Fundamental Concepts of Vectored Propulsion

Benjamin Gal-Or*
Technion—Israel Institute of Technology, Haifa, Israel

Future fighter aircraft may maneuver, especially in the post-stall (PS) domain, by simultaneously directing their jets in the yaw, pitch, and roll coordinates. Consequently, thrust vectoring (TV) may gradually become a key element in helping fighters to survive and win in the close-combat arena. It also provides fighter aircraft with short-takeoff-and-landing (STOL) capabilities. This paper first defines the fundamental concepts associated with pure, or with partial TV powerplants. It then demonstrates that propulsion engineering should be expanded to include such unorthodox engine-design criteria as those of TV maneuverability and controllability. Second, the fundamental concepts of pure vectored propulsion are employed to design, construct, and laboratory test a new type of simultaneous roll-yaw-pitch TV system. Vectored remotely piloted vehicles (RPVs) were then constructed "around" these new propulsion systems. Flight tests of these RPVs since May 1987 have verified the STOL capability and enhanced maneuverability and controllability designable into vectored propulsion systems. They also became the first flight tests of pure vectored propulsion systems. The integrated methodology of laboratory/vectored-RPV-flight tests, as developed for this investigation, has been verified as cost effective and timesaving. Using this methodology a follow-up program was recently launched to help upgrade existing fighter aircraft, such as the F-15, F-16, and F-18, to become partially vectored PS aircraft. Finally, the basic conceptual changes associated with the very introduction of TV engines are summed up in terms of greater emphasis on highly integrated engine/flight-control testing methodologies and on reassessment of conventional concepts.

Nomenclature

C_{fg} = thrust coefficient
CP_y = center of pressure in the y direction
D = dimension defined in Fig. 2, also drag
D^* = dimension defined in Fig. 2
D_x = drag component in the x direction
D_y = drag component in the y direction
F_y = force components in the y direction
F_{cp} = aerodynamic drag force resulting from (steady-state) sideslip flight
H = altitude
M = Mach number
T = unvectored engine thrust force, $C_{fg}T_i$
T_i = ideal (unvectored) engine thrust force
T_x = thrust component in the airframe (forward) x direction during vectoring
T_y = thrust component in the airframe (yaw) y direction during vectoring
T_z = thrust component in the airframe (pitch) z direction during vectoring
W = aircraft weight
Y = dimension defined in Fig. 2
δ_v = jet-deflected angle in the xz plane (pitch vectoring angle) $\equiv \delta_z$
δ_y = jet-deflected angle in the yx plane (yaw vectoring angle)

Introduction

TRADITIONALLY, jet engines have been considered to have little influence on flight-control theories, system designs, and actual flight mechanics. They were a priori limited to provide brute unvectored forward force. The required moments for maneuverability and controllability were reserved for aerodynamic control surfaces, which are a priori limited by external-flow/wing/stall characteristics and, hence, by the so-called stall barrier.

This traditional thinking has totally ignored the unprecedented potentials of controlling the aircraft by engine forces, even beyond its so-called stall limit, i.e., during "impossible" post-stall (PS) maneuvers at extremely high nose turn rates. Consequently, in the past aerodynamicists tended to develop theories in conjunction with only a rudimentary role for the engine. This, in fact, is the "big-airframe, little-engine" approach to propulsion/aircraft design.

On the other hand, engine manufacturers had traditionally used the opposite approach, almost ignoring the best integration methods that might be required by future designers.

However, the increasing demands on aircraft missions and performance have recently begun a radical change in these attitudes. Almost suddenly it was realized that there is no unified approach or integrated design tools and criteria to handle the new PS problems properly. Simple additions of propulsion to flight-control technologies, in some linear simulations/systems, have been quickly found to be inadequate or even misleading.

Thus, a new, really integrated methodology must be evolved in the future, apparently from no verifiable base of low-risk technology. In turn, such an attempt to break the stall barrier may revolutionize the very mode of thinking of many propulsion/aircraft system designers. It may as well change the entire basic approach to aeronautical engineering education, design, and practice.

Preliminary Terminology and the Main Problems

Jet-vectored propulsion/aircraft systems may be divided into those that are "pure" or "partial" as well as into those that are based on engine/nozzle internal thrust vectoring (ITV) or on engine/nozzle external thrust vectoring (ETV). [ETV is based on postnozzle exit, (three or four) jet-deflecting vans that deflect exhaust jet(s) in the yaw and pitch coordinates, and, in a few designs, also in the roll coordinates.[1,2]]

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*Professor, Faculty of Aerospace Engineering, and Head, The Jet Propulsion Laboratory, Israel.

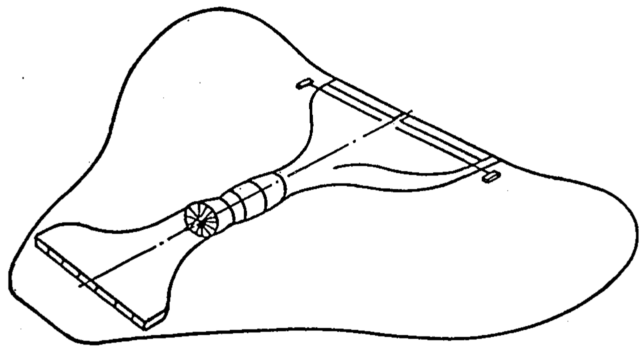

Fig. 1 Jet-powered pure-vectored RPV (nonsplit engine TV nozzle); engine inlet and nozzle are well-integrated with the wing structure (see Fig. 2).

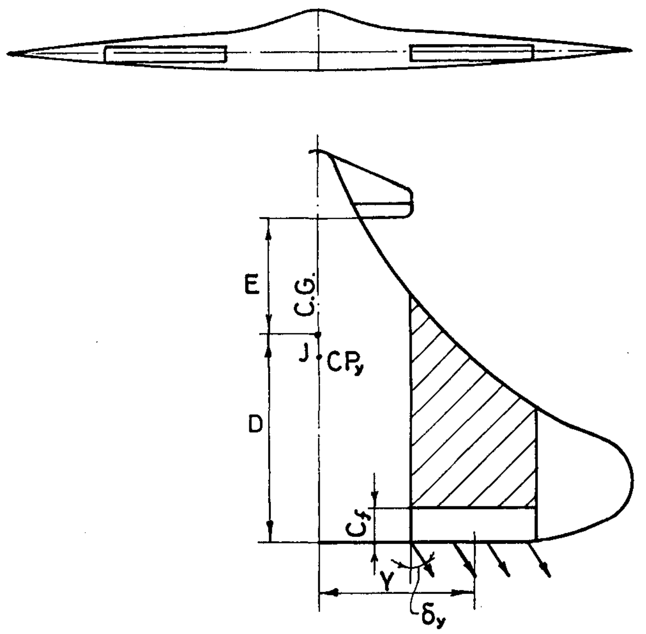

Fig. 2 Example of pure-vectored propulsion; the shaded area represents supercirculation-affected wing sections; PSM is obtainable when the jets are deflected through CP_y as depicted; there are no vertical stabilizers, rudders, ailerons, flaps, etc.

In pure thrust vectoring (TV) (see Figs. 1 and 2) as proposed, designed, constructed, and laboratory/flight tested by this laboratory, the flight-control forces generated by the conventional aerodynamic control surfaces of the aircraft have been replaced by the stronger internal thrust forces of the jet engine(s). These forces may be simultaneously or separately oriented in all directions, i.e., in the yaw, pitch, roll, thrust-reversal, and forward-thrust coordinates of the aircraft.

The first purpose of this work is to evaluate the fundamentals and the pros and cons of the propulsion and testing methodologies proposed by this laboratory—especially for the domain of subsonic post-stall technology (PST) as defined by Figs. 3 and 4.

A secondary purpose is to assess the potential uses of TV remotely piloted vehicles (RPVs) as cost-effective tools in the preliminary "proof-of-concept" tests of different design methodologies for pure-vectored propulsion, including various integrated flight/propulsion control (IFPC) methodologies for pure or partial TV at different altitudes and Mach numbers (Fig. 5).

The third purpose is to assess other problems facing this field; e.g., are the roads to pure-vectored propulsion the only roads to reach PS-supermaneuverability/supercontrollability? What are the bona fide technology limits of each class of vectored propulsion? Are Soviet and Western TV propulsion methodologies similar? How should engine design philosophy be modified to meet PS-supermaneuverability/supercontrollability needs? Is TV becoming a standard propulsion technology for high-performance fighter aircraft? In particular, how important is the new (roll-yaw-pitch) TV methodology proposed here, and how may it be compared with maneuverability/controllability levels obtainable with conventional and other proposed methodologies?

No definite or final answers will be attempted here. Nevertheless, in assessing some of the new concepts, one may arrive at some practical conclusions.

Unfortunately, subject to proprietary limitations stressed in the Acknowledgments, the detailed propulsion/RPV designs as well as the laboratory and vectored RPV flight-testing data cannot be available in the public domain.

Technology Bottleneck

There is an inherent time lag between the pace of evolution, and maturity, of advanced propulsion systems and that of avionics. Although the former shifts into a "new generation" every 10 or 12 years, it may take the latter only four or six. This means that a premature selection of a TV engine may later become the bottleneck in the evolution of high-performance aircraft. Hence, the designers of advanced (manned) airframe systems can test the integration of TV powerplants with advanced aircraft systems only during the last phase of the development/testing process of IFPC systems.[3] However, as will be stressed, the propulsion/flight-control coupling coefficients required for IFPC verification will not be available in time, unless simulated first by the integrated methodology proposed here.

Basic Definitions

Jet-vectored aircraft/propulsion systems may first be divided into those that are pure (see Figs. 1, 2, 8, 13), or partial.[3] Pure jet-vectored propulsion/aircraft sysems are based on the fact that, during flight, the engine forces (for PS-tailored inlets) are less dependent on the external flow than the forces

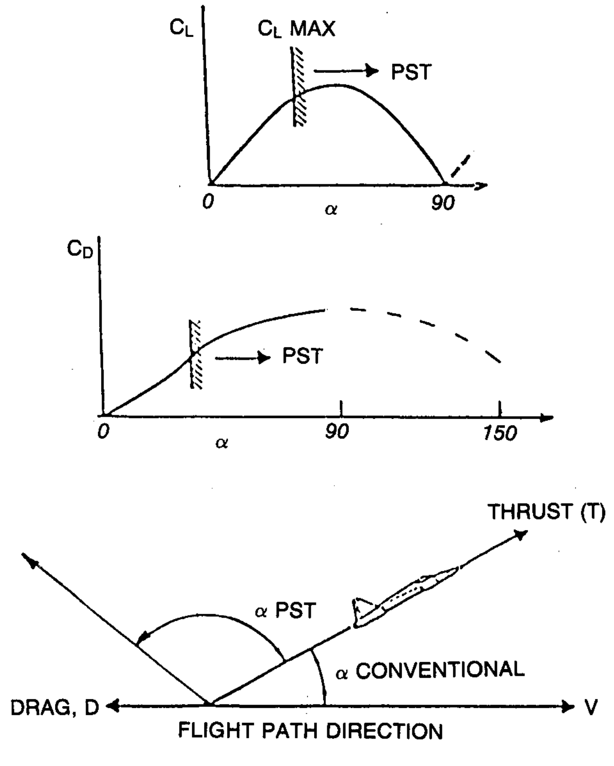

Fig. 3 Definition of PS technology for maneuverability and controllability by new thrust-vectoring powerplants (see Fig. 4).

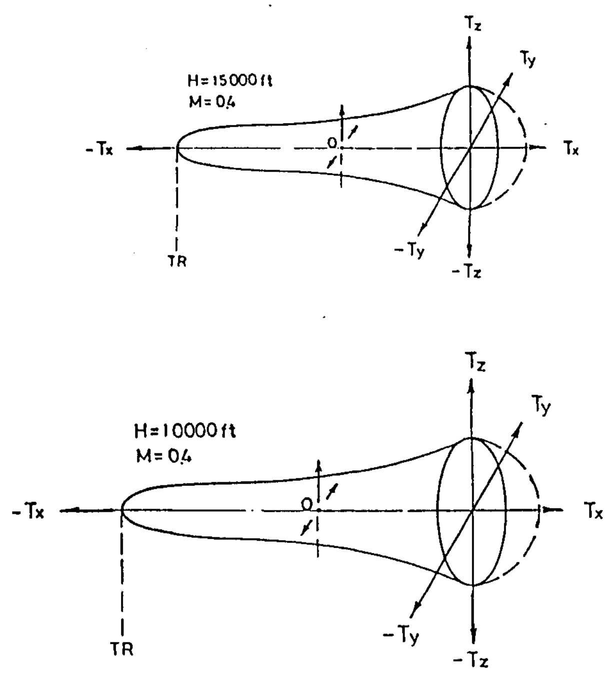

Fig. 4 Engine flight control envelopes change with altitude and Mach number; T_y and T_z are the controllability yaw and pitch engine forces, respectively; *TR* is full thrust reversal.[3]

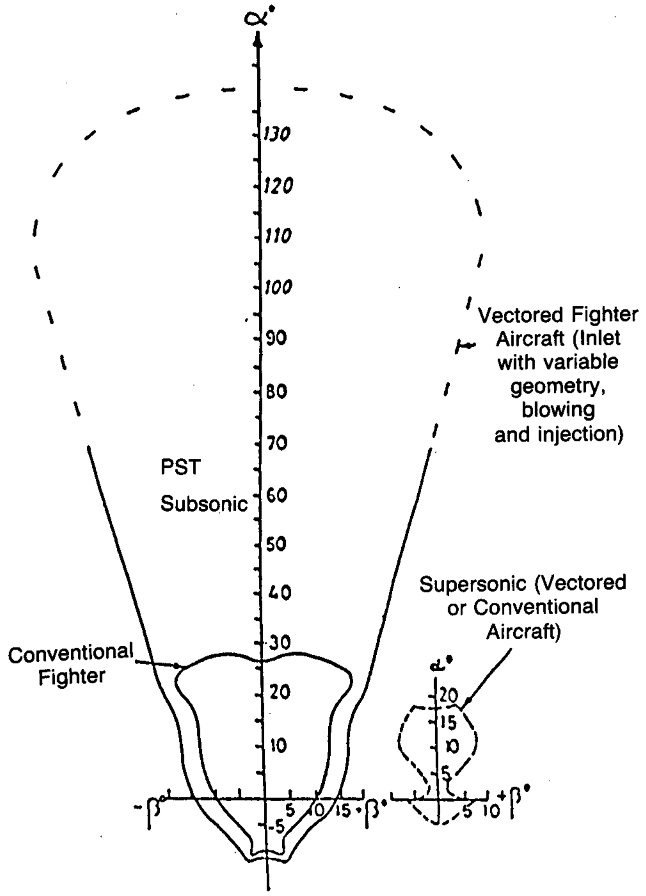

Fig. 5 New engine yaw-pitch, TV moments would expand conventional fighter subsonic AOA (alpha) and sideslip angle (beta); this jet propulsion laboratory now conducts PS/PSM/RANPAS by vectored RPVs in the low subsonic PS domain.[3]

generated by conventional aerodynamic control surfaces. Hence, the flight-control forces of pure vectored aircraft (PVA) remain highly effective even beyond the maximum-lift angle of attack (AOA), i.e., PVA are fully controllable even in the domain of PST (see Fig. 2). (AOA may be split into conventional AOA and PST AOA; in our practice with vectored RPVs, AOA may be greater than 90 deg.)

Therefore, TV flight control provides the highest payoffs at the weakest domains of conventional fighter aircraft [e.g., at PST AOA, low (or zero) speeds, high altitude, high-rate spins, very short runways, and during conventional or PST, rapid nose pointing and shooting (RANPAS), or high-sideslip maneuvers].

Consequently, subject to proper safety-vs-complexity reasonings, no rudders, ailerons, flaps, elevators, and flaperons are designed into our PVA/RPVs and even the vertical tail stabilizers have become redundant. Thus, by employing TV and IFPC, PVA need no conventional "tail" vertical stabilizer(s), or canards, or other (external) aerodynamic control surfaces. Since the elimination of vertical stabilizer reduces total aircraft drag in pure sideslip maneuvers (PSM), RANPAS maneuvers combined with PSM do not degrade aircraft energy/speed as much as a similar high-drag PST/RANPAS maneuver.[3]

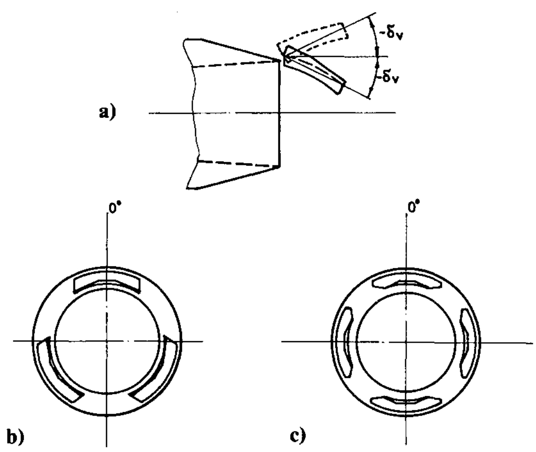

Fig. 6 ETV: a) sideview, b) 3 pedals, c) 4 pedals.[10]

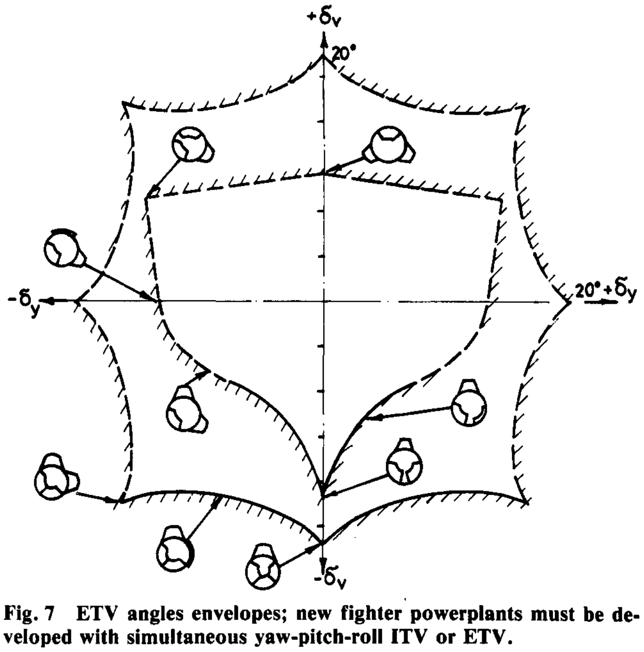

Fig. 7 ETV angles envelopes; new fighter powerplants must be developed with simultaneous yaw-pitch-roll ITV or ETV.

Different Design Methodologies

ETV is based on postnozzle-exit jet deflection, as shown schematically in Figs. 6 and 7. In evaluating different design methodologies, one may have to distinguish first between ETV and ITV efficiencies and operational limitations for various missions and for various IFPC capabilities (see Figs. 8 and 9). To start with, one may stress the experimental fact[3] that, in the subsonic flow domain, two-dimensional ITV (see, e.g., Fig. 10) may have somewhat higher thrust coefficients than conventional (axisymmetric) unvectored nozzles (see Fig. 11). Thus, in general, the yaw and pitch forces/moments available throughout the forces/flight envelopes (see Fig. 5) of ITV aircraft may be somewhat higher than those available for ETV aircraft, both having the same inlet, core engine, and IFPC.

Consequently, optimized ITV or ETV methodologies may soon become a bona fide technology bottleneck for the development of superagile fighter aircraft.

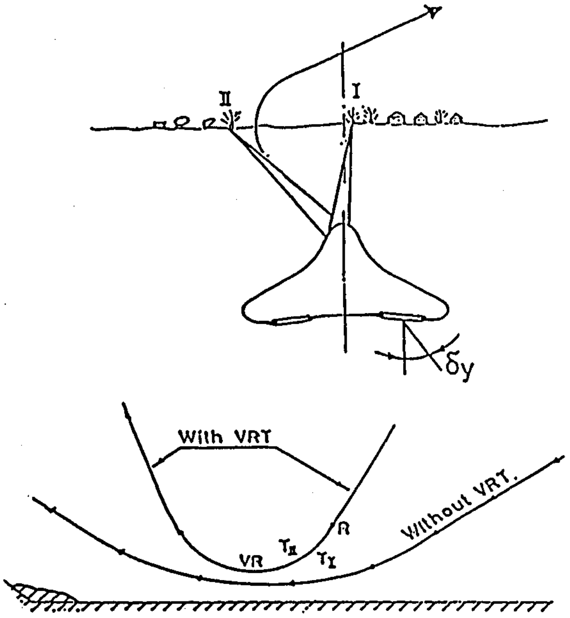

Fig. 8 Air-to-ground PSM/RANPAS; VRT = vectoring/reversing/(yaw) "targeting."[3]

The unsurpassable importance of vectored propulsion is also reflected by the accelerated efforts made recently in this field by governmental, industrial, and academic bodies (see, e.g., Refs. 1–24). Thus, we have most recently witnessed the Central Institute of Aviation Motors in Moscow publish computer simulations of yaw-pitch thrust-vectored aircraft,[4,23] as well as some British,[17] French,[6] Israeli,[3,9,14] and Chinese[22] efforts. These efforts have, in part, been influenced by the early pioneering British technology of the Harrier and by the highly stimulating works of Well[13] and Herbst[8] in West Germany. However, the main thrust in this field has long been the pioneering American programs (see, e.g., the contributions by Berrier and co-workers,[1,2,12] McAtee,[5] Tape et al.,[11] Richey et al.,[12] Bowers, Laughrey, Hiley, Palcza, who are discussed in Ref. 3, Tamrat,[7,15] Banks,[24] Klafin,[18] and others[16,17,19–21]).

One may note also that a thrust-vectored version of the Su-27 is now being developed and that the Soviet scientists present their analysis for aircraft propelled and controlled by simultaneous yaw-pitch TV.

Unlike the Soviets, who appear to be newcomers to this field, the American designers had previously adopted a more conservative design philosophy, concentrating their main research and development efforts only on pitch or on pitch/reversal TV engines, e.g., the pitch/reversal-only (PWA) TV engines installed on the new F-15/MTD.

There are, nevertheless, the (ETV-)X-31A and the (ETV-)F-18 newer programs as well as an extensive NASA program[1,2] for ETV. Furthermore, highly instructive flight simulations of the X-29A with yaw-pitch ITV have been reported recently.[18]

A minor U.S. program (U.S. Air Force, General Electric, General Dynamics, and Teledyne) is also being conducted now in this laboratory to evaluate the pros and cons of simultaneous yaw-pitch-roll ITV.[3,9,14] This program includes laboratory tests and flight testing of vectored RPVs equipped with various two-dimensional nozzles, ranging from 2 to 46.7 nozzle aspect ratio (NAR), and with various conventional and PST inlets (high AOA research). The TV nozzles currently being tested include pitch-only ITV, simultaneous roll-yaw-pitch ITV, and 3 and 4 pedals ETV.

These design differences may be critical in the final assessment of fighter combat effectiveness in the future. Hence, it is imperative, and perhaps timely, to experimentally compare the effectiveness of ETV vs ITV by the proposed methodology.

One may also note that the Soviet simulations have been reported by a propulsion institute, and not by a flight-dynam-

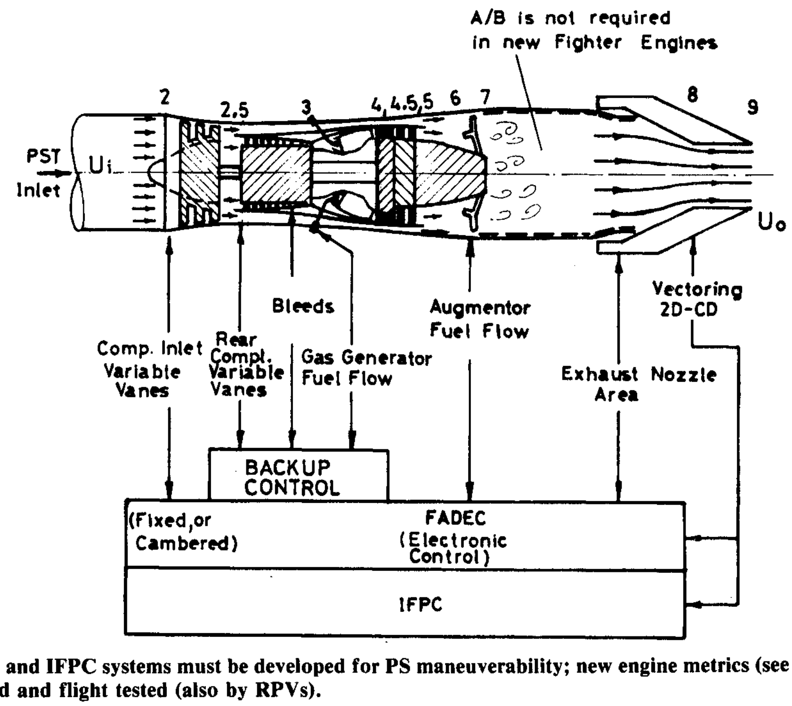

Fig. 9 TV nozzles, PS inlets, and IFPC systems must be developed for PS maneuverability; new engine metrics (see Fig. 14) and control laws (see Fig. 9) must also be developed and flight tested (also by RPVs).

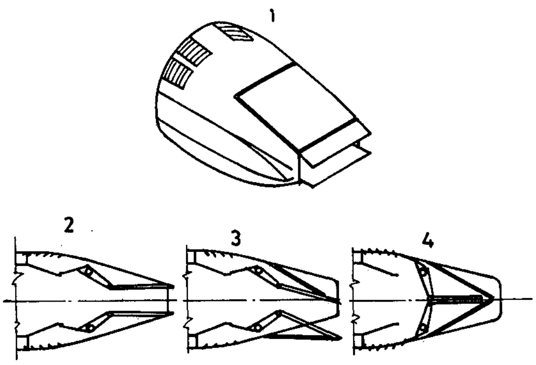

Fig. 10 Example of (pitch/TR-only) engine nozzle ITV: 1) TR outlets, 2) unvectored engine operation, 3) down-pitch TV, 4) engine nozzle during TR.

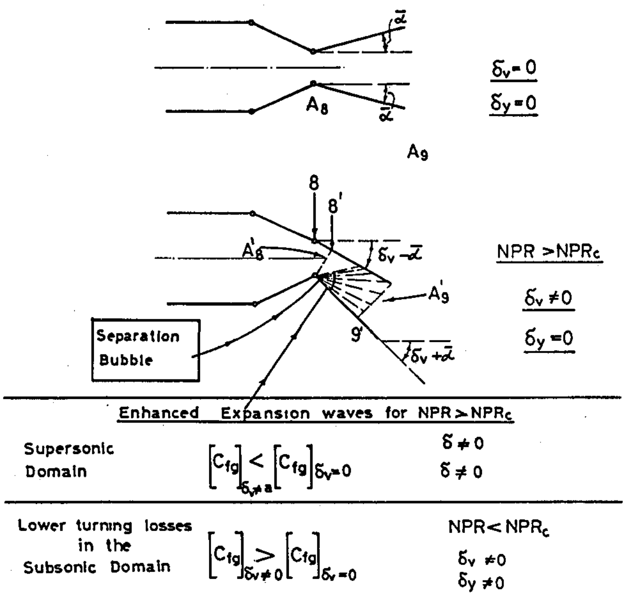

Fig. 11 In the nozzle subsonic domain, the engine thrust coefficients C_{fg} may be higher for TV engines in comparison with conventional engines[3]; separation flow regimes downstream of the corner reduce C_{fg} in the supersonic domain.

ics institute, as is still the tradition in the West. The reason behind this is probably the realization that TV aircraft agility improvements require novel IFPC programs. For this to be properly done, one needs a new, highly integrated research methodology—a methodology that does not exist yet.

Although NASA and American industry have been pursuing IFPC methodologies for years, the problem remains very complicated. Thus, new TV programs such as the (ETV-)X-31A, (ETV-)F-18, and the (ITV-)F-15 S/MTD, as well as this ITV/ETV/RPV program (see Figs. 1, 2, 12, and 13), may gradually help to overcome the problem. Here the ITV/ETV/RPV program may not only save cost, it may save considerable time, for it does not depend on the availability of "fool-proof," full-scale, vectored powerplants and inlets for maintaining high safety during manned flight tests. (In fact, two of our PVA prototypes, no. 2 and no. 4, crashed during the early flight tests.)

Thus, attempting the integration of TV propulsion with superagility concepts may also become the central goal of well-integrated aeropropulsion engineering education and research strategies.

Most important is the assertion that, in future aerial combat, pointing the nose/weapon of the aircraft at the adversary first will be required to win since pointing first may mean having the first opportunity to shoot. It may also become the required technology to dramatically increase survivability.[3,5-7,11,12]

However, as it stands now, this technology is still in its embryonic state. Although the pitch/thrust-reversal TV now appears to be maturing, the most critical technology of simultaneous yaw-pitch-roll TV is still far away from this stage. In light of the prolonged time inherently associated with the advancement and maturity of such an engineering field, one may expect its full exploitation only in the post-ATF era. Nevertheless, some of its proven elements may be gradually incorporated in such upgrading designs as those feasible now for the current F-15, F-18, and F-16 powerplants and perhaps also for other older aircraft having a thrust-to-weight ratio above 0.6—the value above which, according to Herbst,[8] combat effectiveness of vectored fighters becomes significantly higher than that of conventional ones.

Engine Nozzle/Wing Design

The definition of pure-vectored propulsion includes the following variables (see Figs. 2 and 13):

1) Y—the thrust-roll moment arm; Y must be optimized for torsional agility. Thus, for single-engine PVA, our torsional-

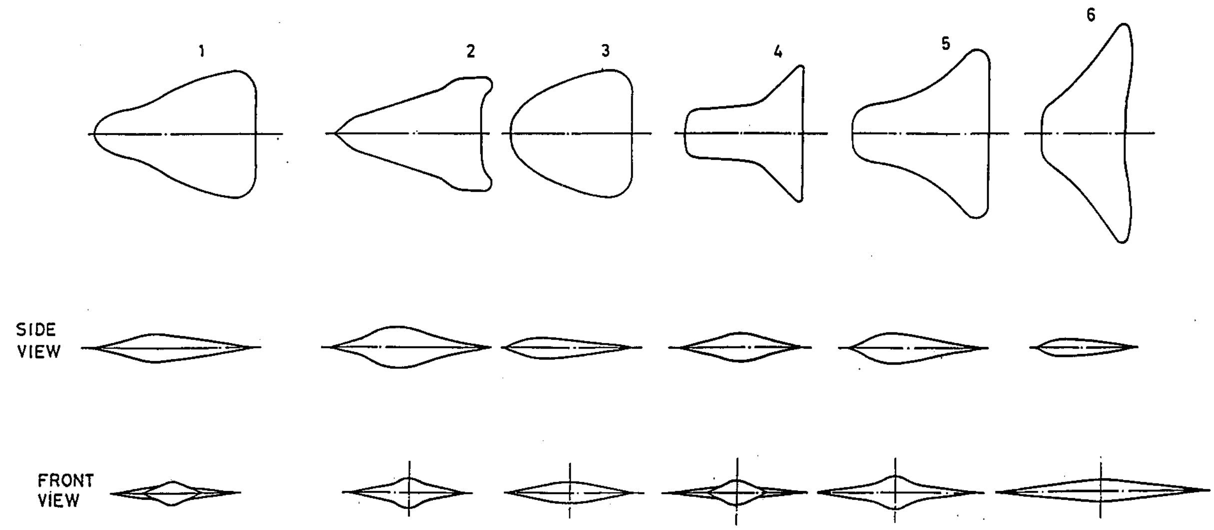

Fig. 12 The first six subsonic PVA/RPV wind-tunnel models tested by this jet propulsion laboratory in 1987; low signatures design concepts have been combined with yaw-roll-pitch TV.

agility-optimized, laboratory/flight-tested designs are based on split-type-thrust-vectoring-nozzles (STTVN) with $Y/D = 0.56$. For twin-engine PVA, we have been led to adopt two symmetric, mirror-like, medium-aspect-ratio, unsplit-type-thrust-vectoring-nozzles (UTTVN), which are so spaced apart as to keep $Y/D = 0.56$.

2) C_{fg} and C_{D8}—characteristic metrics. During yaw-pitch-roll TV with STTVN or UTTVN, the variables have been evaluated experimentally in the new altitude engine test facility of this laboratory using a 400-kg-thrust turbojet engine equipped with standard bellmouth or with low-signature PST inlets. Figure 14 provides an example of these metrics for a subsonic set of nozzle pressure ratio (NPR) values.

3) NAR—the TV-NAR. Combined with the optimized C_f, Y and D dimensions, its value may be estimated from the point of view of integrated external and internal aerodynamics, i.e., by taking into account supercirculation lift enhancement,[3] drag-reduction and engine-out flight/control considerations as well as the required radar cross-sectional signature (RCS)/infrared (IR) optical signatures and optimal performance during cruise and TV maneuverability, takeoff, and landing. Following extensive flight tests with five different PVA/RPVs, we have concluded that the optimized NAR should be between 45 to 50 for STTVN and between 25 to 30 for each of the UTTVN.

4) C_f—the vectoring nozzle flap length (see Figs. 2 and 13). Combined with the optimized Y and D dimensions and with the NAR values, this dimension may be estimated from the integrated point of view of external and internal aerodynamics, i.e., its value must also supply sufficient moment/lift enhancement during engine-out flight, or during emergency landing, as well as the required optimal performance during the varying TV angles. (Here we have assumed that, during engine-out situations, short-time sufficient actuator power would still be available, as in conventional aircraft. Unintentionally, following an engine-out flight, we had to land PVA prototype no. 3 safely by using this design. This successful landing was accomplished by using the two engine flaps as ailerons-wing flaps.) The optimized ratio employed for all of our PVAs is $C_f/Y = 0.45$ (see Fig. 2).

Proof-of-Concept of Pure-Vectored Propulsion

PVA concepts have been substantiated by the author since May 1987 using a cost-effective, timesaving methodology of highly integrated laboratory/vectored RPV flight testing. This resulted in the "first pure-vectored flights" in the "open history of aviation" using a family of 7×4 ft (and, later, 9×4 ft) computerized, radio-controlled, PST/PSM/short takeoff and landing (STOL)/PVA/RPVs (see Fig. 12).[3,9]

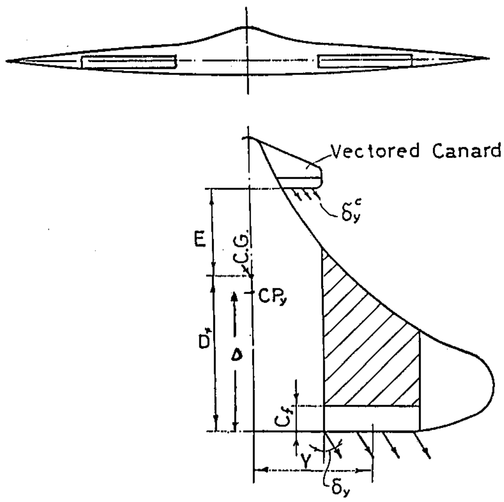

Fig. 13 TV canards (using engine compressor air) may be added to the design of PVAs³; alternatively, nose-reaction control nozzles may replace the canards.

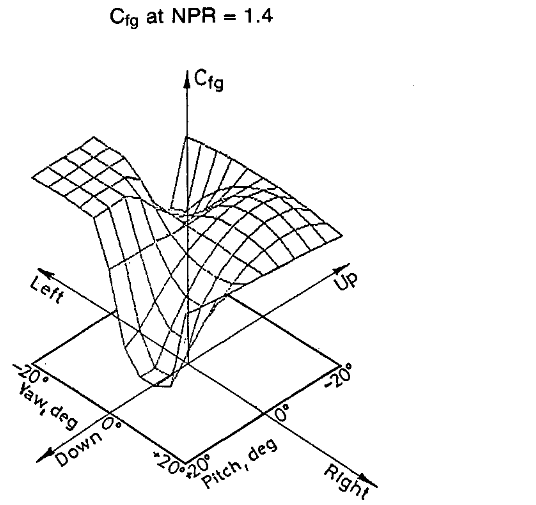

Fig. 14 New powerplant metrics are now required for the development of efficient aerogas turbines and IFPC systems; these should include the effects of yaw and pitch TV on engine thrust, discharge, angularity, and velocity coefficients.

The vectored RPVs are equipped with laboratory-tested, supercirculation-enhanced[3] TV nozzles. Aspect ratios of the TV nozzles are 46.6 for single-engine PVA/RPVs and 25 for each TV nozzle of multiple-engine PVA/RPVs. The TV nozzles have been fully integrated with the wing structure so as to provide low RCS/IR/optical signatures and supercirculation-enhanced lift during down-pitch TV, as shown schematically in Fig. 2. Simultaneous roll-yaw-pitch TV is provided by allowing yaw and pitch TV jet angles to vary during flights in the range of ±20 deg. However, all actual high-performance maneuvers require only a maximum of 5 to 10 deg in the yaw-pitch coordinates.

Onboard computers and video-camera recording are used to compare the agility of these PVAs with that of conventional or partially vectored F-15 and F-16 RPVs of comparable scale. Flight control was initially conducted from the ground by two radio operators, one using conventional aerodynamic control surfaces and the other pure TV. Only pure TV-control power has been employed in all later flights and for all PVA prototypes. The flight tests have been conducted at Ein-Shemmer and Megiddo airfields since May 1987.[3,9]

PVA proof-of-concept has been demonstrated during all of these flights. Moreover, the nose-pointing capability of PVA was found to be significantly higher than that feasible with ("baseline") conventional models, such as (1/7th-scale) F-15 and F-16 RPVs of comparable scale. During the next few years, this methodology will be employed to compare the agility/RANPAS effectiveness of ITV with that of ETV for a family of partially vectored and PVA prototypes.

Powerplant Metrics

For ITV-vectored propulsion systems, the thrust components in the x (forward), y (yaw), and z (pitch) coordinates may be computed by

$$T_x = C_{fg} T_i \cos\delta_z \cos\delta_y \tag{1}$$

$$T_z = C_{fg} T_i \sin\delta_z \cos\delta_y \tag{2}$$

$$T_y = C_{fg} T_i \cos\delta_z \sin\delta_y \tag{3}$$

Thus, these forces vary as T_i varies with engine throttle, altitude, and Mach number and as C_{fg} varies with the yaw and pitch angles of the ITV system. Obviously, yaw and pitch TV can be performed simultaneously. No such definitions can be employed for ETV. Thus, in our comparisons of the efficiencies of ITV with ETV, we measure direct forces by employing our full-scale engine test rig.[3] Thus, C_{fg} comparisons are useful only for comparative studies between, say, high- and low-aspect ratio ITV nozzles.

Interconnected Test Methodology

Four interconnected test phases are being used throughout this program. First, new ideas as well as modified propulsion designs are evaluated experimentally on "component test rigs." These include a vectoring nozzle test rig and a PST-inlet test rig. (The air-mass flow rate used in both is up to about 1 kg/s.)

Second, those designs that had successfully passed phase-one tests are scaled up to a 7 kg/s air-mass flow rate and installed on both ends of a jet engine. The engine is well instrumented and is installed inside a 2 × 14 m altitude/attitude/speed engine test facility.[3] Powerplant metrics at sea-level conditions are evaluated first for various pitch, yaw, roll, or yaw-pitch or roll-yaw-pitch, TV angles using different inlets. Each of these evaluations is made at different engine throttle settings, i.e., at different NPR values.

Third, optimized nozzle and inlet designs are scaled down back to the 1 kg air-mass flow-rate size, and the vectored RPV design is "tailored around" the optimized powerplant system using also the PVA design criteria mentioned previously.

Fourth, STOL and agility comparisons are conducted by flight testing PVA against a set of conventional designs, such as 1/7th-scale F-15 and F-16 computerized RPVs. This comparison, however, generates some yet unresolved problems.[3] [Our PVA/RPVs nos. 4 and 5 were vertical takeoff and landing (VTOL) with an "under-the-center-of-gravity," third, 70-deg-down-pitch, two-dimensional TV nozzle.]

Finally, the flight-test results may be employed to modify the powerplant/RPV components, whereby the entire test cycle may be resumed (see Fig. 15). (Alternatively, the RCS signatures of our PVA may be evaluated and the results employed to modify the entire design. Similar test phases are employed throughout our programs for flight testing semivectored, upgraded F-15 and F-16 RPVs equipped with TV systems of low and high NAR types.)

The proposed methodology of highly integrated laboratory/vectored RPV flight tests has been proved to be cost effective and timesaving. It is currently employed to reassess debated agility concepts and to test IFPC and new TV nozzles and PS inlets for semivectored F-15 and F-16 prototypes during PS or pure-sideslip, rapid-nose-pointing maneuvers.

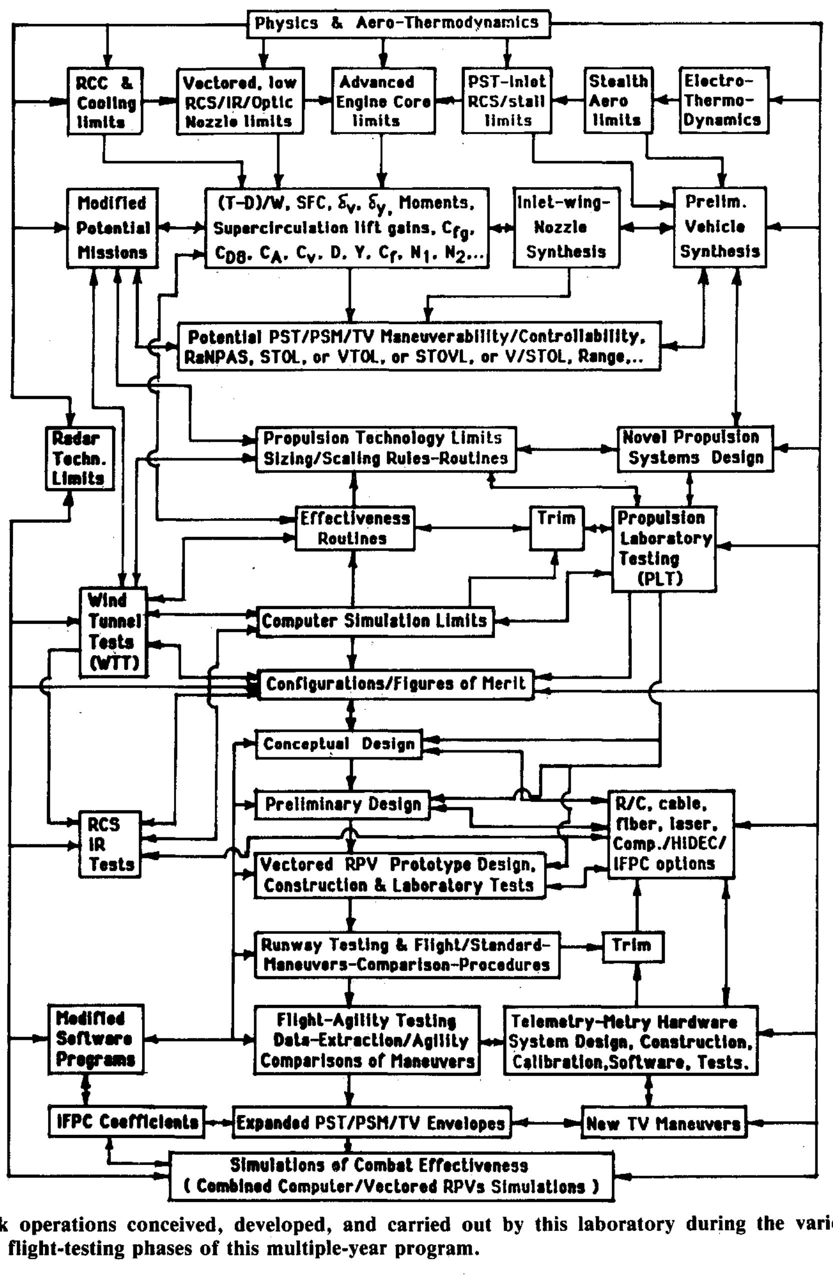

Fig. 15 The main feedback operations conceived, developed, and carried out by this laboratory during the various phases of the design, fabrication, laboratory, and flight-testing phases of this multiple-year program.

Preliminary Powerplant/Airframe Evaluation Problems

The main problems encountered in phase four may be grouped into three categories:

1) The development of a realistic, cost-effective method to measure and compare the agility of two different propulsion system designs, say, a conventional vs a vectored or a semivectored vs purely vectored. The problem, however, is that the very definition of agility is still being debated.[3,5-8] Thus, we have to return to this problem below. [In comparing vectored F-15 or F-16 agility to that of the conventional, we keep various similarity principles,[3] which, inter alia, require data on the conventional (baseline) moments of inertia in all three axes and, accordingly, to modify the mass distribution inside the RPV.]

2) The development of a cost-effective hardware to measure and compare the performance of two different powerplants/RPVs. For this purpose we have developed an onboard, lightweight, low-cost, "metry" computer, which records flight data on its random access memory (RAM). Our new computer is based on an advanced personal computer (PC) "card" that has been considerably modified for this purpose and then combined with amplifiers and analog-to-digital converters and various calibrated sensors. Our first computer records 32 channels every 0.1 s for 180 s—the net time required for "standard" recorded maneuvers. The overall duration of each flight test takes 10 min.

Then, following landing, the flight data are fed to a standby computer, and flight tests are resumed. Combined with proper video recordings, this methodology saves cost, time, and effort. Our inputs to the computer RAM include AOA, sideslip angle, 19 inlet-pressure-distortion probes, accelerometers/rate gyros, all vectoring angles, all aerodynamic-control-surfaces positions, speed, etc. Each data extraction set begins and ends by a radio command at the beginning and at the end of each specially planned standard comparison maneuver (SCM). Thus, each SCM set is properly filed for later anlyses in the laboratory or even near the runway. Under these conditions, and for these purposes, such a metry methodology was found to be highly preferable to any of the currently available heavyweight, expensive telemetry methods.

3) The aforementioned hardware cannot be applied without proper software to feed, calibrate, file, transfer, and identify the data extracted. Hence, the application of this methodology requires the simultaneous development of proper computer software.

How Efficient Is Thrust Vectoring?

How does one evaluate and compare the agility and efficiency obtainable by two different propulsion/flight-control methods? Or, what does one measure, during what kind of SCM, with what RPV, for what purpose, at what cost, under what similarity rules?

In our flight-testing programs we first compare the agility of a conventional F-15 RPV, or F-16, (baseline-1 RPV) with that of a "canard-configured" F-15 (baseline-2 RPV) with that of "pitch-only" vectored F-15 RPV (baseline-3 RPV), with that of yaw-pitch vectored F-15 RPV (baseline-4 RPV), and, finally, with that of "simultaneous roll-yaw-pitch" vectored F-15 RPV (baseline-5 RPV).

However, the last category is further divided into flight-testing vectored-propulsion/RPV systems with or without vertical stabilizers, rudders, and leading-edge devices and also into other important subcategories involving, for example, fixed or movable conventional aerodynamic control surfaces, etc. Yet, above all, the "comparison-metrics" problem has remained unresolved.

Propulsion/Aircraft Debated Comparison Metrics

Anticipating the introduction of vectored aircraft, McAtee,[5] in 1987, defined fighter agility as composed of two complementary concepts: maneuverability and controllability. PST maneuverability is then called "supermaneuverability," and PST controllability is named "supercontrollability." Thus, according to McAtee, the quality of fighter agility is the combination of the following three (measurable) tasks/abilities:

1) 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. Otherwise, with current launch-and-leave weapons, mutual destruction would result. It is, therefore, the key ability to point at the enemy quickly to get the first shot (thereby reducing the sum total of delay times, including missile locking delays and path/time of flight). This ability is measurable in terms of turn rate vs bleed rate of the aircraft/missile.[3]

2) The ability to continue maneuvering at high turn rates over prolonged periods to retain the potential to perform defensive maneuvers or to make multiple kills when appropriate. 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.

3) The ability to accelerate rapidly straight ahead, so as to leave a flight at will, to regain maneuvering speed when necessary, or 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 acceleration vs speed plots of the aircraft.

McAtee concludes that these three measurable tasks/abilities are crucial for success in modern close-in combat. Thus, the critical design features for modern fighters are those that enable the pilot to command very high maximum turn rates over prolonged periods and to perform a 1-g acceleration.

Supercontrollability

Good maneuverability must be integrated with effective controllability, i.e., the ability to change states rapidly (control power) and the ability to capture and hold a desired state with precision (handling qualities). Traditionally, controllability was thought to be degraded at either of two conditions: high Mach number or high AOA. However, the introduction of PST and vectored aircraft technology requires reassessment of the second condition. It also requires the introduction of new definitions, standards, and military specifications.

Pitch and yaw control requirements increase with AOA. For a given roll rate, as AOA increases, the requirements for pitch and yaw forces/moments (for non-TV aircraft) increase exponentially. At the same time, with conventional aerodynamic controls, the forces/moments available decrease as airspeed decreases. Thus, beyond a given limit, conventional control technology becomes obsolete. This technology limit is reached when the size and weight of the aerodynamic control surfaces needed to provide sufficient forces/moments become prohibitive. However, the introduction of PS and vectored aircraft technology (together denoted by McAtee as the new domain of supercontrollability) requires reassessment of all maneuverability and controllability concepts and requirements.

Thus, according to McAtee, new point-and-shoot weapons have reduced engagement times drastically, leaving aircraft with poor maneuverability and controllability at the mercy of those that can use their agility to kill quickly during close-in combat. Vectored PS maneuvers may thus be defined as supermaneuvers.

There are a few dozen candidate supermaneuvers, half of which may demonstrate a real combat promise. In Ref. 3 we provide a few examples for combat payoffs during the proper use and at the proper position/timing of yaw-pitch-roll thrust vectoring during "angles" and "energy" tactics. These tactics employ supermaneuvers well beyond the current flight envelopes of conventional fighter aircraft.

External Thrust Vectoring vs Internal Thrust Vectoring

ETV, or postnozzle thrust vectoring, is accomplished by single or multiaxis postexit "vanes," which provide yaw-pitch controllability (by deflecting the freejet emerging from an axisymmetric nozzle of the X-31). This methodology is associated with relatively simple, readily available, pedal/flap external devices on one hand; and with (high-aspect nozzle-ratio) supercirculation lift gains (X-31), high external nozzle drag, external-flow-dependent, jet-deflection propulsion/flight control laws/reliability, relatively high RCS/IR signatures (especially with circular nozzles), and longer overall propulsion-system length on the other hand.

Nevertheless, the X-31 constitutes one of the most important and most promising aircraft in the evolution of vectored aircraft. Its flight testing would certainly become a significant milestone in aviation history.

Another important contribution to ETV was recently made by NASA Langley Research Center[1,2] and by Northrop.[15] In one of the most promising designs,[1,2,15] postexit vanes were mounted on the side walls of a nonaxisymmetric, two-dimensional converging-diverging (CD) exhaust nozzle. Although the resultant yaw vector jet angles in this design are always smaller than the geometric yaw vector angle, the widest postexit vanes produce the largest degree of jet turning.

Partially Vectored Propulsion/Aircraft Systems

Partial jetborne flight (PJF) may be defined as a flight in which elevons, ailerons, flaps, canards, elevators, leading-edge devices, vertical stabilizers, rudders, etc., are still being used in conjunction with a TV system. Most of the TV methodologies assessed below may be classified as PJF, e.g., those associated with the ETV-X-31, the ETV-F-18, and the ITV-F-15 S/MDT programs. This means that maximal maneuverability and controllability levels obtainable with PVA are reduced, to a degree, by external-flow effects on conventional aerodynamic control surfaces, especially in the PS domain.

Another objective of our PVA/RPV program is, therefore, to discover the bona fide technology limits of PVA and to conclude whether or not the flight/propulsion control during PJF is more or less safe/complicated than that feasible with PVA.

The following conclusions have been obtained so far:

1) PJF with partially vectored F-15 and F-16 1/7th-scaled vectored RPVs involves too many variables, most of which are redundant. On one hand, leaving the multiple aerodynamic control surfaces operative adds safety in case of ITV or ETV failure. On the other hand, the redundancy involved, in comparison with PVA, may decrease safety and increase complexity beyond actual needs.

2) A reliable IFPC system for PJF may have to overcome the lack of proper definitions of the relevant variables involved. However, in spite of extensive NASA and industrial work in this field, there is yet no experimental data base for the proper range, limits, and coupling effects among these variables during actual flight conditions. The main reasons for this lacuna is the redundancy of conventional aerodynamic variables and the high-cost, time-consuming efforts to flight test manned TV, F-15, F-16, F-18, etc.

Hence, it is here that a properly designed, vectored RPV program may be highly cost effective in establishing the yet-unknown bona fide technology limits and in supplying preliminary IFPC data bases.

Integrated Flight/Propulsion Control

Vectored propulsion design should be based on new control laws such as 1) new engine control rules, in particular new nozzle and new inlet rules; 2) new flight-propulsion rules for PST/PSM/RANPAS maneuvers; 3) new flight-propulsion rules for takeoff and landing, e.g., turning the jets up first and, then, following aircraft rotation, turning them down for extra lift by direct engine force and, in a few advanced designs, also by supercirculation[3]; and 4) new coupling rules, e.g., directional thrust vectoring (DTV) to aileron cross feeds to correct DTV coupling into roll, lateral-directional cross-feed paths to provide stability-axis rolls with high AOA, and longitudinal TV gains vs the longitudinal system loop, etc.

For PVA/ITV the simplest control demands are for the TV engine exhaust nozzle, e.g., during thrust vectoring, at a given value of NPR, one must keep the values of A_8^e and A_9^e (see Fig. 11) as a function of $(\cos\delta_v) \times (\cos\delta_y)$. Thus, the throat area variation during simultaneous yaw-pitch, TV may become

$$A_8^e/A_8 = \cos\delta_z \cos\delta_y \tag{4}$$

where A_8^e is the effective throat cross-sectional area defined by point 8 in Fig. 11. However, Eq. (4) neglects two effects:

1) To maintain a predetermined A_9^e/A_8^e ratio for each NPR, the effective nozzle exit area A_9^e should also be subject to the condition

$$A_9^e/A_9 = \cos\delta_z \cos\delta_y \tag{5}$$

2) To maintain the same mass flow rate throughout the engine during yaw-pitch vectoring, at a given NPR, the flaps in the throat area must be "opened" by a factor of

$$A_8(\text{during vectoring})/A_8(\text{unvectored}) = 1/\cos\delta_z \cos\delta_y \tag{6}$$

Similarly, the flaps in the nozzle exit area should be opened by a factor of

$$A_9(\text{during vectoring})/A_9(\text{unvectored}) = 1/\cos\delta_z \cos\delta_y \tag{7}$$

Equations (6) and (7) are the first and the simplest IFPC rules for yaw-pitch TV. Additional control rules are available elsewhere.[3]

Integrated Flight/Propulsion Control and Thrust Levels During Vectoring

IFPC rules for simultaneous roll-yaw-pitch TV should first be based on Eqs. (1–7), where δ_v and δ_y for both ITV and ETV are not the deflection angles of the flaps, vanes, or pedals. They should be the actual jet-deflection angles (which must be evaluated by jet-propulsion laboratory tests). For the roll-yaw-pitch ITV systems tested in our programs, the deviations between the jet and metal deflections are not greater than 3 deg under some specific operating conditions involving no yaw TV. Similar deviations have been measured for the pitch-only two-dimensional-CD nozzles currently tested on the F-15 S/MTD.[3] However, for ETV these deviations may be higher.[1,2]

Our laboratory tests have also shown that, during pitch vectoring, the value of C_{fg} for NPR<2 (i.e., in the subsonic domain) may be a few percent higher than C_{fg} for the same nozzle during unvectored propulsion (see Fig. 11). This may result from the higher payoffs of the "straight" flow passing the upper nozzle throat corner rather than the (subsonic) losses associated with the lower corner. Thus, ITV nozzles may supply the airframer with approximately the same or somewhat higher thrust levels than those available for unvectored flight. Furthermore, in the subsonic nozzle-flow domain, without vectoring, conventional (circular) nozzles may have lower C_{fg} values than those available for two-dimensional-CD nozzles such as the one shown in Fig. 10. The subfigures represent 1) the GE/PW, low NAR, pitch-only/thrust-reversal nozzle; 2) this nozzle during unvectored flight; 3) down-pitch vectoring; and 4) full thrust reversal. The venetian-type vanes are oriented approximately 45 deg forward.

During the approach phase for TV landing, the venetian-type vanes are oriented about 135 deg to the back, the throat remains partially open, the engine throttle is fully open, and the diverging flaps are vectored down. This type of TV reduces the approach speed and, following touchdown, also the landing distance (for the engine spool-up time required in conventional thrust reversing has been saved). However, the cost, weight, and complexity of this kind of thrust reversal may be prohibitive. Hence, thrust reversal (TR) propulsion systems may be rejected from advanced TV fighters.

However, for NPR > NPR (critical), i.e., in the supersonic domain of the nozzle flowfield (see Fig. 11), the expansion waves generated by the separation bubble just downstream of the lower throat corner lowers the value of the "effective" NPR. Consequently, C_{fg} during supersonic vectoring may be lower than that for unvectored operation.

Preliminary Scaling Rules for ITV

A number of dimensionless numbers may be defined for pure-vectored propulsion/airframe scaling methodologies, e.g., for canard-less PVA (see Fig. 2):

$$N_1 = \text{yaw moment/pitch moment}$$

$$= \cos\delta_v \cdot \sin\delta_y / \cos\delta_y \cdot \sin\delta_v \quad (8)$$

$$N_2 = \text{yaw moment/roll moment}$$

$$= D(\cos\delta_v \cdot \sin\delta_y)/Y(\sin\delta_v \cdot \cos\delta_y) = (D/Y)N_1 \quad (9)$$

$$N_3 = \text{roll moment/pitch moment} = N_1/N_2 = Y/D \quad (10)$$

These numbers may be employed during preliminary scaling-up considerations—especially because they do not depend on the thrust level of the engine(s) or on the number of engines used. Our laboratory and flight-testing results have been employed to arrive at an optimized value of

$$N_1/N_2 = Y/D = 0.56 \quad (11)$$

for high torsional agility at high AOA values. This value does not depend on the type of vectoring nozzle or on NAR. Consequently, one can use this value for scaling-up procedures in vectored propulsion design procedures.

Load Factors During Post-Stall Maneuvers

The lift coefficient and the effectiveness of all aerodynamic control surfaces diminish in PS maneuvers. Thus, the load factor on a vectored aircraft depends on the specific design of the TV system, the time-varying directions and values of the vectored jets deflected, engine throttle, the turn rate/radius, body-wing AOA/sideslip angle, speed, altitude, the direction of the gravitational vector, canard/elevators/flaperons deflections/loads, and the time variations in the proper drag components, etc. Moreover, if the aircraft slows down just prior to a vectored-controlled turn maneuver (with or without thrust reversal), the load factor is reduced during the turn performance. Since the lift coefficient falls down at high alpha values (see Fig. 3), a properly designed propulsion/flight control system should maintain the proper load factor/acceleration force according to the mission and the pilot's demands using TV forces and moments to replace the loss in lift force and the loss in moments generated by conventional control surfaces.

Furthermore, as the altitude is increased, the thrust and, hence, the vectoring moments and forces (and, thus, the total load factors) are reduced (see Fig. 5) when other parameters remain unchanged. Still further, one must distinguish between the different maximum g-components that a pilot can sustain for a given duration (in the positive or negative pitch plane, in the yaw plane, and during head-on in-flight "braking").

One must also differentiate between thrust-yaw, thrust-reversal, and thrust-pitch forces for yaw, pitch, thrust-reversal, or simultaneous yaw-pitch, yaw-pitch-roll, or yaw-pitch-roll/thrust-reversal maneuvers.[3] Consequently, for PS/PSM maneuvers, the instantaneous and the "time-averaged" load factors on pilot/powerplant/aircraft may be designed to be lower, and shorter, than those intuitively assumed for conventional maneuvers. It should also be stressed that proper PSM/RANPAS maneuvers, in particular, do not require high AOAs or high loads. Thus, well-performed, PS, or combined PS/PSM/RANPAS/TV maneuvers[3] can be safely employed to increase survivability and killing ratios without surpassing human and structural limitations.

Concluding Remarks

1) The fundamental concepts of vectored propulsion have been verified by an integrated methodology of jet-propulsion laboratory/flight testing of vectored RPVs.

2) The integrated methodology of laboratory/vectored RPV flight testing has been found to be cost effective and timesaving. It may also be expandable to high AOA research and to investigations of new PS inlets in jet-propulsion laboratory tests combined with proper flight testing of vectored propulsion systems.

3) Upgrading existing fighter aircraft, such as the F-15, F-16, and F-18, to become partially vectored aircraft can be effectively tested by the proposed methodology. Such programs can help the final selection of ITV or ETV and the verification of optimized IFPC architecture.

4) Low-cost, low-weight, metry computers can effectively replace expensive, heavyweight telemetry computers in flight testing vectored propulsion systems.

5) The methodology presented here may help accelerate advanced propulsion programs by providing such experimental powerplant/airframe/control "metrics" as:

a) A common set of measurable, TV maneuverability/controllability parameters that can eliminate ITV or ETV for specific missions. Such metrics can be presented as three-dimensional depictions of powerplant dynamic responses, somewhat similar to those proposed recently to depict aircraft agility.[3,5] They should include throttle/pitch/yaw/roll/reversal TV transients for twin- or single-engine propulsion systems as may be implemented in the final IFPC design. Of particular interest is the powerplant design that also affords pure sideslip RANPAS.

b) Thrust, discharge, angularity, and velocity coefficients as those illustrated in Fig. 14, for instance.

6) The unmanned, cargo, and civil aircraft industries may exploit some of the proposed methodologies of vectored propulsion and controllability, for instance, by introducing low-drag, cost-effective, STOL, high-NAR, pure-vectoring propulsion systems.

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The design conclusions extracted from our flight tests and the theoretical and experimental methodologies discussed here in regard to new TV systems, as also extracted from the Advanced Altitude/Attitude Turbojet-Engine Test Facility of this laboratory, are based on a number of ongoing programs currently financed in this laboratory by the U.S. Air Force, General Electric, General Dynamics, and Teledyne. [Note: Most of the experimental work conducted in this laboratory on TV engines and PST inlets and in flight testing of pure-vectored/stealth RPVs is classified as "proprietary" of our financial sources and is, consequently, unpublishable. However, the fundamental concepts and the various practical methodologies described here stand out as a generic, academic investigation.]

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