Flight Test Engineering Reference Handbook

Society of Flight Test Engineers

2013

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Flight Test Engineering Reference Handbook

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Chapter 1

General Information

1.1 Unit Conversions[1]

(references 1.1, 1.2)

Table 1.1: Prefix Multipliers

Exponent	Prefix	Abbreviation
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

[1] Common FTE conversions in boldface

	Multiply	by	To Ob
Angles	circles	1	circum
	circles	12	signs
	circles	21,600	minute
	circles	2π	radians
	circles	360	degree
	degrees	0.011 11	quadra
	degrees	3600	second
	degrees	60	minute
	mils (Army)	0.056 25	degree
	mils (Navy)	0.057 29	degree
	quadrants	90	degree
	radians	57.2958	degree
	revolutions	360	degree
2	sphere	4π	steradi
Angular Acceleration	rev/min^2	0.001 745	rad/se
Angular Velocity	**cycles/sec**	**6.2814**	**rads/s**
	rads/sec	**0.1592**	**rev/se**
	rads/sec	9.549	rpm
	rad/sec	**57.296**	**deg/s**
	rpm	0.016 67	rev/sec
Area	acres	43,560	ft^2
	ares	100	m^2
	barn	10^{-28}	m^2
	centares	1	m^2
	circular mils	7.854×10^{-7}	in^2
	cm^2	100	mm^2
	ft^2	**144**	**in^2**
	ft^2	**0.092 903 04**	**m^2**
	in^2	6.452	cm^2
	in^2	10^6	mils^2
	m^2	10.76	ft^2
	section	2,589,988.1	m^2
	st. mile^2	27,780,000	ft^2
	st. mile^2	2.590	km^2
	township	93,239,572	m^2
	yd^2	9	ft^2
	yd^2	0.8361	m^2
Density	grams/cm^3	0.036 13	pounds
	grams/cm^3	62.43	pounds
	kg/m^3	16.018 463	pounds

	Multiply	by	To Obtain
	slugs/ft^3	**515.4**	**kg/m^3**
	pounds/in^3	**1728**	**pounds/ft^3**
	slugs/ft^3	1.94	grams/cm^3
Electrical Quantities	amperes	0.1	abamperes
	amperes	1.0365×10^{-5}	faradays/sec
	amperes	2.998×10^{9}	statamperes
	amperes.cicmil	1.973×10^{5}	amperes/cm^2
	ampere-hours	3,600	coulombs
	ampere-hours	1.079×10^{13}	statcoulombs
	ampere turn/cm	1.257	gilberts/cm
	ampere turn/cm	1.257	oersteds
	coulombs	0.1	abcoulombs
	coulombs	6.243×10^{18}	electronic charges
	coulombs	1.037×10^{-5}	faradays
	coulombs	2.998×10^{9}	statcoulombs
	faradays	26.8	ampere-hours
	farads	10^{-9}	abfarads
	farads	10^{6}	microfarads
	farads	8.986×10^{11}	statfarads
	gausses	1	maxwells/cm^2
	gausses	6.452	lines/in^2
	gilberts	0.7958	ampere turns
	henries	10^{9}	abhenries
	henries	1.113×10^{-12}	stathenries
	maxwells	1	lines
	oersteds	2.998×10^{10}	statoersteds
	ohms	10^{9}	abohms
	ohms	1.113×10^{12}	statohms
	ohm-cm	6.015×10^{6}	circ mil-ohms/ft
	volts	10^{8}	abvolts
	volts	0.003 336	statvolts
Energy & Work	Btu	1.055×10^{10}	ergs
	Btu	1055.1	Joules (N-m)
	Btu	2.9302×10^{-4}	kilowatt-hours
	Btu	251.99	calories (gram)
	Btu	778.03	foot-pounds
	calories	4.1868	watt-seconds
	calories	3.088	foot-pounds
	electron volt	1.519×10^{-22}	Btu
	ergs	1	dyne-centimeters
	ergs	7.376×10^{8}	foot-pounds
	foot-pounds	**1.3558**	Joules (N-m)**

	Multiply	by	To Ob
	foot-pounds	3.766x10^{-7}	kilowa
	foot-pounds	5.051x10^{-7}	horsep
	hp-hours	0.7457	kilowa
	hp-hours	2546.1	Btu
	Joules	0.238 89	calorie
	Joules	1	Newto
	Joules	1	watt-se
	Joules	10^{7}	ergs
	kilowatt-hours	**3.6x10^{6}**	**Joules**
	thermies	4.1868x10^{6}	Joules
	watt-seconds	0.737 56	foot-po
Force[3]	dynes	3.597x10^{-5}	ounces
	kilograms-force	**9.806 65**	**Newto**
	kiloponds	9.806 65	Newto
	kip (kilopound-force)	4,448.221	Newto
	Newtons	**0.224 808 931**	**pound**
	Newtons	100,000	dynes
	ounces	20	pennyw
	ounces (troy)	480	grains
Fuel[4]	**gal**	**5.8**	**lbs (U**
	gal	**7.5**	**lbs (U**
	Liter (jet A)	**0.812**	**kilogr**
	Liter (jet A)	**1.794**	**pound**
Illumination	candles	1	lumens
	candles/cm^{2}	π	lamber
	candlepower	12.566	lumens
	foot-candles	1	lumens
	foot-candles	10.764	lux
	foot-lamberts	1	lumen/
	lamberts	295.72	candle
	lamberts	929.03	lumens
	lumens	0.001 496	watts
	lumens/in^{2}	1	fots
	lumens/m^{2}	1	lux
	lux	1	meter-
	lux	0.0001	fots
	meter-candles	1	lumens
	millilamberts	0.2957	candle
	millilamberts	0.929	foot-la
	milliphots	0.929	foot-ca
	milliphots	0.929	lumens

	Multiply	by	To Obtain
	milliphots	10	meter-candles
Length	ångströms	10^{-10}	meters
	astronomical units	1.496×10^{11}	meters
	cable lengths	120	fathoms
	caliber	0.01	inches
	cubit	0.4572	meters
	fermi	10^{-15}	meters
	fathoms	6	feet
	feet	12	inches
5	**feet**	**0.3048**	**meters**
	furlongs	40	rods
	hands	4	inches
	inches	**2.54**	**cm**
	kilometers	**3281**	**feet**
	kilometers	**0.539 96**	**nautical miles**
	leagues (U.S.)	3	nautical miles
	light years	5.88×10^{12}	statute miles
	links (engnr's)	12	inches
	links (srvyr's)	7.92	inches
	meters	**3.280 84**	**feet**
	meters	**39.370 079**	**inches**
	microns	10^{-6}	meters
	mils	10^{-3}	inches
	nautical miles	**1.150 78**	**statute miles**
6	**nautical miles**	**1,852**	**meters**
	nautical miles	**6,076.115 486**	**feet**
	paces	0.762	meters
	parsec	1.9163×10^{13}	statute miles
	perch	5.0292	meters
	pica (printers)	0.004 217 5176	meters
	point (printers)	0.000 351 4598	meters
	pole (=rod)	5.0292	meters
	skein	109.728	meters
	statute miles	**5,280**	**feet**
	statute miles	**1.609 344**	**kilometers**
	statute miles	8	furlongs
	yards	3	feet
Linear Acceleration	feet/sec^2	1.097 28	kilometers/hr/sec
	feet/sec^2	0.3048	meters/sec^2
	feet/sec^2	0.6818	mph/sec
	g	**32.174 049**	**feet/sec^2**

	Multiply	by	To Ob
	g	**9.806 65**	**meter**
	gals (Galileo)	0.01	meters
	knots/sec	1.6878	feet/se
	meters/sec^2	3.6	kilome
	mph/sec	0.447	meters
	mph/sec	1.609	kilome
Mass	carats	200	milligr
	grams	0.035 274	ounces
	grains	6.479 891x10^{-5}	kilogra
	hundredweight (long or Imperial)	50.80	kilogra
	hundredweight (short)	45.359 237	kilogra
	kilograms	**0.068 52**	**slugs**
	kilograms	6.024x10^{26}	atomic
	kilograms	**2.2046**	**pound**
	ounces (avd)	28.349 523 125	grams
	ounces (troy)	31.103 4768	grams
	pounds (mass)	1	pounds
	pounds (mass)	**0.453 592 37**	**kilogr**
	pounds (mass)	**0.031 081**	**slugs**
	scruples (apoth)	0.001 295 9782	kilogra
	slugs	**32.174**	**pound**
	slugs	**14.594**	**kilogr**
	tons (long)	1016.047	kilogra
	tons (assay)	0.029 16	kilogra
	tons (metric)	1000	kilogra
	tons (short)	907.1847	kilogra
Moments of Inertia	gram-cm^2	0.737x10^{-7}	slug-ft
	pound-ft^2	0.031 081	slug-ft
	slug-in^2	0.006 9444	slug-ft
	slug-ft^2	**1.3546**	**kg-m^2**
	slug-ft^2	**32.174**	**pound**
	slug-ft^2	12.00	pound-
	slug-ft^2	192.00	ounce-
Power	btu/min	0.017 58	kilowa
	calories(kg)/min	3087.46	foot-po
	ergs/sec	7.376x10^{-8}	foot-po
	ft(lbs)/min	2.260x10-^{5}	kilowa
	ft(lbs)/sec	0.077 12	btu/m
	ft(lbs)/sec	1.356	watts
	horsepower	**550**	**ft(lb)/**
	horsepower	**33,000**	**ft(lbs)**

	Multiply	by	To Obtain
	horsepower	10.69	calories (kg)/min
	horsepower	**745.7**	**watts**
	horsepower (metric)	**735.5**	**watts**
	horsepower	1.1014	**horsepower (met**
	kilowatts	**1.341**	**horsepower**
	watts	10^7	ergs/sec
	watts	1	Joules/sec
Pressure	**atmospheres**	**14.696**	**pounds/in^2**
	atmospheres	**29.92**	**inches of Hg**
	atmospheres	760	mm of Hg
	bars	10^6	dynes/cm^2
	bars	**29.52**	**inches of Hg**
	barye	**0.1**	**Newtons/m^2**
	dynes/cm^2	10	Newtons/m^2
	inches of H_2O	**5.202 37**	**pound/ft^2**
	inches of Hg	**70.726 19**	**pounds/ft^2**
	inches of Hg	0.491 154	pounds/in^2
	inches of Hg	13.595	inches of H_2O
	kiloPascals	**100**	**bars**
	hectoPascals	**1**	**millibars**
	millibars	**0.029 53**	**inches of Hg**
	mm of Hg	0.019 337	pounds/in^2
	mm of Hg	133.32	Newtons/m^2
	Pascals	**1**	**Newton/m^2**
	pieze	1000	Newtons/m^2
	pounds/ft^2	**0.014 14**	**inches of Hg**
	pounds/ft^2	**47.88**	**Newtons/m^2**
	pounds/in^2	**2.036**	**inches of Hg**
	pounds/in^2	27.681	inches of H_2O
	pounds/in^2	**6894.757 28**	**Pascal**
	torrs	133.32	Newtons/m^2
Temperature	**Kelvin**	**Celsius + 273.15**	
	Rankine	**Fahrenheit + 459.67**	
	Celsius	(**Fahrenheit - 32**) * **5/9**	
	Fahrenheit	(**9/5** * **Celsius**) **+ 32**	
Time	days (solar)	24	hours
	days (sidereal)	23.934	hours
	days (solar)	1.0027	days (sidereal)
	hours	60	minutes
	minutes	60	seconds
	months (sidereal)	27d + 7hr + 43min + 11.47sec	

	Multiply	by	To Ob
	months (lunar)	29d + 12hr + 44min + 2.78sec	
	year	365.242 198 79	days
Torque	**foot-pounds**	**1.3558**	**Newt**
	foot-pounds	0.1383	kilogra
	ounce-inches	72.008	gram-c
	pound-inches	1129800	dyne-c
Velocity	inches/sec	0.0254	meters
	km/hr	**0.621 371**	**mph**
	km/hr	**0.9113**	**feet/s**
	knots	**1.687 81**	**feet/s**
	knots (kts)	**1.150 78**	**mph**
	knots (kts)	**1.852**	**km/h**
	knots (kts)	**0.514 44**	**meter**
	meters/sec	3.281	ft/sec
	meters/sec	**3.6**	**km/h**
	meters/sec	**196.85**	**feet/m**
	mph	1.466 667	feet/se
Viscosity	centistokes	10^{-6}	m^2/sec
	ft^2/sec	0.0929	m^2/sec
	pound sec/ ft^2	47.880 258	Newto
	poise	0.1	Newto
	rhe	10	m^2/Ne
Volume	acre-feet	43,560	ft^3
	acre-feet	1,233	m^3
	acre-feet	$3.259x10^5$	gals (U
	barrels	31.5	gals (U
	board-feet	144	in^3
	bushels	1.244	ft^3
	bushels	32	quarts
	bushels	4	pecks
	cm^3	0.001	liters
	cm^3	0.033 81	fluid o
	cm^3	0.061 02	in^3
	cord-feet	4x4x1	ft^3
	cords	128	ft^3
	cups	0.5	pints (
	dram (fluid)	$3.696\ 69x10^{-6}$	m^3
	ft^3	**0.028 3167**	**m^3**
	ft^3	1728	in^3
	ft^3	28.32	liters

Multiply	by	To Obtain
ft^3	**7.481**	**gals (U.S.)**
gals (Imperial)	**1.2009**	**gals (U.S.)**
gals (Imperial)	277.42	in^3
gals (U.K.)	4546.1	cm^3
gals (U.S.)	**231**	**in^3**
gals (U.S.)	**0.003 785**	**m^3**
gals (U.S.)	**3.785**	**liters**
gals (U.S.)	4	quarts (liquid)
gals (U.S.)	0.023 8095	barrels (U.S.)
gills	7.219	in^3
hogshead	2	barrels
in^3	16.39	cm^3
liters	0.028 38	bushels
liters	0.9081	quarts (dry)
liters	1.057	quarts (liquid)
liters	1000	cm^3
liters	61.03	in^3
m^3	1.308	yd^3
m^3	1000	liters
m^3	264.2	gals (U.S.)
m^3	**35.314 667**	**ft^3**
mil-feet (circ.)	0.000 1545	cm^3
ounces (U.K.)	28.413	cm^3
ounces (U.S.)	29.574	cm^3
pecks	8	quarts (dry)
pecks	8.81	liters
perches	0.7008	m^3
perches	24.75	ft^3
pints (dry)	33.60	in^3
pints (liquid)	28.88	in^3
pints (liquid)	4	gals
quarts (dry)	1.164	quarts (liquid)
quarts	2	pints
register tons	100	ft^3
shipping ton (U.S.)	40	ft^3
shipping ton (Br.)	42	ft^3
steres	1000	liters
tablespoons	0.0625	cups
teaspoons	0.3333	tablespoons

[2] solid angle measurement

[3] Converting between force and mass (e.g. kg force to kg mass or pound force to pound mass) uses $g = 32.174 \frac{ft}{s^2}$

1.2 Greek Alphabet

Uppercase	LaTeX Command	Lowercase	LaTeX Command	Name	Say
A	A	α	\alpha	Alpha	æl-fə
B	B	β	\beta	Beta	bei-tə
Γ or $\varGamma$	\Gamma or \varGamma	γ	\gamma	Gamma	gæ-mə
Δ or $\varDelta$	\Delta or \varDelta	δ	\delta	Delta	del-tə
E	E	ϵ or ε	\epsilon or \varepsilon	Epsilon	eps-ill-aan
Z	Z	ζ	\zeta	Zeta	zei-tə
H	H	η	\eta	Eta	ei-tə
Θ or Θ	\Theta or \varTheta	θ or ϑ	\theta or \vartheta	Theta	thei-tə
I	I	ι	\iota	Iota	aai-oh-tə
K	K	κ or $\varkappa$	\kappa or \varkappa	Kappa	kæ-pə
Λ or $\varLambda$	\Lambda or \varLambda	λ	\lambda	Lambda	læm-də
M	M	μ	\mu	Mu	myoo
N	N	ν	\nu	Nu	nyoo
Ξ or $\varXi$	\Xi or \varXi	ξ	\xi	Xi	ksaai
O	O	o		Omicron	oh-mə-kraan
Π or $\varPi$	\Pi or \varPi	π or ϖ	\pi or \varpi	Pi	paai
P	P	ρ or ϱ	\rho or \varrho	Rho	roh
Σ or $\varSigma$	\Sigma or \varSigma	σ or ς	\sigma or \varsigma	Sigma	sig-mə
T	T	τ	\tau	Tau	taa'u
Υ or $\varUpsilon$	\Upsilon or \varUpsilon	υ	\upsilon	Upsilon	oops-ill-on
Φ or $\varPhi$	\Phi or \varPhi	ϕ or φ	\phi or \varphi	Phi	faai
X	X	χ	\chi	Chi	kaai

[4] Fuel densities are temperature dependent

[5] The foot is defined as exactly 0.3048 meters https://www.nist.gov/pml/us-surveyfoot

[6] The SI defines the nautical mile as exactly 1852 meters. https://www.bipm.org/en/publications/si-brochure/

Uppercase	LaTeX Command	Lowercase	LaTeX Command	Name	Say
Ψ or $\varPsi$	\Psi or \varPsi	ψ	\psi	Psi	psaai
Ω or $\varOmega$	\Omega or \varOmega	ω	\omega	Omega	oh-meg-ə

1.3 Greek Symbols Used for Aircraft

Symbol	Used For
α	angle of attack (degrees or radians)
α_τ	tail angle of attack
β	angle of sideslip (degrees)
γ	flight path angle relative to horizontal
γ	specific heat ratio (1.4 for air)
δ	relative pressure ratio ($\frac{P_a}{P_0}$)
δ_a	aileron deflection angle
δ_r	rudder deflection angle
δ_e	elevator deflection angle
ε	downwash angle at tail (degrees)
ζ	damping ratio
η	efficiency
θ	body axis/pitch angle
θ	relative temperature ratio, T_a/T_0
ι	angle of incidence
ι_F	thrust angle of incidence
${\iota_T}^*$	horizontal tail angle of incidence
λ	pressure lag constant
Λ	wing sweep angle
μ	coefficient of absolute viscosity $=\rho\nu$
μ	Mach cone angle
ν	kinematic viscosity $=\mu/g$
π	nondimensional parameter
ρ	density
ρ_a	ambient air density
ρ_0	standard atmospheric density (slugs/ft^3)
σ	air density ratio (ρ_α/ρ_0)
$\sigma_{\rm cr}$	critical density
τ	shear stress (pounds per square inch) psi
τ_R	Roll Mode Time Constant (sec)
ϕ	bank angle (degrees)
ψ	aircraft heading (degrees)

Symbol	Used For
ω	frequency
ω	rotational velocity (radians per second)
ω_d	damped natural frequency
ω_n	natural undamped frequency

1.4 Common Subscripts

Subscript	Meaning
a	aileron
a	ambient
alt	at test altitude
avg	average
c	calibrated
e	elevator
e	equivalent
E	endurance leg of mission
F	final
I	initial
i	inbound leg of mission
i	indicated
ic	instrument corrected
l	subscript for coefficient of rolling moment
m	mission conditions
m	pitching moment
n	yawing moment
O	outbound leg of mission
0	sea-level standard day
0	sea level
r	reserve leg of mission
r	rudder
S	standard day
s	standard day at altitude
SL	sea level
T	True
t	test day

1.5 Common Abbreviations

Abbreviation	Meaning
a	lift curve slope
a	linear acceleration (ft/sec^2 or m/sec^2)
a	speed of sound
A/A	air-to-air
a/c	aircraft
AAA	anti aircraft artillery
AC	aerodynamic center
ac	alternating current
ACM	air combat maneuvering
A/D	analog to digital
ADC	air data computer
ADC	analog-to-digital converter
ADF	automatic direction finder
ADI	attitude direction indicator
AFMC	Air Force Materiel Command
AFOTEC	Air Force Operational Test and Evaluation Center
A/G	air-to-ground
AGL	above ground level
AHRS	attitude heading reference system
AM	amplitude modulation
AOA	angle of attack
AOED	age of ephemeris data
APU	auxiliary power unit
AR	air refuel (mode of flight)
AR	aspect ratio = b^2 / S
ARDP	advanced radar data processor
ARSP	advanced radar signal processor
ASPJ	airborne self protection jammer
ATC	air traffic control
avg	average
a_x	longitudinal acceleration
a_y	lateral acceleration
AZ	azimuth
b	span of wing (feet)
B/N	bombardier/navigator
bbl	barrel
BHP	brake horsepower
BICOMS	bistatic coherent measurement system
BID	bus interface device
BIT	built-in test
BSFC	brake specific fuel consumption

Abbreviation	Meaning
Btu	British thermal unit
BW	bandwidth
°C	degrees centigrade (see T)
c	brake specific fuel consumption (BSFC)
c	speed of light in a vacuum (186,282 miles/sec = 299,792,500 [m/s])
c	mean aerodynamic chord (MAC) of a wing
C/A	coarse acquisition
C/N_0	carrier to noise ratio
CADC	central air data computer
CARD	cost analysis requirement document
C_D	coefficient of drag
C_{D_i}	induced drag coefficient
C_{D_0}	zero lift drag coefficient (also parasitic drag coefficient for symmetric wing)
CDI	course deviation indicator
CDMA	code division multiplex access
CDR	critical design review
CDRL	contracts data requirement list
CDU	control display unit
CEA	circular error average
CEP	circular error probable
C_f	coefficient of friction
CFE	contractor furnished equipment
CFT	conformal fuel tank
cg	center of gravity (normally in % MAC)
C_H	hinge moment coefficient
cine	cinetheodolite
C_l	rolling moment coefficient, airfoil section lift coefficient
C_L	lift coefficient
CLHQ	closed loop handling qualities
C_{lp}	roll damping coefficient
C_{lr}	roll moment due to yaw rate coefficient
C_m	pitching moment coefficient
C_M	moment coefficient
cm	centimeters
cos	cosine
cot	cotangent

Abbreviation	Meaning
C_{l_β}	(dihedral) rolling moment due to sideslip
$C_{l_{\delta_a}}$	aileron power coefficient
C_{m_q}	pitch damping coefficient
Cm_α	longitudinal static stability coefficient
$Cm_{\delta e}$	elevator power coefficient
C_n	yawing moment coefficient
C_{n_r}	yaw damping coefficient
cnst	constant
C_{n_β}	directional stability coefficient
$C_{n_{\delta a}}$	adverse yaw coefficient
$C_{n_{\delta r}}$	rudder power coefficient
COTS	commercial, off–the-shelf
CP	center of pressure
C_P	propeller power coefficient
CPU	central processing unit
c_r	wing root chord
CRM	crew resource management
c_t	wing tip chord
CTF	combined test force
CY	calendar year
C_Y	side force coefficient
C_{Y_β}	side force due to sideslip coefficient
$C_{Y_{\delta r}}$	side force due to rudder coefficient
D	diameter
D	drag
D/A	digital/analog
DAC	digital to analog converter
DAPS	data acquisition and processing system
DARPA	Defense Advanced Research Projects Agency
db	decibel
DC	direct current
deg	degrees
DG	directional gyro
DGPS	differential GPS
DMA	Defense Mapping Agency
DME	distance measuring equipment
DoD	Department of Defense
DOP	dilution of precision
DSN	defense switched network

Abbreviation	Meaning
DT	development test
DTC	data transfer cartridge
DTIC	Defense Technical Information Center
e	Oswald efficiency factor
e	natural mathematical constant = 2.718 281 828 459
E	energy
E	lift-to-drag ratio (C_L/C_D , L/D)
EAS	equivalent airspeed
EC	electronic combat
ECCM	electronic counter countermeasures
ECM	electronic countermeasures
ECP	engineering change proposal
ECS	environmental control system
EGT	exhaust gas temperature
EL	elevation
ELINT	electronic intelligence
ELV	expendable launch vehicle
EM	electromagnetic
$E_{\max}$	maximum lift-to-drag ratio
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EMP	electromagnetic pulse
EO	electro optical
EOM	equations of motion
EPR	engine pressure ratio
EPROM	electrically programmable read only memory
E_s	specific energy
ESA	European Space Agency
ESD	Electronic Systems Division
ESHP	equivalent shaft horsepower
ETA	estimate time of arrival
ETE	estimate time en-route
EW	early warning
EW	electronic warfare
°F	degrees Fahrenheit
f	frequency…hertz (originally cycles per second)
F.S.	fuselage station
F_a	aileron force
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation

Abbreviation	Meaning
FCF	functional check flight
FDC	flight data computer
F_e	elevator force
F_{ex}	excess thrust
F_g	gross thrust
FL	flight level
FLIP	flight information publication
FLIR	forward-looking infrared
FM	frequency modulation
FMC	fully mission capable
FMS	flight management system
FMS	foreign military sales
F_n	net thrust
F_n/δ	corrected thrust parameter
FOM	figure of merit
FOT&E	follow-on test & evaluation
FOUO	for official use only
FOV	field of view
fpm	feet per minute
fps	feet per second
FQT	formal qualification test
F_r	rudder force
FRD	functional requirements document
FRL	fuselage reference line
FRL	force, rudder, left
FRR	force, rudder, right
FRR	flight readiness review
FSD	full scale development
FSI	full scale integration
ft	feet
ft-lb	English unit of work...foot-pound...
fwd	forward
FY	fiscal year
g	acceleration due to gravity at altitude
G	gravitational constant = 6.6732x10^{-11} [N m^2/kg^2]
GAO	Government Accounting Office
GCA	ground control approach
GCI	ground controlled intercept
GDOP	geometric dilution of precision
GMT	Greenwich mean time
g_0	standard acceleration due to gravity (sea level, 46 deg latitude)

Abbreviation	Meaning
GPS	global positioning system
GS	ground speed
GSI	glide slope indicator
h	% MAC
H	altitude
HARM	high-speed anti-radiation missile
H_c	calibrated altitude (assumed to be pressure altitude in flight test)
H_D	density altitude
HDDR	high density digital recorder
HDOP	horizontal dilution of precision
HF	high frequency
Hg	mercury
H_i	indicated altitude
h_m	stick-fixed maneuver point (%MAC)
$h\prime_m$	stick-free maneuver point (%MAC)
h_n	stick-fixed neutral point (%MAC)
$h\prime_n$	stick-free neutral point (%MAC)
hp	horsepower
hr	hour
hrs	hours
HSI	horizontal situation indicator
HUD	head-up display
HV	host vehicle
Hz	hertz
I/O	input/output
IAS	indicated airspeed
IAW	in accordance with
ICAO	International Civilian Aviation Organization
ICU	interface computer unit
ICBM	intercontinental ballistic missile
IFF	identification friend or foe
IFR	instrument flight rules
ILS	instrument landing system
IMC	instrument meteorological conditions
IMN	indicated Mach number
IMU	inertial measuring unit
in	inch
INS	inertial navigation system
INU	inertial navigation unit
IOC	initial operational capability
IOT&E	initial operational test & evaluation

Abbreviation	Meaning
IUGG	International Union of Geodesy and Geographics
I_x, I_x, I_z	moments of inertia
I_{xy}, I_{xz}, I_{yz}	products of inertia
J	joules energy, (Newton-Meter)
J	propeller advance ratio
J&S	jamming and spoofing
JCS	Joint Chiefs of Staff
K	Kelvin (absolute temperature)
K	temperature probe recovery factor
K, k	constants
KCAS	knots calibrated airspeed
KEAS	knots equivalent airspeed
kg	kilogram, metric unit of mass
KIAS	knots indicated airspeed
KISS	keep it simple, stupid
km	kilometer
KTAS	knots true airspeed
kt	knots
L	Lift (lbs)
l	length
L	rolling moment
L/D	Lift-to-drag ratio
LANTIRN	low altitude navigation and targeting IR for night
lat	lateral
lb	pound
$\mathrm{lb_f}$	English unit of force, often just lb (pound)
$\mathrm{lb_m}$	English unit of mass, often just lb (slug)
LCC	life cycle cost
LCD	liquid crystal display
LED	light emitting diode
LLH	latitude, longitude, height
ln	natural log, log to the base e
LO	low observables
Log	common log, to the base 10
LOS	line of sight
l_t	distance from cg to tail's aerodynamic cent
$L_{\delta a}$	rolling moment due to aileron deflection
M	moment (ft-lbs)

Abbreviation	Meaning
M	Mach number
m	mass
m	meter (length)
M	pitching moment
MAG	magnetic
MAP	manifold pressure
mb	millibar
MCA	minimum crossing altitude
M_{cr}	critical Mach number
M_d	drag divergence Mach number
M_{ac}	mean aerodynamic cord
M_{GC}	mean geometric chord
MHz	megahertz
mHZ	millihertz
M_{ic}	instrument-corrected Mach number
MilSpec	military specification
MIL-STD	military standard (publication)
min	minute (time)
mm	millimeter
MOA	memorandum of agreement
MOE	measure of effectiveness
MOP	measures of performance
MOU	memorandum of understanding
MP	manifold pressure
MSL	mean sea level
MTBF	mean time between failures
MTTR	mean time to repair
MX	maintenance
N	newton (force)
N	rotational speed (RPM)
n	load factor (g's)
N	yawing moment
N_1	low pressure compressor speed
N_2	high pressure compressor speed
NACA	National Advisory Committee for Aeronautics
NADC	Naval Air Development Center
NASA	National Aeronautics and Space Administration
NAV	navigation
NED	North, East, Down
NM, nm	nautical mile (6080 feet)
NOE	nap-of-the-earth
NOFORN	not releasable to foreign nationals

Abbreviation	Meaning
NOTAM	notice to airmen
NRC	National Research Council (Canada)
NWC	Naval Weapons Center
N_x	longitudinal load factor (g's)
N_y	lateral load factor (g's)
N_z	normal load factor (g's)
OAT	outside air temperature
OAT	on aircraft test
OEI	One engine inoperative
OPR	Office of Primary Responsibility
OSD	Office of the Secretary of Defense
OT&E	operational test & evaluation
p	aircraft roll rate (degrees/sec)
P	pressure (N/m^2 ,pounds per square inch)
P_a	ambient pressure
PCM	pulse code modulation
P-code	precision code
PD	pulse Doppler
PDM	pulse duration modulation
PGM	precision guided munitions
PIO	pilot induced oscillations
P_{iw}	total thrust horsepower required
Pk	probability of kill
PLF	power for level flight
P_0	standard atmospheric pressure (2116.22 lb/ft^2)
POC	point of contact
P_p	pitot pressure
ppm	parts per million
Prop	propeller
P_s	specific power
P_s	static pressure
PS	pulse search
psf	pounds per square foot
psi	pounds per square inch
P_T	total pressure
PW	pulse width
Q or q	dynamic pressure $= 0.5\rho V^2$
q	aircraft pitch rate
Q	engine torque
q_c	impact pressure $(P_t - P_a)$
°R	degrees Rankine = °F + 459.67

Abbreviation	Meaning
R	perfect gas constant = 8314.34 [J/kmol K]
r	aircraft yaw rate (degrees/sec)
R	earth radius
R	range
R&D	research and development
R&M	reliability and maintainability
R/C	rate of climb
rad	radians
Radar	radio detection and ranging
RAF	resultant aerodynamic force
RAM	radar absorbing material
RAT	ram air turbine
RCS	radar cross section
Re	Reynolds number (dimensionless)
REP	range error probable
RF	range factor
RLG	ring laser gyro
rms	root mean square
RNG	range
ROC	rate of climb
ROC	required obstacle clearance
RPM	revolutions per minute (a.k.a. N)
R/T	receiver/transmitter
RTO	Rejected/refused takeoff
RTO	responsible test organization
S	wing area (ft^2 or m^2)
S_a	horizontal distance between liftoff and specified height or between specified height and touch down
SA	selective availability
SA	situational awareness
SE	specific endurance
sec	seconds (time or angle)
SFC	specific fuel consumption
S_g	ground roll distance
SHP	shaft horsepower
SI	international system of units
SIGINT	signal intelligence
sin	sine
SL	sea level
SLAM	standoff land attack missile
SLR	side-looking radar
S/N	serial number

Abbreviation	Meaning
S/N	signal -to-noise ratio
SOF	special operations forces
SOW	stand-off weapon
SR	specific range
SRB	safety review board
S_T	tail area
std	standard
S_T	total takeoff or landing distance $S_a + S_g$)
STOL	short takeoff and landing
STOVL	short takeoff and vertical landing
T	period of oscillation
T	temperature
t	thickness
T, t	time (sec)
t/c	thickness-to-chord ratio
T_a	ambient temperature
TACAN	tactical air navigation
tan	tangent
T_{as}	standard temperature at altitude
TAS	true airspeed
TBD	to be determined
TD	touchdown
TED	trailing edge down
TEL	trailing edge left
TEMP	test and evaluation master plan
TER	trailing edge right
TEU	trailing edge up
TF	terrain following
THP	Thrust Horsepower
THP_{alt}	horsepower available at altitude
THP_{max}	maximum horsepower available
THP_{min}	minimum horsepower required
THP_{SL}	horsepower required at sea level
TIT	turbine inlet temperature
TM	telemetry
TMN	true Mach number
T/O	takeoff
T_0	standard sea level temperature (59.0°F, 15°C)
TO	technical order
TRB	technical review board
TRD	technical requirements document
TRP	technical resources plan

Abbreviation	Meaning
TSFC	thrust specific fuel consumption
TSPI	time, space, position information
T_t	total temperature
TV	television
T/W	thrust to weight ratio
TWT	track while scan
TWT	traveling wave tube
u	velocity along aircraft's x-axis
UAV	uninhabited aerial vehicle
UHF	ultra high frequency
UPT	undergraduate pilot training
USA	US Army
USAF	US Air Force
USCG	US Coast Guard
USMC	US Marine Corps
USN	US Navy
UT	universal time
UV	ultraviolet
v	velocity along aircraft's lateral axis
V_H	horizontal tail volume coefficient
V_V	vertical tail volume coefficient
V_1	takeoff decision speed
V_2	takeoff safety speed
V_A	design maneuvering speed
VAC	volts AC
V_b	buffet airspeed
V_B	design speed for max gust intensity
V_{br}	velocity for best range
V_c	calibrated airspeed
V_D	design diving speed
VDC	volts DC
VDOP	vertical dilution of precision
V_e	equivalent velocity
V_{FE}	maximum flap extended speed
VFR	visual flight rules
V_g	ground speed
VHF	very high frequency
V_i	indicated airspeed
V_{ic}	indicated airspeed corrected for instrument error
V_{iw}	velocity at sea level std day and std weight
VLE	max speed with landing gear extended

Abbreviation	Meaning
V_{LO}	max speed while operating landing gear
V_{LOF}	lift off speed
VLSIC	very large scale integrated circuit
V_{mc}	minimum directional control speed
VMC	visual meteorological conditions
V_{mca}	minimum directional control speed in the air
V_{mcg}	minimum directional control speed on the ground
$V_m o/M_m o$	maximum operating limit speed
V_{mu}	minimum unstick speed
V_{NE}	never exceed velocity
V_{no}	max structural cruising speed
V_{opt}	optimum velocity for endurance flight
VOR	VHF omni-directional range
VORTAC	VOR + TACAN
$V_{P_{\mathrm{min}}}$	velocity for minimum power
$V_{P_{\mathrm{min}_{\mathrm{SL}}}}$	velocity for minimum power at sea level
V_R	rotation speed
V_S	stall speed
V_{S_0}	stall speed in landing configuration
V_{S_1}	stall speed in some defined configuration
VSTOL	vertical/short takeoff and landing
V_T	true airspeed
VTOL	vertical takeoff & landing
VVI	vertical velocity indicator
V_W	wind velocity
V_X	speed for best angle of climb
V_Y	speed for best rate of climb
W	weight
w	component of velocity along aircraft's Z-axis
WDL	weapon data link
W/δ	weight-to-pressure ratio
W_f	fuel weight
WGS-84	World Geodetic System, 1984
WI	watch item
WIT	watch item
WOD	word of day
WOW	weight on wheels

Abbreviation	Meaning
WPT	waypoint
wrt	with respect to
$\frac{\dot{W}_f}{\delta\sqrt{\theta}}$	corrected fuel flow parameter
W/S	wing loading
W_f	fuel flow (lb/hr)
x	aircraft longitudinal axis, a line running through the nose & tail
X_{ac}	distance from leading edge to aerodynamic center
Xlink	cross link
y	aircraft lateral axis, a line running the wingtips
Y	force along y-axis
Y-code	encrypted P-code
z	aircraft vertical or yaw axis, a line perpendicular to the longitudinal and lateral axes
ΔH_{ic}	altimeter instrument correction
ΔH_{pc}	altimeter position error correction
ΔP_p	pitot pressure error
ΔP_s	static pressure error
ΔV_c	scale attitude correction to airspeed
ΔV_{ic}	instrument correction to airspeed indicator
ΔV_{pc}	correction for airspeed position error
∞	infinity, or freestream conditions

1.6 Sign Conventions

(reference 1.8)

Editor's note There is near unanimous agreement on most sign conventions except for pilot inputs and control surface deflections. Although individual organizations generally are consistent in-house, confusion often arises when trying to mathematically translate inputs & deflections from one organization to another. This section documents the generally accepted "body axes" sign conventions then discusses the rationale for several viewpoints addressing the "inputs & deflections" debate. Below is the SFTE sign convention.

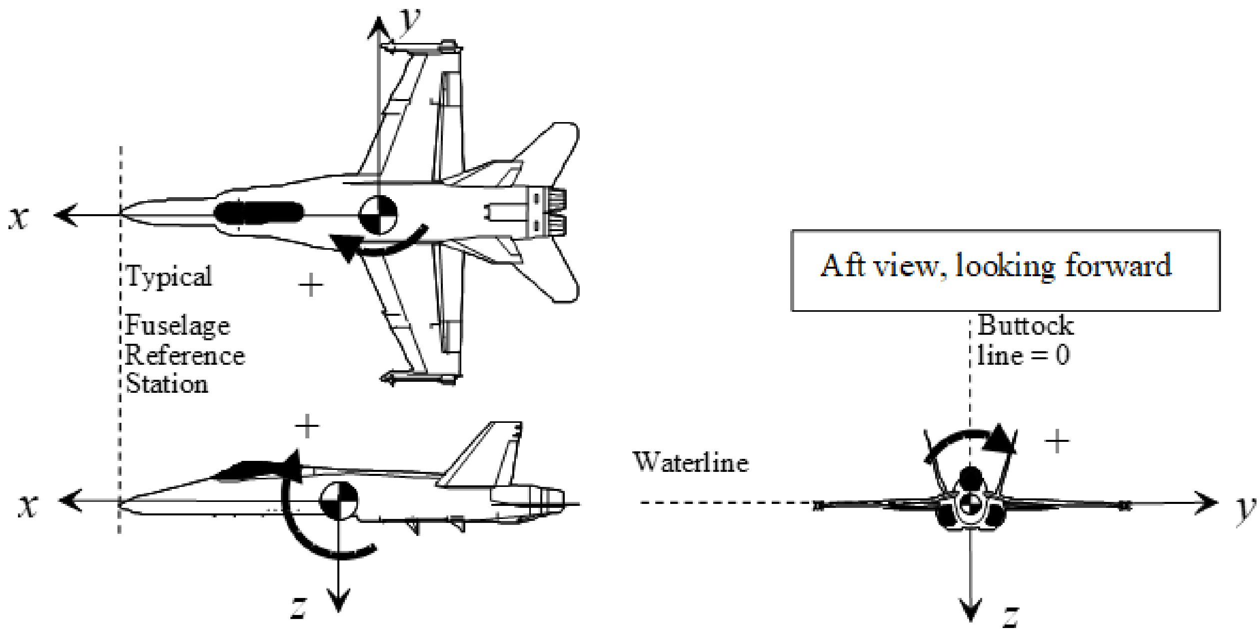
Wind Axes Sign Convention

Winds are listed according to the direction they are coming from. Airports refer winds to magnetic North while winds at altitude are typically referred to true North. Headwind is true airspeed minus ground speed. ($V_w = V_T - V_g$).

Body Axes Sign Convention

The generally accepted body axes sign convention is based on the establishment of a three-dimensional axis system with the following properties:

1. It is right-handed orthogonal
2. Its origin is at the vehicle's reference center of gravity (defined by builder).
3. The axis system moves with the airframe.



Translational displacements, rates, accelerations, & forces are positive along the positive body axes directions. In spite of the simplicity of this logic, it is important to recognize that lift and normal load factor are positive in the *negative* z direction and the drag is positive in the *negative* x direction.

Angular displacements, rates, accelerations & moments, are positive according to the "right hand rule" (a clockwise rotation while looking in the direction of the positive axis) as shown in the figure.

The body axes, forces & translations along them, and moments & rotations about them are shown with arrows indicating the positive direction.

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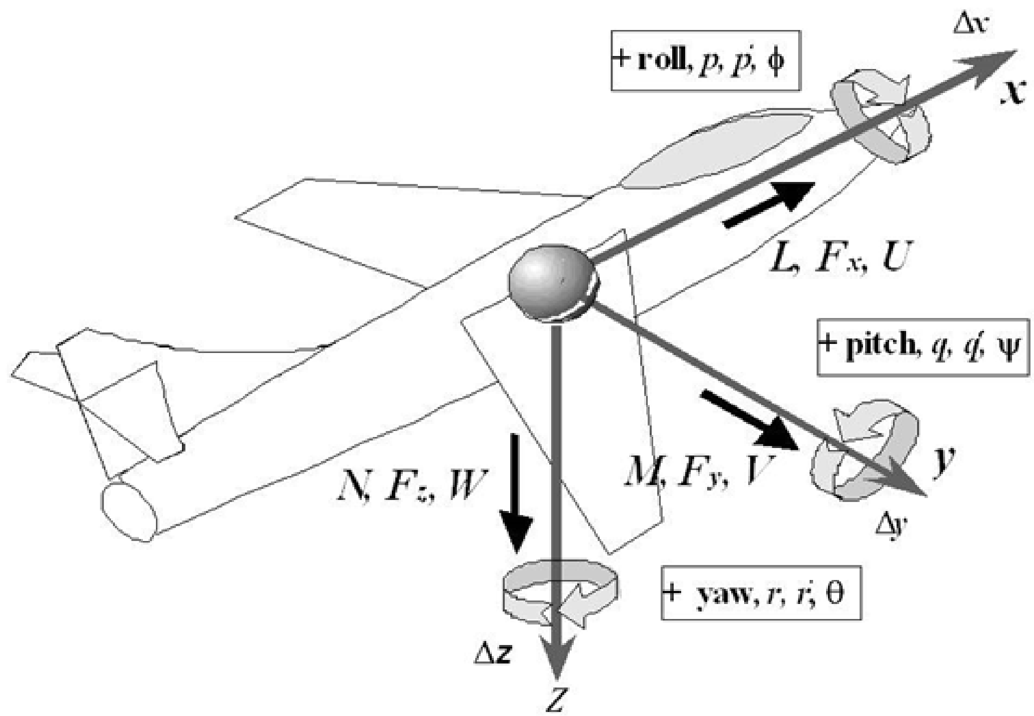


Angle of attack is positive clockwise from the projection of the velocity vector on the xz plane to the reference x body axis. The angle of sideslip is positive clockwise from the xz plane to the velocity vector (wind in the pilot's right ear).

Aircraft *true* heading is the angle between *true* North and the projection of the x-body axis onto the horizontal plane. Mag. heading refers to mag North

The velocity vector is measured relative to the air mass while the flightpath is measured relative to the ground. They are equivalent only when winds are zero.

Flightpath heading angle (ground track heading) σ_g, is the horizontal angle between true North and the projection of the flightpath on the horizontal plane. Positive rotation is from north to east.

Flightpath elevation angle; , is the vertical angle between the flightpath and the horizontal plane. Positive rotation is up. During a descent, this parameter is commonly known as glide path angle.

Flightpath bank angle; μ, is the angle between the plane formed by the velocity vector and the lift vector and the vertical plane containing the velocity vector. Positive rotation is clockwise about the velocity vector, looking forward.

Fuselage reference station (FRS), Water line (WL), and Buttock line (BL) are reference coordinates established by the design group.

Summary of Generally Accepted Body Axes Sign Convention

Parameter Name	**Symbol**	**Positive Direction**
Translational Measurements		
Longitudinal axis	x	from ref *cg* towards nose
Lateral axis	y	from reference *cg* towards right
Vertical axis	z	from reference *cg* towards vehic
Longitudinal velocity	u	along +x axis
Lateral velocity	v	along +y axis
Vertical velocity	w	along +z axis
Long. acceleration	a_x	along + x axis
Lateral acceleration	a_y	along +y axis
Vertical acceleration	a_z	along +z axis
Longitudinal load factor	N_x	along +x axis
Lateral load factor	N_y	along +y-axis
Normal load factor	N_z	along –z axis
Longitudinal force	F_x	along the +x axis
Lateral force	F_y	along the +y axis
Normal force	F_z	along the + z axis
Drag force	D	along the –x axis
Side force	Y	along the + y axis
Lift Force	L	along the –z axis

Summary of Generally Accepted Body Axes Sign Convention

Parameter Name	**Symbol**	**Positive Direction**
Angular Measurements		
Bank angle		right wing down
Pitch angle		nose-up
Heading		0 North, +Eastward
Angle of attack		normal flight attitude
Angle of sideslip		“wind in the right ear”
Roll rate	p	right wing down
Pitch rate	q	nose up

Summary of Generally Accepted Body Axes Sign Convention		
Yaw rate	r	nose right
Roll moment	L	right wing down
Pitch moment	M	nose up
Yaw moment	N	nose right
Flightpath bank angle	μ	| right wing down
Flightpath elevation		climb
Flightpath heading	$_g$	0 true North, + East-ward

Discussion of "Input & Deflection" Conventions

The debate regarding proper inputs and deflections stems from the user's viewpoint. From the body axis convention above, flight testers recognize that a climbing right turn generates positive angular measurements. Logically then, pull, right roll and right yaw pilot inputs and subsequent surface deflections should also be positive. The traditional flight tester's convention follows as "All input forces & displacements, surface deflections, and motions that cause a climbing right turn are positive."

Due to differential nature of aileron deflections, they require more discussion. The flight tester's logic implies (but does not dictate) positive deflections are right aileron up and left aileron down. It is, however, equally acceptable to assign downward (or upward) deflection as positive for both ailerons and calculate the difference between the two as a measure of rolling moment.

The rationale within the wind tunnel community is also logical: any control surface deflection that increases lift is positive. From this, positive deflections are trailing edge down (TED) for each: trailing edge flap, stabilizer, elevator, stabilator, rollervator, ruddervator, canard, aileron, flaperon, and all their tabs. Leading edge flap down is also positive. Similarly, since side force is positive to the right, then positive rudder and rudder tab deflections are trailing left (TEL). The only exception to this straightforward logic is for spoilers and speed brakes that extend only in one direction: this deflection is positive even though it might decrease the lift.

Since the above rationale defines downward deflection as positive for both ailerons, a measurement of rolling moments requires calculation of the differential aileron deflection. This rationale does not, however, specifically dictate whether a "positive" differential deflection should generate right wing down (RWD) or left wing down (LWD) moments. Differential aileron can be calculated as either.

$\delta_a = \frac{\delta_{a_R} - \delta_{a_L}}{2}$ or $\delta_a = \frac{\delta_{a_L} - \delta_{a_R}}{2}$

Selection of the RWD convention is obvious from the flight tester's viewpoint since deflections that generate right rolls are positive. An alternative interpretation is that a positive differential aileron deflection is one that lifts the positive (right) wing lifts more than the left (LWD).

Another common convention for ailerons is one that gives the same sign to both ailerons for any input. The "right hand screw" convention is opposite to the flight tester's convention, but may be more common:

$\delta_{a_R} = +\text{TED}$, $\delta_{a_L} = +\text{TEU}$.

The above wind tunnel rationale dictates only the polarity for individual control surface deflections, and leaves open the sign convention debate about controller (inceptor) input forces & displacements. One approach is that positive inputs should generate positive *motions* while an alternate approach is that positive inputs generate positive *surface deflections*. Only the flight tester's convention states that positive inputs yield positive motions *and* deflections. All approaches are mathematically connected to the hinge moment sign convention discussed below.

The simplest control surface hinge moment convention is that *all* positive hinge moments (generated by the pilot and the aerodynamics) move the surface in a positive direction, i.e., positive input forces yield positive deflections. This has different implications for the different sign conventions:

- According to the above flight tester's sign convention, a positive pull force is required to generate a positive (TEU) elevator deflection (positive stick force generates a climb).

- According to wind tunnel sign convention, a positive *push* force is required to generate a positive (*TED*) elevator deflection (positive stick force generates a *dive*).

The alternate viewpoint defines a positive inceptor hinge moment as one that *opposes* the aerodynamic moments. In other words, a positive inceptor hinge moment moves the surface to a position which generates positive aerodynamic hinge moments or "positive input forces & displacements generate negative surface deflections."

Based on the above background, the SFTE technical council proposes the following standard convention for inceptor & surface forces & deflections:

- Due to its widespread use and its simple & robust nature, use the wind tunnel convention for control surface deflections.

- Due to widespread test pilot & FTE familiarity and logical nature, use the flight tester's convention that positive inceptor forces & displacements generate a climbing right turn.

- A fallout from these conventions is that positive inceptor hinge moments generate positive aerodynamic hinge moments (negative surface deflections).

- Consistent use of the above logic requires that the calculated value for aileron deflection be negative for right wing down moments. Similarly, differential ruddervator deflections generating nose right yawing moments should have negative values.

Conventions for Positive Control Surface Deflections

Parameter	Symbol	Flight Test	SFTE/ Wind Tunnel
Horizontal Stabilizer	$_{i}$	TEU	TED
Elevator	$_{e}$	TEU	TED
Elev. Tab	$_{et}$	TED	
Stabilators or Rollervators, average: differential:	$_{eL}$, $_{eR}$	TEU	TED
	$_{e}$	= ($_{eR}$ + $_{eL}$)/2	
	$_{e}$	= ($_{eR}$ - $_{eL}$)/2	
Elevons average: differential	$_{vL}$, $_{vR}$	TEU	TED
	$_{v}$	= ($_{vR}$ + $_{vL}$)/2	
	$_{v}$	= ($_{vR}$ - $_{vL}$)/2	
Flaperons or trailing edge flap average: differential:	$_{fR}$, $_{fL}$	TED	
	$_{f}$	= ($_{fR}$ + $_{fL}$)/2	
	$_{f}$	= - ($_{fR}$ - $_{fL}$)/2	= ($_{fR}$ - $_{fL}$)/2

Conventions for Positive Control Surface Deflections (Cont'd)

Parameter	Symbol	Flight Test	SFTE/ Wind Tunnel
Canards average: differential	$_{cL}$, $_{cR}$	TED	
	$_{c}$	= ($_{cR}$ + $_{cL}$)/2	
	$_{c}$	= - ($_{cR}$ - $_{cL}$)/2	= ($_{cR}$ - $_{cL}$)/2

Conventions for Positive Control Surface Deflections (Cont'd)			
Leading edge flap Average: Differential:	$_{lefL}$, $_{lefR}$	TED	
	$_{lef}$	$= (_{cR} + _{cL})/2$	
	$_{lef}$	$= - (_{cR} - _{cL})/2$	$= - (_{cR} - _{cL})/2$
Ruddervators Average: Differential:	$_{rvL}$, $_{rvR}$	TEU	TED
	$_{rv}$	$= (_{rvR} + _{rvL})/2$	
	$_{rv}$	$= - (_{rvR} - _{rvL})/2$	
Ailerons Aileron Tab Average:	$_{aL}$, $_{aR}$	$_{aR}$TEU, $_{aL}$ TEDor $\{ _{aR}, _{aL}$TED$\}$	$_{aR}, _{aL}$ *TED*
	$_{at}$	$= (_{aR} + _{aL})/2$	$_{at}$ TED
	$_{a}$	$= - (_{aR} - _{aL})/2\}$	$= (_{aR} - _{aL})/2$ *
Spoilers average: Differential:	$_{sL}$, $_{sR}$	Extended	
	$_{s}$	$= (_{sR} + _{sL})/2$	
	$_{s}$	$= (_{sR} - _{sL})/2$	$= - (_{sR} - _{sL})/2$
Rudders Average:	$_{rR}$, $_{rL}$	TER	TEL
	$_{r}$	$= (_{rR} + _{r\ L})/2$	
Rudder tab	$_{rt}$	TEL	
Speed brake	$_{sb}$	Extended	

Conventions for Positive Inputs and Hinge Moments			
Parameter	**Symbol**	**Flight Test**	**SFTE/ Wind Tunnel**
Stick/Wheel Long Force	F_e	Pull	
Stick/Wheel Lateral Force	F_a	Right	
Pedal Force	F_r	Right pedal push	

Conventions for Positive Inputs and Hinge Moments			
Stick/Wheel Long. deflectn	s_e	Aft	
Stick/wheel Lat. deflection	s_a	Right	
Pedal deflection	$_{pR}, \ _{pL}$	Right pedal push	
Aerodynamic Hinge Moments	C_h C_h C_h $C_{h\ tab}$	positive moments generate positive deflections	
Inceptor Hinge Moments	C_{hFe} C_{hFa} C_{hFr}	+ moments generate + deflections	+ moments generate - deflections

*The wind tunnel rationale does not inherently define the polarity for control surface differential deflections.

#The wind tunnel rationale does not specify a convention for positive inputs or hinge moments. Historically, Dutch, U.S. and some British aircraft use a climbing right turn, while it is a diving left turn for Canadian, Australian, and some British aircraft.

The SFTE Technical Council recognizes that several combinations of the above possibilities are currently in use around the world, and invites comments, additions, or corrections to the above summary and proposal. Although SFTE does not expect all organizations to adopt this standard, it still ***provides a cornerstone for reference purposes***

1.7 Thermodynamics Relations

(references 1.3, 1.4, 1.5, 1.6)

1.7.1 Thermodynamic Definitions

A **Process** is an event with a redistribution of energy within a system.

A **Reversible** process is one that can be reversed such that the system returns to its original state (form, location & amount).

An **Irreversible** process cannot return to its original state due to heat flow from higher to lower temperatures, fluid turbulence, friction, or inelastic deformation. The change in entropy is non-zero.

An **Isothermal** process is one in which the temperature of the fluid is constant.

An **Adiabatic** process is one in which heat is not transferred to or from the fluid.

Work is the energy *transfer* by way of changing mechanical energy.

Heat is the energy *transfer* from one body to another by virtue of a temperature difference between them.

An **Isentropic** process has constant entropy.

Conduction is the energy transfer from a warmer body by tangible contact (transfer of some internal molecular kinetic energy).

Convection is the repositioning the energy of a fluid without state changes or energy transformations (e.g. heated air moving from one room to another room).

Radiation is the energy transmission through space.

1.7.2 Thermodynamic Symbols

Symbol	Use
A	area
C	compressibility factor
c	speed of sound
$E = u$	specific internal energy (e.g. Btu/lb)
H	specific **enthalpy** (e.g. Btu/lb)
J	Joule
Q	energy supplied to a system or region as heat (e.g. Btu/lb)
P	absolute pressure (e.g. lbs/ft^2)
V	specific volume (e.g. ft^3/lb)
W	work (+ if entering)
$\overline{V}$	velocity
Δ	change (final - initial value)
Z	altitude
S	specific entropy
R	gas constant for each gas (for air = 287 J/kg/K = 53.35 ft-lb/lb$_{\text{m}}$R)

Symbol	Use
$\overline{R}$	universal gas constant = 8.314 kJ/kmol/K = 1545 ft lb/lbmol/R
M	molar mass (for air = 28.97 kg/kmol)
N	number of moles
ρ	density

1.7.3 Thermodynamic Laws

The **First Law of Thermodynamics** shows that the net amount of energy added to a system equals the net change in energy within the system (Principle of Conservation of Energy): $W + Q = (E_2 - E_1)$

The **Second Law of Thermodynamics** states that entropy increases during any irreversible process: $S_2 > S_1$

Ideal Gas Equation of State (a.k.a. Perfect gas law):

$$PV = RT \tag{1.1}$$
$$P = \rho RT \tag{1.2}$$
$$PV = mRT \tag{1.3}$$
$$PV = nRT \tag{1.4}$$
$$\tag{1.5}$$

$$\delta = \sigma\theta$$

where

$$\delta = \frac{P_a}{P_0} \tag{1.6}$$
$$\sigma = \frac{\rho_a}{\rho_0} \tag{1.7}$$
$$\theta = \frac{T_a}{T_0} \tag{1.8}$$

Boyle's Law states that when the temperature of a given mass of gas is held constant, then the volume and pressure vary inversely.

$$P_1V_1 = P_2V_2$$

where

$$T_1 = T_2$$

Charles' Law states that when a volume of a given mass is held constant, then the change in pressure of the gas is proportional to the change in temperature.

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

where

$$V_1 = V_2$$

Real Gas Relation:

$$PV = CRT$$

For reversible processes:

$$W = -\int PdV \tag{1.9}$$

$$Q = \int TdS \tag{1.10}$$

For reversible adiabatic processes:

$$\frac{P_1}{P_2} = \left[\frac{V_2}{V_1}\right]^{\gamma} \tag{1.11}$$

$$\frac{T_1}{T_2} = \left[\frac{V_2}{V_1}\right]^{\gamma-1} \tag{1.12}$$

$$\frac{T_1}{T_2} = \left[\frac{P_1}{P_2}\right]^{\frac{\gamma-1}{\gamma}} \tag{1.13}$$

$$\frac{P_1}{P_2} = \left[\frac{\rho_1}{\rho_2}\right]^{\gamma} \tag{1.14}$$

$$\tag{1.15}$$

Steady Flow Energy Equation

$$Q + H_1 + \frac{\overline{V}_1^2}{2g} + Z_1 = W + H_2 + \frac{\overline{V}_2^2}{2g} + Z_2$$

Bernoulli Equation:

$$\frac{\Delta P}{\rho g} + \frac{\overline{V}_2^2 - \overline{V}_1^2}{2g} + \Delta Z = 0$$

Flow per Unit Area:

$$\frac{W}{A} = \sqrt{\frac{\gamma}{R}\frac{P}{\sqrt{T}}\frac{M}{\left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}}$$

Velocity of sound in a perfect gas:

$$c = \sqrt{\gamma g R T}$$

Development of **Specific Heat Relations**:

Specific heat at constant pressure (for air = 1004.76 J/kg/K)

$$c_p \equiv \left.\frac{\partial H}{\partial T}\right|_P$$

Specific heat at constant volume (for air = 717.986 J/kg/K)

$$c_v \equiv \left.\frac{\partial u}{\partial T}\right|_V$$

Ratio of specific heats

$$\kappa = \gamma \equiv \frac{c_p}{c_v}$$

Enthalpy equation in differential form is:

$$dH = du + d(PV)$$

Substituting definitions and ideal gas law gives

$$c_p\, dT = c_v\, dT + R\, dt \tag{1.16}$$

$$\text{or} \tag{1.17}$$

$$c_p = c_v + R \tag{1.18}$$

Rearranging gives

$$c_p = R\frac{\kappa}{\kappa - 1} \tag{1.19}$$

$$\text{and} \tag{1.20}$$

$$c_v = R\frac{1}{\kappa - 1} \tag{1.21}$$

Development of **Poisson's Equation**:

1) From the 1st law:

$$W + Q = E_2 - E_1$$

2) Substitution for each term gives:

$$T\, dS - P\, dV = du$$

3) Divide through by T:

$$dS = \frac{du}{T} + \frac{P\, dV}{T}$$

4) Recall:

$$du = c_v\, dT$$

and

$$PV = RT$$

5) Substitution gives:

$$dS = c_v\frac{dT}{T} + R\frac{dV}{V}$$

6) Assume constant specific heat and integrate:

$$s_2 - s_1 = c_v\, \ln\frac{T_2}{T_1} + R\, \ln\frac{V_2}{V_1}$$

7) Assuming a reversible adiabatic process:

$$c_v\, \ln\frac{T_2}{T_1} = -R\, \ln\frac{V_2}{V_1}$$

8) Substitute

$$c_v = R\frac{1}{\kappa - 1}$$

to get:

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\kappa-1}$$

9) Differentiate H:

$$dH = du + P\,dV + V\,dP$$

10) Substitution into step #2:

$$T\,dS = dH - V\,dP$$

11) Integrate:

$$s_2 - s_1 = c_p\,\ln\frac{T_2}{T_1} + R\,\ln\frac{P_2}{P_1}$$

12) Assuming a reversible adiabatic process:

$$c_p\,\ln\frac{T_2}{T_1} = -R\,\ln\frac{P_2}{P_1}$$

13) Substitute

$$c_v = R\frac{\kappa}{\kappa - 1}$$

to get:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\kappa-1}{\kappa}}$$

14) Combine steps #8, #13 to get:

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\kappa}$$

or

$$(PV)^{\kappa} = \text{const}$$

1.8 Mechanics Relations

1.8.1 Mechanics Symbols

Symbol	Use
a	linear acceleration
a_r	centripetal (radial) acceleration
a_T	tangential acceleration
F	force
g	acceleration due to gravity
G	moment
H	angular momentum
H	height
Hp	horsepower
I	rotational moment of inertia (see section 10)
J	impulse = change in momentum
k	radius of gyration
m	mass
N_r	radial load factor
P	power
L	linear momentum
Q	moment (a.k.a. torque)
r	radius
S	distance, displacement
s	seconds
t	time
V	true inertial velocity
V_0	initial inertial velocity
W	work
q	angular displacement
Vol	volume
ω	angular velocity (radians/second)
$\dot{\omega}$	angular acceleration

1.8.2 Newton's Laws

1st law (law of inertia):

"Every body persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed on it."

2nd Law:

"The change in motion is proportional to the motive force impressed and is made in the direction of the straight line in which that force is impressed" (motion defined as velocity x quantity of matter or linear momentum, $m\,V$).

$$dF = \frac{d(mV)}{dt}$$

For constant mass in rectilinear motion:

$$F = ma$$

For constant mass distribution in curvilinear motion:

$$G = \dot{\omega} I$$

3$^{\text{rd}}$ Law:

"Every action has an equal and opposite reaction; or, the mutual attraction of two bodies upon each other are always equal and directed to contrary parts.(opposite directions)"

1.8.3 Planar Kinetics, Work, Power and Energy

Rectilinear motion		Curvilinear motion	
displacement	S	angular displacement	θ
velocity	$V = \frac{dS}{dt}$	angular velocity	$\omega = \frac{d\theta}{dt}$
acceleration	$a = \frac{dV}{dt}$	angular acceleration	$\dot{\omega} = \frac{d\omega}{dt}$
inertia	m	rotational inertia	$I = \int r^2 dm$
momentum	$L = m\,V$	angular momentum	$H = I\omega$
force	$F = m\,a$	torque	$Q = I\dot{\omega}$

Rectilinear motion		Curvilinear motion	
work	$W = \int F\, dS$	work	$W = \int Q d\theta$
power	$P = F\, V$	power	$P = Q\omega$
kinetic energy	$\frac{1}{2} m V^2$	kinetic energy	$\frac{1}{2} I \omega^2$
potential energy	mgH	n/a	

1.8.4 Planar Kinematics at Constant Acceleration

Rectilinear motion	Curvilinear motion
$V = V_0 + at$	$\omega = \omega_0 + \dot{\omega} t$
$V^2 = V_0^2 + 2aS$	$\omega^2 = \omega_0^2 + 2\dot{\omega}\theta$
$S = V_0 t + \frac{1}{2} a t^2$	$\theta = \omega_0 t + \frac{1}{2} \dot{\omega} t^2$
$S = \frac{1}{2}(V + V_0) t$	$\theta = \frac{1}{2}(\omega + \omega_0) t$
$S = \frac{(V^2 - V_0^2)}{2a}$	$\theta = \frac{(\omega^2 - \omega_0^2)}{2\dot{\omega}}$

Rectilinear motion	Curvilinear motion
$t = \frac{-V_0 + \sqrt{V_0^2 + 2\text{aS}}}{a}$	$t = \frac{-\omega_0 + \sqrt{\omega_0^2 - 2\dot{\omega}\theta}}{\dot{\omega}}$
$a = \frac{2\,(S - V_0 t)}{t^2}$	$\dot{\omega} = \frac{2(\theta - \omega_0 t)}{t^2}$

1.8.5 Curvilinear motion with constant acceleration and radius

$$r = \frac{V^2}{gN_r}$$
$$V = \omega r$$
$$N_r = \frac{a_r}{g}$$
$$\omega = \frac{gN_r}{V}$$
$$\dot{\omega} = \frac{V}{R}$$
$$a_r = r\omega^2 = \frac{V^2}{r}$$
$$a_r = \dot{\omega} r$$

1.8.6 Aircraft in level turn

N_{z_w} = load factor normal to flight path

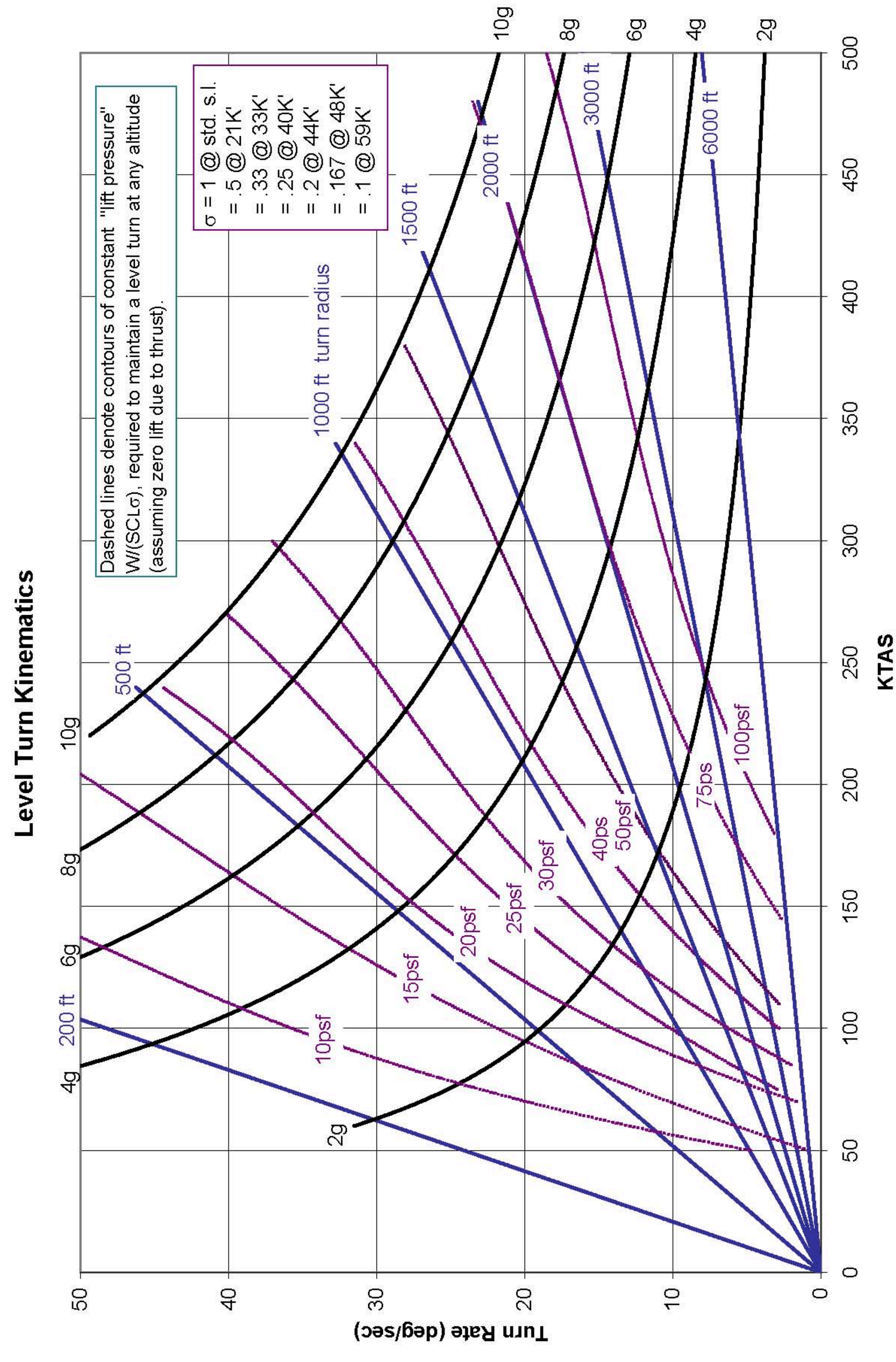
r = turn radius

Ω = turn rate (rad/sec)

$$r = \frac{V^2}{g\sqrt{N_{\text{zw}}^2 - 1}}$$
$$\omega = \frac{g\sqrt{N_{\text{zw}}^2 - 1}}{V}$$
$$N_{z_w} = \sqrt{\frac{\omega V}{g} + 1}$$

V = inertialvelocity

1.8.7 Level Turn Kinematics Character



1.8.8 Gyroscopic Motion

(reference 1.7)

For bodies spinning about an axisymmetric axis

$\dot{\psi}$ = spin rate
$\dot{\phi}$ = precession rate
$\dot{\theta}$ = nutation rate

I_z = moment of inertia about spin axis
I_t = transverse moment of inertia about the spin point (perpendicular to spin axis)
I_{cg} = moment of inertia about the cg (perpendicular to spin axis)
M_x = moment about spin point (acting along plane that defines θ)

For steady precession (constant $\dot{\theta}$, $\dot{\phi}$, $\dot{\psi}$)

$$\sum M_x = -I_t\dot{\phi}^2 \sin\theta\cos\theta + I_z\dot{\theta}\sin\theta\left(\dot{\phi}\cos\theta + \dot{\psi}\right)$$

For torque free motion (gravity is only external force)

$$\dot{\psi} = \frac{I_{\text{cg}} - I_z}{I_z}\dot{\phi}\cos\theta$$

note that $I_{\text{cg}} > I_z$ yields regular precession

while $I_{\text{cg}} < I_z$ yields retrograde precession

1.9 International Phonetic Alphabet and Morse Code

Character	Say	Morse Code
A	Alpha	•
B	Bravo	• • •
C	Charlie	• •
D	Delta	• •
E	Echo	
F	Foxtrot	• • •
G	Golf	•
H	Hotel	• • • •
I	India	• •

Character	Say	Morse Code
J	Juliet	•
K	Kilo	•
L	Lima	• • •
M	Mike	
N	November	•
O	Oscar	
P	Papa	• •
Q	Quebec	•
R	Romeo	• •
S	Sierra	• • •
T	Tango	
U	Uniform	• •
V	Victor	• • •
W	Whiskey	•
X	X-ray	• •
Y	Yankee	•
Z	Zulu	• •
1	One	•
2	Two	• •
3	Tree	• • •
4	Four	• • • •
5	Fife	• • • • •
6	Six	• • • •
7	Seven	• • •
8	Eight	• •
9	Niner	•
0	Zee-ro	

1.10 References

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Chapter 2

Mathematics

2.1 Algebra

(reference 2.1)

2.1.1 Laws

Commutative	$a + b = b + a$, $ab = ba$
Associative	$a + (b + c) = (a + b) + c$
Distributive	$a(b + c) = ab + ac$

2.1.2 Identities

Exponents	Logarithms[1]
$a^x a^y = a^{x+y}$	$\log_b b = 1$
$(ab)^x = a^x b^x$	$\log_b 1 = 0$

Exponents	Logarithms[1]
$(a^x)\,y = a^x y$	$\log_b (MN) = log_b M + log_b N$
$a^{mn} = (a^m)^n$	$\log_b \left(\frac{M}{N}\right) = \log_b M - \log_b N$
$a^0 = 1$	$\log_b (M^p) = p \log_b M$
If $a \neq 0$	
$a^{-x} = \frac{1}{a^x}$	$\log_b \left(\frac{1}{M}\right) = -\log_b M$
$\frac{a^x}{a^y} = a^{x-y}$	$\log_b \sqrt[q]{M} = \frac{1}{q} \log_b M$
$\sqrt[x]{ab} = (\sqrt[x]{a})\left(\sqrt[x]{b}\right)$	$\log_b M = (\log_c M)(\log_b c) = \frac{\log_c M}{\log_c b}$
$a^{\frac{x}{y}} = \sqrt[y]{a^x} = (\sqrt[y]{a})^x$	
$a^{\frac{1}{y}} = \sqrt[y]{a}$	