

RATIONALE

Nozzle thrust vectoring has become a major contributor to military aircraft performance and control. This SAE Aerospace Information Report is intended to provide guidance on the impacts of thrust vectoring on in-flight thrust determination.

AIR6007 has been reaffirmed to comply with the SAE Five-Year Review policy.

FOREWORD

Thrust Vectoring (TV) is defined as the turning of the thrust force vector away from the nominal installed, undeflected thrust axis for the intended purpose of providing additional aircraft capabilities. Some of the additional or expanded capabilities that have been attributed to thrust vectoring are illustrated in Figure 1.

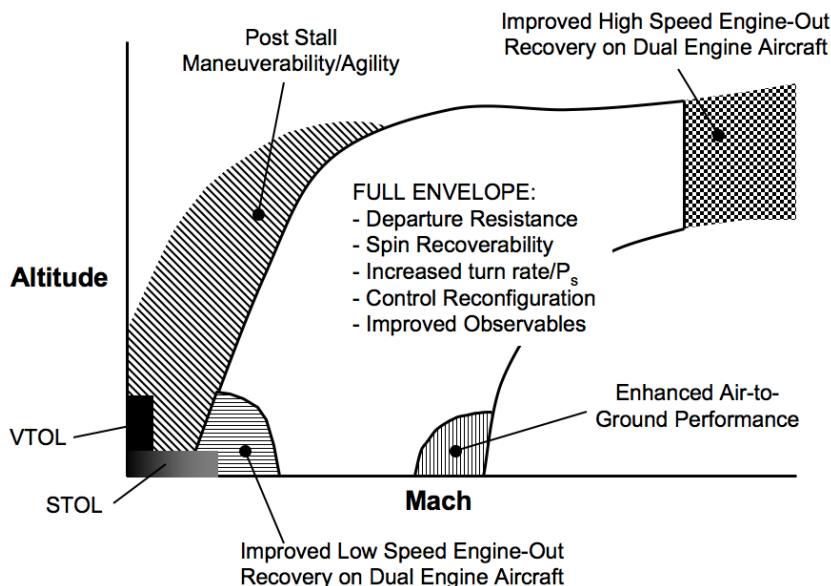


Figure 1 - Thrust vectoring benefits

Because of the increased weight and complexity of thrust vectoring hardware, the additional benefit(s) provided by thrust vectoring are usually required to meet the intended aircraft mission. The added capabilities most often requiring a thrust vectoring capability are vertical take-off and landing (VTOL), short take-off and landing (STOL), and enhanced aircraft control and/or maneuverability.

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A vertical take-off and landing capability allows aircraft to operate from sites that do not have prepared runways, thus enabling front line logistic and ground attack support, or from sites that are too small for conventional take-off and landing aircraft, such as small naval ships. The first use of thrust vectoring to provide a VTOL capability was probably the development of a practical helicopter. In 1923, the Spanish engineer Marquis Raul Pateras Pescara designed, built, and flew (in a controlled manner) the first helicopter to utilize cyclic pitch and a tilting rotor mast to vector rotor thrust to impart forward motion (References 1.1 through 1.4). Helicopters still utilize cyclic control to “tilt” or vector rotor thrust to impart longitudinal and roll motions. The history of thrust vectoring utilization to provide a VTOL capability for fixed wing aircraft is shown in Figure 2 (References 1.1 through 1.3, 1.5, and 1.6). It should be noted that this figure and the following two figures are not all-inclusive and that the dates are approximate. As indicated on Figure 2, a VTOL capability can be provided by (1) rotating the thrust axis by either rotating the entire airplane (with the engine) or rotating the engine alone, (2) installing specifically designed lift engines, fans, or thrust-augmenting ejectors having a nominally vertical thrust axis, or (3) deflecting the engine slipstream or exhaust about 90-degrees. Note that the tilt rotor is shown as a separate line of development even though, except for the XV-3 which tilted only the rotor and not the engine, it is just a special case of rotating or tilting the engine. Some of the VTOL thrust vectoring lines of development, such as body pointing, tilt engine (other than the tilt rotor) and deflected slipstream have not been applied to production aircraft. Others, such as the tilt rotor, lift engine/fan and vectored exhaust lines of development have resulted in current operational aircraft (V-22, Yak-41M, F-35, and AV-8A/AV-8B).

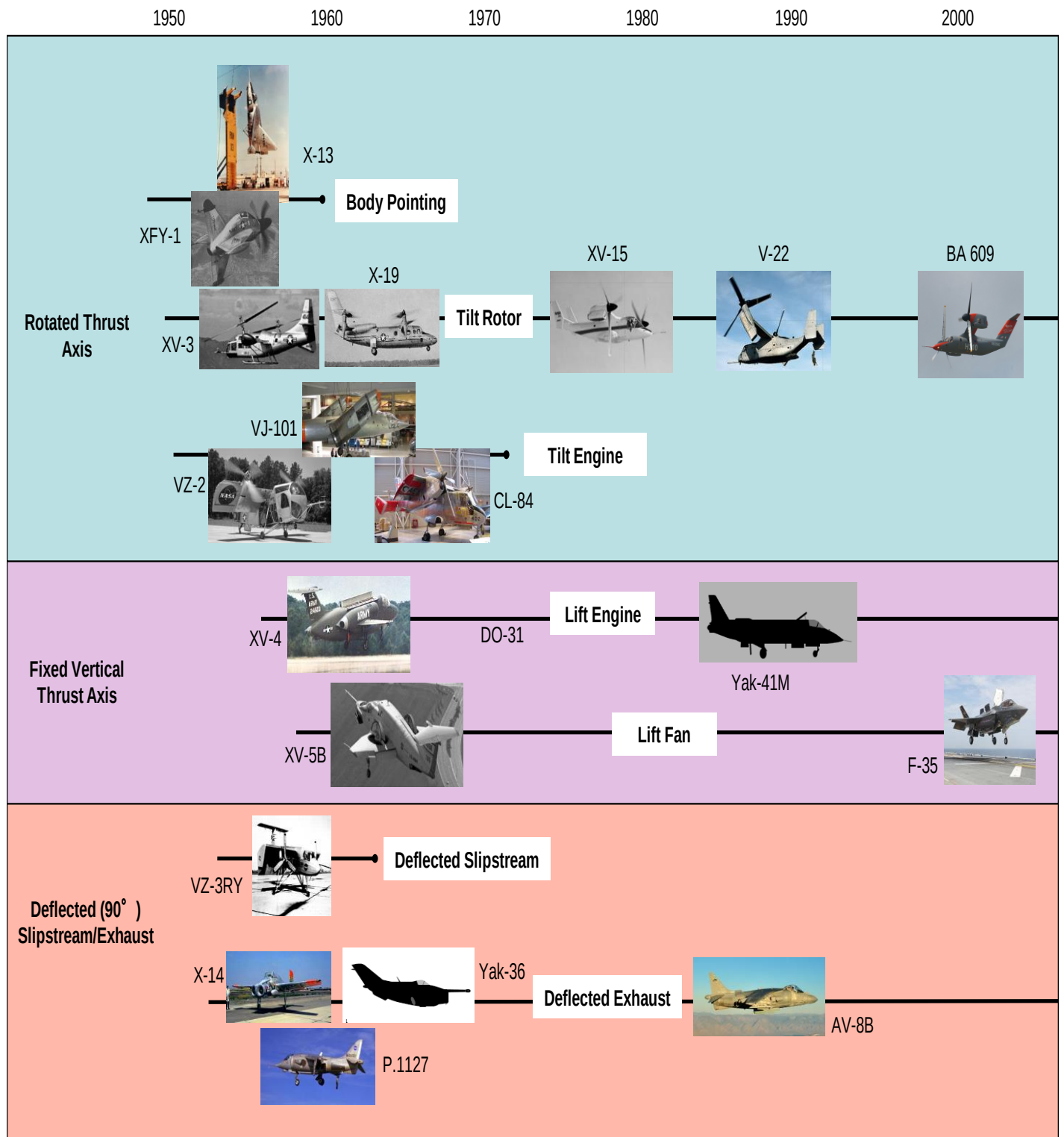


Figure 2 – Thrust vectoring applications for VTOL

A short take-off and landing (STOL) capability allows aircraft to operate from short airfields or from runways that have been shortened by bomb damage while carrying more payload than a comparable VTOL aircraft. This benefit has caused some VTOL aircraft, such as the AV-8B, to operate in a short take-off, vertical landing (STOVL) mode during most aircraft operations. The historical development of thrust vectoring technologies for STOL aircraft applications is shown in Figure 3 (References 1.1 through 1.3 and 1.6 through 1.8). Externally-blown-flap (including boundary layer control such as blown flaps) and upper-surface-blowing vectored thrust technology development resulted in operational aircraft, such as the C-17 and An-72, that are still in service today while the augmentor flap/wing technology has not been applied to production aircraft. Although no operational fighter aircraft have been developed specifically for the STOL mission by utilizing small nozzle thrust vector angles, utilization of nozzle thrust vectoring for other benefits such as aircraft control or maneuverability has been applied and will result in some fall-out STOL capability. Some of the potential STOL benefits attributed to nozzle thrust vectoring in the literature are a 25% reduction in take-off roll by allowing early take-off rotation, a 40% reduction in approach speed (Reference 1.9), 14 to 50% reduction in landing roll (References 1.8 and 1.10 through 1.13); taken together, these benefits can result in a reduced runway length requirement of about 33% (References 1.9 and 1.14).

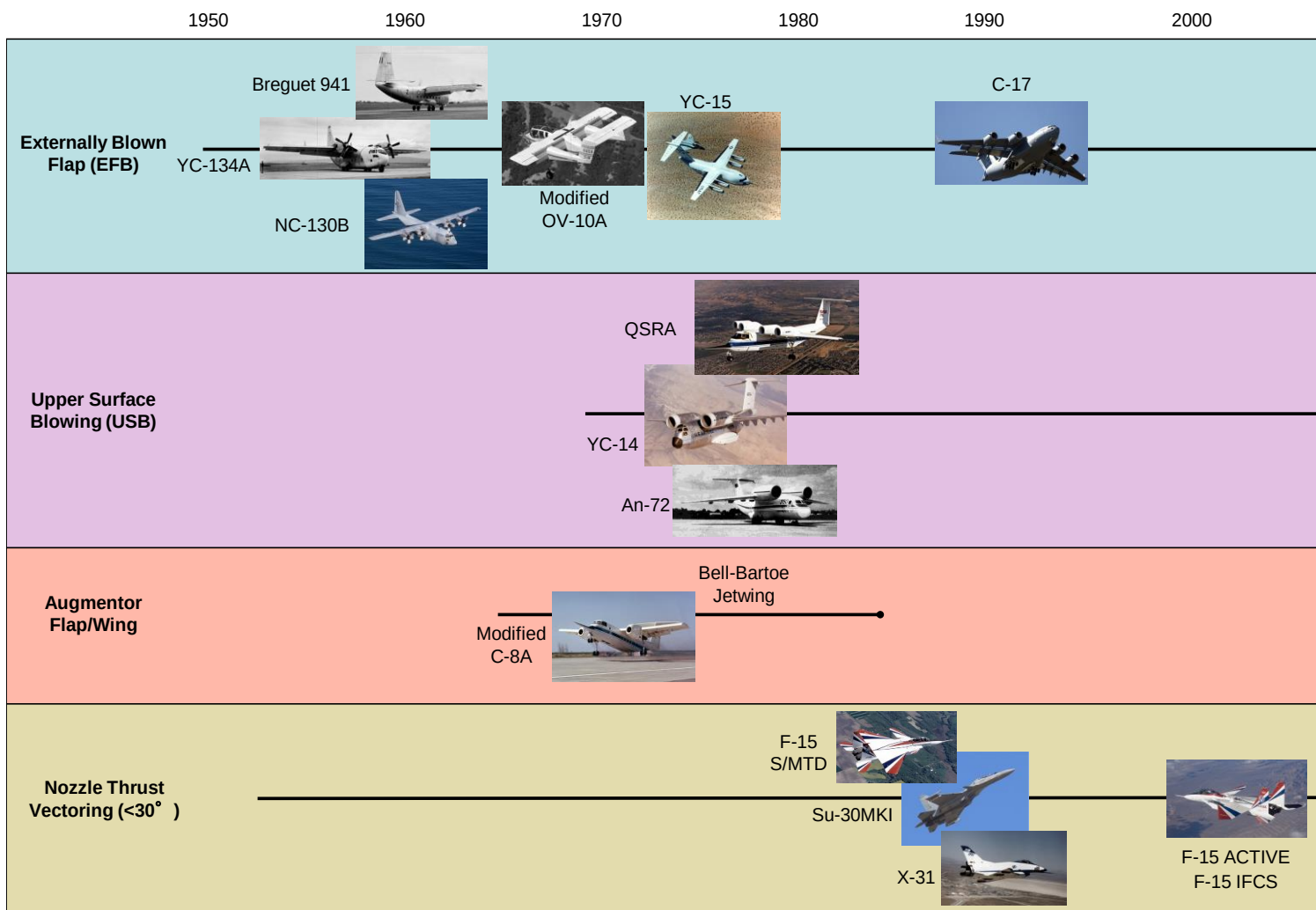


Figure 3 – Thrust vectoring applications for STOL

Use of thrust vectoring, especially utilizing small vector angles for control or improved maneuverability, is not a particularly new technology. The German V-2 rocket, which entered service in 1944, used movable vanes in the rocket exhaust to vector the thrust for vehicle control. In the United States, the X-13 airplane utilized thrust vectoring in 1950 for control during VTOL hover. However, it has been only during the last few decades that the benefits of utilizing thrust vectoring for airplane control and/or enhanced maneuverability has been fully understood (Reference 1.7). Thrust vectoring technology has been shown to increase aircraft maximum lift by up to 33% (References 1.9 and 1.15), increase aircraft pitch rate over 100% (Reference 1.13), increase aircraft turn rate from 4 to 33% (References 1.8 and 1.9) and significantly increase specific excess power, P_s (Reference 1.8). These improved performance parameters result in a significant increase in the low speed combat envelope as shown in Figure 1 (References 1.16 and 1.17) and ultimately result in as much as a 10 to 1 kill ratio over adversaries without thrust vectoring technology (Reference 1.18). In addition to the benefits normally associated with increased maneuverability, thrust vectoring technology has also demonstrated the ability to reduce trim drag (References 1.9, 1.16, and 1.19). Finally, eliminating or reducing tail surfaces by utilizing thrust vectoring for aircraft control (Reference 1.17) can reduce aircraft drag, radar signature, and TOGW. Figure 4 presents the history of thrust vectoring development aimed at providing control during STOL/VTOL operations (primary mission requirement) or aimed at enhanced maneuverability during “up and away” flight. All of the TV aircraft applications aimed at providing control during STOL/VTOL operations would have a “fall-out” benefit of enhanced control/maneuverability during “up and away” flight. As mentioned previously, the X-13 vehicle utilized thrust vectoring for pitch and yaw control during VTOL hover; no literature can be found that would indicate that the TV capability was ever used for enhanced control/maneuverability during conventional flight mode although it is now known that it could. For example, although the thrust vectoring hardware on the P.1127 (and successor) aircraft was developed solely to provide a VTOL capability, an extensive flight test program was conducted on the AV-8A Harrier aircraft to determine the benefits of thrust Vectoring In Forward Flight (VIFF) program. On the other hand, aircraft that have thrust vectoring hardware added primarily to enhance maneuverability and/or control will have some “fall-out” STOL benefits. It should be noted that the F-15 S/MTD (STOL and Maneuver Technology Demonstrator) vehicle shown in both Figures 3 and 4 had program requirements to demonstrate TV benefits on both STOL and maneuverability performance.

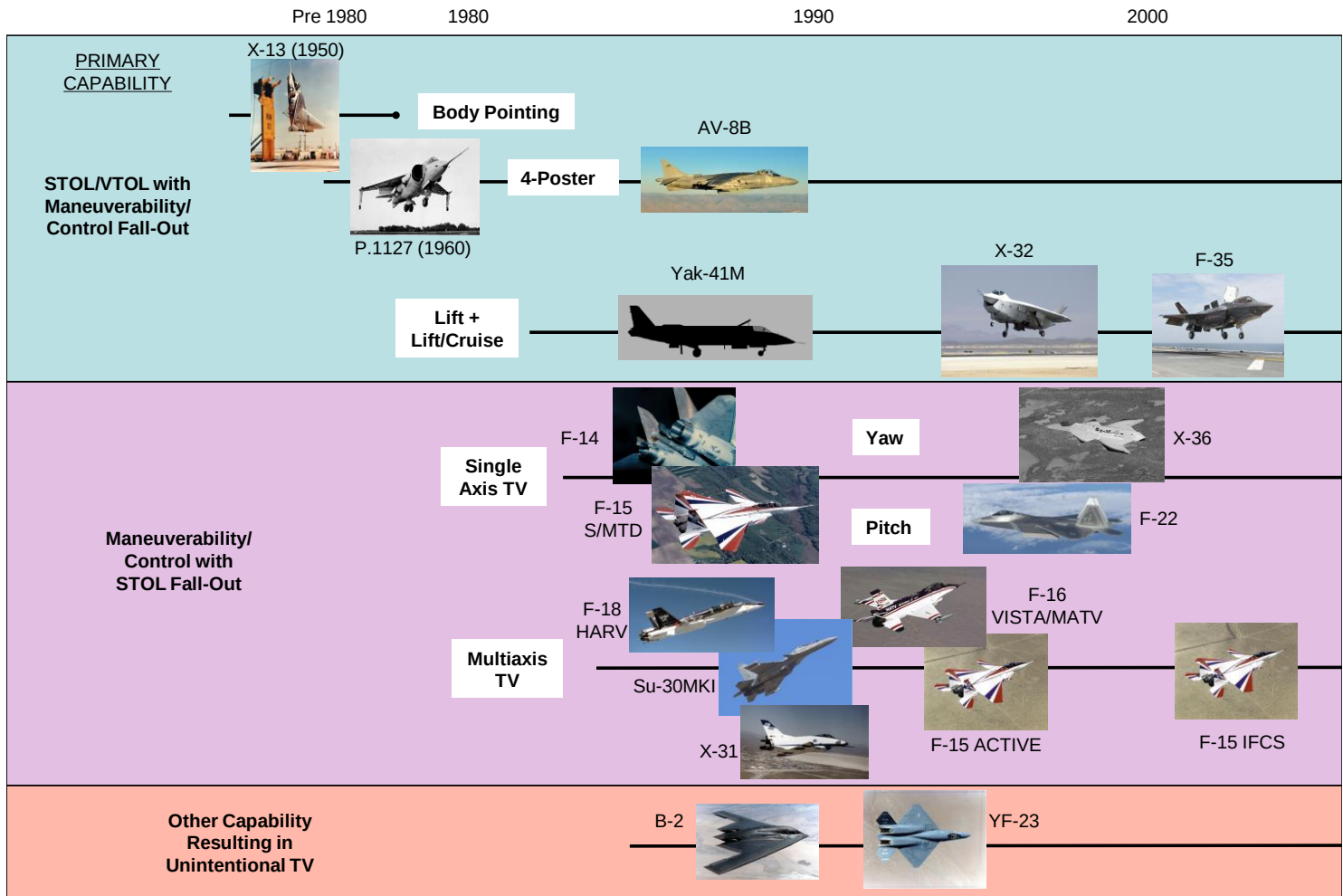


Figure 4 – Thrust vectoring applications for control/maneuverability

Intentional use of thrust vectoring is becoming widely used for performance enhancement and/or aircraft control, especially for military aircraft. However, there is a class of vehicles (shown at bottom of Figure 4) where an asymmetric (or shelf) nozzle is utilized to provide an integration benefit but results in an unintentional and varying thrust vector angle. This variable unintentional thrust vector angle occurs because of a varying pressure distribution on an unopposed nozzle or airframe surface (shelf) as nozzle pressure ratio changes with flight Mach number.

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1. SCOPE

The purpose of this document is to provide guidance on in-flight thrust determination of engines that are impacted by intentional or unintentional thrust vectoring. However, as indicated in the Foreword, the field of aircraft thrust vectoring is varied and complex. For simplicity and coherence of purpose, this document will be limited in scope to multi-axis thrust vectoring nozzles or vanes attached to the rear of the engine or airframe; single-axis thrust vectoring and unintentional thrust vectoring (fixed shelf or deck configuration) are special cases of this discussion. Specifically excluded from this scope are thrust vectoring created primarily by airframe components such as wing flaps, etc.; lift engines, propulsive fans and thrust augmenting ejectors; and powerplants that rotate or otherwise move with respect to the airframe. Note that thrust reversing, which is also a special case of thrust vectoring (vector angles greater than 90 degrees), is covered by a separate SAE Aerospace Information Report (AIR6064) and will not be covered herein.

2. REFERENCES AND NOMENCLATURE

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

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2.3 Nomenclature

Bold items indicate vectors.

Roman	Description	U.S. Customary Units	SI Units
2D	two-dimensional	-	-
ACTIVE	Advanced Control Technology for Integrated Vehicles	-	-
A_e	nozzle exit area	in ²	m ²
A_s	control surface area	ft ²	m ²
AF	axial force	lbf	N
AR	aspect ratio, throat width/throat height	-	-
A_t	nozzle geometric throat area	in ²	m ²

ATF	Altitude Test Facility	-	-
ADEN	Augmented Deflector Exhaust Nozzle	-	-
AVEN	Axisymmetric Vectoring Exhaust Nozzle	-	-
alt	altitude	ft	m
ARC	aerodynamic reference configuration	-	-
CD	convergent-divergent	-	-
Cd	discharge coefficient	-	-
C _D	drag coefficient	-	-
ΔC_{DADJE}	aircraft drag from F_{ADJE} , non-dimensionalized by dynamic pressure	-	-
C _G	gross thrust coefficient	-	-
CFN	Conformal Fluidic Nozzle	-	-
c.g.	center of gravity	in	m
c.g. _{ref}	moment reference center	in	m
C _{VX}	axial thrust coefficient	-	-
ΔC_{VADJE}	thrust increment created by non-dimensionalizing F_{ADJE} by ideal thrust	-	-
D	drag	lbf	N
F_{ADJE}	forces from afterbody drag and jet effects increments	lbf	N
F_{N^*}	Modified net thrust, accounting for installation effect	lbf	N
ΔF_{ADJE}	force increment from reference condition (where F_{ADJE} is included in aircraft drag) and other flight conditions (from 6.2.3)	lbf	N
ΔF_{INL}	External force increment due to the inlet	lbf	N
ΔF_{EXH}	External force increment due to the exhaust system	lbf	N
ΔF_{TRIM}	External control-surface-trim force increment	lbf	N
Δx	reference moment arm	in	m
$F_{I,P}$	ideal thrust of primary jet	lbf	N
$F_{I,S}$	ideal thrust of secondary jet	lbf	N
$F_{N,ACT}$	net thrust (AIR1703A Section 6)	lbf	N
$F_{G,ACT}$	gross thrust (AIR1703A Section 6)	lbf	N

FTV	fluidic thrust vectoring	-	-
f	vector force caused by the shear stress acting tangential to the surface	lbf	N
GMA	geometric minimum area	in ²	m ²
HARV	High Alpha Research Vehicle	-	-
h_e	nozzle exit height	in	m
h_l	secondary nozzle throat height	in	m
h_t	nozzle throat height	in	m
h_u	primary nozzle throat height	in	m
IFCS	Intelligent Flight Control System	-	-
i	unit vector along the x axes	-	-
j	unit vector along the y axes	-	-
k	unit vector along the z axes	-	-
L	lift force	lbf	N
L	rolling moment, positive right wing down	lbf-ft	N-m
l_s	axial length from nozzle throat to nozzle exit	in	m
M	Mach number	-	-
M	pitching moment, positive nose up	lbf-ft	N-m
M_{ADJE}	moments from afterbody drag and jet effects increments	lbf-ft	N-m
ΔM_{ADJE}	moment increment from reference condition (where F_{ADJE} is included in aircraft drag) and other flight conditions (from 6.2.3)	lbf-ft	N-m
MATV	multi-axis thrust vectoring	-	-
MTV	mechanical thrust vectoring	-	-
N	engine rotational speed, Eq. 6.3	rpm	rpm
NF	normal force	lbf	N
NPR	nozzle pressure ratio	-	-
NPR _D	design nozzle pressure ratio	-	-
n	surface normal vector pointing out of the control volume	-	-
P	thrust vector point of application	-	-
P	angular velocity around the x axis	radians/sec	radians/sec

P _s	specific excess power, (T-D)V/W	ft/s	m/s
N	yawing moment, positive nose right	lbf-ft	N-m
NPR ₇	pressure ratio, total pressure at nozzle station 7 to freestream static pressure-		-
PYBBN	pitch/yaw balance beam nozzle	-	-
p	local surface static pressure	lbf/ft ²	N/m ²
p ₀	free stream pressure	lbf/ft ²	N/m ²
P _{s0}	freestream static pressure	lbf/ft ²	N/m ²
P	total pressure	lbf/ft ²	N/m ²
P _t	total pressure	lbf/ft ²	N/m ²
Q	angular velocity around the y axis	radians/sec	radians/sec
R	angular velocity around the z axis	radians/sec	radians/sec
R	resultant force	lbf	N
RM	resultant moment	lbf-ft	N-m
r	position vector taken from the point at which the moment is desired	-	-
S	result of equation = $(\cos^2(\delta_p) \sin^2(\delta_y) + \cos^2(\delta_y))^{(-1/2)}$	-	-
SCF	spherical convergent flap	-	-
SERN	single expansion ramp nozzle	-	-
SF	side force	lbf	N
S/MTD	STOL and Maneuver Technology Demonstrator	-	-
sqrt	square root	-	-
STOL	Short Take-Off and Landing	-	-
STOVL	Short Take-Off, Vertical Landing	-	-
SVC	shock vector control	-	-
T	total temperature	R	K
TOGW	take-off gross weight	lbm	kg
TR	thrust reversing	-	-
TS	throat shifting	-	-
TV	thrust vectoring	-	-

U	translational velocity along the x axis	ft/s	m/s
V	translational velocity along the y axis	ft/s	m/s
V	velocity vector	ft/s	m/s
V _o	freestream velocity (fig. 4.1)	ft/s	m/s
V_n	thrust direction vector	-	-
v _n	velocity normal to the surface area	ft/s	m/s
Vec	vector actuator setting	-	-
VEER	variable external expansion ramp	-	-
VIFF	Vectoring In Forward Flight	-	-
VISTA	Variable-stability In-flight Simulator Test Aircraft	-	-
V/STOL	Vertical/Short Takeoff and Landing	-	-
VTOL	Vertical Take-Off and Landing	-	-
v _n	Velocity normal to the surface area or (V · n)	ft/s	m/s
W	translational velocity along the z axis	ft/s	m/s
W	mass (or weight) flow	slug/sec / lbm/sec	kg/sec
W	weight	lbm	kg
W _{inj}	mass flow rate of injection flow	slug/sec / lbm/sec	kg/sec
x	longitudinal axis system	-	-
X	force component along x axis	lbf	N
x _e	axial distance from nozzle connect station to nozzle exit station	in	m
x _s	axial distance from nozzle connect station to end of left sidewall	in	m
x _t	axial distance from nozzle connect station to nozzle throat station	in	m
Y	force along y axis	lbf	N
y	lateral axis system	-	-
Z	force along z axis	lbf	N
z	vertical axis system	-	-
α	angle of attack	deg	deg
β	angle of sideslip	deg	deg

δ_{t2}	ram-pressure ratio	-	-
δ_l	lower-flap rotation angle	deg	deg
δ_p	nozzle pitch thrust vector angle	deg	deg
δ_u	upper-flap rotation angle	deg	deg
δ_v	upper nozzle-flap terminal divergence angle	deg	deg
δ_v	geometric vector angle	deg	deg
$\delta_{v,p}$	geometric pitch vector angle measured from model centerline	deg	deg
$\delta_{v,y}$	geometric yaw vector angle measured from model centerline	deg	deg
δ_w	resultant wedge camber angle	deg	deg
δ_y	nozzle yaw thrust vector angle	deg	deg
λ	direction cosine along the x axis between axis systems	deg	deg
μ	direction cosine along the y axis between axis systems	deg	deg
ν	direction cosine along the z axis between axis systems	deg	deg
ρ	local density	slugs/ft ³	kg/m ³
θ	the angle from the x-axis of the spherical axis system	deg	deg
θ_{t2}	ram-temperature ratio	-	-
Φ	the angle of projection in the y-z plane of the line of action of the resultant thrust vector in the spherical axis system	deg	deg
subscripts			
0,1,2,etc	station designations (Figure 2 of AIR1703A)		
ACT	actual value		
ARC	aerodynamic reference configuration		
b, B	body		
eff	effective		
G	gross		
inj	injection		
jet	jet effects		
metal	nominal vector angles for mechanical systems which represents the physical position of the vector hardware		