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Fundamentals of Catastrophic Failure Prevention by Thrust Vectoring

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The authors' proposal to convert military thrust vectoring flight control (TVFC) technologies into civil transport applications, translates combat-agility capabilities into unprecedented flight-safety standards. Dealing with the latter, this article compares future vectored-aircraft safety potentials and classes with current unsafe flight standards dictated by conventional flight control (CFC). A few simplified analytical results are presented to illustrate new classes and fundamentals of catastrophic failure prevention when TVFC replaces partial or complete loss of CFC in future civil and fighter aircraft.

Nomenclature

b = reference span, m
C_D = drag coefficient
C_{fg} = thrust coefficient-metrics
C_L = lift coefficient
C_l = rolling moment coefficient
C_{lp} = roll damping derivative, 1/rad
C_{lr} = roll moment derivative vs yaw rate, 1/rad
$C_{l\beta}$ = roll moment derivative vs sideslip angle, 1/rad
$C_{l\delta a}$ = aileron effectiveness derivative, 1/rad
$C_{l\delta e}$ = elevator [stabilator] effectiveness derivative, 1/rad
$C_{l\delta r}$ = rudder effectiveness derivative, 1/rad
$C_{l\delta\Delta e}$ = differential elevator stability effectiveness derivative, 1/rad
C_m = pitching moment coefficient
C_{mo} = basic pitching moment coefficient
C_{mq} = pitching moment derivative vs pitch rate, 1/rad
C_n = yawing moment coefficient
C_{np} = yaw moment derivative vs roll rate, 1/rad
C_{nr} = yaw damping derivative, 1/rad
$C_{n\beta}$ = yaw moment derivative vs sideslip angle, 1/rad
$C_{n\beta^*}$ = asymmetric yawing moment increment
$C_{n\delta a}$ = yaw moment derivative vs aileron deflection, 1/rad
$C_{n\delta e}$ = yaw moment derivative vs stabilator deflection, 1/rad
$C_{n\delta r}$ = rudder effectiveness derivative, 1/rad
$C_{n\delta\Delta e}$ = yaw moment derivative vs differential stabilator deflection, 1/rad
C_x = longitudinal force coefficient
C_{Yp} = side-force derivative vs roll rate, 1/rad
C_{Yr} = side-force derivative vs yaw rate, 1/rad
$C_{Y\beta}$ = side-force derivative vs sideslip-angle, 1/rad
$C_{Y\beta^*}$ = asymmetric side-force increment
$C_{Y\delta a}$ = side-force derivative vs aileron deflection, 1/rad
$C_{Y\delta e}$ = side-force derivative vs stabilator deflection, 1/rad
$C_{Y\delta\Delta e}$ = side-force derivative vs differential stabilator deflection, 1/rad
$C_{Y\delta r}$ = side-force derivative vs rudder deflection, 1/rad
C_y = side-force coefficient
C_z = normal-force coefficient
C_{zSC} = supercirculation coefficient due to vectoring
c = reference mean aerodynamic chord, m
D^* = distance from nozzle exit to aircraft c.g., m
D^*_Δ = differential distance from nozzle exit to aircraft centerline, m
G_z, G_y, G_x = 'g-loads,' m/s²
I_x = moment of inertia about roll axis, kg-m²
I_{xy} = cross product of inertia between roll and pitch axes, kg-m²
I_{xz} = cross product of inertia between roll and yaw axes, kg-m²
I_y = moment of inertia about pitch axis, kg-m²
I_z = moment of inertia about yaw axis, kg-m²
M = vehicle mass, kg, also Mach number
p = roll rate, rad/s
q = pitch rate, rad/s
$\bar{q}$ = dynamic pressure, N/m²
r = yaw rate, rad/s, radius, m
s = reference surface area, m²
T = installed thrust, kgf, also temperature, K
T_i = ideal isentropic [net] thrust, kgf
$T_{x,y,z}$ = thrust-vectored components, kgf
t = time, s
V = true airspeed, m/s
V_{mca} = minimum controlled air speed, m/s
V_{mcg} = minimum controlled ground speed, m/s
W = flying vehicle weight, kgf
α = angle of attack, deg or rad
β = angle of sideslip, deg or rad
$\Delta C_{l\beta}$ = roll moment increment vs two-place canopy
$\Delta C_{n\beta}$ = yaw moment increment vs two-place canopy
ΔZ_{off} = thrust-offset distance, m
δ_a = aileron deflection, deg or rad
δ_e = elevator deflection, deg or rad
δ_r = rudder deflection, deg or rad
δ_{TV} = effective jet angle, deg or rad
δ_v = effective pitch jet angle, deg or rad
δ_y = effective yaw jet angle, deg or rad
$\delta_{\Delta e}$ = differential elevator deflection, deg or rad
$\delta_{\Delta v}$ = differential pitch/roll TVFC, deg or rad
θ = pitch angle, deg
ρ = air density, kg/m³
ϕ = bank angle, deg
ψ = heading angle, deg

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Introduction

CURRENT aircraft become unsafe under high-alpha and spin flight conditions, loss of conventional flight control (CFC) elements, low airspeeds, and asymmetric loss of propulsion. In turn, newly proposed classes and means of future vectored aircraft[1-14] may combine CFC with new roll-yaw-pitch (TVFC) technologies to significantly improve catastrophic failure prevention during takeoff, flight, and landing.

This article deals with the first author's proposal[1,13] to convert military thrust-vectoring technologies into future civil transport applications by means of new complete (roll-yaw-pitch) thrust vectoring flight control TVFC safety classes. Its major aim is to translate TVFC-induced combat-agility capabilities into unprecedented safety options and classes, and to illustrate them by a few simplified analytical results dealing with TVFC replacing partial or complete loss of CFC in future civil and fighter aircraft.

Safest Flight Methodology

Complete TVFC was first verified by this laboratory in 1987 via flight tests of roll-yaw-pitch-TVFC unmanned vehicles.[1] The results demonstrated that the highest TVFC-induced safety standards are extractable at the weakest domains of CFC, i.e., at low (or zero) speeds, loss of CFC element(s), during spin, short takeoff and landing, and under poststall conditions.

Thus, in comparison with CFC, roll-yaw-pitch TVFC[1-14] represents alternative and safer technology. As illustrated below, it may also enhance safety during loss of all airframe hydraulics/actuators, or loss of one or more engines.

New Classes of Catastrophic Failure Prevention

Five new TVFC-based catastrophic failure prevention (CFP) classes have been recently proposed to the U.S. Department of Transportation via the Federal Aviation Administration's (FAA's) CFP activities[13]:

Class 1: TVFC replacing one or more CFC elements that have failed.

Class 2: TVFC regaining controllability when one engine, or two engines on one aircraft side, or on both sides, have failed, or failed/separated.

Class 3: TVFC replacing CFC that has failed via the loss of all airframe hydraulics, and or actuators, or emergency CFC connections.

Class 4: TVFC replacing combined CFC element loss and the failure of one or more engines.

Class 5: Fully operative, mixed CFC/TVFC, overcoming loss of aircraft controllability caused by poststall, icing, windshear/microbursts, or during adverse external flow regimes, e.g., below CFC V_{mca} and V_{mcg}, or when the undercarriage has failed.

TVFC Recoveries from Total Airframe Hydraulics/Actuators Failures

Our proposed principles to safely recover from total airframe hydraulics (or actuators) failures are based on actuating all roll-yaw-pitch TVFC nozzle kits by extant hydraulic/air sources of operating jet engines only. Namely, we avoid flight-safety reliance on airframe hydraulics, actuators, and emergency manual CFC connections, except via redundant cross-linking options with complete TVFC.

Hence, roll-yaw-pitch TVFC must entirely be based on engine extant oil-pump-hydraulic control power, or on engine compressed air. Namely, this methodology provides the highest flight safety standard for future flight. Its earliest adoption by engine, airframe, and airline industries, in upgraded or new designs, will bolster air transport safety. References 1–14 also discuss feasible fuel-saving via TVFC reoptimized cruising height, TVFC trimming, and TVFC tailless/partial-tailless designs.

Vectoring Categories

TVFC technology introduces five major categories:

1) CFC + pitch-only TVFC. (This combination is available in the F-22. Its PWA-F119 engines are equipped with two-dimensional nozzles of the pitch-only jet-deflection type.)

2) CFC + yaw-pitch TVFC. (Upgraded F-22, and other, upgraded, vectored fighters, may be based on fast-rotating yaw vanes inside F-22/PWA-F119-type two-dimensional nozzles,[11] or on axisymmetric multiaxis TVFC-nozzles.[12,14])

3) Pure roll-yaw-pitch TVFC. (Such a cruise missile, with no conventional flight-control wings/fins, is illustrated in Ref. 1.)

4) Complete TVFC/CFC. This flight-control mix provides the highest possible safety standard.

5) Tailless vectored aircraft. TVFC or TVFC/CFC technologies allow partial or complete removal of vertical tails. Tailless aircraft represent the same safety standard as that of category 4. Candidates currently under study here include fighter and transport jets.[1-14]

Identifying Safety Parameters by Vectoring

Six-degrees-of-freedom mathematical phenomenology for vectored jet vehicles is presented below. It quantifies major TVFC and CFC/TVFC moments and rates and guides our proposed TVFC-CFP principles. In body-system coordinates it reads

$$\dot{\alpha} = q + \{-[\bar{q}sC_x/MV - (g/V)\sin\theta + r\sin\beta]\sin\alpha + [\bar{q}sC_z/MV + (g/V)\cos\theta\cos\phi - p\sin\beta]\cos\alpha\}\sec\beta \tag{1}$$

$$\dot{\beta} = -\{[\bar{q}sC_x/MV - (g/V)\sin\theta]\sin\beta + r\}\cos\alpha + [\bar{q}sC_y/MV + (g/V)\cos\theta\sin\phi]\cos\beta - \{[\bar{q}sC_z/MV + (g/V)\cos\theta\cos\phi]\sin\beta - p\}\sin\alpha \tag{2}$$

$$\dot{p} = \{-[(I_z - I_y)/I_x + I_{xz}^2/I_xI_z]qr + [1 - (I_y - I_x)/I_z] \times I_{xz}pq/I_x + \bar{q}sb/I_x[C_l + I_{xz}C_n/I_z]\}/[1 - I_{xz}^2 I_x I_z] \tag{3}$$

$$\dot{q} = \bar{q}scC_m/I_y + [(I_z - I_x)/I_y]pr + I_{xz}(r^2 - p^2)/I_y \tag{4}$$

$$\dot{r} = \{[I_{xz}^2/I_xI_z - (I_y - I_x)/I_z]pq - [1 + (I_z - I_y)/I_x] \times (I_{xz}/I_z)qr + (\bar{q}sb/I_z)[(I_{xz}/I_x)C_l + C_n]\}/[1 - I_{xz}^2/I_xI_z] \tag{5}$$

$$\dot{V}/V = [\bar{q}sC_x/MV - (g/V)\sin\theta]\cos\alpha\cos\beta + [\bar{q}sC_y/MV + (g/V)\cos\theta\sin\phi]\sin\beta + [\bar{q}sC_z/MV + (g/V)\cos\theta\cos\phi]\sin\alpha\cos\beta \tag{6}$$

$$\dot{\theta} = q\cos\phi - r\sin\phi \tag{7}$$

$$\dot{\phi} = p + r\cos\phi\tan\theta + q\sin\phi\tan\theta \tag{8}$$

$$\dot{\psi} = q\sin\phi\sec\theta + r\cos\phi\sec\theta \tag{9}$$

$$C_x = C_L(\alpha, \delta_e, M)\sin\alpha - C_D(\alpha, \delta_e, M)\cos\alpha + T_x/\bar{q}s \tag{10}$$

$$C_y = C_Y(\alpha, |\beta|, \delta_e) + C_{Y\delta a}(\alpha)\delta_a + C_{Y\delta r}(\alpha)\delta_r + [b/2V][C_y(\alpha)r + C_{Yp}(\alpha)p\} + C_{Y\beta^*}(\alpha, \beta) + C_{Y\delta\Delta e}(\alpha, \delta_e)\delta_{\Delta e} + T_y/\bar{q}s \tag{11}$$

$$C_z = -[C_L(\alpha, \delta_e, M)\cos\alpha + C_D(\alpha, \delta_e, M)\sin\alpha] + C_{zSC}\delta_{TV} + T_v/\bar{q}s \tag{12}$$

$$C_l = C_{l\beta}(\alpha, |\beta|)\beta + C_{l\delta a}(\alpha, \delta_a)\delta_a + C_{l\delta r}(\alpha, |\delta_r|)\delta_r + (b/2V)[C_{lp}(\alpha)p + C_{lr}(\alpha)r] + C_{l\delta\Delta e}(\alpha, \delta_e)\delta_{\Delta e} + \Delta C_{l\beta}(\alpha, \beta) + C_{lTV}\delta_{TV} \quad (13)$$

$$C_m = C_{mo}(\alpha, \delta_e, M) + [c/2V]C_{mq}(\alpha, M)q + T[\Delta Z_{\text{off}}]/\bar{q}sc + C_{mSC}\delta_{TV} + C_{mTV}\delta_{TV} \quad (14)$$

$$C_n = C_{n\beta}(\alpha, \beta, \delta_e)\beta + C_{n\delta a}(\alpha)\delta_a + C_{n\delta r}(\alpha, \beta, \delta_r, \delta_e)\delta_r + [c/2V][C_{np}(\alpha)p + C_{nr}(\alpha)r] + C_{n\delta\Delta e}(\alpha, \delta_{\Delta e})\delta_{\Delta e} + \Delta C_{n\beta}(\alpha, \beta) + C_{n\beta^*}(\alpha, \beta) + C_{nTV}\delta_{TV} \quad (15)$$

$$T_x = C_{fg}[\delta_v, \delta_y, \text{NPR}]T_i[M, T]\cos\delta_v \cos\delta_y \quad (16)$$

$$T_v = -C_{fg}[\delta_v, \delta_y, \text{NPR}]T_i[M, T]\sin\delta_v \cos\delta_y \quad (17)$$

$$T_y = C_{fg}[\delta_v, \delta_y, \text{NPR}]T_i[M, T]\cos\delta_v \sin\delta_y \quad (18)$$

(NPR = nozzle pressure ratio).

When installed engine/nozzle metrics are known

$$T_x = TS\cos\delta_v \cos\delta_y \quad (19)$$

$$T_v = -TS\sin\delta_v \cos\delta_y \quad (20)$$

$$T_y = TS\cos\delta_v \sin\delta_y \quad (21)$$

where $S = [\cos^2\delta_v + \cos^2\delta_y \sin^2\delta_v]^{-1/2}$. $S = 1$ for pure δ_v or δ_y commands. For simultaneous maximum realistic δ_v/δ_y jet-deflections $S = 1.005$. Hence, one can practically replace S by unity.

Recovery from an Elevator Failure

To illustrate and quantify our TVFC-CFP proposals we first assess the minimal pitch jet-deflections required to restabilize a horizontally-flying vehicle whose CFC elevator has failed. To restabilize it under steady-state, CFP flight conditions, we require that $\delta_e = \delta_a = \delta_r = \delta_{\Delta e} = q = r = p = 0$, viz.,

$$-\bar{q}sC_l[\alpha] - C_{fg}[\delta_v, \text{NPR}]T_i[M, T]\sin[\delta_v + \alpha] + Mg[\cos\gamma] = 0 \quad (22)$$

$$-\bar{q}sC_D[\alpha] + C_{fg}[\delta_v, \text{NPR}]T_i[M, T]\cos[\delta_v + \alpha] - Mg[\sin\gamma] = 0 \quad (23)$$

$$-D^*C_{fg}[\delta_v, \text{NPR}]T_i[M, T]\sin\delta_v + \bar{q}scC_{mo}[\alpha] = 0 \quad (24)$$

For relatively small γ values the solution of (22–24) becomes

$$\delta_v = -[\Gamma + \Omega] \quad (25)$$

where, for technical reasons $\delta_v > -35$ deg, and

$$\Gamma = \arcsin\{Mg/\Pi C_{fg}[\delta_v, \text{NPR}]T_i[M, T]\} = \arcsin\{1/[T/W][1/\Pi]\} > 0 \quad (26)$$

$$\Omega = \text{arc } tg\{\sin\alpha/[D^*C_l[\alpha]/cC_{mo}[\alpha] + \cos\alpha]\} \quad (27)$$

$$\Pi = [\sin^2\alpha + \{D^*C_l[\alpha]/cC_{mo}[\alpha] + \cos\alpha\}^2]^{1/2} \quad (28)$$

and, via a constant $\bar{q}$ for each selected vectoring angle and alpha

$$V = \{-2D^*C_{fg}[\delta_v, \text{NPR}]T_i[M, T]\sin[\Gamma + \Omega]\}^{1/2} \quad (29)$$

$$\gamma = \arcsin[\{C_{fg}[\delta_v, \text{NPR}]T_i[M, T]\cos[\delta_v + \alpha] - 0.5\rho V^2 sC_D[\alpha]\}/Mg] \quad (30)$$

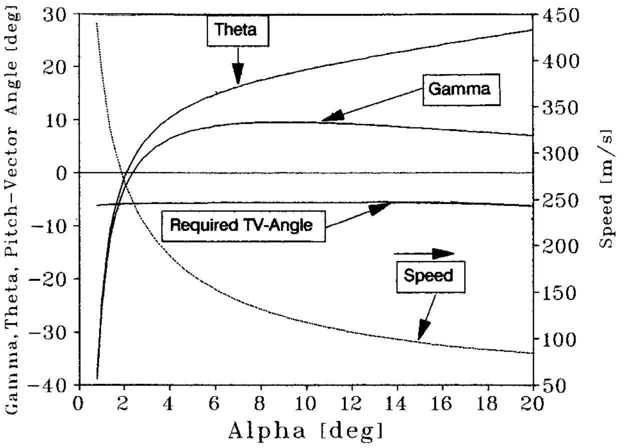

Fig. 1 Pitch jet-deflection required to stabilize a horizontally flying F-15B whose elevator has failed; dry power.

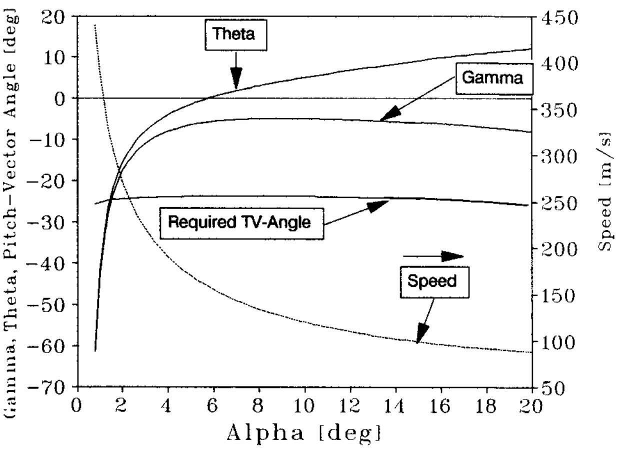

Fig. 2 Pitch jet-deflection required to stabilize a horizontally flying F-15B whose elevator has failed; 25% of dry power.

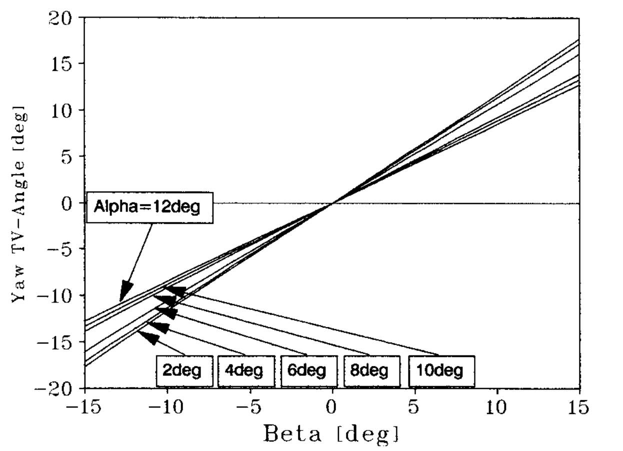

Fig. 3 Yaw jet-deflection required to stabilize a horizontally flying F-15B whose conventional flight control has totally failed; M = 0.3.

Increasing the T/W ratio decreases Γ, while Ω and γ may be negative or positive. Regaining such flight safety strongly depends on the D^* parameters via the number and distribution of operational TVFC nozzles. These may best be all far aft [e.g., in fighter jets, 727, MD-88] or both aft and ahead of c.g. [e.g., in 747, 340]. The latter dictate various other TVFC–CFP procedures.[13]

Figure 1 depicts restabilization predictions via Eqs. (25–30) for a "combat takeoff weight" F-15B jet fighter equipped with PWA-F-100-100 engines. Only 6-deg jet-pitch deflection

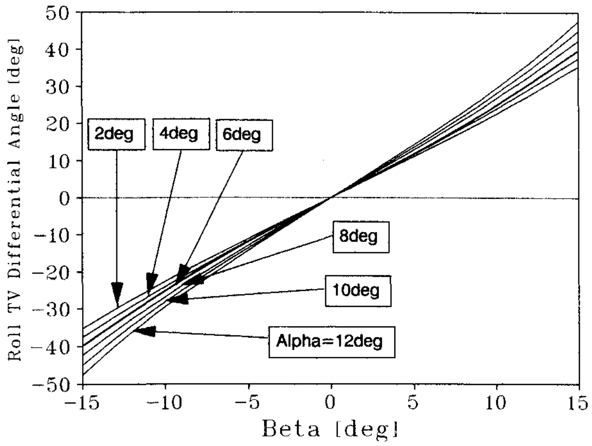

Fig. 4 Differential pitch jet-deflection required to stabilize a horizontally flying F-15B whose conventional flight control has totally failed; $M = 0.3$.

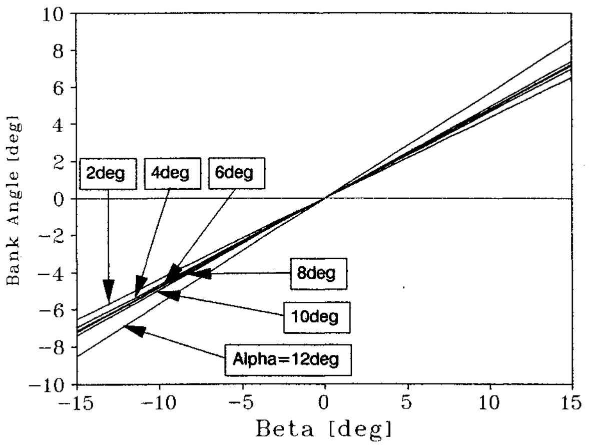

Fig. 5 Bank angles of a horizontally flying F-15B whose conventional flight control has totally failed; $M = 0.3$.

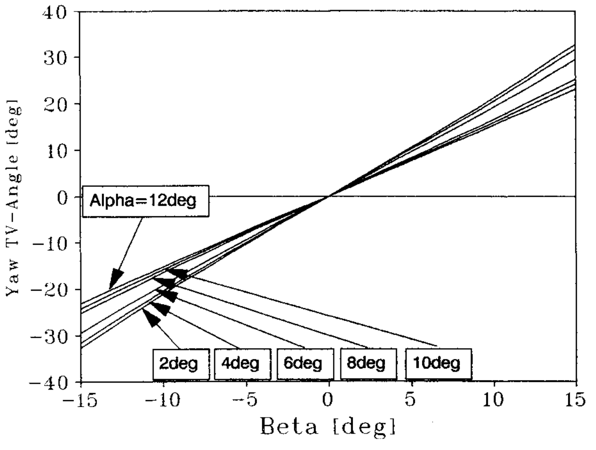

Fig. 6 Yaw jet-deflection required to stabilize a horizontally flying F-15B whose CFC has failed; $M = 0.4$.

is required to stabilize this aircraft during, say, takeoff at dry power at the depicted combinations of speed and alpha. Smaller values are required with afterburner. Landing with, e.g., 25% power, requires 24-deg pitch jet deflection, as depicted in Fig. 2.

Recoveries from Total Conventional Flight Control Failures

We next investigate minimal yaw and pitch jet-deflections required to restabilize a horizontally flying vehicle whose el-

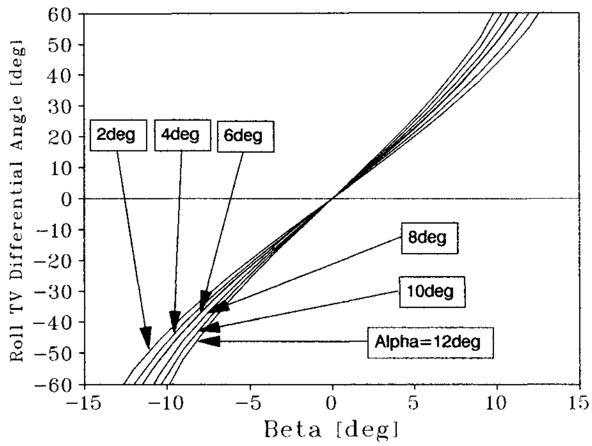

Fig. 7 Differential pitch jet-deflection required to stabilize a horizontally flying F-15B whose CFC has failed; $M = 0.4$.

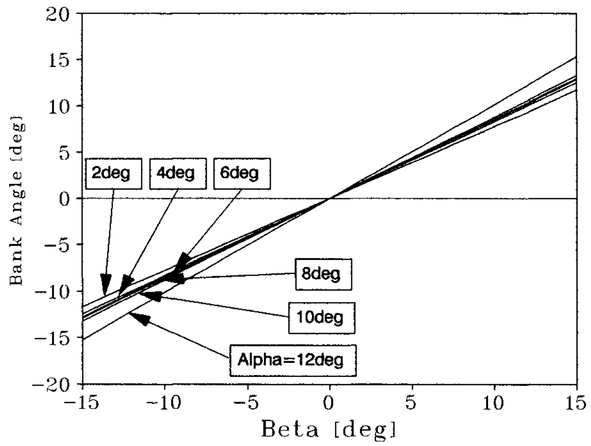

Fig. 8 F-15B bank angles with complete TVFC; $M = 0.4$.

evator, rudder, and ailerons have all failed. Such emergency situations may be caused by a total airframe hydraulics/actuators failure. Adopting Eqs. (25) and (29), and employing Eqs. (11), (13), and (15) with $\delta_e = \delta_a = \delta_r = r = p = \delta_{\Delta e} = 0$, we obtain

$$\bar{q}sbC_{l\beta}(\alpha, |\beta|)\beta + D^*_\Delta C_{fg}[\delta_v, \delta_y, \text{NPR}]T_i[M, T]\sin \delta_{\Delta v} = 0 \tag{31}$$

$$\bar{q}sbC_{n\beta}(\alpha, \beta,)\beta - D^* C_{fg}[\delta_v, \delta_y, \text{NPR}]T_i[M, T]\sin \delta_y = 0 \tag{32}$$

$$\bar{q}sC_Y(\alpha, |\beta|) + C_{fg}[\delta_v, \delta_y, \text{NPR}]T_i[M, T]\sin \delta_y + Mg \sin \phi = 0 \tag{33}$$

$$\delta_y = \arcsin\{[\bar{q}sbC_{n\beta}(\alpha, \beta,)\beta]/[D^* C_{fg}[\delta_v, \delta_y, \text{NPR}]T_i[M, T]]\} \tag{34}$$

$$\delta_{\Delta v} = \arcsin\{[\bar{q}sbC_{l\beta}(\alpha, |\beta|)\beta]/[D^*_\Delta C_{fg}[\delta_v, \delta_y, \text{NPR}]T_i[M, T]]\} \tag{35}$$

$$\phi = -\arcsin\{[\bar{q}s/Mg][C_Y(\alpha, |\beta|) + bC_{n\beta}(\alpha, \beta,)\beta/D^*\} \tag{36}$$

Such CFP methodologies can save an otherwise doomed aircraft.

Figures 3 and 4 depict TVFC corrective jet-deflections required to save a combat takeoff weight F-15B fighter. Bank angles associated with this case are shown in Fig. 5. At $M = 0.4$ the required TVFC–CFP jet-deflections are provided by Figs. 6–8.

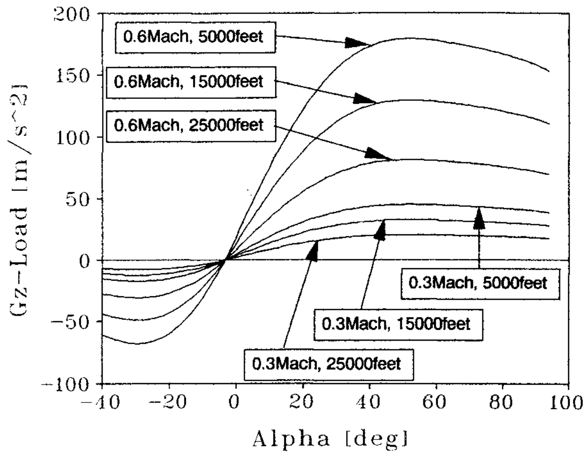

Fig. 9 Vertical load forces in the negative and positive poststall domains are characterized by two fixed extreme values. Data are for the F-15B.

Safe Dynamic Loads on Airframe and Pilot

Flight tests conducted here with subscaled CFC/TVFC F-15, F-16, and F-22 unmanned vehicles have demonstrated smaller and shorter maximum "g-loads" on airframe and pilot when maximized TVFC-induced agility is compared with maximized CFC-induced agility for the same aircraft-nose turning combat needs.[14] To explain this, one must imagine a hypothetical pilot's head at c.g. during such rapid pitch-up maneuvers which, however, keep the vehicle flight path almost horizontal. The g-loads on the pilot are then generated mainly by high-alpha drag. To flight-quantify such conclusions we introduce[3,13] the concept standard agility-safety comparison maneuver (SASCOM).

Under such pitch-up SASCOM conditions, ϕ, β, $\dot{\beta}$, $\dot{p}$, p, $\dot{r}$, r, δ_e, δ_a, δ_y, or $\delta_{\Delta e}$, C_l, C_n, and C_Y vanish, while $\theta \cong \alpha$, $\dot{\alpha} \cong q$ and

$$C_x = C_L(\alpha, M)\sin\alpha - C_D(\alpha, M)\cos\alpha + T_x/\bar{q}s \quad (37)$$

$$C_Y = 0 \quad (38)$$

$$C_z = -[C_L(\alpha, M)\cos\alpha + C_D(\alpha, M)\sin\alpha] + T_v/\bar{q}s \quad (39)$$

$$C_l = 0 \quad (40)$$

$$C_m = C_{mo}(\alpha, M) + [c/2V]C_{mq}(\alpha, M)q + C_{mTV}\delta_v \quad (41)$$

$$C_n = 0 \quad (42)$$

$$\dot{q}I_y = \bar{q}sc[C_{mo}(\alpha, M) + [c/2V]C_{mq}(\alpha, M)q + C_{mTV}\delta_v] \quad (43)$$

$$T_x = C_{fg}[\delta_v]T_i[M, T]\cos\delta_v \quad (44)$$

$$T_v = -C_{fg}[\delta_v]T_i[M, T]\sin\delta_v \quad (45)$$

$$T_y = 0 \quad (46)$$

The pilot's maximized g-load histories during maximized pitch-SASCOM δ_v and/or δ_e commands, are then

$$G_z = -\{\bar{q}s[C_L(\alpha, \delta_e, M)\cos\alpha + C_D(\alpha, \delta_e, M)\sin\alpha] + T_v\}/M \quad (47)$$

Safe Vectoring Up to a Structural Limit

Critical safety parameters include the variations of pilot and airframe structural loads with alpha, Mach number, and altitude, during such TVFC/CFC-induced pitch-reversal-command SASCOMs at constant engine throttle.[13] As a simplified illustration we differentiate Eq. (47) with respect to alpha and obtain

$$\left[C_D(\alpha, \delta_e, M) + \mathrm{d}C_L \frac{(\alpha, \delta_e, M)}{\mathrm{d}\alpha}\right] \Big/ \left[C_L(\alpha, \delta_e, M) - \mathrm{d}C_D \frac{(\alpha, \delta_e, M)}{\mathrm{d}\alpha}\right] = tg\alpha \quad (48)$$

Equation (48) harbors two max-min alpha values in the negative and positive poststall domains, respectively. Figure 9 illustrates these max-min g loads, one at $\alpha = 52$, the other at $\alpha = -30$ deg for various speeds and altitudes during a constant pure pitch thrust vectoring SASCOM command, namely, when $\delta_y = 0$ and $\delta_e = \text{const}$. It is imperative, from the CFP point of view, to estimate for each CFC/TVFC design the values of these two maximized loads, one at $\alpha < +90$ deg, and the other at $\alpha < -45$ deg.

Concluding Remarks

1) New fundamental concepts have been introduced and illustrated for TVFC-based CFP criteria and classes.

2) The new TVFC-induced safety concepts have been employed to formulate a simplified mathematical phenomenology for poststall vectored fighters and for transport jets with maximized CFP capabilities.

3) The highest payoffs of TVFC are extractable at the weakest domains of CFC.

4) Roll-yaw-pitch TVFC technology provides the safest flight capability for future mixed CFC/TVFC civil and fighter aircraft.

Acknowledgments

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