Jet Propulsion Laboratory, Faculty of Aerospace, TIIT

Tailless Vectored Fighters

Theory, Laboratory and Flight Tests

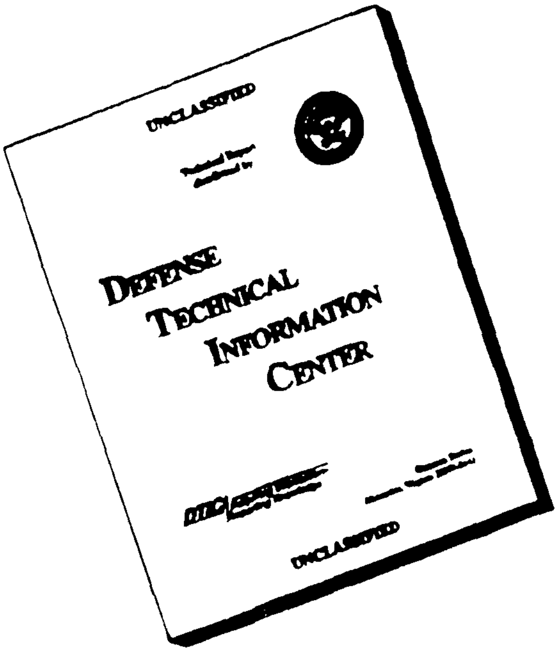
Including Vectorable Inlets/Nozzles and

Tailless Flying Models vs. Pilot's Tolerances

Affecting Maximum Post-Stall Vectoring Agility

Submitted with A Master Review Video Tape

Benjamin Gal-Or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Presenting the major problems confronting the development, tests and validation of Post-Stall (PST) Thrust-Vectored Fighters (TVF), this project is based on the development of an integrated laboratory-flight testing methodology of PST-F-15-TVF/RPVs, including the tests of new types of yaw-pitch and roll-yaw-pitch thrust-vectoring nozzles and high-alpha, PST inlets. Mathematical phenomenology of PST-TVF has been added to define the methods required to maximize PST-TV agility and to measure it.

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REPORT OF INVENTIONS AND SUBCONTRACTS

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Gal-Or, Benjamin BENJAMIN GAL-OR ISRAEL INSTITUTE OF TECHNOLOGY TECHNION CITY HAIFA ISRAEL	Yaw-Pitch and Roll-Yaw-Pitch Thrust-Vectoring, 2D-CD and 2D-C nozzles cf. App. A. p. 72 and p. 55, Report I April 21, 91. B. Gal-Or BENJAMIN GAL-OR [illegible] TECHNION CITY	-	X		X			

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Tailless Vectored Fighters

Theory, Laboratory and Flight Tests

Including Vectorable Inlets/Nozzles and
Preliminary Studies of Tailless Aircraft
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Maximum Post-Stall Vectoring Agility.

WL/WRDC/FIMM Research Titles:
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2nd-Year Report

Submitted with Video Tapes No. 5 & 6 [A Master Review]

April 1, 1990 to June 30, 1991
Report Date : July 15, 1991

Program Manager: **Douglas Bowers**
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TABLE OF CONTENTS

Theory

Laboratory & Flight Tests

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Mr. Douglas Bowers, Program Manager, this Project, WRDC[WL]/FIMM, WPAFB,

Mr. Eli Benstein, Chief Scientist, Teledyne CAE,

Mr. Don Dunbar, Director of Combustion-Nozzle Dept., General Electric,

Mr. F. Ehric, Chairman, ASME-Aircraft Engines Comt., General Electric,

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USAF Capt. Daniel D. Baumann, Flight Tests Manager, F-15 SMTD, WL/FIMX, WPAFB, USAF and active participant in this Program within USAF/WOE visit to this Laboratory, Jul-Aug 1991 [see next-page and Appendix A].

Participants & Contributors

Pilots

Daniel Baumann [USAF Capt., pilot, M.Sc. Aero-Eng., Flight Test Manager, USAF/McDD [pitch thrust-vectored] F-15 STOL Maneuver Technology Demonstrator. Active participant in this program within USAF/WOE visit].

Berkovitch Raphi [IDF Lt. Colonel & F-16 Pilot. Design & construction of elevator-less/rudderless ['Semi-tailless'], Yaw-Pitch-Roll , Thrust-Vectored F-16 RPV which made its first flight test on May 9, 91. "Engine Design Course"].

Sapir Shaul [IDF Major & 707 pilot. Design, construction, and lab tests of the 4th-generation, elevator-less/rudderless ['Semi-tailless'], yaw-pitch-roll F-15 RPV which has not yet been flight tested. "Engine Design Course"].

Gal-Or Amir [IDF Capt. & F-4 pilot, participated in the conceptual design and the reviews of flight test results]

Gal-Or Gillad [IDF Lt. & A-4 pilot, participated in the conceptual design and the reviews of flight test results]

Flyers

Amir Yogev [IDF authorized, "Day/Night/Operational" Military RPV Flyer. Our Flyer of vectored F-15 & F-16 RPVs from March 1990 to July 1990].

Baran, Shlomo [Best-payed flyer of unmanned vehicles in Israel. Flies also IAI RPVs & Unmanned Helicopter. Our flyer of vectored F-15 RPVs during Nov.-Dec 90].

Cohen Zahi [Construction and early flyer of pure vectored RPVs & Stand-by flyer for the vectored F-15 & F-16 RPVs till Feb. 1990].

Friedman Erez [Constructor & 1st-rank flyer of pure vectored RPVs and vectored F-15 & F-16 RPVs till March 1990. B.Sc Aero Eng.]

Turgeman Mike [Our 1st-rank constructor & and flyer of our 1st thrust-vectored RPV in 1987 and of the TV-F-15 & F-16 RPVs in 90/91. B.Sc & M.Sc. Aero-Eng.]

Greenberg Israel [Israel's Champion for flying R/C models - since 87. 2nd-Position in the 88 European Cup. A candidate flyer for future tailless PST-TV RPVs & SACOMs].

Aero-Engine Technicians & Engineers & Faculty

Dekel Eli [Vectored Nozzles tests with 'full-scale' jet engines. F-15 subscale and fullscale inlet/nozzle work. Construction of 2nd and 3rd-generation F-15 & F-16 RPVs]

Gal-Or, Dr. Benjamin [Coordinator and principal investigator of this project. Head, JPL. Professor, Faculty of Aerospace Eng. Video-camera operator during flight tests.]

Meshaich Eli [Vectored Nozzles tests with 'full-scale' jet engines. F-15 subscale and 'fullscale' inlet work. Construction of 2nd and 3rd-generation F-15 & F-16 RPVs].

Rasputnis, Dr. Alexander ['Fullscale', F-15 vectoring nozzle calibrations & tests & computing procedures. 'Full-scale' engine test rig instrumentation and calibrations].

Scherbaum, Dr. Valery ['Fullscale' jet-engine tests., F-15 vectoring-nozzle tests & computing work. May 9, 91'post-flight-analysis].

Lichtsinder, Dr. Michael [Control theory, Gyroscopic effects calculations, instrumentation principles/practice]

Rakotch, Dr. Efraim [Solution of partial Differential equations/computer software].

Soreq Ilana [JPL Secretary. Administration of contracts].

Voroveichik Sara [Mechanical Engineer. Mechanical calculations & Drawing].

The PCSI Company: Pesach Pascal and Doron Rozenwaser [a computer laboratory which designed and manufactured our 2 onboard and 2 ground computers].

The following participants are part-time paid workers selected from the TIIT's computer, aerospace and mechanical engineering community of students or students within their final, 2-semesters "Engine Design Project".

Smaddar Eli & Yael [Computer Engineering Experts. Modifications of software for Post-flight analysis and calibration equations for gyros and RPVs probes].

Gafni U. [Construction of elevator-less (<u>tailless</u>) Yaw-Pitch-Roll TV F-15 RPV].

Igal Harel [Construction/laboratory tests of F-15 RPV. Forces/Moments Metrics].

Rami Aristoraz and Oren Yoav [pure-vectored, 4th-generation, elevator-less F-15 wind-tunnel models construction & tests & analysis].

Schnaider, Rafi, [Field data/Computer secretary and RPVs calibrations].

Shlomo, Moshe and Igal [Partial construction of 4th-generation, elevator-less/rudderless, yaw-pitch-roll F-15 & F-16 RPVs].

Spector, Ben-Zion, Vershavsky Dan, and Soffer Dan [Construction, calibration and preflight tests of F-15 RPV; construction and calibration of onboard computer-probes & hardware. Field/Laboratory operating Instructions].

Outline

This laboratory conducted the first flight tests of thrust-vectored [TV], unmanned vehicles [1987], and the first TV-induced positive and negative '**Cobra**' maneuvers, using a 9-foot scale F-15 model [1989]. It is also the only laboratory that flight tests tailless/stealth/vectored, dynamically-scaled models of US fighter aircraft.

The methodology used is based on integrating theory, wind-tunnel and full-scale jet-engine-laboratory tests to design, construct, instrument and flight test novel, **Post-Stall** [PST] TV-models of aircraft such as the **F-15**, **F-16**, and [probably, beyond 1991], novel TV versions of **C-130, F-117, F-18** and **F-22**, including tailless/stealth, PST, STOL or VTOL models. Two million dollars have already been invested for this purpose during the last three years, half of which has been provided by the **USAF, General Dynamics, Pratt and Whitney, Teledyne, and General Electric**.

Funding for 1992 includes projects directed by USAF/Human-System Division on the maximization limits of TV agility due to pilot tolerances. Our next-phase test results will be used for conducting large-centrifuge simulations of TV-induced pilot-tolerances in WPAFB's Armstrong Laboratory and at BAFB. Currently there is no other data source for such simulations.

Recommended extension projects which are currently unfunded include adding yaw-pitch **TV to F-117, F-22, C-130 and F-18**, as enumerated next to this Outline.

Other recommended extension projects are: Measurements of Pilot-to-Flyer Delay Times vs. Aircraft Gross and Net Agility Components, Model-to-Aircraft IFPC-Delay-Times, ETV vs ITV Agility, tailless TV-model flight-tests with F-16 & F-15 'Baselines', and the **latest USAF-JPL-Extension-project on 'DES-TV-Baselines'** [See Report End].

We also recommend using our kits [Roll-Yaw-Pitch-TV-nozzles + Vectorable PST-inlets] in **spin-off applications** [see below], and to test upgraded fighter performance by means of our methodology. **Other recommendations are**: i - Use of PVA as 'Ideal Standards' for maximizing PST-TV-agility/flight-control power, ii - Extracting new TV-potentials to further reduce any fighter's optical, infra-red and radar signatures; iii - Using this laboratory as a host laboratory for the new **DOD/AASERT and WOE programs**.

* * *

Without risking lives, at low cost and relatively short time, our pre-calibrated and instrumented models, utilizing TV and conventional aerodynamic control surfaces, measure velocity, alpha, sideslip angle, pitch, roll and yaw rates and accelerations during newly-defined SACOMs. The angle of attack, sideslip angle, velocity and pitch, yaw and roll rate gyros have successfully and precisely provided the required data. The calibration methods for the gyros/probes/onboard-computer have been found reliable and repeatable.

Model responses to Conventional, TV + Conv. and pure TV commands are precisely measured and accurately recorded by our instrumentation/computers/calibration/software. The recordings allow verification of what we call practical SACOMs. These have evolved from our theoretical studies. We recommend using them in all similar future studies.

The model extracted data are dynamically scalable to full-scale fighter aircraft. Hence the data can be used to compare one aircraft design to another and also to project and predict agility limitations due to pilot tolerances.

The proof-of-concept/feasibility-studies include full-scale jet-engine tests, a few windtunnel tests of tailless configurations, tests of a **vectorable, distortion-free**, Post-Stall [PST] F-15 **inlet** and a new mathematical phenomenology required to maximize PST-TV-agility. The mathematical phenomenology contains PST-TV terms, which, in combination with **Dynamic Scale Factors** [DSF], provides physical insight and new guidelines to maximize PST-TV agility by means of dynamically-scaled models. While 'accuracy levels' of our DSF and 'practical' SACOMs can be further improved, the results obtained so-far allow, for the first time, realistic comparisons of agility components between one TV-Control system to another. First-ever **Pure Side-slip Maneuvers** by means of tailless PVAs will be tested next.

The proven methodology provides cost-effective and time-saving means to design, construct and flight-test correct-DSF-Scaled models in search of maximized PST-TV-Control power. Our Yaw-Roll-Pitch TV-nozzles open-up new possibilities to effectively eliminate the tail from practically any conventional jet-aircraft, thereby increasing range and safety levels during takeoff and landing, and, simultaneously, reducing weight, drag, SFC and optical, infra-red and radar signatures.

Full-scale aircraft agility is approximated by model aircraft agility modified by DSF involving aircraft-to-model average-densities-ratio times moments-of-inertia ratio multiplied by the fifth power of the linear-scale-factor **L**. Likewise, the DSF for weight is the ratio of densities multiplied by $[\mathbf{L}]^{3}$ and for Full-Scale **Angular Velocities** [Roll, Pitch, Yaw Rates] it means multiplication of model angular velocities by $[\mathbf{L}]^{-0.5}$.

Pitch rates extracted from current TV-F-15 and TV-F-16 models are around 150 deg/s, which, for the full-scale fighters, become $[150][7]^{-0.5} \approx 56$ deg/s, i.e., about **twice the current turn rate.** Thus, our methodology allows estimations of agility limitations due to **pilot negative-g-onsets/side-force tolerances,** and other, otherwise unmeasurable, PST-TV-induced biodynamic accelerations, as functions of the [scaled] distance of the pilot from the [unknown, translating] TV-center-of-rotation which must be measured next year.

Deflection of the yaw vanes of our TV-designs and 'tailless' models very-effectively steer the model on the runway, with no need for a front-wheel gear-steering-mechanism. It also provides strong moments at very low air speeds and/or high angles of attack, when the rudder-moments are too small for safe control.

Tailless, **Pure Vectored Aircraft** [PVA] are analysed as **"Ideal Standards"** to maximize PST-TV-Agility for superior combat effectiveness. Accordingly, full-scale, jet-engine tests are conducted with novel yaw-pitch and roll-yaw-pitch TV-nozzles and vectorable, PST-inlets and the PVAs are designed "around" these novel propulsion systems.

Scaling down the nozzles, flight testing them by means of RPVs, and, according to results, redesigning the nozzles for full-scale jet-engine tests, completes a typical cycle in our holistic approach to gain supermaneuverability, enhanced safety and reduced signatures.

Within such holistic cycles a mathematical phenomenology has been developed to assess the main components which strongly affect TV-agility/supermaneuverability. The theory identifies the main TV-propulsion moments and forces required to gain effective, deep-PST-TV-maneuvers. The theory, the full-scale/jet-engine tests and the flight tests are also intended for next-phase RPV simulations of maximum angular accelerations/onsets/reversals vs pilot tolerances. The results will be of direct importance to next-phase centrifuge simulations and next-phase pilot training with new TV-aircraft.

An elevatorless/rudderless, 1/8-scale F-16 model has been successfully tested by the JPL on May 1991. using the criteria enumerated in this work. With a similar F-15 RPV it is to be further used as a flying simulator to verify the concepts enumerated in this study.

No evidence was found for the need of a canard to obtain flight stability, PST-TV agility and good control power. STOL and VTOL properties can now be evaluated by means of our recently verified DSF equations. Roll-yaw-pitch TV means rapid-nose-turning-rates, even in the deep PST domain, excellent controllability, maximized PST-TV-agility and successful recovery **from any spin situation**. Demonstration/validation of these conclusions are available in the Report and in Video Tapes No. 5 and 6.

Flight tests of these models revealed strong **coupling phenomena** between pitch rates and roll rates, largely due to gyroscopic forces and/or control surface trim/deflections to counterbalance initial asymmetric drag/moments at low AoA. These effects cause left-roll during pitch-up and right-roll during pitch-down. The phenomenon is linked to the facts that the ducted fans employed to generate cold jets rotate at around 20,000 RPM, the perpendicular nose turning rates are very rapid and the SACOM is conducted at high angles of attack. Other interesting coupling effects have been detected.

External thrust vectoring [**ETV**] by means of 4 TV-paddles [of the type being flight tested recently on the X-31 and F-18], was compared with Internal Thrust Vectoring [**ITV**] by means of yaw-pitch two-dimensional nozzles of our design. ITV has demonstrated PST-agility [including positive and negative 'Cobra' maneuvers], while ETV was hardly sufficient to surpass the 'stall barrier'. This is due to inefficient deflection of exhaust jet streams beyond nozzle exit, and to inherent ETV-delay-times between commands and the time the paddles touch/deflect the jets in actual PST-TV-flight. Nevertheless, ETV allows us to demonstrate precise recordings of SACOMs, by providing extra thrust to carry extra heavy gyros/batteries, probes and an on-board computer.

Pitch rates obtained from our models conventional aerodynamic control surfaces correspond to that extractable from full-size F-15As, when our DSF are employed. By adding ETV to conventional roll command we obtained more than twice the current turn-rate of conventional F-15As. However, the maximum pitch rate obtained was a coupled one. In turn, ITV provides such and higher turn rates by resorting only to pure pitch-TV command.

Recent publications which have resulted from these studies include:

1 - **Maximizing Post-Stall, Thrust-Vectoring-Induced Agility.**

B. Gal-Or, AIAA J. Aircraft. In press.

2 - **Fundamental Concepts of Vectored Propulsion.**

B. Gal-Or, AIAA J. Propulsion, Vol.6, Nov.-Dec., 747-757, 1990.

3 - **Vectored Propulsion Supermaneuverability and Robot Aircraft,**

B. Gal-Or, Springer Verlag, N.Y., 1990.

4 - **Mathematical Phenomenology for Multifunctional Thrust-Vectoring Aircraft.** To be published with D. Bowers and D. D. Baumann. Cf. Part I, 'Theory'.

5 - **Flight Tests of TV-F-15 Model.** To be published with Bowers and Baumann.

6, 7 - Two additional papers with Baumann and Bowers are now being written.

Extension/Spin-Off Projects

The following extension/spin-off projects are based on a well-proven infrastructure in theoretical work, laboratory facilities [about US $ 10,000,000] and instrumented TV-models [via contracts with General Electric, Teledyne, Pratt & Whitney, General Dynamics, US Air Force, etc.]. Each is a direct extension of this methodology/program, and each is based on extended use of equipment, computers, software, and, in a few cases, on flying scaled models designed, constructed and flight-tested within the framework of this USAF-contract.

The generic, extension/spin-off projects will be presented during our Sept 14-30 visit to **Lockheed, PWA, Human Systems & FDL & Training Requirements @ WRDC [WL/FI]/WPAFB and BAFB,** as well as during seminars delivered to **Army, Navy and civil industry** staff-members.

1 - The first project has already been approved , starting from June 1, 91. Hence, it is described in more details in the last Chapter. Its title is:

"Synergetic Investigations of Thrust Vectoring Induced Accelerations/Limitations Using A New Research Vehicle/Methodology"
[Dynamic Scaling of Prototypes Using Radius Of Gyration Method]

2 - **Ultra-Fast Electro-Chemical TVC.** A novel concept which revolutionizes the [micro-seconds] response times and effectivity of ultra-fast TVC systems is recommended for a generic, proof-of-concept/feasibility study. A 3-years framework.

3 - **Converting C-130 to STOL TV-Cargo.** In close co-operation with Allison Gas Turbine, GM, a 3-years framework was submitted to WRDC. The TV-kit replaces current engine nozzle by a smaller-diameter one equipped with simple yaw-pitch vectorable flaps-vanes of a type well-proven by this lab. The kit significantly increases overall propulsion efficiency for both T-56 engines now in use. Current use

of 8 rockets during takeoff, whose installation takes long critical time in a front runway, is eliminated, or the pilot opts for additional payload. Takeoff and landing runs are drametically reduced, while aircraft range and safety qualities are significantly increased. [A seminar to be presented at Lockheed via Lockheed's President invitation.]

4 - **Converting F-117A to STOL-PST-TV-Fighter.** Make the present [rectangular, high-aspect-ratio, engine-nozzles] fixed vanes rotatable to extract powerful yaw thrust vectoring control power at very low cost and negligible weight penalty. Adding pitch and roll TVC can reduce vertical stabilators size, or eliminate them altogether, to further reduce radar and optical signatures. A 3-years framework. Applicable to the (pitch-Only-TVC) **F-22** with our (Yaw-Pitch) **PWA**-project newest design for Super-Effective TVC. [A seminar to be presented at Lockheed via Lockheed's President invitation. Following the **Lockheed visit**, to be discussed at **PWA**]

5 - **Converting Extant Navy & Army Aircraft to STOL-PST-TV-Aircraft.** Cf. spin-off projects 3 & 4. A 3-years framework.

6 - **Converting Extant Trainers to STOL-PST-TV-Trainers.** PST-TV is to become a standard training requirement in advanced pilot training. However, no such educational system nor such a trainer exists now. Flight-tests are first proposed to simulate the expected performance via our low-cost methodology. A 3-years work.

7 - **Upgrading Cargo & Civil Aircraft.** TVC advantages include increased propulsive efficiency, range, safety levels and ground maneuverability in addition to significant gains in STOL qualities. We recommend to add TV kits to extant aircraft and to flight-test them first by simulating performance via our infrastructure.

8 - **Super-Maneuverable, Roll-Yaw-Pitch [finless] TV-Cruise Missiles, Etc.** Our newest, 'tailless', low-signature, TVC-kits [TV-nozzles + V-inlets] are now ready to be flight-tested during low-subsonic supermaneuvers via our methodology.

THEORY

Part I

Mathematical Phenomenology for Thrust-Vectoring-Induced Agility Comparisons and Scaling-Up Dimensionless Numbers

Abstract

Tailless, Pure Vectored Aircraft [PVA] are analysed as "Ideal Standards" to maximize Post-Stall [PST] Thrust-Vectoring [TV] Agility for superior combat effectiveness Accordingly, full-scale, jet-engine tests are conducted at the JPL/TIIT with our novel yaw-pitch and roll-yaw-pitch TV-nozzles and vectorable, PST-inlets.

Scaling down the nozzles, flight testing them by means of RPVs, and, according to results, redesigning the nozzles for full-scale jet-engine tests, completes a typical cycle in our holistic development/design approach to gain enhanced PST-TV maneuverability.

Within such holistic cycles a mathematical phenomenology has been developed to assess the main components which strongly affect TV-agility/supermaneuverability. The theory identifies the main TV-propulsion moments and forces required to gain effective, deep-PST-TV-maneuvers.

The theory, the full-scale/jet-engine tests and the flight tests are also intended for next-phase PST-TV-RPVs simulations of maximum angular accelerations/onsets/reversals vs pilot tolerances. The results will be used in USAF's centrifuge simulations, and in training with simulated TV-aircraft.

Standard Agility Comparison Maneuvers [SACOM], are assessed in PART II for the purpose of comparing and maximizing agility parameters of different Thrust-Vectored fighter aircraft. -

levatorless/rudderless, 1/8-scale F-16 model has been successfully tested by JPL on May 1991, using the criteria enumerated in this work. With a similar F-15 RPV it is to be further used as a flying simulator to verify the concepts enumerated in this study.

Notation

b = reference span, [m]

c = reference mean aerodynamic chord, [m],

C_D = drag coefficient, dimensionless

CG = center of gravity, % mean aerodynamic chord.

C_{fg} = engine nozzle thrust coefficient. Its value varies with the jet-deflection angles and the nozzle pressure ratio [which include the effects of throttle angle, Mach Number, altitude, etc.] dimensionless, [cf. eqs. 16-18],

C_{jTV} [j = z, n, L, l] = thrust-vectoring moment/force terms which vary with the type of the TV-SACOM. Force/Deg. or rad. or Moment/Deg or rad.

C_L = lift coefficient, dimensionless

C_l = rolling moment coefficient, dimensionless

$C_{l\beta}$ = rolling moment derivative with respect to sidslip angle, 1/rad,

$C_{l\delta a}$ = aileron effectiveness derivative, 1/rad,

$C_{l\delta e}$ = stabilator effectiveness derivative, 1/rad,

$C_{l\delta \Delta e}$ = differential stabilator effectiveness derivative, 1/rad,

C_{lor} = rudder effectiveness derivative, 1/rad,

C_{lp} = roll damping derivative, 1/rad,

C_{lr} = rolling moment derivative with respect to yaw rate, 1/rad,

C_m = pitching moment coefficient, dimensionless

C_{mo} = basic pitching moment coefficient, dimensionless

C_{mq} = pitching moment derivative with respect to pitch rate, 1/rad,

C_n = yawing moment coefficient, dimensionless

$C_{n\beta}$ = yawing moment derivative with respect to sideslip angle, 1/rad,

$C_{n\beta*}$ = yawing moment derivative high angle-of-attack increment with respect to sideslip angle, 1/rad,

$C_{n\delta a}$ = yawing moment derivative with respect to aileron deflection, 1/rad,

$C_{n\delta e}$ = yawing moment derivative with respect to stabilator deflection, 1/rad,

$C_{n\delta \Delta e}$ = yawing moment derivative with respect to differential stabilator deflection, 1/rad,

$C_{n\delta r}$ = rudder effectiveness derivative, 1/rad,

C_{np} = yawing moment derivative with respect to roll rate, 1/rad,

C_{nr} = yaw damping derivative, 1/rad,

C_{py} = side-center-of-pressure [for PSM in the y-direction],

C_x = longitudinal force coefficient, dimensionless

C_y = side force coefficient, dimensionless

$C_{y\beta}$ = side force derivative with respect to sideslip angle, 1/rad,

$C_{y\beta*}$ = asymmetric side force derivative high angle-of-attack increment with respect to sideslip angle, 1/rad,

$C_{y\delta a}$ = side force derivative with respect to aileron deflection, 1/rad,

$C_{y\delta e}$ = side force derivative with respect to stabilator deflection, 1/rad,

$C_{y\Delta e}$ = side force derivative with respect to differential stabilator deflection, 1/rad,

$C_{y\delta r}$ = side force derivative with respect to rudder deflection, 1/rad,

C_{yp} = side force derivative with respect to roll rate, 1/rad,

C_{yr} = side force derivative with respect to yaw rate, 1/rad,

C_z = normal force coefficient, dimensionless,

D = the distance from TV nozzle exit to aircraft C_{py}, [m],

D^* = the distance from TV nozzle exit to aircraft **CG**, [m],

D_{cpy} = the drag operating @ C_{py}, [kgf],

g = gravitational constant, m/sec^2,

I_X = moment of inertia about the roll axis, [kg-m^2],

I_{XY} = cross product of inertia between roll and pitch axes, [kg-m^2],

I_{XZ} = cross product of inertia between roll and yaw axes, [kg-m^2],

I_Y = moment of inertia about the pitch axis, [kg-m2],

I_Z = moment of inertia about the yaw axis, [kg-m^2],

M = aircraft mass, [kg],

N_i = dimensionless numbers, [i = 1, 2, 3, ...],

NPR = Nozzle pressure ratio, dimensionless,

p = roll rate [rad/sec],

PSM = pure sideslip maneuver,

PST = post-stall,

q = pitch rate [rad/sec],

$\bar{q}$ = dynamic pressure, $(1/2)\rho V^2$, [N/m^2],

r = yaw rate [rad/sec],

s = reference area,[m^2],

SACOM = Standard Agility Comparison Maneuver,

t = time

T = actual [net] thrust, [cf. eqs. 16-18], [kgf],

T_i = ideal isentropic [net] thrust, [cf. eqs. 16-18] , [kgf],

$T_{x,y,z}$ = thrust-vectored components in the x-, y-, z- directions [cf. eqs. 16-18], [kgf],

T_v = vertical [pitch] thrust vectoring component [identical with T_z], [kgf],

TV = thrust vectoring

TVC = thrust-vectoring control

V = aircraft true airspeed,[m/sec],

Y = the distance from aircraft centerline to [split-type] TV nozzle centerline, [m],

Greek

α = angle of attack, also AoA, deg, or rad,

β = angle of sideslip, deg, or rad,

δ_a = aileron surface deflection, [may be a differential angle], deg, or rad,

δ_e = elevator [stabilator] surface deflection, deg, or rad,

$\delta_{\Delta e}$ = differential elevator surface deflection, deg, or rad,

δ_r = rudder surface deflection, deg, or rad,

δ_{TV} = effective deflection angle of the jet during pitch and/or yaw thrust vectoring, [may be a differential angle during a TV-roll command], deg, or rad,

δg_{TV} = geometric deflection angle of nozzle vanes & flaps during pitch and/or yaw thrust vectoring, [may be a differential angle during a TV- roll command], deg, or rad,

δ_{TVD} = effective, differential TV-nozzle/jet deflection during TV-roll-command, deg, or rad,

δg_{TVD} = geometric, differential TV-nozzle vanes and flaps deflection during TV-roll-command, deg, or rad,

δ_v = effective pitch thrust-vectoring angle, [may be a differential angle during a TV- roll command], deg, or rad,

δg_v = geometric pitch thrust-vectoring angle, [may be a differential angle during a TV- roll command], deg, or rad,

δ_y = effective yaw thrust vectoring angle, [may be a differential angle during a PSM-Yaw-command], deg, or rad,

δg_y = geometric yaw thrust vectoring angle, [may be a differential angle during a PSM-Yaw-command], deg, or rad,

ΔZ_{offset} = thrust offset, m,

ϕ = bank angle, deg,

θ = pitch angle, deg,

ψ = heading angle, deg.

Introduction

To maximize agility and flight-control power during low-speed, post-stall [PST], defensive or offensive combat maneuvers, a future pilot may use partial or full thrust-vectoring-control [TVC] [1, 2]. The designers of such aircraft may thus face the recently-debated problem [3] of defining and testing conventional vs TV-agility and controllability during high Angle-of-Attack [AoA] maneuvers. Reviews of the problems involved are available elsewhere [1, 2, 3].

Moreover, scaling-up concepts are needed now for simulations of pilot tolerances during maximal PST-TV onsets.

However, the mathematical techniques used to estimate the aerodynamic characteristics from dynamic flight test data are becoming increasingly complex as the AoA is increased beyond about 70 deg. [4-6]. Thus, at the present time it may not be practical to extract PST-TVC coupling coefficients, stability and control derivatives, from conventional mathematical phenomenology. Nevertheless, as attempted below, one may add proper TVC terms into conventional phenomenology and then try to extract new guidelines under the restriction imposed by a set of simplifying assumptions. These assumptions take into account the limitations and new needs posed by PST-TV.

The Proposed Mathematical Phenomenology

The phenomenology presented below is characterized by the bold assumption that to describe the aerodynamic behavior of PST-TV-aircraft one may still use the first-order partial derivatives as an approximation. Thus, the 6-degree-of-freedom equations of motion, with the yet unspecified thrust-vectoring terms, are:

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

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

$$\dot{p} = \{ - [(I_z - I_y)/I_x + I_{xz}{}^2/I_xI_z]\, qr + [1 - (I_y - I_x)/I_z]\, I_{xz}pq/I_x + qsb/I_x[C_l + I_{xz}C_n/I_z]\}/[1 - I_{xz}{}^2/I_xI_z] \qquad [3]$$

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

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

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

$$\dot{\theta} = q\cos\phi - r\sin\phi \qquad [7]$$

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

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

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

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

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

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

$$C_m = C_{m_c}(\alpha,\delta_e) + [c/2V]Cmq(\alpha)q + T[\Delta Z_{offset}]/\bar{q}sc + C_{mSC}\delta_{TV} + C_{mTV}\delta_{TV} \qquad [14]$$

$$\begin{aligned} C_n = {} & C_{n\beta}(\alpha,\beta.\ \delta_e)\beta + C_{n\delta_a}(\alpha)\delta_a + C_{n\beta}(\alpha,\beta) \\ & + C_{n\delta_r}(\alpha,\beta.\ \delta_r,\ \delta_e)\delta_r + [c/2V][C_{np}(\alpha)\,p + C_{nr}(\alpha)\,r] \\ & + C_{n\delta_{\Delta e}}(\alpha,\delta_{\Delta e})\delta_{\Delta e} + \Delta C_{n\beta}(\alpha,\beta) \\ & + C_{n\beta *}(\alpha,\beta) + C_{nTV}\delta_{TV} \qquad [15] \end{aligned}$$

$$T_x = C_{fg}\,T_j\cos\delta_v\cos\delta_y \qquad [16]$$

$$T_v = C_{fg}\,T_j\sin\delta_v\cos\delta_y = T_z \qquad [17]$$

$$T_y = C_{fg}\,T_j\cos\delta_v\sin\delta_y \qquad [18]$$

This set of 18 equations completes our simplified phenomenology for thrust-vectoring-induced maneuvers. The set is written for a body-axis set of coordinates.

Applicability Restrictions

Only linear expansions of moments and forces have been employed, including the unspecified "**TV**" notation for thrust-vectoring-induced supercirculation **[zSC]** in eqs. 12 and 14 (for definitions and physico-aerodynamic fundamentals see ref. 1). This phenomenology is based on effective jet-deflection angles δ_v, and δ_y, or, in general, on δ_{TV}. For instance, C_{mTV} is the pitching moment per radian of effective jet deflection in the pitch coordinates. Similarly C_{lTV} denotes the roll-thrust-vectoring moment per radian due to differential jet-deflection in [split-type] single or S-type twin-engine nozzle(s) [1].

The T_x, T_v, and Ty terms which appear in eqs. 10 to 12 denote the direct effective thrust-vectoring forces in the x, z and y directions, respectively, as defined by equations 16 to 18.

The roll, yaw, and pitch thrust-vectoring commands should not to be confused with the effective, or geometric [or surface] TV-deflection-angles of the pitch-flaps, or of the yaw-vanes inside 2D-CD nozzles, or outside [paddle-type], or inside axisymmetric multi-function TV nozzle(s).

A modified F-16 fighter, equipped with, say, a single yaw-pitch axisymmetric TV-nozzle would thus produce a very poor roll moment about the velocity vector under deep PST conditions. This fact was recently demonstrated by our flight tests. However, replacing that nozzle with a roll-yaw-pitch nozzle/TVC resolves this difficulty and provides excellent PST roll TVC, as was demonstrated in May 1991 by our flying model. Hence we shall concentrate on such TVC in this study.

Of cardinal importance to maximize roll agility during high-AoA-maneuvers is the length of the TVC-rolling arm, **Y**. E.g., for the split-type TV-nozzle of the elevatorless/rudderless F-16, we have maximized the distance **Y** from turbine centerline to each nozzle centerline during differential pitch jet deflections. This requires internal streamlined vanes to be designed and tested with our "full-scale" jet engine to minimize nozzle losses.

The normal-force $\mathbf{C_z}$-equation contains the $\mathbf{T_v}$ term associated with pitch thrust-vectoring. However, only high-aspect-ratio nozzles which are well-integrated with the wing trailing edge increase lift during down-jet-deflections.

There are two types of coupling: Kinematic and aerodynamic. The coupling terms cannot be neglected in an exact analysis of PST-TV flight, unless some simplified, decoupled-SACOMs are made [see below]. For instance, due to separated flows and stalling effects, PST-TVC-aircraft flying at AoA > 70 deg exhibit strong aerodynamic/propulsion coupling. E.g., it has been recently demonstrated during our flight tests with 1/7-scale PST-TVC-F-15 models, that a pure TVC-yaw command produces a strong TV-induced roll, depending on the size of the vertical stabilator. However, depending on the particular tailless-TVC-aircraft design [1], and on the particular SACOM, these effects can be minimized, or neglected in a preliminary analysis of PST-TVC-SACOM [1, 2, 3].

Parameters which are not listed here include the Mach number and altitude. However, their effect partially enters the phenomenology through the effect of Nozzle Pressure Ratio [NPR] on $\mathbf{C_{fg}}$, etc. [1]. A low-speed SACOM is also assumed [i.e., $M = < 0.6$]. Hence, the flight can be assumed to be in the incompressible flow regime. Various other effects have been neglected in this model. For instance, the asymmetric effects due to thrust, fuel distribution, and aerodynamics have been neglected, as well as engine gyroscopic effects and turbulence noise [cf. refs. 3 and 4 and below].

In assessing this phenomenology one must stress the following additional restrictions:

1 - Various eight-state $[\alpha, \beta, p, q, r, \theta, \phi, V]$ aircraft models are available in the literature [Cf., e.g., Refs. 5 to 19]. The approximations presented here are not intended nor implied to be a complete definition of PST-TVC. The thrust-vectoring terms introduce, by themselves, no new physico-mathematical insights into classical control theory, with or without statisticsal-stochastic analysis [cf., e.g., 6, 10, 13 and below].

Consequently, this study is limited to the derivation of a few general conclusions that are sufficient for gaining an improved insight into PST-TVC-SACOMs.

2 -The present deterministic phenomenology must be further modified by the presence of a superimposed spectral density of the TVC-SACOM measurement noise, especially when flying our low-weight/low-moment-of-inertia scaled models [1, 3, 6, 11, 18, 19]. Available

"stochastic-statistical" methods may then be combined with a Standard Spectrum for Atmospheric Turbulence and with "maximum likelihood estimation concepts" [5, 6, 10, 13].

3 - Cross-coupling terms are normaly not included in the analyses when the flight data are gathered during stabilized flight at low AoA. These terms are needed when the aircraft is expected to have aerodynamic cross-coupling between the longitudinal and lateral-directional aerodynamic modes.

4 - Eqs. 1 to 6 can be divided into two sets: (i) - The longitudinal, and, (ii) - the lateral-directional equations.

The Basic Cobra Reversal SACOM

For a cobra-type, horizontal, PST-TVC-SACOM [2, 3], performed with PVA, or with frozen conventional control surfaces, the ϕ, β, $\dot{p}$, p, $\dot{r}$, r, $\dot{\beta}$, δ_e, δ_a, δ_r, $\delta_{\Delta e}$, C_l, C_n and C_Y terms vanish, while $\theta = \alpha$ and $\dot{\alpha} \cong q$. Moreover, the supercirculation term can be neglected for low-aspect-ratio TVC-nozzles, as, for instance, is the case with some of our early 1/7-scale PST-TVC F-15 flying models. This conclusion is due to the low surface area affected by such nozzles [1, 2].

The term $T[\Delta Z_{offset}]$ vanishes when the nozzle(s) thrust acts through the aircraft center of gravity. This assumption is usually not met in reality. Yet, using conventional control surfaces, the flyer can pre-trim the aircraft so as to approximate the total equivalent effects of the aforementioned assumptions for each particular SACOM. Under these conditions, the flyer command is a pure δ_V input, for which the aircraft response in controlled horizontal Cobra-flight is determined only by

$$C_x = C_L(\alpha) \sin\alpha - C_D(\alpha) \cos\alpha + T_x/\bar{q}s \qquad [19]$$

$$C_Y = 0 \qquad [20]$$

$$C_z = -[C_L(\alpha) \cos\alpha + C_D(\alpha) \sin\alpha] + T_V/\bar{q}s \qquad [21]$$

$$C_l = 0 \qquad [22]$$

$$C_m = C_{mo}(\alpha) + C_{mTV}\,\delta_V \qquad [23]$$

$$C_n = 0 \qquad [24]$$

$$Mg = \bar{q}s[C_x \sin\alpha - C_z \cos\alpha] \qquad [25]$$

$$\dot{q}I_y = \bar{q}sc[C_{mo}(\alpha) + C_{mTV}\,\delta_V] \qquad [26]$$

$$M\dot{V} = \bar{q}s[C_x \sin\alpha + C_z \cos\alpha] \qquad [27]$$

For this SACOM eqs. 16 to 18 reduce to

$$T_x = C_{fg}\, T_j \cos\delta_v \qquad [28]$$

$$T_v = C_{fg}\, T_j \sin\delta_v \qquad [29]$$

$$T_y = 0 \qquad [30]$$

Equations 19 to 30 define our simplified phenomenology for such a "pure" PST-TV-SACOM. Various numerical and analytical solutions of this set [with particular initial and boundary conditions] can be investigated and gradually employed for working back and forth between theory and well-defined flight tests. One of these, perhaps the most useful one, is considered next.

Jet-Reversing At 90-deg. AoA Cobra SACOM

This particular SACOM is schematically described in **Fig. 1**. It involves reversing the direction of the jet from maximum deflection angle in one direction, to the other, during positive or during negative Cobra maneuvers at 90 deg AoA [while keeping the flight-path horizontal throughout the maneuver].

At AoA = 90 degrees [positive or negative], the aerodynamic lift vanishes. We then consider small variations of θ, $\dot{\theta}$, q, $\dot{q}$, etc. around this value. The purpose of making this bold assumption is to examine the main variables which affect the maximization of thrust-vectored control power during such a reversal, in line with the principles set forth in PART II below. [In practice even the value of C_{fg} varies throughout the maneuver.] Now, by freezing all conventional variables, and by concentrating only on the δ_v command, we obtain a very simple and useful set:

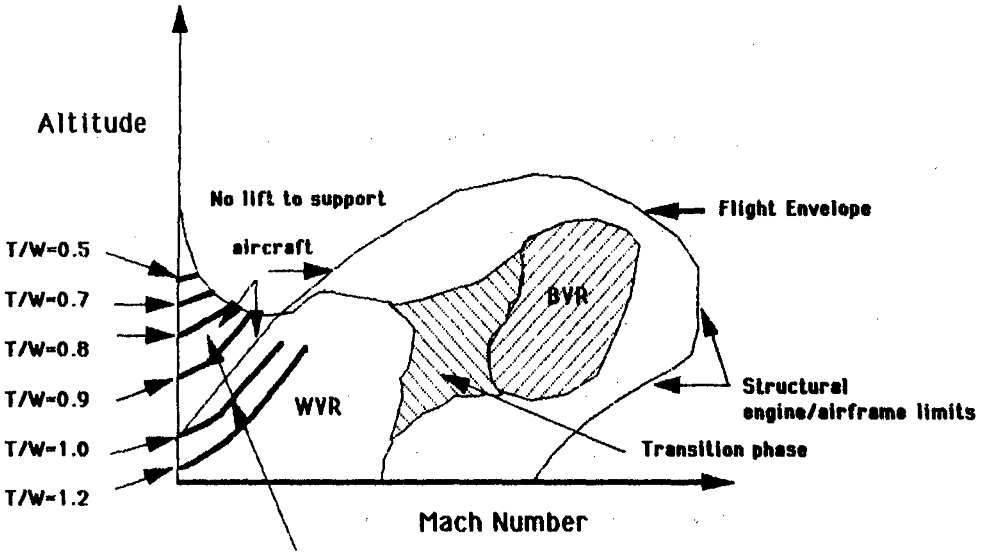
$$C_x = C_{fg}\, T_j \cos\delta_v / \bar{q}s \qquad [31]$$

$$C_z = -\, C_D(90) + C_{fg}\, T_j \sin\delta_v / \bar{q}s \qquad [32]$$

$$C_m = C_{mo}(90) + C_{mTV}\,\delta_v \qquad [33]$$

$$Mg = C_{fg}\, T_j \cos\delta_v = T_x \qquad [34]$$

$$\dot{q}I_y = \bar{q}sc[C_{mo}(90) + C_{mTV}\,\delta_v] \qquad [35]$$



Transient PST-TV Supermaneuverability Domain Where T/W < 1 or T/W > 1 and DSF Rules must be Devised to Estimate Maximal Nose/Bottom Turning Rates From Flight Tests of Correctly-Scaled Models.

Transition from Beyond Visual Range Engagements to Within Visual Range Engagements increases pilot's needs for transient PST-TV Supermaneuverability using all-aspect missiles, etc.

Maximal thrust-vectoring-induced nose turning rates surpass conventional 'corner rates' and provide the pilot with an option to drastically shorten missile path/time to target [during computing and delay times required to release missile], so as to

increase the probability to destroy the target prior to its capability to launch its weapon. Hence, PST-TV becomes a key element in close-in combat engagements. Yet, it also provides advantages under certain supersonic flight regimes.

Notes: At constant altitude thrust increases with Mach number, up to a maximum value. At constant Mach number thrust decreases with altitude. PST-TV maneuvers at constant maximum thrust are therefore represented by the lines shown in the figure.

The horizontal 'Cobra' maneuver cannot be performed above the T/W = 1.0 PST-TV domain.

Transient tail slides or tail-first maneuvers may be assigned negative Mach Number values. Transient PST-TV maneuvers are possible at zero and negative M values. T/W decreases with altitude and reduced speed. Hence, high-performance PST-TV fighters with nominal S.L., M=0 T/W > 1.0 would perform PST-TV maneuvers at high altitudes with T/W < 1.0. Once air engagement has closed to WVR combat, PST-TV maneuver becomes the most important aircraft capability.

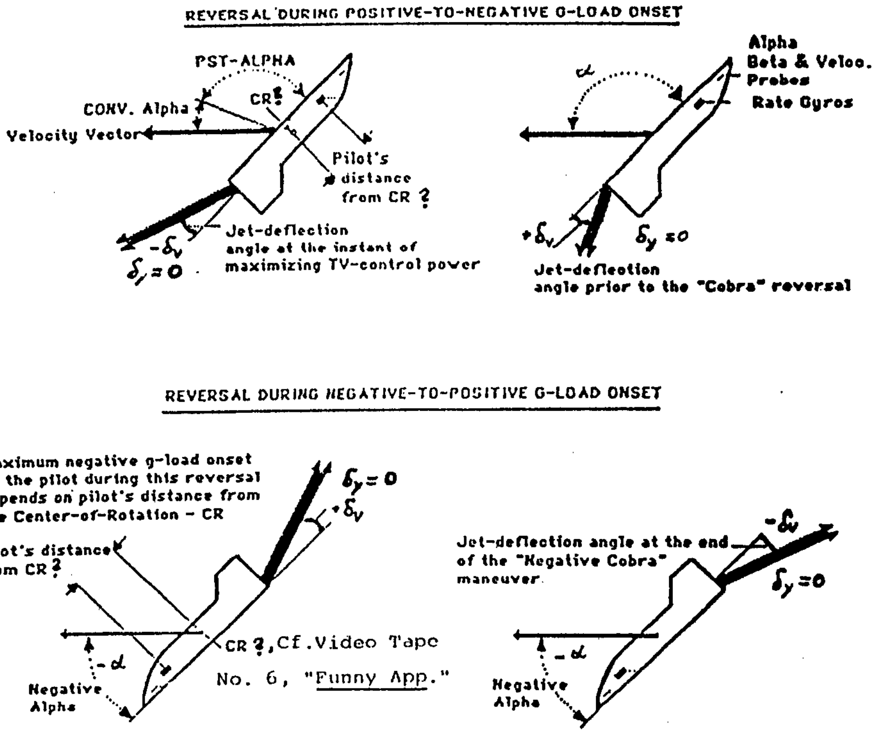


Fig. 1

MAXIMIZED THRUST-VECTORING CONTROL POWER IS REQUIRED DURING REVERSALS OF NEGATIVE and POSITIVE POST-STALL "COBRA" MANEUVERS WITH PST-TV-SCALED MODEL FLIGHT TESTS.

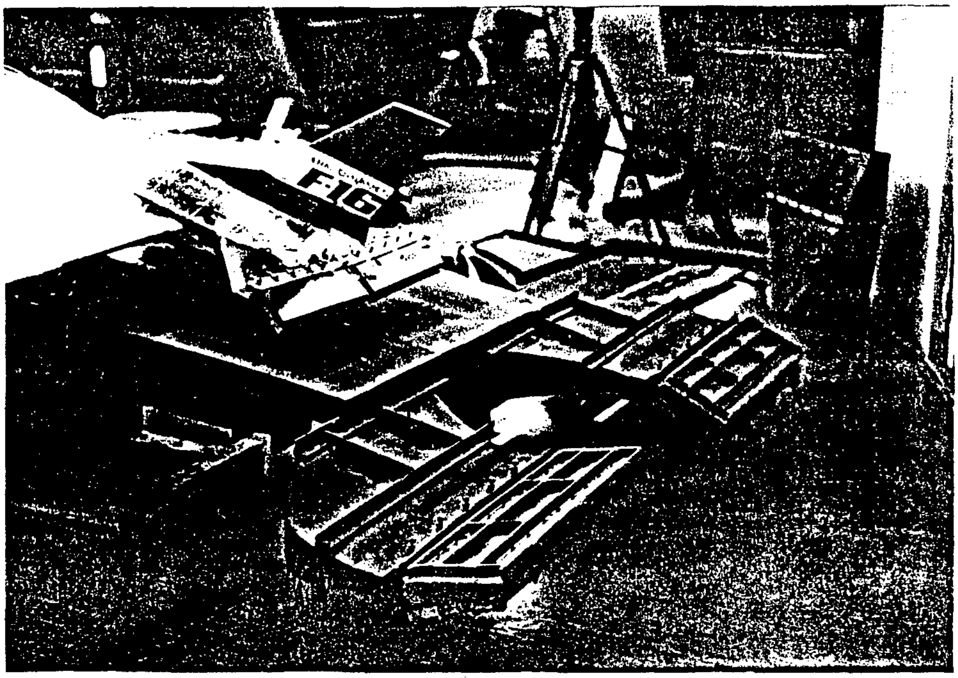


Fig.1a: Effective Roll-Yaw-Pitch TV-nozzles

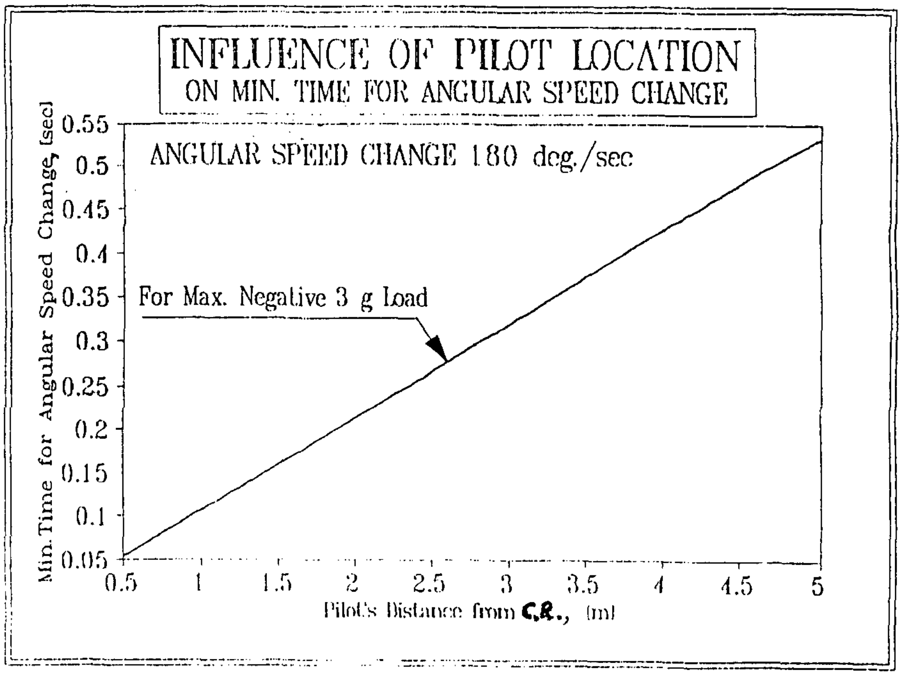


Fig.1b: A human-tolerance limit to TV-agility.

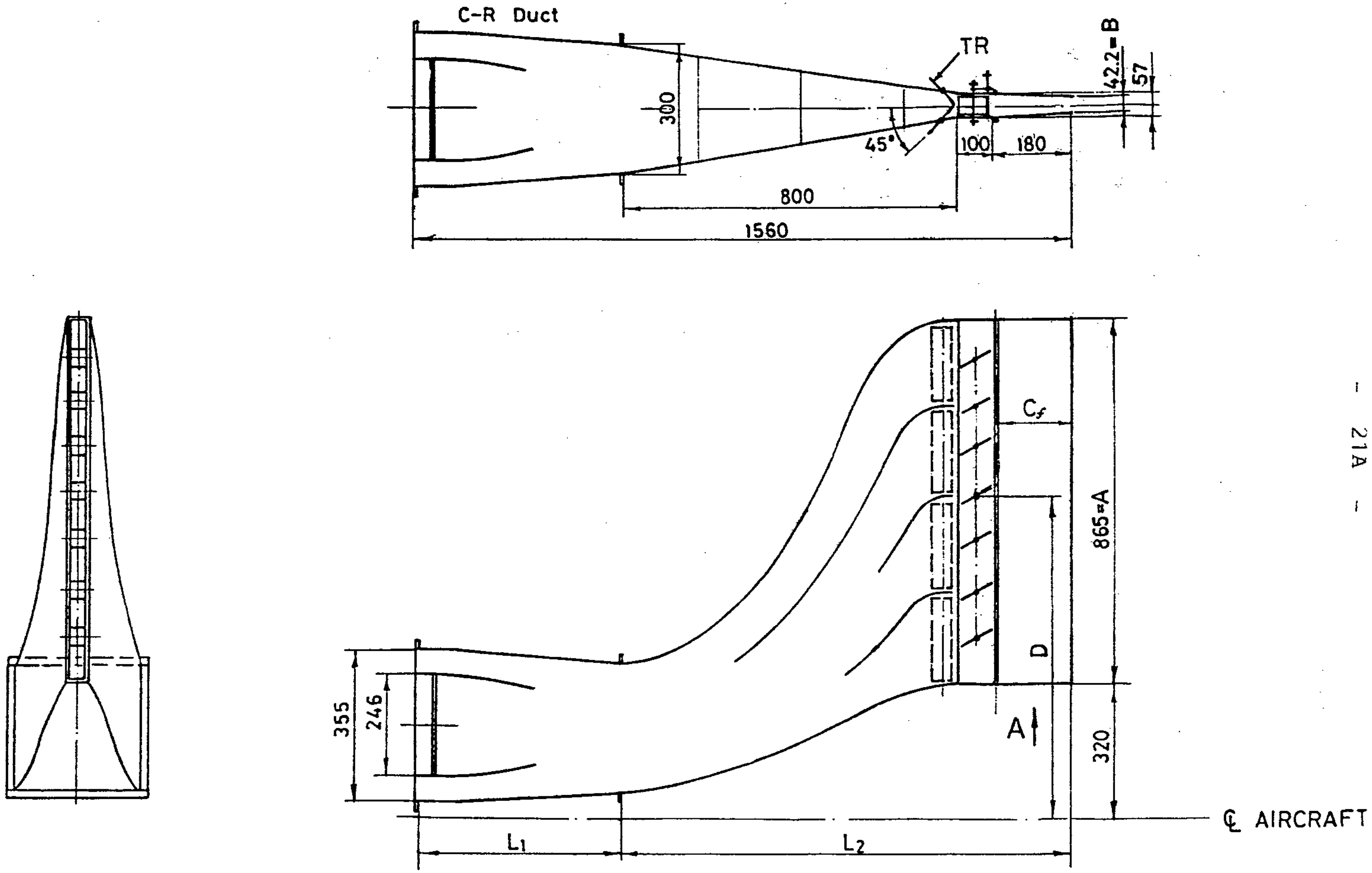


Fig. 1c

Roll-yaw-pitch TV-Nozzle for twin-jet fighter aircraft designed, constructed and tested on the full-scale Jet-Engine Test Facility of JPL. It was then scaled down and flight tested on PVA Nos. 3,4 and 5. It is to be flight tested next on a 1/7-scale F-15 RPV.

$$M\dot{V} = C_{fg} T_i \cos \delta_v = T_x - Mg \qquad [36]$$

A positive PST-TVC cobra-type SACOM entails two commands: [i] - a [δ_v]-nose-up command, and, [ii] - when the AoA reaches, say, 90 degrees, a rapid [$-\delta_v$]-nose-down command. These commands reverse the sign of the forces and moments. They generate rapidly opposing "g-onsets" on the pilot [i.e., from positive to negative 'g' loads during positive Cobra SACOM-reversals, and vice versa during the negative ones] .

PART II below provides the reasonings for maximizing the TV control power via such δ_v-pitch-reversal commands.

Alternatively one may examine a TV-pitch-only-SACOM, in which the AoA remains constant, while pitch acceleration changes. One possibility is to perform a constant-AoA climb in the vertical plan so that instead of eq. 35 one can establish the functional

$$\dot{q} = f[\delta_v(t)] \qquad [37]$$

However, this SACOM invalidates the assumption that **q** and the time derivative of the AoA are approximately equal. Hence, such a maneuver may hardly serve as a PST-TVC-SACOM. Consequently, this phenomenology dictates that PST-TVC-SACOMs be performed with only the horizontal Cobra-reversal-type onsets at 90 degrees AoA.

The maximum range of the nozzle's δ_v jet deflection determines this agility component [3]. It is determined also by the fastest rate of full-reversal of the TV nozzle flaps, or, from the TV-system-design point-of-view, the minimization of the inherent delay times associated with the propulsion-control/nozzle-mechanisms.

Therefore, to maximize TV control power and PST-TV-agility one must maximize C_{mTV}, C_{lTV}, C_{nTV}, $C_{[zSC]}$ and C_{mSC}, and, for a given design, to maximize the δ_v and δ_y time-rate of reversals [see also below].

Potential Pure-Sideslip-Maneuvers

Tailless, pure, or "ideal" thrust-vectored aircraft can perform Pure Sideslip Maneuvers [PSM] with constant [steady-state], horizontal heading, without banking [1, 2]. During such a PSM one nozzle is employed to deflect its jet in the yaw direction until its vector coincides with the side-center-of-pressure, C_{py}. This causes PSM zero yawing-rate and banking, i.e., $\dot{r}$, $\dot{p}$, $\dot{q}$ and $\dot{\beta}$ vanish, but not β. [To perform this SACOM, the non-yawing, axial thrust generated by the 2nd nozzle is somewhat reduced to equal that left-over by the 1st nozzle, so as to avoid a yawing moment on the TV-aircraft.]

Alternatively, the 2nd nozzle yaw-deflection potential may be employed for very rapidly yawing the nose of the aircraft [again, without banking], so as to acquire a target with minimal energy dissipation. [A similar PST-TV acquisition, on the other hand, dissipates considerably more energy [1]. Hence, to acquire any target, such a TV-PSM-YAW may be combined with a partial roll [1]]. A simplified phenomenology for guiding the design of such SACOMs is provided below.

Consider the simplest model, e.g., we assume that such PSM or PSM-YAW SACOMs are performed at zero AoA and zero pitch attitude with no banking and roll. For tailless pure vectored aircraft we also assume the dominance of TV forces and moments over the conventional ones [or the absence of conventional flight control means], as well as negligible coupling between TV-yaw and TV-induced roll through the tail, etc. Here the α, $\dot{\alpha}$, θ, ϕ, $\dot{p}$, $\dot{q}$, q, r, δ_v, δ_e, δ_a, δ_r, $\delta_{\Delta e}$ $T[\Delta Z_{offset}]$, C_z, C_l, C_m, C_n terms vanish, and from eqs. 2, 6, 10 and 11 one obtains,

$$C_y \cos\beta = C_x \sin\beta \qquad [38]$$

$$\dot{V}/V = [\bar{q}s/MV][C_x \cos\beta + C_y \sin\beta] \qquad [39]$$

$$C_x = [C_{fg}\, T_i \;\cos\delta_y]\,/\bar{q}s - C_D[\alpha(0)] \qquad [40]$$

$$C_y = C_y(\beta) + [C_{fg}\, T_i \;\sin\delta_y]/\bar{q}s \qquad [41]$$

$$T_x = C_{fg}\, T_i \;\cos\delta_y \qquad [42]$$

$$T_v = 0 \qquad [43]$$

$$T_y = C_{fg}\, T_i \;\sin\delta_y \qquad [44]$$

Transient PSM/Yaw-SACOMs

For extracting maximal TV-induced roll and yaw flight control, the pitch and yaw deflections of the jet in each of the two nozzles are independently controlled. Under such yawing conditions each nozzle, or half-nozzle, provides different thrust efficiency, i.e., each may operate with a different C_{fg} value. Hence, during independent yaw-deflections, eqs. 40 and 41, with the aforementioned assumptions, become

$$C_x = (\, C_{fg1}T_{i1} \cos\delta_{y1} + C_{fg2}T_{i2} \cos\delta_{y2})\,/\bar{q}s - C_D[\alpha(0)] \qquad [45]$$

$$C_y = C_y(\beta) + [C_{fg1}T_{i1} \sin\delta_{y1} + C_{fg2}T_{i2} \sin\delta_{y2}]/\bar{q}s\,, \qquad [46]$$

where the numbers refer to each of the two TV jets/nozzles.

Recalling that during a pure, steady-state PSM, the jet of one nozzle is yaw-deflected until its vector coincides with the side-center-of-pressure, the yaw-δ_{y2} of the other nozzle is zero, and the axial thrust generated by this nozzle is throttle-adjusted to equal that left-over by the first nozzle, one concludes that the pure vectored aircraft performs PSM without yaw-rate and banking, provided all sums of moments vanish.

A maximum TVC-induced yaw rate is extractable when both nozzles direct the jets in the same yaw direction. Yet, maximization of TVC power is demonstratable, as in the previous PST-TVC-SACOM, only through a TVC-yaw-reversal, when a proper δ_y-command is performed. Under these conditions one can investigate the maximum rate-of-change of **r**-dot of two competing aircraft.

A more promising, yet more complicated maneuver is obtainable as follows. During, say, a defensive PSM, the jet of the 2nd nozzle is simultaneously yaw-deflected for yawing the nose of the aircraft [without banking], so as to acquire a target with minimal energy dissipation. Since a similar PST-TVC acquisition dissipates considerably more energy, one may perform a rapid half-TV-roll, followed by such a TV-yaw or PSM/Yaw maneuver, especially in target-rich scenarios [1-3].

A similar notation may be employed to rewrite the equations for differential TV-pitch maneuvers, e.g., during PST-TVC-roll-commands of tailless TVC-aircraft, and, especially during TVC-roll-reversal-SACOMs at very high AoA [3]. [Note: At AoA = 90 deg the roll-SACOM transforms into a yaw-SACOM.]

Dimensionless Numbers For Simplified TVC Scaling-Up Concepts

For scaling-up procedures, under the aforementioned conditions, the first dimensionless number of TVC may be defined as:

$$N_1 = \text{[Vectoring Pitching Moment]/[Vectoring Yawing Moment]}$$
$$= [\sin \delta_v \cos \delta_y]/[\cos \delta_v \sin \delta_y] \qquad [47]$$

N_1 is independent of the size, shape and scale of the aircraft, or of its internal moment-arm dimensions [such as D^* and Y]. It is also independent of the thrust level of the engine(s), nor of the number of engines. Hence, N_1 is useful for initial scaling-up procedures, as well as for establishing basic TVC rules.

Both pitch and yaw TVC are involved in the definition of TV-agility. To maximize only the pitching moment one must differentiate N_1 with respect to time, while δ_y remains constant, i.e. $d(\delta_v)/dt$ should be maximized, while for PSM the $d(\delta_y)/dt$ term should be.

During pure TV-rolling

$$\delta_v\text{(left nozzle)} = -\delta_v\text{ (right nozzle), or vice versa} \qquad [48]$$

while $\delta_y = \delta_y$ for both nozzles at any thrust level. The next dimensionless number may therefore be defined as

$$N_2 = [\text{Vectoring Yawing Moment}]/[\text{Vectoring Rolling Moment}] =$$
$$= D[\cos\delta_v \sin\delta_y]/Y[\sin\delta_v \cos\delta_y] = D/[YN_1] \qquad [49]$$

Again, the dimensionless number is independent of the size, shape and scale of the aircraft, provided the ratio of its internal moment-arms **D** and **Y** remain invariant. N_2 is also independent of the thrust level of the engine(s), or of the number of engines. Hence, N_2 is also useful for preliminary scaling-up procedures, as well as for establishing basic TVC rules. [During our studies of PVA we have used $D/Y = 0.56$]

Both roll and yaw TVC are involved in the definition of TV-agility. To maximize only the rolling moment one must differentiate N_2 with respect to time, while δ_y remains constant, i.e., $d(\delta_v-[-\delta_v])/dt$ should be maximized.

We may now re-express N_2 as

$$N_2 = C_n/C_l \qquad [50]$$

i.e.,

$N_2 = C_{lTV}\delta_{TV}$[in yawing radians]/ $C_{nTV}\delta_{TV}$[in pitch-thrust-vectoring differences in radians]

and introduce these expressions in eqs. 13, 15, etc. Further scaling-up considerations are available in Ref. 1.

Agility Restricted By Pilot Location

The effects of negative [pitch] "g-onsets" on critical physiological functions of the pilot during maximum, low-subsonic, PST-TVC "Cobra" maneuvers, etc. [3], are to be investigated next year. These effects depend, inter alia, on the distance from the pilot to the center of rotation during rapid TVC maneuvers. However, we do not know the location of this center of rotation [cf. video tape No. 6, and especially its "Funny Appendix"]. cf. Fig. 1b, p. 21.

Performing a SACOM During Atmospheric Turbulence Under Separated-Flow Conditions

Neither full-scale aircraft, nor scaled-models used in this study, can avoid flying in atmospheric turbulence. Hence, it is desirable to devise analytical tools that properly extract meaningful engineering conclusions from flight data that have been collected under such conditions. These flight data include a kind of superimposed spectral density of the measurement noise, especially when flying low-weight/low-moment-of-inertia scaled models. Available "stochastic methods" may then be combined with a Standard Spectrum for Atmospheric Turbulence (SSAT) to generate "maximum likelihood estimation concepts" [6] .

Another situation occurs under separated-flow conditions in the PST domain, when the aircraft, or the scaled dynamic model, is driven by "unknown" "stocastic inputs".

Unless the separation is mild enough to permit a well-verified mathematical model to approximate the SACOM, little can be done to extract meaningful engineering conclusions under these conditions.

While various ad hoc methods have been devised to overcome these problems for what is currently categorized as "high AoA research", no reliable solution to the problem presently exists beyond approximately 70 deg AoA.

Scale and Inherent Measurement Difficulties

The very method of measurement affects the results produced by flying models. The combined weights of probes, batteries, computers, telemetry/metry equipment, servos, wires and safety devices, affect the moments of inertia, stability margin, thrust-to-weight-ratio, etc. In turn, the additional masses may be properly used to generate certain preferred similarities between model and full-size vehicles [1]. For instance, in comparing the performance of vectored with unvectored models, both should have the same mass, mass distribution, stability margin, thrust-to-weight-ratio, drag, etc.

However, the maximum thrust available by all small-scale, two-dimensional TV-nozzles is considerably lower than that extractable from similar axisymmetric nozzles. [This is not the case with full-sized nozzles.] Hence, external thrust vectoring, i.e., the vectorable thrust produced by small axisymmetric nozzles that are equipped with variable external pedals [and provide unhindered cruise thrust], have been verified by our flight tests as the optimal choice.

Serious problems are also posed by the unavailability of PST [vectorable] engine inlets. Moreover, materials, servos, engines, nozzles, cooling means, IFPC, etc. do not scale-up easily by general rules. Hence the expected SACOM-reference-baseline is dictated by technology limits in each of the aforementioned categories. Similar restrictions apply to differences in Reynolds number, turbulence spectrum, propulsion coupling to stability and control derivatives, conventional and TV control effectiveness, as well as to different uncertainties in the measured values of $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{\theta}$, $\boldsymbol{\phi}$, $\mathbf{p}$, $\mathbf{r}$, $\mathbf{q}$, and $\mathbf{V}$ at high AoA.

Considerable differences have also been observed when a comparison was made between wind-tunnel estimates of our tailless, 1/32-scaled, PST-TV-models, and such 1/7-scaled model flight tests. These differences are partially attributable to differences in aerodynamic flow between the static wind-tunnel tests and the dynamic flight maneuvers.

Flight tests of unpowered remotely piloted 3/8-scaled F-15 model [11, 18] have also indicated considerable differences from full-scale F-15's dynamic behavior above an angle of attack of 30 degrees.

Such differences make proper PST-TVC-SACOM tests a very demanding subject indeed.

Nevertheless, in line with our flight-testing experiences, the proposed methodology/phenomenology can guide the design of SACOMs and delineate the sources of such similarities and differences.

Conclusions

There is a lack of confidence in the ability of current mathematical phenomenology to predict thrust-vectored-induced agility qualities at the deep post-stall domain. Hence, new experimental and theoretical concepts are needed [3, 11, 18]. Simultaneously, conventional concepts must be re-examined, and, if warranted, modified to include the effects of thrust vectoring forces and moments, especially at high AoA, low subsonic maneuvers.

While the proposed methodology/phenomenology harbors certain uncertainties during the non-linear flow regime associated with PST-TV, it has been found to be essential in designing and conducting a limited number of well-defined SACOMs. Moreover, classical equations of motion can be modified and employed to provide an improved physical insight into the main variables, causes and effects of thrust-vectoring-induced phenomena.

Highly-simplified equations for working back and forth between theory and flight tests in the TV-induced, deep Post-Stall (PST) domain, and during the various design phases of new PST-TV-SACOMs, have been formulated. The analysis presented is applicable only to PST, PSM, YAW or PSM-YAW-SACOMs. It may also be employed during flight tests of pure vectored RPVs, or of various PST-TV-scaled-model upgrades of extant fighter aircraft. As such it has been adapted to conform with Ref.-3 concepts, definitions and methods of SACOM-measurements.

Vectored and unvectored SACOM-models must have the same mass, mass distribution, stability margin, thrust-to-weight-ratio, etc. However, the very method of measurement affects the results extractable from these flying models.

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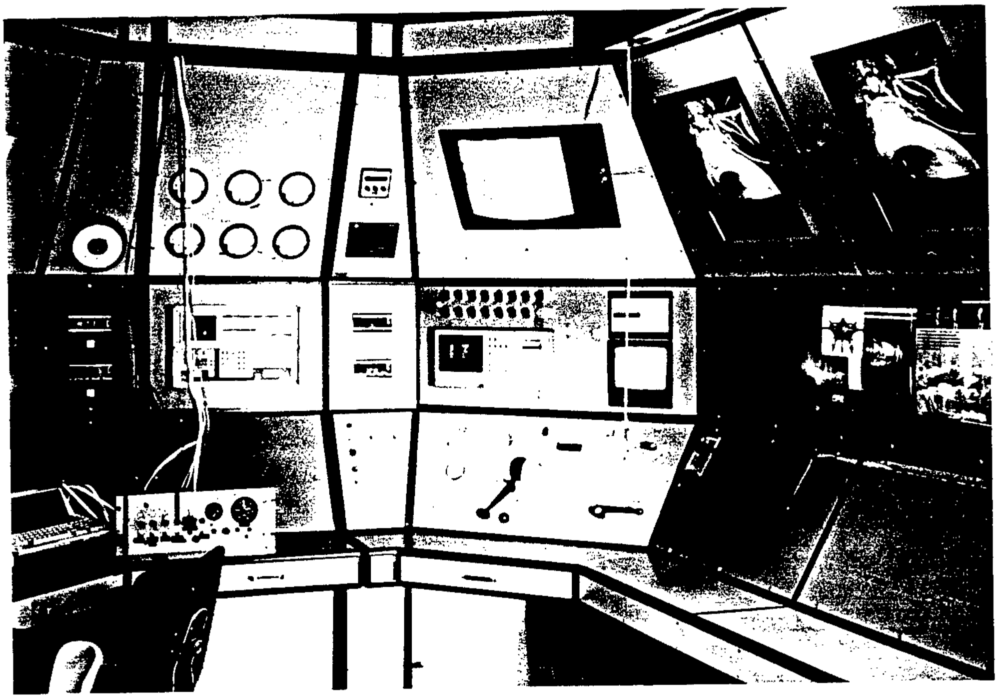
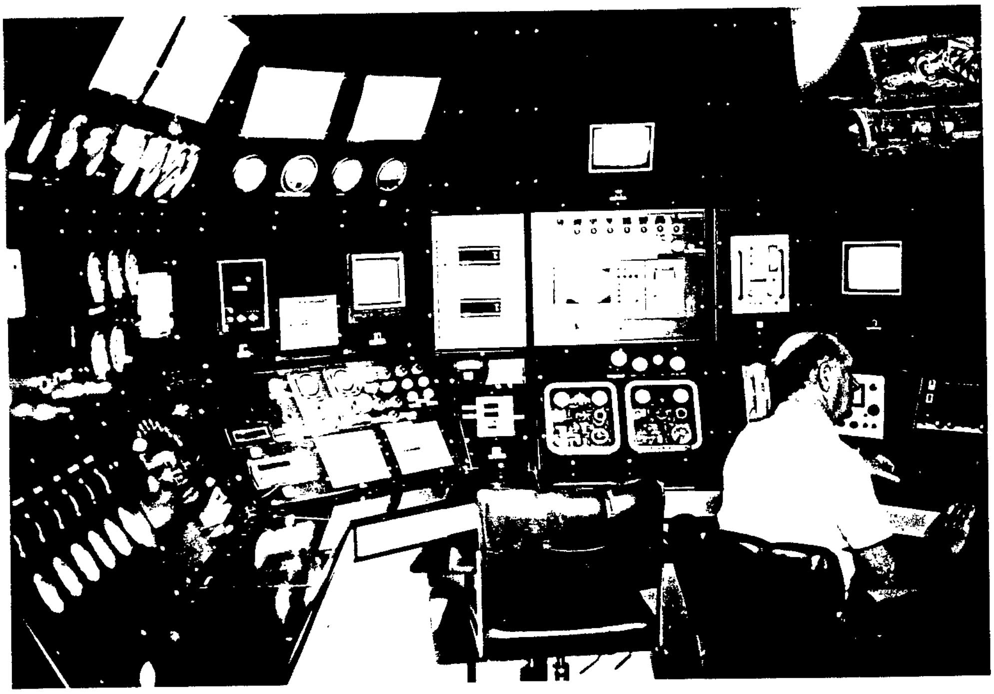
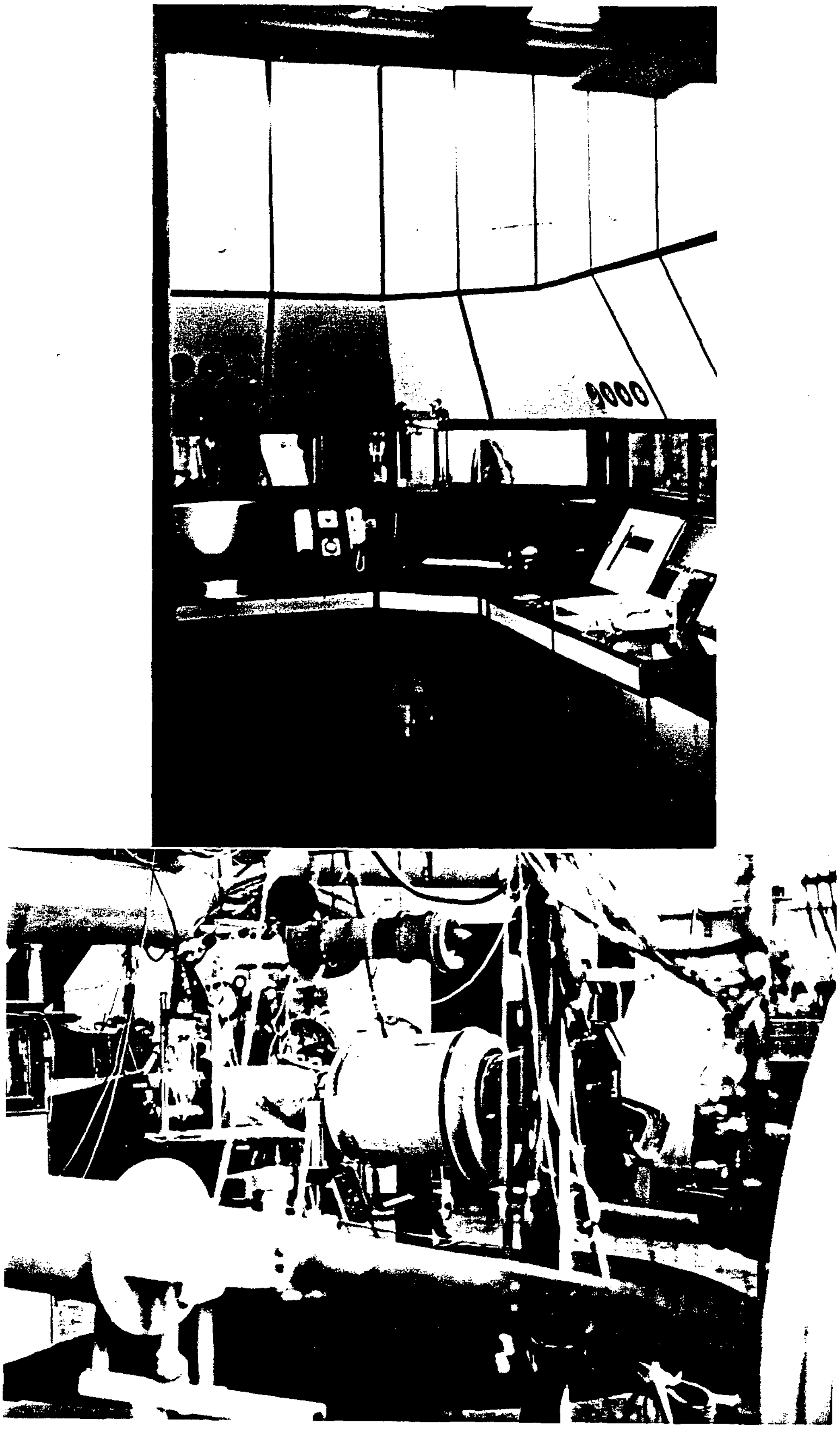
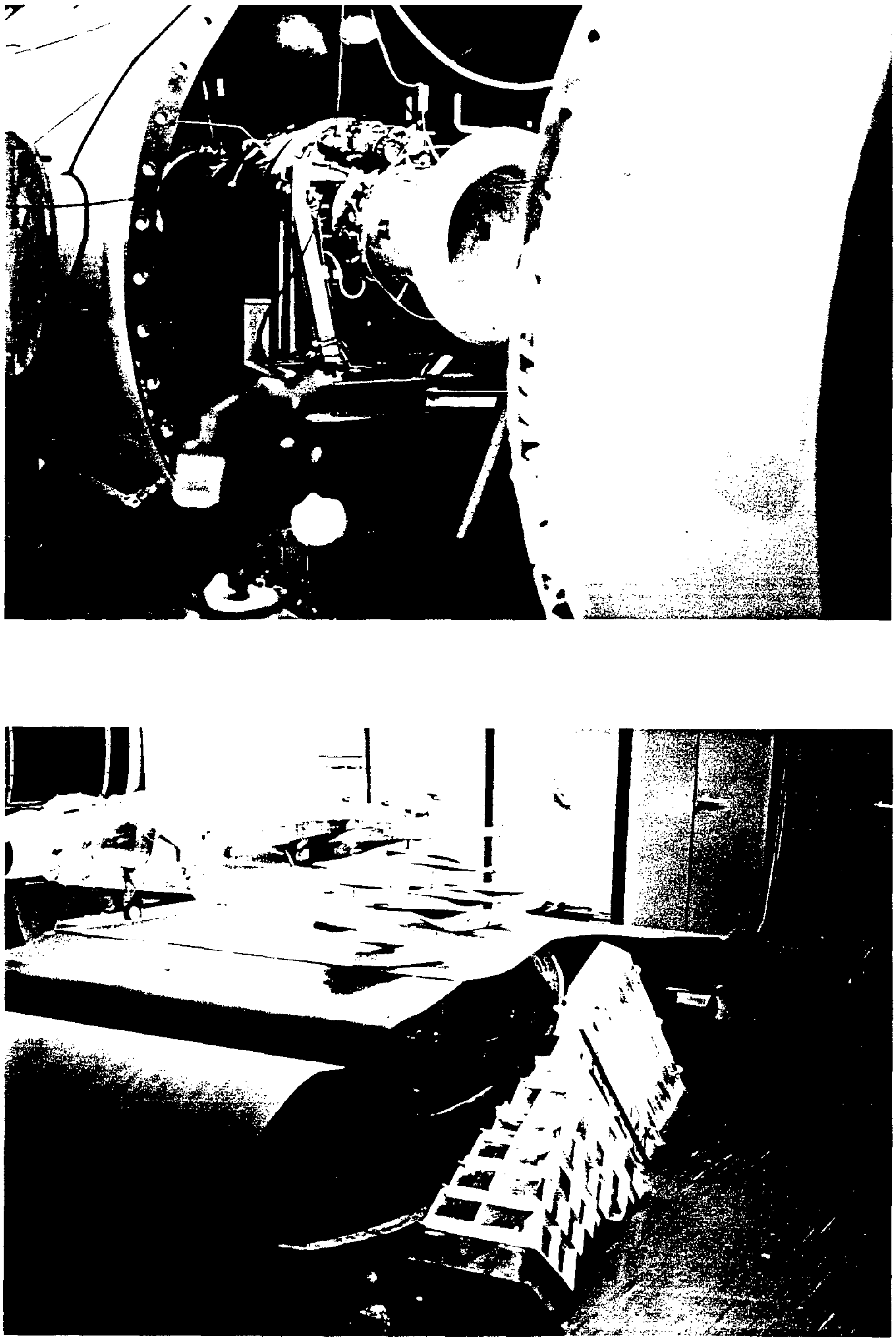




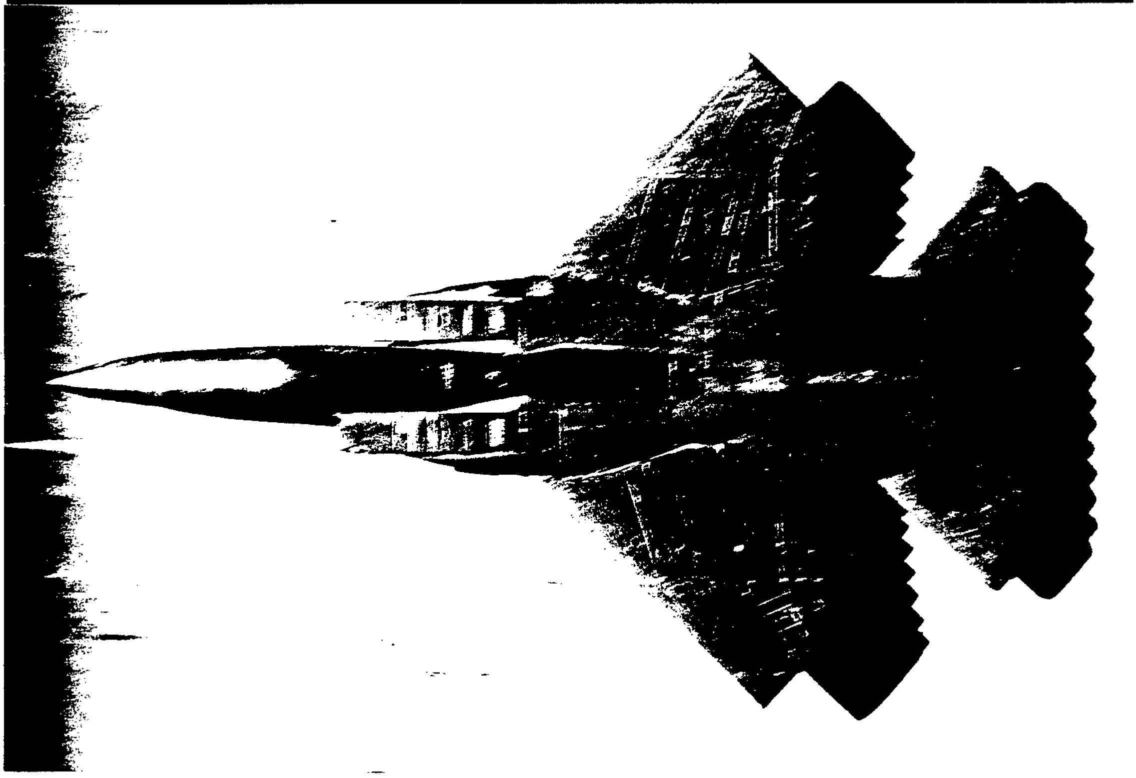
Control Rooms No.5 (above) and 3 (below)



Control Room No. 4 (above) and component test room (below).

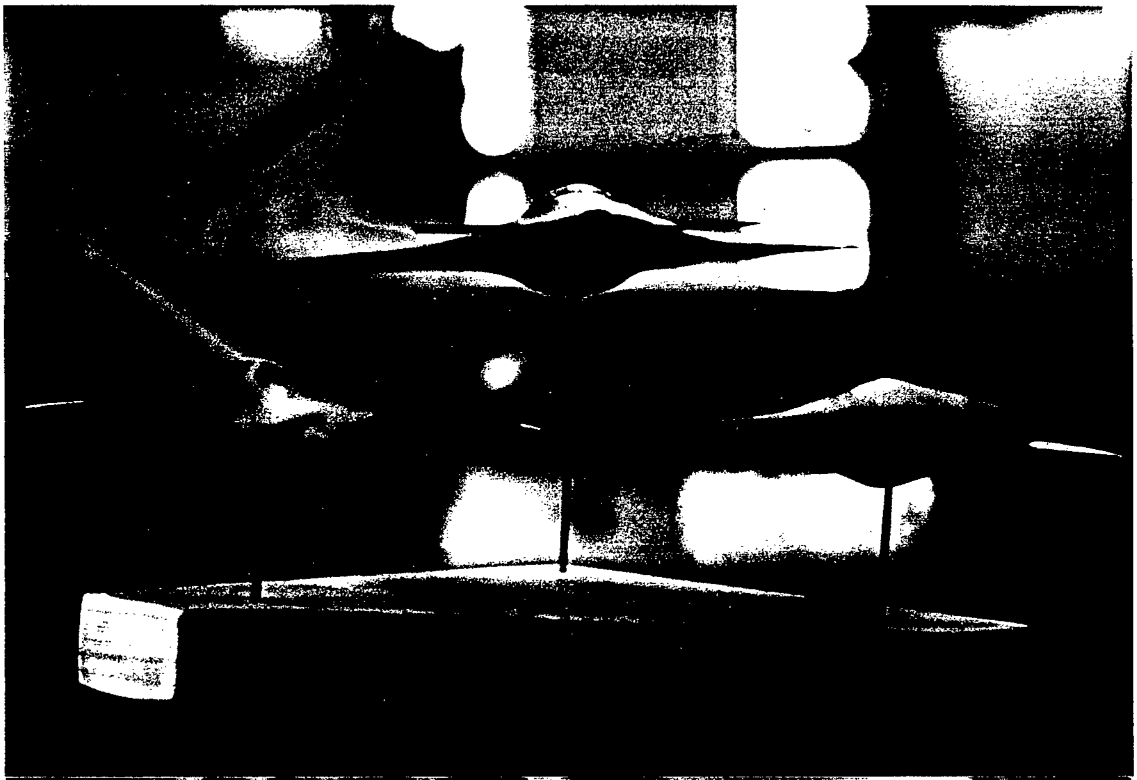


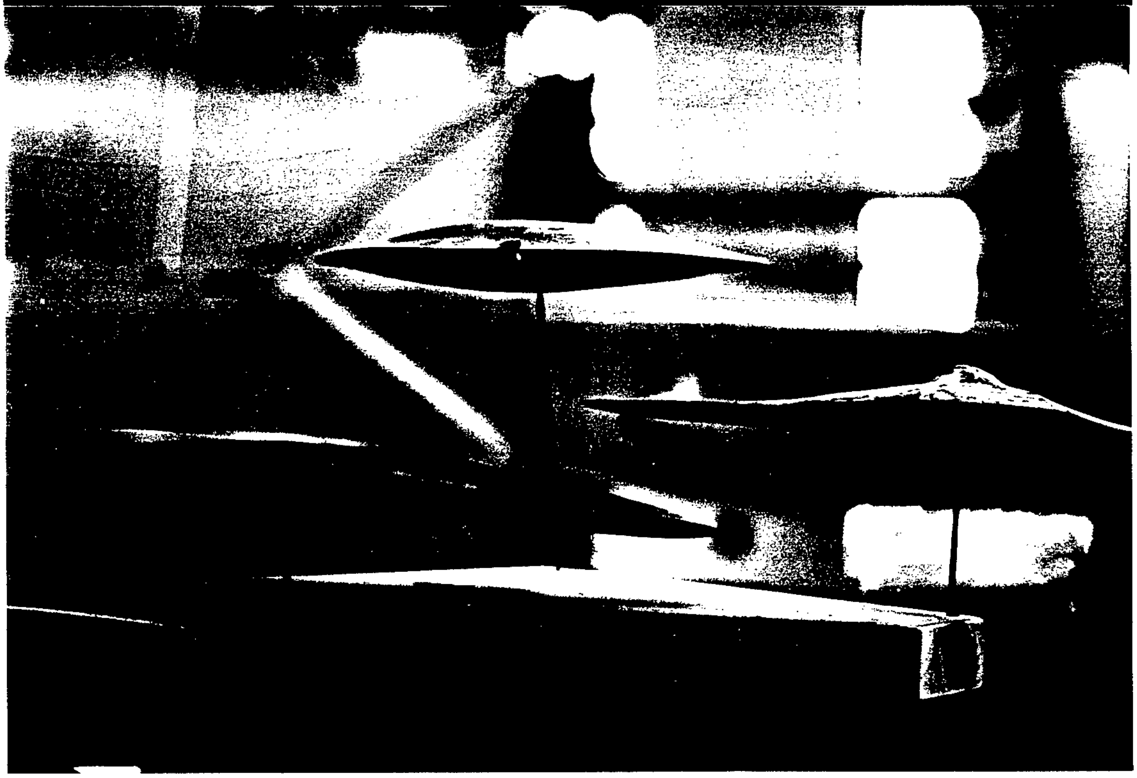
Altitude Jet-engine test facility (above) and low-signature, high-angle-of-attack inlet with wing-imbedded engine and roll-yaw-pitch Thrust-Vectoring nozzle.



Above: The Tailless F-16 wind-tunnel Model.

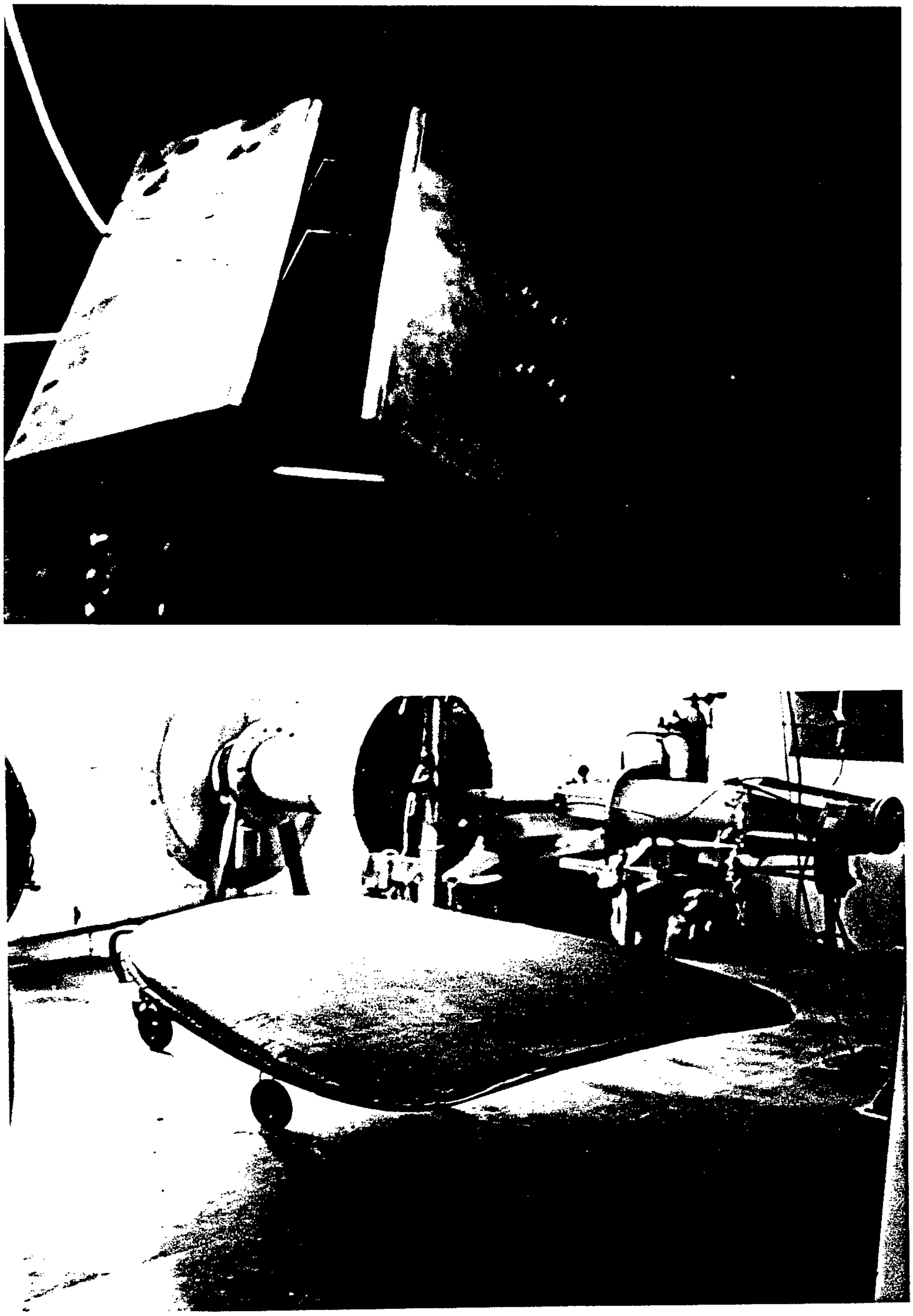
Below: The Tailless F-15 wind-tunnel Model.



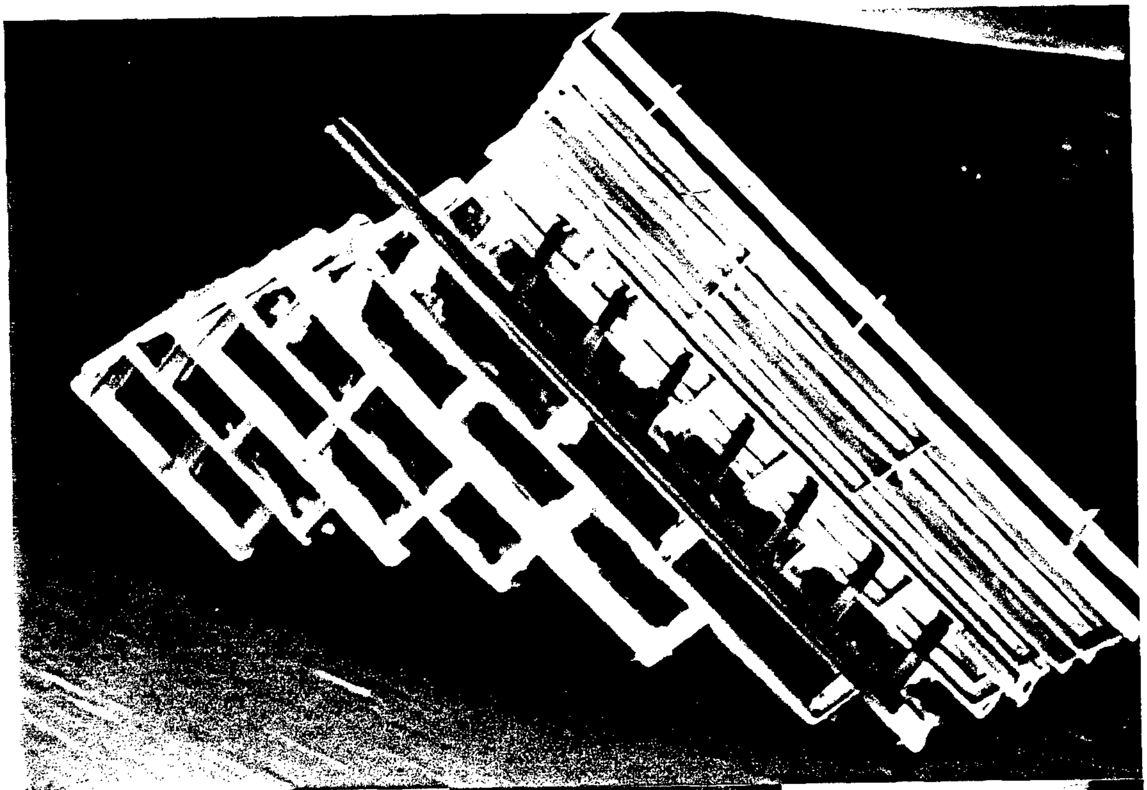


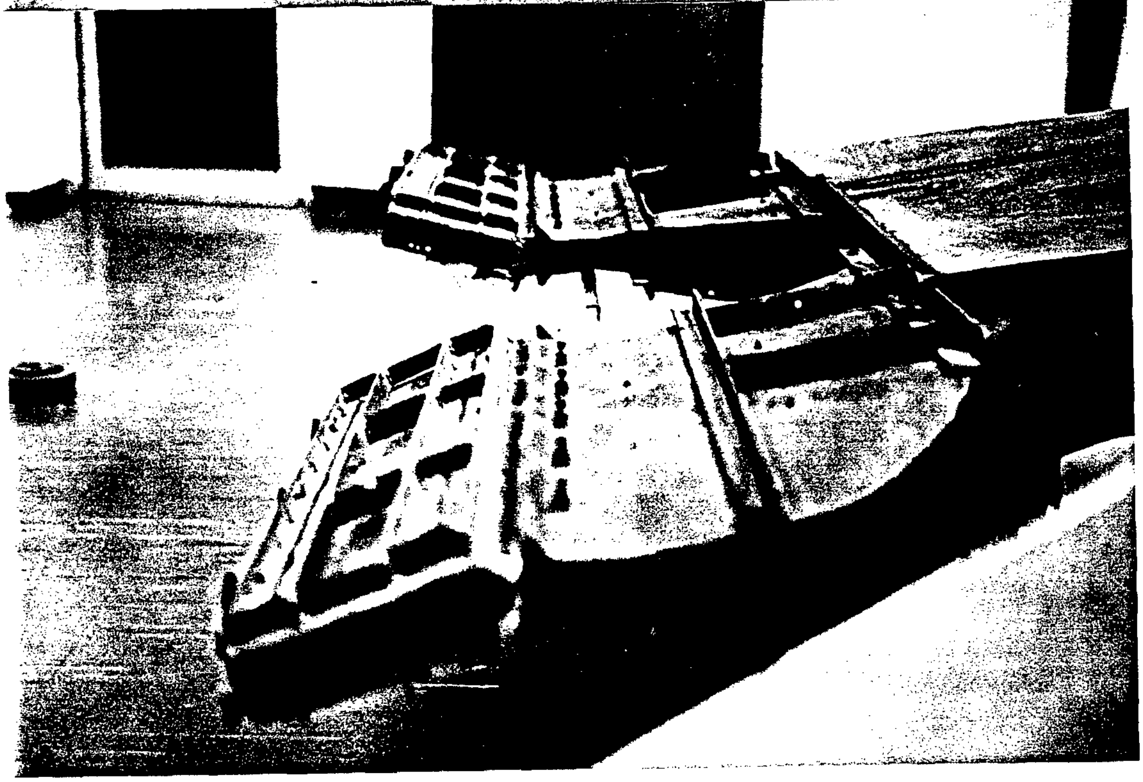
Above: Tailless configurations.
Following wind tunnel tests the upper configuration was enlarged and flight tested as PVA.

Below: Other tailless configurations for which we have wind tunnel data.



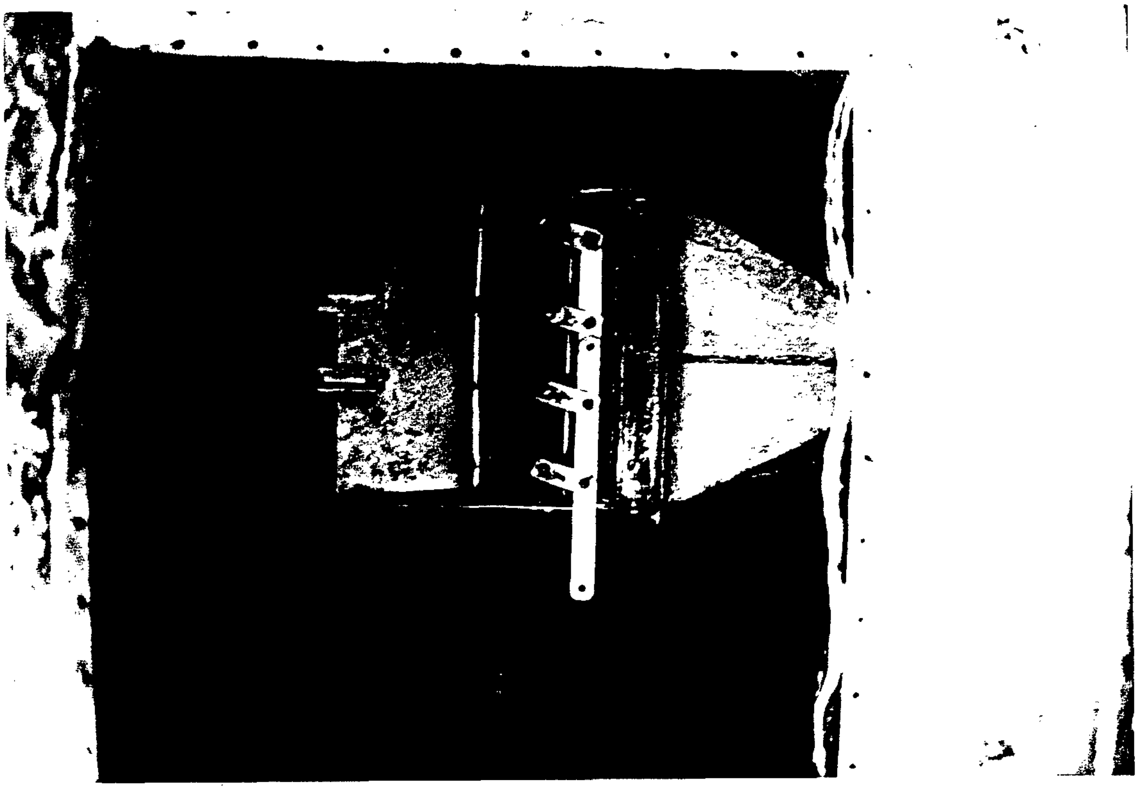
Yaw-Pitch, Low-aspect-ratio TV nozzle (for F-22 type fighters). Below: One of our PVAs. Background : Component test facility shown in Fig. 16.

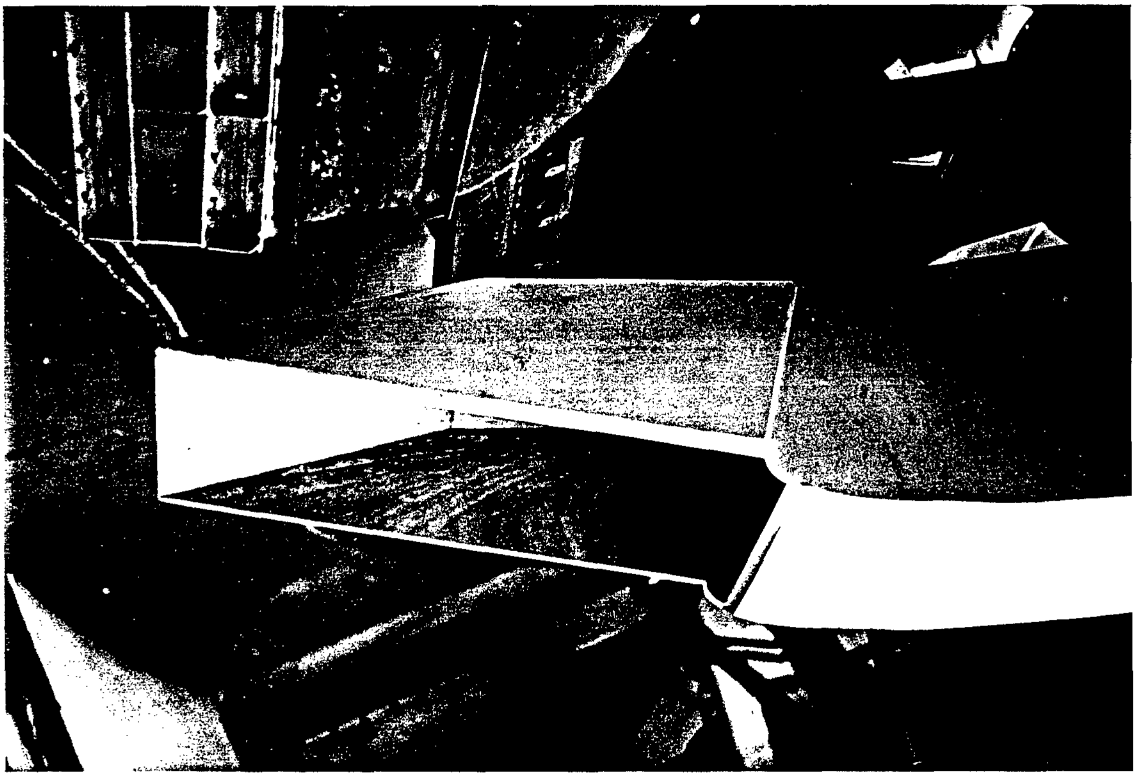




Above: The Roll-Yaw-Pitch TV Nozzle contracted work for General Electric Co.

Below: The Roll-Yaw-Pitch TV Nozzle contracted work for Teledyne CAE.





Above: The "full-scale" PWA Yaw-Pitch TV Nozzle undergoing tests in the jet-engine test facility.

Below: The "full-scale" F-15 inlet to be installed on the Jet engine for distortion-free tests with vectorable lips.

THEORY

Part II

MAXIMIZING THRUST-VECTORING CONTROL POWER AND AGILITY METRICS

Abstract

Debated agility metrics are reassessed in light of new developments in multiaxis thrust vectoring. Standard Agility Comparison Maneuvers [SACOMs] are proposed for testing the maximization of thrust-vectoring control power during post-stall, manned and unmanned flight tests.

Notation:

AoA - Angle-of-Attack

IC - Initial Conditions

EC - End Conditions

RaNPAS - Rapid Nose Pointing and Shooting

PJC - Partial Jet Control

PSM - Pure Sidslip Maneuver

PST - Post Stall

PVA - Pure Vectored Aircraft

SACOM - Standard Agility Comparison Maneuvers

TM - Transient Maneuver

TV - Thrust Vectoring

TVC - Thrust Vectoring Control

Introduction

The availability of post-stall [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 [1-4]. 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.

Four debated methods to measure agility have been proposed recently (5, 6, 18, 19, 20 22). Each proposes to measure and compare a different set of design/flight-testing/control parameters.

This chapter 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 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. 2]**.

Since engine forces (for post-stall-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 maximum-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. It also provides the highest safety margins, for instance, in emergining from any spin situation [Video tape No. 6], or in correcting asymmetric yaw at the loss of one engine during take-off or approach and landing situations.

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 [Video tape No. 6] with that of the PJC models proved that the maximal levels of agility obtainable with PVA are reduced by the degrading external-flow effects on conventional control surfaces.

The 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, 4-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

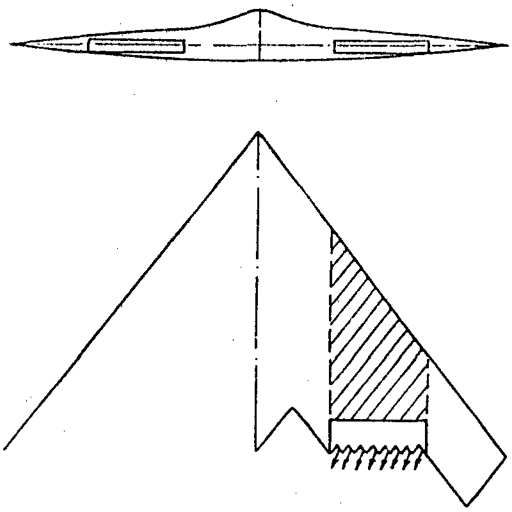


Fig. 2: Pure Vectored Aircraft operate without conventional flight control surfaces. Yaw TV allows Pure Sideslip Maneuvers [PSM]. Shaded area represents supercirculation-affected wing area, while parallel wing/nozzle edges help reduce signatures (1).

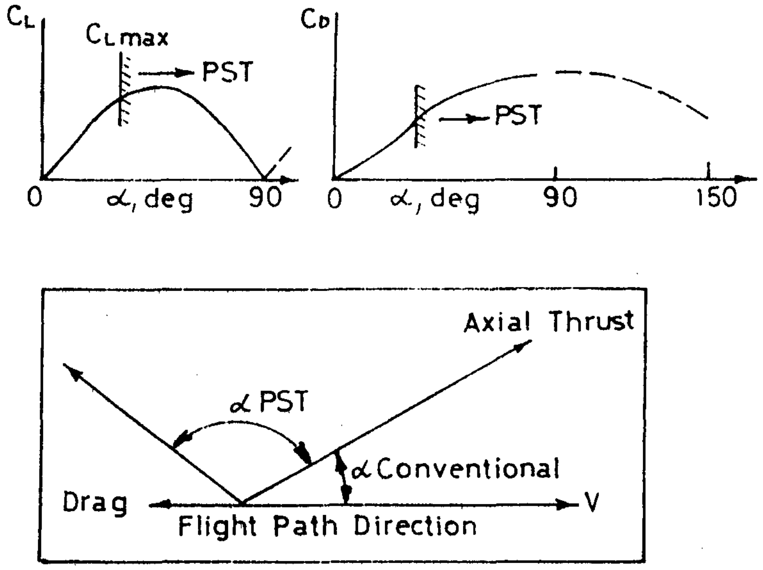


Fig.2a:Definition of the PST domain.

- BASED ON EXISTING COMPARISONS
- F-15/F-16 vs F-4/F-5
- 10,000 FT
- 50% FUEL

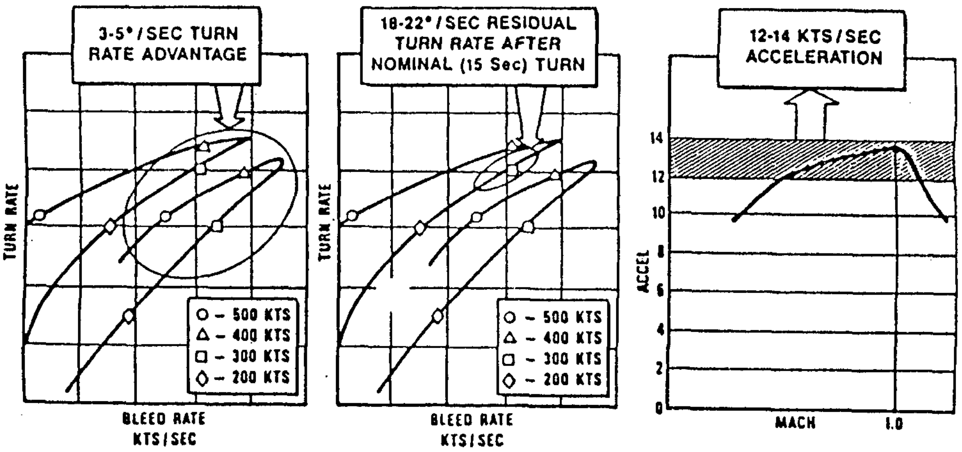


Fig. 3: GD's agility-definition proposal includes Dynamic-Speed-Turn plots.

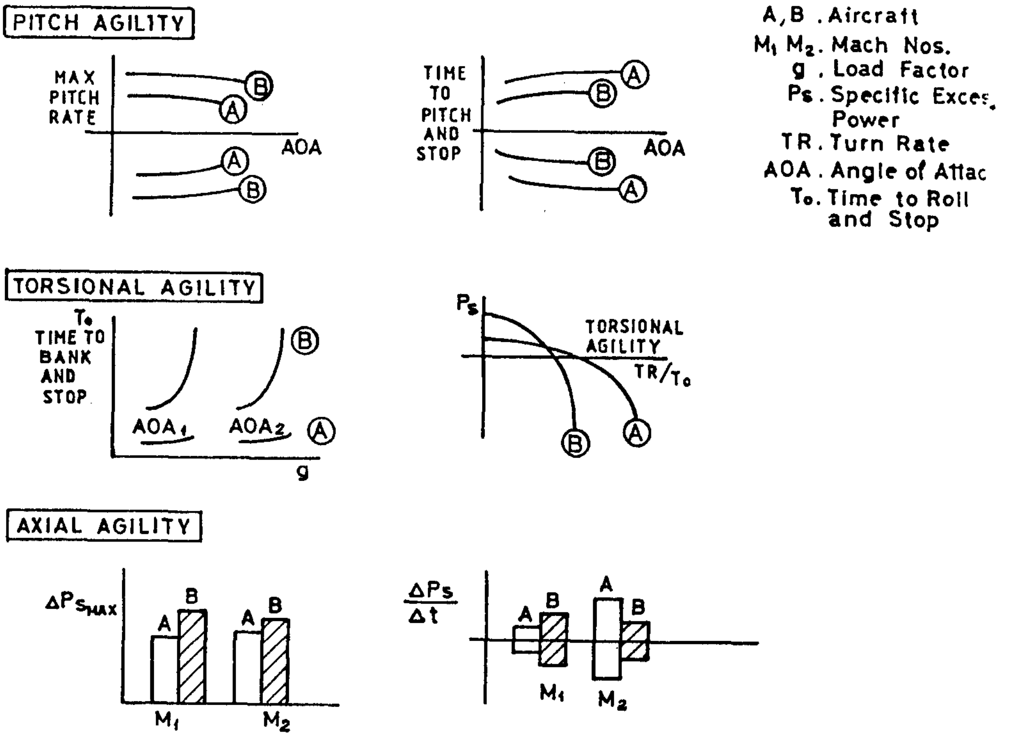


Fig. 4: AFFTC's agility-definition proposal includes the metrics shown.

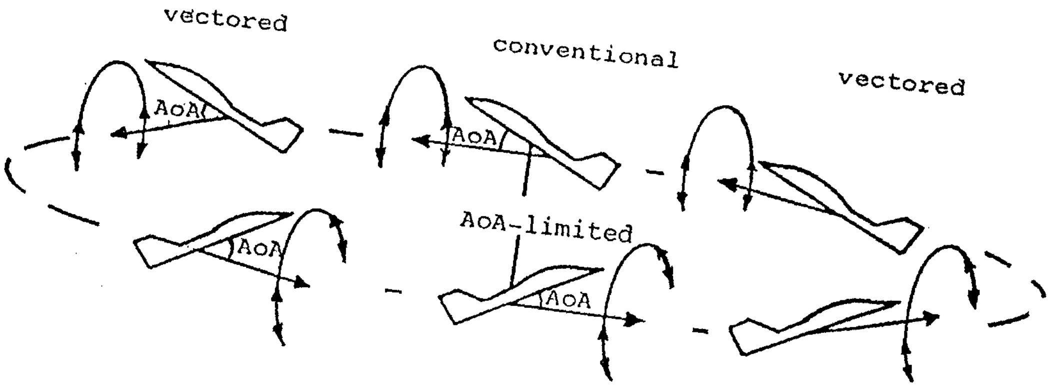


Fig.5:Maximizing Torsional PST-TV-Roll-Reversal SACOM.

Fig. 6: Simple, Yaw-Pitch, low-aspect-ratio, TV nozzles installed on a 1/7-scale, computerized, flying F-15 model.

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 agility power 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-snap shots, 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 diference 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 numbers 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: [i] **Functional agility** as the "time-to-achieve-a-final-desired-aircraft-state", such as time to capture a desired PST-pitch-angle; [ii] **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, and 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 2nd 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; 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

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 flight tests with PJC or conventional models of the same scale, weight, moments of inertia, thrust-to-weight ratio, stability margins, etc.

For this purpose the following 4-component definition of TV-agility is asserted to be more useful than the former 3-component metrics which characterize each of the former debated definitions of agility:

1 - Maximizing Roll-Reversal TV-Agility

This torsional agility component refers to the capability of an aircraft to rapidly change the plane of its PST maneuver. Fig. 5

Initial Conditions [IC]: - [i] - Straight and level flight at different speeds/altitudes. [ii] - Sustained level turn at different speeds/altitudes.

Transient TV-Maneuver [TM]: - Maximum TV-roll-rate and TV-roll-reversal rate [rate-of-change of the osculating plane], during "up" and "down" 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 at maximum roll-rate under PST conditions.

End Conditions [EC]: - As close as possible to IC.

Functional Component [FC]: - "Time to" from IC to EC for each cycle during "up" or "down" roll-reversals, and for various conventional and PST AoA, turn radii, speeds and altitudes at constant throttle setting.

Min-Max Limitations: - Maximal trimable/controllable AoA under which such controllable SACOM can be achieved.

[Using our models we have established that TVC with two adjacent low-aspect-ratio nozzles is ineffective. Consequently, a new type of TV-propulsion has been proposed by introducing high-aspect-ratio, roll-yaw-pitch TV nozzles [1, 10] which increase the roll-moment arm. 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.]

2 - Maximizing Pitch-Reversal TV-Agility:

IC: - [i] - Straight and level flight at different speeds/altitudes, starting the SACOM from the lowest controllable-sustained speed. [ii] - Sustained level turn at different speeds/altitudes, starting the SACOM from the smallest controllable-sustained turn radius.

TM: - [a] - A very rapid, positive-PST-rotation, and reversal to [negative g-load] PST-rotation, and, finally, rapid stop back at IC [i], or at IC [ii], respectively, with and without conventional control power. [b] - Similar TM in a reverse order. [These are positive and negative "Cobra"-brakings].

This agility component provides not only functional TV-pitch-rate metrics for different TV-aircraft, e.g., time to maximum PST-AoA and stop at maximum pitch-rate, but also the onset of maximal TV-control power under PST conditions.

EC: - As close as possible to IC.

[FC]: - "Time-delay" from IC to maximum AoA and capture, or the time to positive AoA PST braking, or to negative AoA PST braking, or the minimal, total, integrated time from IC to EC during negative or positive reversals.

Min-Max Limitations: - Maximum positive and negative "Cobra" braking, minimal time required to avoid passing, say, a "negative 3g human tolerance", maximum trimable/controllable AoA, minimal speed/turn radius, altitude, etc., under which such controllable SACOM can be achieved.

3 - Maximizing Pure-Sideslip-Maneuver [PSM] Agility:

This component applies only to PVA. 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 twin-engine PVA can provide such TV yaw forces.] 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: - Maximal trimable/controllable sideslip angle under which such controllable SACOM can be achieved for various AoA-throttle-TVC settings.

4 - Maximizing Axial TV-Agility:

IC: - Straight and level sustained flight at specified speeds and altitudes.

TM: - Acceleration to a given maximum speed and reversal to initial speed, by maximum throttle-change-rate, and/or airspeed-brake, and/or thrust-reversal deployment 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, minimal speed under which such controllable SACOM can be achieved.

Comments

The proposed SACOM and 4-component TV-agility include:

1) - "Transient" agility metrics expressible in terms of "2nd-time-derivatives" of the velocity vector, i.e., "point rates" , which, however, might be too wildly scattered and thus not very meaningful to the operational pilot.

2) - Time-integrated metrics ["time to .."] that are meaningfully displayable to the pilot as a "functional" agility.

3) - Human tolerances expressible by the same language as the proposed metrics .

4) - Metrics which can be cycled back to the jet propulsion laboratory, to the windtunnels, etc. for further improvements of TVC .

5) - Metrics which 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 propsed 4-component SACOM is asserted to be more useful than the former 3-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.

TV-agility is an interdisciplinary subject involving a revolution in engineering and pilot education.

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Laboratory & Flight Tests

Part I

Technology Limits

Technology Limit No. 1: Hot Propulsion

Unless proven vectorable inlets [with minmal distortion coefficients] for PST-TV maneuvers are available, one cannot control vectored models with jet engines in the deep PST domain without risking engine-out situations and total loss of model and its onboard computer, probes, etc.

Yet, using our new, low-distortion, vectorable inlets for this purpose, the limitation may be removed.

Suitable jet engines for this purpose are the new Teledyne 305 family of 6"-diameter engines, each costing about $ 25,000 and lasting for up to 10 hours. Their use would drive the cost of this program a few hundreds percents upwards, but they have the potential of overcoming technology limit No. 2.

Technology Limit No. 2: Cold Propulsion

Cold-jet propulsion, generated by ducted fans driven by two-stroke engines, requires no vectorable inlets and is therefore much less risky and considerably faster and more cost-effective for simulating maximum PST-TV agility and demonstrating new feasibilities of TV control power at low speeds.

However, to operate the required-size 6"-diameter ducted fans to generate sufficiently fast cold jets, one must rotate them at least as fast as 20,000 to 25,000 RPM.

Technology Limit No. 3: Piston Propulsion

Currently, there is no engine available above 5 HP which operates in the range 20,000 to

25,000 RPM. [Increasing engine HP results in reduced RPM. Hence the current technology limit is around 4 HP per engine for the 1/7-scale flying model.]

Technology Limit No. 4: Agility Measurement Affects Agility

Technology limit No. 3 limits the thrust-to-weight ratio of the flying models.

While the weight of the onboard computer required to measure TV agility is only about 100 grams, the combined additional weight of gyros, extra batteries, probes, two radio-controls, recording accessories, etc., is about a kilogram. This extra weight decreases the thrust-to-weight ratio beyond the minimum required for safe flight and good maneuverability. Thereby, we have encountered serious technology limitations that have caused frequent aborted takeoffs and crashes and the total loss of valuable equipment.

To conclude: The very method to measure agility affects the maximum agility extractable from a TV-model based on cold propulsion.

Technology Limit No. 5: Accelerometers vs. Gyros

At one point during the study we replaced the relatively heavy gyros/batteries with low-weight accelerometers. Excellent performance was obtained in the laboratory. However, when we operated the engines, the low-weight structure of the flying model introduced such vibrations that filtering them out was apparenly not effective. Hence, we had to switch back to gyros, at the cost of losing time, funds and agility.

Technology Limit No. 6: ETV Instead of the more effective ITV

Internal Thrust Vectoring [ITV] requires ducts whose area cross-section changes from circular to rectangular shape. However, such ducts, with the availble cold propulsion, causes about 33 % loss of thrust. On the other hand, our laboratory test results and the flight experience [without the gyros and instrumentation] have demonstrated that ITV provides maximum PST-TV agility for any given model.

With no solution available now to this problem, we have been forced to concentrate during the last year on External Thrust Vectoring [ETV], consisting of 4 vectoring external paddles which provide yaw and pitch thrust-vectoring control. This method does not reduce the maximum thrust available at takeoff and during climb, as do Internal

Thrust-Vectoring [ITV] nozzles. However, this method provides relatively low efficiency of thrust-vectoring control power during SACOMs.

Without the additional weight of computer, gyros, batteries etc. we have thus demonstrated the "Cobra" maneuver with ITV. However, flight tests with the computer/gyros, required the use of ETV.

Nevertheless, with ETV we have, so far, demonstrated at least twice $\dot{\alpha}$ values, in comparison with conventional flight control.

Technology Limit No. 7: Moments-of-Inertia, Stability Margins, Etc.

The following ratios of the moments-of-inertia of the USAF SMTD F-15 with fuel are:

Izz/Iyy = 1.15 and **Izz/Ixx = 6.25.** cf. p. 50-52.

In comparison, the following ratios of the moments-of-inertia of our TV F-15 model with a full fuel tank are [2% error in the measurement. Cf. our Progress Report from 1990 and below]:

Izz/Iyy = 1.11 and **Izz/Ixx = 6.46.**

On one hand this good agreement provides reasonable similarity.

On the other hand, the very low moments-of-inertia values, which characterize our flying models, cause amplification of air turbulence, engine vibrations, and unwanted sideslips, rolls, etc., during SACOMs.

Therefore, the results provided here for windtunnel, laboratory and flight tests should be used with caution during scaling-up procedures and scale corrections.

Our flying models are based on a +5 % static stability margin, with and without fuel. [See also the effect of fuel on the values of the moments-of-inertia of the scaled and the actual F-15s.] On the other hand, new vectored aircraft would maintain negative static stability margins and use fly-by-wire control methodologies. In addition, our flyer's hand responses [as recorded by our ground computer 43 times per second], do not scale-up. Furthermore, materials, servos, 1/7-scale TV-nozzles & engine inlets do not scale-up, or require additional empirical work prior to their adaptation to full-scale aircraft.

Technology Limit No. 8: Scaling up of Vectorable Nozzle and Inlet Test Results.

Performance test results for our yaw-pitch and roll-yaw-pitch family of TV-nozzles have been extracted from operating the nozzles installed on a 700 lbf jet engine in our "full-scale" engine test facility. These complicated "full-scale" nozzles do not scale-down to the 1/7 scale of our flying models. For this reason, and for saving weight, the yaw vanes and the pitch flaps employed for thrust-vectoring control of the flying models have been constructed from simple flat surfaces which do not correspond to the "full scale" yaw vanes and pitch flaps of the optimized TV-nozzles.

Report No. 1 [April 24, 1990] provides the calibrations of the axial, vertical and sidewise forces and moments operating on the flying models during TV-commands to deflect the jets. These data were measured under static test conditions, but when the flying-model engines operate at full throttle. We boldly assume, however, that these calibrations remain practically invariant during the dynamic flight conditions.

It should further be stressed that the geometric yaw or pitch flap deflection angles, δg_v and δg_y are not the actual jet deflections, δ_v and δ_y. Hence, to estimate the actual forces and moments on the model during SACOMs, one must use these calibrations.

Somewhat similar precautions apply to the inlet distortion coefficients reported here for unvectored and "vectored" F-15 scaled inlets.

Laboratory & Flight Tests

Part II

Methodology

The methodology employed and the systems used are briefly described in this chapter. The figures are self explanatory.

Additional details and calibration data are available in the Chapter "Technology Limits", in the Appendicies, in the Annual Report of April 24, 1990, as well as in our Video Tapes No. 1 to 6.

Dynamic Scaling

With the rapid advance of new technologies, close-combat engagement times get shorter, and inherent delay-times of pilot and IFPC-hardware become more critical to combat effectiveness.

Our present flyer delay times [see below] are of the same order-of-magnitude as those associated with the four, net, Dirac-type, time-related-reversal components [Cf. 'Theory'-Part-II] & with our 'Model-Net-Agility' **[MoNA]**. Hence, as a linear approximation, we propose to estimate the four [gross, Dirac-type, time-related-reversals] components of Aircraft Gross Agility **[AGA]** by:

$$\boxed{\mathbf{AGA = MGA \cdot [DSF] \cdot F_1[Turb.\text{-}MLEM] \cdot F_2[PDT/FDT] \cdot F_3[A\text{-}IFPC]/[M\text{-}IFPC]}}$$

where

MGA is Model Gross Agility SACOMs [MGA data are provided below],

DSF are **Dynamic Scale Factors**, to be defined below.

F_1[Turb.-MLEM] are the functions of '**Turbulence Noise and Maximum Likelihood Estimation Method**' [Cf. 'Theory' - Part I, p.109].

F_2[PDT/FDT] is the ratio of pilot to flyer delay times during actual, in-flight, SACOM, Dirac-type delta-function reversals. [A few FDT data are provided below].

$\mathbf{F_3[A\text{-}IFPC]/[M\text{-}IFPC]}$ is the yet-unknown functional relating inherent Aircraft-IFPC to Model-IFPC delay times, etc. [IFPC is Integrated Flight Propulsion Control.] [A few M-IFPC delay times are provided below].

Dynamic Scale Factors

Assumptions:

1 - [MGA][DSF] data reported here are strictly confined to proof-of-concept/feasibility studies.

3 - Pitch, yaw and roll rates reported below are moments-of-inertia-dependent angular velocities .

4 - Differences in aerodynamic effects between model and full-scale aircraft are of 'second-order' in comparison with moments-of-inertia-related angular velocities & accelerations. This approximation is backed by the high **Re No.** range [see below] and by keeping strict proportional size-shape similarity between the full-scale F-15**A** aircraft and the 1/7-scale model.

5 - For using **MGA**-Angular-Reversal-Rates[ARR] , such as the pitch, roll and yaw rates reported below, the following **general equation** is proposed

$$\begin{aligned}&\mathbf{AGA}[\mathrm{ARR}] =\\&= \mathbf{MGA}[\mathrm{ARR}][\mathbf{L}]^{-0.5}\mathbf{F_1[Turb.\text{-}MLEM]\ F_2[PDT/FDT]F_3[A\text{-}IFPC]/[M\text{-}IFPC]} \cong\\&\cong \mathbf{MGA}[\mathrm{ARR}][\mathbf{L}]^{-0.5}\end{aligned} \qquad \mathbf{[1]}$$

where **L** is the '**linear-scale-factor**', and $F_1 F_2\ F_3$ is approximately unity.

For instance, the maximum [gross] TV-pitch and TV-roll rates observed with our 1/8-scale TV-F-16 models during Pitch and roll 'Reversals' [Cf. 'Theory' - Part II], was at least around *150* **deg/s.** For full-scale TV-F-16 fighter aircraft based on our design-concepts, this rate means around $[150][8]^{-0.5} \cong 53$ **deg/s**, when $F_1 F_2$

F_3 is approximately unity

The error involved in using such 'Indicative Approximations' in computer simulations of aircraft agility and pilot tolerances, may be deduced from the DST and M-IFPC data reported below, and from the error involved in using simplified verifications of moments-of-inertia-based-DSF. The fundamental approximation is [cf. the derivation of eq. 5 below]:

$$\boxed{\textbf{DSF} = [\textbf{Aircraft Average Density/Model Average Density}][L]^5 \qquad [2]}$$

This important result does not depend on any assumption related to the Model or full-scale Reynolds or Froude numbers, as discussed below. It is a fundamental equation based on simple physical laws, irrespective of aerodynamic and boundary-layer funambolism.

'Realistic' comparisons are provided below as a partial verification of our methodology. Other partial verifications are extracted below for internal moments-of-inertia ratios and for weight-ratios.

Additional [dimensionless] scaling-up methodologies have been enumerated in 'Theory' - PART I, and in our book [1].

Moments-Of-Inertia-Based Dynamic Scaling Factors

Under the aforementioned assumptions we write

$$[dx_i]_A/[dx_i]_M = L \quad [i = 1, 2, 3, \text{ or } x, y, z] ; \quad r_A = L\, r_M \qquad [3]$$

$$W_M = Mg \cong g\bar{\rho}_M \int_{V_M} [dx_i]_M = g\bar{\rho}_M L^{-3} \int_{V_A} [dx_i]_A = \underline{W_A\, L^{-3}\, [\bar{\rho}_M/\bar{\rho}_A]} \;! \qquad [4]$$

$$I_M = \int_{M_M} r_M{}^2 dM_M \cong \bar{\rho}_M \int_{V_A} L^{-2}\, r_A{}^2 L^{-3}\, [dx_i]_A =$$

$$= \bar{\rho}_M L^{-5} \int_{V_A} r_A{}^2\, [dx_i]_A \quad = \underline{I_A\, [\bar{\rho}_M/\bar{\rho}_A]\, L^{-5}} \;! \qquad [5]$$

$$\text{where} \int_{V_A} r_A{}^2\, [dx_i]_A \cong I_A/\bar{\rho}_A\, , \qquad [6]$$

and **M** is mass, **W** weight, and the subscripts **M** and **A** refer to model and full-scale aircraft, respectively, $\bar{\rho}$ is the average density, L the linear-scale-factor, and **I**, **x**, **y** and **z** are the moment-of-inertia components and coordinates as defined in 'Theory' - Part I.

Assumption No. 6: **The Average Density Ratio of Aircraft-to-Model = 3.0**

[This assumption is based on the following materials composition of our '9-foot', flying TV-F-15 model : Thin pressed fiberglass for fusalage & inlets; highly-foamed plastic for wings and tail; aluminum for 6 wing-fusalage-tail beams/rods; 2 ducted fans from plastic; 2 engines from aluminum; 3 batteries (nickel-cadmium), cables, 3 rate gyros and 10 servos from plastic (covers), S.S. & other metal parts; landing gear from plastic & highly-foamed rubber; electric wires from plastic & copper; FM + PCM rec. + onboard computer from silicon-copper + plastic covers; medium-weight and light balsa-wood for internal ribs; thin plasitic covers on wings & tail; 'Nitro' fuel; plastic fuel tanks and fuel pipes; cold-jet ducted pipe from thin accetate; TV-nozzles from light-balsa and steel-aluminum for frames, flaps, vanes and hinges.]

'Accuracy-Limit' I

The Weight 'Scaling Factor'

Notes:

1 - The PST-TV 'Cobra-maneuver' was generated with 1st-generation, **ITV**-F-15 RPV.

2 - MGA flight-testing data were generated with 2nd-generation **ETV**-F-15 RPV.

3 - Flight-test data are normally recorded about 3-5 minutes past takeoff, when the fuel tank is almost empty.

F-15B Gross Weight [clean configuration] with no fuel: **33,400 lbs.**

1st-Generation ITV Model Gross Weight [canardless, ITV-F-15 RPV]:

14.7 kg [32.5 lb] with no fuel.

2st-Generation ETV Model Gross Weight [canardless, ETV-F-15 RPV]:

13.4 kg [29.51 lb] with no fuel.

From eq. 4

$$W_A/W_M = [\bar{\rho}_A/\bar{\rho}_M]\, L^3 = 3[7]^3 = \underline{1029}$$

'Accuracy Limit I' for ITV: W_A/W_M = 33,400/32.5 = **1027** **[- 0.2 %]**

'Accuracy Limit I' for ETV: W_A/W_M = 33,400/29.5 = **1231.8** **[+9.9 %]**

Moments-Of-Inertia Dynamic Scaling Factors

'Accuracy-Limit' II

The moments-of-inertia of the **Full-Scale F-15** STOL Manuevering Technology Demonstrator [SMTD] are:

With Fuel	**Without Fuel**
I_{zz} = **222,959 slug-ft^2**	I_{zz} = **204,088 slug-ft^2**
I_{yy} = **194,106 slug-ft^2**	I_{yy} = **185,744 slug-ft^2**
I_{xx} = **35,875 slug-ft^2**	I_{xx} = **24,266 slug-ft^2**

The corresponding values for our **ETV F-15 scaled model** are:

With Fuel	**Without Fuel**
I_{zz} = **4.18 slug-ft^2**	I_{zz} = **4.09 slug-ft^2**
I_{yy} = **3.76 slug-ft^2**	I_{yy} = **3.70 slug-ft^2**
I_{xx} = **0.646 slug-ft^2**	I_{xx} = **0.596 slug-ft^2**

The corresponding **Scaling Ratios** between the Full-Scale TV F-15 SMTD and our 1/7-scale ETV F-15 model are therefore:

With Fuel	**Without Fuel**
I_{zz}scale ratio =222,959/4.18=**53,339,**	I_{zz}scale ratio=204,088/4.09 =**49,899**
I_{yy}scale ratio =194,106/3.76=**51,623,**	I_{yy}scale ratio=185,744/3.7= **50,201**
I_{xx} scale ratio=35,875/0.646=**55,534,**	I_{xx} scale ratio=24,266/0.596=**40,714**

Using **50,218** as 'Average Moment-of-Inertia-Design-Scale-Ratio', we obtain, from eq. 5;

$$I_A/I_M = [\bar{\rho}_A/\bar{\rho}_M]\,L^5 = 3\,[7]^5 = \mathbf{50{,}421}$$

This 'Accuracy Limit' is 0.5% below the 'expected' values via eq. 5. However, for the no-fuel 'configuration', the average ratio = 46938, which is 7% below the 'expected' value. Yet, a more 'realistic' comparison is with an empty F-15B, for which we have no data. However, in Capt. D. D. Baumann's M.Sc. Thesis [AFIT, Dec. 1989, p. 73], we found the followings for **F-15B** [TOGW]:

I_{zz} = **192,000 slug-ft^2**

I_{yy} = **172,800 slug-ft^2**

I_{xx} = **33,400 slug-ft^2**

The corresponding **Scaling Ratios** between the **canardless**, Full-Scale **TOGW F-15B** and our 1/7-scale F-15 model **with fuel** are:

I_{zz}scale ratio = 192,200/4.18 = **45,980,**

I_{yy}scale ratio = 172,800/3.76= **45,957**

I_{xx} scale ratio = 33,400/0.646 = **51,702**

F-15B TOGW values vary from 2.5% above to 5% below the 'expected' values via eq. 5. As we shall see below, the internal ratios of moments-of-inertia also correspond inside the full-scale and inside the model.

'Accuracy Limit' III

The internal ratios of the moments-of-inertia of the **USAF/McDD [canard-configured] SMTD TV-F-15** **with fuel** are:

I_{zz}/I_{yy} = **1.15**

I_{zz}/I_{xx} = **6.25.**

The same ratios for the **canardless F-15B TOGW** are:

I_{zz}/I_{yy} = 192,000/172,800 = **1.11**

I_{zz}/I_{xx} = 192,000/33,400 = **5.74**

In comparison, the following internal ratios of the moments-of-inertia of **our [canardless] TV F-15** model **with a full fuel tank** are:

I_{zz}/I_{yy} = **1.11**

I_{zz}/I_{xx} = **6.46.**

The corresponding **'internal-similarity-degree'** obtained, and the previous results, provide **partial verification of DSF** [subject to eq. 1 & assumptions].

However, the very low moments-of-inertia values characterizing our flying models, do not prevent 'amplification' of air turbulence, internal engine-flexible-airframe-structure vibrations [as was verified in a separate methodology-test with onboard-accelerometers. (Not reported here.)], and unwanted sideslips, rolls, etc., during the flight tests.

Therefore, the results provided here for windtunnel, laboratory and flight tests should be used with caution during scaling-up procedures and 'scale-corrections' .

'Accuracy Limit' IV

The Compound Pendulum test method is shown in **Fig.** 20

By giving the model a small push in the appropriate direction, and by timing its oscillations, the oscillatory period is measured as the total number of seconds divided by the total number of complete cycles. The greater the number of cycles, the greater is the timing accuracy. Knowing the period, the weight of the model and the vertical distance of the cg from the pivot point, the moments of inertia are measured in the three axes shown. The experimental error involved in these measurements was found to be **up to 2%.**

New Unknown Scaling/Accuracy Domains

This work deals with the introduction of new variables into dynamic scaling methodology. Together with conventional categories the new variables generate 7 interconnected categories:

1) Post-Stall Thrust Vectoring [PST-TV]

2) Tailless TV-Aircraft [TaTVA]

3) Conventional Aerodynamic Control [CAC]

4) Static Wind-Tunnel Tests [SWTT].

5) Model Flight Tests [MoFT] [by means of TaTVA with or, in PVA, w/o CAC].

   5.1 - Wind-Tunnel Free-Flight/Spin Tests.

   5.2 - Unpowered Drop-Model Flight/Spin tests.

   5.3 - Powered Model Flight/Spin tests [So far conducted only by this laboratory.]

6) Centrifuge Simulations of Vectoring [CeSoV]

7) Full-Scale Aircraft Flight Tests [FuScAFT].

Subcategory 5.3 and categories 1, 2, and 6 are new. MoFT introduces an important, low-cost/low-risk intermediate stage between SWTT and FuScAFT. MoFT responses involve moments-of-inertia-related responses, with particular DSF rules, as presented above. Hence, unlike SWTT, MoFT provides dynamic responses to flight-control commands. Bona fide TV-commands/responses and dynamic scaling rules are therefore unattainable with SWTT.

To predict FuScAFT by means of TaTVA , we resort to both SWTT and MoFT-5.3. And each presents its own accuracy limitations, some of which are not yet fully understood. Even CAC and SWTT are not yet fully understood in the deep PST domain. Consequently, only a brief review of CAC/SWTT accuracy limitations is presented below.

Froude-Number-Based Scaling

Froude number [Fr] relates inertia to gravity forces. Hence, its value is relevant for DSF between MoFT and FuScAFT.

In reviewing dynamic stability parameters for [Unpowered] **'DROP MODEL'** flight tests, **Chambers** [of NASA Langley], **Illif** [of NASA Dryden] and **Woodcock** [of AFFDL/WPAFB] base their DSF on Fr, Re and the lift coefficient to arrive at the same results which were independently derived in this work. [CF. Chambers, Joseph, R. 'Status of Model Testing Techniques' AFFDL/ASD Stall/Post-Stall/Spin Symposium, WPAFB, Dec. 15-17, 1971; Chambers, Joseph, R. and Kenneth W. Illif, Estimation of Dynamic Stability Parameters from Drop Model Flight Tests', Internal Report?, Date 1980?; Woodcock, Robert, J., 'Some Notes on Free-Flight Model Scaling' AFFDL-TM-73-123-FGC, WPAFB, 73-26, 636, Aug. 1973].

However, there is a difference between DSF equations reported by these authors in the 70s and in the 80s. Our DSF equations agree only with the later results. [We had derived our DSF equations prior to knowing of the aforementioned works. Copies of these works were given to us on July 22, 91, by USAF Capt. D. D. Baumann, during his USAF WOE visit to this lab.]

To Conclude:

1 - Our results do not depend on any assumption concerning the Fr, Re or other aerodynamic/boundary-layer coefficients and assumptions.

2 - As demonstrated by eqs. 4 and 5, ours are based on simple, straight-forward physical definitions.

3 - We agree with the later DSF-equations reported by Chambers and Illif.

Conventional Reynolds Number Scaling Limitations

CAC/SWTT test Re No. of 1,500,000 to 2,500,000 may be needed if extrapolation is intended for FuScAFT drag estimations. However, FuScAFT drag due to flap and aileron cutouts, TV-engine-nozzle actual modifications, inspection doors, pitot tubes, missile/bombs launch devices, etc., cannot be well-represented by SWTT. Moreover, SWTT presents correction problems due to support, interference, blockage, walls, FuScAFT aeroelasticity effects, etc.

Based on average wing-chord and the recorded velocities during our MoFT [Cf. the graphs in Part VI], our MoFT-Re varies from **800,000 to 1.800,000**.

However, between CAC/SWTT and FuScAFT the value of the Re No., is seldom a scaling factor of consequence . Indeed, Re effects on the lift curve is profound but often unpredictable by SWTT. Scaling of SWTT pitching moment curves, etc. as provided by this work, and of flaps, ailerons, longitudinal, directional and lateral stability and control and the correlation limitations between SWTT and FuScAFT have been well-documented.

[Cf., e.g., NASA [NACA] TR 586, 1937, TR 667, 1939, TN 1773, 1948 (TR 964), TN 4363, 1958, TN D-3579, 1966, J. Aircraft, 18, 801-809, 1981, 18, 838-843, 1981, 19, 425-437, 1982, and R. D. Neal, 'Correlation of small-scale and full-scale wind tunnel data with flight test data on the Lear Jet Model 23', Paper 7000237, SAE National Business Aircraft Meetings, 1970.]

Yet, with current computational ability to design high-AoA, actual, complicated airfoil sections with leading edge devices and the effects of high-alpha, thrust-vectoring-induced supercirculation and vortices on high lift, flap and aileron cutouts, inspection doors, pitot tubes, missile/bombs launch devices, etc., the problem of extrapolating flying models and/or wind-tunnel data may gradually become possible with a reasonable accuracy degree.

Nevertheless, we do not yet know the **virtual wing/flap TV-induced extra area**' generated by pitch-down jet deflections which cause the flow at high AoA during TV to be deflected down as if a physical flap of unknown area is present at the high-aspect-ratio nozzle exit. Cf. Ref. 1, Fig. III-10 .

Other 'Accuracy Limits'

In terms of approximate values required for preliminary feasibility studies, we next assume that, like its full-size counterpart, our ETV F-15 model dynamically corrresponds, in responses, to similar inertial forces and inertia-propulsion inputs, of future TV F-15 upgrades. This, however, is a bold assumption, for a few reasons:

1 - Future vectored upgrades may have different dynamic mass parameters.

2 - Our preliminary flight tests with a canard-configured F-15 model have demonstrated a low-degree of performance [Video Tape No. 6].

3 - Serious doubts exist as to the very need of a canard on vectored-stealth fighter aircraft [1].

Model Static Stability Margin

The 1/7-scale F-15 Flying Model Overall length: 2.62m

The Measured F-15 Model Center-of-Gravity:

1.52m from nose tip with fuel.

1.55m with no fuel.

0.12m from upper skin with fuel

0.12m from upper skin with no fuel.

The Static Stability Margin :

+5% with fuel at the beginning of the flight tests.

+6% with no fuel at the end of the flight tests.

Maximum Thrust-Vectoring Deflections

Maximum [yaw-pitch] ITV Nozzle Geometric Deflections:

Symmetric **25, or 20** degrees in pitch and yaw directions.

Maximum [yaw-pitch] ETV Nozzle Geometric Deflections

ETV with Extended Paddles:

Up ETV: 15 deg upper paddle, 19 deg lower paddle, 14 deg upper extended metal, 18 deg lower extended metal. Average: 17 degrees maximum up-deflection.

Down ETV: 28 deg upper paddle, 24 deg lower paddle, 27 deg upper extended metal, 23 deg lower extended metal. Average: 25 degrees maximum down-deflection.

ETV with Non-Extended Paddles:

Up ETV: 20 deg upper and lower paddles.

Down ETV: 20 deg upper and lower paddles.

M-IFPC Hardware Delay Times

During Pure Thrust-Vectoring Commands [Engines at full throttle]:

1.04 sec for a 'step function' via pitch TV-control stick **command** from -25 to + 25 degrees **ITV**. The corresponding limiting command rate is therefore: **48 deg/s.**

0.50 sec for a 'step function' via pitch TV-control stick **command** from -20 to + 20 degrees **ITV**. The corresponding limiting command rate is therefore: **80 deg/s.**

0.74 sec for a 'step function' via the pitch TV-control stick **command** from 17 deg up to 24 down in pitch **ETV with extended paddles**. The corresponding limiting command rate is therefore: **55 deg/s.**

0.85 sec for a 'step function' via the yaw TV-control stick **command** from 20 deg left to 20 deg right in yaw **ETV with extended paddles**. The corresponding limiting command rate is therefore: **47 deg/s.**

During Conventional Commands:

0.68 sec for a 'step function' via the conventional elevator, etc. control stick **command** from +12 to -12 deg with the **ETV** flying model. The corresponding limiting command rate is therefore: **35 deg/s.**

0.30 sec for a 'step function' via the conventional elevator, etc. stick **command** from 4 degrees [nose-up] to -7 degrees [nose-down] with the **ITV** flying model. The corresponding limiting command rate is therefore: **36 deg/s.**

Flyer's Delay Times

Figures 35, 38, and 42 provide samples of 'step commands' from minimum to maximum stick-deflections, as effected by our flyer and recorded by the ground computer. These are the PCM transmission signals to the flying model as recorded 43 times per second by the ground computer. Using our calibration charts we have converted the 'Computer numbers' ['Computer N'], to proper deflection angles.

The maximum flyer's rate recorded during flight tests is **230 degrees per second**.

This value reflects our flyer's inherent delay time during these particular flight tests with this particular PCM and flying systems.

Gross vs. Net Agility Rates

Our present flyer delay time during our particular flying conditions may be represented by **230 deg/s**, while that of the F-15 flying model hardware by **48 to 80 deg/s** for ITV, and **47 to 55 deg/s** for ETV, and **41 to 75 deg/s** for the elevator in the ITV and ETV modes, respectively. Hence, the values extracted from the onboard computer represent **gross rates**. Therefore, characteristic **net** rates should have higher values [See Methodology Charts, and below].

Computers Sampling-Feeding Methodologies

Our computer 'metric' methodology is described in the diagrams provided below.

Available Flight-Testing-Software Infrastructure

Elaborate feeding, transfer, calibration, pre-flight and post-flight analyses have been designed and tested during the last two years. The evolving software has gone through numerous modifications and improvement procedures. Unfortunately, the need to modify was caused by numerous failures at the runway and in the laboratory.

Changing from gyros to accelerometers, and back, was relatively a minor cause for change. Yet the change consumed a few months. Hard-landings frequently changed calibration equations and hardware responses and trimming. Despite such 'Technology Limits', our software and hardware form now quite a mature infrastructure, ready for further validation flight tests.

Computers Sampling Rates and Maneuvers

Time Calibration

Ground Computer Sampling Rate of Flyer's Commands: **43** times per second.

Onboard Computer Sampling Rate of Flying Model Responses: **18.466** times per second.

The time in seconds marked on the flight-testing graphs is calculated from computer lines recorded during flight from the 'Ze' of 'start session', namely, for each 100 seconds the onboard computer recorded 1846 lines. Hence the time accuracy level is very high. A backup system is provided by the simultaneous video recording, as explained in Part VI below - 'Monitoring Maneuvers with Video Tape No. 5'.

Reducing Data Noise

The only approximation used in preparing the graphs which provide the flight test data is a simple 5 to 9 points avaraging of the recorded graphs via computer-software smoothing of the recorded noise. High-frequency noise is thus reduced, but low-frequency disturbances are retained, as evidenced in the turbulence noise levels reported in Part VI.

Model Gross Weight [2nd Gen]:

14.2 kg [31.3 lb] with fuel tank full [ETV].

13.4 kg [29.51 lb] with no fuel.

Cold-Jet Static Thrust:

up to **4 kgf** per engine with ITV 2D yaw-pitch nozzles [S.L., 28C].

up to **5 kgf** per engine with ETV paddle-type yaw-pitch [S.L., 28C].

ITV F-15 T/W: **0.56** with fuel tank full at T.O.

0.60 with fuel tank empty at the end of the flight test.

ETV F-15 T/W: **0.70** with fuel tank full at T.O.

0.75 with fuel tank empty at the end of the flight test.

'Technology Limits' associated with these values are discussed in the chapter 'Technology Limits'.

T/W ratio may be significantly increased with **Teledyne 305 Jet Engines providing 56 to 90 lb thrust**. Despite the additional weight, including considerable reinforcement of structure, **T/W > 1.0** is expected, and significantly higher speeds. However, the cost is around $ 27,000 per engine. Including hard landing and crashes, the cost of engines alone should be around $ 110,000. Alternative upgrading are considered now, including tandem ducted fans.

Flyer's TV-Control Methodology

Flight control was initially conducted by two radio operators, one using conventional control surfaces, the other Thrust-Vectoring Control [TVC].

Only one flyer uses now our Combined Conventional-TVC transmitter panel. It is of interest to see the evolution of the flyer's self-training to simultaneously, or separately handle both control methods. Simultaneous conventional and TVC, in actual flight-testing of our PVA and F-15 and F-16 TV models, was not an easy task. It was easy, and safe, only with PVA [1].

In fact, a few of our hard-landings and crashes are attributed to new **TVC demands vs. human factors**, a subject treated below.

Flight Control Modes for Tailless Vectored Fighters

A - Flight Control Modes for Yaw-Pitch Vectored Models

Flight control for our 'mixed' [yaw-pitch-TV+Conv.] F-15 and F-16 models provided the flyer with 3 options:

1 - Conventional control via right-hand-stick: Ailerons by yaw stick-motion and elevators by pitch stick-motion.

2 - Yaw-pitch TV control via left-hand-stick: Yaw TV-moments by yaw stick-motion and Pitch-TV moments by pitch stick-motion.

3 - Maximum Agility by CCTV Control [Combined Conventional & TV] :

- A - Roll via conventional stick control [ailerons].
- B - Max pitch-moment via max pitch-deflection of both sticks.
- C - Max yaw-moment via max yaw-deflection of both sticks. [It generates enhanced roll with extant tail. Roll rate may decline under PST flight conditions].

All 'May-9, 91' flight data provided in the graphs below were generated in response to such [3-modes] commands. But it took a heavy toll. The flyer had to master the 3-modes, especially when rapid responses were required at takeoff and landing [Cf. Video Tapes].

B - The Indispensable Thrust-Vectoring Control: An Example

To save the instrumented model from crashing during emergency landing perpendicular to the runway, Mike Turgemann had to resort to the utilization of the pitch-TV, for the model did not respond to conventional elevator command during the last second, low-speed maneuver needed to raise the nose to avoid vegetation near the runway. And that use of TV saved the vehicle. Under such situations TV is indispensable .

When we added a new flight-control variable; the TV-roll, it became confusing. To start with, there was no free-stick-motion left-over for the new variable [See below].

C - Pilot Loads vs. 'Tailless' Vectored Models

Differential TV-pitch jet deflections generate effective TV-roll with split-type nozzles. It remains effective even in the deep PST domain, where conventional control fails [1]. Tailless configurations, reduced signatures and enhanced PSM maneuvers become feasible with TV-roll, and bona fide maximization of TV-agility is attainable [Cf. 'Theory']. That is precisely the logic behind flying our [elevatorless/rudderless] F-16 model on May 9, 91, and behind our readiness for similar flight tests with tailless F-15, F-16, F-18, C-130, F-117 and F-22 configurations.

The pilot [or flyer] enters, at this point, into totally new and unknown domains. To start with, no free-stick-motion is left-over for the required new jet-deflections differences.

Off-the-shelf multi-mode flyer controls exist. [E.g., Multiplex Prof. 30-30]. By electronically switching software the flyer may switch between flying modes. With 'mixed', tailless, TV fighter models, equipped with Roll-Yaw-Pitch TV-nozzles, the flyer can opt for the following flight-control modes [Not including yet PSM!

Cf.'Theory-Part I']:

1 - **Emergency-Conventional Control [ECC].**

Right-hand stick: Ailerons via yaw stick-motion and 'elevators' by pitch stick-motion, while the left-hand-stick is yaw-deflected for rudder control, and pitch-deflected for engine PLA. (By 'elevators' in tailless designs we mean large-surface-area emergency nozzle-flaps-control-means for engine-out situations [1].)

2 - **Mixed Control [MC]** [Yaw-pitch-TV + conventional flight control].

Right-hand-stick: As before. Left-hand-stick used for yaw-TV and pitch-TV controls. PLA is operated via a separate, third stick/knob. Rudder control is frozen at zero defection angle.

3 - **PVC** [Pure Vectored Control via Roll-Yaw-Pitch TV-nozzles].

All conventional control surfaces are frozen in prefixed angles.

Right-hand-stick: TV-Roll via yaw deflections. TV-Pitch via pitch deflections.

Left-hand-stick: TV-Directional-Yaw via yaw deflections. Engine PLA via pitch deflections. [This, in fact, was the mode used since May 1987 in flying our PVAs. It generated minimal training/performace loads on the flyer. It was also the safest mode for flying unknown, entirely new designs, during proof-of-concept, first-flights-ever.]

4 - **Enhanced PVC & Emergency Modes.**

Maximization of [relatively-low-AoA] TV agility by tailless fighers becomes feasible by combining PVC and conventional control in an entirely new machine-man-system. Other emergency modes are feasible, when a system/mode is damaged, or is malfunctioning.

Note: On May 9, 91, the flyer had to struggle with odd flight-control modes: TV-Roll control via pitch stick-deflections. The results were odd too ! [Cf. the first flight attempt recorded on Video Tape No. 5]. The rudder was frozen. Engine PLA was on a side knob. The TV-Pitch-Yaw-Controls were on L.H.S, while ailerons on the R.H.S, as in conventional mode. Option: Roll-rate may be enhanced by combined [diagonal] stick-deflections.

The Need For [PST-TV] PDT Simulations By New Centrifuges

A linear, or non-linear deduction of 'our' particular flyer and 'our' particular Model Integrated-Flight-Propulsion-Control **[M-IFPC]**-hardware delay times, to estimate the four [net-time-related] components [Cf. 'Theory'-Part-II] of Aircraft-Net-Agility' **[ANA]**, is not acceptable, unless a priori information on expected delay times of future systems and particular pilots in PST-TV SACOMs is at hand. I.e., the aforementioned Dynamic Similarity Factors **[DSF]** should be multiplied by a-yet-unknown, pilot/flyer-dependent function of **[PDT]/[FDT]**, when, for the maximization of PST-TV agility, the pilot, unlike the flyer, is under limiting flight-conditions of [the-yet-unknown] high-'g-PST-TV-onsets'. Centrifuge simulations backed by our flight-testing MGA data and video-tape demonstrations, are therefore required to further advance this rapidly-changing new technology.

Range of Models Constructed and Flight Tested

The following '9-feet' F-15 models have been constructed and flight tested:

- **['Baseline-1']** Unvectored F-15 RPV [with circular, axisymmetric, fixed nozzles]; Fig. 82.
- **['Baseline-2']** Canard-configured, unvectored F-15 RPV [with circular, axisymmetric, fixed nozzles];
- **['Baseline-3']** Pitch-only, vectored F-15 RPV [Paddle-type ETV nozzles]; Fig. 96.
- **['Baseline-4']** Yaw-pitch, vectored F-15 RPV [Paddle-type ETV nozzles] with 100% vertical stabilizers surface area; [The same RPV as 'Baseline 3'].
- **['Baseline-5']** Yaw-pitch, vectored F-15 RPV [Paddle-type ETV nozzles] with 75% vertical stabilizers surface area; [The same RPV as

'Baseline 3']. Fig. 91.

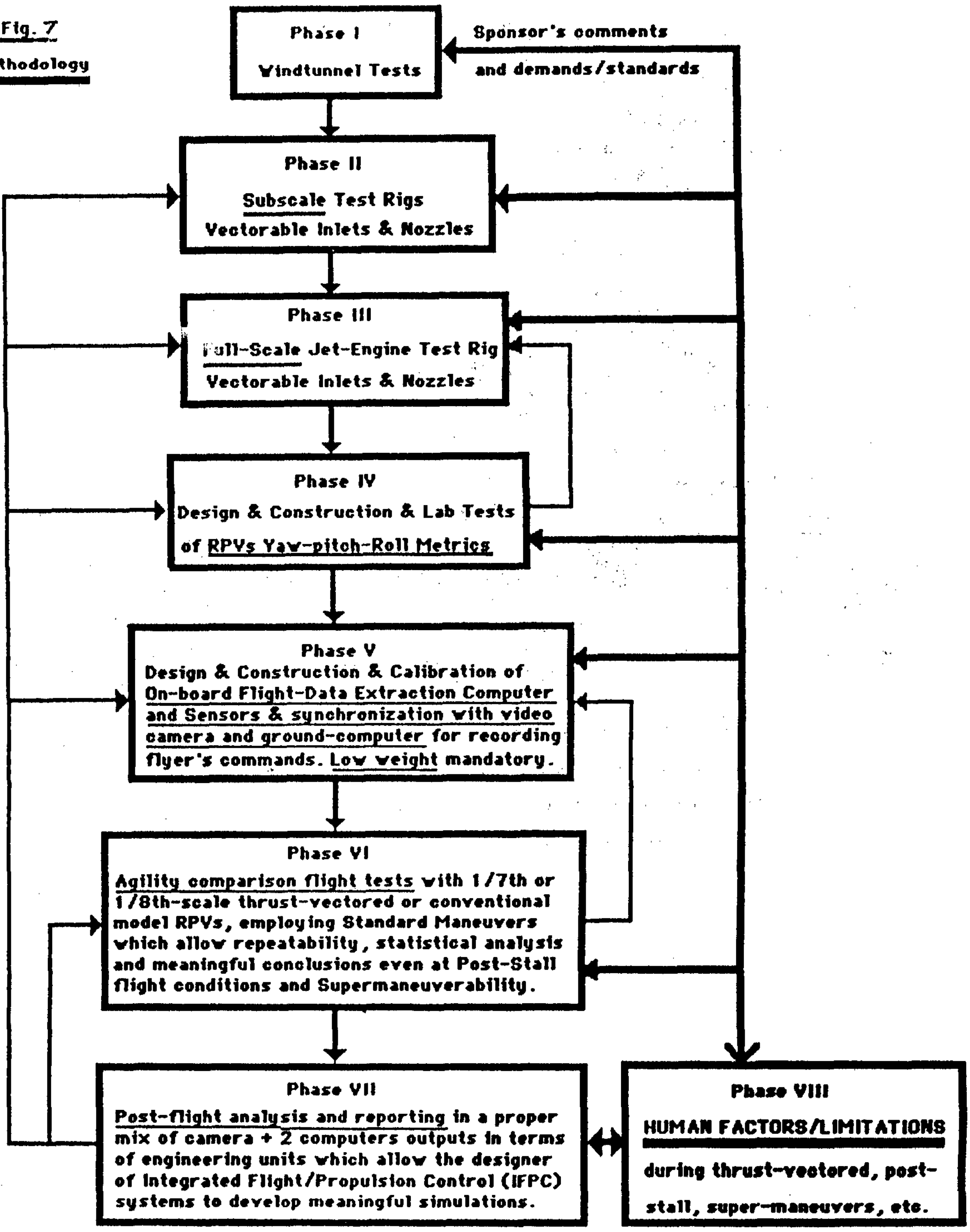
- ['**Baseline-6**'] Pitch-only, vectored F-15 RPV [Flap-type ITV nozzles];
- ['**Baseline-7**'] Yaw-pitch, vectored F-15 RPV [Flap-yaw-vanes-type ITV nozzles]; [The same RPV as 'Baseline 6' in which the yaw vanes are used]. Figs. 83, 84, 94.

For reasons enumerated in 'Technology Limits' [low T/W ratios], the qualitative results include all Baselines while the quantitative ones have to be confined to' Modified-Baselines-1' ['Conventional' flight control via ETV model] and Baselines 3 and 4. Additional, Enhanced ETV-Baselines' were generated during flight tests; i.e., by 'Combined ETV & Conventional Flight Control'.

Methodologically, ETV means considerable quantitative data at hand while ITV means maximization of PST-TV performance.

Fig. 7

Methodology



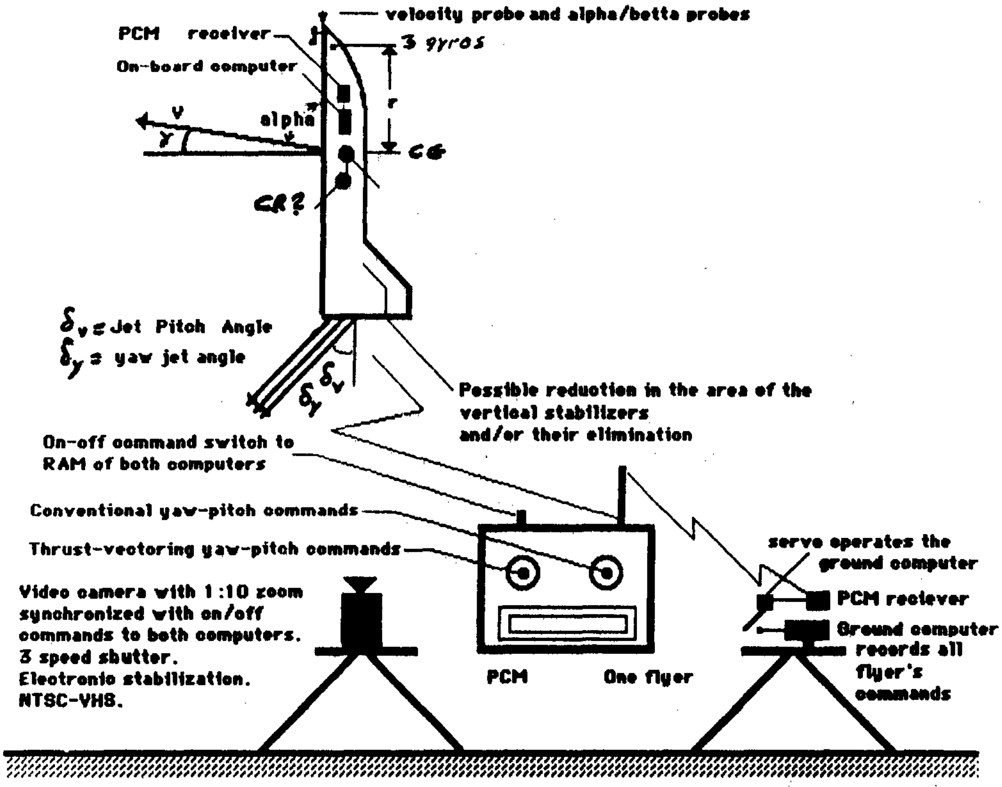


Fig. 8 : Computers/probes/camera/controls synchronization methodology as used during Phase VI of the program. RPV is shown during a Post-Stall maneuver. Conventional-Vectoring PCM R/C system for a single flyer, as shown here, has replaced earlier systems involving 2 flyers and, later, a single flyer with 2 separate R/C control systems. Thrust-vectoring joy-stick operates the yaw-pitch thrust-vectoring nozzle flaps/vanes in the same manner as the conventional joy-stick located on the right hand of the new, modified, control system .

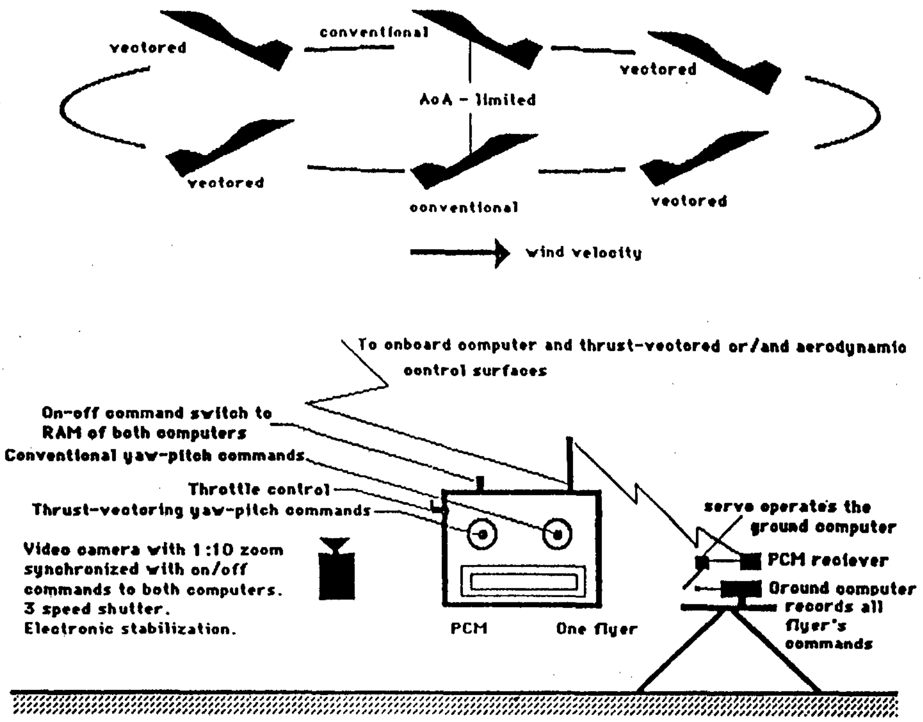


Fig. 9 : Pitch Rate & Turn Rate Tests at various speeds. Alternatively the flight tests may be conducted with only thrust-vectored control followed by only aerodynamic control and finally by both controls for maximum performance. However, conventional control may fail beyond a given AoA. Hence the comparison may be limited to pitch-rate tests up to that AoA.

Repeatability of the flight tests under similar conditions is required for statistical analysis and the generation of meaningful engineering results and conclusions.

Provided the video-camara is almost perpendicular to the flight path, its recordings [at high-shutter speeds] may be employed to verify pitch rate results obtainable from the computer.

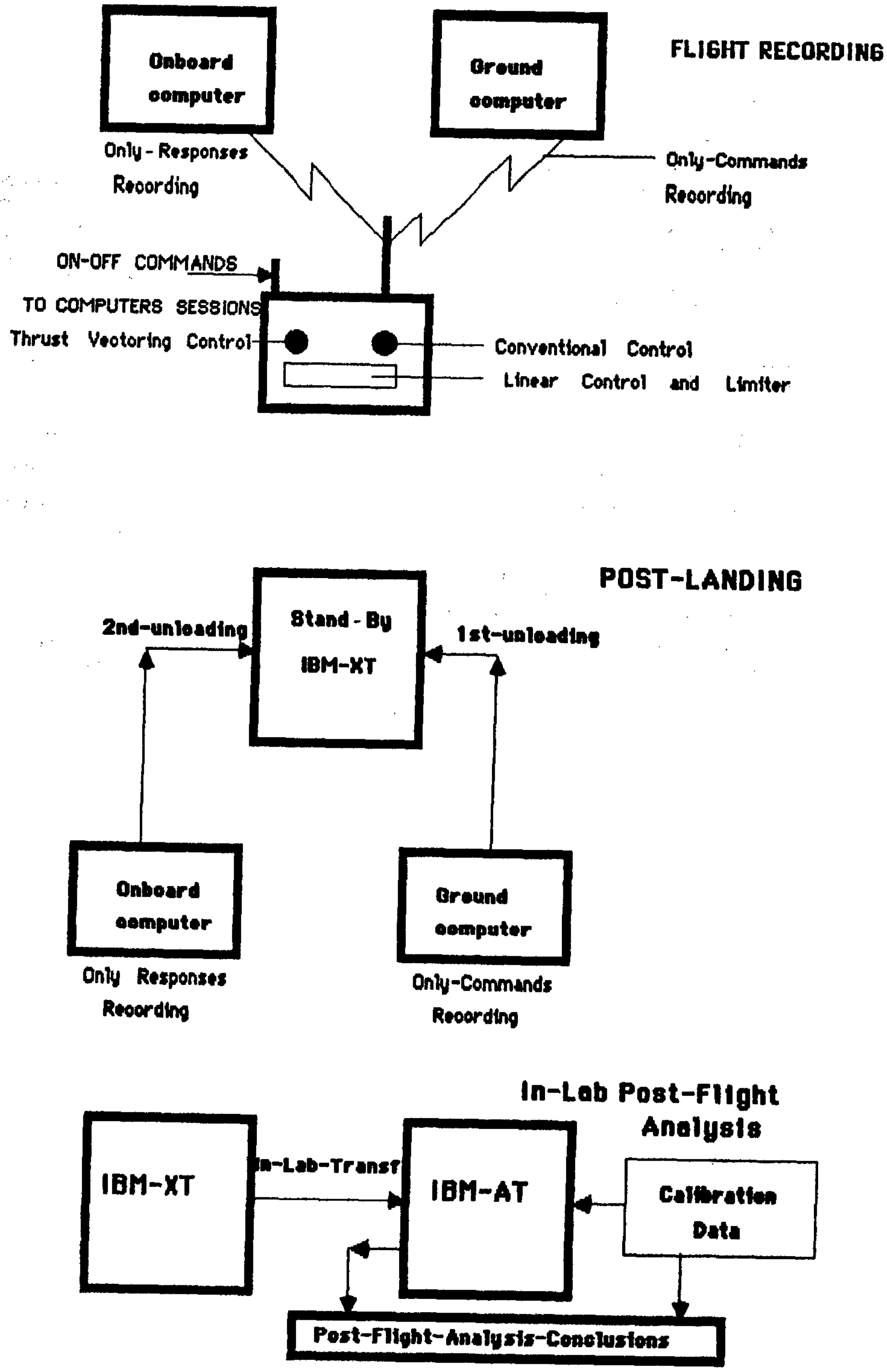
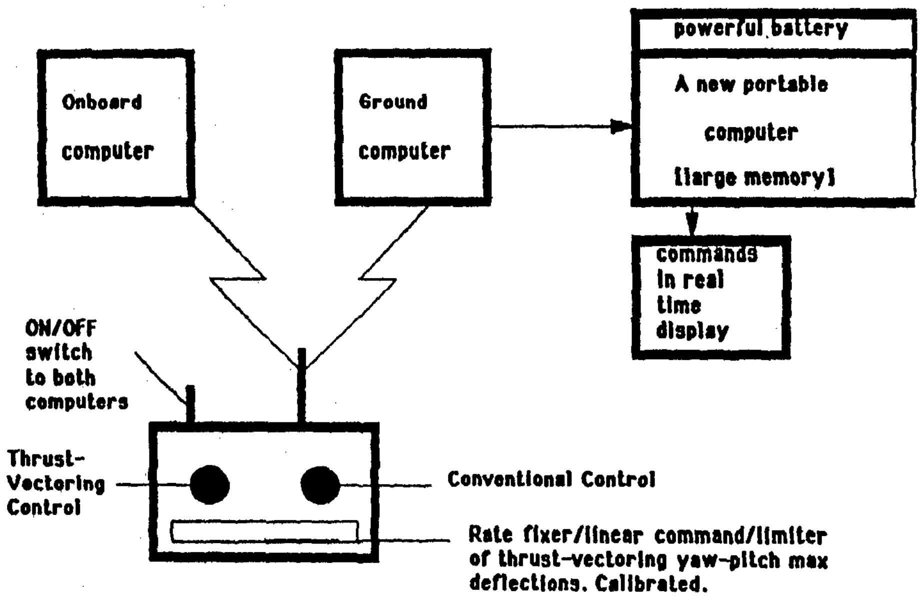

Onboard computer
Ground computer
FLIGHT RECORDING
Only - Responses Recording
Only-Commands Recording
ON-OFF COMMANDS TO COMPUTERS SESSIONS
Thrust Vectoring Control
Conventional Control
Linear Control and Limiter
POST-LANDING
2nd-unloading
Stand - By IBM-XT
1st-unloading
Onboard computer
Ground computer
Only Responses Recording
Only-Commands Recording
In-Lab Post-Flight Analysis
IBM-XT
In-Lab-Transf
IBM-AT
Calibration Data
Post-Flight-Analysis-Conclusions

Fig. 10

FLIGHT RECORDING/ANALYSIS



IN-FLIGHT CONNECTIONS

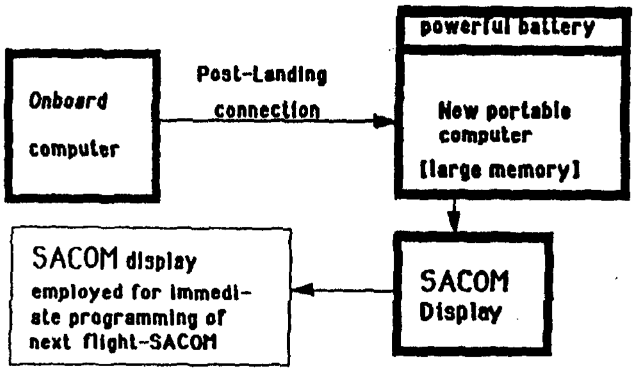
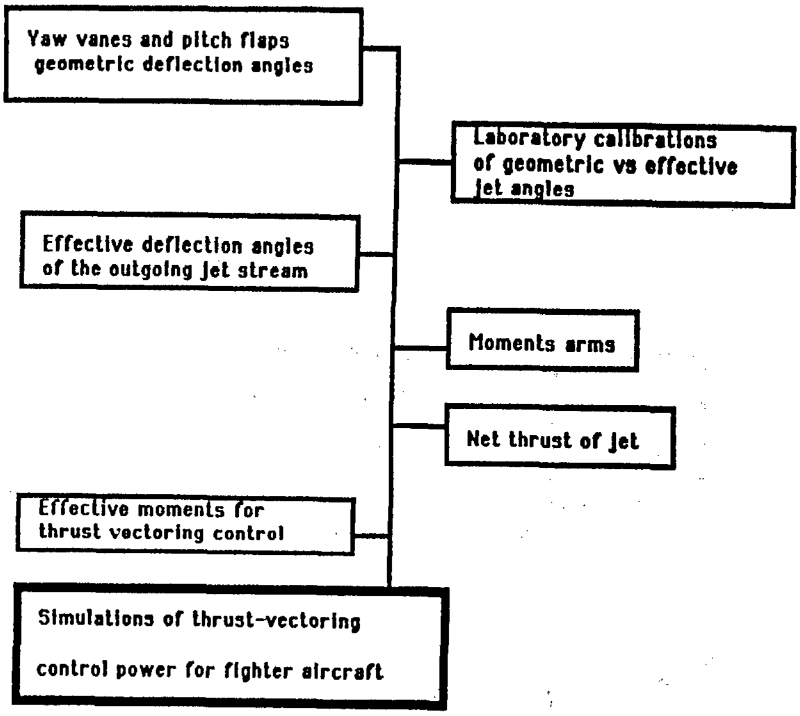


Fig. 11

POST-LANDING ANALYSIS

&

PROGRAMING OF NEXT SACOM



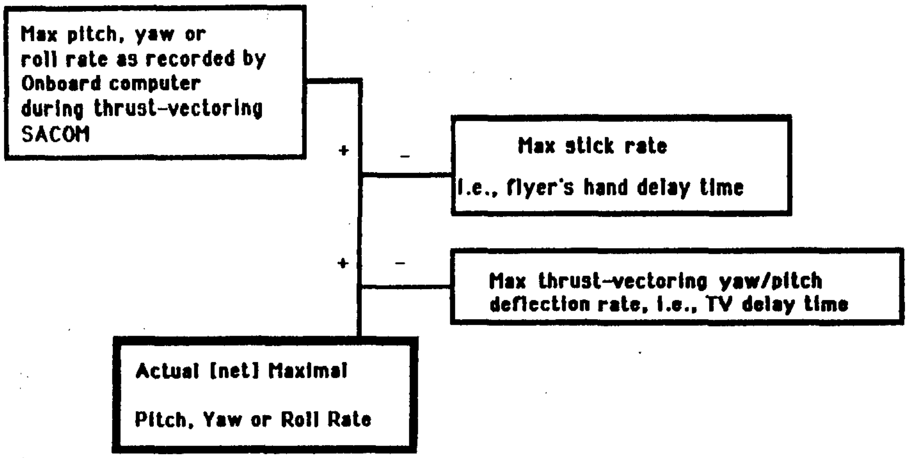
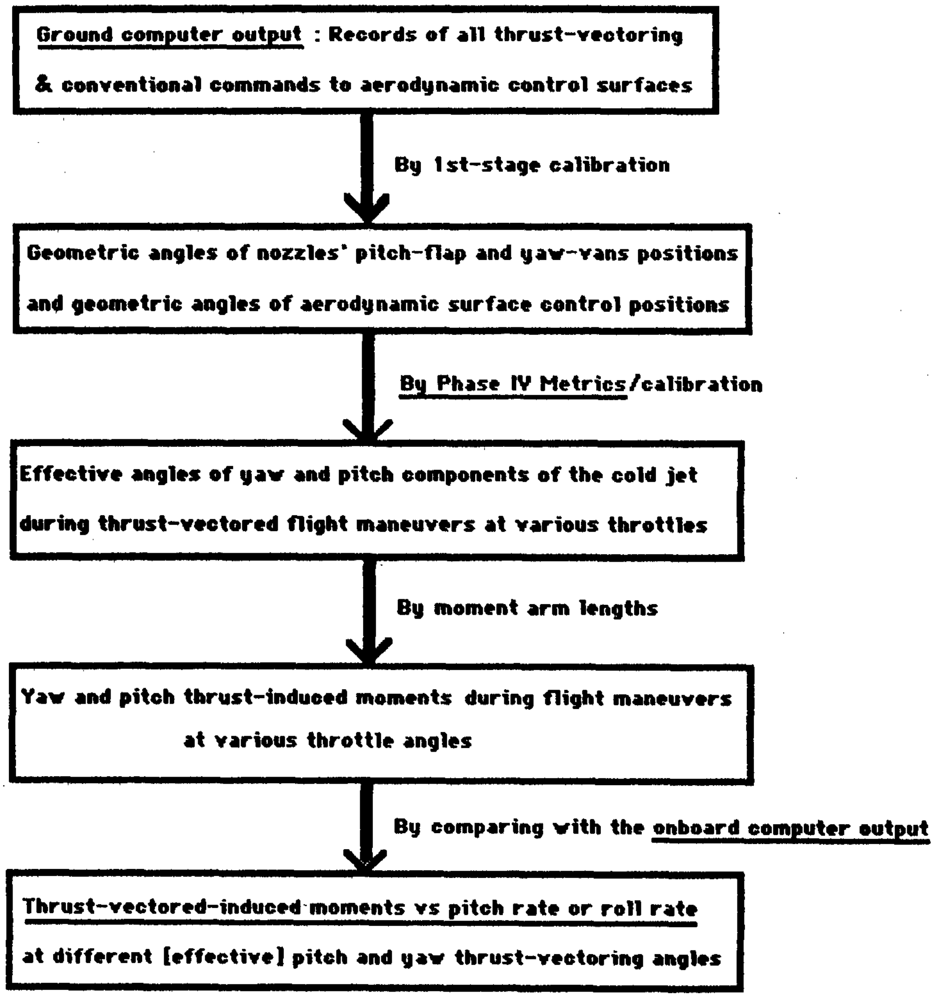
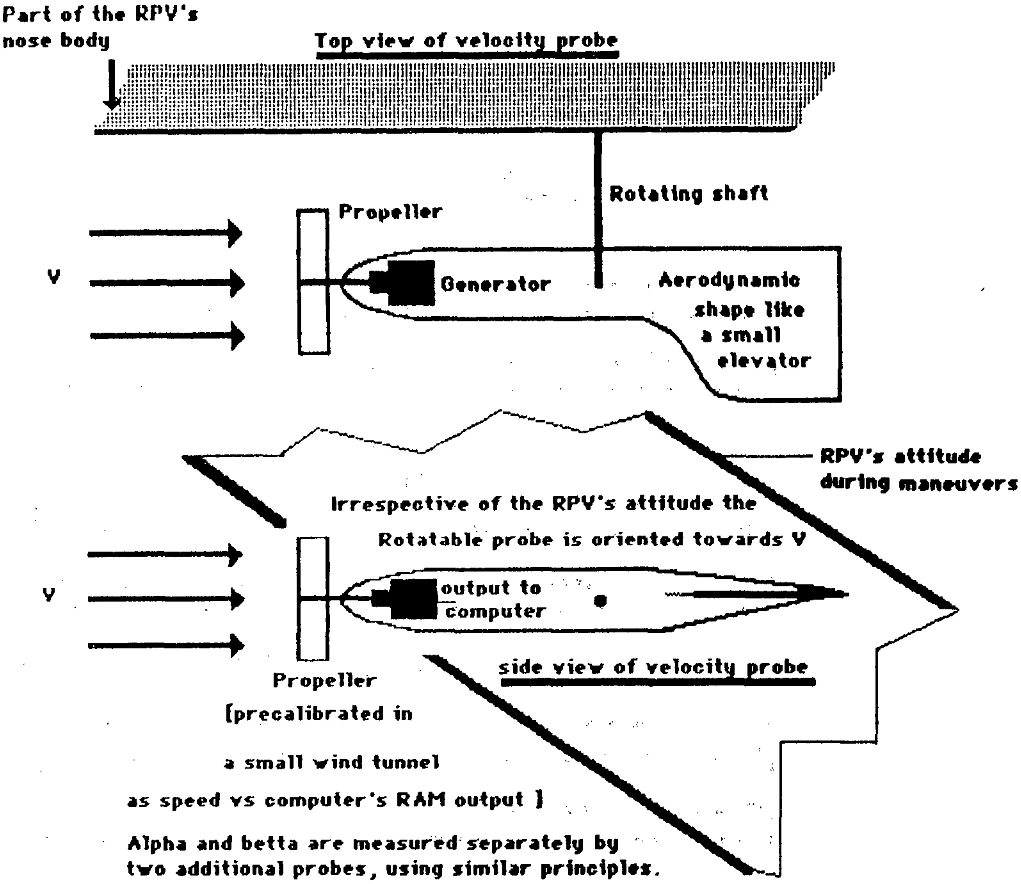


Fig. 12

Ideally the command and the yaw-pitch deflection rates should be "step functions", thereby the yaw/pitch/roll responses of the flying models are equal to the net rates. Actually there are the delay times marked in the figure. These are measured and should be substracted from the onboard computer responses.

Fig. 13: Calibration Chart





[precalibrated in

a small wind tunnel

as speed vs computer's RAM output]

Alpha and betta are measured separately by two additional probes, using similar principles. [However, their shafts are each connected to a precalibrated, rotatable potentiometer. The potentiometer output is fed to the computer's RAM]

Fig. 14.

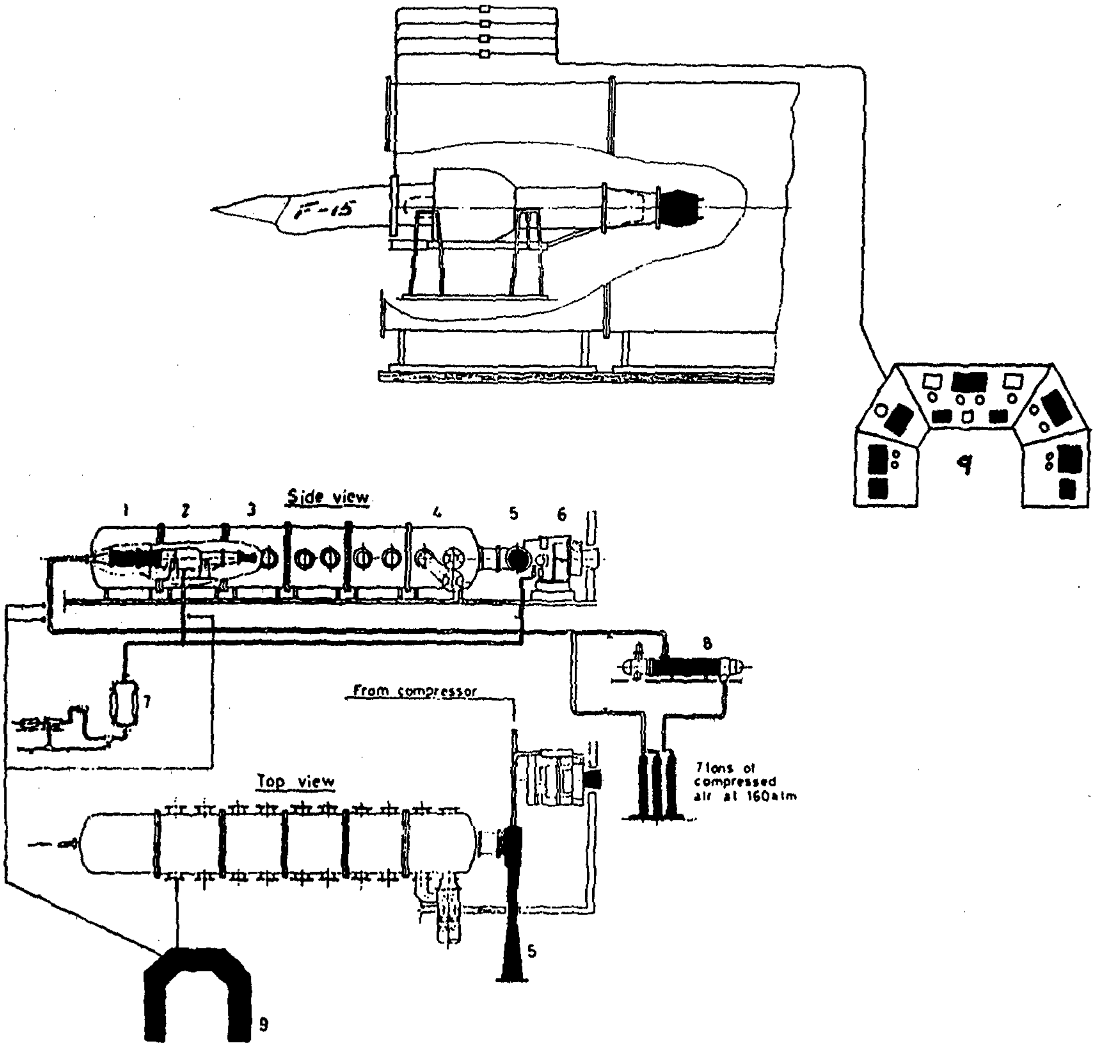


Fig.15
The fullscale (altitude) engine test facility.

1,2,3, - Engine sector 4,5,6, -Evacuation facilities. 7-fuel-supply systems. 8-"7-ton" S.S. heat exchanger for high-pressure/temperatures operating conditions, or for low-temperatures simulations.

9 - Control Room NO.5.

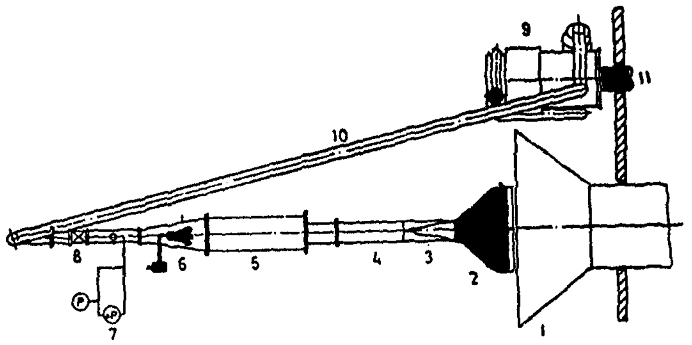


Fig.16
The subscale vectoring nozzle test rig.

1-Exhaust system. 2-Roll-yaw-pitch thrust-vectoring nozzle.

3-4: Transition/cooling section.

5-"T-56 combustor". 6-Fuel injector. 7-Flow monitoring.

8-Flow-control valve. 9-Gas turbine.

10-connecting pipe. 11-Gas turbine exhaust.

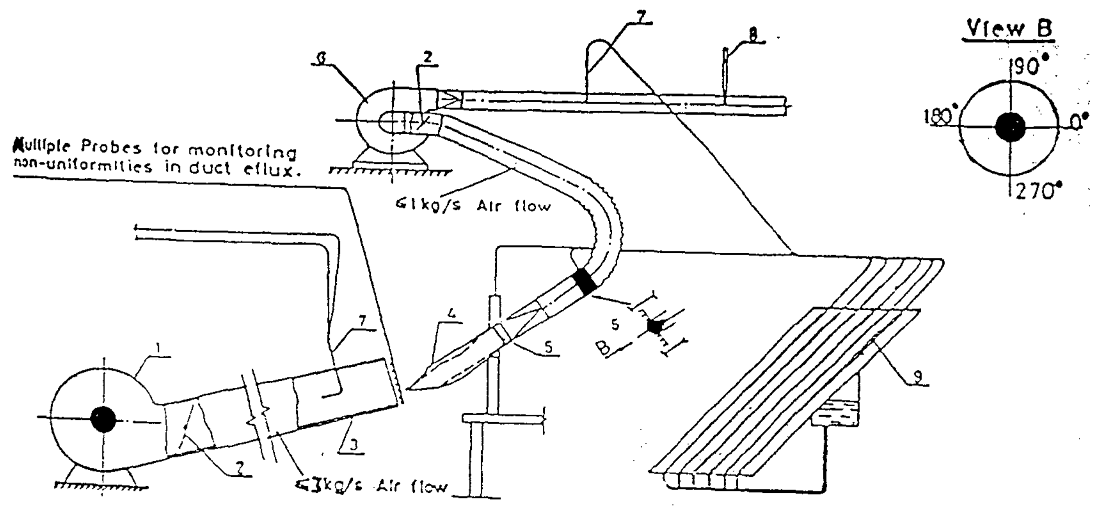


Fig. 17 : TIIT/JPL -Sub-scale test-rig-setup for F-15 inlet.

(View B is the most critical section). cf. Figs. 97, 98. Test Results: p.88-92.

1 - Blowing Fan; 2 - "Free-stream-velocity-control".
3 - Duct - size is larger than F-15 Inlet-size.
4 - Vectorable lip provides "Distortion-Free" Inlet. p. 91, 92.
5 - AoA control mechanism
6 - Suction Fan Simulates Engine Suction
7 - Blowing & Suction rates monitors
8 - Air Temp. monitoring
9 - Multiple-tubes monometer, cf.p. 88-92

PURE VECTORED*

Model 1, Roll-Yaw-Pitch TV with aerodynamic control and no canards. Single engine. Transformed into No. 2

Model 2 is in fact No. 1 with a variable canard. It was crashed on its 1st flight, May 1987. Its nozzle is in the lab.

Model No. 3 is the first PVA. It has no elevators, flaps, or rudders. It has vertical stabilizers & variable canard. It provided the best agility & STOL characteristics before it was damaged by a taxi driver. Single engine. May 87.++

Model 4 had 3 engines. After short flight crashed by radio interference. Was very fast. June 87. Had a VTOL option.

Model 5 had VTOL option with a single engine. Was damaged.

THRUST-VECTORED F-15 & F-16*

Model 7* is a Yaw-Pitch TV-F-15 RPV which was flight tested first as non-vectored model [w & w/o canards] and then w 2D nozzles w/o canards. May-Aug. 89. Aug 90 was tested w reduced vert. stabl. and 4 TV pedals. Was damaged & repaired a few times.

Model 9 was a Yaw-Pitch TV-F-16* RPV. Was tested first w axi nozzle and then w TV nozzles. Was damaged during flight tests in 1989.

Models 11, 15, 17 and 19 are 2nd-generation F-15 and F-16 models equipped w onboard computer. The computerized F-16 crashed, Dec. 7, 89, and the computerized F-15 in June 1990. Half of the crashed F-15 has been incorporated into '3rd-genr.' computerized F-15.**

Model 21 is the 3rd-gen. F-15 w the 25%-Cut Vertic. Stab. ITV* ETV*

Model 23 is F-16 w Roll-Yaw-Pitch TV nozzle. Flight Tested, May 91 +

Fig. 18

* cf. Figs. 77-102, p.62

** Was flight tested between Oct. 19, 90 to May 9, 91, with ETV cf. p.106-153. ETV see p. 172. Was Re-named "2.5 Gen." - F-15.

\+ Was flight tested on May 9, 91, "Elevatorless/Rudderless ("Tailless") Configuration. See Video Tape No.6.

++ cf. p.163-165. For definition of PVA see p. 183

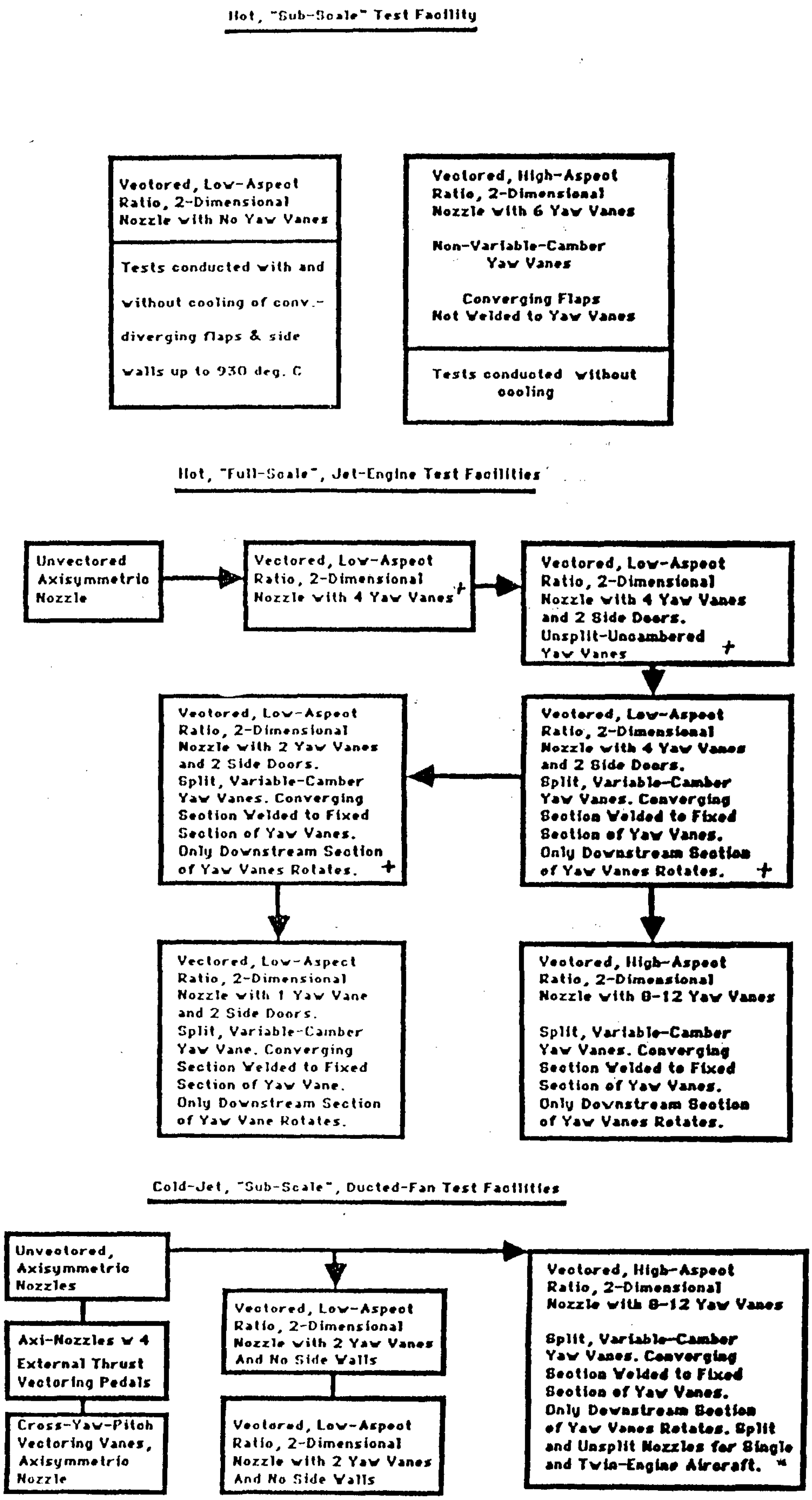


Fig. 19. *cf. Figs. 87-89, 102

+ PWA Project at JPL, Dec. 15, 90-Dec. 31, 91

Moment of Inertia Test Definition cf. p. 52.

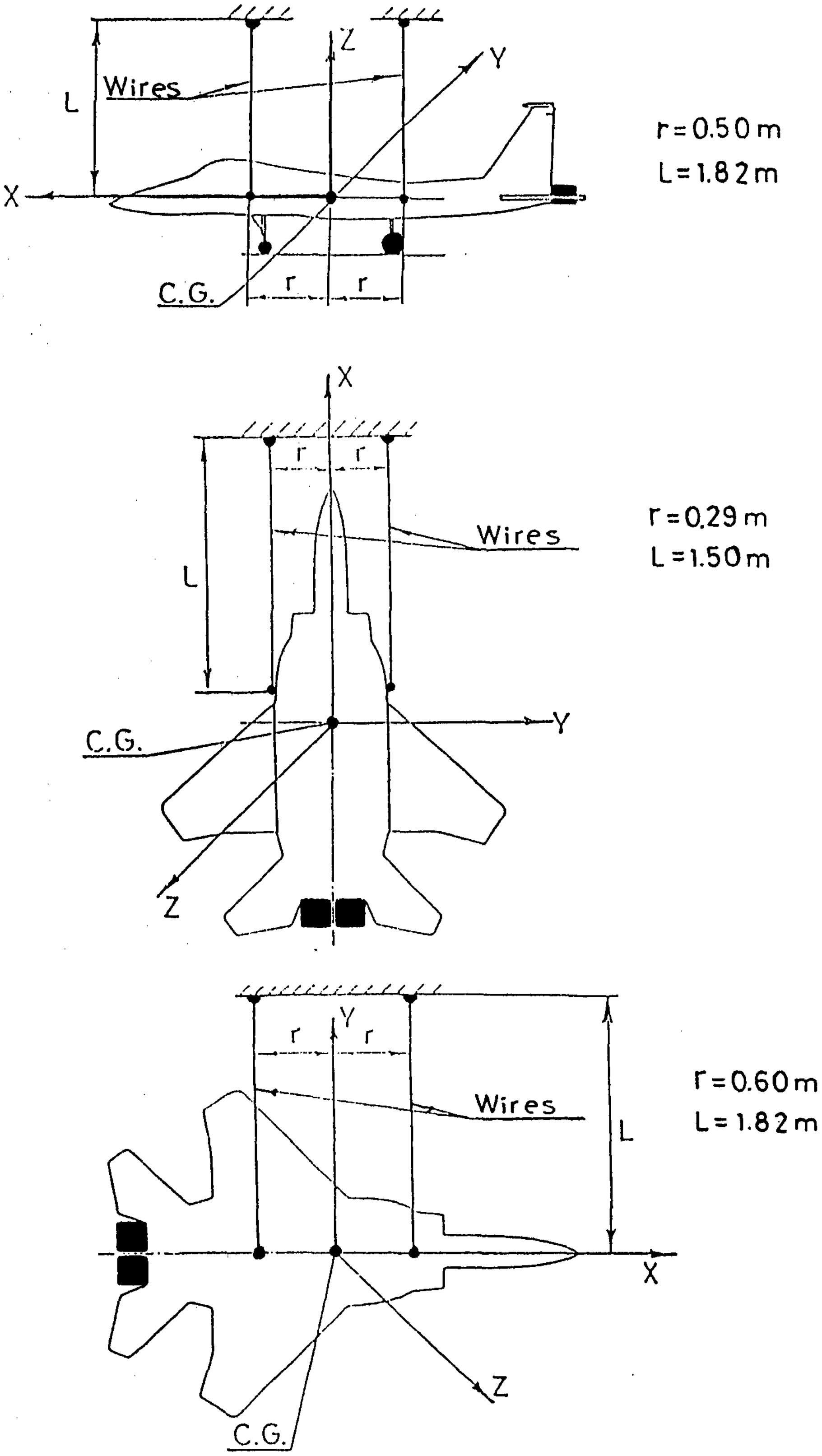


Fig. 20

Gyro Calibration
Date:April 21, 1991

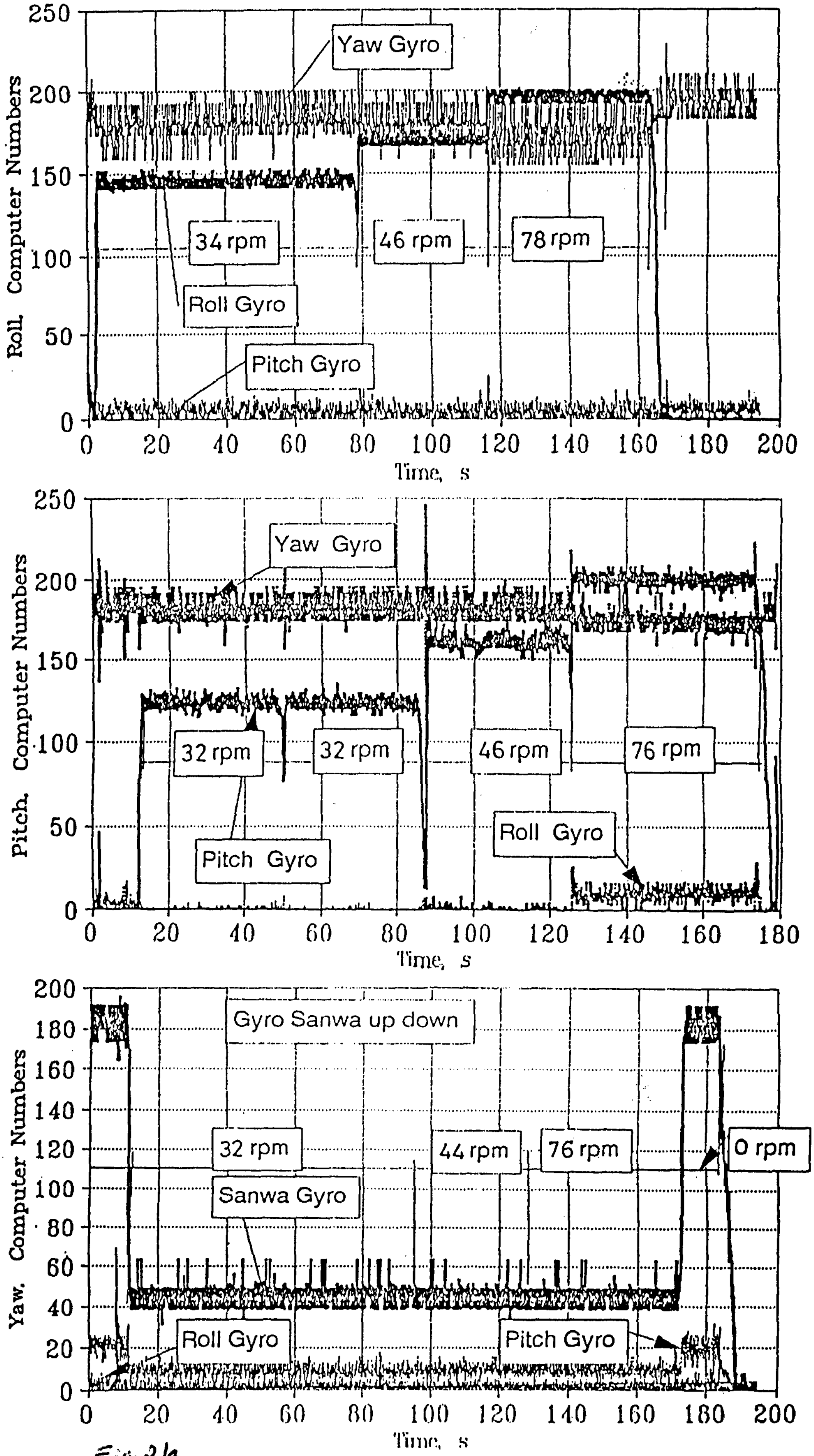


Fig. 2a

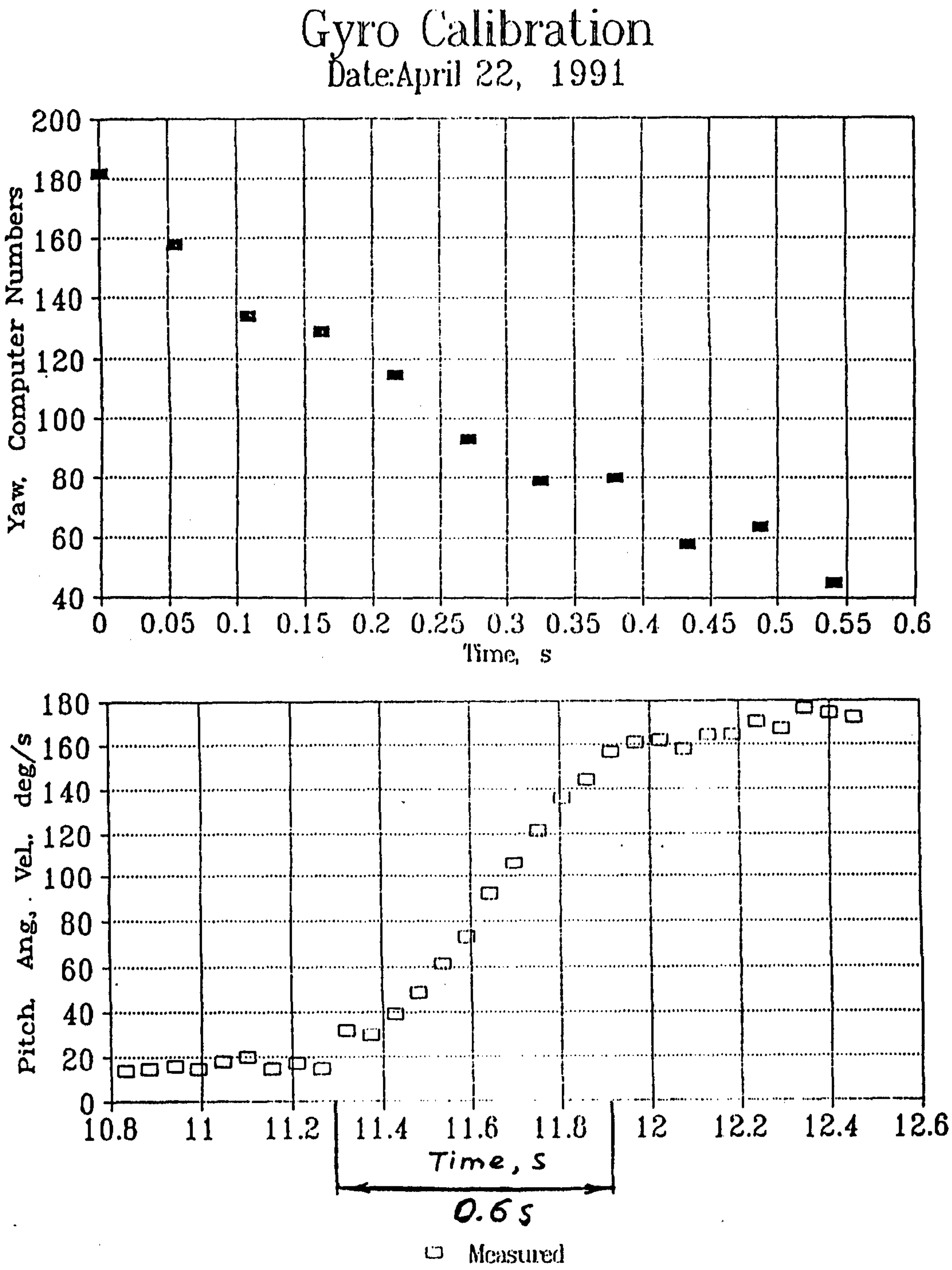

Gyro Calibration
Date:April 22, 1991
Yaw, Computer Numbers
200
180
160
140
120
100
80
60
40
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
Time, s
Pitch. Ang. Vel., deg/s
180
160
140
120
100
80
60
40
20
0
10.8
11
11.2
11.4
11.6
11.8
12
12.2
12.4
12.6
Time, s
0.6 s
Measured

Fig. 21b

Orientation-Calibration Verification of Gyros Readings

Three gyros have been installed on board of the dynamically-scaled flying models: A highly-sensitive, narrow-range Sanwa gyro for measuring the yaw rate, and two large-range Multiplex gyros, one for pitch rate and one for roll rate. All three were proprely installed in the nose section with Ni-Cad batteries and the onboard computer.

Two tasks were performed to verify proper gyros' orientations and to establish verifiable gyros calibration, using a turn table on which the gyros, batteries and computer have been mounted in three different axes, and the radio command employed to activate them for different computer-recording sessions. Except for a yaw-rate gyro calibration [see below], the 3 gyros were always permanently linked together with their proper axes perpendicular to each other. For repeatable, separate yaw, pitch and roll orientation-calibration tests the gyro-package was properly positioned on the turn table in three different space orientations.

The turn table was then operated at 3 different angular velocities. The test results are shown in Fig. 21a for 32-34, 44-46 and 76-78 RPM measurements. RPM for each test was calibrated by an accurate watch stopper.

Orientation verification is provided by the fact that only Roll, or only Pitch, or only Yaw rates were recorded for each test, and by the fact that the tests are exactly repeatable.

The calibrations of the pitch and roll rates gyros are provided by Figs. 21a, 21c and 22.

Calibration of the highly-sensitive Yaw rate gyro presented a problem: There was no RPM to test it. To overcome this problem we had installed on the turn table the Multiplex 'Pitch' gyro with its axis parallel to the [Sanwa] Yaw gyro and followed the transient response of both during 0.6 sec. Then using the calibrated data for the pitch-rate gyro we calibrated the yaw-rate gyro [Fig. 21b]. [The upper drawing in Fig. 21b shows its 'COMPUTER-NUMBER" response during 0.6 sec. The time coordinate is computer-line-calibrated time.] The pitch gyro was then re-installed in the package. The package was re-tested and the entire package installed on the F-15 with no modification.

Velocity Probe Calibration was performed by means of our small subsonic wind-duct [Fig. 17]. Alpha and betta probes are connected to rotating potentiometers. Their calibration was conducted by measuring deflection angles vs comp. No.

F-15 Model Test Calibration

April 15.04.91

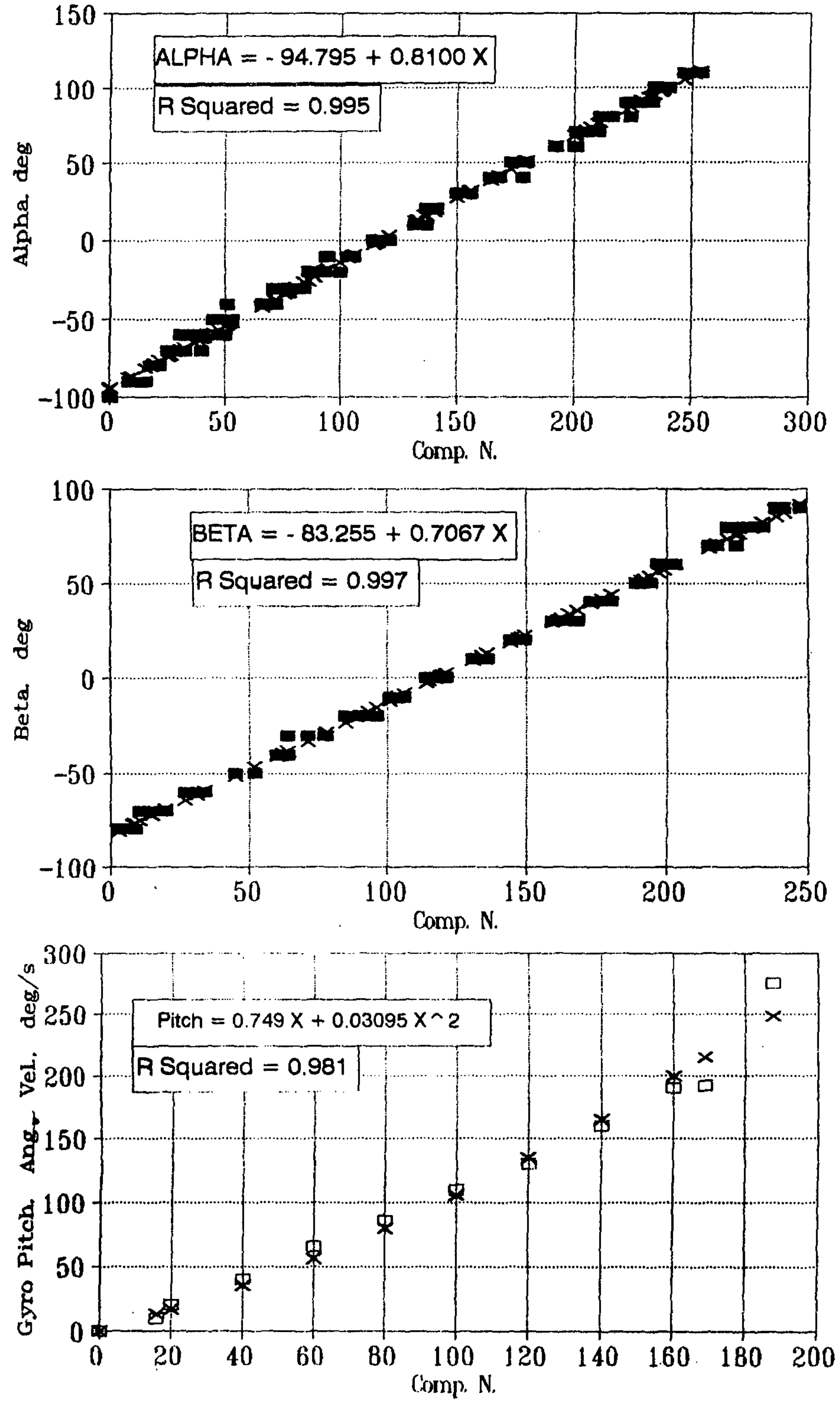


Fig. 21c.

F-15 Model Test Calibration

April, 21.04.91

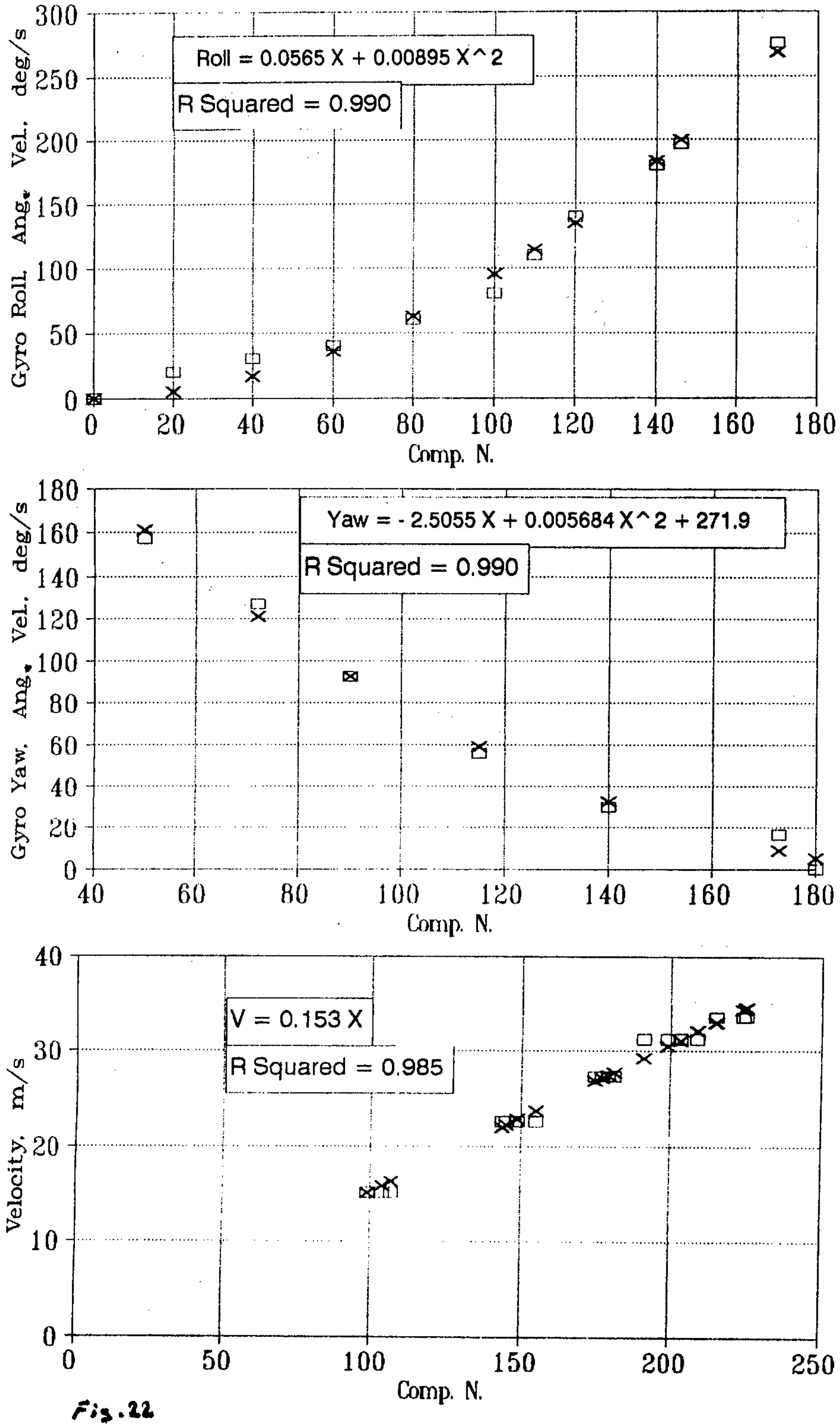


Fig. 22

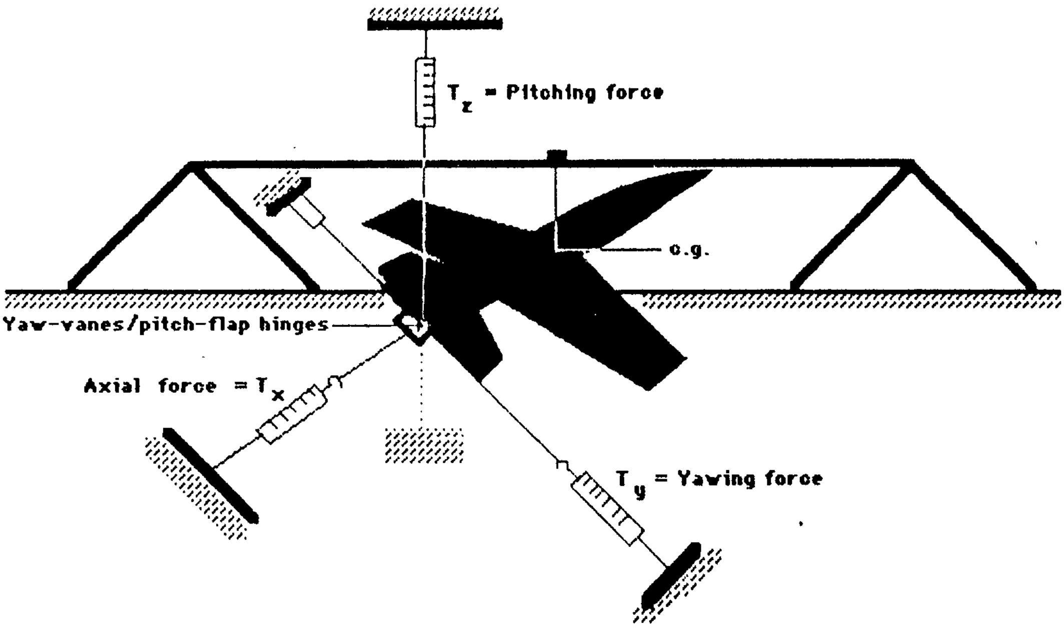


Fig. 23: RPV powerplant metrics are measured during Phase IV by this simple test rig. The most important results are those which compare GEOMETRIC with EFFECTIVE YAW and PITCH angles during thrust - vectoring . Each set of test results is obtained at a different throttle setting. Simultaneous yaw-pitch thrust vectoring is also evaluated experimentally by this test rig. The designer of IFPC systems needs such data whenever he employs the flight test data, i.e., when, say, a command of 9 degrees yaw is made, the actual jet-yaw-angle may be higher or lower, depending on the particular thrust-vectoring nozzle used during the agility-comparing maneuvers.

Hence, what must be done during the last phase of this project is to re-express the commands recorded by the ground computer [the geometric angles of the yaw-vanes and pitch-flaps] in terms of the EFFECTIVE yaw-pitch angles of the jet(s). However, prior to that we must precalibrate the zero setting of the joy-stick with zero settings of the yaw and pitch geometric angles. It is only by going first through these stages that one can evaluate such parameters as the degree of coupling between yaw and roll for various vertical stabilizers, various speeds, various throttle settings, various maneuvers, etc. All initial maneuvers will be performed at constant FULL THROTTLE.

Laboratory & Flight Tests

Part III

Wind-Tunnel Test Results For Tailless F-15 Configuration

Wind tunnel test results for tailless F-15 models are provided below. Data for tailless F-16 and PVA configurations have also been documented in JPL files.

Please note that to transform the F-15 model into a tailless configuration we had to replace the elevators by equal-projection area roll-yaw-pitch TV-nozzles.

To pass engine gases for PST-TV control of the tailless model, the nozzles have been designed with a greater thickness than that of current elevator airfoils. While we trim these TV-nozzles 'leading edges' by aerodynamic 'covers' for low subsonic and supersonic drag, the resulting tail-drag is higher for the tailless design in comparison with the conventional tail design [Cf. Fig. 24].

Consequently, drag reduction with tailless designs is feasible only with wing-integrated roll-yaw-pitch TV-nozzles, e.g., **as might be expected with a tailless vectored version of the subsonic F-117**.

Note also the change in stability for the Roll-Yaw-Pitch TV tailless F-15 model as indicated by the moment coefficient dependence on the lift coefficient [Fig. 25].

Scaling and Instabilities

Directional stability in FuScAFT is different than that indicated by SWTT data. This dictates redesign of the vertical tail and caution in predicting instabilities. An improved understanding of stabilities is extractable by scaling from our 1/32 SWTT-scale to the 1/7-MoFT-scale of the F-15 model. We therefore flight-tested semi-tailless and tailless F-15, F-16 and PVAs configurations. Then we flight-tested an F-15 with 25%-cut vertical tail. The reduced stability was observed during TV-pitch reversals [Cf. Video Tape No. 6]. The next phase is to flight-test tailless designs of PVA, F-15, F-16, F-18, C-130, F-117 and F-22.

Disagreement between SWTT and FuScAFT for aileron power is generally expected, due largely to the effects of aeroelasticity. For fully reversible control systems, slight differences in cable stretch and wing flexibility may be important. Hence, we assume that our SACOM roll-reversals with conventional aileron commands vs conventional + Roll vs yaw-TV commands, may not well-represent expected FuScAFT responses, even when our DSF and Flyer/IFPC delay times are taken into account. [Cf. DSF, Reynolds and Froude numbers, etc. in 'Methodology'.]

Additional Test Results:

Fig. 24 demonstrates somewhat higher lift coefficient [for AoA > 30 degrees] for the tailless configuration in comparison with conventional and semi-tailless configurations.

Cost Sharing

These tests constitute supplemental, cost-sharing work for this AFOSR-89-0445 Grant. Additional cost-sharing was provided by unpayed work of students and other participants.

TERMINOLOGY

ROLL-YAW-PITCH TV TAILESS F-15 MODEL: 1/32-scaled F-15 model in which the elevators have been replaced by equal projection area, roll-yaw-pitch thrust-vectoring nozzle of high - aspect ratio type described in our 1st-year Report [April 24, 1990], and in which the two vertical stabilizers have been removed. [A TV model w 25%-cut vert. stabil. was flight-tested in Aug. 90]

PARTIALLY MODIFIED TV F-15 MODEL: Similar to the previous model but with the vertical stabilizers intact.

CONVENTIONAL F-15 MODEL: 1/32-scaled F-15 model .

V=30 : Subsonic windtunnel air-speed equals 30 m/sec.

AL=-20÷30 : Angle-of-attack [Alpha] variations from -20 to +30 degrees. However, for the Roll-Yaw-Pitch TV Tailess F-15 model alpha varied from -25 to + 40 degrees.

Xref=36cm: The reference distance for CM of the PARTIALLY-MODIFIED and the CONVENTIONAL Models. For the ROLL-YAW-PITCH model it was 37.8cm [= 35% of the average chord].

$Xac = -\partial Cm/\partial C_L \cdot \bar{C} + Xref = 14.74cm$ for the TV TAILESS model.

CM : The [body] moment coefficient.

C_L : The lift coefficient.

CD : The drag coefficient.

BETA : The slip angle variation [from -45 to 40 degrees] at constant alpha = 5 degrees. [Tests made only with the ROLL-YAW-PITCH TV TAILESS F-15 MODEL.]

CY(BODY): The side force during "BETA" tests.

CR(BODY): The roll moment during "BETA" tests.

CN(BODY): The yaw moment during "BETA" tests.

CNOR: The slope of the lift curve.

CM(BODY): The pitch moment.

Bottom model mount was employed for obtaining aft-end effects of the Roll-Yaw-Pitch TV nozzle

REDUCED TAIL F-15 MODEL VS CONVENTIONAL F-15

B. GAL-OR, AFOSR-89-0445, May-June 1990, JPL

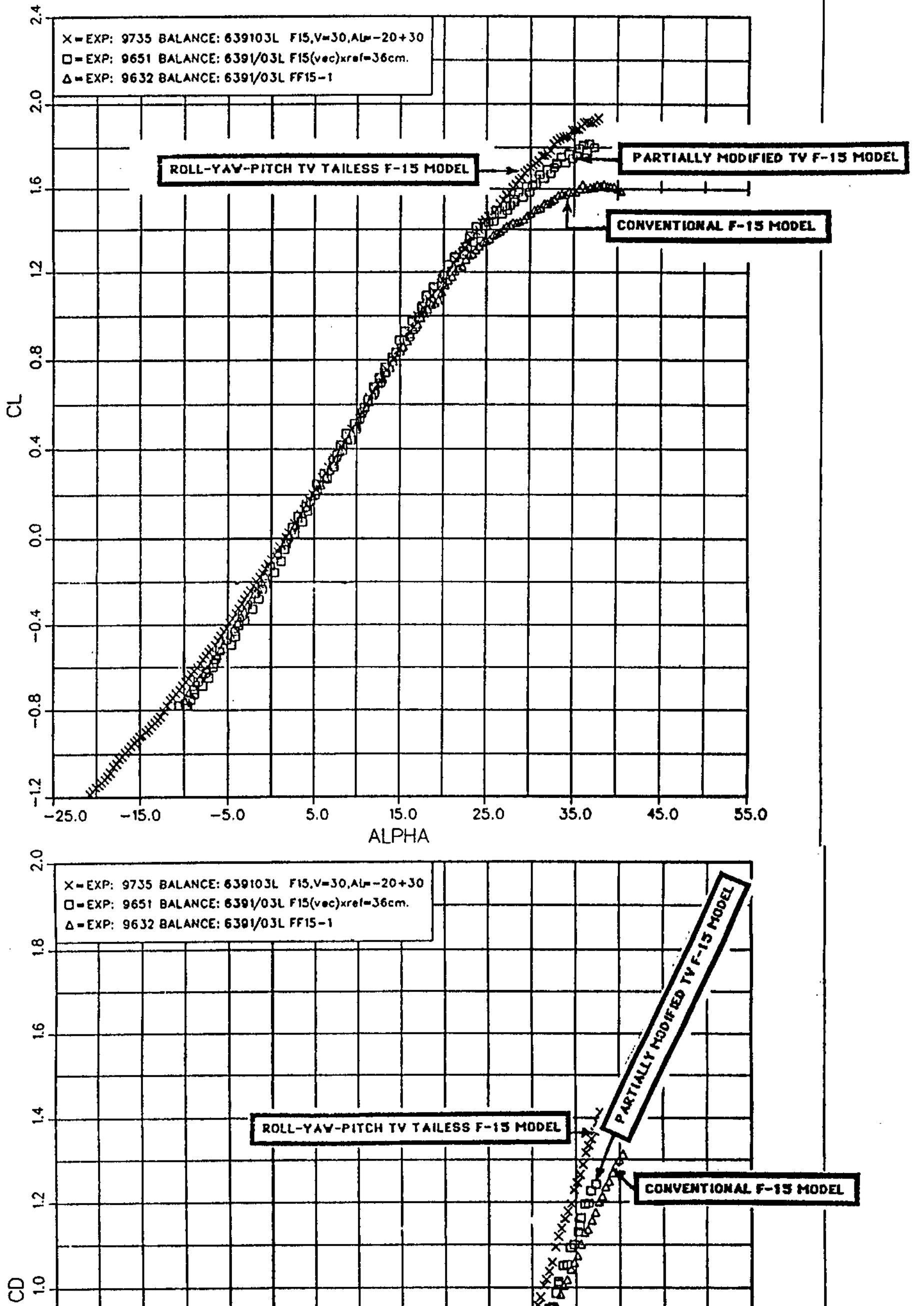
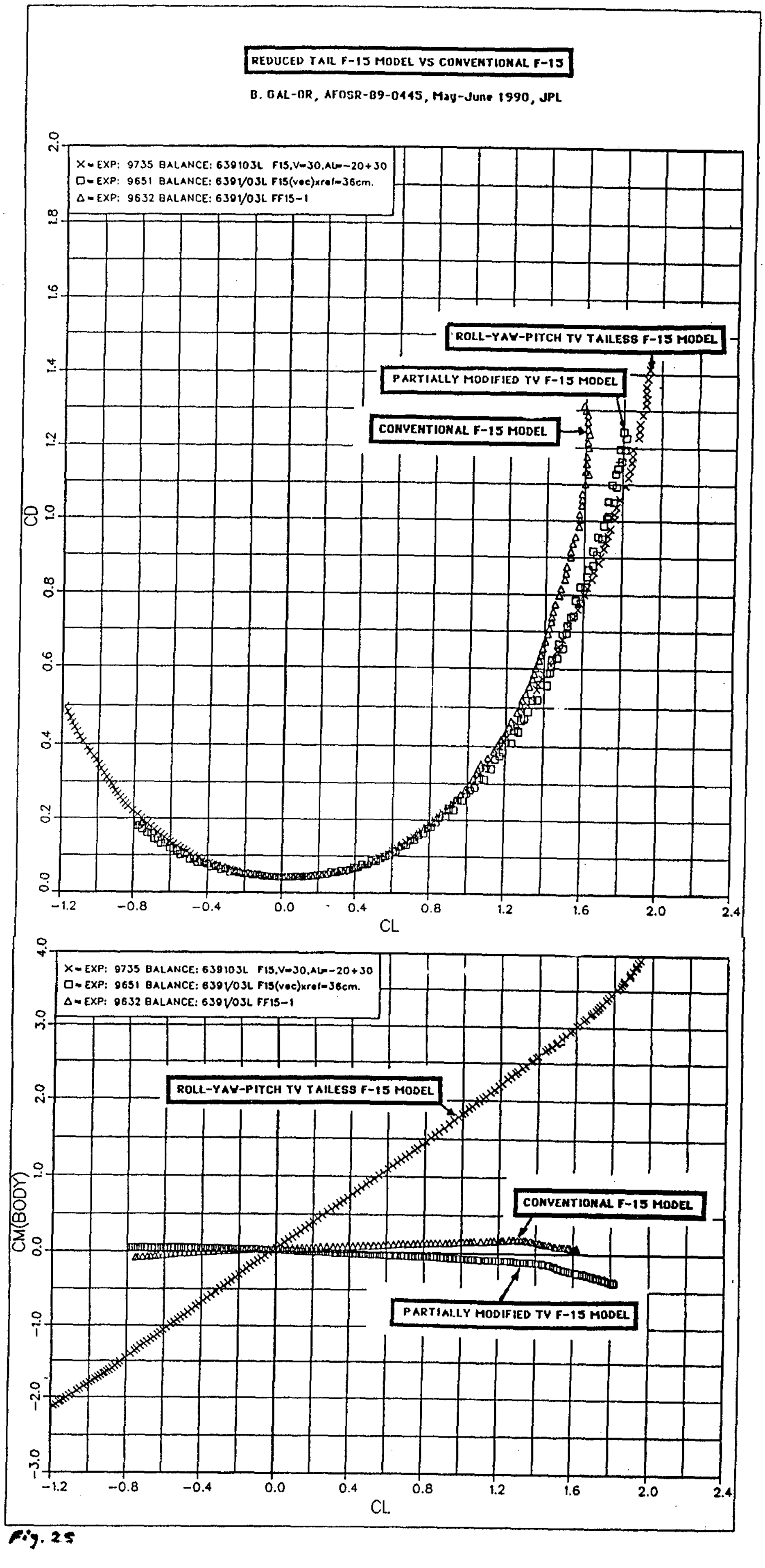


Fig. 24



REDUCED TAIL F-15 MODEL VS CONVENTIONAL F-15

B. GAL-OR, AFOSR-89-0445, May-June 1990, JPL

Fig. 25

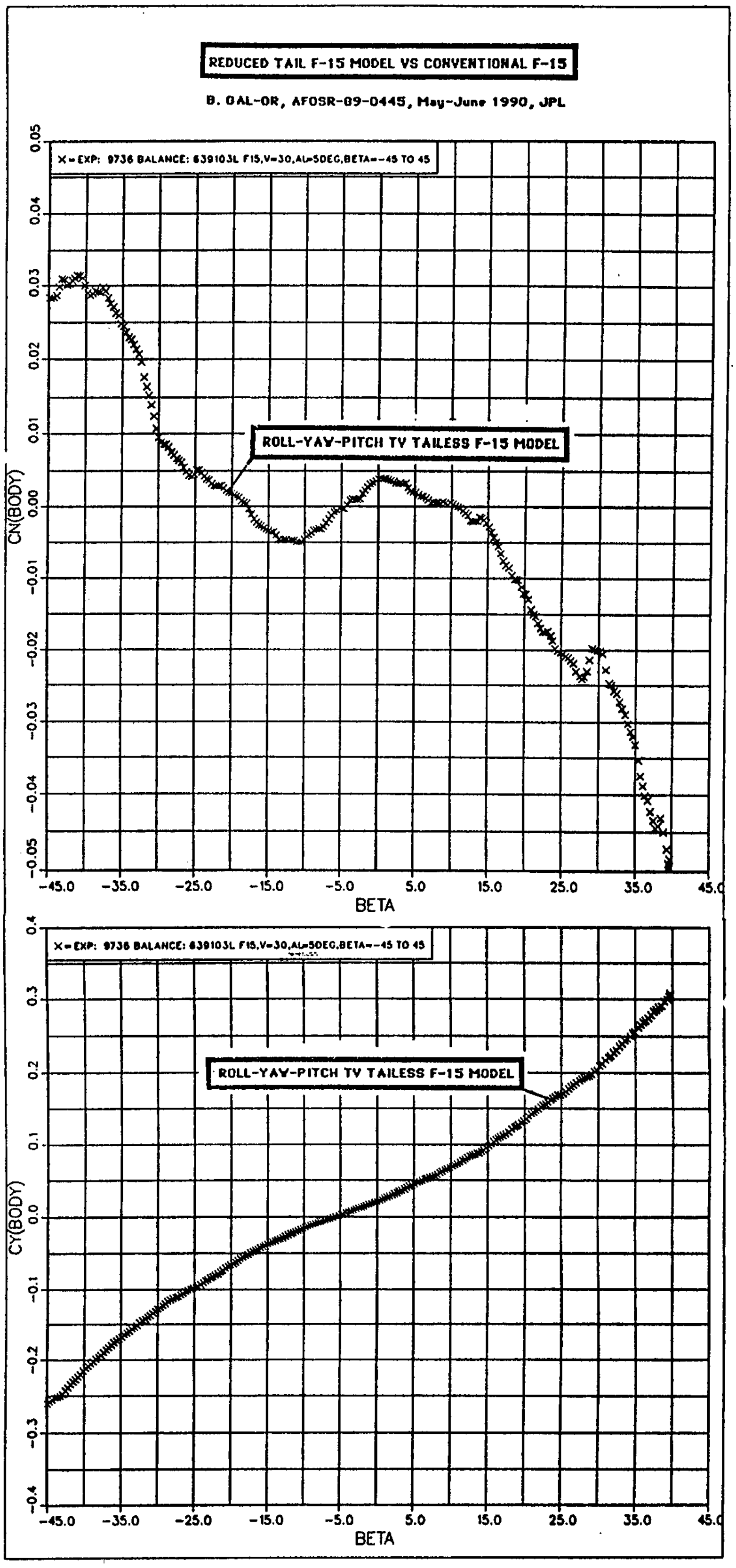
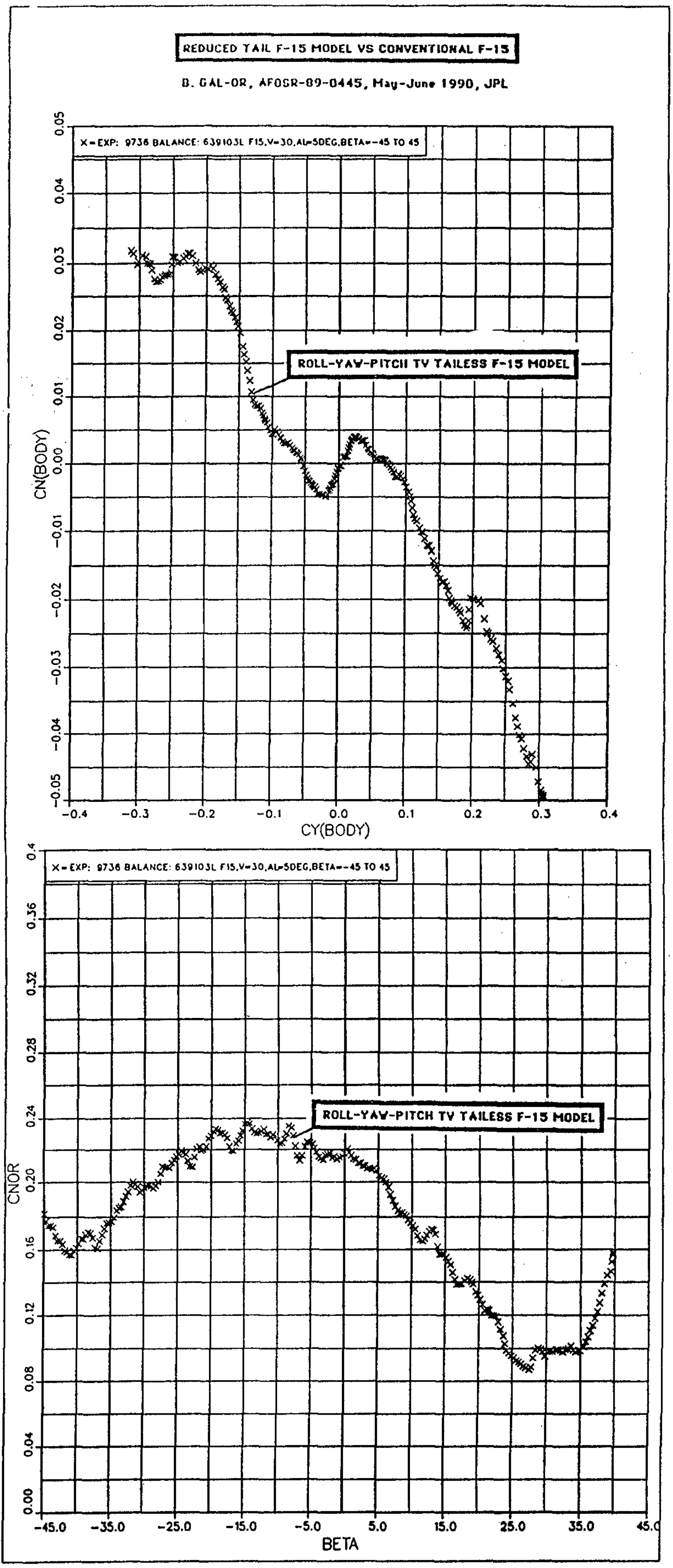

REDUCED TAIL F-15 MODEL VS CONVENTIONAL F-15
B. GAL-OR, AFOSR-89-0445, May-June 1990, JPL
X=EXP: 9736 BALANCE: 639103L F15,V=30,AL=50DEG,BETA=-45 TO 45
ROLL-YAW-PITCH TV TAILESS F-15 MODEL
CN(BODY)
0.05
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-45.0
-35.0
-25.0
-15.0
-5.0
5.0
15.0
25.0
35.0
45.0
BETA
X=EXP: 9736 BALANCE: 639103L F15,V=30,AL=50DEG,BETA=-45 TO 45
ROLL-YAW-PITCH TV TAILESS F-15 MODEL
CY(BODY)
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-45.0
-35.0
-25.0
-15.0
-5.0
5.0
15.0
25.0
35.0
45.0
BETA

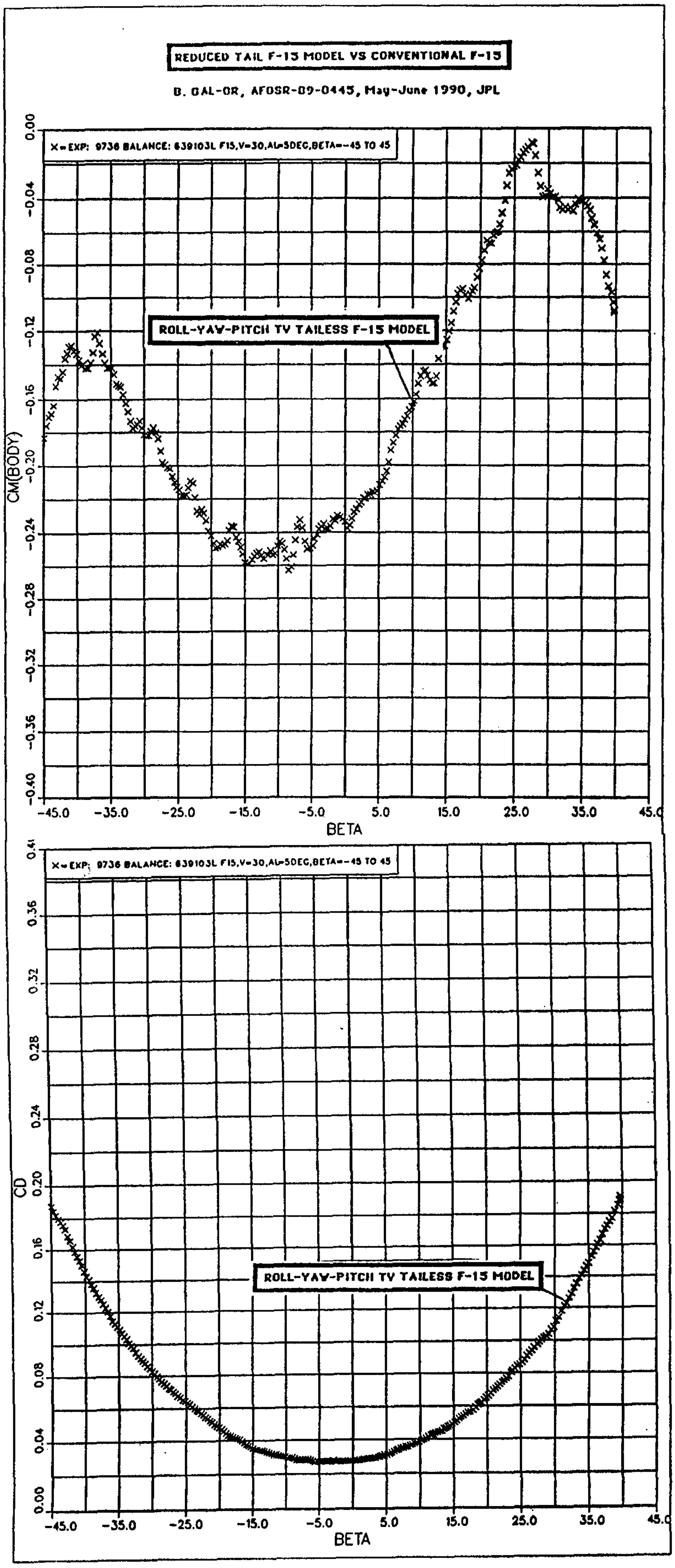
Fig. 26



REDUCED TAIL F-15 MODEL VS CONVENTIONAL F-15

B. GAL-OR, AFOSR-89-0445, May-June 1990, JPL

Fig. 27



REDUCED TAIL F-15 MODEL VS CONVENTIONAL F-15

B. GAL-OR, AFOSR-89-0445, May-June 1990, JPL

Fig. 28

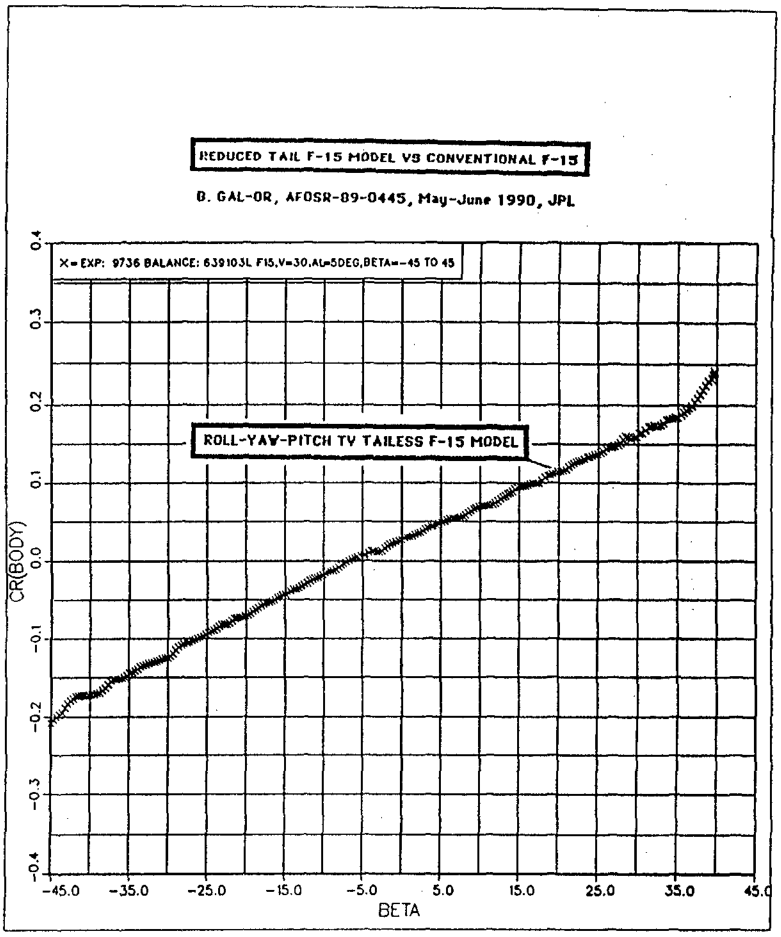

REDUCED TAIL F-15 MODEL VS CONVENTIONAL F-15
B. GAL-OR, AFOSR-89-0445, May-June 1990, JPL
X= EXP: 9736 BALANCE: 639103L F15,V=30,AL=5DEG,BETA=-45 TO 45
ROLL-YAW-PITCH TV TAILESS F-15 MODEL
CR(BODY)
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-45.0
-35.0
-25.0
-15.0
-5.0
5.0
15.0
25.0
35.0
45.0
BETA

Fig. 29

Laboratory & Flight Tests

Test Results & Conclusions

Part IV

Vectorable 'Distortion-Free' Inlets

PST-Vectorable F-15 Inlet

Test results For 1/7-scale F-15 Engine Inlet: Figures 30 to 34.

PST-Vectorable F-16 inlet and **' Full-Scale' F-15 inlet** [installed on a 350-kg-thrust jet engine equipped with a vectorable nozzle] are new spin-off research activities at JPL.

Test Facility: Fig. 17.

Methodology: 28 pressure probes, arranged on a rotating flange-cross, provide data every 10 degrees. A total of 252 points [cf. station 5, View B, Fig. 17, and Figs. 30 to 34]. Uniformity of flow is verified via monitoring air-flow eflux from fan 1 at different AoA of the 1/7-scale F-15 inlet. 4. Engine suction is simulated by fan 6 and throttle 2. Local Distortion coefficients contours are than plotted via an elaborate computer program designed for this purpose.

Conclusions

1 - Fig. 33 and 34 are the most instructive: Fig. 33 demonstrates high Distortion Coefficient [DC] values [up to 8] at AoA = 75 degrees. Fig. 34 demonstrate a significant reduction of DC values [down to 4] at AoA = 75 degrees, when a "Vectorable Inlet Lip" is vectored against the velocity vector.

2 - Such a single vectorable inlet may suffice to operate Teledyne 305 engines with our flying models. Following next-phase verification on the 'Full-Scale' test rig, the method can be extended to full-size inlets, perhaps with the addition of cambered lips.

ZERO ROTATION OF INLET LIP

AoA = 32°

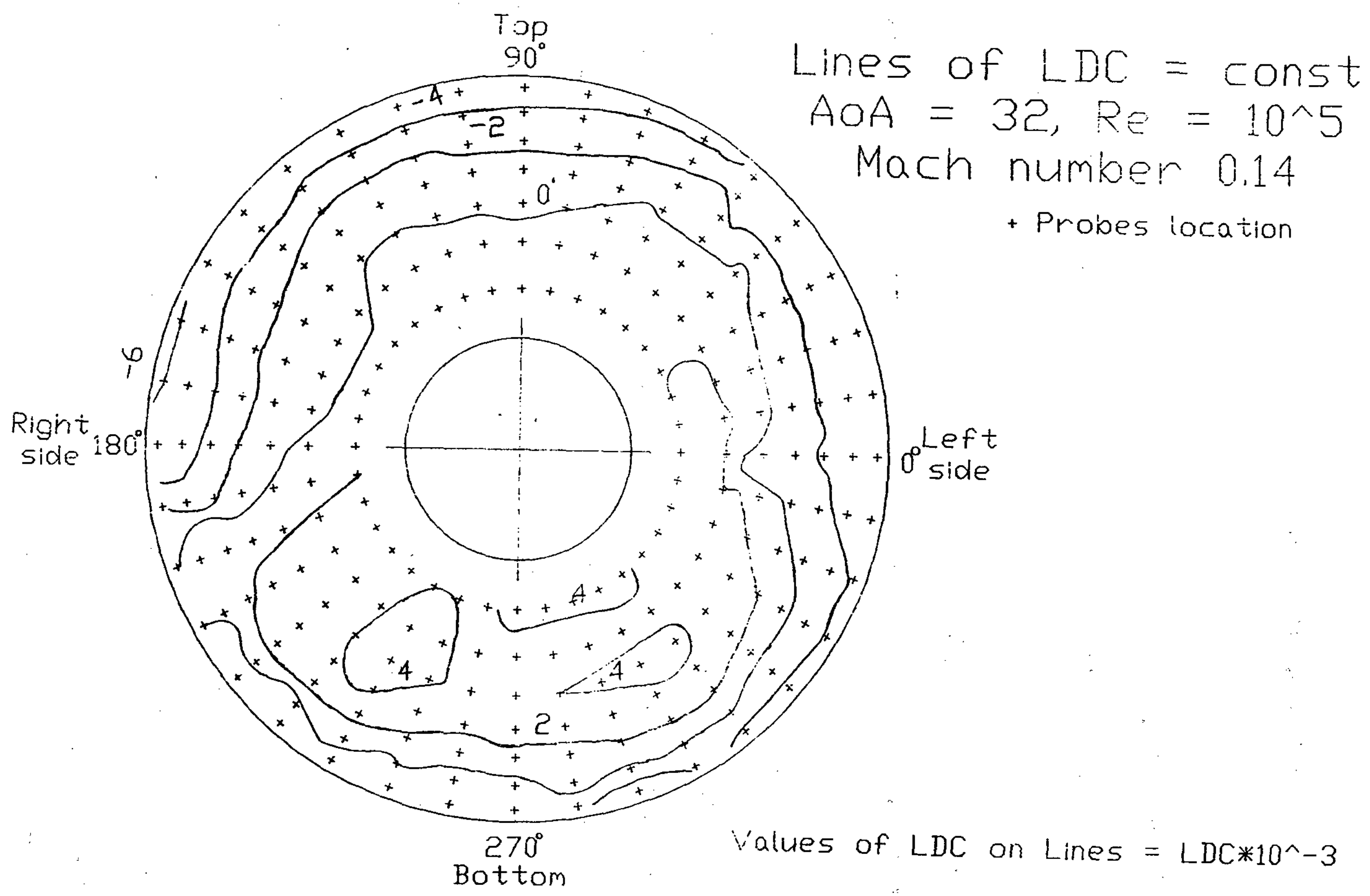


Fig. 30 Local Distortion Coefficient (LDC) contours
LDC = (Pt loc = Ptav) Ptav
Pt loc - "Engine-face" local total pressure
Ptav - "Engine-face" local total pressure

ZERO ROTATION OF INLET LIP

AoA = 38°

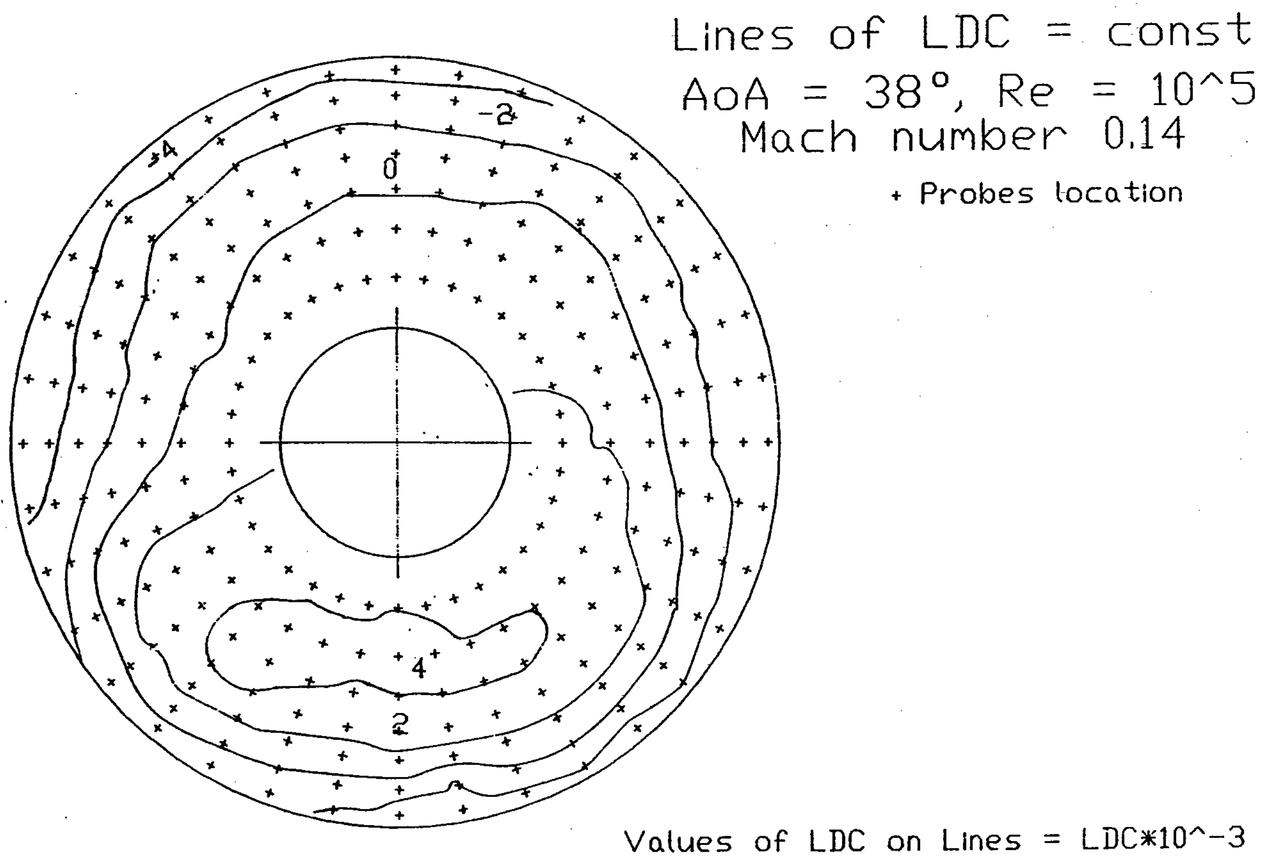


Fig. 31 Local Distortion Coefficient (LDC) Contours
LDC = (Pt loc - Ptav) / Ptav
Pt loc - "Engine-face" local total pressure
Ptav - "Engine-face" local total pressure

ZERO ROTATION OF INLET LIP

AoA = 62°

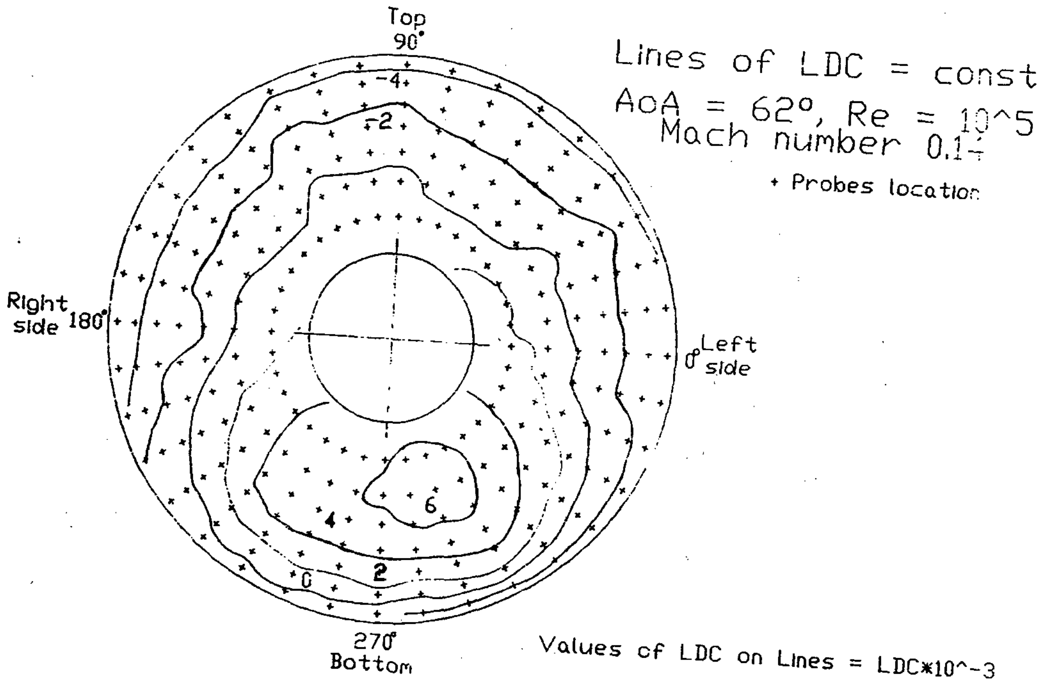


Fig. 32 Local Distortion Coefficient (LDC) contours
LDC = (Pt loc - Ptav)/Ptav
Pt loc - "Engine-face" local total pressure
Ptav - "Engine-face" local total pressure

ZERO ROTATION OF INLET LIP

AoA = 75°

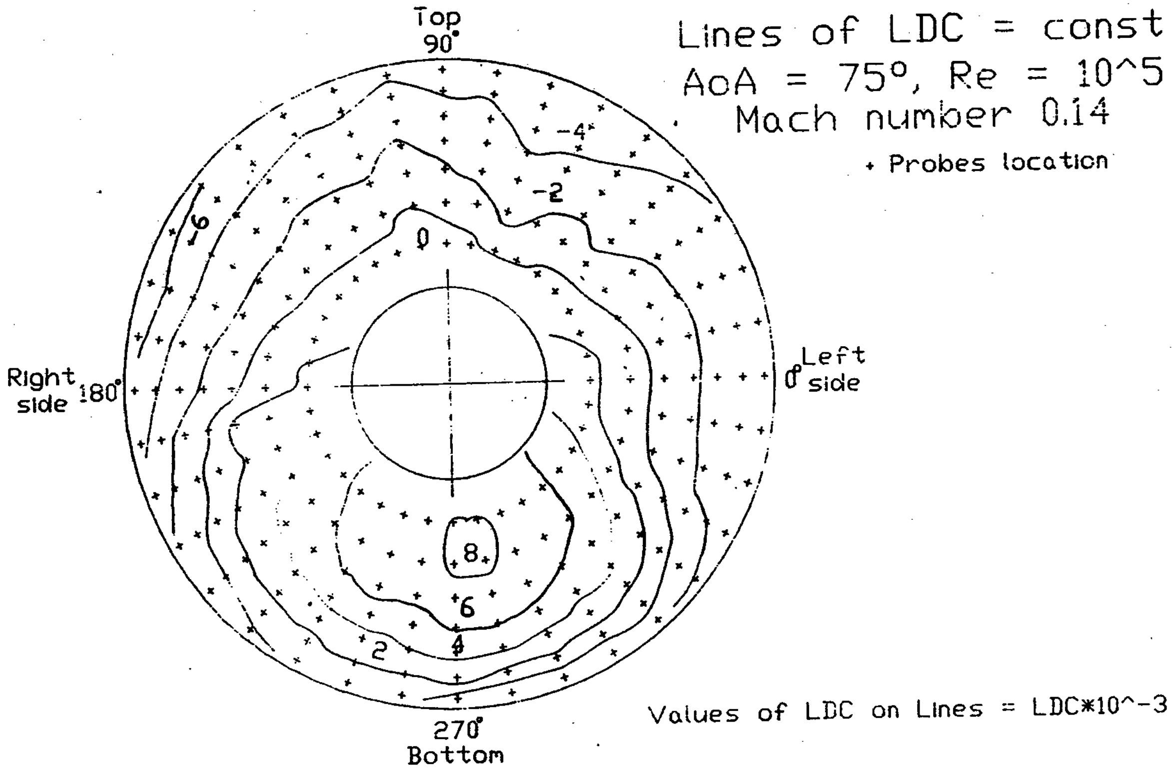


Fig.33: Local Distortion Coefficient (LDC) Contours
LDC = (Pt loc - Ptav) / Ptav
Pt loc - "Engine-face" local total pressure
Prav - "Engine-face" local total pressure

75° ROTATION OF INLET LIP

AoA = 75°

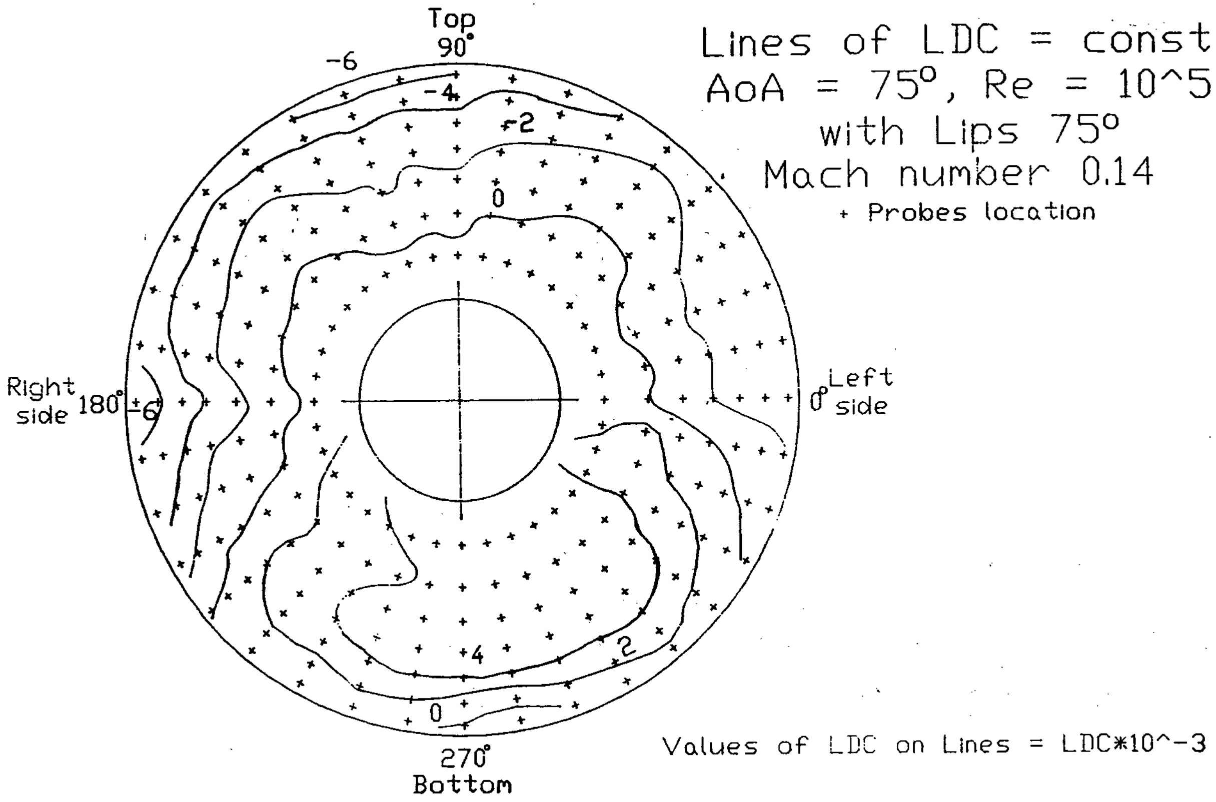


Fig 34: Local Distortion Coefficient (LDC) Contours

LDC = (Pt loc - Ptav)/Ptav

Pt loc = "Engine-face" local total pressure

Ptav - "Engine-face" local total pressure

Laboratory & Flight Tests

Test Results & Conclusions

Part V

Toward 'Practical' SACOM-Commands

<u>Six Partially-Recorded Or Rejected Attempts</u>

With All Calibrated Probes & Instrumentation Onboard

The purpose of this Part is to document characteristic FDT and efforts to develop **a 'practical' SACOM** which does not contradict theoretical defintions provided in 'Theory'-Part II. Only a few non-rejected, or surviving test-data are reported below.

A 'practical' SACOM means in-flight flyer's approximations to a 'step-function' or 'step-function-reversals', with all probes and instrumentation onboard [see **B** below].

Reaching for this goal had caused a few <u>catastrophic crashes,</u> and dozens of hard-landings, which, in turn, affected the readings of well-calibrated gyros, etc., and have caused <u>program delays</u>.

The examples Provided Below Have Been Taken From Flight Tests Conducted on:

<u>Oct. 19, 1990</u>; **<u>Dec. 7, 90</u>;** **<u>April, 25, 91</u>**

[Three additional, unsuccessful attempts, have been made in between Oct. 19, 90 and April 25, 91.]

A Few Remarks on 'Practical' SACOMs

A - Flyer's PCM control options include [electronically-enhanced] 'accelerated' or 'proportional' commands, electronic stops, and other command 'mixing' and 'sensitivities'. To evaluate inherent FDT, the proportional mode, with no modified or 'mixed' sensitivity, was selected.

B - A 'practical' SACOM deviates from 'well-defined' IC, EC, steady-state level flight, and 'pure-step-function-commands'. It deals with in-flight responses of low-moment-of-inertia models to air turbulence, wind direction, slight asymmetric deviations in the 'pure' commands, safety corrections & trimming during flight, and optical-distance effects on flyer's ability to judge SACOM IC and EC, as well as contending with flight in 'eliptic-circles' 'in-front-and-above' flyer/camera during a 3-minutes time limit.

These requirements dictate intense, trial-and-error flight training, especially with the added Flyer Control Options with TV'. [Cf. Methodology, Part II, and recorded turbulence noise, Flight Test Results: May, 9, 91; Part VI]

A few Non-Rejected velocity and alpha responses to conventional and TV commands are reported here.

[Reason: We had to reject onboard computer records of at least 2 well-calibrated rate gyros, following their 'unsteady' output, which was probably caused by an earlier 'hard-landing'. Unfortunately, the 'unsteady' output was sporadic, and had not been detected during pre-flight calibration procedures. It was later detected by post-flight analysis.]

Non-Rejected Flight-Test Results

[Time is counted from computers 'Start Session' PCM command]*

TV-IC: 67.5 sec; around **6 deg AoA** **TV-EC**: 74 sec; around **6 deg AoA**

Conv.-IC: 4.5 sec; around **5 deg AoA** **Conv.-EC**: 11 sec; around **7 deg AoA**

* cf. p. 106, 108.

1 - **Alpha range**: From max + 25 to - 7 deg in conventional SACOM.

From max + 28 to - 14 deg in pitch-TV SACOM.

2 - **Velocity change:**

With TVC: From 27 m/s to 13 m/s. With Conv. Control: From 26 m/s to 13 m/s.

TV-IC: Around 27 m/s TV-EC: Around 24 m/s

Conv.-IC: Around 26 m/s Conv.-EC: Around 23 m/s

3 - **Max alpha-dot:**

TV: around **73 deg/s** Conv.: around **35 deg/s**

4 - **Flyer's 'Step Function' FDT [Figs.** 35,38,42 :

Transient Conv. Control stick: **Max 48 deg/s.**

Transient TV control stick: **Max 229 deg/s [TV].**

Reason for FDT 'gap': Probably a biased Flyer's Intention to favor TVC.

3rd Partially Recorded Flight Test

Dec. 7, 1990; Cf. Figs. 38 to 41.

Notes:

A - The first conv. roll was not acceptable as a 'unit operation', for the flyer had decided to simulatneously roll and trim the elevator 'to raise the suddenly-declina model-nose'.

B - Consecutive commands appear as independent 'unit operations'. Yet, following this flight test we have instructed the flyer to switch to 'Independent Reversals' [with no 'hold' in between 'step-functions', and a 'pure', pitch, yaw or roll reversal command].

A Few Non-Rejected FDT and Model Responses

A comparison of TV and conv. command rates demonstrates that the previous flyer's bias in favor of TVC has been moderated:

Range of Commands & FDT *

Ailerons [Corrected]:	+17 to -13 degrees.	Max Rate: 110 deg/s
Conv. elevator [Not corrected]:	+27 to +5 degrees.	Max Rate: 140 deg/s
Yaw TV [Corrected].	+20 to -20 degrees.	Max Rate: 160 deg/s
Pitch TV [Corrected]:	+20 to -13 degrees.	Max Rate: 110 deg/s

A Sample of a Non-Rejected Response to Aileron Roll Command

Max Conv. **pitch rate**:	**+ 110** to **-140** deg/s.	IC: **0** deg/s.	EC: **0** deg/s
Max Conv. **yaw rate**:	**+ 40** to **-7** deg/s.	IC: **0** deg/s.	EC: **15** deg/s

[Yaw and roll rates were rejected.]

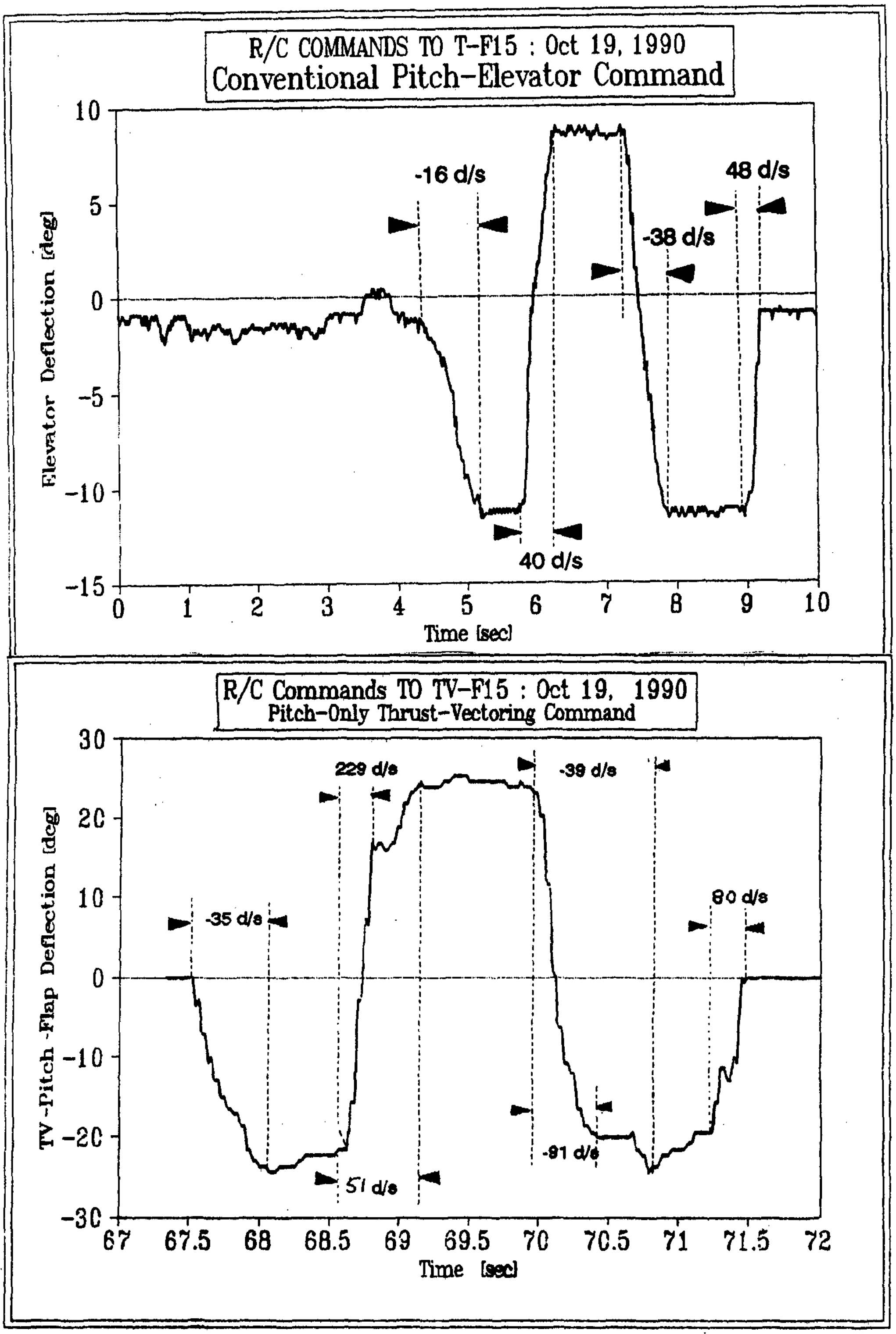
6th Partially Recorded Flight Test

April 25, 1991; Cf. Fig. 12.

These examples show unsuccessful attempts to improve SACOM in-flight commands.

A software failure prevented storage of onboard-computer data.

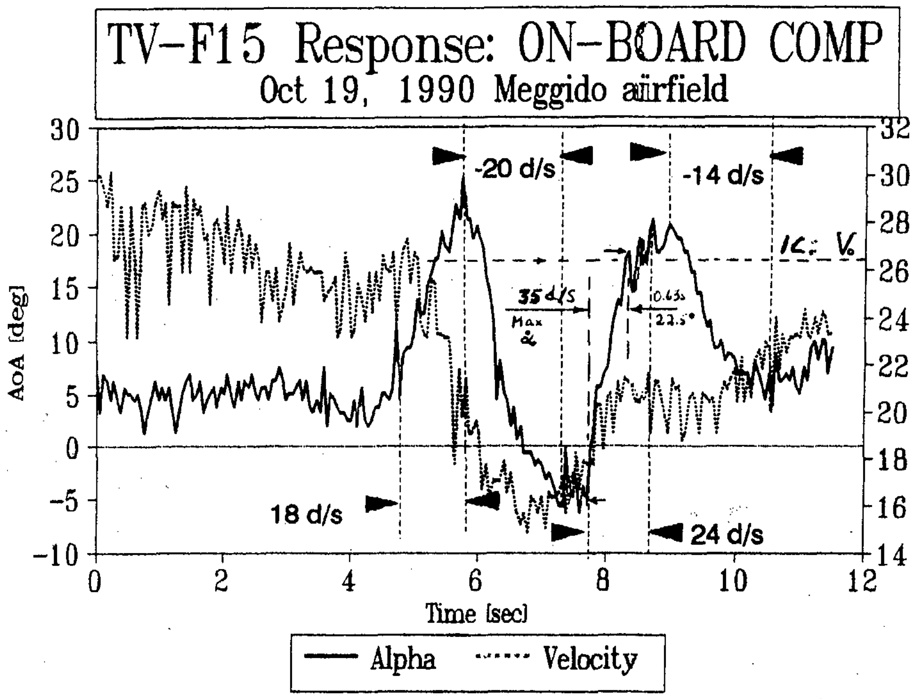
* cf. p. 108.



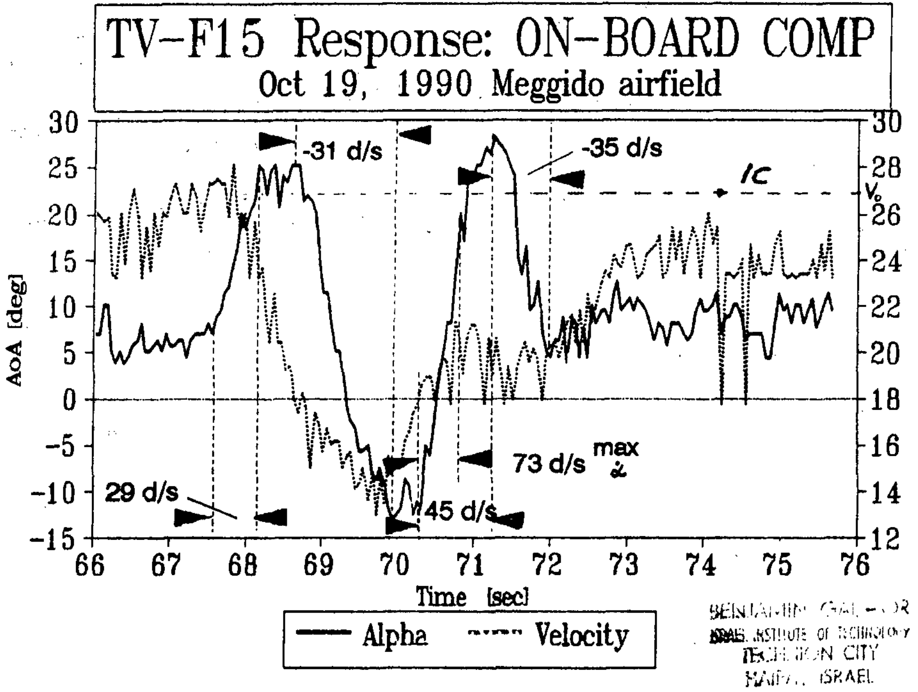
R/C COMMANDS TO T-F15 : Oct 19, 1990
Conventional Pitch-Elevator Command

R/C Commands TO TV-F15 : Oct 19, 1990
Pitch-Only Thrust-Vectoring Command

Fig. 35.



Response to conventional pitch-only command



Response to thrust-vectoring pitch-only command

Fig. 36.

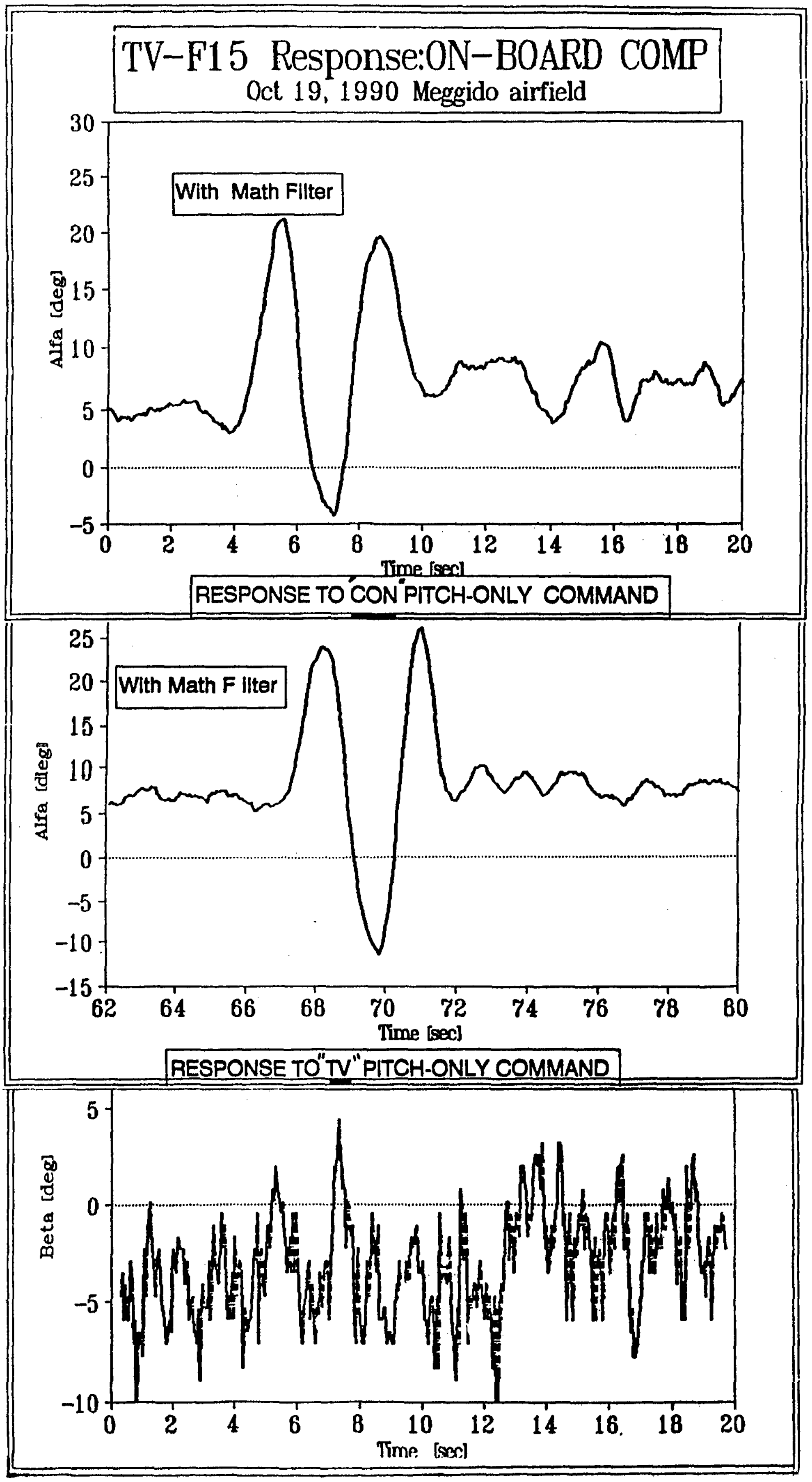

TV–F15 Response:ON–BOARD COMP
Oct 19, 1990 Meggido airfield
With Math Filter
Alfa [deg]
30
25
20
15
10
5
0
–5
0
2
4
6
8
10
12
14
16
18
20
Time [sec]
RESPONSE TO "CON" PITCH-ONLY COMMAND
With Math F ilter
Alfa [deg]
25
20
15
10
5
0
–5
–10
–15
62
64
66
68
70
72
74
76
78
80
Time [sec]
RESPONSE TO "TV" PITCH-ONLY COMMAND
Beta [deg]
5
0
–5
–10
0
2
4
6
8
10
12
14
16
18
20
Time [sec]

Fig. 37

TV-F15 Ground Computer
Dec.7, 1990 Megido airfield

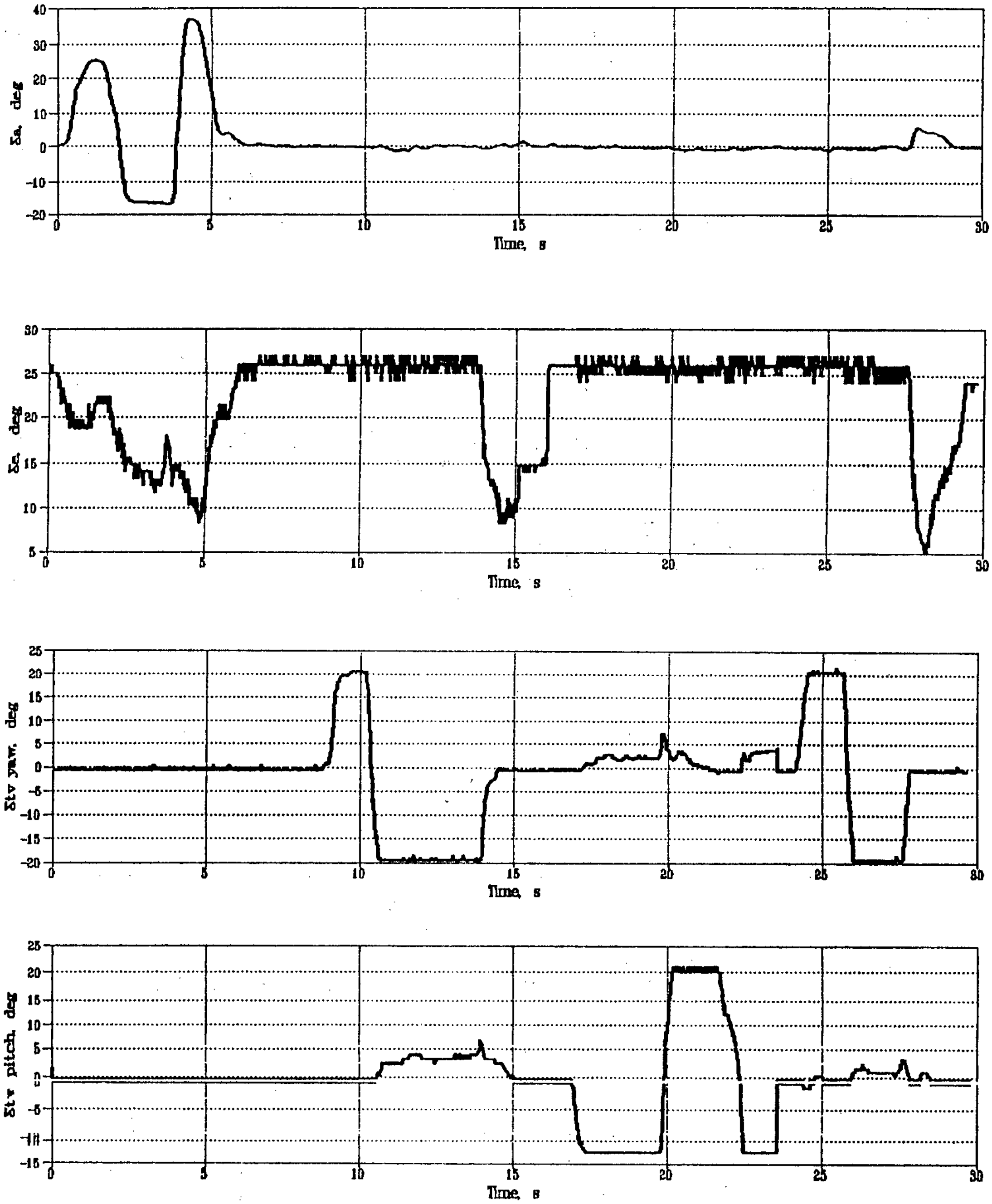


Fig. 38

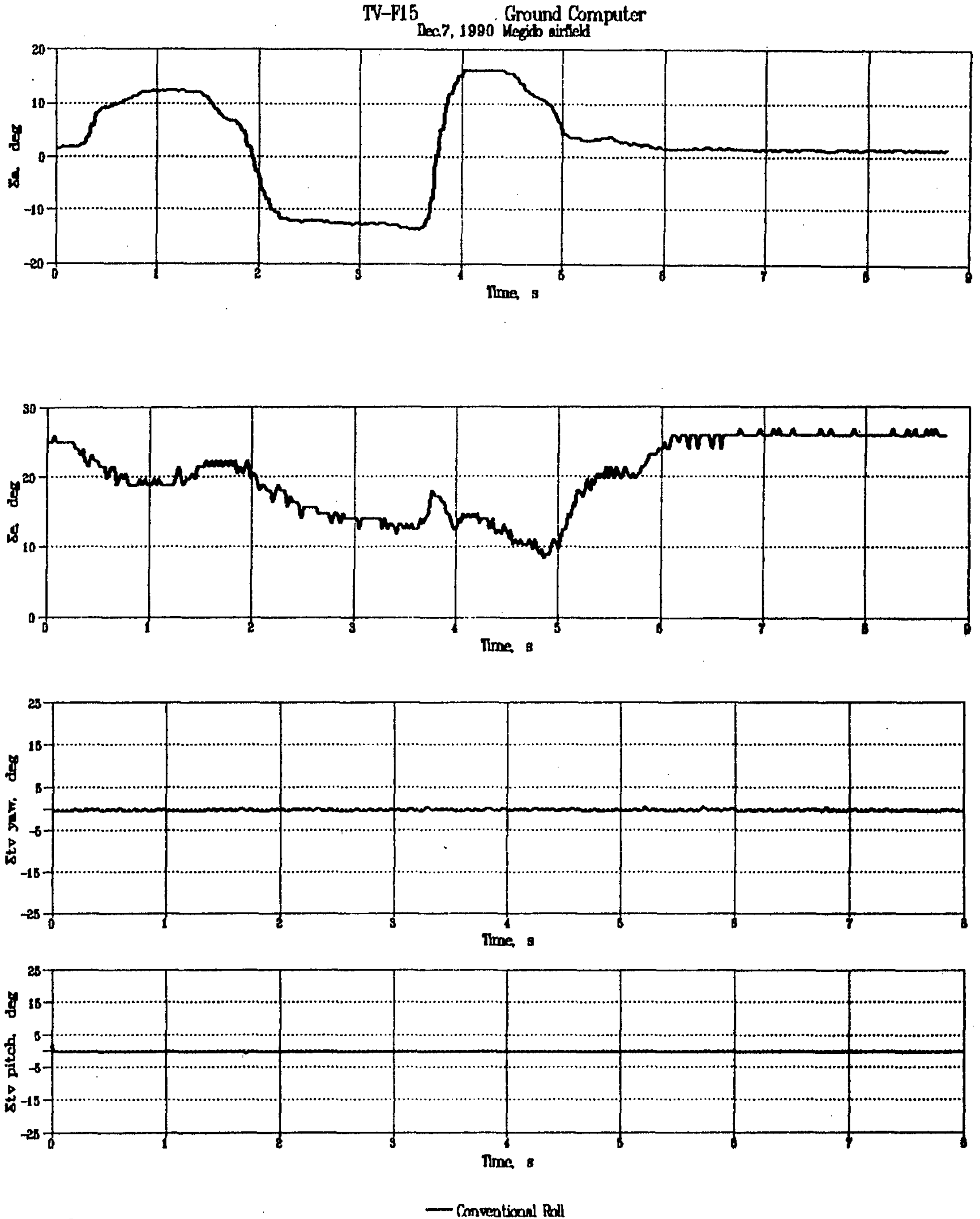

TV-F15 Ground Computer
Dec.7, 1990 Megido airfield
δa, deg
20
10
0
-10
-20
Time, s
0
1
2
3
4
5
6
7
8
9
δe, deg
30
20
10
0
δtv yaw, deg
25
15
5
-5
-15
-25
δtv pitch, deg
Conventional Roll

Fig. 39

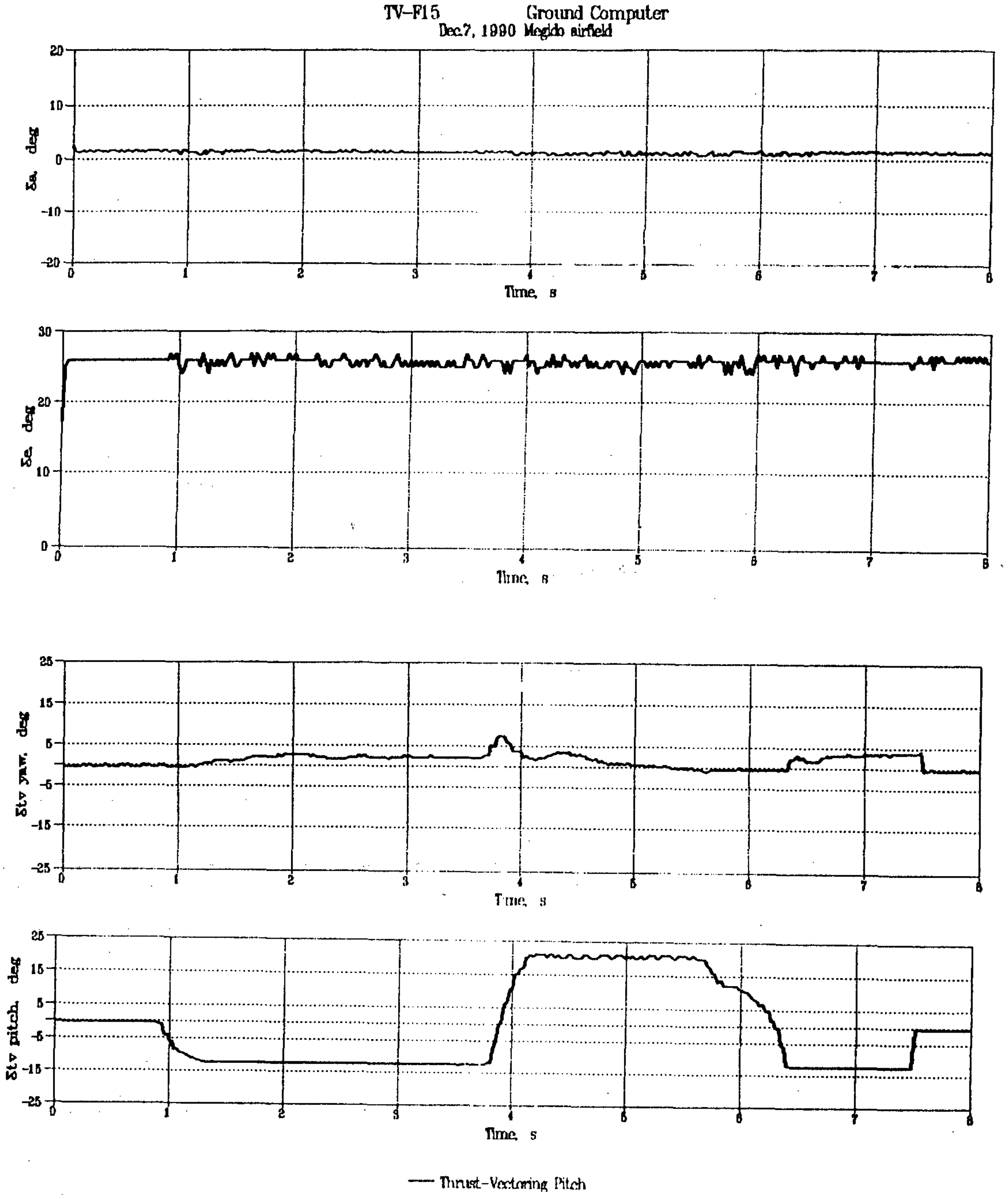

TV-F15 Ground Computer
Dec.7, 1990 Megido airfield
δa, deg
20
10
0
-10
-20
Time, s
0
1
2
3
4
5
6
7
8
δe, deg
30
20
10
0
Time, s
δtv yaw, deg
25
15
5
-5
-15
-25
Time, s
δtv pitch, deg
25
15
5
-5
-15
-25
Time, s
— Thrust-Vectoring Pitch

Fig. 40

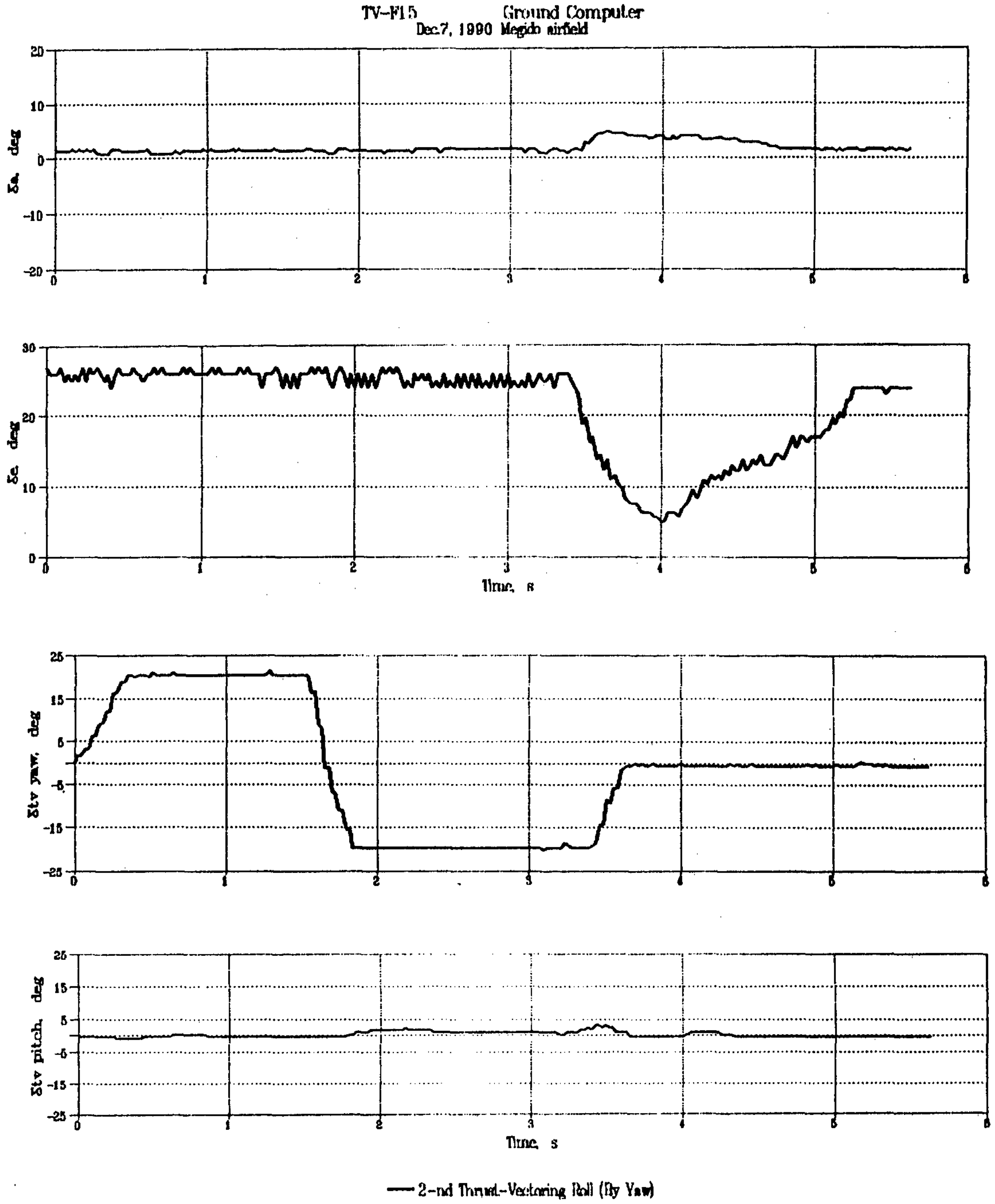
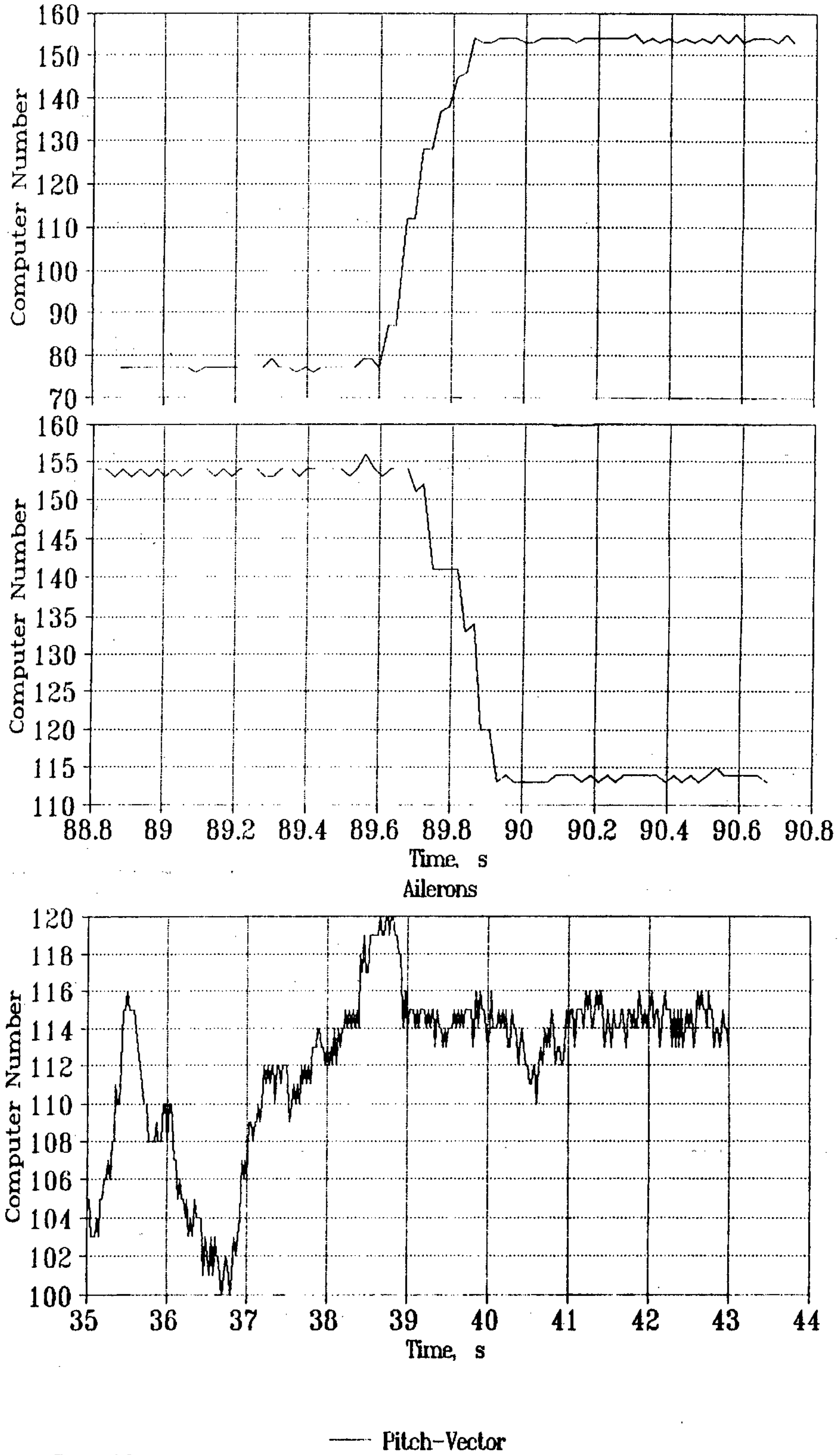

TV-F15 Ground Computer
Dec.7, 1990 Megido airfield
δa, deg
20
10
0
-10
-20
0
1
2
3
4
5
6
δe, deg
30
20
10
0
Time, s
δtv yaw, deg
25
15
5
-5
-15
-25
δtv pitch, deg
Time, s
2-nd Thrust-Vectoring Roll (By Yaw)

Fig. 41



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, April 25, 1991

Ailerons

Fig. 42.

Laboratory & Flight Tests

Test Results & Conclusions

Part VI

The 'MAY-9, 91' Flight Tests

Flight Instructions for Standard Agility Comparisons Maneuvers

Background: Thrust vectoring means tailless PVA as the ideal standard for maximizing agility. Maximizing TV-agility means maximization of 4 components: Axial-engine-power and TVC + conventional flight-control means for enhanced pitch, roll and, in the case of tailless PVA, pure-sideslip reversals. Reversals are required for at the reversal point the required TVC-power must be maximized, especially in the deep PST domain.

Agility cycle reversals, i.e., EC = IC at the end of a standard maneuver, reflect ability to regain multiple-target power, or pursue a departing target, or defend against attacks, by unloading rapidly and accelerating away so as to leave a flight-path/state/engagement at any time, irrespective of conventional wing/control-surface stall conditions. [Cf. Part II, 'Theory'].

Agility measurement includes Functional Component [FC]. FC is defined as "**Time to** ...." for, say, θ, α, ϕ, β, ψ, or **V** complete [EC = IC] reversals, or 'time to acquire-target/stop and start tracking target with *a priori*-defined precision'.

Thus, agility reflects potential to 'outpoint' the opponent, i.e., pointing at him before he points at you. This advantage must be such that the oppenent does not have the opportunity to launch his weapon before he is destroyed.

Pilot selection of a particular FC critical variable depends on maneuver/mission and the combined aircraft/missile agility. The EC=IC SACOM-reversal requirement is therefore a key aircraft ability, whose importance increases as all-aspect, missile-target computing-delay-times, including locking-releasing delays and path/time of missile flight, are decreased.

Therefore, FC for the present flight tests is defined as the total duration from IC to EC, when EC =IC and each variable is independently measured as a response to a full-stick-deflection reversal, i.e., as the total duration of all complete reversal cycles for each variable, divided by the number of complete cycles per maneuver, when a cycle is defined by EC approximately equals IC within allowable turbulence noise for each variable.

The SACOM Instructions

Perform 1, 2 or 3 Pitch or Roll Reversals per maneuver, while keeping, within turbulence-noise level to be established, independent approximations: Pitch and Alpha EC about equal to IC; Banking, Roll and yaw-rates and Betta EC about equal to IC; Velocity EC about equal to IC. [Previous results (Cf. Fig. 36, p. 99), indicate that relatively long velocity-delay-times characterize the last requirement. Hence, no new maneuvers are allowed prior to end of velocity-EC. See also the Last Appendix].

Start each maneuver from steady, straight, level flight, with fuel tank half empty. Conduct 'wind-direction' SACOMs, i.e., nose or tail-wind. [Wind velocity was: 6 knots, from W to E.].

Review of Results-Ranges-Conclusions

Conventional pitch rate obtained by our model well-corresponds to that extractable from conventional, full-size **F-15As**, when our DSF are employed [+53 deg/s to -49 deg/s at 36.5 m/s IC. **DSF: 20 deg/s at 0.3M IC,** which **is,** approximately, the maximum F-15A turn performance during a horizontal turn at **5000' 0.3M**, Max Power, as taken from 'energy-speed-turn/rate maps (which are not to be reported here)].

Combined pitch-ETV/elevator commands produce more than twice the current pitch-rate of conventional F-15s. [+160 deg/s to -155 deg/s . **DSF: +60 to -58.6 deg/s at 0.3 M,** which is more than twice the current rate with conventional full-size F-15As [See below].

ITV provides similar pitch-rate values by resorting only to pitch-ITV command. [It was demonstrated by the uninstrumented model in 1989. Cf. Video Tape No. 6].

The results obtained so-far allow, for the first time, comparisons of gross and net agility components between one TVC-system to another. Hence, the newly-proven methodology provides cost-effective and time-saving means to design, construct and flight-test correct-DSF-Scaled models in search of maximized TVC power and the total elimination of any conventional tail.

Model responses to Conventional, TV + Conv. and TV commands are well-measured and well-recorded by JPL instrumentation, calibration, software and post-flight procedures. Hence, a proof-of-concept of the proposed methodology has been made.

Each reversal maneuver started from a steady, level/straight flight condition. Each was therefore initially characterized by the level of turbulence-noise evaluated during the same flight time-span. Within this 'noise-range', the SACOM-requirements for approximate equality of EC to IC is reasonably attainable, especially with additional flyer training.

Hence, the maneuvers recorded represent 'practical' SACOMs, in a somewhat limited analogy to the newly proposed mathematical phenomenology and TV-agility definitions [PARTS I and II, 'Theory'].

Pitch-FC values for a conventional elevator command are longer than for a pitch-TV+conventional elevator command. Pure pitch-TV command produces the shortest FC times. However, this particular result is not conclusive, for the command must be verified by additional tests.

Roll-FC values for conventional aileron command are shorter than for a conv. aileron + TV-Yaw Command, i.e., coupled roll by yaw-TV is hindering FC.

Velocity-FC periods are longer than pitch, roll, yaw, AoA, and betta FC values.

The present ETV-results do not and cannot represent maximization of TV-agility [Cf. 'Technology Limits' - Part I].

The results are limited to current ETV/IFPC capability, and to our flyer current experience.

Additional flyer training and enhanced ITV systems can maximize PST-TV agility with tailless designs of correctly-DSF-Scaled ITV-F-15 and ITV-F-16 flying models.

Subject to our DSF restrictions, the performance ranges obtained by flying 1/7-scale-ETV-F-15 model provide the corresponding full-size-DSF-F-15 aircraft ranges reported below:

To Monitor Maneuvers on Video Tape No. 5:

1 - Rewind tape. Then reset video index to **0000** .

2 - FF to around **2500** on the video index [which is 2500 seconds play time]. Then search for the "**May 9, 91**" printed date. [Semi-Tailless F-16 flight tests are around **3000**. Tape ends around **3500**.]

3 - About one minute past take-off the flyer says: **4...,3...,2...,1...,** **Zero !,** '**START SESSION**', and operates the computers at "**Ze**", by a radio command.

4 - **Reset** video index counter to **0000** exactly at the sound of "**Ze**" !

5 - Video-index-numbers now show time since computer-recorded '**Session**' started.

If in seconds, the numbers 'correspond' to [computer-calibrated] **'Time, s'** values marked on performance graphs. [Otherwise use a stopwatch.]

Use of Performance Graphs + Video Tape Recordings

1 - Two series of flight tests were conducted and recorded on that day. The first maneuver of the 1st-flight started around **36 s** from 1st session start.

2 - Flight data from **18 to 27** seconds are measured from session start of 2nd flight.

3 - Each set of performance graphs represents a single maneuver. Each can be monitored on the tape to extract additional information.

4 - Radio commands recorded on ground computer were lost due to a malfunction in computer-to-computer data-transfer-software. However, all maneuvers commands, were stated by the flyer and were recorded, and the characteristic Flyer Delay Time [FDT] can be deduced from the ground-computer recordings from previous flights [cf. FDT in Part V]. Comments & 'next-maneuver' proposals made during the flight, have also been recorded on the video tape.

5 - Parameters ranges, Initial and End Conditions [IC and EC] for each maneuver [set of graphs] are shown in each graph, prior to, during, and post each maneuver [see below for preliminary conclusions].

Air Turbulence Noise Reference Data

Two examples are provided for steady, straight/level flight, which characterizes Initial Conditions [IC] for each maneuver. The data are directly useful as a 'REFERENCE-BASELINE' for correct-DSF-scaled conclusions that are reported in the next paragraph.

Subject to DSF restrictions enumerated in 'Methodology' - Part II, the ranges obtained are:

Pitch Rate: 8 deg/s [plus/minus]. DSF: 3 deg/s [plus/minus].

Roll Rate: 7 deg/s [plus/minus]. DSF: 2.6 deg/s [plus/minus].

Yaw Rate: 10 deg/s [plus/minus]. DSF: 3.8 deg/s [plus/minus].

Pitch Acceleration: 9 deg/s^2 [plus/minus]. DSF: 1.3 deg/s^2 [plus/minus].

Roll Acceleration: 7 deg/s^2 [plus/minus]. DSF: 1 deg/s^2 [plus/minus].

Yaw Acceleration: 31 deg/s^2 [plus/minus]. DSF: 4.4 deg/s^2 [plus/minus].

AoA: 5 deg [plus/minus]. DSF: 5 deg [plus/minus].

Betta: 3 deg [plus/minus]. DSF: 3 deg [plus/minus].

Alpha Dot: 30 deg/s [plus/minus]. DSF: 11.3 deg/s [plus/minus].

Betta Dot: 10 deg/s [plus/minus]. DSF: 3.8 deg/s [plus/minus].

Velocity: 1.5 m/s [plus/minus]. DSF: 4 m/s [plus/minus].

Responses to SACOMs

Pitch Rate:

Corrected Full-Scale Pitch-Turbulence Noise: Plus/minus 3 deg/s and plus/minus 0.03M.

Conv. pitch-only Command: +53 deg/s to 49 deg/s at 36.5 m/s IC. **DSF: 20 deg/s at 0.3M IC,** which **is,** approximately, the maximum F-15A turn performance during a horizontal turn at **5000' 0.3M**, Max Power, as taken from 'energy-speed-turn/rate maps (which are not to be reported here).

ETV-pitch-command only: +39 to -26 deg/s; DSF: 14.7 to 9.8 deg/s at 0.25M. This value is lower than the conventional pitch rate. On May 9, 91 it was tested only once.

ITV-pitch-command only: The following value was obtained in Aug. 1989, using the uninstrumented ITV F-15 model. The pitch rate was extracted from the video tape. It reached about 150 deg/sec, which, for the full-scale ITV F-15 means about 57 deg/s, about twice the rate extractable from conventional F-15A [But see also below].

Coupled Pitch By TV-yaw + Aileron Roll command: The value reported below has been obtained in response to TV-yaw + aileron roll command. The maximum coupled pitch rate is +160 deg/s to -155 deg/s, which corresponds to +60 to -58.6

deg/s at 0.3M for the full-scale F-15s. Gyroscopic effects and/or lateral asymmetries associated with the interaction of the air flow at increased alpha values with the ETV paddles, and/or vortex generation due to the velocity, alpha or betta probes might be the source of the strong coupling between pitch and roll. It should be stressed that the uninstrumented ITV model did not show such coupling.

Maximum ETV-Roll Rate by TV-yaw + aileron command: 150 deg/s to -150 deg/s . DSF: 56.7 deg/s to - 56.7 deg/s .

Maximum Yaw Rate: 23 deg/s to -13 deg/s . DSF: 8.7 deg/s to -5 deg/s .

Maximum Pitch Acceleration: 350 to -340 deg/s^2 . DSF: 50 to -48.5 deg/s^2 .

Maximum Roll Acceleration: 300 to - 370 deg/s^2 . DSF: 43 to -53 deg/s^2 .

Maximum Yaw Acceleration: 47 to -52 deg/s^2 . DSF: 6.7 to -7.4 deg/s^2 .

Maximum AoA: 27 to - 20 deg . DSF: 27 to - 20 deg .

AoA IC: -2 to +5 deg, within turbulence noise.

AoA EC: About as IC, plus/minus up to 5 deg, within turbulence noise.

Maximum Betta: 12 to -12 . DSF: 12 to - 12 deg.

Betta IC: A few degrees around zero, within turbulence noise.

Betta EC: About as IC for pitch and roll reversals, within turbulence noise.

Maximum Alpha Dot: 62 to -58 deg/s. DSF: 23.5 to - 22 deg/s .

From the Oct 19, 90 flight test, cf. Fig. 36:

Conv.: 35 deg/s. DSF : 13.2 deg/s.

ETV: **73 deg/s.** DSF: 27.5 deg/s.

The conv. 35 deg/s value is less than the conv. pitch-rate 53 deg/s value, while the ETV 73 deg/s value is higher than the 39 deg/s extracted with ETV-command only. Combined with the moments-of-inertia, pitch rate, etc. for full-scale aircraft, Eqs. 25, 26, 27, 28-30, 1 and 4, can next be employed, subject to noise levels recorded, say in the yaw direction during the recorded pitch SACOM performed. This effort is left for the extension/spin-off projects, with the participation of USAF Capt. Baumann [See Extension/Spin-Off projects at Report End.]

Maximum Betta Dot: 21 to - 22 deg/s . DSF: 8 to -8.3 deg/s .

Maximum Velocity Drop: From 36.5 to 21 m/s. DSF: 96.6 to 55 m/s [**0.3 M to 0.16 M**].

Velocity IC: 31, 34, 35 m/s. DSF: 82, 90, 93 m/s [**0.25M, 0.27M, 0.28M].**

Velocity EC: Approaching IC for pitch and roll reversals, within turbulence noise.

Maximum Linear Acceleration Range, Pilot's G-onsets, and Effective TV-Moments and coefficients can be deduced next year from recorded and calibration data.

Functional Agility Component [FC]:

FC for Pitch Reversals:

By Conv. Elev. Com.:

Pitch Rate: [26-21]/2 = 2.5s [Fig. 65];

Roll Rate: [25.3-21.0]/ 2= 2.15s [Fig. 66];

Yaw Rate: [25.3-20.3]/2 = 2.5s [Fig. 66]

Alpha: [24.8-20.3]/2 = 2.25s [Fig. 65]

Velocity: [26.3-20]/2 = 3.15s [Fig. 68]

By Conv. Elev. + TV-Pitch Com.

Pitch Rate: [86-80]/3 = 2.0s [Fig. 54];

Roll Rate: [86.5-80.0]/3 = 2.16s [Fig. 55];

Yaw Rate: [85.5-80.0]/3 = 1.83s [Fig. 55]

Alpha: [85.2-80.2]/3 = 1.66s [Fig. 54]

Velocity: [87.7-79.7]/3 = 2.66s [Fig. 54]

By TV-Pitch Com.

Pitch Rate: [166.4-165.6]/1 = 0.8s [Fig. 74];

Roll Rate: [166.7-165.7]/1 = 1.0s [Fig. 75];

Yaw Rate: Not Attainable/Extractable

Alpha: Not Attainable/Extractable

Velocity: Not Attainable/Extractable

FC for Roll Reversals:

By Conv. Aileron Com.:

Pitch Rate: [159.7-157.8]/3 = 0.63s [Fig. 63];

Roll Rate: [159.8-157.5]/ 3 = 0.76s [Fig. 63];

Yaw Rate: Not Attainable/Extractable

Alpha: Not Attainable/Extractable

Velocity: [160.2-156.7]/3 = 1.16s [Fig. 63]

By Conv. Aileron + TV-Yaw Com.

Pitch Rate: [114.7-111.2]/3 = 1.16s [Fig. 58];

Roll Rate: [114.6-111.3]/3 = 1.12s [Fig. 59];

Yaw Rate: Not Attainable/Extractable

Alpha: Not Attainable/Extractable

Velocity: Not Attainable/Extractable

Pitch Rate: [43.2-40]/2 = 1.6s [Fig. 51];

Roll Rate: [43.2-40]/2 = 1.6s [Fig. 75];

Yaw Rate: [42.3-39.9]/2 = 1.2s [Fig. 51]

Alpha: Not Attainable/Extractable

Velocity: Not Attainable/Extractable

'May 9, 91' Flight Tests

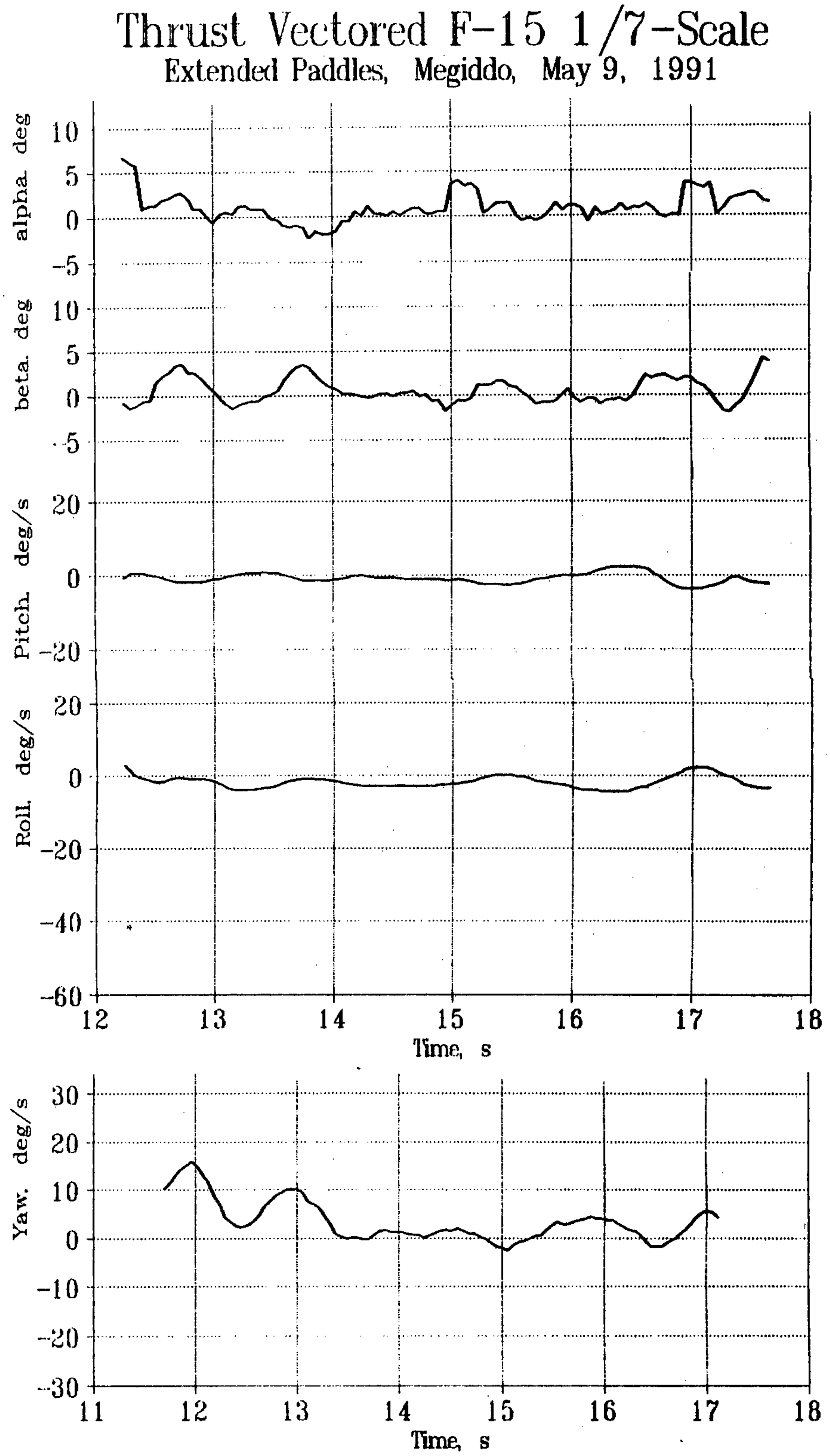
For Each Measured Channel [2 Channels per Variable (Positive and Negative Channels)], Onboard Computer Numbers for Each Variable Are Independently Converted into Engineering Units by Means of The New Post-Flight Software, Variables Calibration Charts, Correspondence with the Video Tape Voice Commands, Time-Span and Ordinate-Scale Selections. The Time in Seconds Marked is Computer-Lines-Converted Time. It Corresponds with Video Time Since Recording 'Session Start'.

Flyer Command: 'No Command'

Level Flight Recording For 'Turbulence-Noise-Reference'

Recorded Flight Tests With

All Pre-Calibrated Probes & Instrumentation Onboard



Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

Fig. 43

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

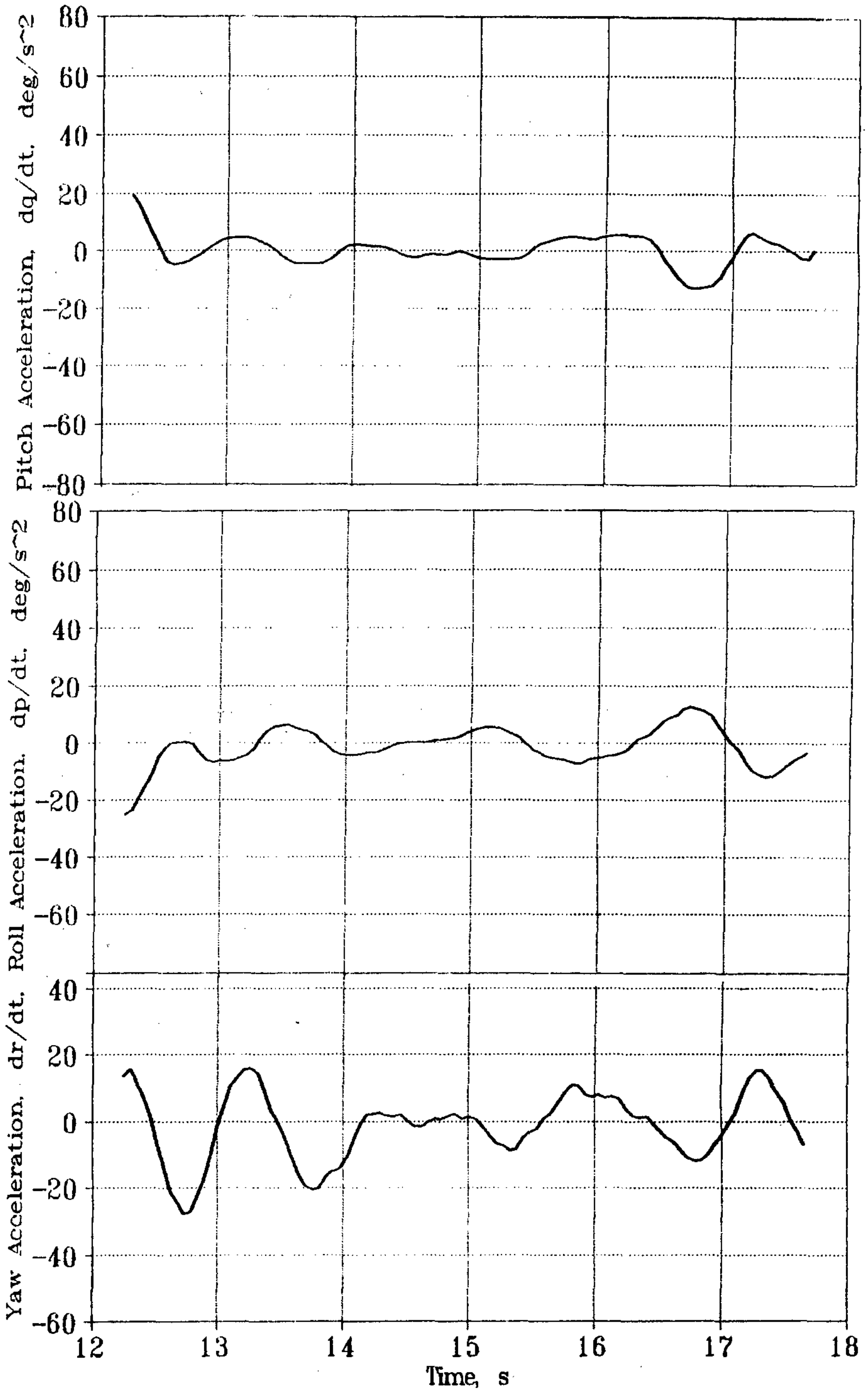


Fig. 44

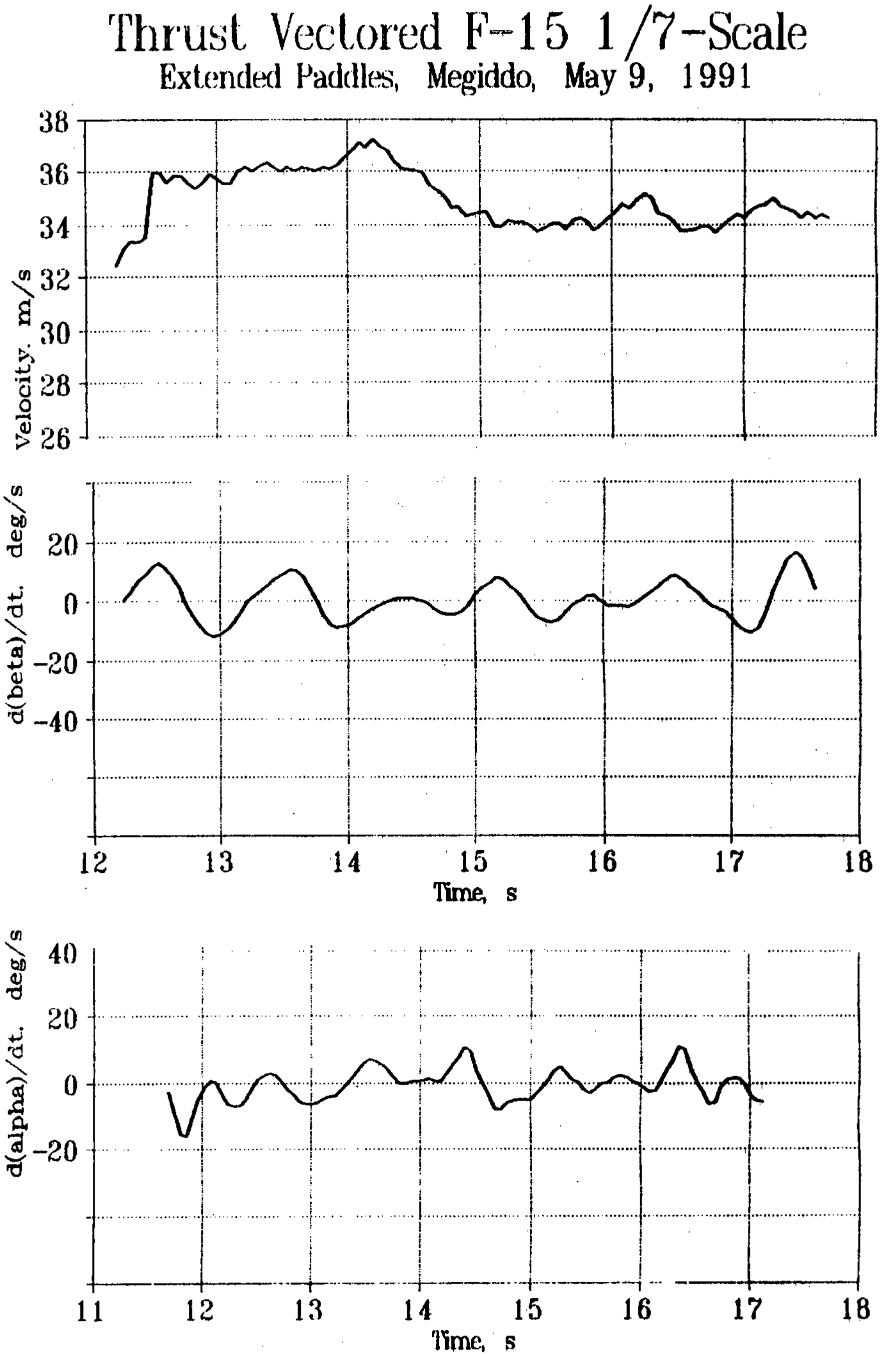
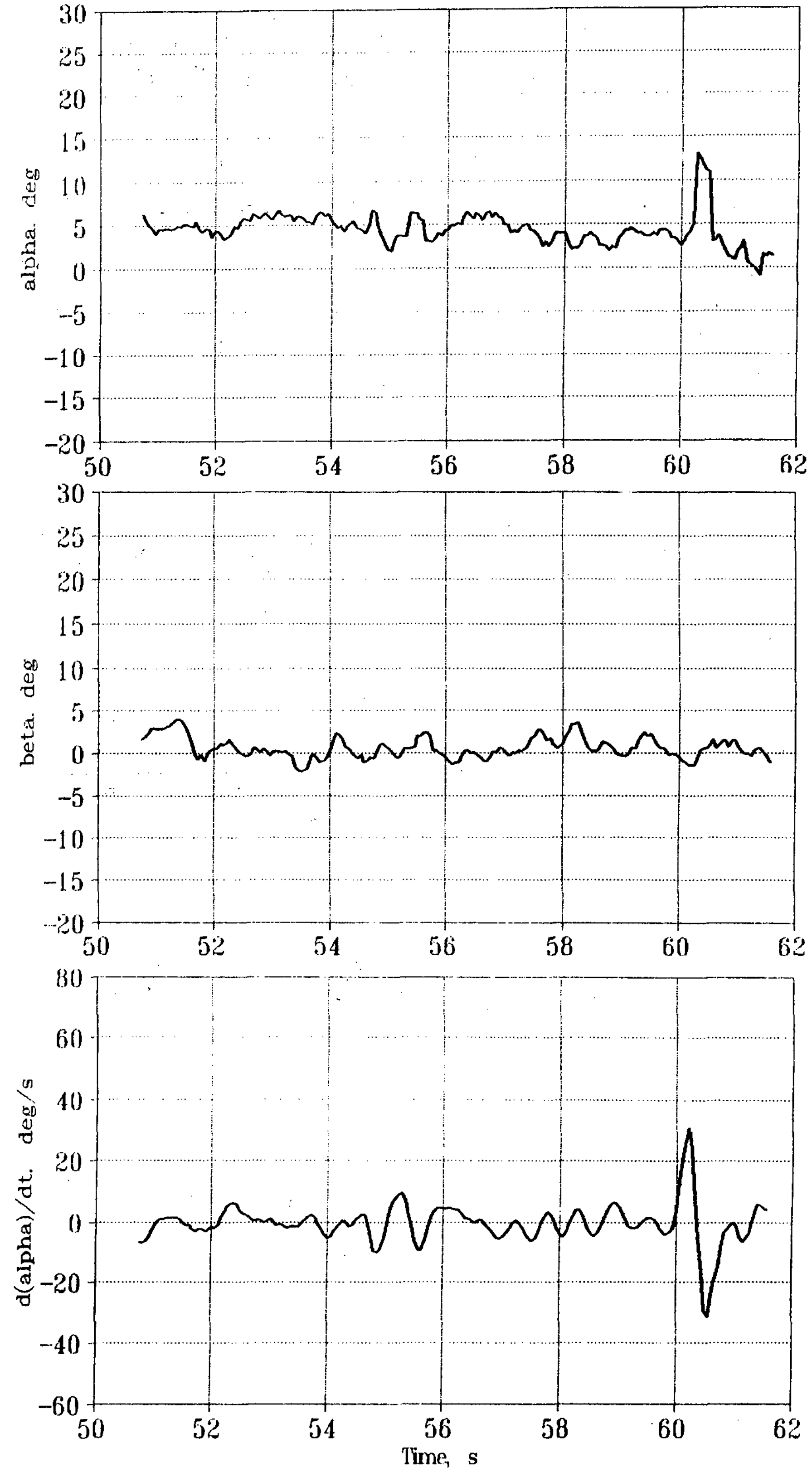
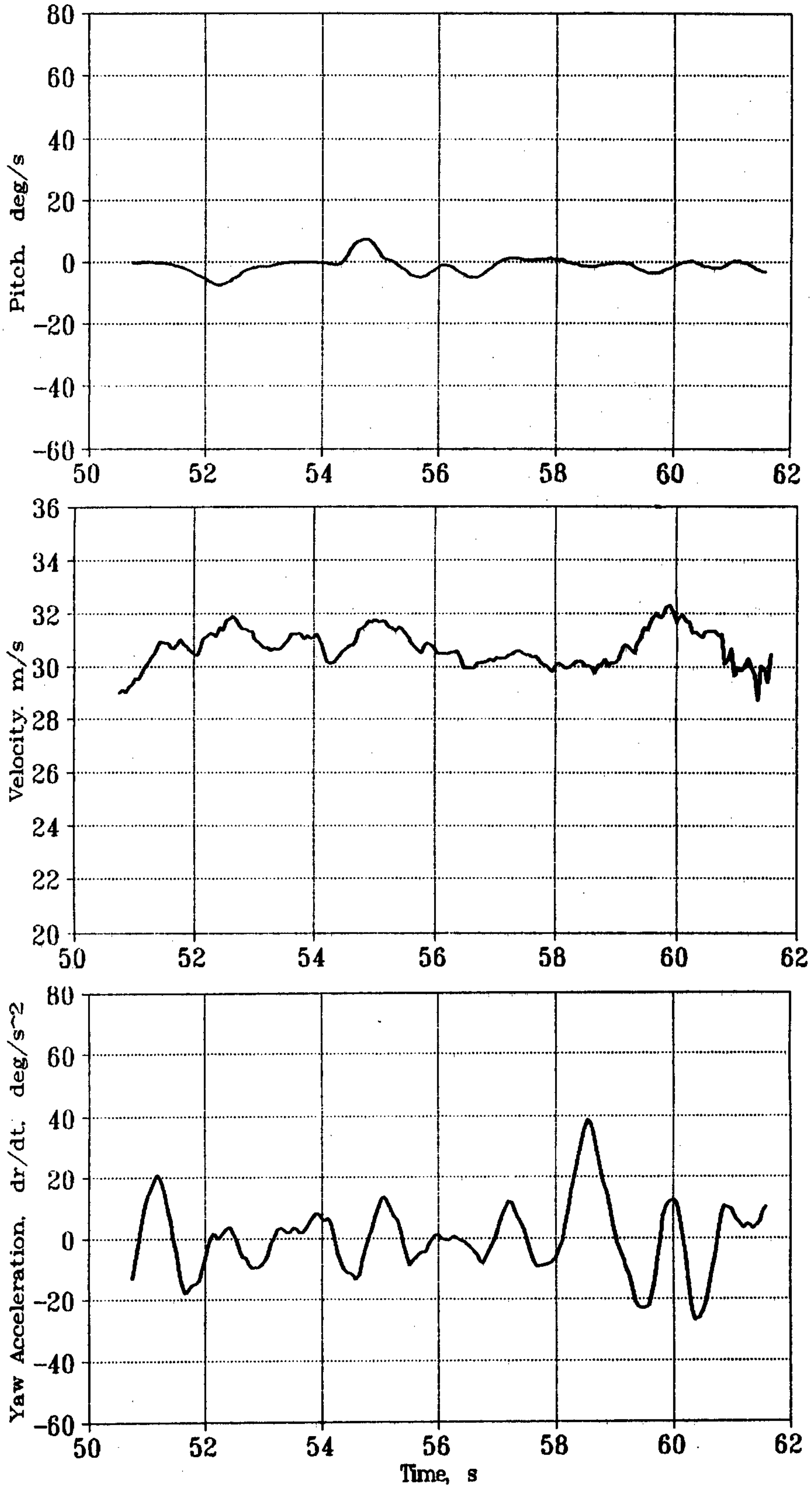

Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991
Velocity. m/s
38
36
34
32
30
28
26
d(beta)/dt. deg/s
20
0
-20
-40
12
13
14
15
16
17
18
Time, s
d(alpha)/dt. deg/s
40
20
0
-20
11
12
13
14
15
16
17
18
Time, s

Fig. 45



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

Fig. 46



Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

Fig. 47

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

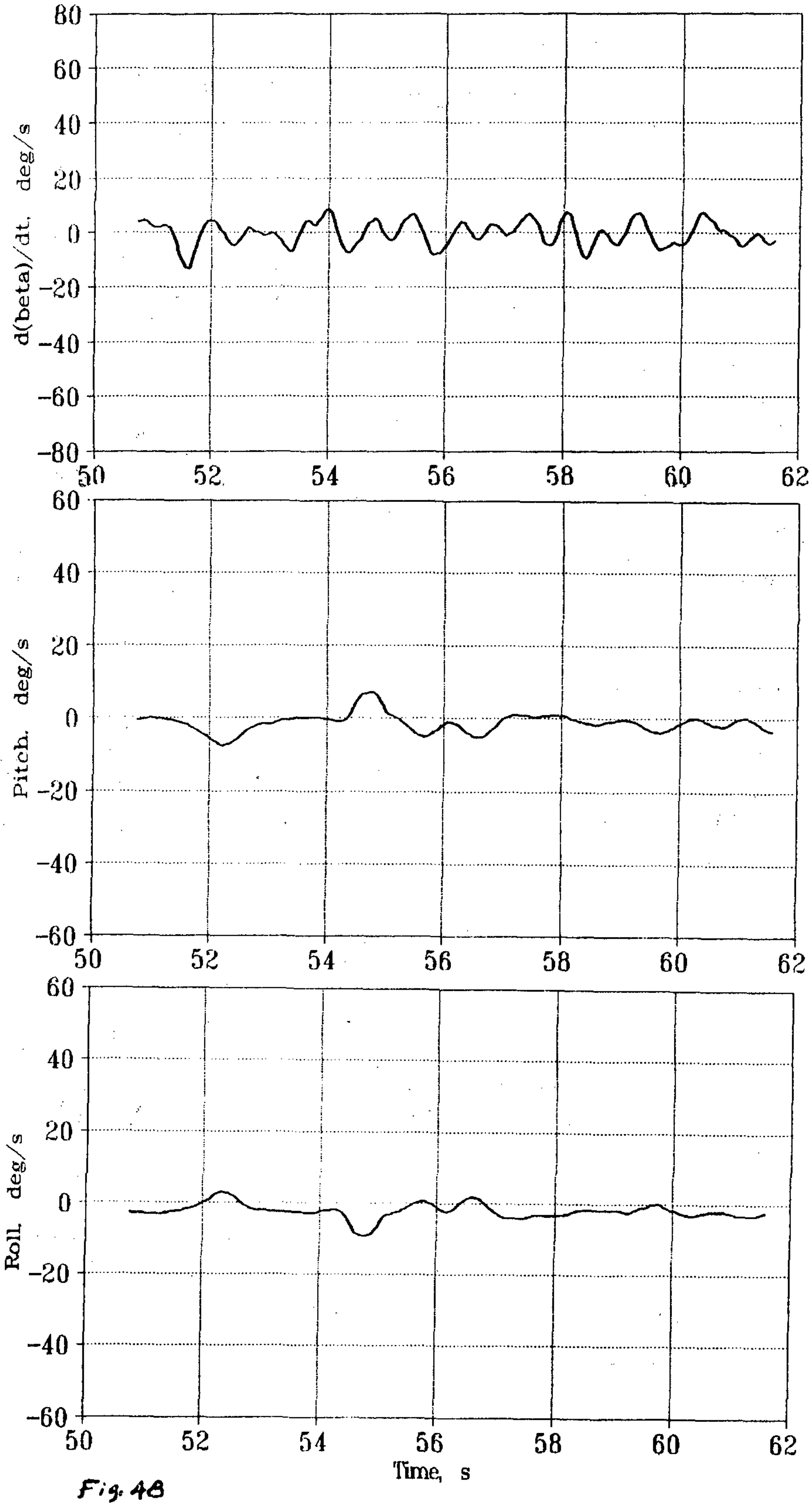


Fig. 48

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

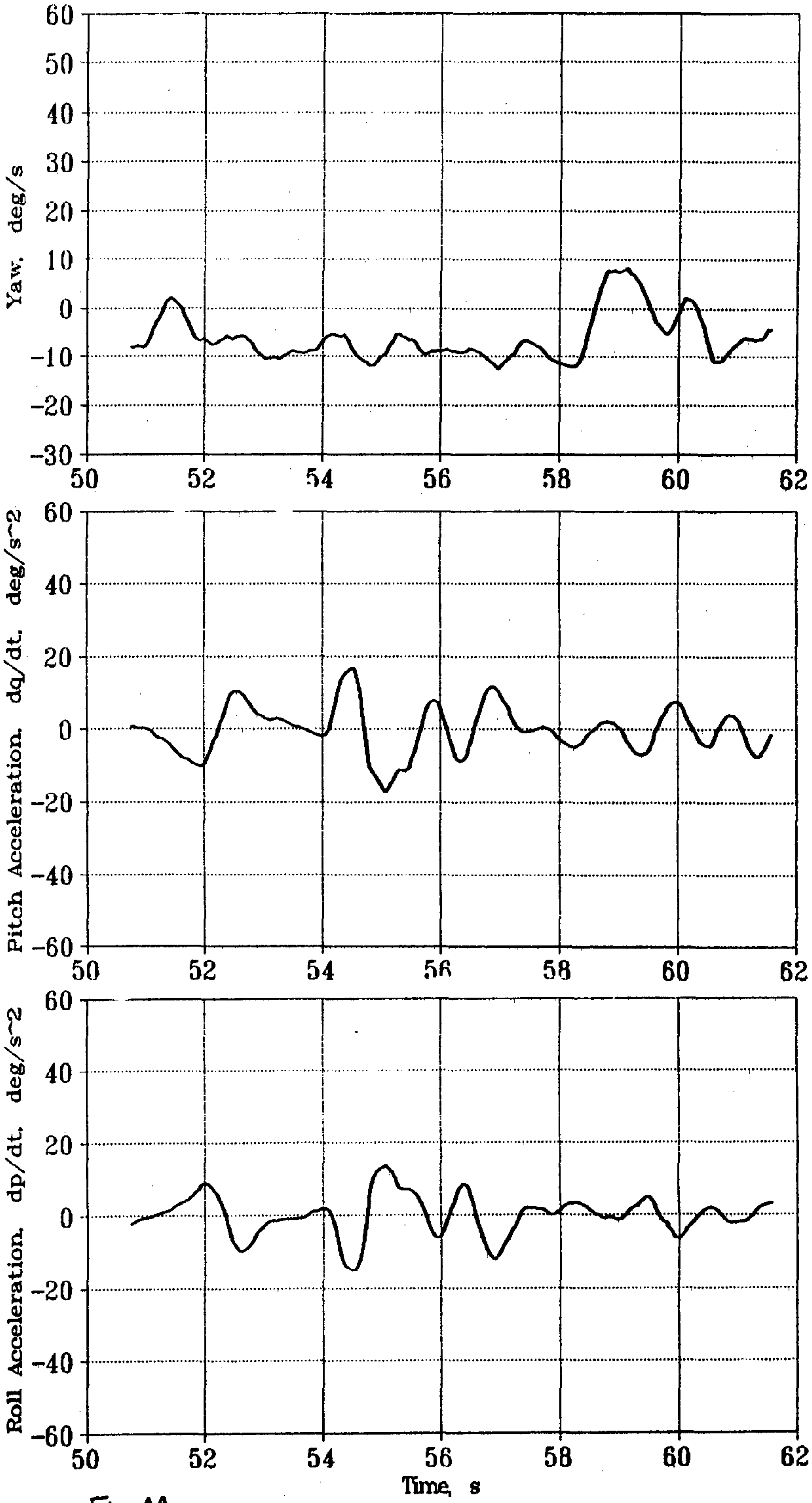


Fig. 49

'May 9, 91' Flight Tests

For Each Measured Channel [2 Channels per Variable ('Positive and Negative Channels')], Onboard Computer Numbers for Each Variable Are Independently Converted into Engineering Units by Means of The New Post-Flight Software, Variables Calibration Charts, Correspondence with the Video Tape Voice Commands, Time-Span and Ordinate-Scale Selections. The Time in Seconds Marked is Computer-Lines-Converted Time. It Corresponds with Video Time Since Recording 'Session Start'.

Flyer Command: Roll Reversal

By TV-Yaw + Aileron Commands

Recorded Flight Tests With

All Pre-Calibrated Probes & Instrumentation Onboard

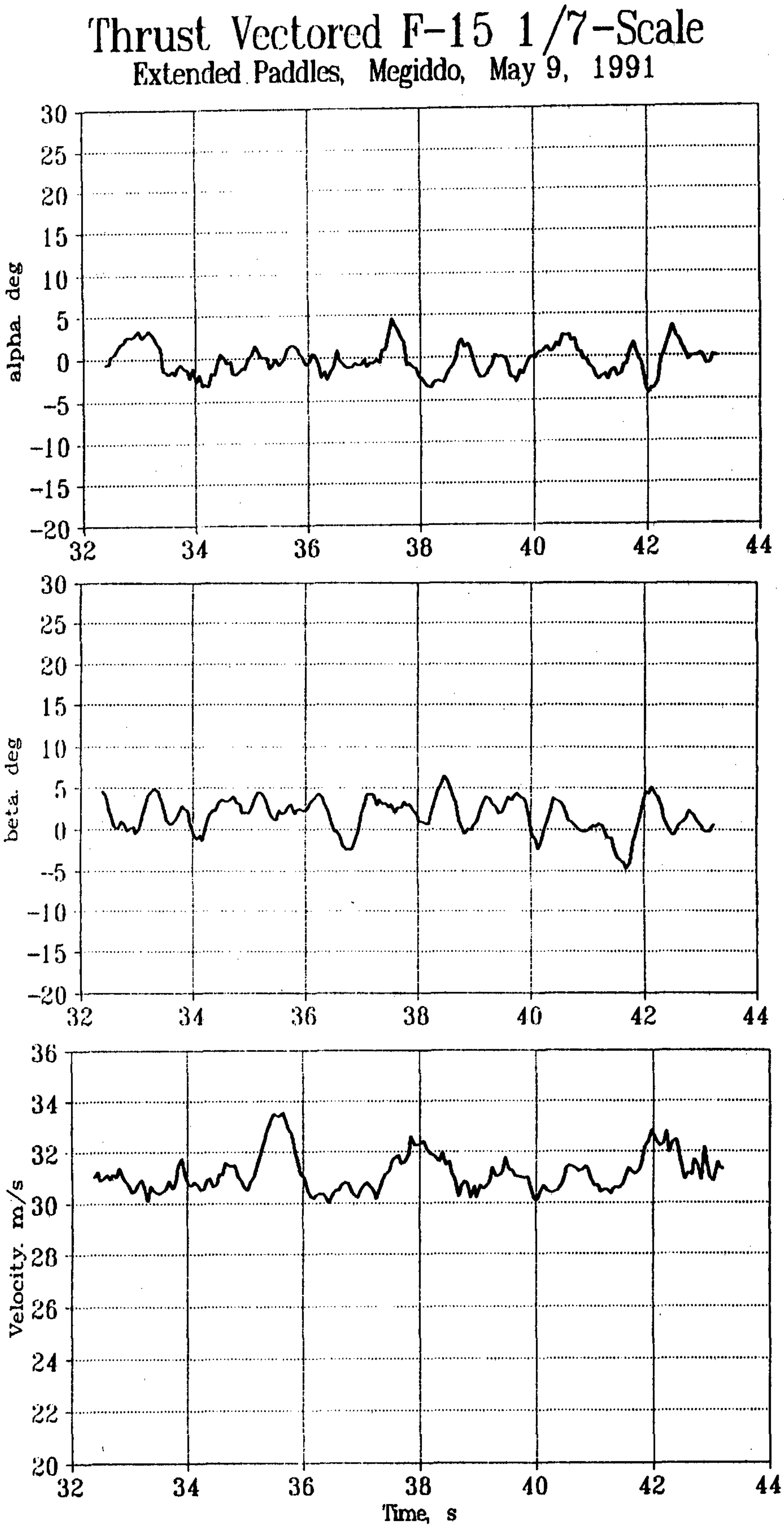

Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991
alpha deg
30
25
20
15
10
5
0
-5
-10
-15
-20
32
34
36
38
40
42
44
beta deg
30
25
20
15
10
5
0
-5
-10
-15
-20
32
34
36
38
40
42
44
Velocity m/s
36
34
32
30
28
26
24
22
20
32
34
36
38
40
42
44
Time, s

Fig. 50

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

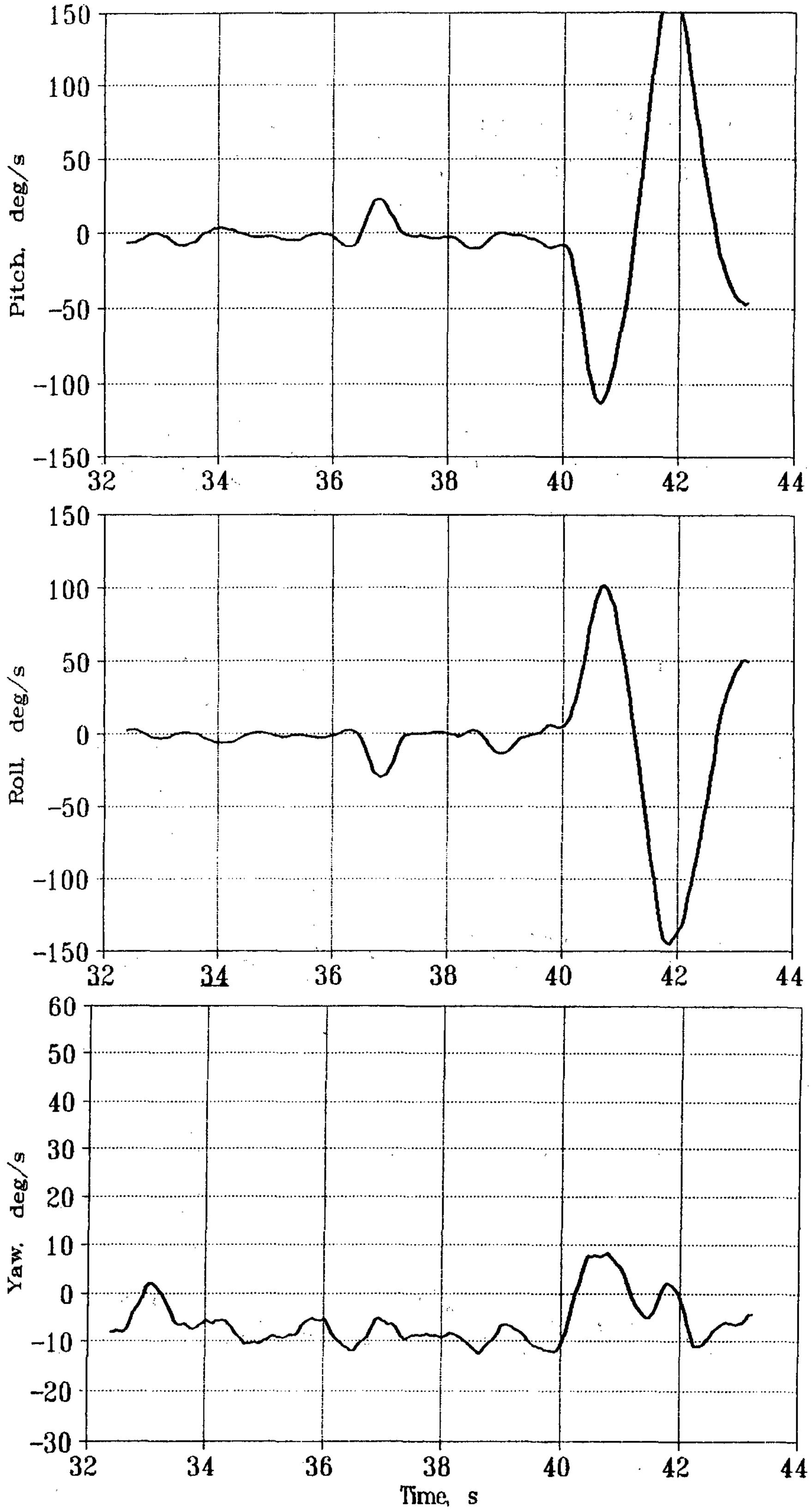


Fig. 51

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

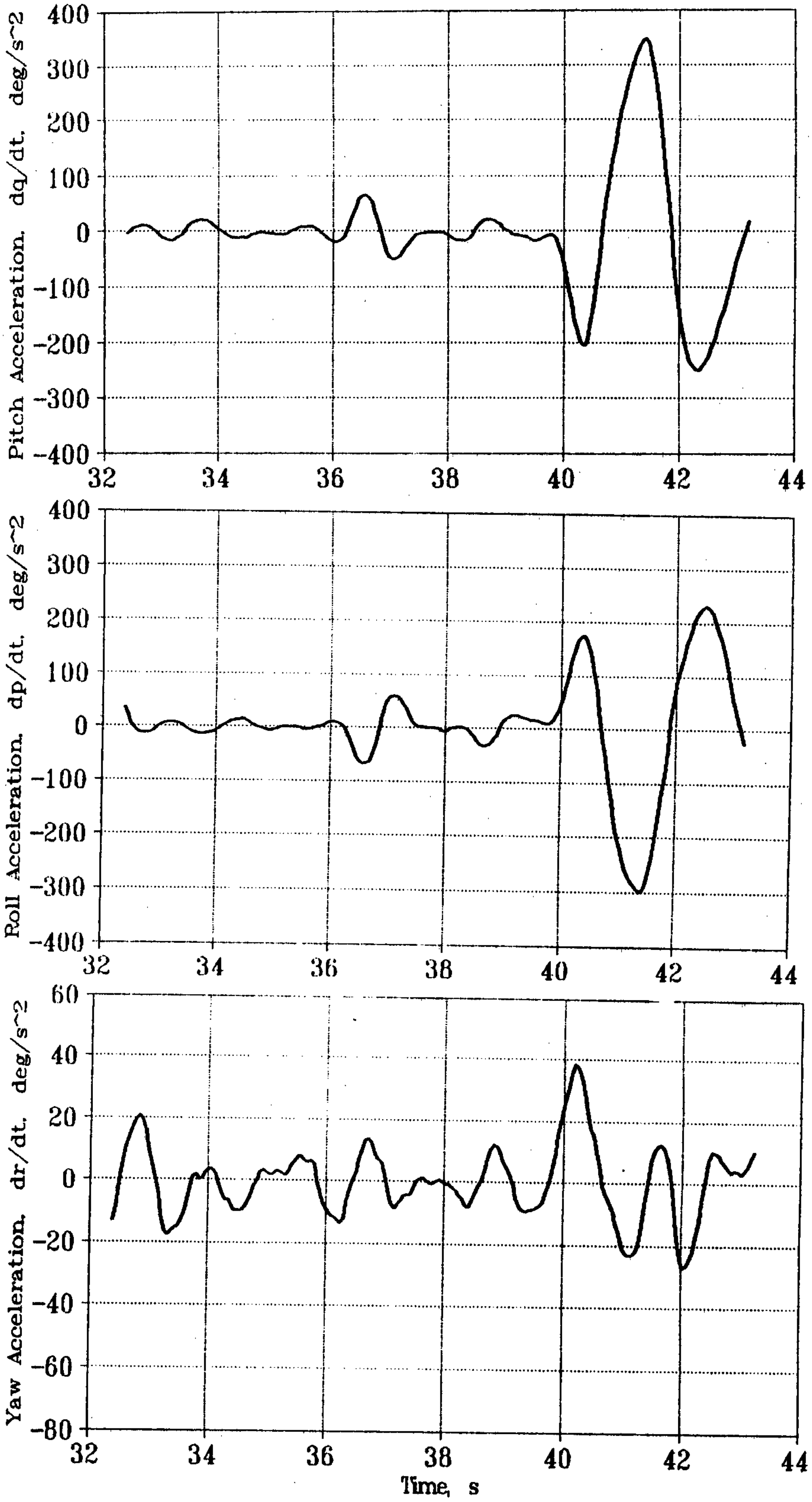
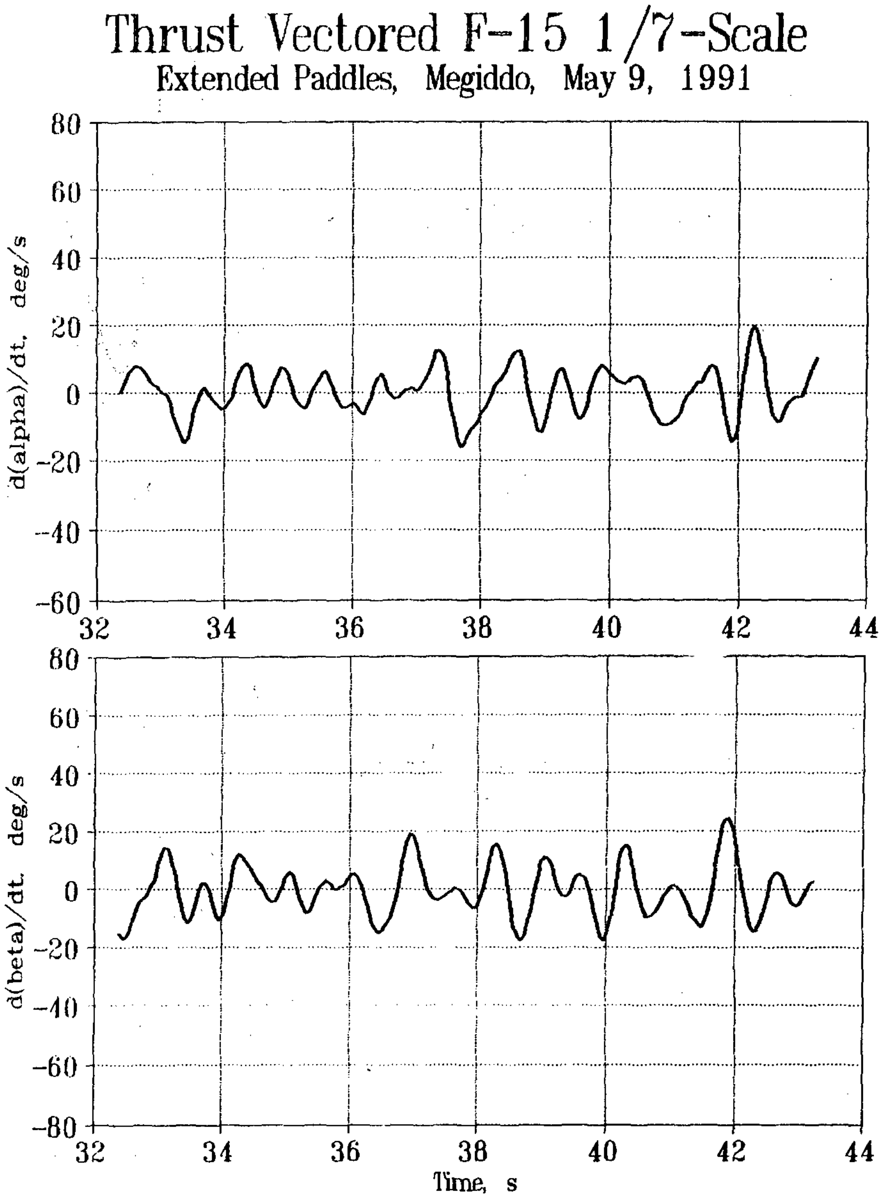


Fig. 52



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

Fig. 53

'May 9, 91' Flight Tests

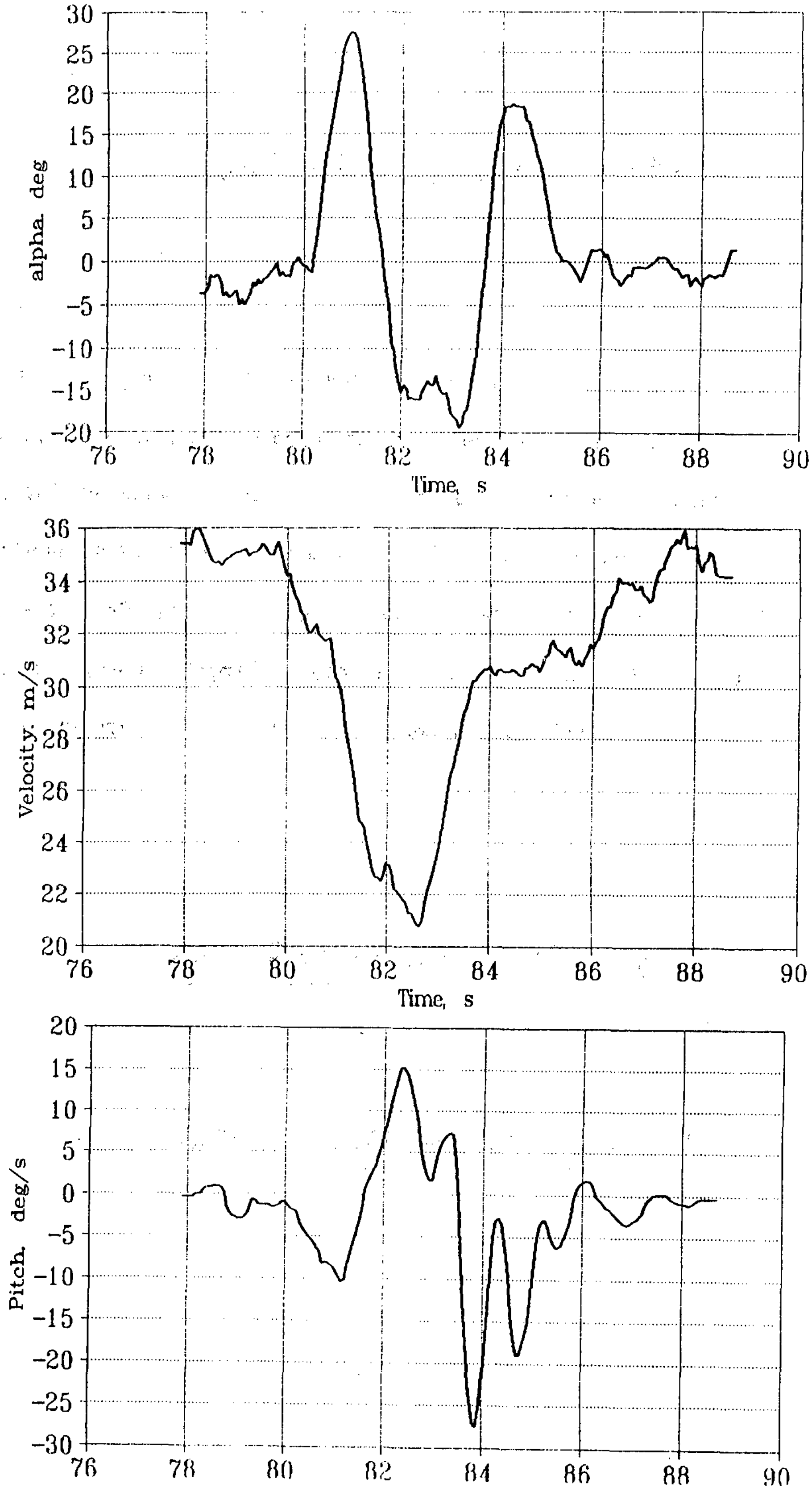
For Each Measured Channel [2 Channels per Variable ('Positive and Negative Channels'], Onboard Computer Numbers for Each Variable Are Independently Converted into Engineering Units by Means of The New Post-Flight Software, Variables Calibration Charts, Correspondence with the Video Tape Voice Commands, Time-Span and Ordinate-Scale Selections. The Time in Seconds Marked is Computer-Lines-Converted Time. It Corresponds with Video Time Since Recording 'Session Start'.

Flyer Command: Pitch Reversal

By TV-Pitch + Conventional Elevator Command

Recorded Flight Tests With

All Pre-Calibrated Probes & Instrumentation Onboard



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

Fig. 54

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

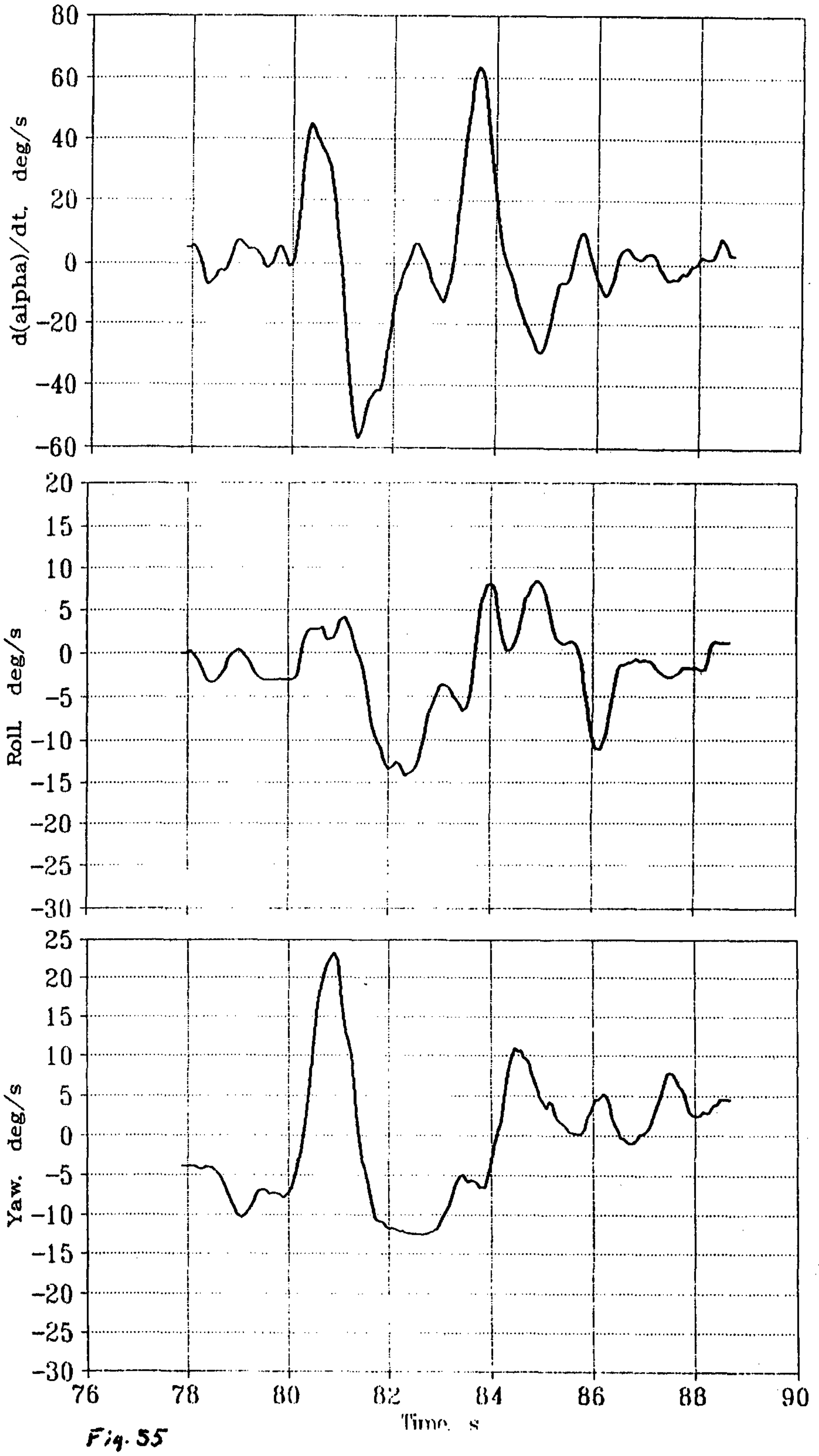
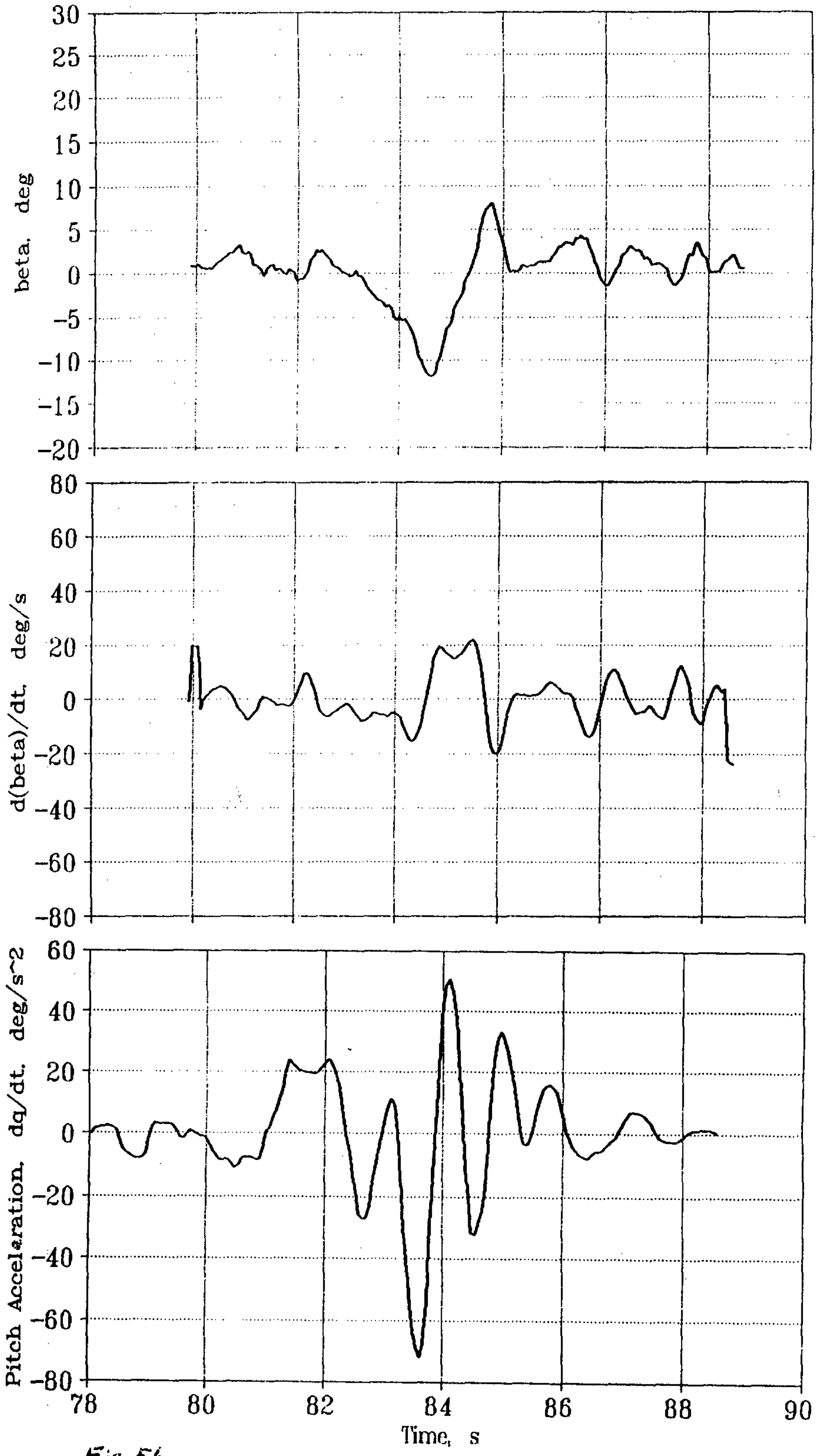


Fig. 55



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

Fig. 5b

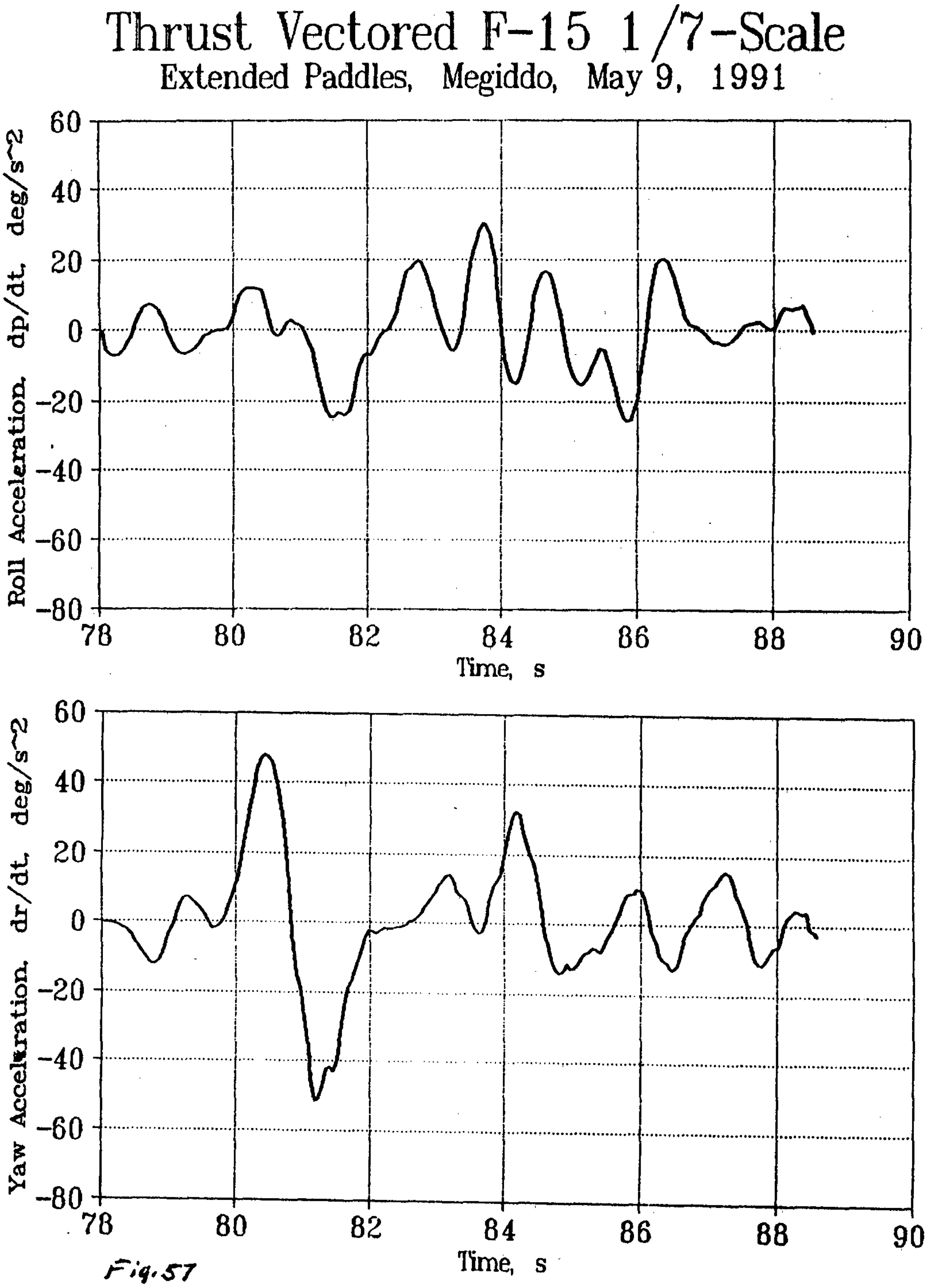

Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991
Roll Acceleration, dp/dt, deg/s^2
60
40
20
0
-20
-40
-60
-80
78
80
82
84
86
88
90
Time, s
Yaw Acceleration, dr/dt, deg/s^2
60
40
20
0
-20
-40
-60
-80
78
80
82
84
86
88
90
Time, s

Fig. 57

'May 9, 91' Flight Tests

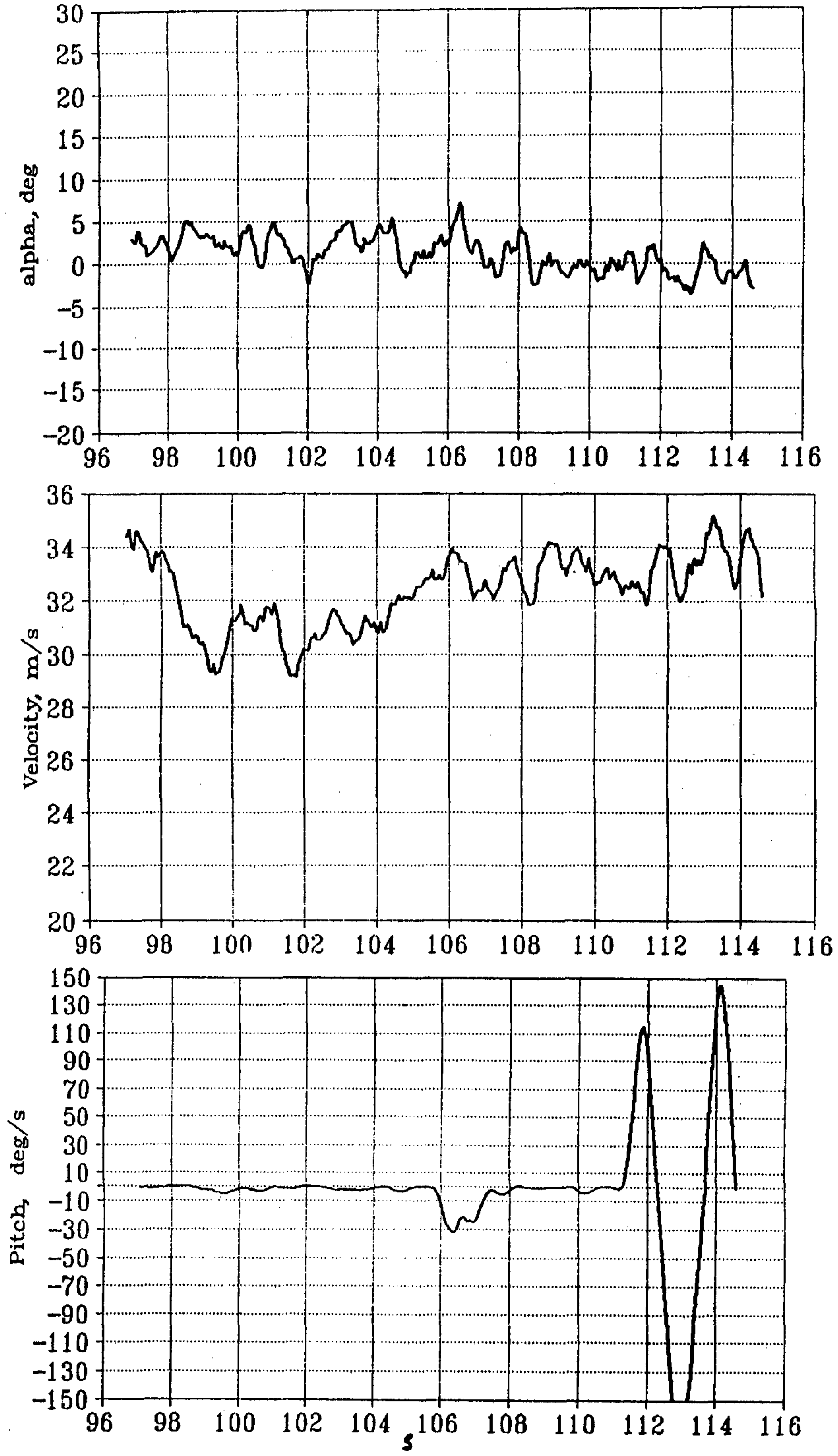
For Each Measured Channel [2 Channels per Variable ('Positive and Negative Channels')], Onboard Computer Numbers for Each Variable Are Independently Converted into Engineering Units by Means of The New Post-Flight Software, Variables Calibration Charts, Correspondence with the Video Tape Voice Commands, Time-Span and Ordinate-Scale Selections. The Time in Seconds Marked is Computer-Lines-Converted Time. It Corresponds with Video Time Since Recording 'Session Start'.

Flyer Command: Roll Reversal

By TV-Yaw + Aileron Commands

Recorded Flight Tests With

All Pre-Calibrated Probes & Instrumentation Onboard



Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

Fig. 58

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

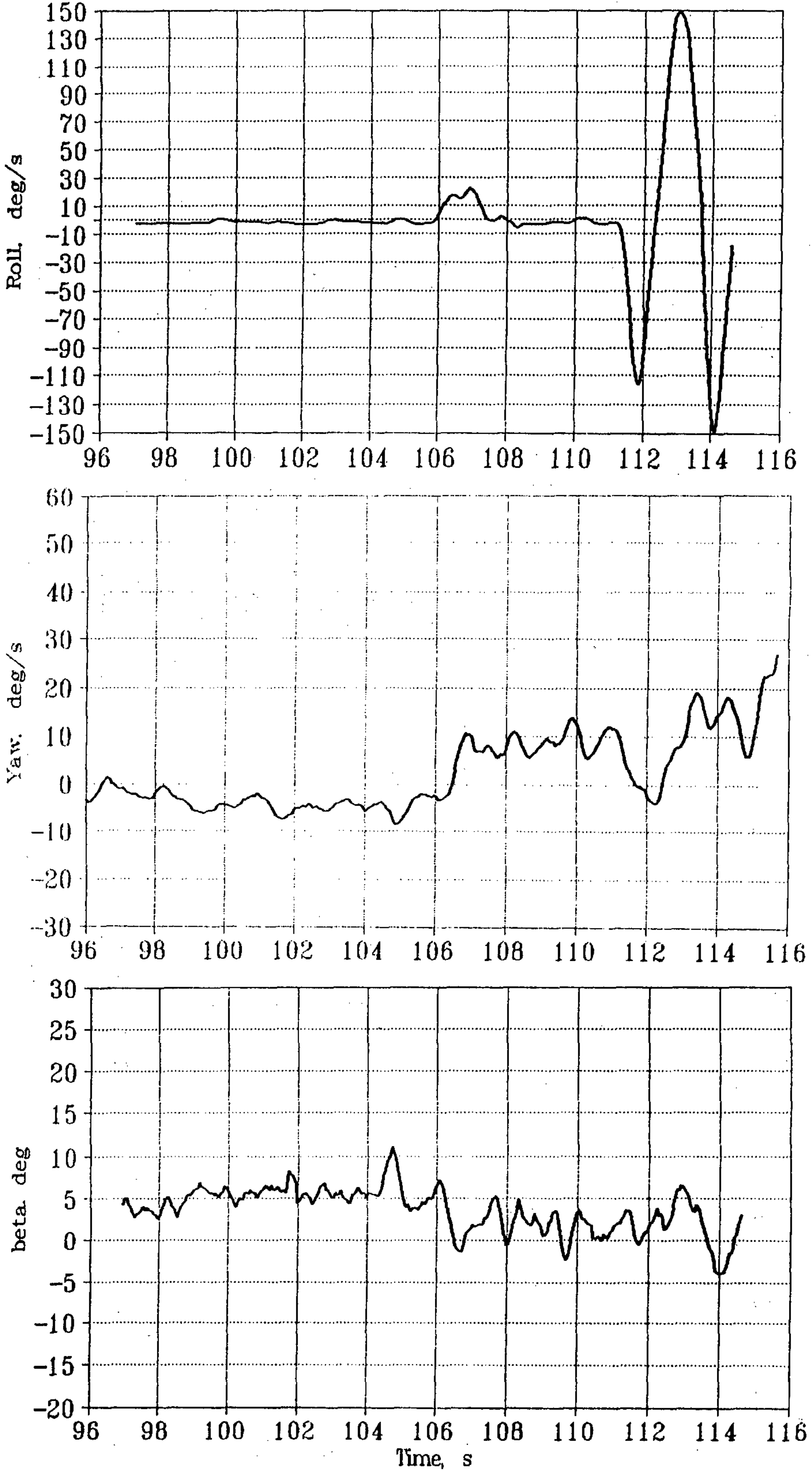
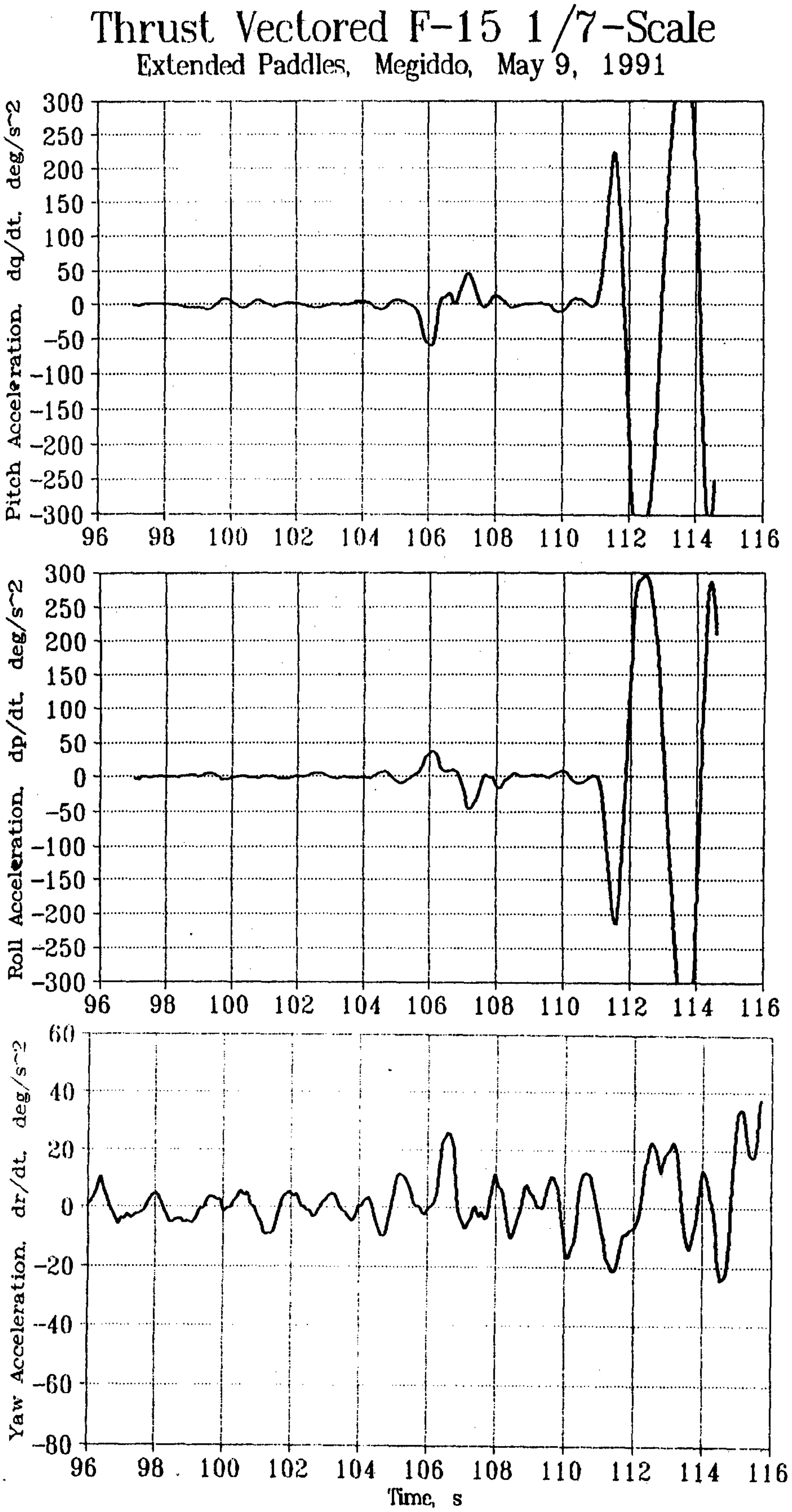
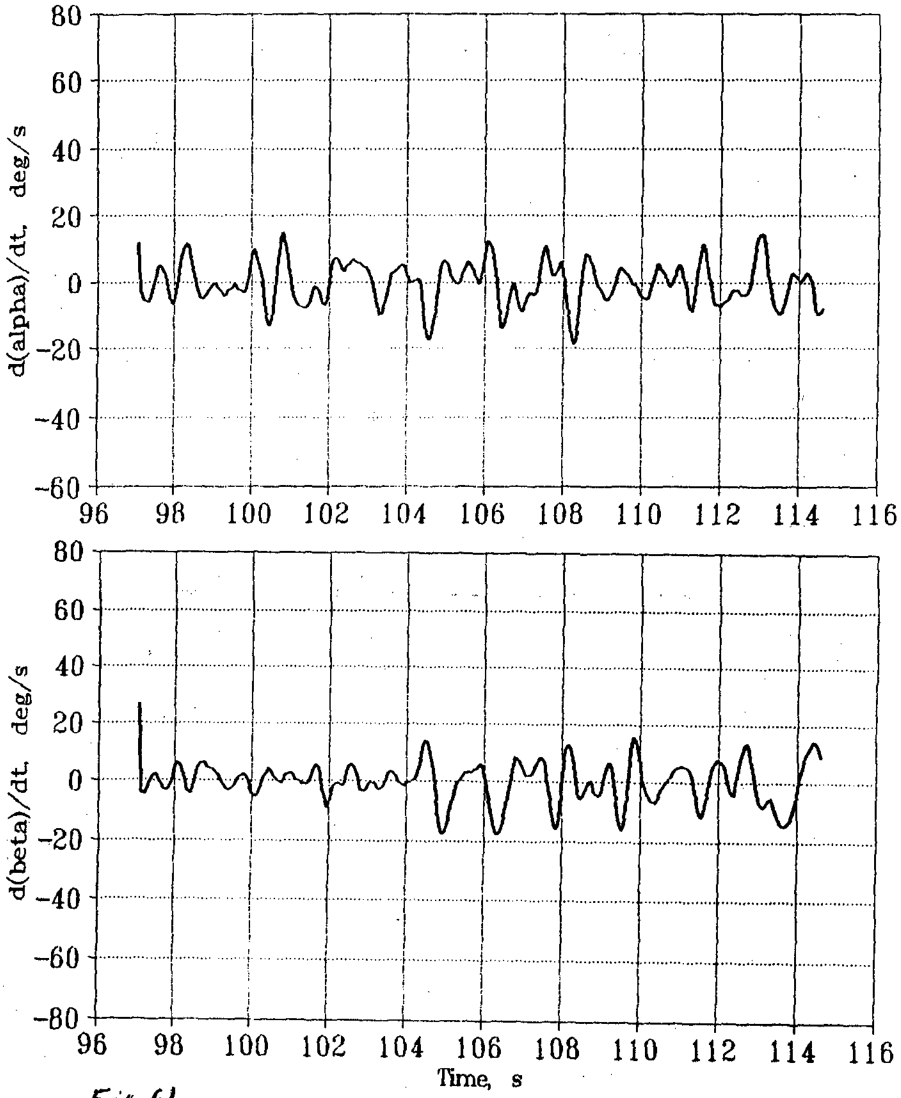


Fig. 59



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

Fig. 60



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

Fig. 61

'May 9, 91' Flight Tests

For Each Measured Channel [2 Channels per Variable ('Positive and Negative Channels')], Onboard Computer Numbers for Each Variable Are Independently Converted into Engineering Units by Means of The New Post-Flight Software, Variables Calibration Charts, Correspondence with the Video Tape Voice Commands, Time-Span and Ordinate-Scale Selections. The Time in Seconds Marked is Computer-Lines-Converted Time. It Corresponds with Video Time Since Recording 'Session Start'.

Flyer Command: Roll Reversal

By Conventional Aileron Command

Recorded Flight Tests With

All Pre-Calibrated Probes & Instrumentation Onboard

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

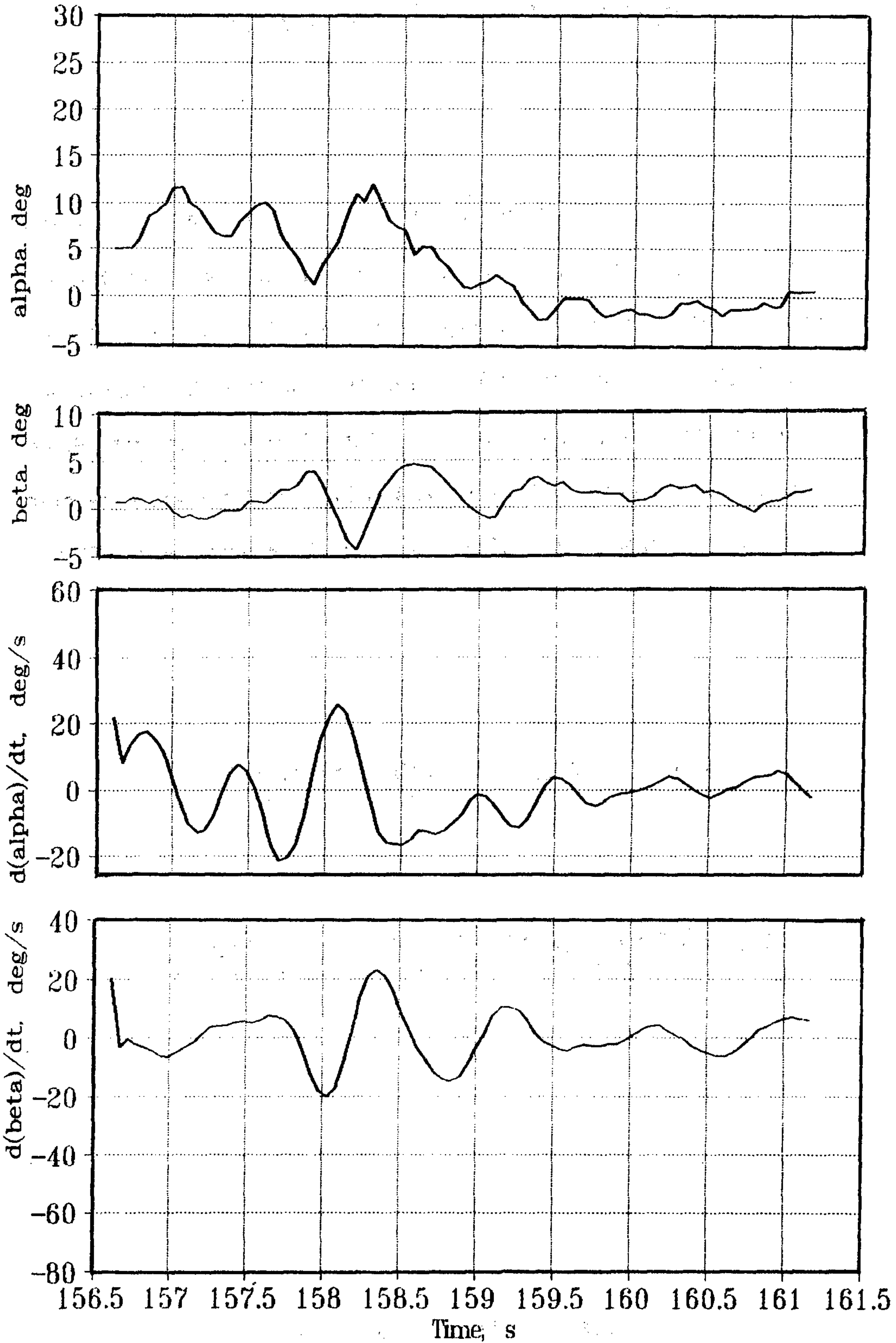
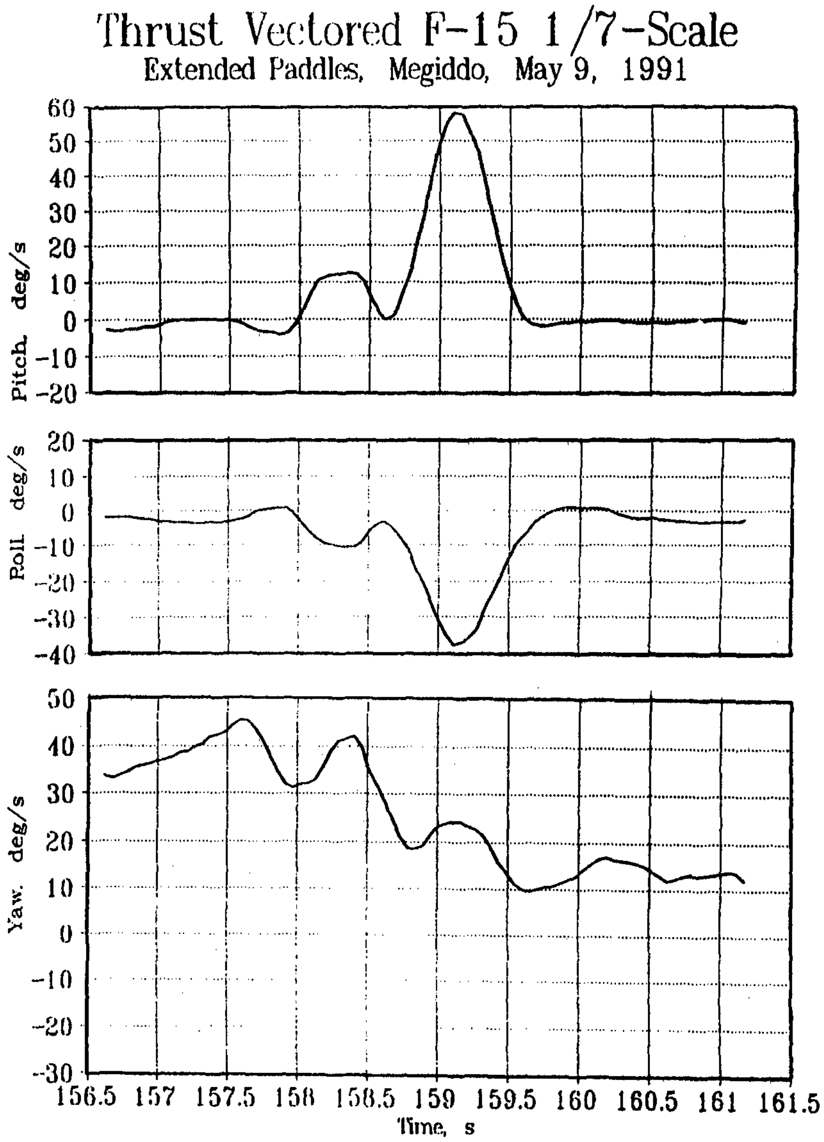
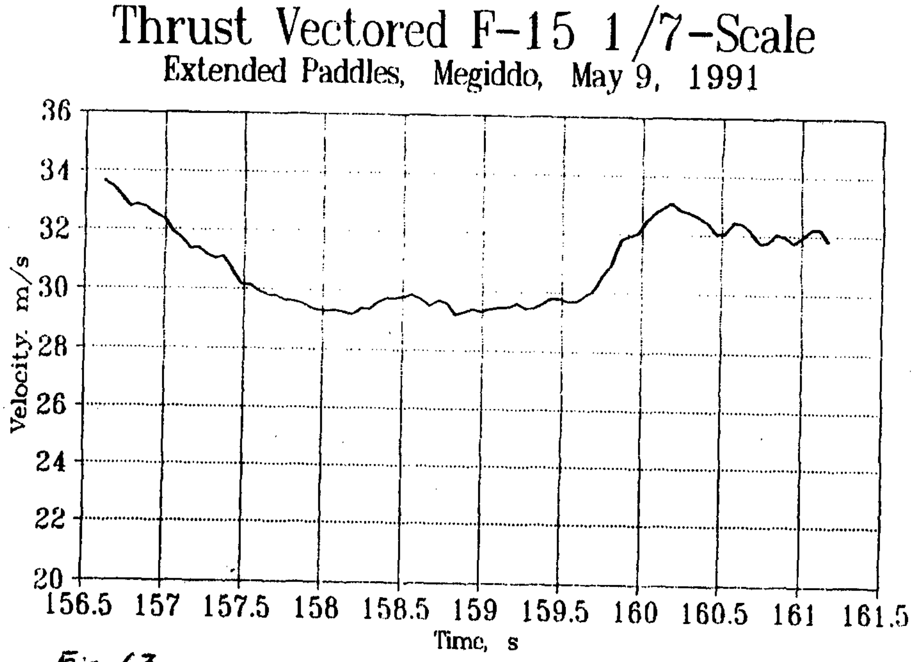


Fig. 62



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

Fig. 63

Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

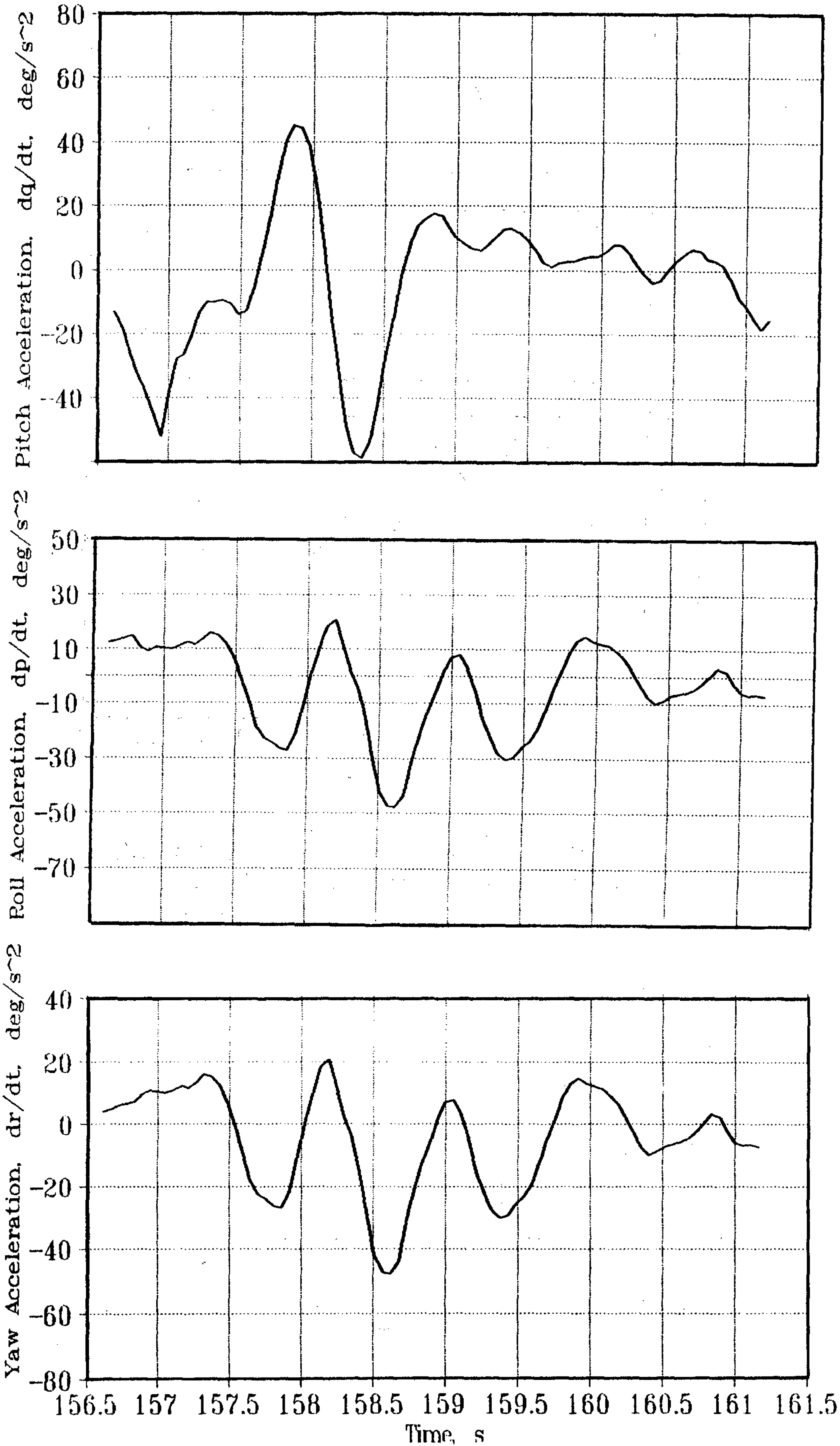


Fig. 64

'May 9, 91' Flight Tests

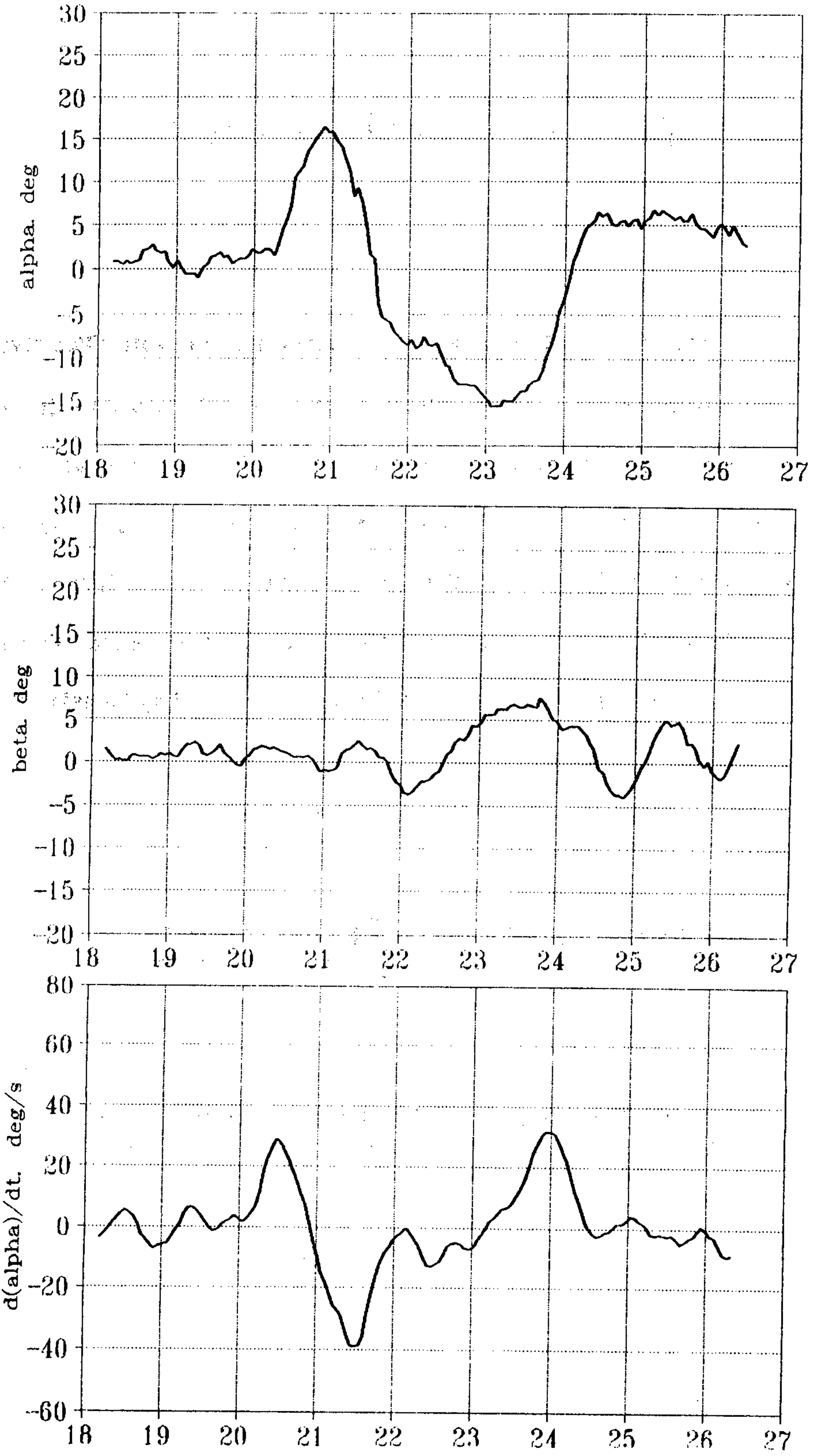
For Each Measured Channel [2 Channels per Variable ('Positive and Negative Channels'], Onboard Computer Numbers for Each Variable Are Independently Converted into Engineering Units by Means of The New Post-Flight Software, Variables Calibration Charts, Correspondence with the Video Tape Voice Commands, Time-Span and Ordinate-Scale Selections. The Time in Seconds Marked is Computer-Lines-Converted Time. It Corresponds with Video Time Since Recording 'Session Start'.

Flyer Command: Pitch Reversal

By Conventional Elevator Command

Recorded Flight Tests With

All Pre-Calibrated Probes & Instrumentation Onboard



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

F.g. 65

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

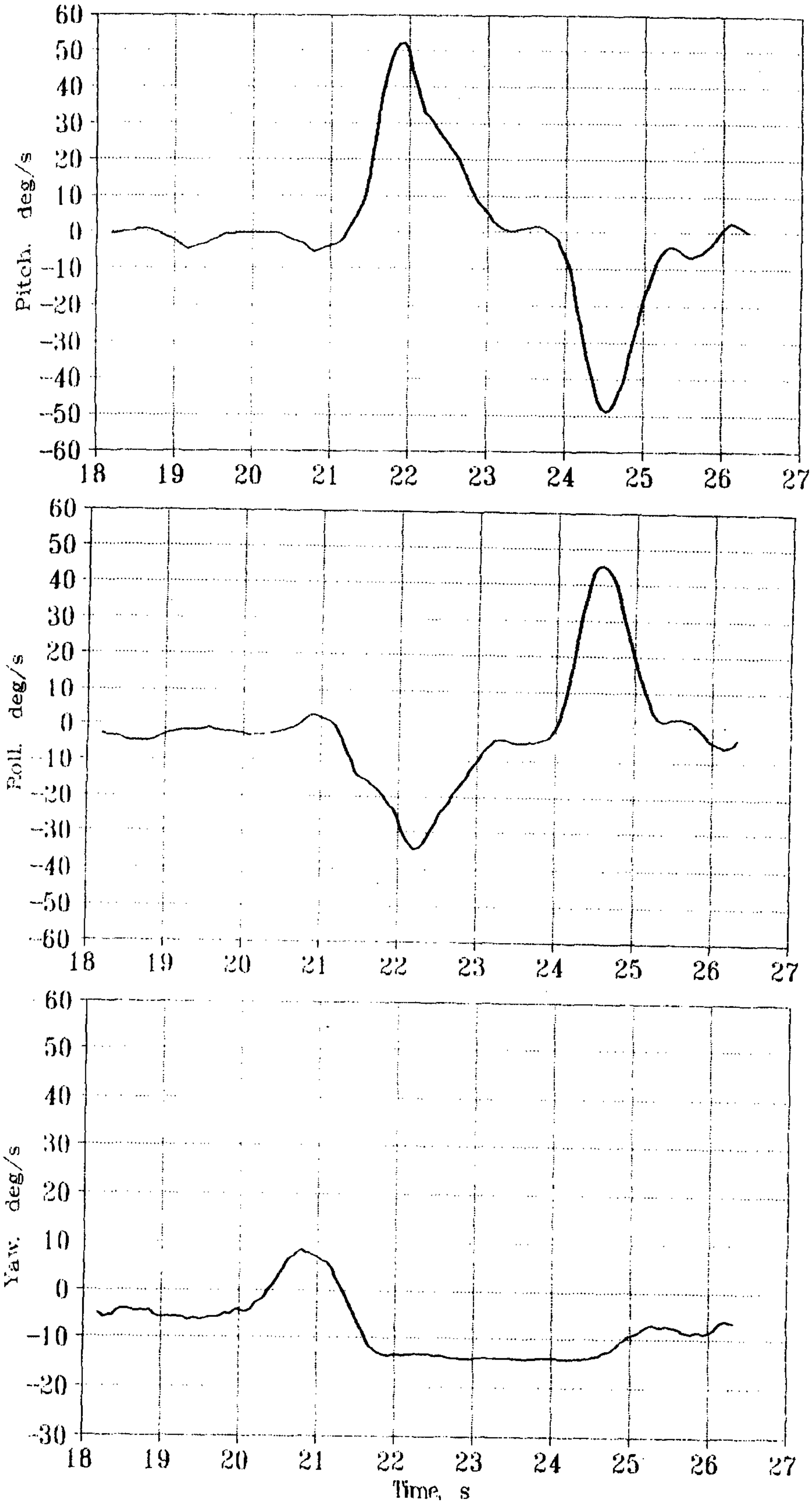
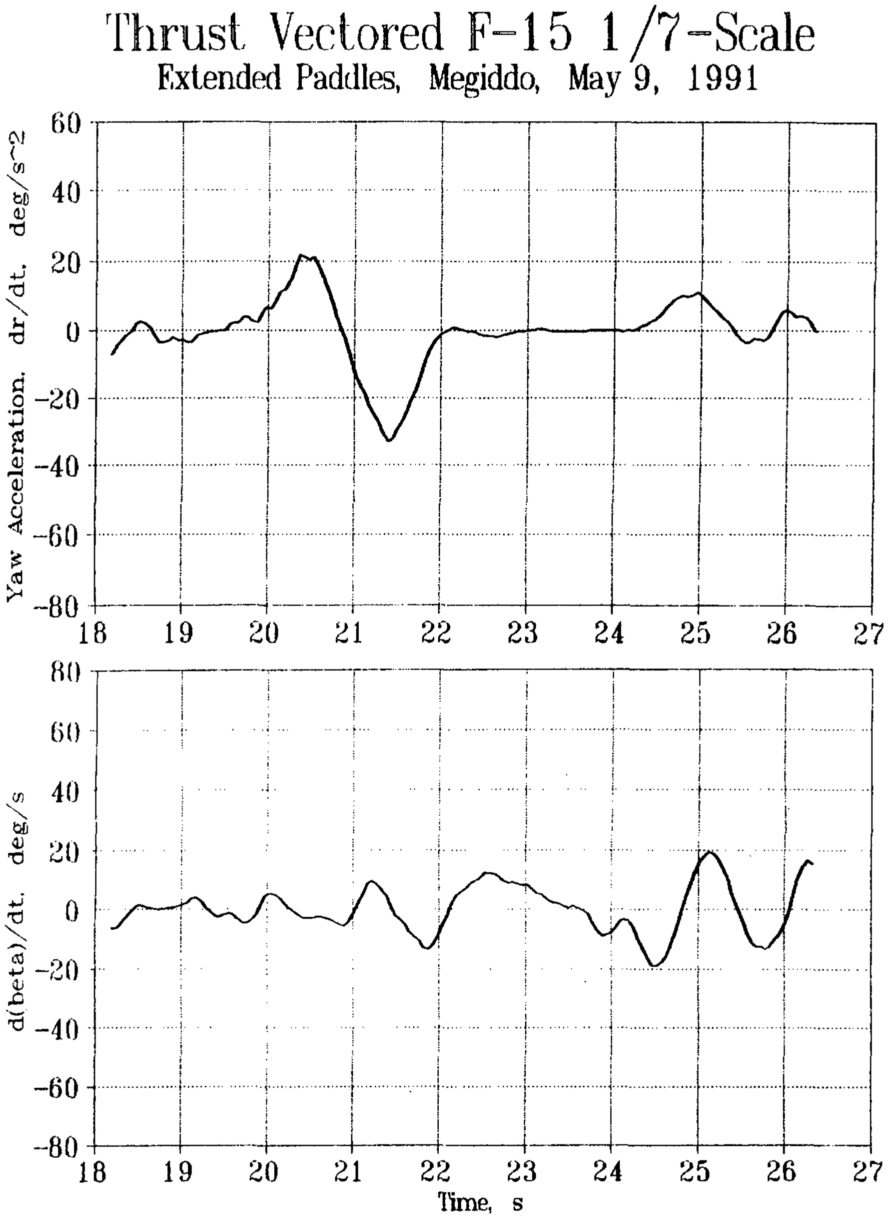


Fig. 66



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

Fig. 67

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

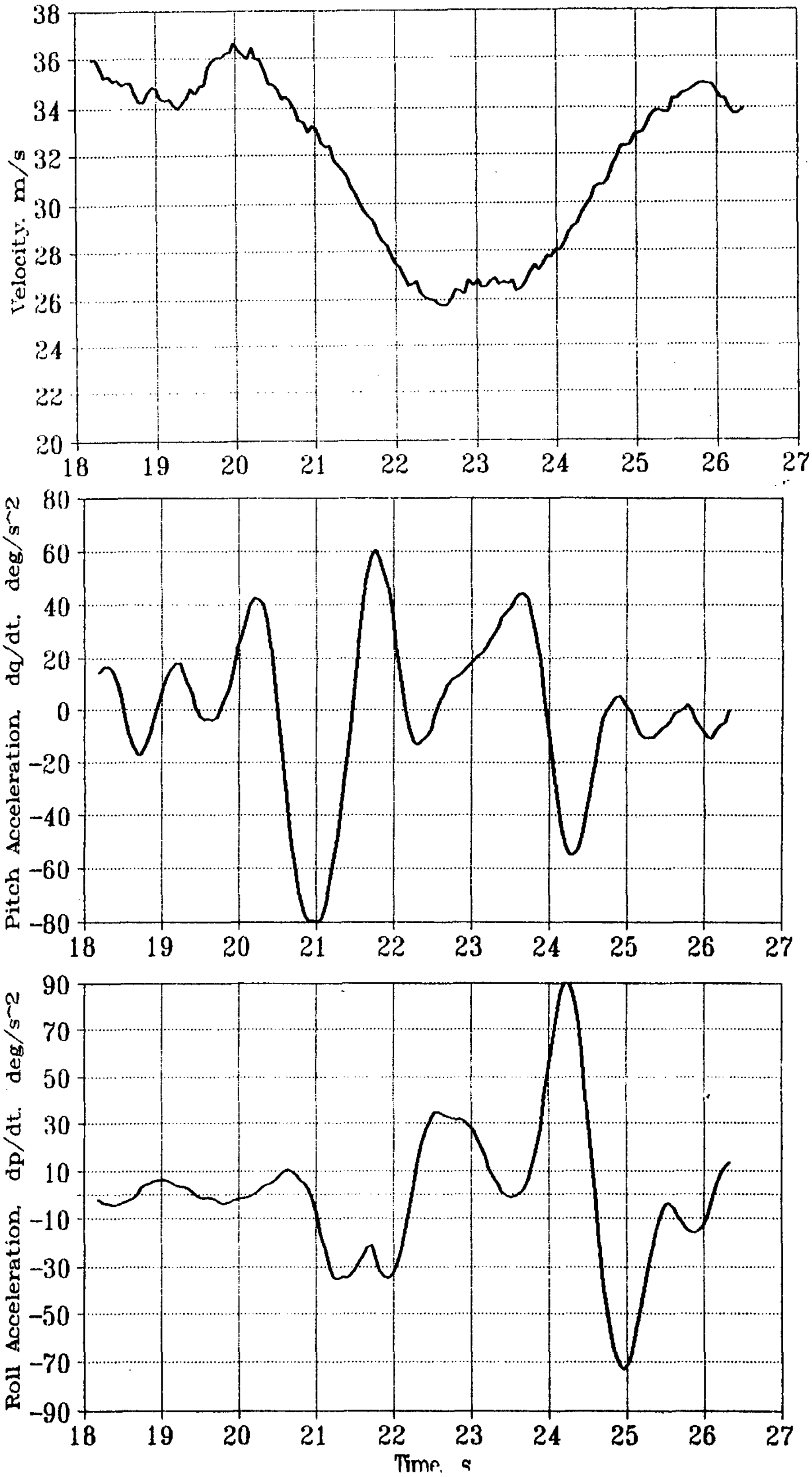


Fig. 68

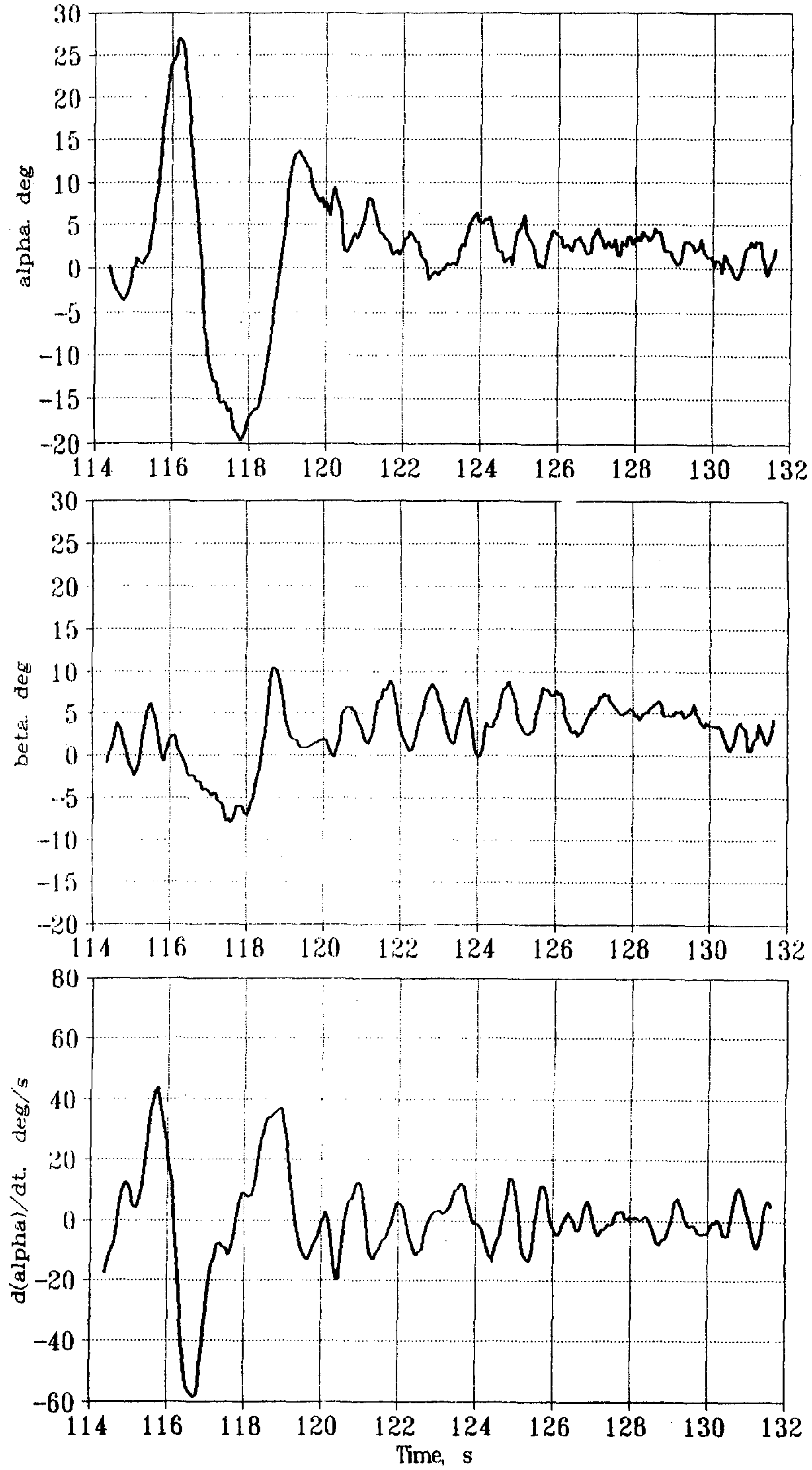
'May 9, 91' Flight Tests

For Each Measured Channel [2 Channels per Variable ('Positive and Negative Channels'], Onboard Computer Numbers for Each Variable Are Independently Converted into Engineering Units by Means of The New Post-Flight Software, Variables Calibration Charts, Correspondence with the Video Tape Voice Commands, Time-Span and Ordinate-Scale Selections. The Time in Seconds Marked is Computer-Lines-Converted Time. It Corresponds with Video Time Since Recording 'Session Start'.

Flyer Command: Roll Reversal

By Conventional Ailerons Command

Recorded Flight Tests With
All Pre-Calibrated Probes & Instrumentation Onboard



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

Fig. 64

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

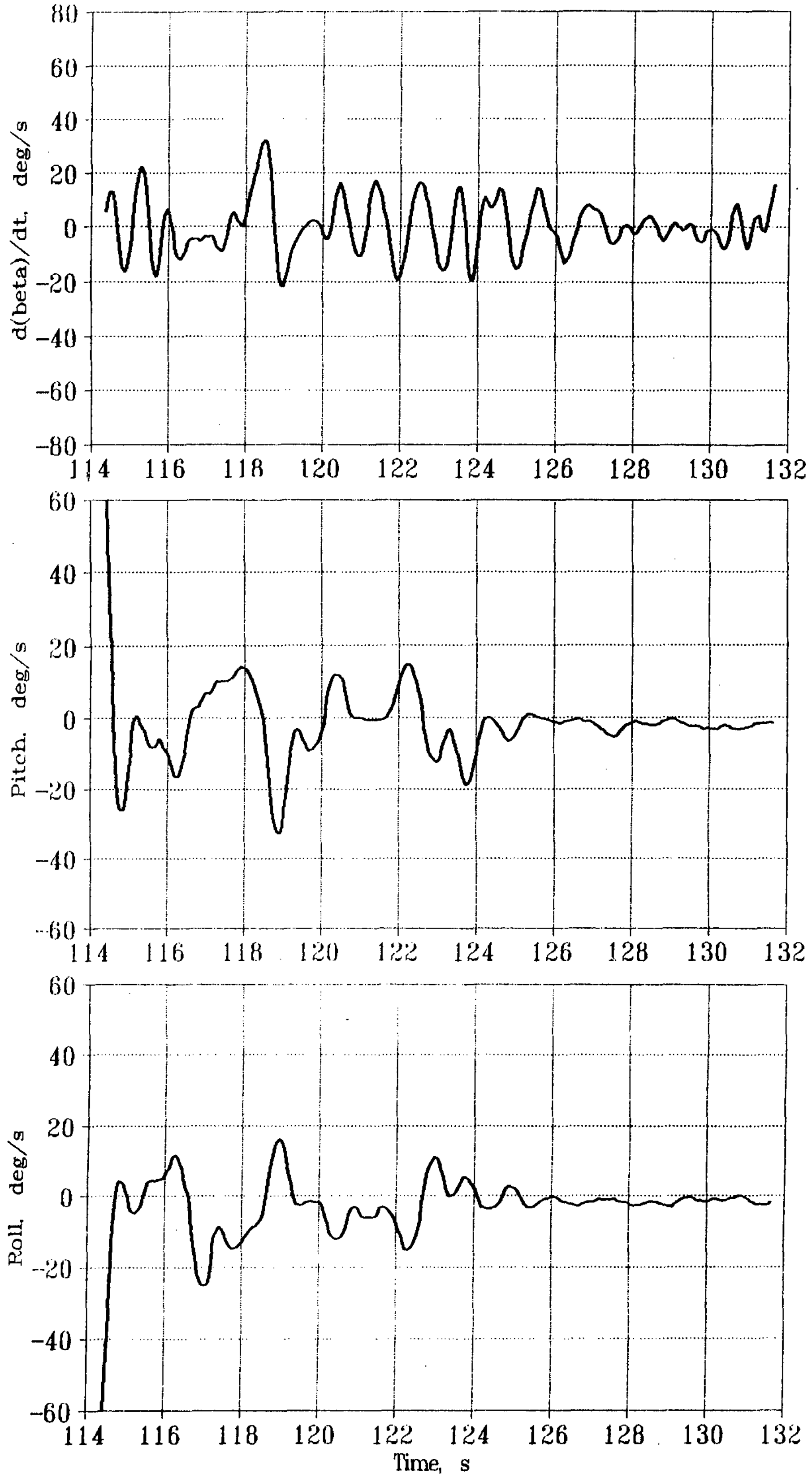
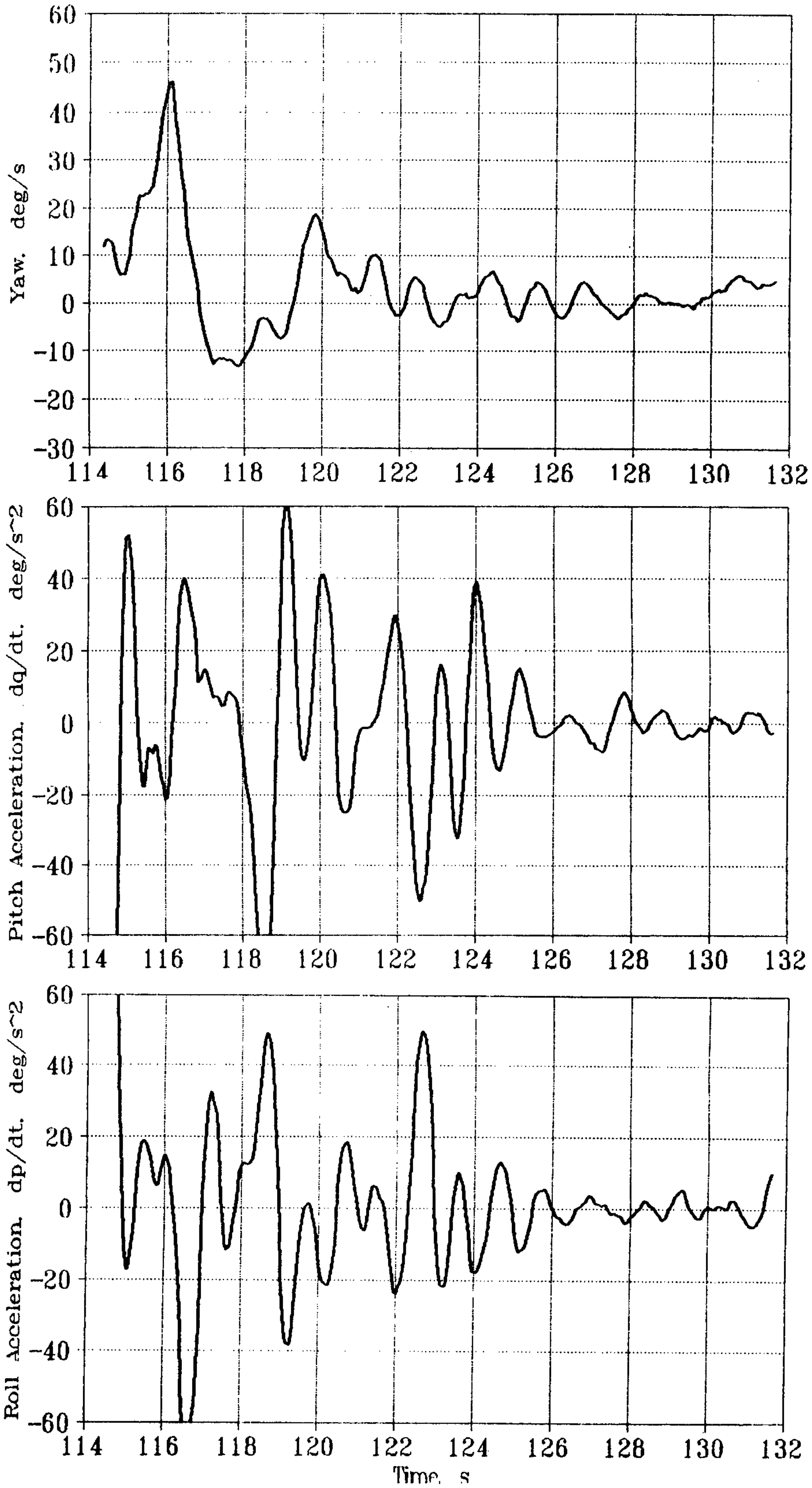
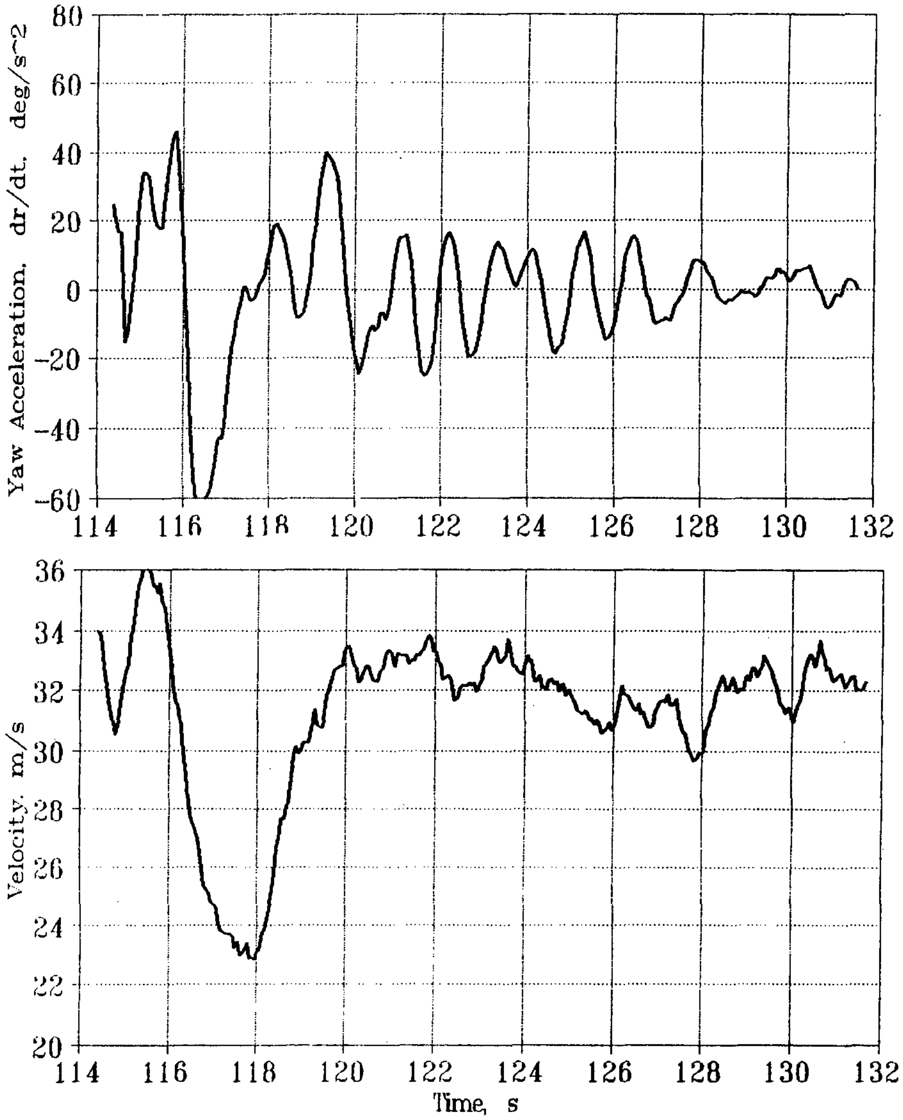


Fig. 70



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

Fig. 71


Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

Fig. 72

'May 9, 91' Flight Tests

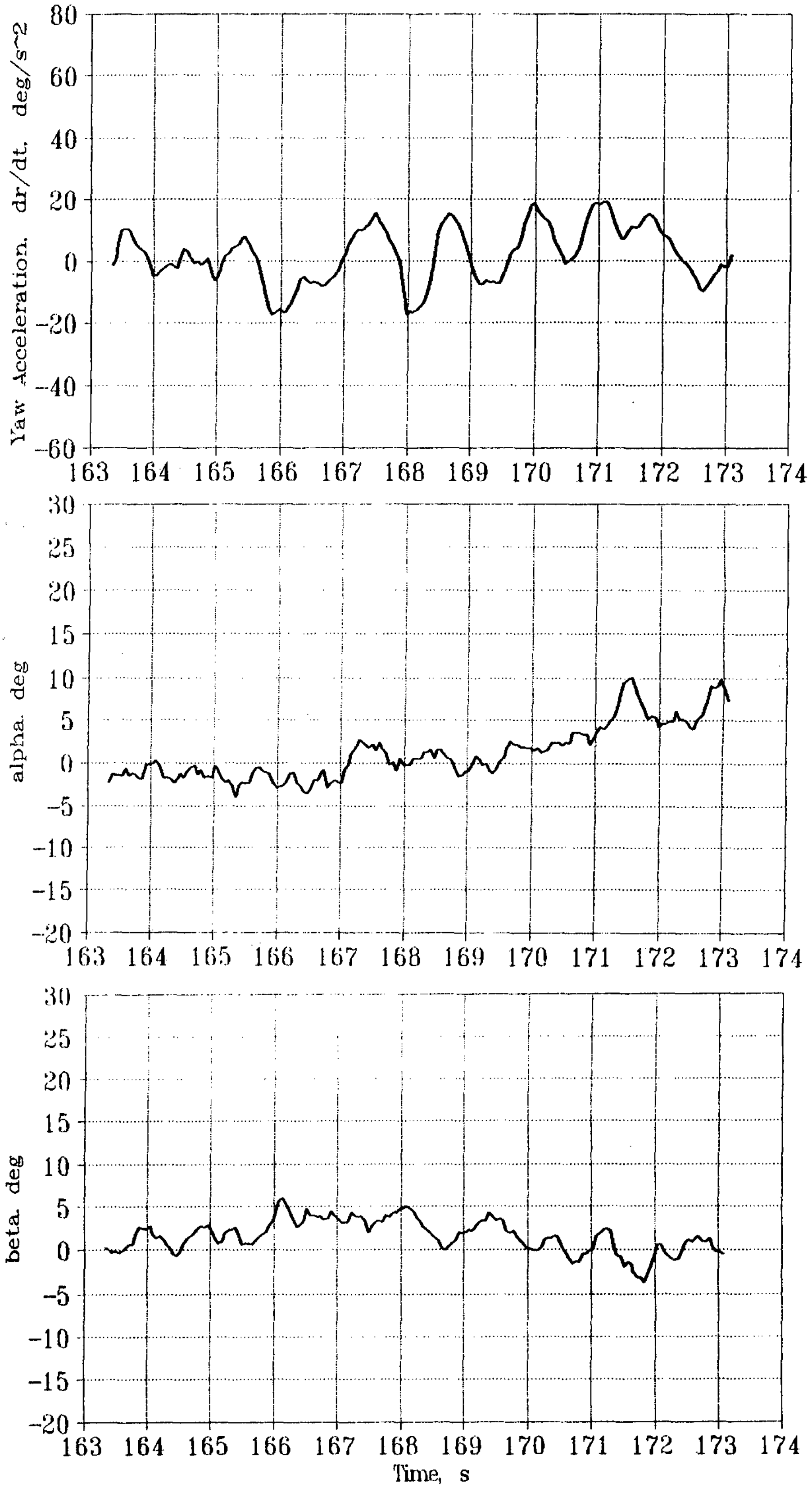
For Each Measured Channel [2 Channels per Variable ('Positive and Negative Channels')], Onboard Computer Numbers for Each Variable Are Independently Converted into Engineering Units by Means of The New Post-Flight Software, Variables Calibration Charts, Correspondence with the Video Tape Voice Commands, Time-Span and Ordinate-Scale Selections. The Time in Seconds Marked is Computer-Lines-Converted Time. It Corresponds with Video Time Since Recording 'Session Start'.

Flyer Command: Pitch Reversal

By TV-Pitch Command

Recorded Flight Tests With

All Pre-Calibrated Probes & Instrumentation Onboard



Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

Fig. 73

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991

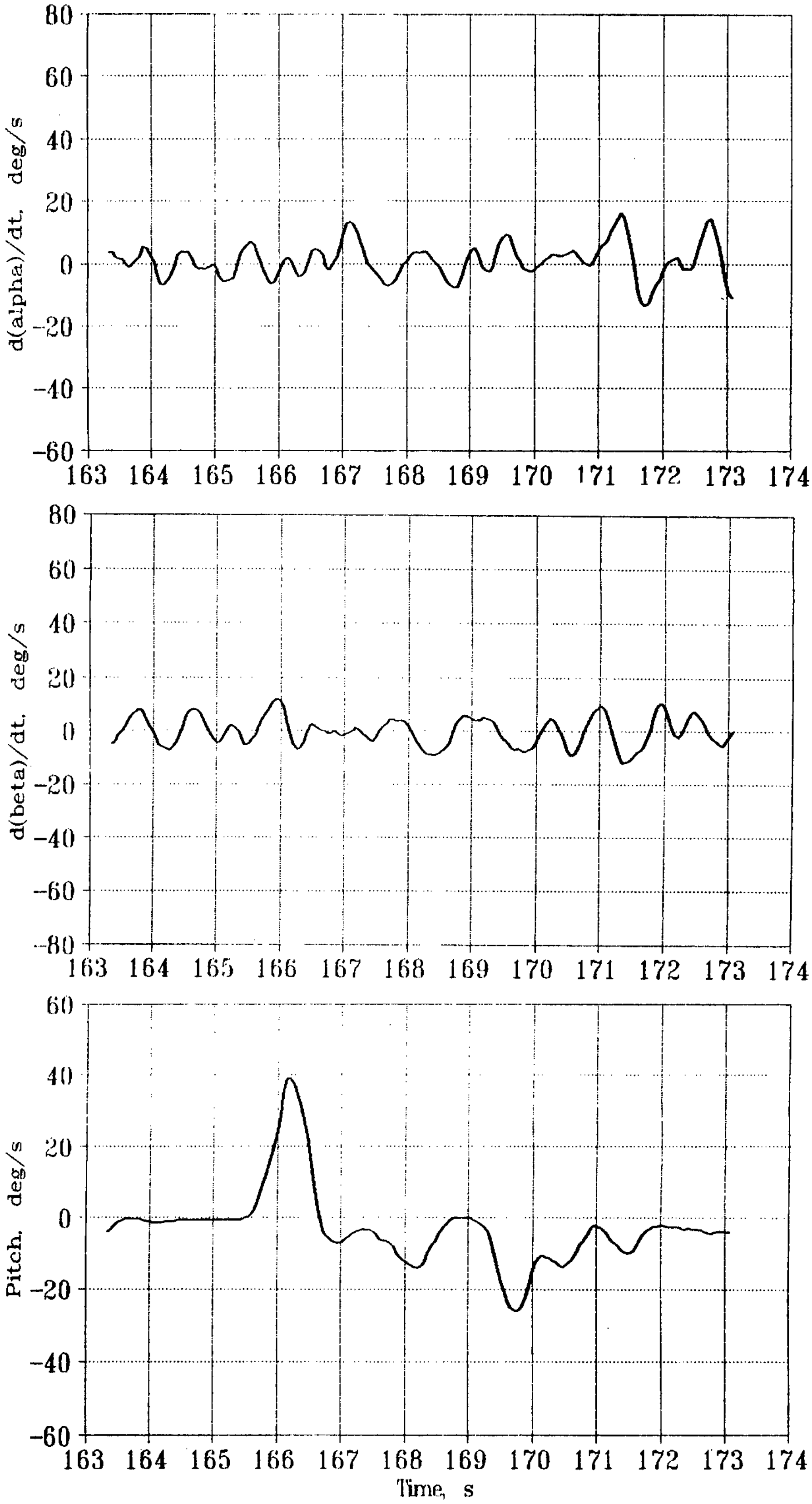


Fig. 74

Thrust Vectored F-15 1/7-Scale
Extended Paddles, Megiddo, May 9, 1991

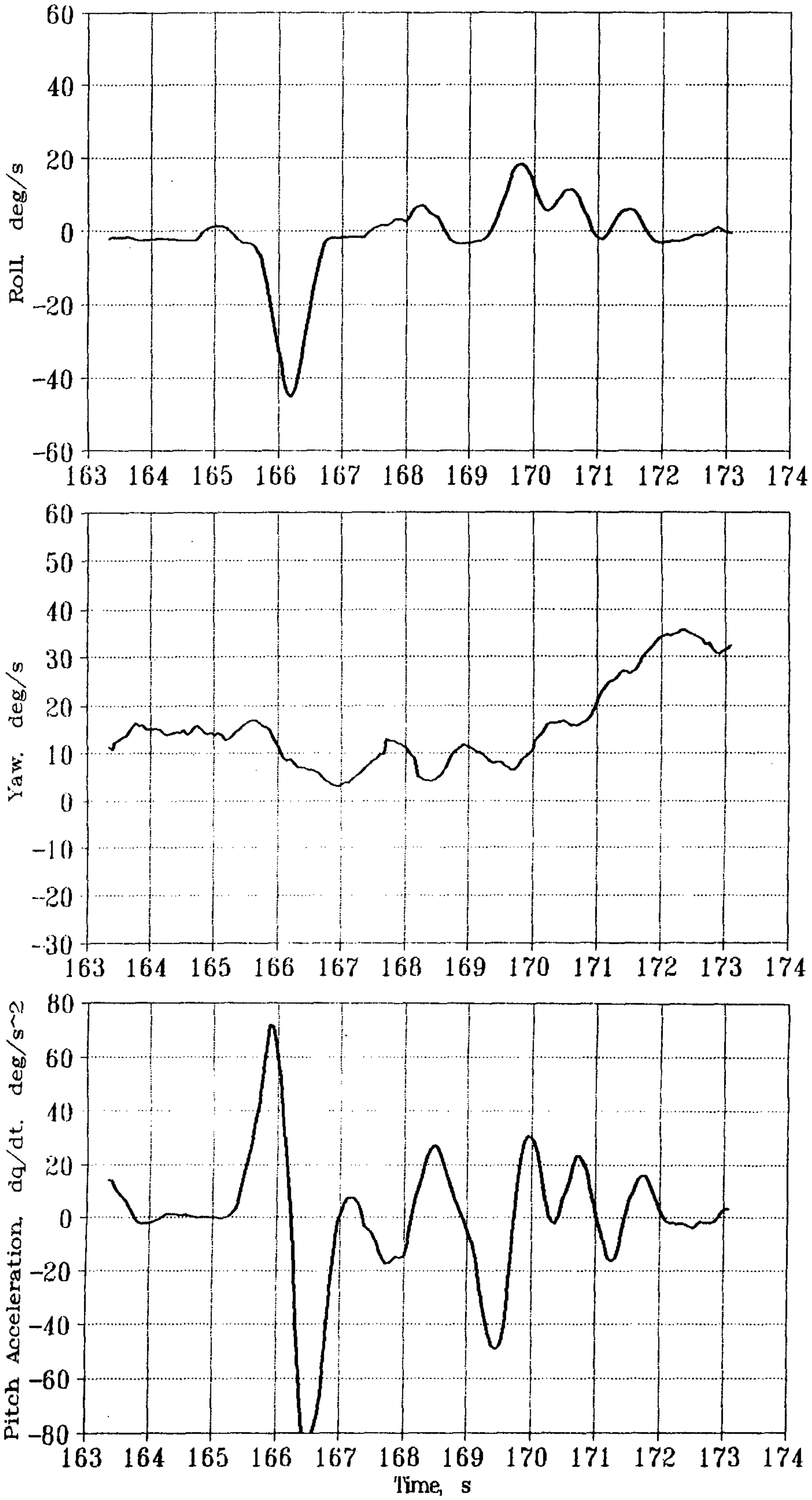
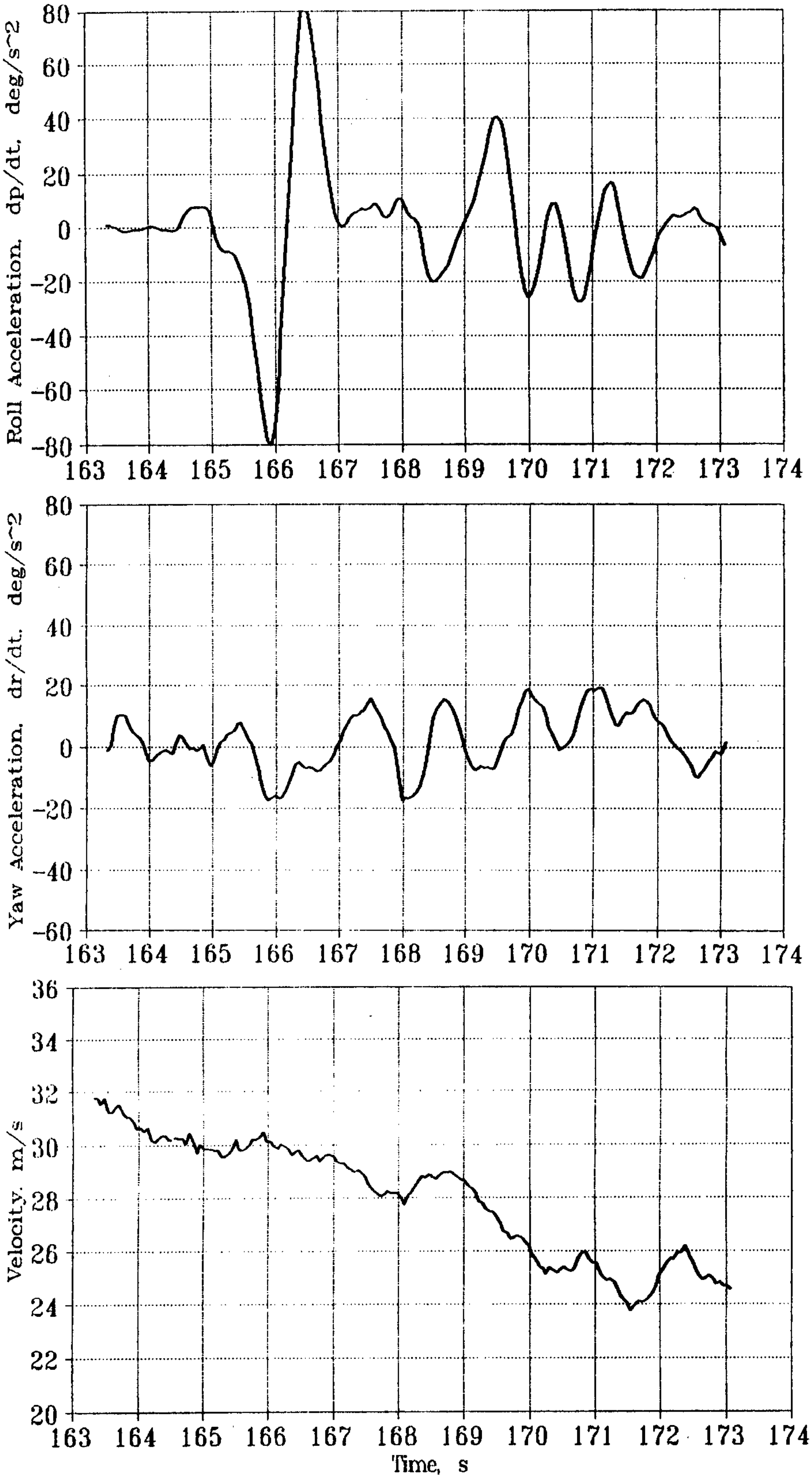


Fig. 75

Thrust Vectored F-15 1/7-Scale

Extended Paddles, Megiddo, May 9, 1991



F.ig. 76

Conclusions & Recommendations

To maximize thrust-vectoring [TV] enhanced agility of future aircraft, a new methodology has been proposed and verified by intensive efforts during two years.

Without risking lives, at low cost and relatively short time, our pre-calibrated and instrumented models, utilizing TV and conventional aerodynamic control surfaces, measure velocity, alpha, sideslip angle, pitch, roll and yaw rates during newly-defined Standard Agility Comparisons Maneuvers [SACOMs]. The model extracted data are dynamically scalable to full-scale fighter aircraft. Hence the data can be used to compare one aircraft design to another and also to project and predict agility limitations due to pilot tolerances.

Model responses to Conventional, TV + Conv. and pure TV commands are precisely measured and well-recorded by our instrumentation/computers/calibration/software. The recordings allow verification of what we call practical SACOMs. These have evolved from our theoretical studies. We recommend using them in all future studies.

The proof-of-concept/feasibility-studies were performed through flight tests of 1/7-scale F-15 and 1/8-scale 'Semi-tailless' F-16 models. The studies included windtunnel tests of tailless configurations and tests of vectorable, distortion free Post-Stall [PST] F-15 inlet, as well as a new mathematical phenomenology required to maximize PST-TV-agility. The theory contains PST-TV terms, which, in combination with Dynamic Scale Factors [DSF], provides physical insight and new guidelines to maximize PST-TV agility by means of dynamically-scaled models. While 'accuracy levels' of our DSF and 'practical' SACOMs can be further improved, the results obtained so-far allow, for the first time, realistic comparisons of agility components between one TV-Control system to another and extraction of flight test data

The proven methodology provides cost-effective and time-saving means to design, construct and flight-test correct-DSF-Scaled models in search of maximized PST-TV-Control power. Our Yaw-Roll-Pitch TV-nozzles open-up new possibilities to effectively eliminate the tail from practically any conventional jet-aircraft, thereby increasing range and safety levels during takeoff and landing, and, simultaneously, reducing weight, drag, SFC and optical, infra-red and radar signatures.

These studies include the development of the fundamental principles, and the first flight tests, of **Pure [tailless] Vectored Aircraft** [PVA]

We recommend to use PVA as the '**Ideal Standards**' for maximizing PST-TV-agility and PST-flight-control power, as well as for extracting new potentials to further reduce fighter aircraft optical, infra-red and radar signatures.

Full-scale aircraft agility is approximated by model aircraft agility modified by DSF involving aircraft-to-model average-densities-ratio times moments-of-inertia ratio multiplied by the fifth power of the linear-scale-factor **L**. Likewise , the DSF for weight is the ratio of densities multiplied by $[\mathbf{L}]^3$ and for Full-Scale **Angular Velocities** [Roll, Pitch, Yaw Rates] it means multiplication of model angular velocities by $[\mathbf{L}]^{-0.5}$.

Pitch rates extracted from current TV-F-15 and TV-F-16 models are around 150 deg/s, which, for the full-scale fighters, become $[150][7]^{-0.5} = 56$ deg/s, i.e., about **twice the current turn rate.**

Thus, our methodology allows estimations of agility limitations due to pilot negative-g-onsets/side-force tolerances, and other, otherwise unmeasurable, PST-TV-induced biodynamic accelerations, as functions of the [scaled] distance of the pilot from the [unknown, translating] TV-center-of-rotation which must be measered next year.

Flight tests of these models revealed strong coupling phenomena between pitch rates and roll rates, largely due to gyroscopic forces generating yaw deflections, which, in turn, cause left-roll during pitch-up and right-roll during pitch-down. The phenomenon is linked to the fact that the ducted fans employed here to generate cold jets rotate at around 20,000 RPM and the nose turning rates are also characterized by high values at high angles of attack. Other interesting coupling effects have been detected.

External thrust vectoring [ETV] by means of 4 TV-paddles [of the type being flight tested recently on the X-31 and F-18], was compared with Internal Thrust Vectoring [ITV] by means of yaw-pitch two-dimensional nozzles of our design. ITV has demonstrated PST-agility [including positive and negative 'Cobra' maneuvers], while ETV was hardly sufficient to surpass the 'stall barrier'. This is due to inefficient deflection of exhaust jet streams beyond nozzle exit, and to inherent ETV-delay-times between commands and the time the paddles touch/deflect the jets in actual PST-TV-flight. Nevertheless, ETV allows us to demonstrate precise recordings of SACOMs, by providing extra thrust to carry extra heavy gyros/batteries, probes and a computer on-board.

Pitch rates obtained from our models conventional aerodynamic control surfaces correspond to that extractable from full-size F-15As, when our DSF are employed. By adding ETV to conventional roll command we obtained more than twice the current turn-rate of conventional F-15As. However, the maximum pitch rate obtained was a coupled one. In turn, ITV provides such and higher rates by resorting to pure pitch-TV command only.

Extension studies are recommended on: Pilot-to-Flyer Delay Times vs. Aircraft Gross and Net Agility Components, Model-to-Aircraft IFPC-Delay-Times, ETV vs ITV Agility, tailless TV-model flight-tests with F-16 & F-15 'Baselines', and the **latest USAF-JPL-Extension-project on 'DES-TV-Baselines'** [See Report End].

We also recommend using our kits [Roll-Yaw-Pitch-TV-nozzles + Vectorable PST-inlets] in **spin-off applications** [see below], and to test upgraded fighter performance by means of our low-cost, dynamic-scaling methodology.

SWTT data for tailless F-15 models have been compared with data for conventional and semi-tailless F-15 models. Data for tailless F-16 and PVA configurations have also been documented in JPL files.

To transform the F-15 model into a tailless configuration the elevators have been replaced by equal-projection area roll-yaw-pitch TV-nozzles. To pass engine gases for PST-TV control of the tailless model, the nozzles have been designed with a considerably greater thickness than that of the current elevator airfoils. The resulting tail-drag is higher for the tailless design in comparison with the conventional tail design. Consequently, drag reduction with tailless designs is feasible only with wing-integrated roll-yaw-pitch TV-nozzles, e.g., as might be expected with a tailless vectored version of the subsonic F-117.

The change in stability for the Roll-Yaw-Pitch TV tailless F-15 model is indicated by the moment coefficient dependence on the lift coefficient.

An improved understanding of stabilities is extractable by scaling from our 1/32 SWTT-scale to the 1/7-MoFT-scale of the F-15 model. The F-15 with 25%-cut vertical tail had been flight tested and the reduced stability was verified.

Tailless F-16 model with roll-yaw-pitch TV nozzles replacing the elevator, while rudder-motion is frozen in zero position, have demonstrated exeptionally good pitch and roll maneuverability.

During negative or positive 'TV-induced Cobra' maneuvers the F-15 ITV-model position can be held with precision at high AoA, with no unwanted sideslips or nose-slips.

Maximum AoA range attained with F-15 ETV is +27 to -20 deg., while with ITV it was about 75 degrees, a figure which may be further increased next year. Maximum sidslip angles were 12 degrees to both sides. Maximum pitch rate attainable with both

ITV and ETV F-15 models is about 160 deg/s [About 60 deg/s for full-scale F-15s]. [For the ETV F-15 model it was a coupled pitch rate obtained in response to TV-yaw + aileron command.] Increasing all these rates is contemplated for next year efforts.

Deflection of the yaw vanes of our TV-designs and 'tailless' models very-effectively turns the model on the runway, with no need for a front-wheel gear-steering-mechanism. It also provides strong moments at very low speeds, when the rudder-moments are too small for safe control.

The alpha, betta, velocity and 3 gyros have successfully and precisely provided the required data. The calibration methods for the gyros and the flying model probes have been found reliable and repeatable.

No evidence was found for the need of a canard to obtain flight stability, PST-TV agility and good control power.

The method to be tried next is to return to ITV and to overcome the T/W technology limit by introducing an improved propulsion system.

ITV means rapid-nose-turning-rates, excellent controllability, maximized PST-TV-agility and successful recovery from any spin situation.

Extension / Spin-Off Projects

Extension/spin-off projects will be presented in the 2nd-part of Sept. 91 via seminars to be delivered at:

Lockheed [By an invitation from Lockheed President. It includes proposals to add Roll-Yaw-Pitch TV to F-117, C-130 and F-22. See below].

Pratt & Whitney [Via PWA $ 125K contract with JPL for 1991 research project on Low-Aspect-Ratio TV-nozzle. The seminar includes the presentation of recent laboratory test results]

FDL/WL, Training and AAMRL, WPAFB and Human System Division at BAFB [Via the Extension/Spin-Off Project detailed below.]

Seminars may also be presented at Army and Navy Bases & and at civil aircraft installations.

The following extension project has already been approved for start-up on June-Sept 91. It is therefore described below in more details.

Title:

"Synergetic Investigations of Thrust Vectoring Induced Accelerations/Limitations Using A New Research Vehicle/Methodology"

USAF-JPL/TIIT Contract Sub-Title Should Clearly States: "**Based on Extended Use of US Government Equipment, Prototypes and Software Acquired Via Grant No. AFOSR-89-0445/Technion Res. No. 160-0559**"

Secondary Title , as Proposed By Dr. Daniel W. Repperger, AAMRL, WPAFB, Responsible Scientist/Extension:

Dynamic Scaling of Prototypes Using Radius Of Gyration Method

Last Modified and Updated: Jul 5, 1991 in response to Dr. Daniel W. Repperger's telephone conversation and Fax of Jul 3, 91 and Capt. J. C. Wigle's telephone conversation and Fax from June 20, 91, including copies of Col. John B. Tedor's, Col. James C. Rock's, Dr. Daniel W. Repperger's and Dr. William B. Albery's Reviews.

Preliminary Proposal Date to EOARD: Oct. 16, 1990.

EOARD Request for 'Full Research Proposal' : Mar 15, 1991.

'Full Research Proposal' was submitted on Mar. 18, 1991 [Fax] in response to recommendations of Jan 25, and Feb 21, 91, made by Dr. William B. Albery, WPAFB and Col. John B. Tedor, BAFB, via EOARD (Mar 15, 91, Capt. Jeffery C. Wigle)]

Approved Starting Date: Jul 1, 91.

Minimum Budget Required: $ 150K per year for 3 years by USAF on top of $150K-JPL-cost-sharing base.

Allocated $ 90K Preliminary USAF Seed Funding:

Jul 1,91 - Sep 30, 91: **$ 24.5K** by EOARD [Wigle, Mar 15, 91, June 19, 91].

Oct 1, 91 -Sep 30, 92 [initial seed fundung]: **$ 45K** [Repperger, Jul 3, 91].

Oct 1, 91 -Sep 30, 92 [initial seed fundung]: Around **$ 20K** by EOARD [Wigle].

USAF Participant:

USAF Capt. Daniel D. Baumann, Flight Tests Manager, F-15 SMTD, McDD/USAF, M.Sc. Aer.Eng., within USAF/WOE visit to JPL/TIIT, Jul 20 -Aug 20, 91, and possibly also in Oct-Dec -91.

Other Participants:

Other [IDF] Combat Pilots, Flyers, Aero-Engine technicians, engineers and faculty, mathematicians, and aero-engineering students may participate, as in the present project.

Background [Text in line with Dr. Repperger's proposal. Fax: Jul 3, 91]

The research work which is proposed here is to make F-15 prototypes at JPL, TIIT, more correctly, in a dynamic motion sense, replicate F-15s which fly today.

This effort is designed to investigate supermaneuverable flight trajectories in 1/7-scale prototypes and to extract valuable data to be used in a motion field simulator [DES Centrifuge] at The Armstrong Laboratory, WPAFB. Presently 3 supermaneuvers have been simulated on the DES centrifuge. The motion simulation of these supermaneuvers is based on somewhat sketchy data from the literature. It is desired to have more accurate complex acceleration profiles and time histories of attitude variables to correctly replicate the motion fields. The role of the of the AL/WPAFB centrifuge will be to investigate multi-axes simulation of these supermaneuvers and the associated human factors' issues due to complex accelerations and rotations, and a host of other issues.

JPL/TIIT has been flying 1/7-scale prototypes of F-15s in supermaneuvers, and has partially collected the data mentioned above via its [uninstrumented] ITV mode of propulsion. Its early work has focused on determining Engine-IFPC [Integrated Flight Propulsion Control] limitations under extremely untoward flight scenarios, as evidenced by its written and video tape Reports to WL/WPAFB during the last two years. Well-instrumented and calibrated flight tests have recently been made via ETV mode of propulsion, under less extreme flight conditions.

The dynamic responses of the [1st-Generation, uninstrumented] ITV F-15 prototype have been video-taped during post-stall supermaneuvers, while those of the [2nd-Generation, instrumented] ETV F-15 prototype have been well-documented by means of an onboard computer and rate gyros at less extreme flight conditions. The lower agility is due to the lower vectoring moments provided by ETV and the extra weight of gyros, batteries, etc., which adversely affect maximum agility ratings.

Hence, to overcome the 'measurement vs agility problem', modified [two tandem engines] propulsion systems must be designed, constructed and flight tested. In addition, the moment-of-inertia of the prototype must more accurately correspond, via proper Dynamic Scale Factors [DSF], to those of a specific F-15 Aircraft production-model, at TOGW or with minimum fuel and clean configuration. The data collected by JPL will be given to AL/CFBS and thus more accurate replication of the motion fields on the DES centrifuge can be conducted for these unusual flight trajectories.

Approach:

The technical approach involves the matching of the radius of gyration of the prototype to that of the actual aircraft. Combined with a proper DSF methodology, this provides the correct dynamic response of the prototype to emulate the actual F-15 production-model selected.

The linear and rotational data to be collected from the prototype will replicate [within a 'measured-degree of accuracy'], that data obtained from actual F-15s when they fly supermaneuverable trajectories. In the actual matching of the inertia of the prototypes, the radius of gyration will be matched in all three aircraft axes.

SOW/Milestones

Jul 1 to Sep 30, 91

1 - USAF Responsible Scientist(s) select(s) "**DES-BASELINE(s)**" F-15 aircraft production-model(s) required for DES or newer simulations [See also Task 1 below].

2 - USAF provides JPL/TIIT with additional moment-of-inertia data, weight, etc., with and without internal fuel, clean configuration, of "DES-BASELINE(s)". [E.g., F-15A, F-15B F-15 SMTD, etc., see Tasks below]]

[F-15 SMTD data (with and without fuel) have already been provided by USAF to JPL. The data, however, are for a canard-configured aircraft. In Capt. Baumann's M.Sc. Thesis we found F-15B data, but only with internal fuel tank full.]

DSF for "JPL-BASELINES' are being evaluated now.

Accuracy Limits for moments-of-inertia-DSF vary between -0.5% for F-15-SMTD/F-15-ETV-model, to 5% for F-15B, and -0.2% [ITV model] to +9.9% [ETV model] weight-DSF for F-15B. Accuracy Limit for our method to measure the 3-axes moments-of-inertia is 2%.

3 - JPL re-examines, following USAF's Fax response to this Fax, and/or during Capt. Baumann's WOE visit, and/or during the Sept. visit to WPAFB and BAFB, the aforementioned 'Accuracy Limits' for the USAF-selected F-15 'DES-Baseline(s)' [including future tailless designs with lower signatures as flight tested on May 9, 91 by JPL?, Cf. Video Tapes No. 5 and 6 to be shown here soon to Capt. Baumann and during the Sep-USAF-Seminars], in line with DES requirements, JPL capability to construct new/modified prototypes & instrumentation with a priori defined Accuracy Limit for a set of variables, flight test them under PST-TV conditions, Milestones/SOW, Reporting pace, minimal budget and duration of contract.

4 - JPL will soon supply USAF with preliminary flight test data by reworking present flight-tests data according to DES needs, and, accordingly re-define Supermaneuverability with ITV, High-maneuverability with ETV, or 'Tailless Designs of F-16 vs F-15 vs. pay-offs in terms of cost-time-accuracy-of-data to be delivered.

5 - Methodology, DSF, Baselines, Accuracy Limits, Agility Limits, Milestones, SOW, Budget and Duration are to be frozen not later than Sept. 30, 91 with the Responsible USAF Scientist at WPAFB.

Oct 1, 91 - Jun 30, 94 [Subject to the aforementioned remarks]

Task 1. Design and construct/calibrate USAF-selected DES-BASELINE(s) and improved-performance-reliability-accuracy-instrumentation, software and post-flight analysis method, adding also a proper treatment of turbulence-noise, flyer-delay-times, IFPC-delay-times and flyer-commands, according to USAF-selected performance needs, DES-BASELINE(s), DSF-accuracy limits, DSF-Pilot-agility limits, budget, duration, and JPL/TIIT-capability/incapability.

Task 2. Subject to agreed/frozen USAF-JPL-DSF-methodology, and to the 'Background', 'Approach' and remarks stated above: Gradually build-to-dynamic-scale and flight-test, according to DSF rules, precision-defined prtotypes, while performing extreme new maneuvers, so as to establish PST-TV agility limitations via a priori defined pilot tolerances. The type of supermaneuvers may not be defined a priori. Extreme spin maneuvers/recoveries are to be recorded too.

Task 3. Establish new, expanded PST-TV envelopes which are of interest to both BAFB and WPAFB, including negative and positive "Cobra" and "Herbst" PST-TV agility-reversals and spin-recoveries at 3 to 10g onsets.

Task 4. Gradually adopt instrumentation/calibration, onboard and post-flight-analysis computers to the expanded new needs in performance and DSF-DES-precision.

Task 5. Produce meaningful high-performance test data that are useful to design human-PST-TV-agility-limiters, new centrifuges, etc.

Task 6. Provide angular velocities, accelerations, attitude, AoA, slip angle, velocity, and other relevant flight-testing data, transformed to DSF-pilot's-head/location/orientation, through undefined and well-defined PST-TV maneuvers. Video-tape maneuvers to help verify computer-recording of Initial Conditions, maneuvers-histories-attitudes and End Conditions.

Converting C-130 to STOL TV-Cargo

In close cooperation with Allison Gas Turbine, GM, a formal proposal was submitted to WRDC. The TV-kit replaces current engine nozzle by a smaller-diameter one equipped with simple yaw-pitch vectorable flaps-vanes of a type well-proven by this lab. The kit significantly increases overall propulsion efficiency for both T-56 engines now in use. Current use of 8 rockets during takeoff, whose installation takes long critical time in a front runway, is eliminated, or the pilot opts for additional payload. Takeoff and landing runs are drametically reduced, while aircraft range and safety qualities are significantly increased.

The yaw-TV control is especially critical to safety qualities at low-speed emergency situations and final approach corrections, including highly-effective [asymmetric] control needs during one-engine-out situations, as well as excellent ground maneuverability and good extra controllability in take-off & landing into strong cross-winds.

The resulting overall propulsion efficiency [of propeller + jet thrust] for the converted engines is estimated to be significantly higher then that of the present ones. [Comperative performance graphs are available from this lab.].

Funding frameworks, milestones and technical details may be discussed with the Technical Director of **WRDC, GM and Lockheed** during the Sept. visit.

Converting F-117A to STOL-PST-TV-Fighter

Make the present [rectangular, high-aspect-ratio, engine-nozzles] fixed vanes rotatable to extract powerful yaw thrust vectoring control power at very low cost and negligible weight penalty. Adding pitch and roll TVC can reduce vertical stabilators size, or eliminate them altogether, to further reduce radar and optical signatures.

On the basis of what is known here today about this fighter's structure, qualities, missions, signatures, etc., as well as in light of the decision to terminate its production, we reinforce our previous recommendation to WRDC/Lockheed to upgrade these aircraft by these simple, low-cost means and by flight-testing them first via our low-cost methodology.

Funding frameworks, milestones and technical details may be discussed with the Technical Director of **WRDC** and **Lockheed**, during the Sept. visit.

Converting Extant Trainers to STOL-PST-TV-Trainers.

PST-TV is to become a standard training requirement in advanced pilot training. However, no such educational system nor such a trainer exists now. Flight-tests are first proposed to simulate the expected performance via our low-cost methodology.

We therefore recommend to add PST-TV kits to extant trainers and to flight-test them first by simulating the expected performance via our scaled flying models.

Funding frameworks, milestones and technical details may be discussed with the **Commanders of USAF Training Requirements - WPAFB**, and consulted with the Technical Director of **WRDC**, during the Sept. visit.

Upgrading Cargo & Civil Aircraft

It is a recommendation published in our book to provide TV-nozzles to cargo and passenger aircraft. Pay-offs include, as with the C-130 analysis, increased propulsive efficiency, range, safety levels and ground maneuverability in addition to significant gains in STOL qualities.

Most important, with one of our [low-aspect-ratio] yaw-pitch nozzles, which have been recently-tested by means of our Jet-Engine-Lab facilities [via funding provided by PWA], <u>we have succeeded to significantly reduce weight, complexity and expected production costs</u>, in comparison with current pitch-only TV-nozzles, such as those installed on the new F-22 fighter aircraft.

We recommend to flight-test the expected performance via this methodology.

Funding frameworks, milestones and technical details may be discussed with **Burt Rutan's Scaled Composites, representatives of military & civil aircraft industries @ WPAFB**, and the Technical Director of **WRDC**, during the Sept. visit.

TV-Cruise Missile, Etc.

As was published in 1990 in our book, it is recommended to use TV-nozzles and vectorable inlets to enhance performance of cruise missiles, etc. It is recommended to flight-test expected performance via present methodology.

Funding frameworks, milestones and technical details may be discussed with **Navy and Army Officials**, and the Technical Director of **WRDC/WL**, during the Sept. visit.

Ultra-Fast Electro-Chemical TVC

A novel design which revolutionizes the [micro-seconds] response times and effectivity of ultra-fast, control systems, is recommended for a generic, proof-of-concept/feasibility studies of ultra-fast response times, forces, moments, geometries, control-means, etc.

Converting Extant Navy & Army Aircraft

to STOL-PST-TV-Aircraft

Our mature infrastructure and the newest, 'tailless', low-signature, TVC-kits [TV-nozzles + V-inlets] may be cost-effectively used during PST-TV-flight-tests via our methodology. A 3-years framework. Minimum budget: $ 150K per year, on top of a $ 150K per year TIIT/JPL-Cost-Sharing effort. Cf. the aforementioned projects.

Appendices

APPENDIX A

ANALYSIS OF PITCH AND ROLL COUPLING DURING F-15 AND F-16 MODEL FLIGHT TESTS

D.D.Baumann, V.Sherbaum and M. Lichtsinder

As shown by the time-history plots of pitch and roll during pitch-reversal and roll-reversal manuevers, the currently flight-tested F-15 and F-16 remotely piloted vehicles models, have consistently demonstrated the tendency to roll counterclockwise, when pitched nose-up, and clockwise, when pitched nose-down, when viewed from the aircraft's tail.

A number of possible explanations as to the cause of this aircraft behavior were investigated, since understanding the cause may be crucial to interpreting future experimental results, and affect future implemented test procedures. The following possible causes of pitch-roll coupling were investigated, both as the sole source, or as one of the contributing factors:

1) Thrust asymmetry (right engine thrust > left engine thrust).
2) Torque effects (both engines rotate counter-clockwise when viewed from back).
3) Asymmetrical drag as a function of angle of attack (excess drag on left-side of wing when pitched-up, and on right-side, when pitched-down) - left-engine inlet and airspeed-velocity,
4) "P" factor of fan blades (center of thrust shifts off blades axial center, as a function of angle of attack).
5) Adverse jet flow interaction with ETV pedals, (Fan exhaust introduces flow rotation that interacts with ETV pedals to cause unwanted side force)
6) Horizontal stabilizer introduces flow field asymmetries with jet exhaust.
7) Vortex generation by airspeed-probe, affects left-wing lift.
8) Gyroscopic effects of the engines.

At the present time the effects of 1 through 7 are discounted due to the following reasons: Good pilot technique, causing rotation in the wrong direction, causing rotation in only one direction and not the other, magnitude of induced moment is too small,and/or flow field interactions not clearly understood. Factor #8, gyroscopic effects of the engines, were investigated further, since the vector cross product of the engines rotation and the pitch rate resulted in the correct direction for aircraft yaw and subsequent as metrical distribution of lift on the wings due to a difference in the relative wind-velocity over the left and right wings,which causes the aircraft to roll. Video tapes corroborate the behavior shown on the time-history plots.

A quantitative analysis of the effect is given below.

1. Pitch up maneuver is carried out with deflection thrust-jet.

So pitch-force is

$$T_q = T \cdot \sin \delta_q \,, \qquad (1)$$

where δ_q is deflection jet angle, T-gross thrust.

The Equation of the pitch-motion is given by

$$I_{yy} \cdot \dot{q} = T \sin \delta_q \cdot L_c - M_{qD} \,, \qquad (2)$$

where Iyy is moment of inertia, M_{qD} - drag-forces moment in pitch direction, Lc - distance between point of force application and aircraft center-of-gravity.

The Gyroscopic moment is expressed by the following relationship

$$\vec{M}_0 = I_0 \cdot \vec{\omega}_0 \times \vec{q} \,, \qquad (3)$$

where I_0 and ω_0 are moment-of-inertia and angular velocity of shaft-engine and its direction is shown on Fig. A.

The yaw-angular-velocity induced by the gyroscopic moment is given by

$$I_{zz} \cdot \dot{r} + K_r \cdot r = M_0 \qquad (4)$$

$K_r \cdot r$ = the drag-moment (It will be estimated below).

We assume that yaw-rotation induces roll-rotation, because of the difference in the lift forces on the left and right wings. It is connected with velocity changes and is given by the expression

$$\Delta F_l = F_{l1} - F_{l0} \,, \qquad (5)$$

where ΔF_l is lift-force change, F_{l1} =lift-force during yaw-rotation, Flo = lift-force during horizontal flight, and its value is proportional to the velocity squared, i.e.

$$F_{l1} = F_{l0}\left(1 + \frac{\Delta v}{v_0}\right)^2$$

v_0 = velocity during horizontal flight,

Δv = yaw-rotation,

expression (5) may be rewritten as

$$\Delta F_e = F_{eo}\left[\left(1+\frac{\Delta v}{v_o}\right)^2-1\right] \approx 2\cdot F_{eo}\,\frac{\Delta v}{v_o}\,, \tag{6}$$

$$\text{if}\quad \frac{\Delta v}{v_o} >> \left(\frac{\Delta v}{v_o}\right)^2 .$$

We have the sign + on one wing, and - on the other, so that the moment in roll-direction is given by

$$M_x = \Delta F\cdot 2R\,, \tag{7}$$

where R - distance between wing-center-of-pressure and the X-axis.

Drag-moment in roll-direction is assumed proportional to roll-rotation. Hence, the equation for roll-rotation may be written as

$$I_{xx}\dot{p} + K_p\cdot p = M_x . \tag{8}$$

where K_p is the drag coefficient for roll velocity.

In our calculations of gyroscopic moments we do not use equations (1) and (2), for we use data about pitch-velocity-rotation from the time-history plots.

2. Initial data:

Moment-of-inertia for the rotating parts of the RPV's engine is

$$I_o = 5\cdot 10^{-4}\,kgm^2$$

Engine velocity-of-rotation n_o=22 000 RPM = 2304 Rad/s

Model's moments-of-inertia [Kgm^2] (cf.p.50) are:

$$I_{xx} = 0.88\,,\quad I_{yy} = 5.09\,,\quad I_{zz} = 5.63$$

Average Flight-velocity of the F-15 model is

$$v = 30\,m/s$$

Distance between X-axis and wing-center-of-pressure (Fig. A):

$$R = 0.5m$$

Mass of F-15 model:

$$m = 14.2\ kg$$

Pitch-rate-rotation dependence vs time is taken from the time-history plot (p.123, Fig.54). It may be approximated as

$$q = 0.5\ \sin 4.33t\ [Rad/s]$$

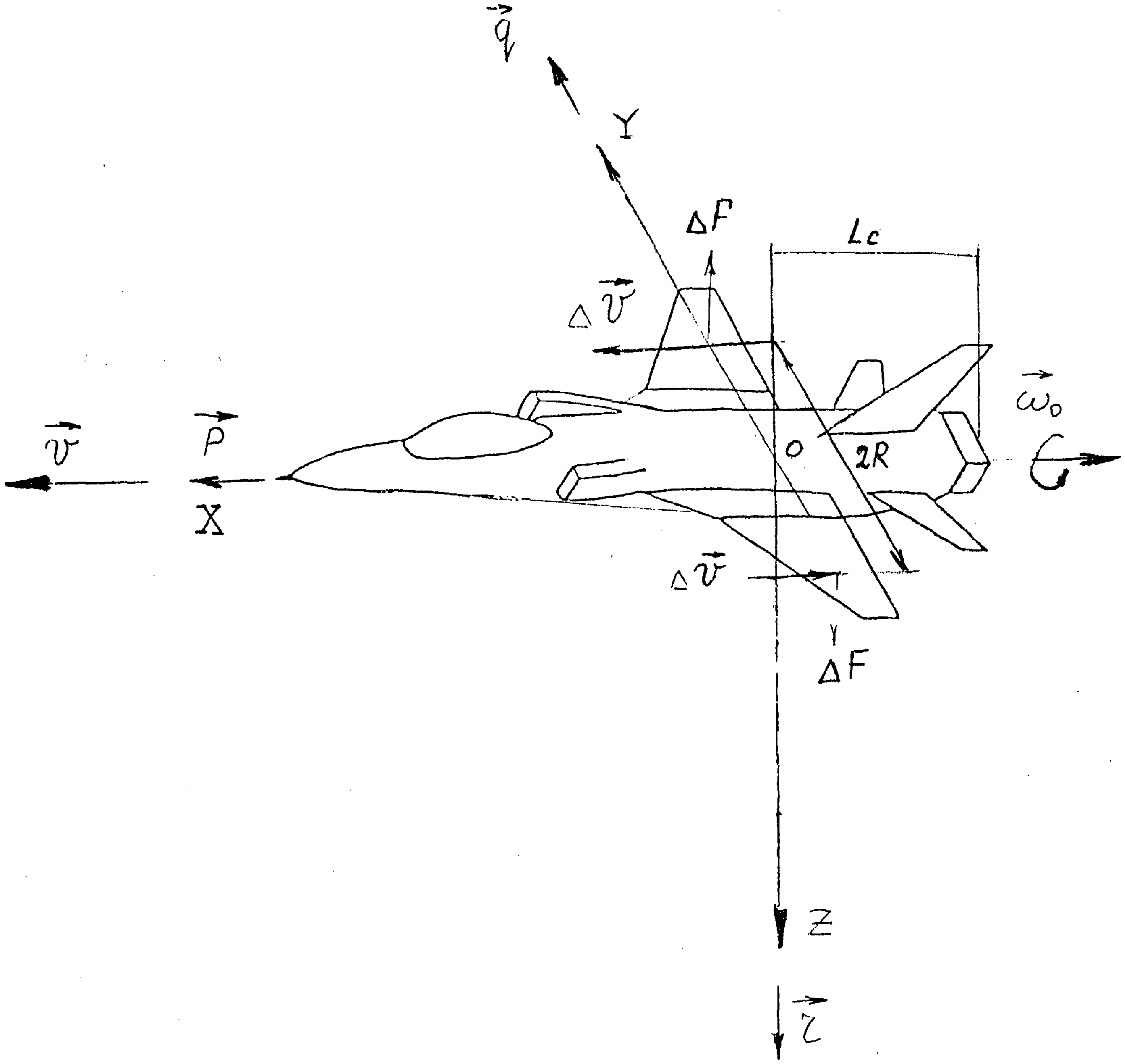

$\vec{q}$
Y
ΔF
L_c
$\Delta \vec{v}$
$\vec{\omega}_0$
$\vec{v}$
$\vec{P}$
X
o
2R
$\Delta \vec{v}$
ΔF
Z
$\vec{l}$

Fig. A

for the time interval 83.6 ÷ 84.3s.

The gyroscopic moment according to equation (3) is

$$Mo = 2.5 \cdot 10^{-4} \cdot 2304.05 \sin 4.33T = \approx 1.15 \sin 4{,}33T \ [Nm] \qquad (9)$$

Dependence of the drag-moment during yaw-rotation may be presented as a sum of fuselage and wings drag-moments, i.e.

$$M_{rD} = M_{DW} + M_{Df} .$$

According to [1] drag-forces for fuselag and wings are approximately equal. During horizontal flight with constant velocity, the gross drag-force direction is balanced by thrust component in the X-axis direction, and for the F-15 model it is equal to 75N, so a wing-drag force is

$$F_{DW} = \frac{75}{4} = 18.75 \ [N]$$

By analogy with expression (6), the drag force change for each wing because of yaw-rotation is

$$\Delta F_{DW} = 2 \cdot F_{DW} \frac{\Delta v}{v_o}$$

and the drag-moment becomes

$$M_{DW} = 2.F_{DW} \cdot \frac{P.r}{V_o} \cdot 2 =$$

$$= 37.5 \cdot \frac{05.r}{30} \cdot 20.5 = 0.625\, r \ [Nm] \qquad (11)$$

Drag-moment of fuselage is neglected for at the point of application o, the resultant drag-force is close to the center of gravity. So equation (4) becomes

$$5.63\, r + 0.625r = 1.15 \sin 4.33t \ [N.m] \qquad (12)$$

Drag-moment during roll-rotation is induced by the angle of attack change

$$\Delta F_{Dp} = 5.7 F_{eo} \cdot \Delta\alpha , \qquad (13)$$

where

$$tg\alpha = \frac{P.R}{v_o} \qquad (14)$$

For small angles

$$\Delta\alpha \approx tg\Delta\alpha = 0.0167\, p \ [Rad] . \qquad (15)$$

According to expressions (13) - (15), the drag-moment during roll-rotation is

$$M_{Dp}=2R\cdot 5.7\cdot F_{e_0}\Delta\alpha = 2\cdot 0.5\cdot 5.7\cdot 70\cdot 0.0167\cdot p = 6.67p .$$

So equation (8) may be written as

$$0.88\dot{p} + 6.67p = M_x . \qquad (16)$$

M_x must be derived from equation (12).

4. Solution of equation (12): If t=o and r = o

$$r = \frac{M_{om}\cdot K_z}{\sqrt{1+\tau^2\omega^2}}\left[\sin(\mathrm{arctg}\,\omega\tau)e^{-\frac{t}{\tau}} + \sin(\omega t - \mathrm{arctg}\,\omega\tau)\right], \qquad (17)$$

where

Mom = 1.15 [N.m], the maximum gyroscopic moment, and

$$\omega = 4.33\ [Rad/s],$$

$$K_z = \frac{1}{0.6} = 1.6,$$

$$\tau = \frac{5.63}{0.625} = 9.0\ [s].$$

Since

$$e^{-\frac{t}{\tau}} \approx 1 - \frac{t}{\tau} + 0.5\left(\frac{t}{\tau}\right)^2 - \dots \approx 1 \quad \left(\frac{t}{\tau} \ll 1\right),$$

$$r = \frac{M_{om}}{I_{zz}\cdot\omega}(1-\cos\omega t) = -0{,}0469(1-\cos 4.33t). \qquad (18)$$

The center-of-pressure-wing-velocity-change caused by gyroscopic moment is

$$\Delta v = r\cdot R = -0.0234(1-\cos 4.33t)\ m/s \qquad (19)$$

The change in lift-force due to velocity difference (expression (6)) is

$$\Delta F \approx 2F_e\frac{\Delta v}{v} = -2\frac{mg}{2}\cdot\frac{0.0234(1-\cos 4.33t)}{30} =$$

$$= -0.11(1-\cos 4.33t)[N].$$

and

$$M_x = 2 \cdot R \cdot \Delta F = -2 \cdot 0.5 \cdot 0.11(1-\cos 4.33t) = -0.11(1-\cos 4.33t)\,[N \cdot m]. \quad (20)$$

The solution of equation (16), with expression (20), is

$$P = 0.016\left[0.87 \sin(4.33t + 1.06) - \left(1 - 0.243\, e^{-\frac{t}{0.13}}\right)\right] \quad (21)$$

Calculations show that the roll-rate vs time during the pitch maneuver (cf. Table 1) varies as

Table 1

t, [s]	0.2	0.4	0.6	0.8
P, [deg/s]	-0.12	-0.64	-1.3	-1.7

Conclusions

The preliminary calculations of the theoretical roll rate of the F-15 RPV as induced by the engines-gyroscopic-moment, is less than that measured in actual flight test, which implies that it may not be the sole cause.

Control surface trim settings may also be big contributors to the F-15 RPV's Pitch-Roll coupling during Pitch changes through the following mechanism-description:

Before all pitch-manuever-demonstrating, the RPV is trimmed to maintain as close as possible "equlibrium" steady-state straight and level flight. It is suspected that there is a larger amount of drag on the left side of the RPV, than on the right side, due to the inlet configuration and the velocity probe. The counterclockwise moment (when vertical axis viewed from above the RPV) created by this asymmetric drag would have to be compensated for by a clockwise moment generated by a yaw-force from the F-15 RPV's rudders. Since the yaw-force generated by the rudder is offset from the RPV's longitudinal axis, it also generates a clockwise moment about the longitudinal axis, when viewed from the rear. This would, in turn, require a deflection of the ailerons to generate a balancing counterclockwise moment. In straight and level flight, these forces and moments would balance. However, during pitch maneuvers, this is not the case. During extremely nose-high-pitch-up maneuvers, the rudder is effectively "washed out" by the wings, causing it's yaw-force to decrease, while the drag on the RPV's left-side remains constant, thereby generating a counterclockwise moment about the vertical axis, and adding to the engines-gyroscopic-yaw-moment.

The counter-clockwise moment about the longitudinal axis also decreases, but it's overall effect is assumed to be smaller and cancelled by the clockwise moment generated by the ailerons. The net effect during a pitch-up maneuver is a roll in the counterclockwise direction about the longitudinal axis, when viewed from the rear of the RPV.

Using a similiar argument during a nose-pitch-down manuever, the same control surface deflections would cause a roll in the clockwise direction.

In both pitch-up and pitch-down, the yawing moment generated by the yaw-force of the tail is assumed to be larger than the rolling moment generated by the tail. During a pitch-up manuever the yaw-force decreases, causing a counter-clockwise moment about the vertical axis, when viewed from above. During an extreme nose-pitch-down manuever the incremental increase of wind velocity over the tail, causes an incremental increase in the tails yawing-force, causing a clockwise moment about the vertical axis, also adding to the engines-induced gyroscopic moment.

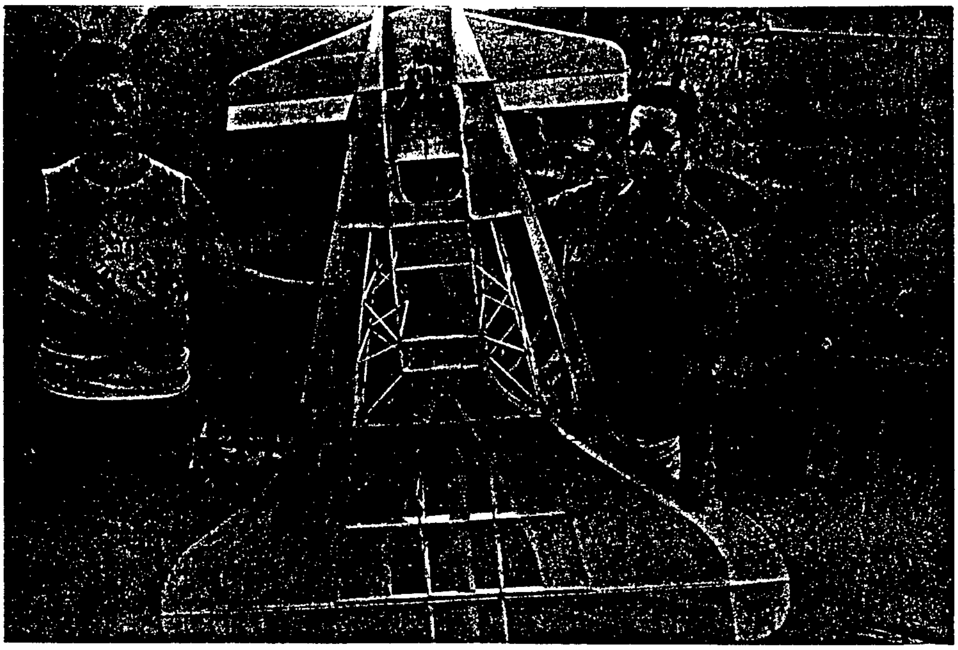


Fig.77 : 1st PVA, with split-type Roll-Yaw-Pitch Nozzle. May, 1987, JPL, TIIT.

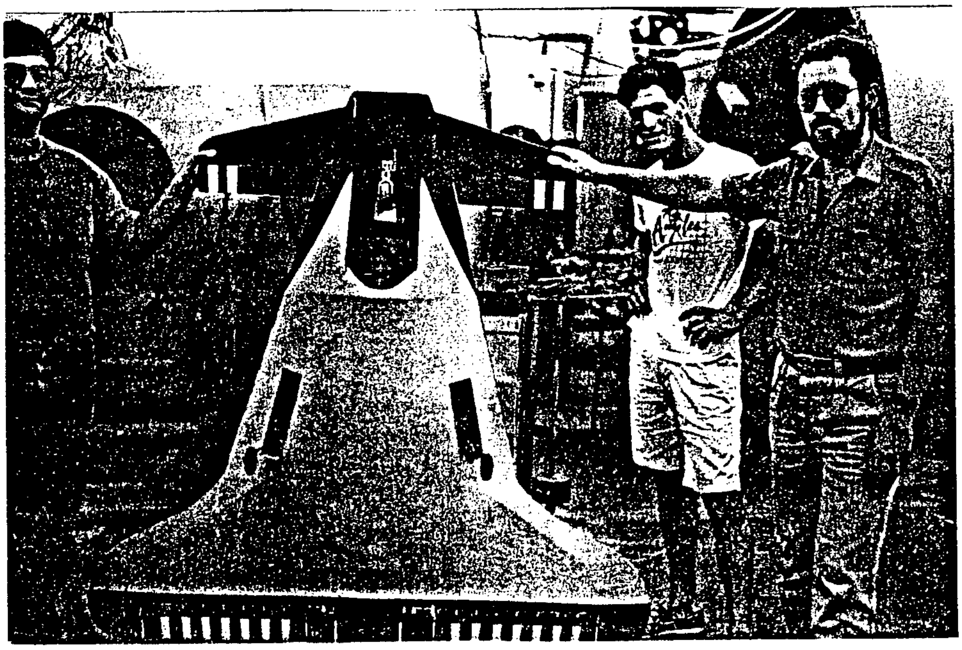
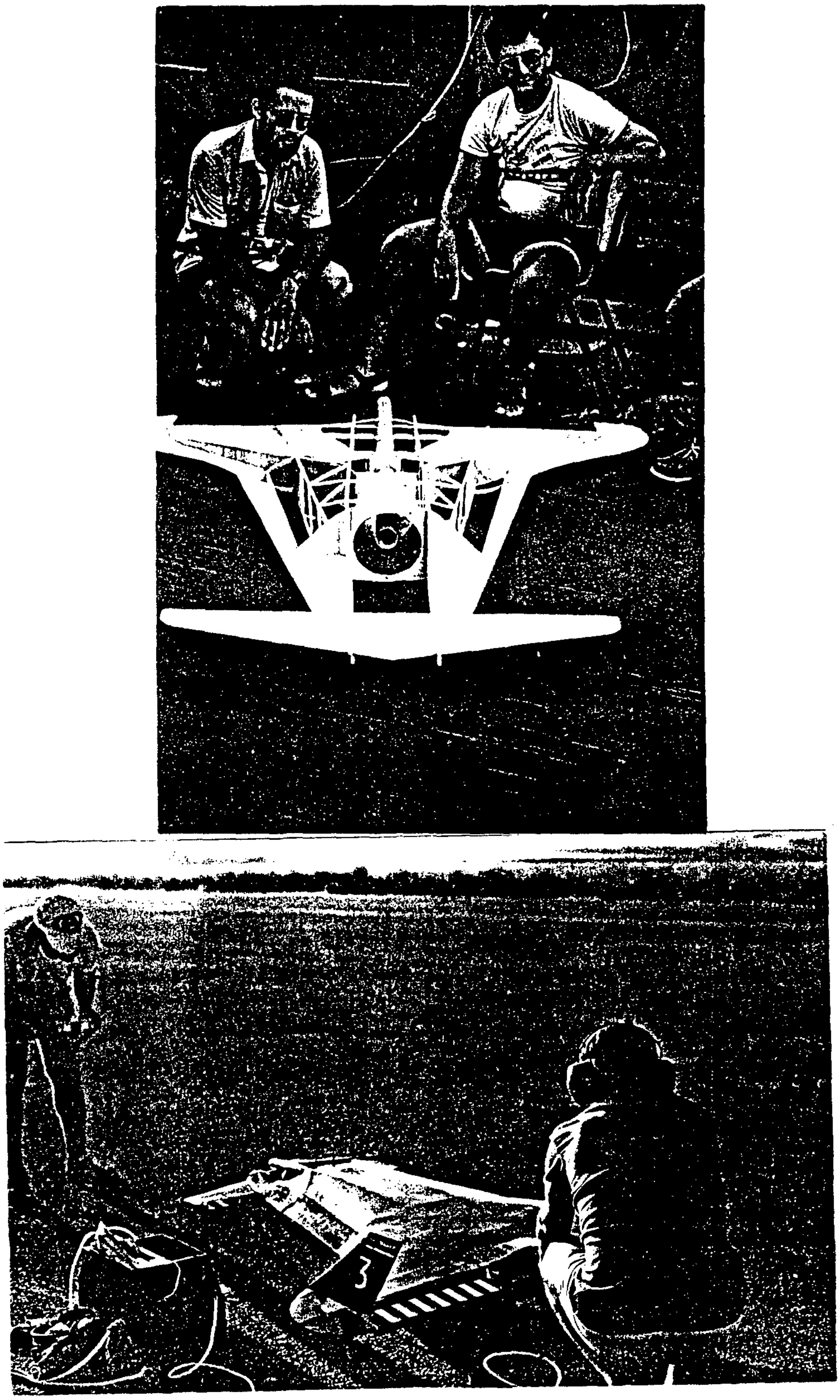


Fig.78 : Retractable gear test prior to 1st flight-test in May 1987. JPL, TIIT.



Figs. 79,80 : 1st PVA.Sitting: Mike Turgeman (right), Erez Friedman, our two 1st-rank flyers.

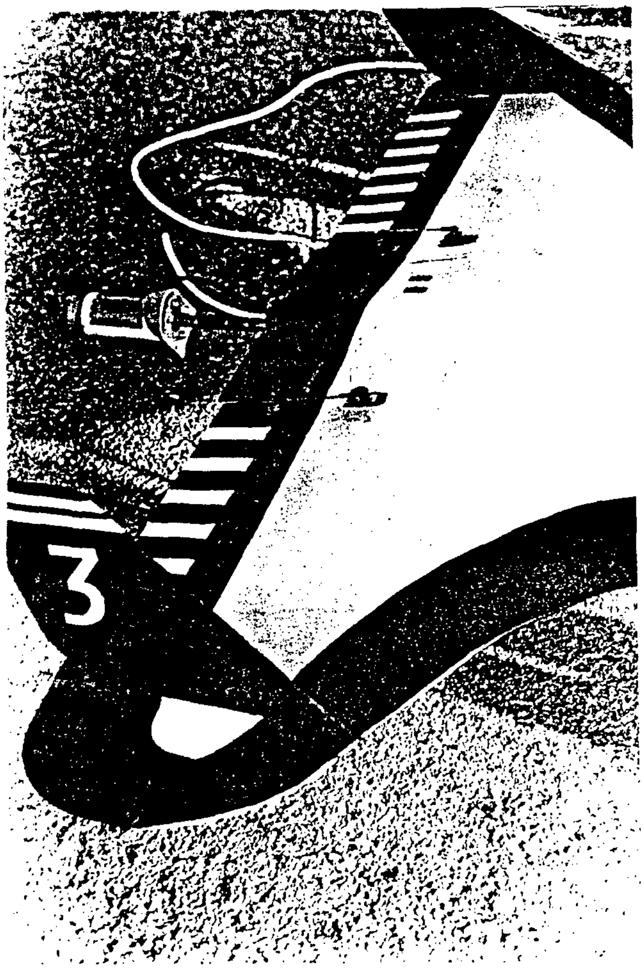


Fig. 81 : Starter & Roll-Yaw-Pitch-cold-jets-TVC.

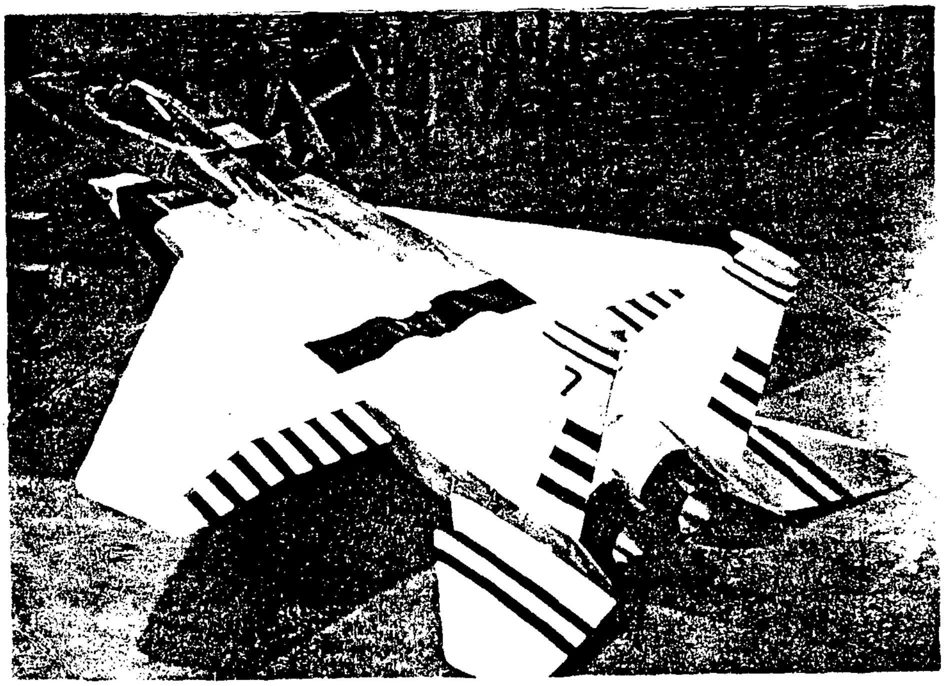
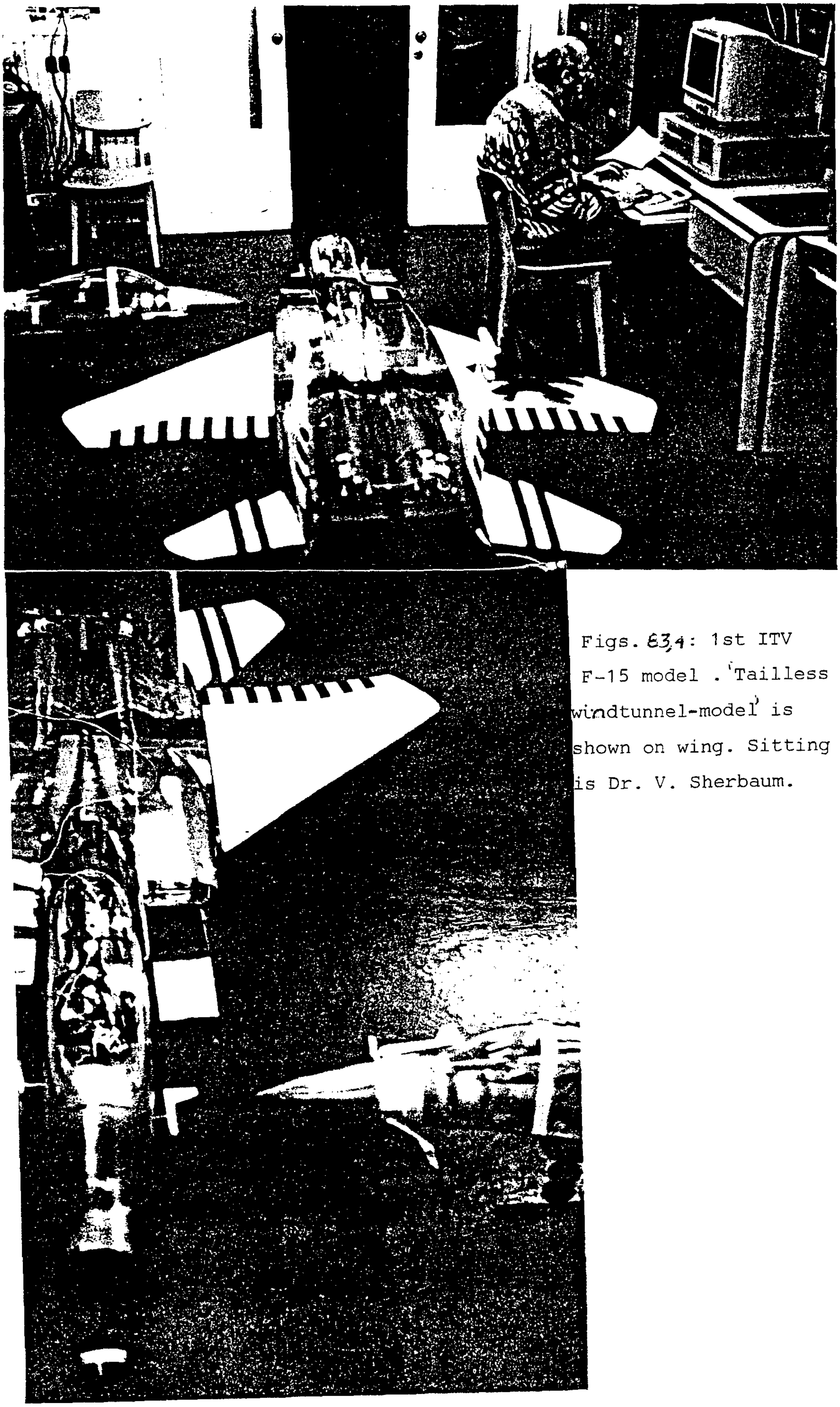
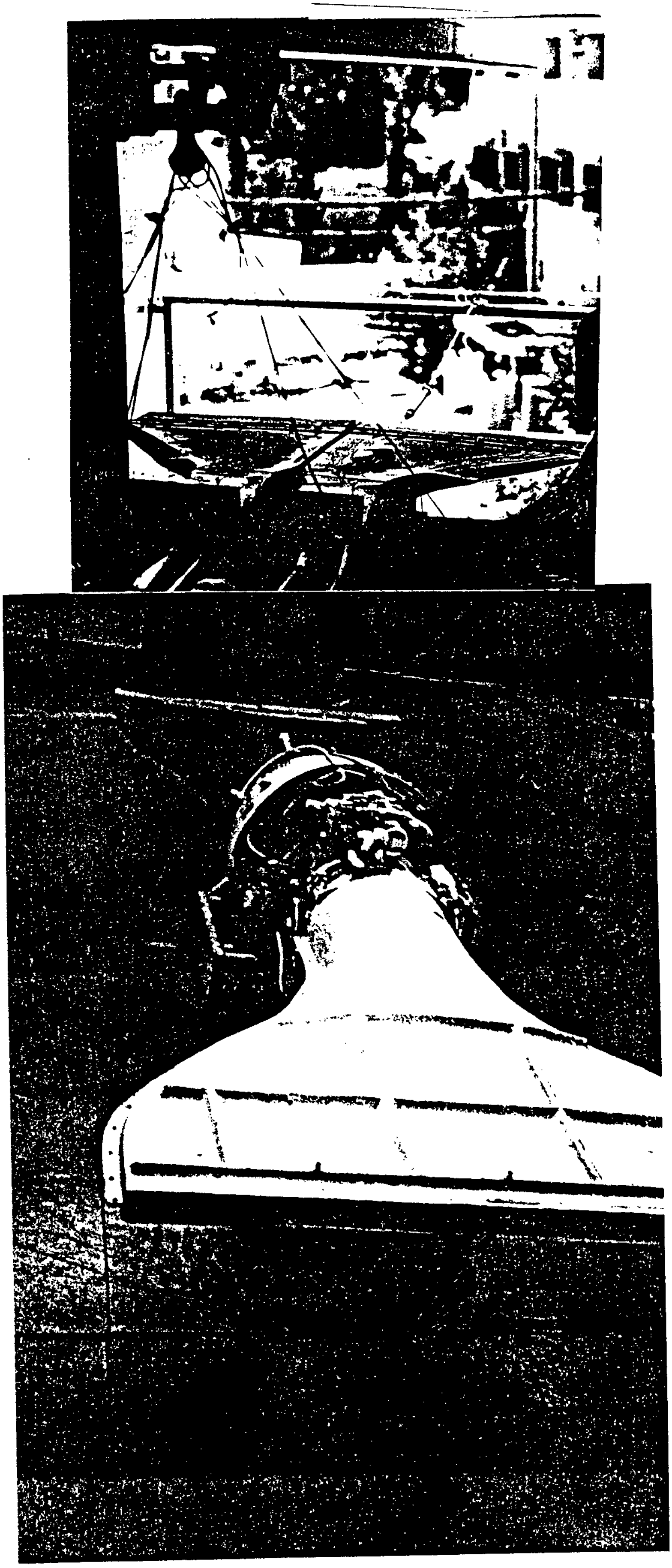


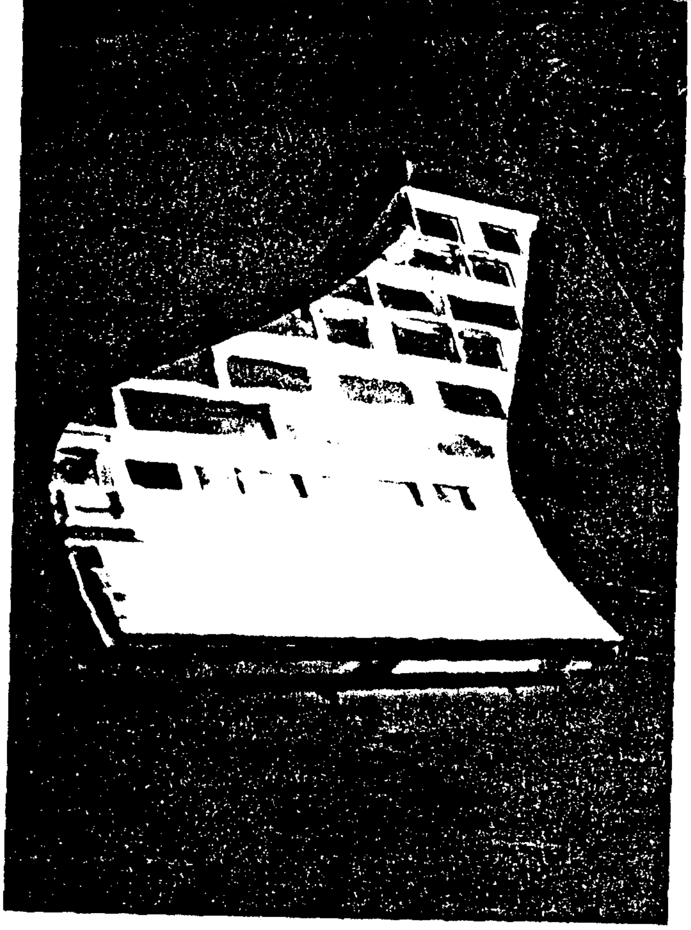
Fig. 82 : "Baseline 1", unvectored, 1/7-scale F-15 model.



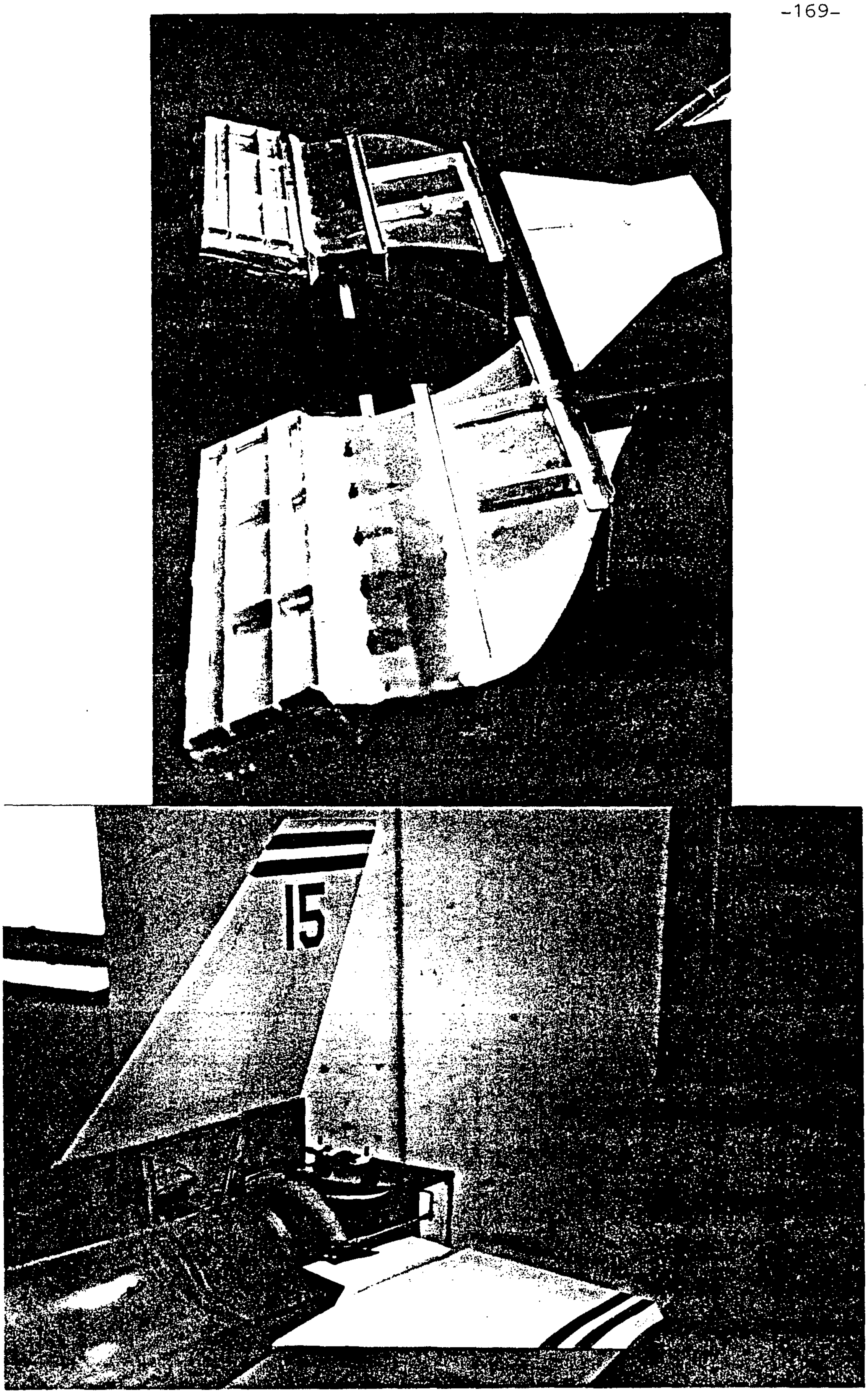
Figs. 63,4: 1st ITV F-15 model. 'Tailless windtunnel-model' is shown on wing. Sitting is Dr. V. Sherbaum.



Figs. 85,86 : (Above) The yet untested R-Y-P nozzles for the"TAILESS F-15". (Below) The wing-embedded inlet. (The upper picture shows the calibration test of the R-Y-P nozzles, using springs on the 3 axes).



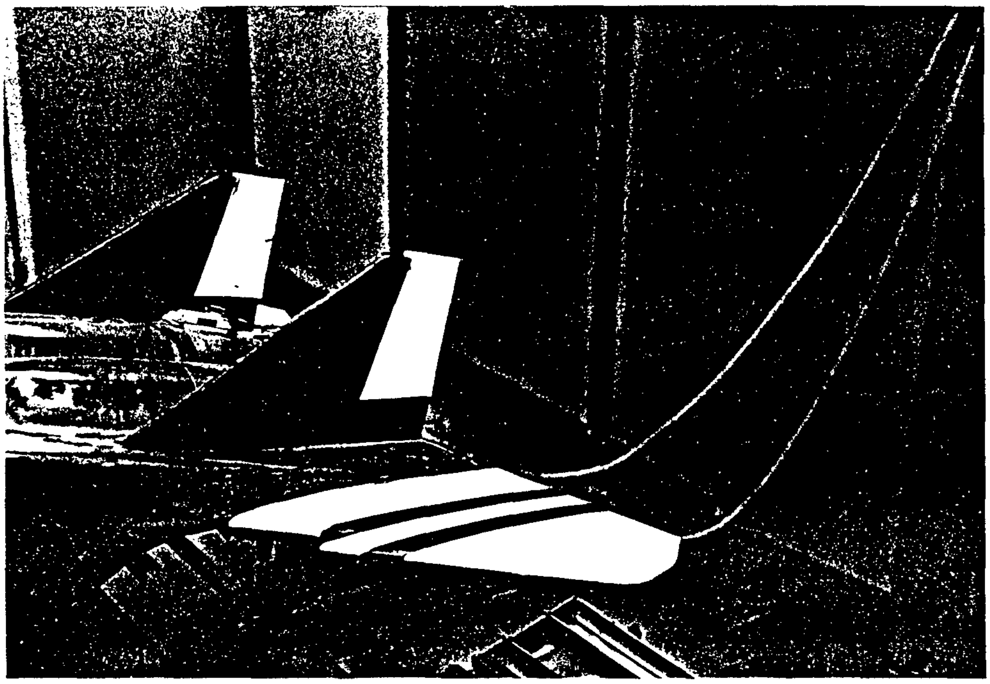
Figs. 87, 88 : The R-Y-P TVC system payed for by GE. (Designed for twin-engine TVC).



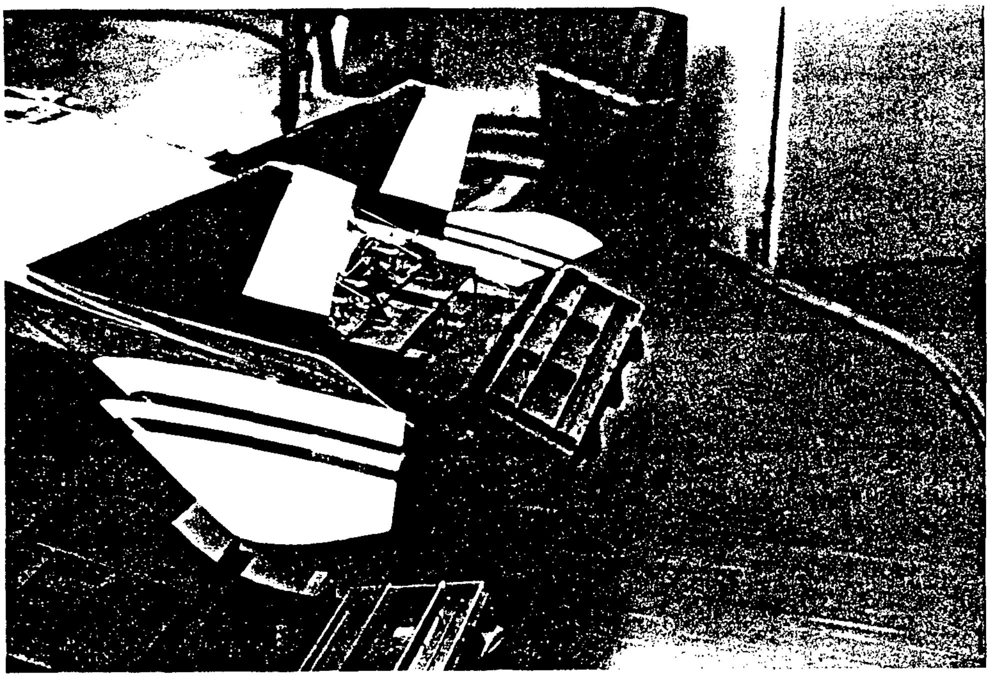
Figs. 89,90 : (Above) The R-Y-P nozzle payed for by Teledyne. cf. p. 168.*

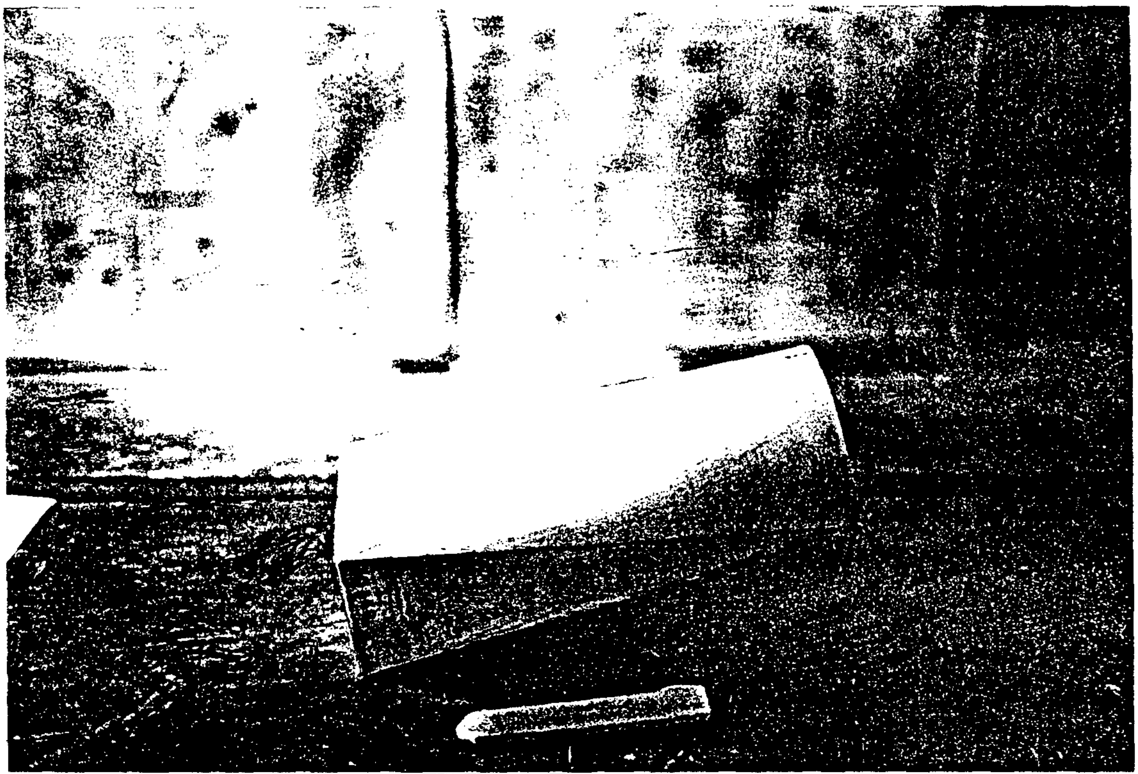
(Below) The Y-P nozzle on the F-16 (Payed for by GD).

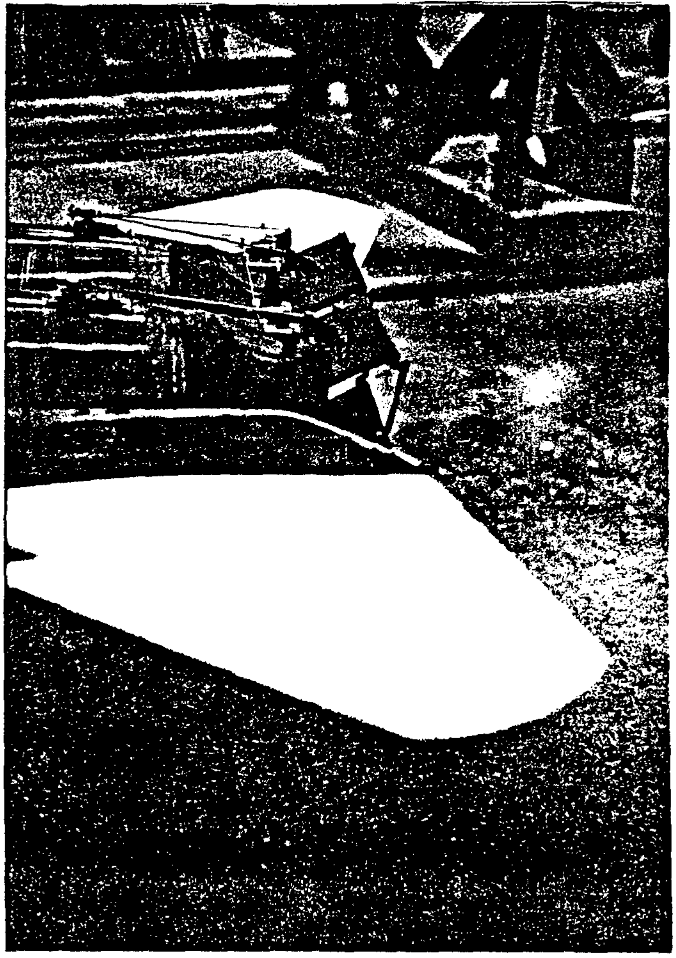
* It was scaled-down and flight tested in May 1987.
Yaw vanes are upstream of pitch flaps.



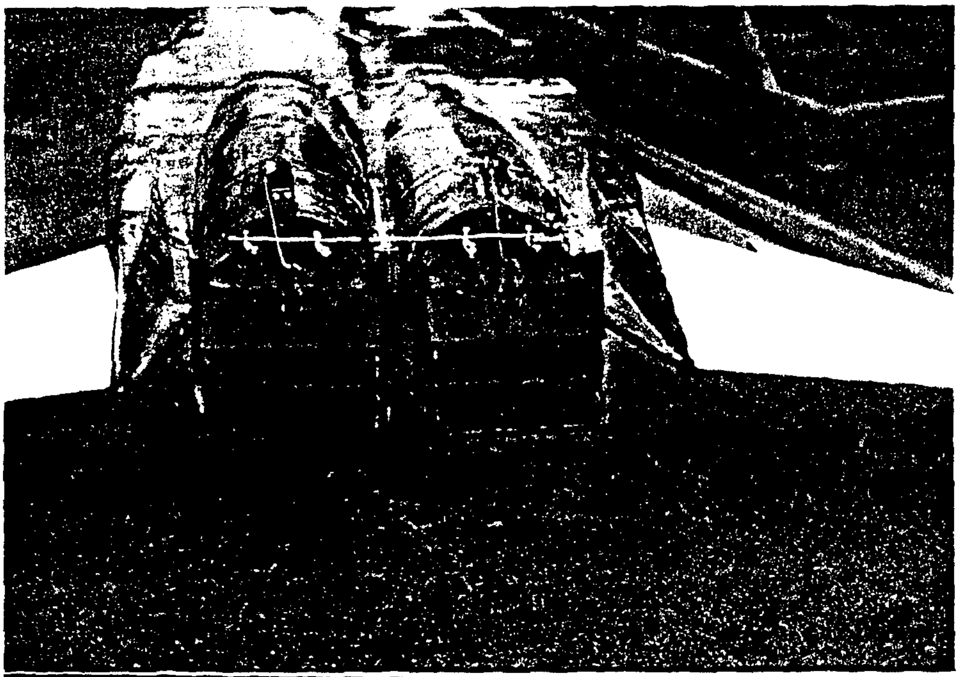
Figs. 91,92 : 25%-cut vertical stabilators, with TVC, in comparison with our R-Y-P TVC.

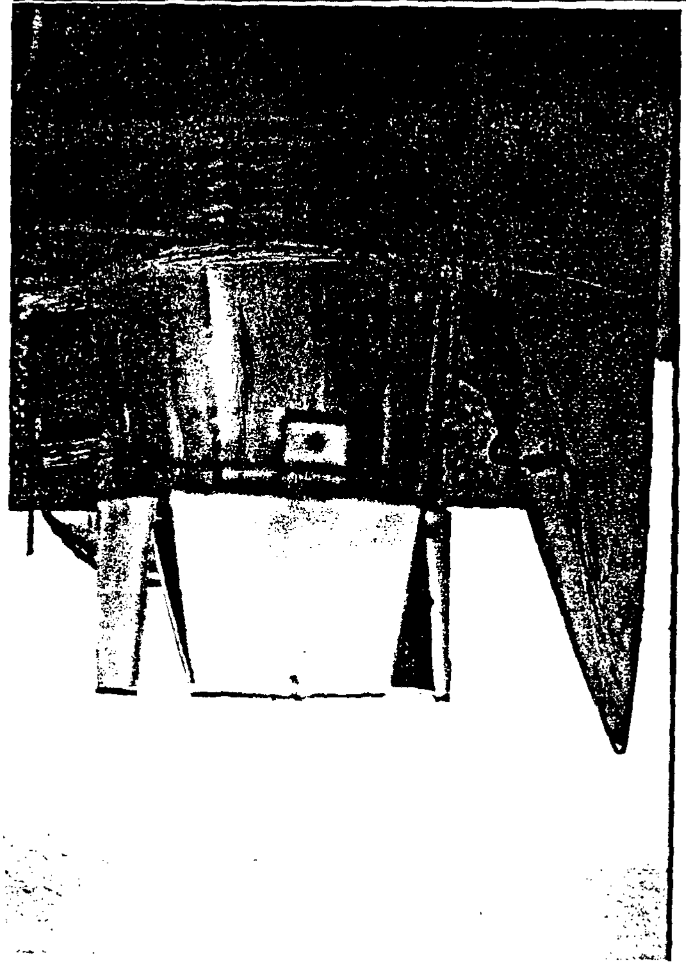






Figs. 93, 94 : (Above) The C-R adapter for ITV causes great losses with cold ITV propulsion.
(Below) F-15 ITV.





Figs.95,96 :
(Above) ITV
(Left) ETV.

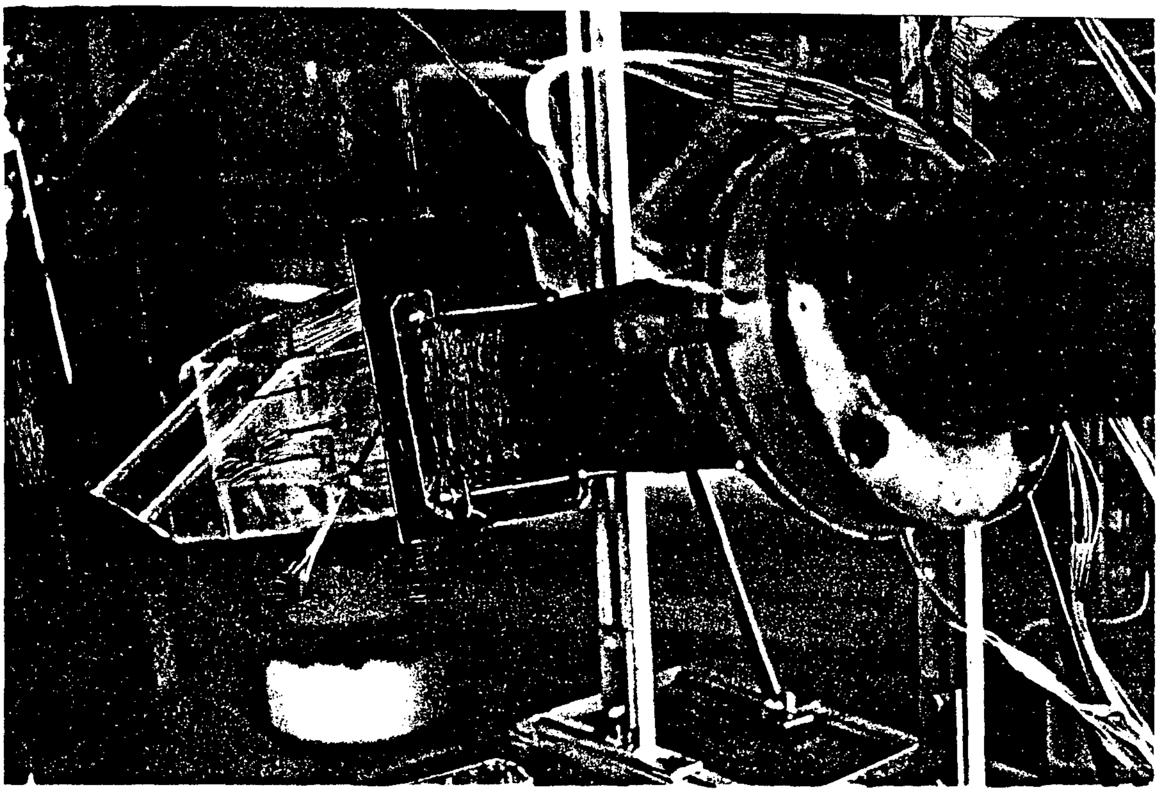


Fig. 97 : 1/7-scale F-15 inlet at zero AoA Distortion Coefficient laboratory tests. DC probes are inside the rotatable flange equipped with the handle.

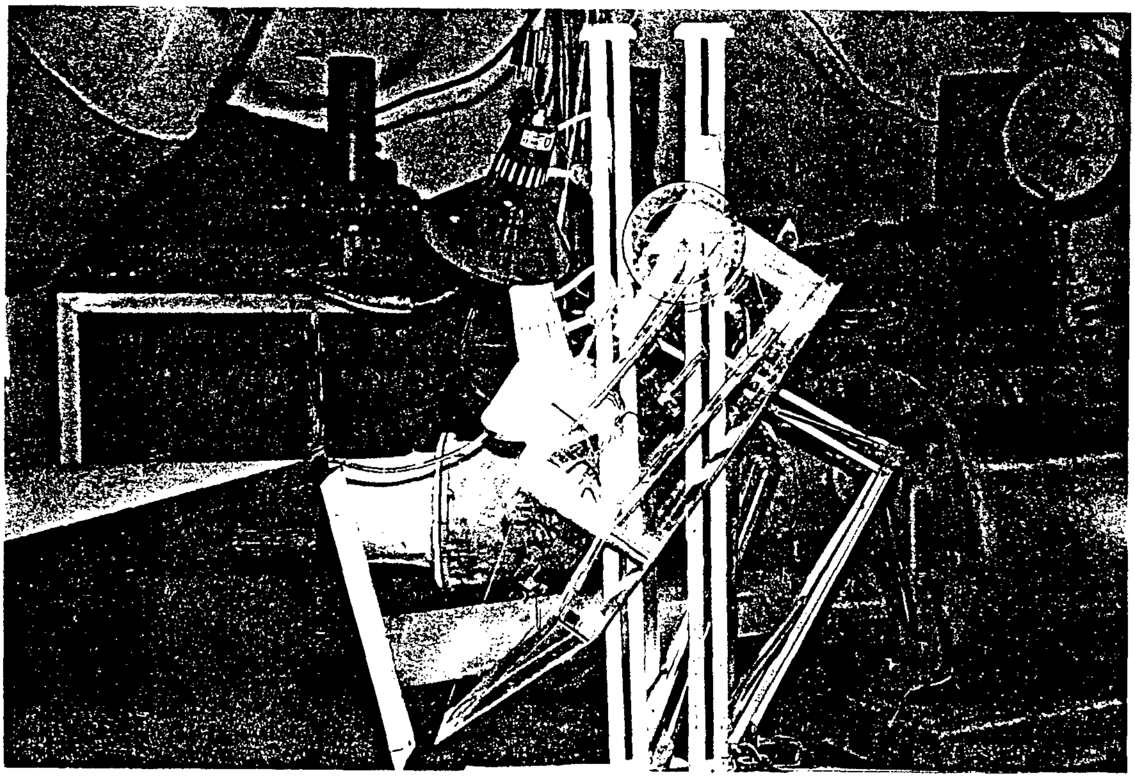
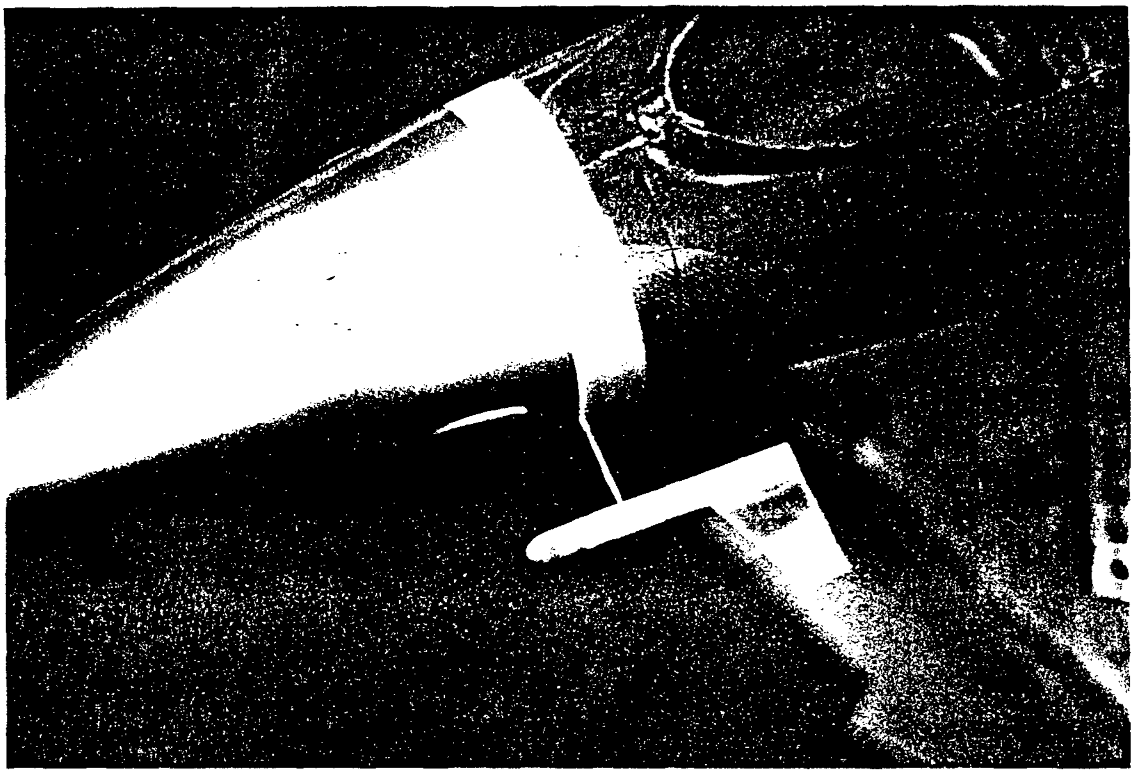
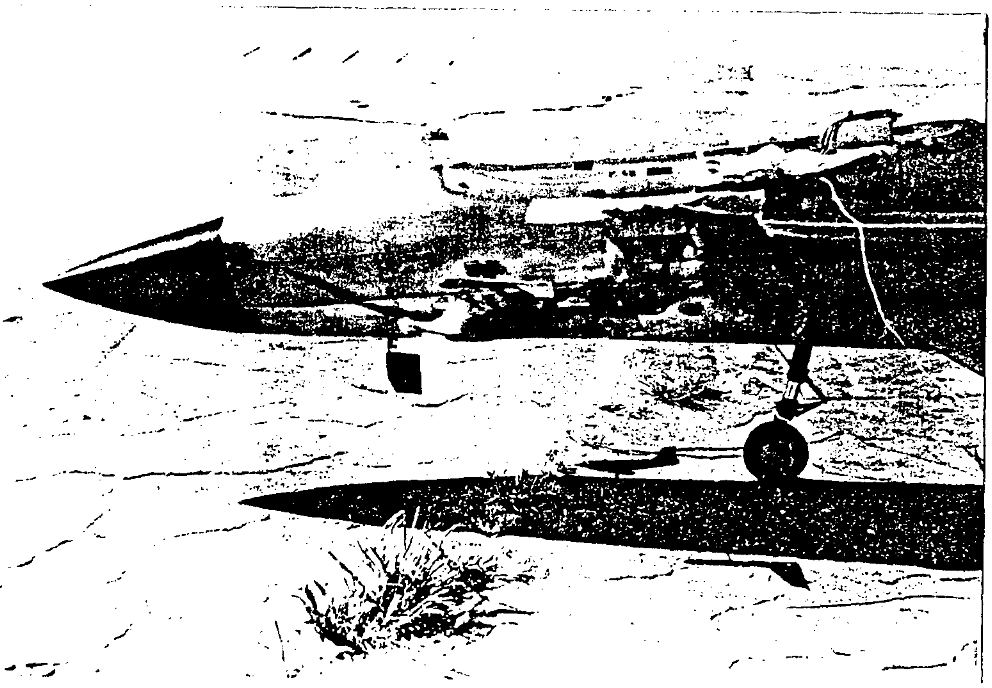


Fig. 98 : High-AoA DC orientation.



Figs.99,100: (Above) Alpha probe. (Below) Betta probe.



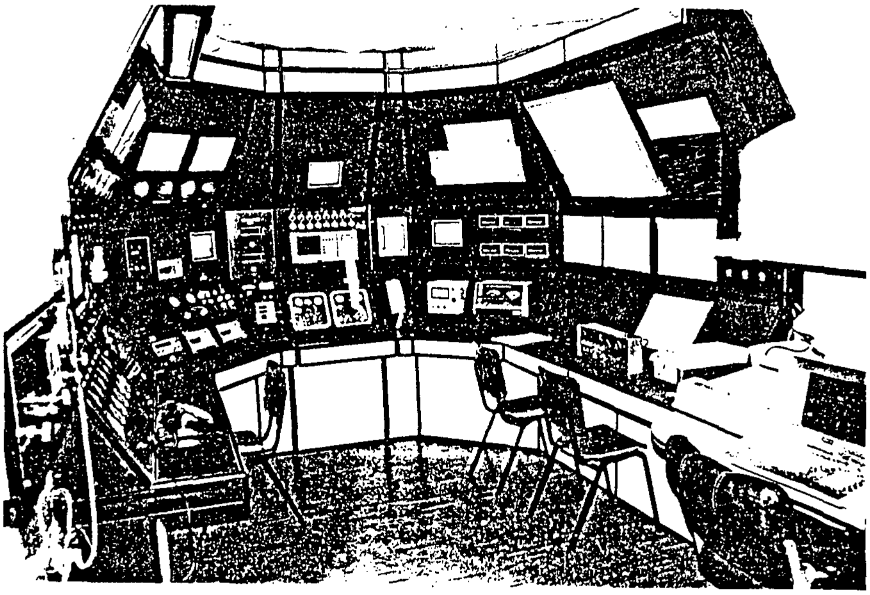


Fig. 101 : (Above) JPL Control Room No. 3 (TVC component tests)

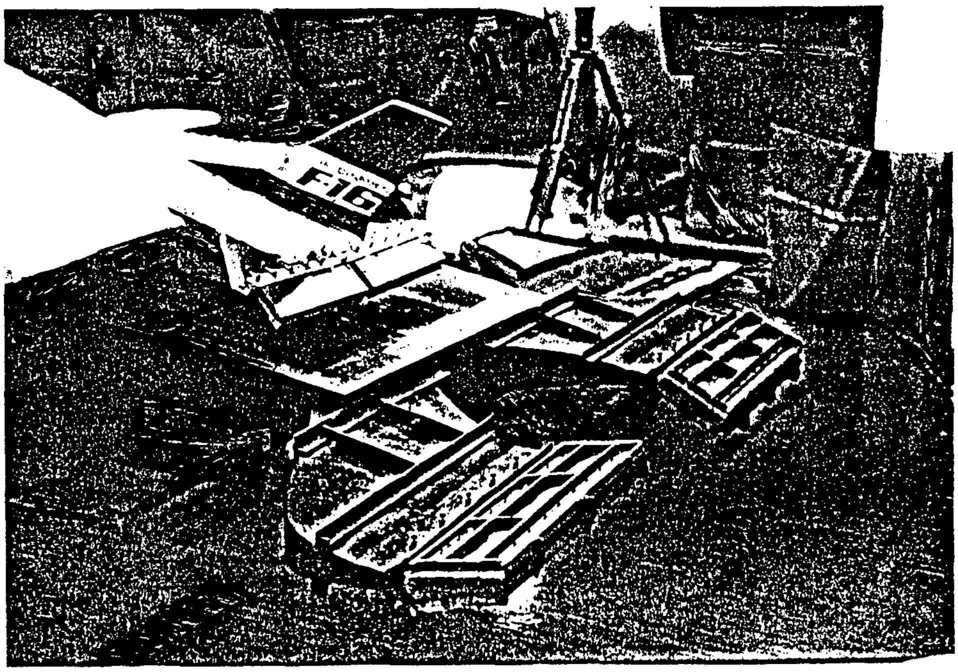


Fig.102 : Our new "Tailless" (Elevator-less/rudder-less) F-16 model on top of the nozzle proposed now for a "Tailless" F-15 model. The F-16 model was successfully flight-tested on May 9, 91. The F-15 ("Tailless") has not been tested yet.

Flight Program, Post Flight Analysis and Simulations

The PST-TV F-15, F-16 and PST-TV F-117 Flying Models

SACOM = Standard Agility Comparison Maneuver.

This term includes a comparison between conventional and Thrust-Vectoring (**TV**) control powers, and between various designs of Post-Stall (**PST**), TV control/airframe/propulsion systems.

Flyers : Mike Turgemann and Shlomo Barran, or Shlomo Barran and Amir Yogev.
Video-Camera operator: B. Gal-Or.
Electronic Connections/Verification: Dan Sofer and Ben Zion Spector.
Computers and Instrumentation: Rafi Schnaider, Eli Smadar, Yael Smadar, Ben-Zion Spector, Dan Soffer, Dan Grushkevitzh.
Ground Team: Eli Mashiach, Eli Dekel.
Flight Secretary: Eli Smadar or Rafi Schnaider. [Ambient temperature, Pressure, Wind direction & speed, time, timer vs commands, Timer vs computers files, post-landing-connection of back-up battery, back-up discs for computers-flight-data recording, etc.]
Fuel/time monitoring: Eli Mashiach.
Safety: Eli Mashiach, Eli Dekel, Mike Turgemann, Shlomo Barran and, overall, B. Gal-Or.
Post-Flight Analysis: Rafi Schnaider, Eli Smadar, Yael Smadar, Ben-Zion Spector, Dan Soffer, Dan Grushkevitzh, Dr. A Rasputnis, Dr. V. Sherbaum.
On-board and ground computers Hardware/Software Modifications: Pessach Pascal and Doron Rozenwasser.
Typing, Budget Monitoring and General Secretary: I. Soreq.
General Superviser: B. Gal-Or

Pre-Flight Laboratory Simulations/Calibrations/Verification Tests

1 - First distinguish between pre-flight laboratory simulations with and without operating engines.

1.1 - Simulations/ Verification Tests with Engines.

Laboratory simulations with the engines operating should be undertaken whenever a new type of gyros or accelerometers have been installed, or whenever a new engine/airframe/control system has been installed, or following any hard-landing which may have affected engines, flight-control systems, and airframe.

This test/simulation is subdivided into two:

1.1.1 - **Thrust Engine Tests** with PCM and FM transmitters operating, while the thrust levels obtained at the prevailing ambient temperature/barometric pressure is being recorded at the thrust-stand. Yaw and pitch TV commands should be tested. Only the systems that pass this stage may proceed to stage - 1.1.2.

1.1.2 - **Full Laboratory Simulation of a SACOM** [with the Engines Operating].

This pre-flight simulation is the most complete one. It is required, however, only as a result of a hard-landing which may have affected engines, flight-control systems, airframe, onboard computers, gyros, alpha, beta or velocity probes, or whenever a new type of gyros or accelerometers have been installed. To perform it follow the instructions provided in parag. 2 below when the engines are operating at full throttle.

2 - **System Verification VIA Laboratory Simulations of a SACOM**
[without Operating the Engines].

This is the most common pre-flight simulation/verification test.

Laboratory simulations [without running the engines] should be undertaken as a result of any hard-landing which may have affected the flight-control systems, airframe, onboard computers, gyros, alpha, beta or velocity probes.

The following steps should be taken:

2.1 - Put the relevant PST-TV Flying Model on a suitable stand in the computers room. Make sure two people can raise it and simulate roll, yaw and pitch movements at increasing time rates.

Charge all computers, transmitters, and stand-by batteries. Make relevant computer software available. Make connection cables between model and IBM-XT computer available.

2.2 - Operate and load the relevant computer programs on all 3 IBM computers.

2.3 - This test can be done separately. Hence, one can start the simulation from parag. 2.4 below. Moreover, the test should be performed only once before each trip to the airfield.

Operate the ground computer and the PCM transmitter. [The flyer's commands are to be recorded on the RAM of this computer, about 40 times per second. It is to run for 3.0 - 3.5 minutes and stop by itself.]

2.3.1 - Operate the ON and RECORD switches of the ground computer. Operate the "Computers-ON" switch on the PCM transmitter and perform all conventional and TV commands twice, one set with a maximum "step-function" rate, the other with slower rates.

2.3.2 - Stop, via the "Computers-OFF" PCM command. This is your first computer recording session. [A similar one will simultaneously be recorded on the onboard computer during actual flight tests.] Now operate it again, repeating the aforementioned commands. This is your 2nd session. DO NOT STOP THE LAST SESSION. Let the computer run for 3.5 minutes.

2.3.3 - Use the written instructions available in the room and the special cable to feed, using [once], the "DUMP" switch, the recorded data to the IBM-XT computer [which will also be present near the airfield]. Follow the instructions exactly ! [It now takes about 20 minutes to unload. This period will be reduced later-on in the program, by Doron and Pesach.]. There are about 4700 lines to be loaded. The running number is shown on the computer display. Watch the variations in the computer numbers of the various channels recorded. If no variations are observed after a while, repeat the simulation again.

2.3.4 - When the feeding is completed a disk and another back-up disk are available for post-flight analysis.

2.3.5 - To test and simulate the Post-Flight-Analysis, refeed the data into the IBM-AT computers, and proceed as stated in the chapter on "Post-Flight Analysis".

TESTING THE ONBOARD COMPUTER AND THE GYROS AND PROBES

2.4 - Operate the onboard computer switch, the gyros switch, the PCM radio switch, and the PCM radio transmitter. Check free motion of the alpha, beta and velocity probes. Check correct motion of all conventional and TV flight control means.

[The onboard computer is used to record the PST-TV model responses during each SACOM. The flight responses of each channel are recorded on the computer's RAM about 20 times per second. The gyros responses are recorded on two channels for each gyro, mark and note them for later analysis.]

2.5 - Hold the PST-TV model on a stand which allows pure roll, pitch and yaw movements at increasing time rates.

2.6 - While somebody measures time and record the order and type of the SACOM sequence, perform relevant motions in space-time to simulate expected PST-TV SACOMs.

2.6.1 - Include a few air blowings on the velocity probe and a few expected motions on the alpha and beta probes.

2.6.2 - Increase SACOM-time rates for each SACOM recorded session.

2.7 - Stop and restart recorded sessions by R/C commands [see 2.8 below]. Repeat maneuvers 2.6.

2.8 - At simulation end do NOT stop "COMPUTER-ON" switch on the PCM transmitter for at least 3.5 minutes. You can, however, shut-off the GYROS switch on the model and the the PCM itself. [The last operation would leave the on-off computer servo switch on the model unchanged.] Alternatively you can perform these operations mechanically by moving the on-off switch on the model with the PCM radio shut-off.

2.9 - After 3.5 minutes, connect the BACK-UP BATTERY to the onboard computer socket, shut-off the "COMPUTER-ON" switch on the model, and feed the data into the IBM-XT computer, following the written instructions exactly !

2.10 - Prepare a disk and [in the airfield] a back-up disk.

2.11 - Feed the data into the IBM-AT computer and proceed as in the chapter on Post-Flight Analysis.

General Pre-Flight Laboratory Instructions

1 - Charge all computers, transmitters, and stand-by batteries the night before the flight test.

2 - Preflight equipment checks & loading/unloading: Each participant according to assigned job.

Notes: Never touch control surfaces during loading/unloading or during laboratory simulations. Use the equipment list to verify that everything required has been taken to the airfield.

3 - Normal loading time of equipment in the Jet Engine Laboratory: 06:45 AM.

4 - Regular Destination: Megiddo Airfield, to start safty **prep-pre-flight** around 08:30 AM.

Pre-SACOM Air-Field Instructions

A - Perform low-level, maximum nominal flight-program distance, safty prop-preflight to verify that there is no radio interference and no loss of control at very low levels.

B - Move "Gyros" and "Computer" switches to ON at takeoff stand, after both engines have been started and the model stands at the actual takeoff position.

C - **NEVER TURN AFTER TAKE-OFF. FIRST GAIN ALTITUDE WITH VERY SLIGHT TURN.** Gain altitude and gradually come back and stay near the runway.

D - Start straight level flight, [or sustained level turn]. Do not use conventional rudder, except for safty.

E - Maintain full engines throttle throughout all recorded SACOM, unless specified differently.

F - Always use maximum ["step-function"] commands.

G - State in english what you do.

H - You may shut-off computers while regaining altitude between SACOMs. [3-minutes net recording time is available for SACOM]

SACOM Flight Instructions

001 - Loudly state readiness to start SACOM. Verify that the video-cammera is ready.

002 - Following that statement the Flight Secretary switches the Ground Computer to ON and the RECORD switch to ON.

003 - Count loudly with constant time-intervals: 4,...3,...2,...1,...0 and operate the computers switch at "zero" - when the "Zee" is first sounded. A lamp in front of the video camera may replace this procedure later.

004 - Operate the video camera at "three".

Perform: cf. p. 106.

1) - **Two [max-rate] conventional roll-reversals followed, as soon as possible, by two [max-rate] yaw-stick-TV rolls** [each 90 deg left then 90 deg right during level flight].

2) - **One [max-rate] TV pitch to max positive COBRA, then to minor negative COBRA and back to level flight**, then accelerate and back to altitude and the same speed/level flight.

3) - **Repeat [yaw-stick]-TV roll reversals at increasing AoA**, possibly by combining pitch/yaw TV commands, while you may remove the max-rate "step-function" requirement.

4) - **Repeat COBRA-Pitch-TV [2], then try to match it with conventional control.**

5) - **Repeat TV roll-reversals with COBRA !!! Repeat AGAIN at up to 90 deg AoA.**

6) - **Repeat pure-TV-pitch COBRA at higher speed and increasing AoA [<140 deg].**

7) - **Repeat [TV-yaw] roll-reversals at higher speed and increasing AoA.**

8) - **Perform repeated pure TV roll commands at increasing AoA.**

The Next Flight and Post-Flight Program [Jan 91 - ______]

The next flight program is exponentially-loaded with actual test and post-test work:

9) - Repeat steps[1] to [8] for statistical analysis, especially by flying perpendicular to the wind direction during the SACOM and by modifying throttle, speed, max positive AoA, max negative AoA, max command rate, min yaw-vanes response time, number of vanes, type of vanes, min pitch-flaps response time, faster computer sampling, inlet instrumentation, etc., so as to establish the technology limits of this particular design option.

10) - Repeat the 1 to 9 program for different longitudinal static stability margins. Fly-by-wire techniques may have to be introduced.

11) - Replace Vertical Stabilizers with shorter ones and Repeat steps[1] to [10].

12) - Repeat 11 with further reduced-size vertical stabilizers.

13) - Install CANARDS and repeat flight program 1 to 10.

14) - Install high-aspect-ration TV nozzles for **ideal** roll-yaw-pitch PST-TV and repeat flight program 1 to 13 w and w/o vertical stabilizers and w and w/o canards.

15) - Desigh special SACOM for establishing **pilot physiological limitations** on PST-TV agility.

16) - Repeat program for the **PST-TV-F-117.**

17) - Repeat one selective flight program with **"vectorable inlets"** and additional instrumentation for measuring inflight distortion coefficients.

18) - Repeat one selective program with **Teledyne 305 jet engines.**

Post-Landing Instructions

1 - DO NOT SHUT OFF "COMPUTER" SWITCH ON THE PCM TRANSMITTER at the end of the flight program nor after landing. Also DO NOT shut off ground computer ON and RECORD switches.

2 - Run to landing site and install the BACK-UP BATTARY. Then put rubber rings around it.

3 - Following step 2, you can shut-off "GYROS" and "COMPUTER" switches on the model.

4 - Following step 3, you can shut-off the engines and then the PCM transmitter.

5 - Load the model and the ground computer on a car and drive to CHIMAVIR building. Unload the model near the IBM-XT computer. [About 10 minutes]

6 - Operate the IBM computer and first unload the ground computer. [About 20 minutes]

7 - Unload the onboard computer. [About 20 minutes]

8 - Display a few relevant responses.

9 - Define the next SACOM and return to runway with model and ground computer. [About 10 minutes].

10 - Remove back-up battery and proceed as before.

NOTES:

The total delay time between flights is now about 60 minutes. With an improved computer software this delay time may be reduced to around 30 minutes. Purchasing a suitable portable computer [with batteries that supply up to 4-hours operation without recharging], may reduce the minimal delay time between flights to around 10 minutes.

Post-Flight Analysis

1 - Use the ground-computer-numbers/time calibration to first display overall commands vs time .

2 - Mark the time scale for each particular SACOM.

3 - Expand the command time-scale for each SACOM to fill the entire display/graph screen.

4 - Print all **commands vs time** graphs, i.e., one for each SACOM.

5 - Use sensors and time-calibrations to display the SACOM **responses** [from onboard computer] for each command-time interval printed via step 4, namely, per each command figure, print [at least] the following ***10*** figures:

5.1- AoA and speed vs time.

5.2 - Betta and yaw rate vs time.

5.3 - AoA and pitch rate vs time.

5.4 - AoA and roll-rate vs time.

5.5 - AoA and yaw-rate vs time.

5.6 - Alpha dot and p vs time.

5.7 - Time derivatives of relevant variables vs time.

5.8 - $\dot{p}, \dot{q}, \dot{r}$ vs time.

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Fundamental Concepts of Vectored Propulsion

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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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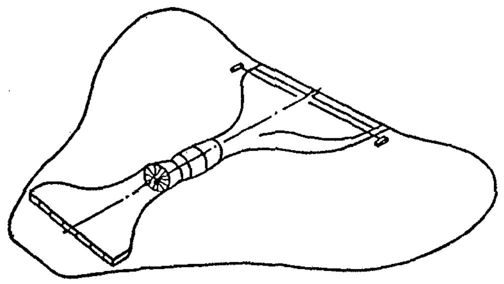

Fig. 1 Jet-powered pure-vectored RPV (nonsplit engine TV nozzle); engine inlet and nozzle are well-integrated with the wing structure (see Fig. 2).

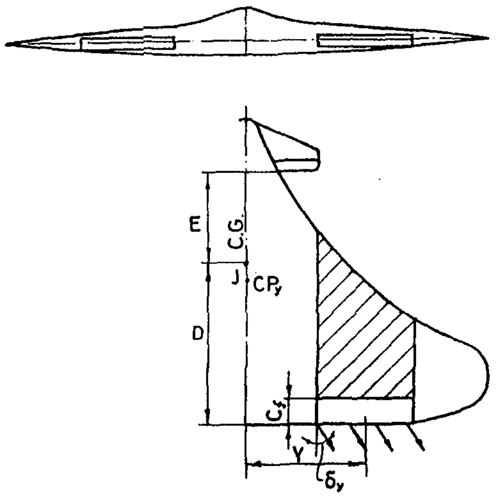

Fig. 2 Example of pure-vectored propulsion; the shaded area represents supercirculation-affected wing sections; PSM is obtainable when the jets are deflected through CP_y as depicted; there are no vertical stabilizers, rudders, ailerons, flaps, etc.

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

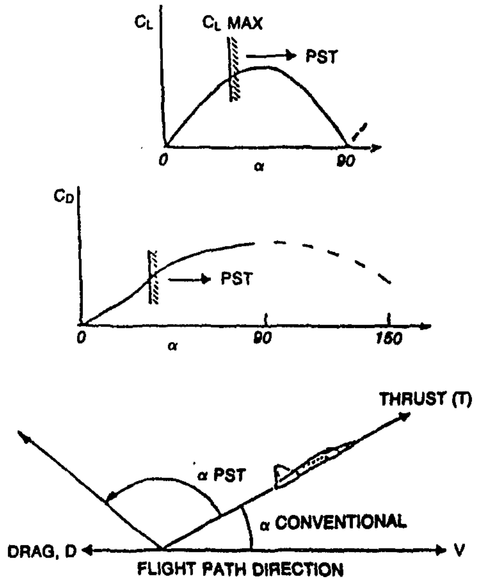

Fig. 3 Definition of PS technology for maneuverability and controllability by new thrust-vectoring powerplants (see Fig. 4).

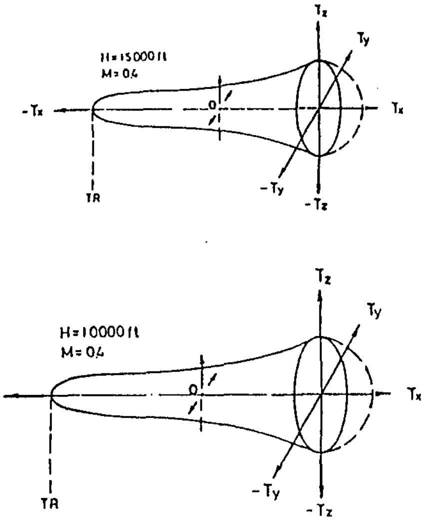

Fig. 4 Engine flight control envelopes change with altitude and Mach number; T_y and T_z are the controllability yaw and pitch engine forces, respectively; *TR* is full thrust reversal.[3]

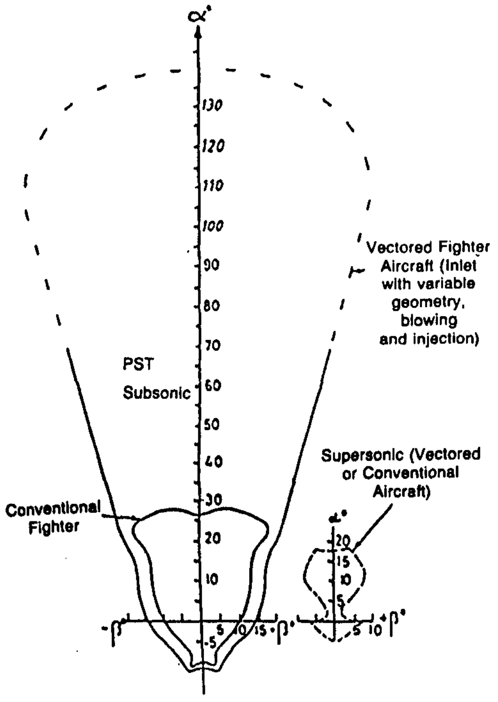

Fig. 5 - New engine yaw-pitch, TV moments would expand conventional fighter subsonic AOA (alpha) and sideslip angle (beta); this jet propulsion laboratory now conducts PS/PSM/RANPAS by vectored RPVs in the low subsonic PS domain.[3]

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]

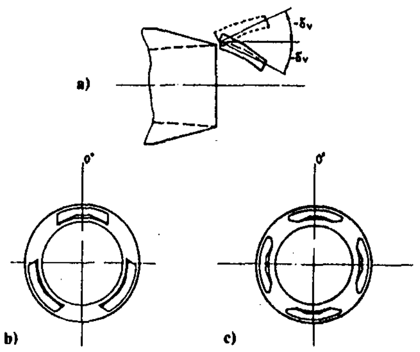

Fig. 6 ETV: a) sideview, b) 3 pedals, c) 4 pedals.[10]

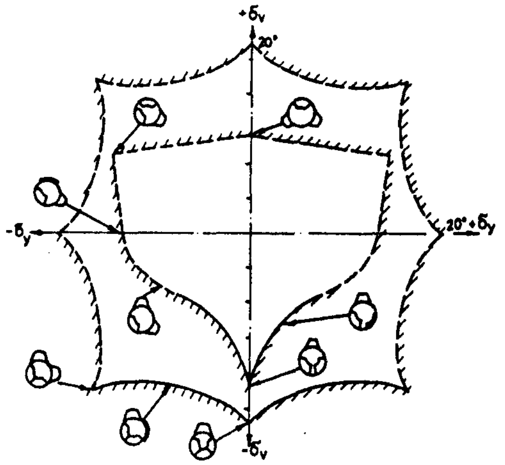

Fig. 7 ETV angles envelopes; new fighter powerplants must be developed with simultaneous yaw-pitch-roll ITV or ETV.

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.

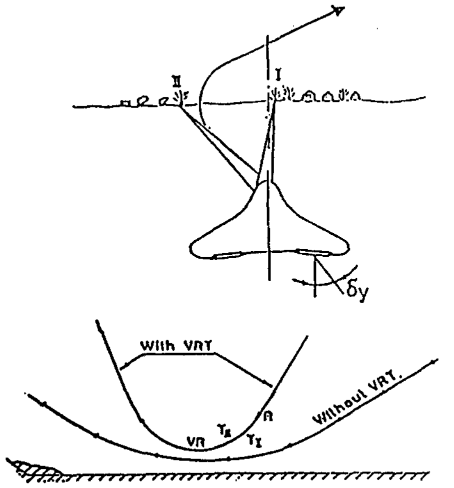

Fig. 8 Air-to-ground PSM/RANPAS; VRT = vectoring/reversing/(yaw) "targeting."[3]

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-

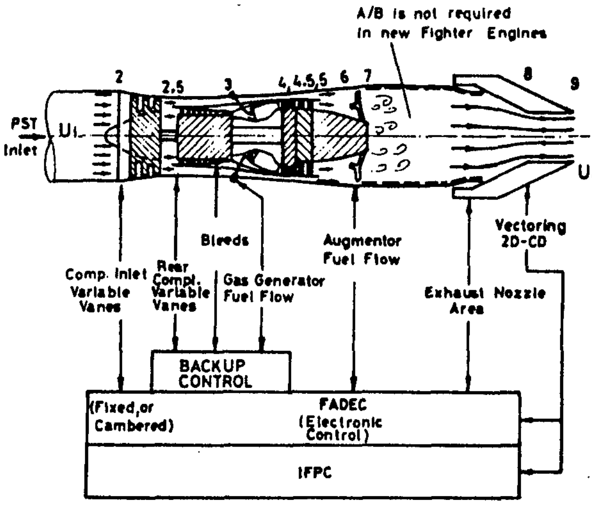

Fig. 9 TV nozzles, PS inlets, and IFPC systems must be developed for PS maneuverability; new engine metrics (see Fig. 14) and control laws (see Fig. 9) must also be developed and flight tested (also by RPVs).

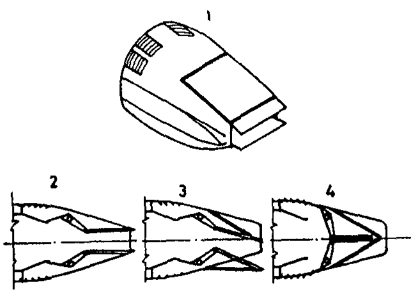

Fig. 10 Example of (pitch/TR-only) engine nozzle ITV: 1) TR outlets, 2) unvectored engine operation, 3) down-pitch TV, 4) engine nozzle during TR.

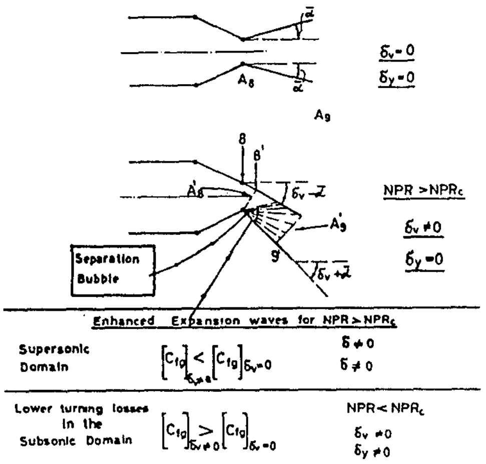

Fig. 11 In the nozzle subsonic domain, the engine thrust coefficients C_{fg} may be higher for TV engines in comparison with conventional engines[3]; separation flow regimes downstream of the corner reduce C_{fg} in the supersonic domain.

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-

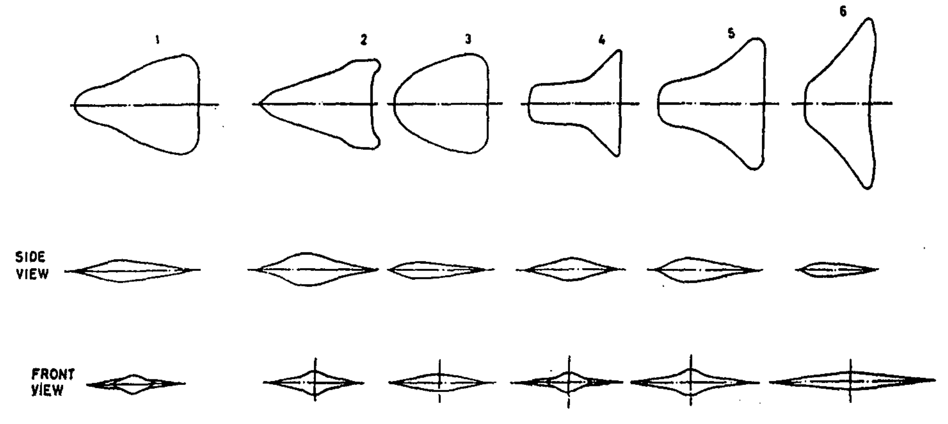

Fig. 12 The first six subsonic PVA/RPV wind-tunnel models tested by this jet propulsion laboratory in 1987; low signatures design concepts have been combined with yaw-roll-pitch TV.

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]

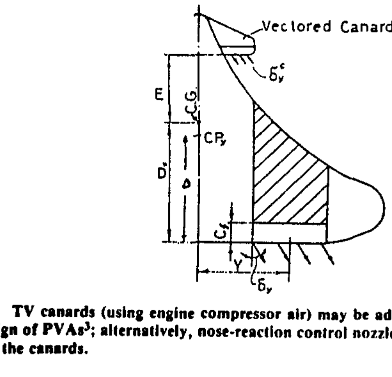

Fig. 13 TV canards (using engine compressor air) may be added to the design of PVAs[3]; alternatively, nose-reaction control nozzles may replace the canards.

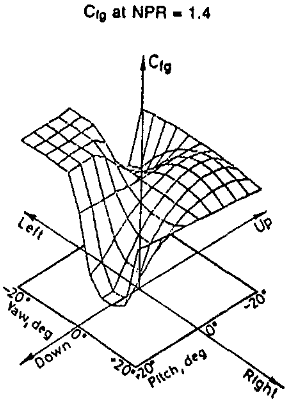

Fig. 14 New powerplant metrics are now required for the development of efficient aerogas turbines and IFPC systems; these should include the effects of yaw and pitch TV on engine thrust, discharge, angularity, and velocity coefficients.

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.

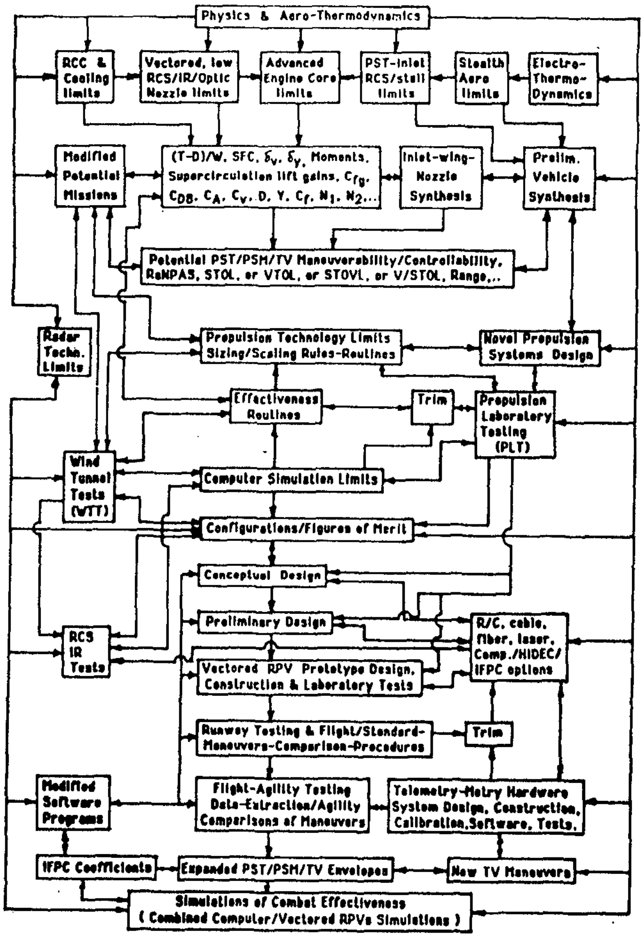

Fig. 15 The main feedback operations conceived, developed, and carried out by this laboratory during the various phases of the design, fabrication, laboratory, and flight-testing phases of this multiple-year program.

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' and A_9' (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

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

where A_8' 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'/A_8' ratio for each NPR, the effective nozzle exit area A_9' should also be subject to the condition

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

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):

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

$$= \cos\delta_v \cdot \sin\delta_v / \cos\delta_v \cdot \sin\delta_v \qquad (8)$$

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

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

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

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

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

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.

Acknowledgments

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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Appendix C : Terminology for Next-Year Project and Pilot Tolerances

Snap TV-roll reversals/stops and RaNPAS/reversals/stops by PST, or by PSM, may cause some **physiological effects** on the pilot. The physiological effects of various g loads are:

1) Difficulty of motion of body and limbs because of the weight increase;
2) Circulatory dysfunction concomitant with blood pooling, resulting in blackout and tissue hypoxia on the one hand and congestion on the other,
3) Displacement of viscera and other moveable parts;
4) Structural damage.

Tolerance generally means "**time until loss of consciousness at a given g load**". Tolerance to a given g value depends upon the duration and the direction of acceleration with respect to the body. When acceleration is from feet to head it is called "**positive**"; when from head to feet it is "**negative**"; when from front to back or back to front it is **transverse**.

Human tolerances to acceleration at various rates show that for **0.1 - 0.3 sec** duration of a "**g-onset**", the typical times for the onset of TV-agility, the tolerances are:

3.0 - 7.5g for negative g loads.

7.0 - 10g for positive g loads.

Rotation, whether about one's own axis or some other, produces "motion sickness", especially when the subject must, in addition, move his head in some manner other than straight up and down. PST-TV-roll reversal/stops and TV-RaNPAS-rotations generate rapid rate-of-change in **sidewise g loads,** in positive and negative g loads, and in **centrifugal** g loads. Thus, during TV-RaNPAS, it is mainly the rapid initiation of rotation and its quick stops that generate sidewise, and positive and negative g loads on the pilot. **For negative PST-RaNPAS the limit is 3.0 - 7.5 g.**

A relevant factor to 2nd-derivatives of the velocity vector during rapid TV-roll reversals/stops is as follows. In each ear there are 3 fluid-filled semicircular canals which are set in three planes **at right angles** to one another. In the absence of visual cues, the brain interprets stimuli arising from the semicircular canals in the following manner -

a - Constant velocity as "rest".

b - Acceleration as "movement".

c - Time-rate-of-changes in acceleration as "acceleration".

Furthermore, during straight and level longitudinal acceleration the pilot feels a false sensation of "**pitch-up**" change in attitude. During straight and level deceleration the pilot feels a false "**pitch-down**" change in attitude. Moreover, sudden linear acceleration - catapult, snatch, or "rocket launch" - produces the sensation of "**rotating backward**", heels over head, while sudden linear deceleration - crash impact, or arrester wires, produces the sensation of "**rotating forwards**", head over heels. Nodding movements of the head occuring whilst other rotational movements are taking place in a different plane, can give rise to considerable mental confusion and lead to disorientation.

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2 - Cosmology, Physics and Philosophy, Springer-Verlag, N.Y., 1st Ed. 1981, 2nd Ed. 1983, 3rd Ed. 1987.

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6 - Turbo and Jet Engines, Vol I, 1980, [ASME-IGTA], Vol II published by the Int. J. Turbo and Jet Engines, 1984.

88 papers in international professional journals. 3 patents [thrust vectoring].

D.Sc. & M.Sc. Supervisor: Supervised 10 D.Sc. and 16 M.Sc.[See list below *].

Aerospace Award: The Laskovitch Award and Gold Medal for best original research work in aerospace; from the New-York Academy of Sciences, 1971/1972.

Current Research Projects

The following projects have been paid for by contracts with **US Air Force, General Electric, General Dynamics, Teledyne, Pratt and Whitney,** and other bodies.

- First thrust-vectoring [TV] flights of unmanned vehicle [1987] and first TV-induced positive and negative 'Cobra' maneuvers by 9-foot F-15 model [1989].
  [Cf. Aviation Week, May 18, p. 21, 1987; 'All the World Aircraft', 1988/9 - RPVs [Israel], Flight International, 7-3 March 1990, p. 18.
- Novel yaw-pitch and roll-yaw-pitch thrust-vectoring engine-nozzles/airframe systems.
- Post-stall [PST], thrust-vectoring agility definition and measurement.
- Distortion-free, vectorable, PST-engine-inlets;

Previous Research Topics

- Supersonic and Hypersonic Plasma-Jet Guns: Theory and Applications.
- Pressurized Fluidized Beds linked to Gas Turbines;
- Dust Filtration systems for helicopters and tanks.
- Chemically-Reacting two-phase flows and combustion systems.
- The Origin of Irreversibility;
- Thermodynamics of large space systems;
- The Physics of Asymmetries;

* --

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2 - Tark, M.Sc. [Hopkins]
3 - Camilus, D.Sc. [Pittsburgh]
4 - Tavlarides, D.Sc. [Pittsburgh]
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