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Maximizing Thrust-Vectoring Control Power and Agility Metrics

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A new set of standard agility comparison maneuvers (SACOM) is proposed for testing the maximization of thrust-vectoring control power during poststall, manned, and unmanned flight tests. An innovative approach is presented to help define and simulate agility in a low cost manner by means of unmanned scaled models. Debated agility metrics are reassessed in light of new developments in multiaxis thrust vectoring.

A methodology for measuring and maximizing TV-agility under PST conditions has been identified. Excellent controllability and very rapid nose pointing are easily obtainable during PST-TV maneuvers. TV-agility is an interdisciplinary subject involving a revolution in engineering and pilot education.

Introduction

THE availability of poststall (PST) thrust-vectored (TV) fighter aircraft, helmet-sight aiming systems, and all-aspect missiles, requires reassessment of the optimal balance between aircraft and missile agilities. Whatever is that balance, high-performance fighter aircraft will be gradually based on improved thrust-vectored control systems. Thus, maximizing TV agility and TV control power may have to be demonstrated and verified by establishing a (yet unavailable) set of standard agility comparison maneuvers (SACOM). Such SACOM should compare different TV control abilities.

However, the definition of TV agility, the methods to measure it, and its proper relationships to future combat effectiveness are the subjects of recent debates in government and industry circles. Questions such as: "What is conventional and TV agility?" and "How should maximal agility be measured during flight tests?" are being asked by members of government, industry, and academia. Government and industry conferences on agility have tried to respond to such questions. The results of these efforts have been a general agreement on the importance of TV agility and a general disagreement on how should it be measured.

Different pitch-only and yaw-pitch TV methodologies have recently been reported by Russian,[2,14] French,[3,21] German,[6,17,22] Israeli,[1,10] Chinese,[13] and American[4,7,8,9,11,12,15,18,19,20] authors. A review of these methodologies is available elsewhere.[1,10]

Four debated methods to measure agility have been proposed recently by the U.S. Air Force, General Dynamics, Eidetics International, and Messerschmitt, Baum, and Bovery (MBB).[5,6,18,19,20,22] Each proposes to measure and compare a different set of design/flight-testing/control parameters.

This paper examines the debated methods in light of new PST-TV concepts which affect the measurement and maximization of TV control power and, accordingly, the design to maximize maneuverability and controllability. It also presents an innovative approach to help define and simulate agility in a low cost manner by means of unmanned scaled models.

Use of Flying Models to Maximize TV Agility

Thrust-vectored flight control (TVC) is either "pure" or "mixed." In pure TVC, the AoA-dependent moments generated by conventional, aerodynamic control surfaces, are entirely replaced by moments generated by rapidly deflected engine-exhaust jet(s), i.e., pure TV aircraft can deliver top PST-agility and control qualities without recourse to ailerons, flaps, elevators, and rudders, and even the vertical tail-stabilizer may become redundant (Fig. 1).

Such ($\frac{1}{7}$-scale, 35 lb, including rate gyros and an onboard computer) pure and mixed TV-model aircraft have been successfully flight tested by this laboratory since 1987 during rapid nose turn rates PST flight-control/agility tests.[1]

Multi-axis-jet-deflections have been employed in these tests to orient the jet efflux in the required yaw, pitch, roll, and forward thrust coordinates of the models. The flight-control power of these systems was maximized and was found to be independent of the PST-AoA (Fig. 2). Therefore, proper upscaling of such systems to manned TV aircraft can render them significantly expanded TV flight-control qualities, both below and beyond the so-called "stall barrier." When matured and scaled-up, this technology will, no doubt, improve current rapid-nose-pointing-and-shooting (RaNPAS) capabilities and PST maneuverability and controllability.[1]

Since engine forces (for poststall-tailored inlets), are considerably less dependent on the external-flow regime than the forces generated by conventional control surfaces, the TV control forces available for pure vectored aircraft (PVA) design options, remain highly effective even beyond the maxi-

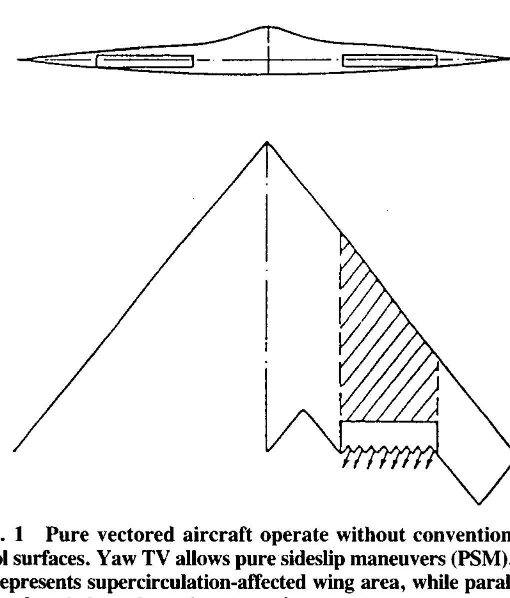

Fig. 1 Pure vectored aircraft operate without conventional flight control surfaces. Yaw TV allows pure sideslip maneuvers (PSM). Shaded area represents supercirculation-affected wing area, while parallel wing/nozzle edges help reduce signatures.[1]

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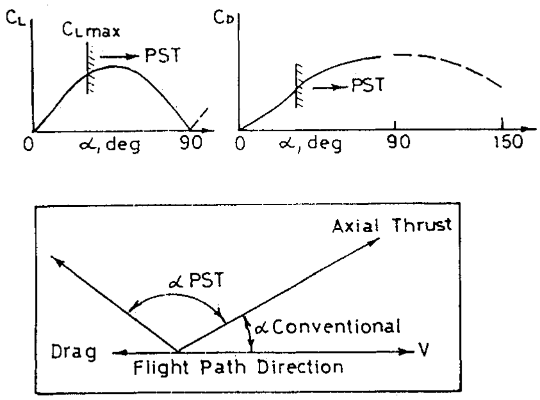

Fig. 2 Definition of the PST domain.

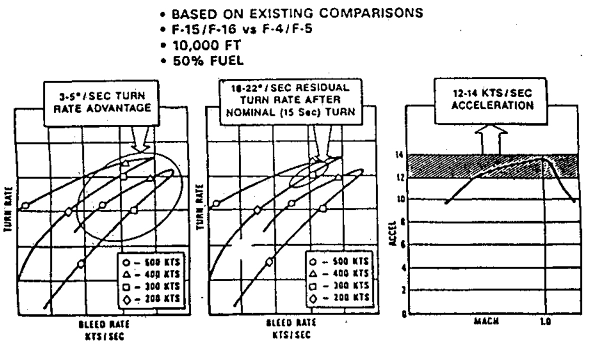

Fig. 3 GD's agility-definition proposal includes dynamic-speed-turn plots.

mum-lift AoA. Therefore, PVA present the highest potentials to maximize agility, even in the domain of deep PST. Hence, PVA concepts must be established as the standard reference to maximize agility and PST controllability.

Such a standard must be based on verifiable flight-tested databases that prove that multiaxis TVC provides the highest payoffs at the weakest domains of conventional fighter aircraft, i.e., at low (or zero) speeds, high altitude, high rate spins, very short runways, and during PST and RaNPAS maneuvers.

Partial (or "mixed") jet control (PJC) is used in TV aircraft in which ailerons, flaps, elevators, rudders, etc., are still being used in conjunction with TVC. Comparing the flight-test results of our PVA models with that of the PJC models proved that the maximal levels of agility obtainable with PJC is extractable by combining TV with conventional control throughout the conventional flight envelope. During these flight tests we have successfully employed the SACOM proposed in this paper.

Debated Agility Definitions

Four agility definitions/metrics have been recently proposed by General Dynamics,[5] AFFTC,[19,20] MBB,[6,22] and Eidetics International.[18] Each consists of essentially 3 components, and each entails a somewhat different design approach. Prior to the introduction of an expanded, four-component definition/metrics of PST-TV agility, the main metrics which characterize each are summarized below.

Agility metrics, according to McAtee,[5] include:

Component I—The ability to "outpoint" the opponent (pointing at him before he points at you). This advantage must be such that the opponent does not have the opportunity to launch his weapon before he is destroyed. It is a key ability whose importance increases as missile-target-computing delay times, including locking-releasing delays and path/time of missile flight are decreased. It is measurable as turn-rate vs bleed-rate [deceleration] as shown in Fig. 3 in terms of Dynamic-Speed-Turn plots.

Component II—The ability to continue maneuvering at high turn rates over prolonged periods to retain the potential for performing defensive maneuvers, or make multiple kills when appropriate, i.e., to defend against attacks from other aircraft, or to accomplish multiple kills if the opportunity exists, an "agile" aircraft must be able to continue maneuvering at high turn rates over prolonged periods. This key ability is measurable in terms of Residual turn rate vs bleed rate of the aircraft (middle graph in Fig. 3).

Component III—The residual ability to unload rapidly and accelerate away rapidly so as to leave a flight-path/state/engagement at any time, irrespective of conventional wing/control-surface stall condition. In offensive engagement it means to regain multiple-target ability when necessary and, in defensive situations, to pursue a departing target when appropriate. This includes the ability to disengage or escape from a battle without being destroyed in the process, as well as the acceleration necessary to "chase down" an enemy that is trying to escape. This key ability is measurable by the DST and acceleration vs speed plots of the aircraft (right-hand graph in Fig. 3).

AFFTC's definition is also centered around three components (Fig. 4):

1) *Pitch agility*—The difference in pitch agility of two competing aircraft, A and B, is demonstrated by two criteria 1) maximum pitch rate obtainable at different AoA; and 2) time to pitch and stop as a function of AoA. This is represented by the ("integrated") time to capture body axis heading or pitch angle vs initial load factor, altitude, etc. Accordingly, it is combat-effective to measure the minimal time for maximum pitch rate up to a desired AoA, capture and hold with precision and then the integrated periods delay times to pitch-down, capture and hold with precision, unload and recover, as, for instance, in conventional, or in PST snapshots, or during various (negative-AoA, or positive-AoA) PST "Cobra" maneuvers in 1 vs 1 or in 2 vs 2, or in target-rich environments.

2) *Torsional agility*—The difference in torsional agility of two competing aircraft, A and B, is demonstrated by two criteria 1) the difference in the minimal time to bank and stop at various AoA and loads; and 2) turn rate divided by the minimal time to roll and stop as a function of AoA, load and SEP (specific excess power).

This torsional agility refers to the capability of an aircraft to rapidly change the plane of its maneuver. Though this chiefly involves a rolling maneuver, the necessity to roll more nearly about "the wind axis" at PST-AoA, or to perform a loaded roll, has led to proposals to include in the definition of torsional agility times-to-bank and stop and turn rate divided by time to bank and stop. The latter expression is an attempt to augment a traditional agility measure with a time function so that it would have the appearance of an "averaged" second time-derivative term.

3) *Axial agility*—The difference in axial agility of two competing aircraft, A and B, is demonstrated by two criteria 1) the difference in maximum SEP change at various Mach num-

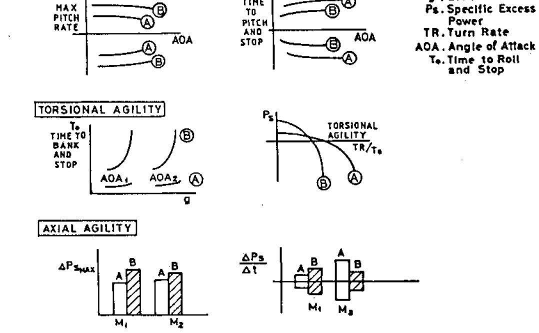

Fig. 4 AFFTC's agility-definition proposal includes the metrics shown.

bers for a maximal throttle change; and 2) the "averaged" difference in SEP rate of change at various Mach numbers. This component is represented by (the "integrated") time to final airspeed vs initial airspeed and load factor. Hodgkinson et al.[19] also attempt to relate agility to instantaneous "rate of change" of "aircraft state."

AFFTC identifies two additional agility concepts 1) functional agility, as the "time-to-achieve-a-final-desired-aircraft-state," such as time to capture a desired PST-pitch-angle; 2) transient agility, which refers to acceleration/deceleration, such as engine transient responses. Thus, agile aircraft are associated with high PST sustainable g and g onset rates, large roll-rates at elevated g loads, large positive energy values, and fast engine response transients. These topics have recently been expanded by Butts and Lawless,[20] especially for nose-pointing and flight path agility design parameters and aircraft agility flight test maneuvers.

Herbst and Kiefer of MBB define agility as a mathematical property of the flight path. Their definition describes the time derivative of the maneuver state defined by the first time derivative of the velocity vector. Thus, they express longitudinal acceleration as a g factor, or as SEP multiplied by speed, the lateral acceleration as a g factor, or in terms of angular acceleration (turn rate). Therefore, longitudinal agility is the time derivative of longitudinal acceleration (longitudinal g onset), i.e., it is a function of any throttle change or of the time derivative of speedbrake or thrust-reversal deployment. Accordingly, lateral agility is the time derivative of lateral acceleration during, say, rapid sidewise g loading changes/reversals, or during nose turn rate-g onsets/stops. This agility component is a function of any stick change (conventional and/or TVC). For torsional agility they use the "result" of an angular rotation change of the lift vector. (However, this agility component is not directly derivable as a second derivative of the velocity vector. It may thus be defined as the rate of change of the osculating plane, i.e., of the curving maneuver plane.) MBB's definition requires a choice of a reference system, e.g., inertial or a system bound to the flight path.

However, flight-test data reduction and analysis would be difficult with this definition, due to the scattering of first and second derivatives of the flight-test data. Consequently, it is not well displayable to the combat pilot.

Eidetics International also divides agility into three components[18] 1) acceleration/deceleration along the flight path; 2) symmetrical turning perpendicular to the flight path; and 3) rolling about the velocity vector to reorient the flight path. As with MBB's definition, the stress here is on "transient" agility and somewhat less on "functional" agility. However, according to Bitten,[18] Eidetics has recently added an agility metric consisting of a time-to-pitch-up-to-and-stop at a specified g level and unload.

Standard Agility Comparison Maneuvers for Thrust-Vectored Aircraft

The rest of this paper defines practical aircraft flight test maneuvers which could be flown and quantified for agility studies, especially for maximizing PST-TV control power and agility metrics.

To maximize agility and flight control power one must introduce the PVA standard as an "ideal TV agility" and measure it by flying unmanned models during well-defined PST-SACOM. Using the same SACOM one must next repeat the

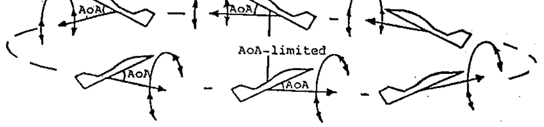

Fig. 5 Maximizing torsional PST-TV roll-reversal SACOM.

flight tests with PJC models of the same scale, weight, moments of inertia, thrust-to-weight ratio, stability margins, etc., as those of the PVA and the (dynamically scaled-down) fighter aircraft to be designed or upgraded. Figure 5 describes the practice employed during our SACOM flight tests. It depicts the proposed use of roll-control-power reversals for conventional, TV, and TV + conventional SACOM commands defined below.

A 6 DOF mathematical phenomenology of PST-TV control requirements during SACOMs has been completed recently.[16] Following the physicomathematical conclusions we obtain that maximum conventional and/or TV control power is required at each state of pitch, roll, yaw, and axial reversals as defined below. Each SACOM reversal should be performed with a "Dirac-Type" of stick motion, i.e., by the fastest possible deflection a pilot or a model flyer can perform until maximum stick range is obtained and immediately backing the stick to its initial condition and holding.

To perform a "start/step-function/stop" SACOM is of interest to simulate combat engagements. As before, it requires

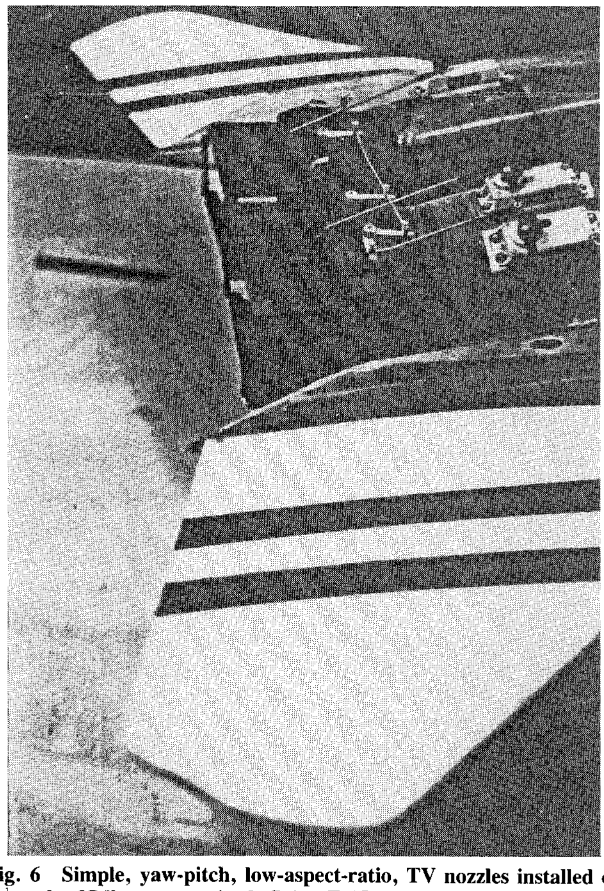

Fig. 6 Simple, yaw-pitch, low-aspect-ratio, TV nozzles installed on a $\frac{1}{7}$-scale, 37 lb computerized, flying F-15 model.

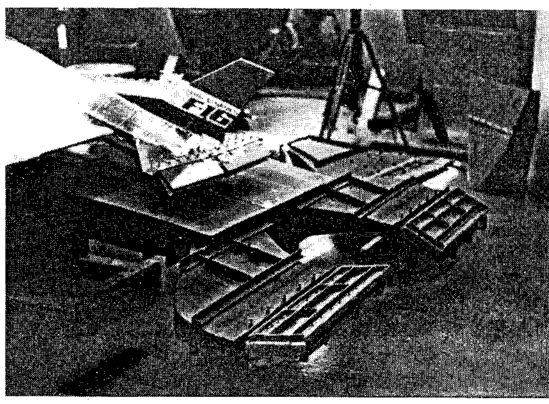

Fig. 7 Effective roll-yaw-pitch TV nozzles.[24,25]

high control moments to start, accelerate, and stop/hold/track a moving target with precision under conventional or PST conditons, say, at positive or negative 90-deg AoA pitch-SACOM (see below).

Finally, one must devise proper dynamic scale factors to project model SACOM test results to predict the performance of full-scale aircraft.[16]

For this purpose the following four-component definition of TV agility is asserted to be more useful than the former three-component metrics which characterize each of the former debated definitions of agility.

Maximizing Roll-Reversal TV Agility

This torsional agility component refers to the ability of an aircraft to rapidly change the plane of its PST maneuver. It is performed as rapidly as possible with full lateral stick input until maximum stick deflection is achieved and then reversing to initial conditions. (There is no need to wait until the maximum roll rate is reached.) At high AoA, the reversing roll-control-power is maximized when the roll-reversal motion opposes the gravity vector, and the roll is strongly coupled to pitch, as depicted in Fig. 5. Hence, it is recommended to use both SACOM types; the Dirac-type-reversal and the gravity reversal.

Initial Conditions (IC)—Straight and level flight at different speeds/altitudes; sustained level turn at different speeds/altitudes.

Transient TV Maneuver (TM)—Maximum roll-reversal (rate-of-change of the osculating plane), during roll reversals/stops (Fig. 5). This component is a function of maximal (roll) stick rate-of-change (conventional and/or TVC). It maximizes TV torsional rate metrics, e.g., time to bank and reverse the maneuver.

End Conditions (EC)—As close as possible to IC.

Functional Component (FC)—"Time to" from IC to the maximum roll angle achieved for various conventional and PST AoA, turn radii, speeds, and altitudes at constant throttle setting. FC is the time period both the aircraft designer and the combat pilot are interested in.

Min-Max Limitations—Maximal controllable AoA under which such SACOMs can be achieved. (Using our models we have established that the "roll" TVC with two adjacent low-aspect-ratio nozzles is ineffective. Consequently, a new type of TV propulsion has been proposed by introducing split-type, high-aspect-ratio, roll-yaw-pitch TV nozzles[1,10,16] which increase the roll-moment arm, thereby maximizing roll rate in the deep PST domain. One may also note that at AoA = 90 deg the TV roll becomes pure TV yaw, and the roll-reversal is similar but not equal to PSM reversal—see below.)

Maximizing Pitch-Reversal TV Agility

Since maximum control power is required at positive or negative pitch reversal states, each should be performed with a Dirac-type of stick reversal. This SACOM may have a pitch-up and capture of maximum controllable AoA (positive or negative) variation. Therefore, a "start/step-function/stop" SACOM is also recommended, for to stop and hold/track with precision, say at 90 deg AoA, requires large PST-TV-control moments.

IC—Straight and level flight at different speeds/altitudes, starting the SACOM from the lowest controllable-sustained speed. 2) Sustained level turn at different speeds/altitudes, starting the SACOM from the smallest controllable-sustained turn radius.

TM—1) A very rapid, positive PST rotation, a reversal to [negative *g* load] PST rotation, and, finally, stop back at IC: i, with TV only; ii, with conventional control only; and, iii, combined conventional/TV control. 2) Similar TM in a reverse order. Pilot's *g* tolerances play here a double role: The negative-*g* rotation via the "blood-to-head" negative *g* onset plus the positive-*g* deceleration of the aircraft. [TM (1) and (2) are actually positive and negative "Cobra"-brakings/maneuvers.]

EC—As close as possible to IC.

FC—"Time delay" from IC to maximum AoA and stop/capture, or the minimal time from IC to EC.

Min-Max Limitations—Both physical and human tolerances limit PST-TV-induced agility. (Our next SACOM results will be used by the Human System Division of the USAF to design a new large centrifuge to simulate such human limits of PST-TV-induced agility, cf. Fig. 9 as an example. The first negative "Cobra" maneuver was performed by this laboratory on Aug. 28, 1989, using a 9-ft, yaw-pitch, TV-F-15 model.)

Maximizing Pure Sideslip Maneuver (PSM) Agility

This component applies only to PVA and tailless vectored fighters. It evaluates steady, high-sideslip-angle flight control power and transient yaw-RaNPAS with Minimum Energy Bleeding.[1] Its performance is similar but not equal to TV-pitch agility. (Only split-type, roll-yaw-pitch TV nozzles on tailless, single-engine PVA or twin-engine PVA can provide such TV yaw forces.[1,16]) The following SACOM is proposed to evaluate its metrics:

IC—Straight and level flight at different speeds/altitudes.

TM—Maximal PSM rate and stop and hold with precision, or performing a PSM-reversal. This component provides new types of metrics.

EC—As close as possible to IC.

FC—"Time to" from IC to first stop, or from IC to EC.

Min-Max Limitations—As previously stated.

Maximizing Axial TV Agility

This is a well-known SACOM in all agility definitions.

IC—Straight and level sustained flight at specified speeds and altitudes.

TM—Deceleration/acceleration to a given minimum or maximum speed and reversal to initial speed, by maximum

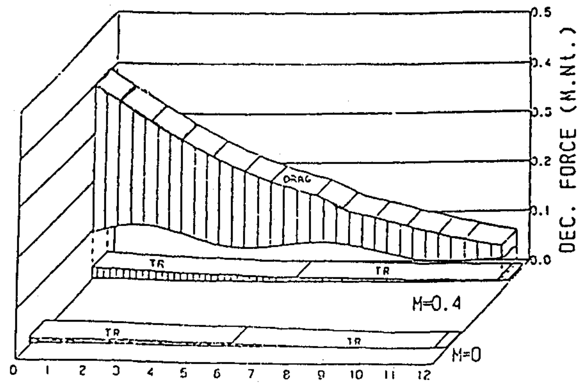

Fig. 8 Flat-plate drag vs reversed thrust variations with altitude and speed demonstrate that, for subsonic speeds, PST braking is more effective than thrust reversal.

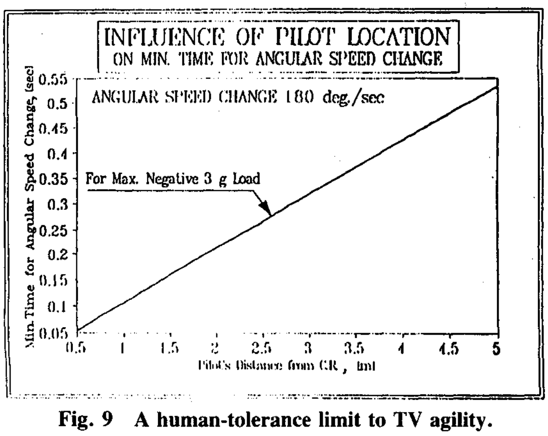

Fig. 9 A human-tolerance limit to TV agility.

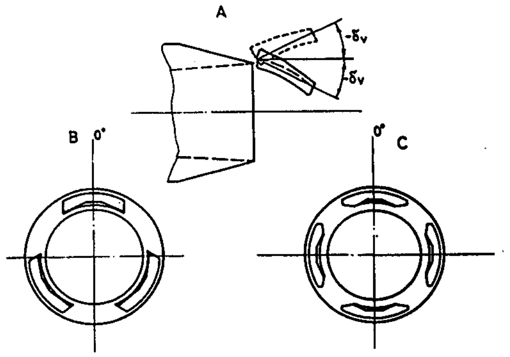

Fig. 10 Four or three post-nozzle-exit pedals produce yaw-pitch TV.

throttle change rate, and/or airspeed brake, and/or thrust-reversal depolyment rate, while maintaining straight and level flight path.

EC—As close as possible to IC.

FC—"Time delays" from IC to a given airspeed, and that required to return to IC.

Min-Max Limitations—Maximum throttle rate-of-change at various AoA, minimum or maximum speeds under which such controllable SACOMs can be achieved at various altitudes.

Comments

The proposed SACOMs are characterized by 1) four novel "transient" metrics, expressible in terms of "second-time derivatives" of the velocity vector, provide the fighter aircraft designer with a yardstick of "quickness" about the aircraft instantaneous agility. They directly relate to the required angles/time-to-capture-recover/states achievable about the axis under study. 2) "Time to . . ." Functional Agility Components (FC) are directly measured by means of the four SACOMs proposed. These combat-critical components may be displayed to the pilot during combat engagements, as an option. However, reading cockpit displays during multi-target combat scenarios may not be practical. 3) Without risking lives, at low cost and relatively short times, one can deduce pilot-induced limitations of PST-TV agility from flight data extracted from flying dynamically scaled models according to the proposed SACOMs. 4) The SACOM metrics can be cycled back to jet-engine research laboratories for further improvements of TVC and the development/validation of distortion-free, PST, vectorable engine inlets. 5) The proposed metrics allow a comparison of conventional with TV aircraft agility and of one PST aircraft to another.

Concluding Remarks

A new methodology for measuring and maximizing TV agility under PST conditions has been identified. The proposed four-component SACOM is asserted to be more useful than the former three-component metrics which characterize each of the former debated definitions of agility. An innovative approach is presented to help define and simulate agility in a low-cost manner by means of unmanned scaled models. PST-TV agility is an interdisciplinary subject involving a revolution in engineering and pilot education.

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