed to make the numbers "nice"? These decisions change the numbers, and, unfortunately, different organizations use slightly different combinations of unit multipliers and times. To maximize consistency with prior literature, the metric unit terms used in *Jane's All the World's Aircraft*[6] and in Stinton's *The Design of the Aeroplane*[47] were employed in this book. Values in this book are presented first in British units, and then in metric units enclosed in braces {}.

A key issue and the source of much confusion is the treatment of "weight" in metric units. Weight by definition is a force, not a mass. However, pilots and working engineers describing the weight of the Airbus A340 would say 126,000 kg, not 1,235,682 kN. What those pilots and engineers really mean is, "the Airbus exerts a weight force equivalent to that exerted by a 126,000 kg mass in a 1-g gravitational field." This book follows this common practice—don't let it confuse you! When doing an analysis such as calculating lift force and equating it to weight, the "weight" of 126,000 kg (actually mass) must first be converted to proper force units (Newtons) by multiplying by the 1-g acceleration constant ($g = 9.807\ \text{m/s}^2$).

This verbal equating of weight with force in a 1-g gravitational field is carried over to the definitions of ratios such as wing loading (kg/m^2) and power loading (kg/kW). Because of this, the values of these ratios as given in the tables are not technically correct when applied to the various equations that use them. The mass terms must be converted to force by multiplying by g. Thus, a wing loading given in "pilot talk" as $586\ \text{kg/m}^2$ must be converted to $5{,}746.9\ \text{N/m}^2$ to apply in equations relating lift to weight (for example, see Table 5.5).

The values given for thrust-to-weight ratio (T/W) do not require conversion. In traditional (fps) practice the thrust is given in lbs-force, and the weight is given in lbs-mass (exerted force assuming a 1-g field), so that the ratio is nondimensional and the same as the desired SI units of Newtons/Newton. A T/W greater than one means the aircraft can accelerate straight up, regardless of the units in which it was designed!



X-15 rollout (U.S. Air Force photo).

Learjet (USAF C21-A) (U.S. Air Force photo).

NOMENCLATURE

Coefficients, parameters, and Greek letters commonly used in aircraft design are listed below, followed by various abbreviations and acronyms. For updates and more definitions, see www.aircraftdesign.com/abrv.html. The terms specific to the statistical weights equations presented in Chapter 15 are listed in that chapter and are not repeated here.

Aircraft Design Coefficients and Parameters

A	aspect ratio of wing ($=b^2/S_{\text{ref}}$)
A	helicopter rotor disk area
A_c	capture area of jet engine inlet duct
A_{wetted}	wetted aspect ratio ($=b^2/S_{\text{total wetted area}}$)
A^*	cross-section area if that flow stream was at Mach 1
b	wing span
BMF	Battery Mass Fraction
C	chord length
C	specific fuel consumption (also SFC)
C	exhaust velocity (rockets)
C_{bleed}	bleed coefficient (adjusts thrust for amount of bleed air)
C_D	wing or whole airplane drag coefficient
C_{Di}	induced-drag coefficient
C_{Dmin}	minimum drag coefficient ($=C_{D0}$ if uncambered)
C_{Dwave}	supersonic wave-drag coefficient (also C_{Dw})
C_{D0}	drag coefficient at zero lift
C_d	airfoil drag coefficient
C_f	flat-plate skin-friction coefficient
C_{fe}	equivalent skin-friction coefficient
C_{HT}	horizontal tail volume coefficient
C_L	wing or whole airplane lift coefficient
C_l	airfoil lift coefficient
C_l	rolling-moment coefficient
$C_{L\alpha}$	wing or whole airplane slope of the lift curve
$C_{l\alpha}$	airfoil slope of the lift curve ($=2\pi$ theoretically)

$C_{l\beta}$	rolling moment with sideslip angle (dihedral effect)
C_m	airfoil pitching-moment coefficient
C_m	wing or whole airplane pitching-moment coefficient
$C_{m\alpha}$	pitching-moment derivative with angle of attack
C_n	yawing-moment coefficient
$C_{n\beta}$	yawing-moment derivative with sideslip angle
C_{ram}	ram coefficient (adjusts thrust for inlet pressure recovery)
C_{VT}	vertical tail volume coefficient
E	Young's modulus, or modulus of elasticity
EHA	Electrohydrostatic Actuator
E_{sb}	battery specific energy {wh/kg}
E_{wd}	wave-drag efficiency factor [$=C_{\text{Dwave}}/C_{\text{Dwave(Sears-Haack)}}$]
e	Oswald's span efficiency factor (adjusts aspect ratio)
FAA	Federal Aviation Administration
FAI	Fédération Aéronautique International (aviation record certifying agency)
FF	form factor term (pressure drag) for parasitic drag calculation
f_s	fuel specific energy (P_s/fuel flow)
g	acceleration due to gravity, standard values: $32.174\ \text{ft/s}^2$ or $9.80665\ \text{m/s}^2$
G	shear modulus, or modulus of rigidity
h_e	energy height (actual height plus height equivalent of kinetic energy)
$I\text{sp}$	specific impulse (rocket propellant consumption)
I_{xx}	rolling mass moment of inertia
I_{yy}	pitching mass moment of inertia
I_{zz}	yawing mass moment of inertia
i	incidence angle
J	propeller advance ratio ($=V/nD$)
K	drag due to lift factor
L/D	lift-to-drag ratio
LE	leading edge (of airfoil or wing)
M	Mach number (multiple of speed of sound)
m	total aircraft mass {kg}
MAC	mean aerodynamic chord
m_b	mass of batteries {kg}
M_{cr}	critical Mach number (where shocks first form)
M_{DD}	drag-divergent Mach number (where drag increases)
n	load factor
P_s	specific excess power
P_{used}	average motor power used {kW}
Q	interference factor for parasitic drag calculation
Q	production quantity

q	dynamic pressure (of air)
q	dynamic pressure, $= \frac{1}{2}\rho V^2$
$R\#$	Reynolds number (also R or R no.)
RAND	RAND Corp. -Research ANd Development (think-tank for USAF)
R_{cutoff}	Cutoff Reynolds number, adjusts skin friction for roughness
S	leading-edge suction (force or percent attainment)
S_{exposed}	exposed wing planform (wing less portion of wing covered by fuselage)
SFC	specific fuel consumption (also C)
T/W	thrust-to-weight ratio
t	airfoil thickness
t/c	airfoil thickness-to-chord length ratio
TE	trailing edge (of airfoil or wing)
U_{de}	derived equivalent gust velocities (used for gust load calculation)
Ve	equivalent airspeed (dynamic pressure based, $Ve = V_{\text{actual}}$ sqrt[ρ/ρ_0])
V_{NE}	never-exceed speed
Vp	maneuver (pullup) speed (max. speed for full controls deflections)
V_1	takeoff decision speed
V_2	takeoff safety speed
W_{dg}	flight design gross weight
W_e	empty weight
W_f	fuel weight
W_{o}	takeoff gross weight
W/S	wing loading

Aerospace Applications of Greek Letters

α (alpha)	angle of attack
β (beta)	sideslip angle
β (beta)	Prandtl–Glauert compressibility correction
δ (delta)	change in some parameter
δ (delta)	deflection of controls
Δ (Delta)	wing sweep (see also Λ)
ε (epsilon)	unit strain
γ (gamma)	shearing strain
γ (gamma)	flight-path angle
Γ (Gamma)	wing dihedral angle
η (eta)	efficiency
η_{b2s}	total system efficiency from battery to motor output shaft
η_p (eta-p)	propeller efficiency

η_p (eta-p)	propulsive efficiency (rockets)
λ (lambda)	wing taper ratio ($C_{\text{tip}}/C_{\text{root}}$)
Λ (Lambda)	wing sweep (see also Δ)
μ (mu)	viscosity
μ (mu)	micro (one millionth $= 1/10^6$)
π (pi)	3.141592653589793...
Π (Pi)	product operator
ρ (rho)	air density
ρ (rho)	conic shape parameter
ρ (rho)	radius of gyration
σ (sigma)	unit stress
σ (sigma)	air density ratio ($=\rho/\rho_0$)
Σ (Sigma)	summation operator
τ (tau)	unit shear stress

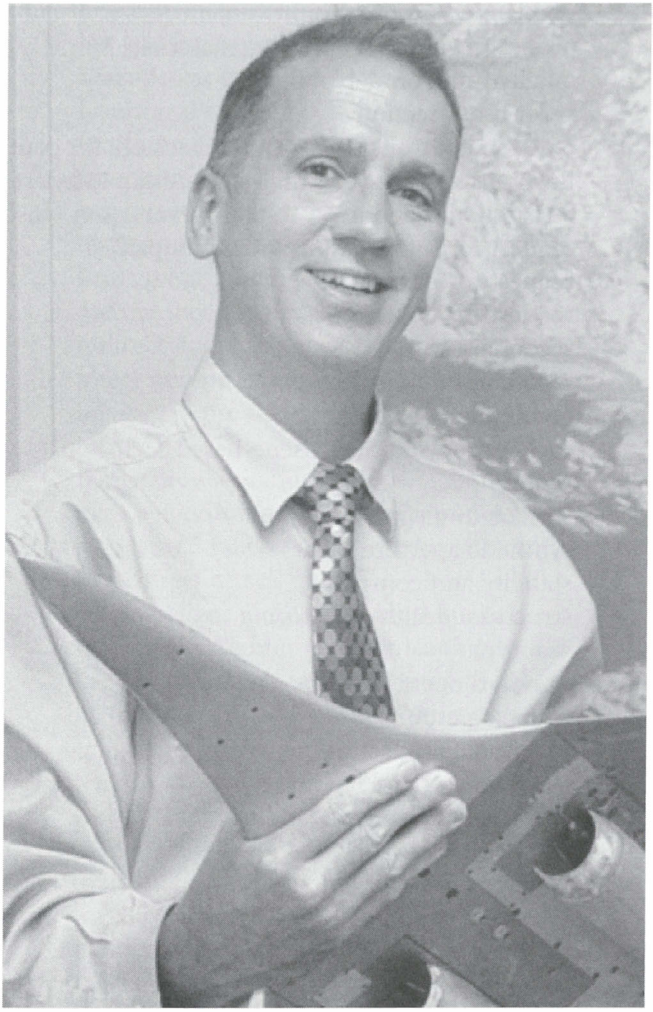
Abbreviations and Acronyms

AAW	active aeroelastic wing
ABC	activity-based costing
A/C	aircraft
AC	Alternating Current
AF	Air Force
AFRL	Air Force Research Lab
AMAD	airframe mounted accessory drive
AMPR	airframe manufacturers planning report
AMRAAM	advanced medium-range air-to-air missile (now AIM-120)
AOA	angle of attack
APU	auxiliary power unit
ASW	antisubmarine warfare
ATC	air traffic control
ATF	Advanced Tactical Fighter (F-22 predecessor program)
AWACS	airborne warning and control system
BFL	balanced field length
BINGO	fuel state at which a pilot must begin to return to base
BL	boundary layer
BMI	bismaleimide (high-temp composite material)
BPR	turbofan engine bypass ratio
CAD	computer-aided design
CAIV	cost as an independent variable
CAM	computer-aided manufacturing
CAS	calibrated airspeed
CCC	command, control, and communications ("C-cubed")
CER	cost-estimating relationship
CFD	computational fluid dynamics

c.g.	center of gravity
COTS	commercial off-the-shelf (no development required)
CS	EASA Certification Specifications (like FARs)
CTOL	conventional takeoff and landing
CV	aircraft carrier, heavier-than-air aircraft
CVN	aircraft carrier, heavier-than-air, nuclear powered
DAPCA	development and procurement cost of aircraft (cost model)
DARPA	Defense Advanced Research Projects Agency
DATCOM	Data Compendium (USAF aerodynamics methodology report)
DC	Direct Current
DCPR	defense contractors planning report
Decalage	incidence angle between two wings of a biplane
DOC	direct operating costs
DoD	Department of Defense
DOF	degree of freedom (6-DOF = X, Y, Z, roll, pitch, yaw)
Drag Counts	four digits to right of decimal place in coefficient
EAS	equivalent air speed
ECCM	electronic counter-countermeasures
ECM	electronic countermeasures
ECS	environmental control system
EHP	equivalent horsepower
EASA	European Aviation Safety Agency (like FAA)
ESHP	equivalent shaft horsepower (includes residual thrust)
EW	electronic warfare
F/A	fighter/attack
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations (certification specs)
FAR	Federal Acquisition Regulations
FB	fighter-bomber
FBW	fly by wire
FEM	finite element method (for calculation, usually of structures)
FLIR	forward-looking infrared
FOD	foreign object damage
FSW	forward-swept wings
FY	fiscal year
GA	general aviation
GA	genetic algorithm (optimization method)
G&A	general and administrative (overhead expenses)
Gap	vertical distance between two wings of a biplane
G&C	guidance and control
GLOW	gross liftoff weight (Wo for rockets)
GPS	global positioning system
HALE	high-altitude long endurance

Helo	helicopter
HGI	hot-gas ingestion
hp	horsepower (=550 ft-lb/s = 746 W)
HUD	head-up display
IAS	indicated airspeed
ICAO	International Civil Aviation Organization
IFR	instrument flight rules
IFR	in-flight refueling
ILS	instrument landing system
INS	inertial navigation system
IOC	indirect operating costs
IPPD	integrated product and process development
IPT	integrated product team
IR	infrared
ISO	International Standards Organization
JAR	joint aviation requirements (European cert. specs)
JATO	jet-assisted takeoff
JDAM	joint direct attack munition
JP	jet propellant (kerosene-based fuel)
JSF	Joint Strike Fighter (project leading to F-35)
KISS	keep it simple, stupid (attributed to Ed Heinemann)
LCC	life-cycle cost (total cost from product development to retirement)
LOX	liquid oxygen
L&P	leakage and protuberances (causing additional drag)
LTA	lighter than air (airship)
MECO	main engine cutoff (shutdown)
MDO	multidisciplinary design optimization
MMH/FH	maintenance man-hours per flight hour
MSL	mean sea level
MTOW	maximum takeoff weight
MZFW	maximum zero fuel weight
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis (FEM software)
NAV	navigation
NC	numerically controlled
NOTAR	no tail rotor (helicopter)
NPV	net present value
NS	Navier–Stokes (high-end CFD)
NURBS	nonuniform rational B-Spline (curve equation for CAD)
O&S	operations and support
OEM	original equipment manufacturer
OEI	one engine inoperative
p-Effect	yawing moment due to propeller

PPPI	preplanned product improvement (P^3I or P-cubed I)
pre-preg	pre-impregnated (composite materials)
QFD	quality function deployment
RCS	radar cross section
RCS	reaction control system (small thrusters for control)
RDS	Raymer's design system (aircraft design software)
RDT&E	research, development, test, and evaluation (costs)
RFI	request for information (usually unpaid)
RFP	request for proposals
RFQ	request for quotations
Recce	reconnaissance
Recon	reconnaissance
RPM	revolutions per minute
RP	rocket propellant (kerosene-based fuel)
RPV	remote-piloted vehicle
SAM	surface-to-air missile
SAR	synthetic aperture radar
S&C	stability and control
SHM	structural health monitoring
SL	sea level
SOP	standard operating procedure
SST	supersonic transport
Stagger	longitudinal offset of two wings of a biplane
STOL	short takeoff and landing
STOVL	short takeoff/vertical landing
T&E	test and evaluation
TAS	true airspeed
TRL	technology readiness level
TOGW	takeoff gross weight
TPS	thermal protection system (for reentry)
TQM	total quality management
TVC	thrust vector control
UAV	unmanned or uninhabited aerial (or air) vehicle
UCAV	unmanned or uninhabited combat air vehicle
VFR	visual flight rules
VIFF	vectoring in forward flight
V/STOL	vertical/short takeoff and landing
VTO	vertical takeoff
VTOL	vertical takeoff and landing
WBS	work breakdown structure
WIG	wing-in-ground effect
ZFW	zero fuel weight



Daniel P. Raymer at the North American Aviation Trisonic Wind Tunnel, holding a supersonic model of his Advanced Tactical Fighter design.

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