Computer Control for Automated Flight Test Maneuvering

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The application of an experimental flight test maneuver autopilot test technique for collecting aerodynamic and structural flight research data on a highly maneuverable aircraft is described in this paper This technique, which was developed to increase the quality and quantity of data obtained during flight test, was applied to the highly maneuverable aircraft technology (HiMAT) vehicle A primary flight experiment was to verify the design techniques used to develop the HiMAT aerodynamics and structures This required the performance of maneuvers for collection of large quantities of high quality pressure distribution, loads, and wing and canard deflection data Flight data obtained while executing these research maneuvers are presented to demonstrate the effectiveness of this new technique

Nomenclature

a_n	= normal acceleration, g
h	= altitude, ft
$\dot{h}$	= altitude rate, ft/s
M	= Mach number
α	= angle of attack deg
$\dot{\alpha}_{cmd}$	= angle of-attack command rate deg/s
α_0	= trim angle of attack, deg
Δh	= altitude error from commanded altitude ft
ΔM	= Mach error from commanded Mach number
Δt_α	= time that commanded angle of attack is to be held during pushover pullup s
$\Delta\alpha$	= incremental angle of attack commanded during pushover pullup maneuver, deg
ϕ	= bank angle deg

Introduction

AN experimental flight test maneuver autopilot (FTMAP) was developed and flown to increase the quantity of the data obtained in the flight testing of the highly maneuverable aircraft technology (HiMAT) remotely piloted research vehicle (RPRV) The FTMAP was designed to perform pre scribed maneuvers precisely while maintaining critical flight parameters within close tolerances The specific maneuvers mechanized in the FTMAP were designed to collect high quality repeatable data These data were used to facilitate comparison of flight-measured pressure distributions, loads, and deflections of the HiMAT wings and canards with analytic and ground test data The FTMAP operated as a nonflight critical outer loop controller and augmented the vehicle's primary flight control system

Of the numerous technological advances applied to the HiMAT vehicle, the two that were incorporated in the design and manufacturing of the wing and canard demanded a particularly exacting flight test; these were the close coupled canard/wing configuration and the aeroelastic tailoring of the lifting surfaces The evaluation and validation of tools used in the design of wings and canards required precise, controlled flight test maneuvers to permit comparison of flight measured pressure distribution loads and deflections with the predicted values

Presented as Paper 83 2137 at the AIAA Atmospheric Flight Mechanics Conference Gatlinburg Tenn , Aug 15 17 1983; received Sept. 18 1983; revision received May 25 1984 This paper is declared a work of the U S Government and therefore is in the public domain

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This paper discusses the application of the experimental FTMAP flight test technique in the collection of research flight data The effectiveness of the FTMAP is illustrated using flight test data. The data obtained from FTMAP flown maneuvers in some cases are compared with data from pilot flown maneuvers The results demonstrate the quality, consistency, and repeatability of the data in various FTMAP flown flight conditions

HiMAT System Description

The HiMAT vehicle (Fig 1) was designed to incorporate technological advances in many fields: close coupled canard configuration aeroelastic tailoring, transonic aerodynamics, composite and metallic structures, digital fly by wire con trols, and digitally implemented integrated propulsion control systems [1] The HiMAT vehicle is a 0 44 scale version of an envisioned full scale fighter aircraft with an 8g sustained turn capability at Mach 0 90 and an altitude of 25,000 ft

The operational concept for the HiMAT vehicle is similar to that for previous RPRVs The 3370 lb vehicle is air launched from a B-52 aircraft at 45,000 ft and carries 660 lb of fuel for the J85 21 engine The vehicle is controlled by a research test pilot located in a ground based RPRV facility cockpit Flight test activity is monitored on the ground by use of a telemetry downlink Flight control laws for both primary and backup operation are implemented through two ground-based and two airborne digital computers: the primary control system (PCS) computers are ground based and consist of a decommutation and a controls law computer (Fig 2); the

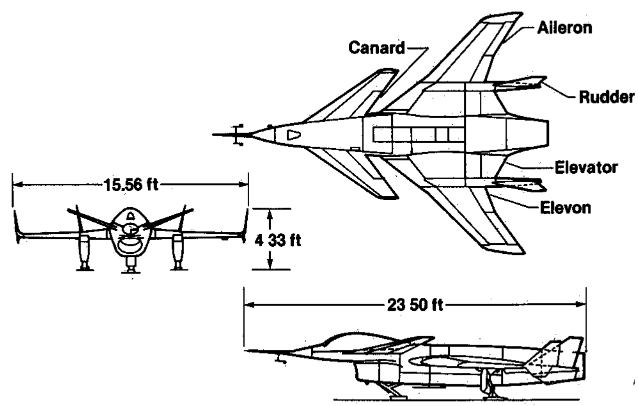

Fig 1 Three view drawing of the HiMAT vehicle

two airborne computers provide backup control The vehicle is equipped with landing skids and forward looking television for horizontal recovery on the surface of the Edwards dry lake.

In the primary mode of operation (Fig 2), aircraft sensor data are transmitted to the ground by a telemetry downlink The downlinked data are used both to drive the ground cockpit instruments and as input to the ground based control law computer The control law computer combines the pilot input commands with the downlinked aircraft sensor data in the execution of the HiMAT control laws, and then formats a servoactuator command for each of the vehicle control surfaces: elevons, rudders, canards, elevators, and ailerons These surface commands are output to the uplink encoder and then transmitted to the aircraft [2]

FTMAP System

The FTMAP operates as an outer loop control to the primary system shown in Fig. 2, employing two additional ground based computers (Fig 3) In this system, while the FTMAP is active, the normal primary control system pilot input commands (longitudinal stick, lateral stick, and throttle position) are replaced by corresponding commands generated in the FTMAP computer (The pilot retains rudder pedal control in order to trim sideslip because no FTMAP input is provided in the yaw axis) The primary control system control laws execute at the same time as the FTMAP control laws, and provide the inner loop stability augmentation Both the FTMAP and primary control system computers receive the aircraft response parameters from the downlink processing (decommutation) computers The data available to the FT MAP computer are identical to those input to the primary control system computer The FTMAP computer accepts data from a cockpit input panel (Fig 4) that allows definition of the test condition parameters, such as a maneuver number, angle of attack, normal acceleration, and Mach number This input panel includes thumbwheel switches and an annuciator display

The procedure for flying a maneuver with the FTMAP requires the pilot to fly to the desired test altitude When altitude rate is within a nominal ±3000 ft/min range and the vehicle is at the target altitude, the FTMAP is engaged by using the cockpit input panel Each maneuver consists of three phases: straight and level, maneuver control, and maneuver disengagement Engagement of the FTMAP establishes a reference altitude and puts the FTMAP into an altitude hold mode with the vehicle flying straight and level For any of the FTMAP maneuvers, the straight and level phase can be selected independent of the other two phases and used as an altitude hold autopilot with Mach number control During the maneuver control phase, the FTMAP flies the vehicle into the

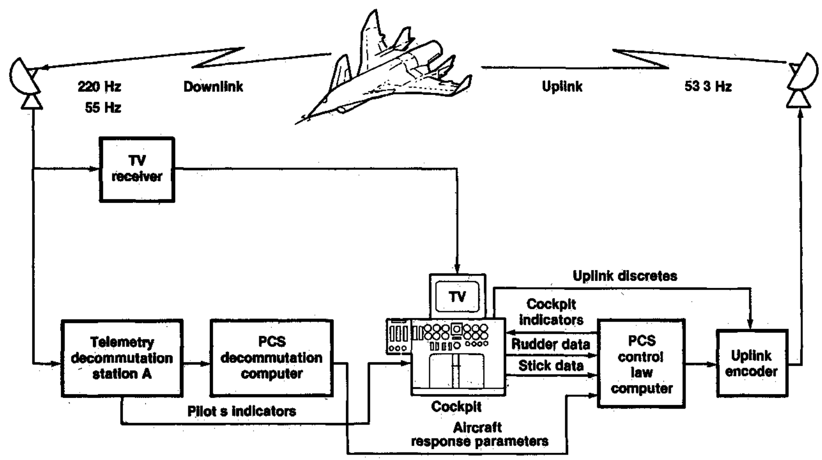

Fig 2 HiMAT RPRV primary control system

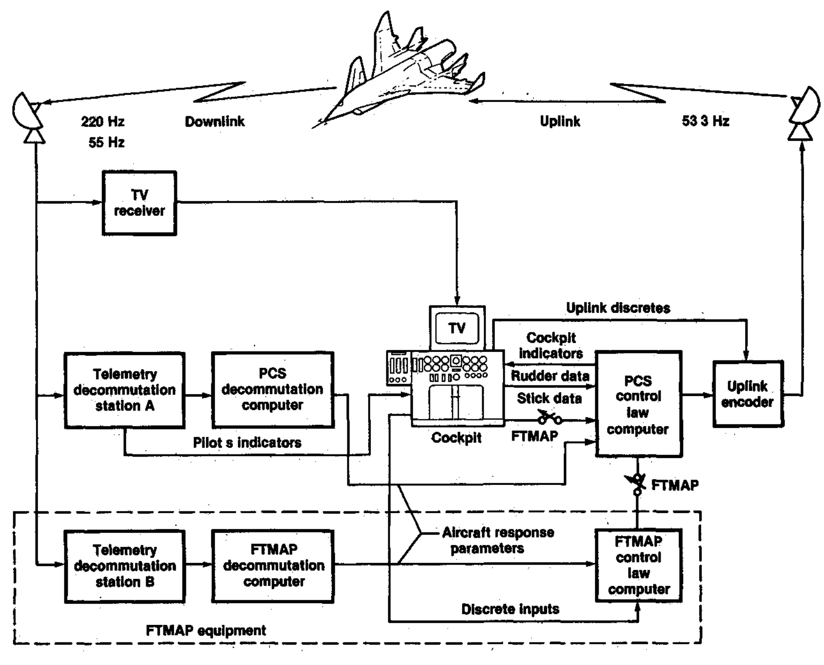

Fig 3 HiMAT flight system with FTMAP

test maneuver and monitors the vehicle state to determine when the test conditions are met or whether any predefined mission limits are exceeded The normal exit from a maneuver is initiated by disengaging the FTMAP maneuver switch This action puts the FTMAP into the maneuver disengagement phase, which returns the vehicle to wings level flight, and then automatically transitions it back into the straight and level phase

Maneuver Requirements

To accomplish the research objectives of the primary project, three maneuvers were required: pushover pullups, excess thrust windup turns, and thrust limited windup turns The precision required for these maneuvers necessitated the development of a technique to provide automatic, multiaxis control. Terminal conditions were specified to exacting ac curacies, as were the rates at which these conditions were to be achieved For a pilot using manual control and normal piloting techniques, the rate of onset of a flight maneuver is the most demanding requirement The design goal of the project was to control the rate of onset to 0 25 deg/s for angle-of attack commanded maneuvers, and 0 2 g/s for normal acceleration commanded maneuvers while controlling the vehicle to tolerances of ±0 5 deg angle of attack or ±0 5g normal acceleration at ±0 01 Mach number and ±500 ft altitude

Pushover Pullups

The pushover pullup is a wings-level maneuver that is performed at a constant Mach number The maneuver consists of varying the aircraft angle of attack about the trim condition (α_0). Figure 5 illustrates the pitch axis task for the pushover pullup The stick is pushed forward until the measured angle of attack is a specified angle-of-attack in crement ($\Delta\alpha$) below the trim condition. This angle of attack is held for a predetermined condition-hold time (Δt_α) before the stick is pulled back past the trim point, until the measured angle of attack increases to the specified increment above the trim angle of attack After the hold time, the stick is moved forward until the aircraft returns to straight and-level flight During this maneuver, lateral stick is used to maintain a wings level condition The constant-Mach maneuver is a three axis task, requiring active control of Mach number with the throttle The longitudinal and thrust axes are strongly coupled during the constant-Mach number pushover pullup

The pushover-pullup maneuver is used to obtain drag, and wing and canard pressure data at angles of attack above and below trim The maneuver is to be performed to a measured angle of attack within ±0.5 deg of the two end conditions: trim angle of attack plus or minus the specified $\Delta\alpha$ In ad- dition, the rate of change of angle of attack must be main tained at 0 5 deg/s during the maneuver The end condition hold time, Δt_α (originally specified at 5 s), is zero For the constant-Mach pushover pullup, the tolerance on Mach error is ±0.01 Mach number

Turns

The excess thrust windup turn is a constant altitude turn at elevated normal accelerations and a constant Mach number The longitudinal stick is used to control angle of attack or normal acceleration, the lateral stick is used to control altitude rate, and the throttle is used to control Mach number The windup turn is a generic description of those turns in which the normal acceleration and angle of attack are in creased to some target value at a constant altitude and a constant Mach number The thrust-limited windup turn is an extension of the excess power windup turn, and is performed, not at constant altitude, but with the nose of the aircraft pointing slightly downward, aligning the gravity vector more closely with the aircraft body axis to act as a thrust-aiding force

For the HiMAT program it was required that any of these turns have the capability to be angle-of-attack commanded or normal acceleration commanded, with the target condition specified in terms of an angle of attack or a normal ac

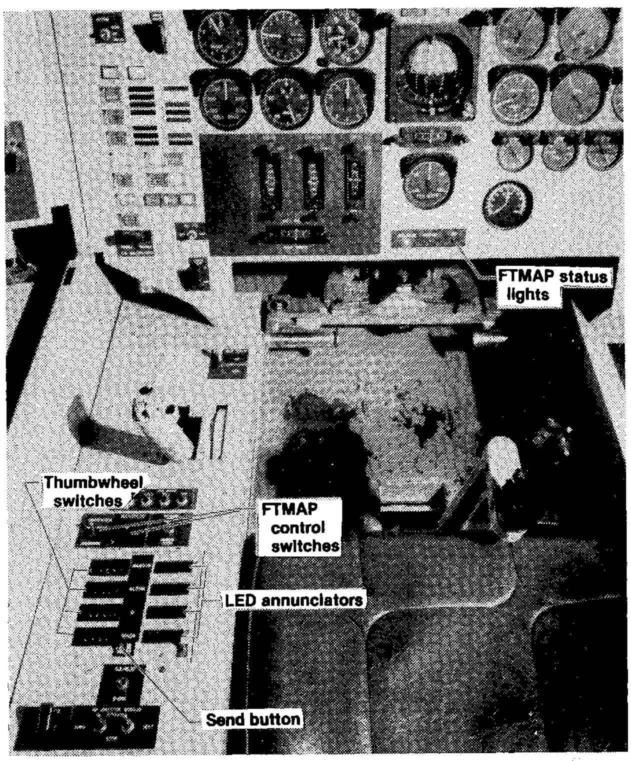

Fig. 4 HiMAT cockpit showing FTMAP input panel and status lights

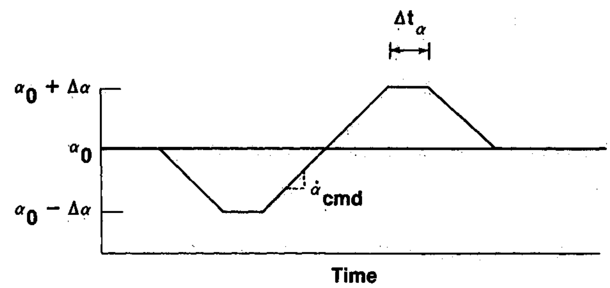

Fig 5 Angle of attack command for the pushover-pullup maneuver

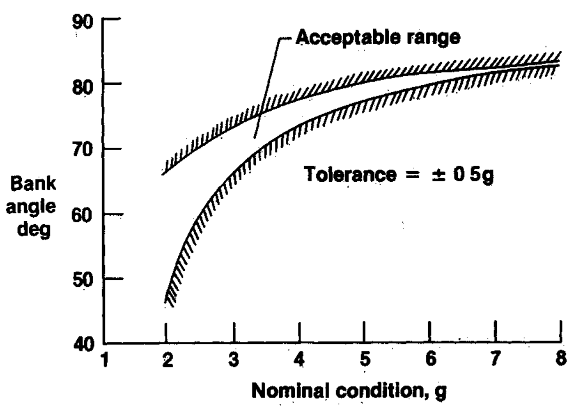

Fig. 6 Bank angle tolerance for level turning flight

celeration respectively During these turns the objective was to maintain altitude within ±500 ft to maintain Mach number within ±0.01 of the nominal, and to increase the commanded parameter from the trim to the target condition at a specified rate of 0 25 deg/s for angle of attack commanded turns and 0 2 g/s for normal acceleration commanded turns An additional constraint was that the target condition be achieved to a tolerance of ±0 5 deg angle of attack or ±0 5g normal acceleration

The command rate is the most demanding requirement for the pilot although as the normal acceleration of a maneuver increases, so does the difficulty of controlling the vehicle to the other mission tolerances To illustrate the increasing piloting task as a function of increasing normal acceleration, Fig 6 relates normal acceleration requirements to bank angle range Figure 6 is based on the normal acceleration tolerance (±0 5g) and the relationship for a constant altitude turn

$$\phi = \cos^{-1}\frac{1}{a_n}$$

The figure shows that the acceptable range for bank angle decreases dramatically as the target normal acceleration increases Thus, lateral control of the vehicle becomes more demanding as the target normal acceleration increases The tolerance for bank-angle error decreases as a function of increasing target normal acceleration, and the amount of time until altitude is out of tolerance decreases, requiring more attention to the lateral axis The windup turn is a highly coupled three axis task A change in angle of attack and normal acceleration requires a compensating change in the bank angle to hold altitude, and an immediate throttle change is required to maintain Mach number in the face of changing drag

Control Law Mechanization

The FTMAP control laws are composed of several modes: altitude hold, angle-of attack control normal acceleration control, wings level control, turn control and throttle control The control modes actually used at any given time are dependent on the maneuver being executed The altitude hold mode maintains altitude during straight and level flight In this mode, the longitudinal command to the aircraft is controlled by an altitude rate feedback signal and an altitude error signal The angle of attack control mode provides control of the longitudinal axis in the angle-of attack commanded windup turn and pushover pullup maneuvers This mode is based on an angle of attack error signal which is the difference between the commanded FTMAP angle of attack and the sensor-measured angle of attack of the aircraft. The normal acceleration control mode is used exclusively in the normal-acceleration commanded windup turn This mode is identical in every respect to the angle of attack control mode except for its inputs The main inputs in this mode form a normal acceleration error signal, which is the difference between the commanded FTMAP normal acceleration and the sensor-measured aircraft normal acceleration The wings level control mode provides control of the lateral axis of the aircraft in both straight and-level flight and the pushover pullup maneuver The aircraft's bank attitude is maintained near zero through the use of roll rate and bank angle feed back signals, which are scaled before being combined The turn control mode provides lateral axis control during any of the windup turn maneuvers A roll rate error signal, an altitude error signal, and an altitude-rate feedback signal are the primary inputs The reference altitude is maintained by means of the altitude rate and altitude error signals The roll-rate and altitude error signals are used to provide effective bank angle control The throttle control mode is used in all FTMAP maneuvers except the pushover pullup with fixed throttle The equivalent throttle command is derived from the combination of an impact pressure error signal and an impact pressure rate feedback signal A detailed description of these control laws and their implementation is contained in Refs 3 and 4

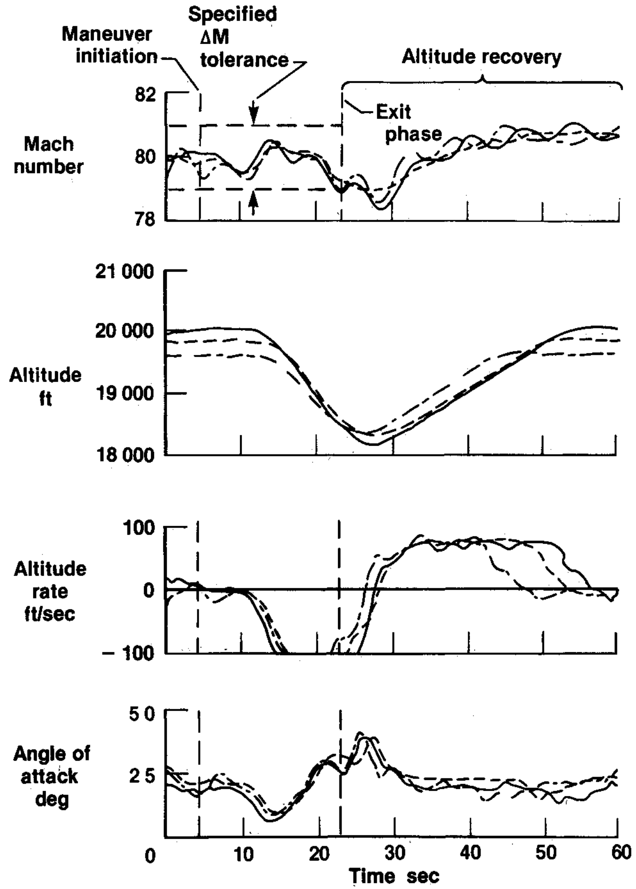

Fig 7 Comparison of two FTMAP flown pushover pullup maneuvers at Mach 0 8 and 20,000 ft

Flight Results

The FTMAP was used to fly a large number of maneuvers throughout the HiMAT flight envelope Schedule constraints precluded a separate flight development and test program for the FTMAP; the HiMAT research data collection therefore coincided with the FTMAP flight demonstration Each maneuver was intended to collect pressure, loads, and wing deflection data rather than to assess the performance of the FTMAP Thus, while the FTMAP allowed the collection of data of exceptional quality, not all design requirements were met (for example, Mach number was not consistently held to within ±0.01 Mach number) In spite of this, large quantities of high quality data were collected, there was increasing precision in meeting test conditions, and repeatability was achieved.

The following subsections present flight results to illustrate data repeatability and quality from a gross maneuver per spective These results are compared to pilot flown maneuvers wherever that data is available The lack of pilot flown maneuvers for these comparisons is, in itself, testimony to the success of the FTMAP Because the FTMAP was ex perimental, the option of allowing the pilot to fly these maneuvers was always available to the HiMAT research team; this option was never exercised after the FTMAP became operational

Maneuver Repeatability

Figure 7 is a comparison of three FTMAP flown pushover pullup maneuvers from a nominal 20 000 ft altitude and

Mach 0 8 flight condition. The time histories in this figure show Mach number, altitude, altitude rate, and angle of attack While the time histories are from three separate flights, the resulting maneuvers are virtually identical The altitude rate time histories show that the pushover-pullup maneuver is a highly dynamic maneuver with altitude rates exceeding −100 ft/s The only differences between the maneuvers (from maneuver initiation until the initiation of exit phase) occur in the altitude time history, and these are not significant Even the altitude recovery phases of these maneuvers show reasonable repeatability

Figure 8 compares two pilot flown windup turns at a nominal 25,000 ft altitude and Mach 0 9 These maneuvers represent attempts, on two separate flights, to demonstrate the 8*g* sustained turn design point of the HiMAT vehicle These maneuvers were initiated from a wings-level, 1*g* flight condition The object of each maneuver was either to increase the normal acceleration at 0 2 *g*/s or the angle of attack at 0 25 deg/s until the design point was achieved. Two features of these maneuvers are important: maneuver quality and maneuver consistency (The difficulty of flying these maneuvers is shown in the time histories) In all three maneuvers, the rate of increase of normal acceleration and angle of attack was irregular and erratic Both Mach number and altitude tolerances were exceeded Further, the maneuvers vary greatly There is little repeatability from maneuver to maneuver

In contrast to the pilot flown maneuvers shown in Fig 8, three FTMAP flown windup turns are shown in Fig 9 Both the nominal flight conditions and objectives for these maneuvers were the same as those for the pilot flown maneuvers In Fig 9, the FTMAP maneuvers are highly repeatable up to the thrust-limited condition The rate of onset of angle of attack is regular and controlled Altitude tolerance is maintaned throughout the maneuver The Mach number tolerance is still exceeded; however, this Mach number excursion is no worse than for the pilot-flown maneuvers

The discrepancies in the altitude hold performance are the results of two FTMAP control laws For flight 6, the thrust limited logic was not available and the FTMAP attempted to hold altitude at the expense of Mach number as angle of attack increased For the other two maneuvers, the thrust limited logic was active, and the FTMAP attempted to hold Mach number by commanding a downward spiral Even with these differences, the repeatability of the FTMAP flown maneuvers is apparent

Maneuver Quality

The pushover-pullup maneuver at the trim flight condition of Mach 0.9 and 25,000-ft altitude shown in Fig 10 illustrates the quality of maneuvers obtainable with the FTMAP The dynamics of the maneuver can be seen from the altitude rate time history Mach number is controlled to within the specifications The angle of attack time history is comparable to the target-commanded angle of attack according to the schedule shown in Fig 6 with Δt_α at zero There were no pilot-flown pushover pullups because of the performance of the FTMAP; therefore, a comparison with a baseline is not possible

Figure 11 compares two windup turns nominally to the HiMAT design point of Mach 0 9 at a 25,000-ft altitude, and at 8*g* normal acceleration Figure 11a shows a pilot flown maneuver; Fig 11b shows at FTMAP-flown maneuver While neither of these turns achieved the maneuver requirements completely, the FTMAP flown maneuver was more regular and controlled than the pilot flown maneuver The FTMAP met the maneuver requirements, except for a slight Mach number decrease near the end of the maneuver.

To appreciate the increase in maneuver quality obtainable with the FTMAP, two facts must be considered First, the pilot flown maneuver is representative of pilot flown windup turns—some are better, but some are worse Second, the FTMAP maneuver is predictable and repeatable from flight to flight. During a flight research program, an appreciable

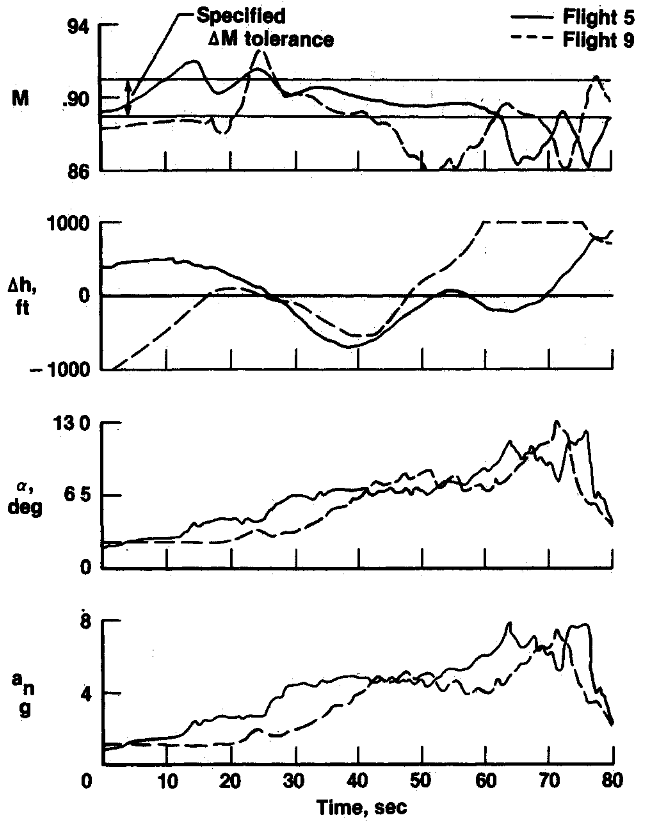

Fig. 8 Comparison of two pilot flown windup turns at Mach 0 9 and 25,000 ft

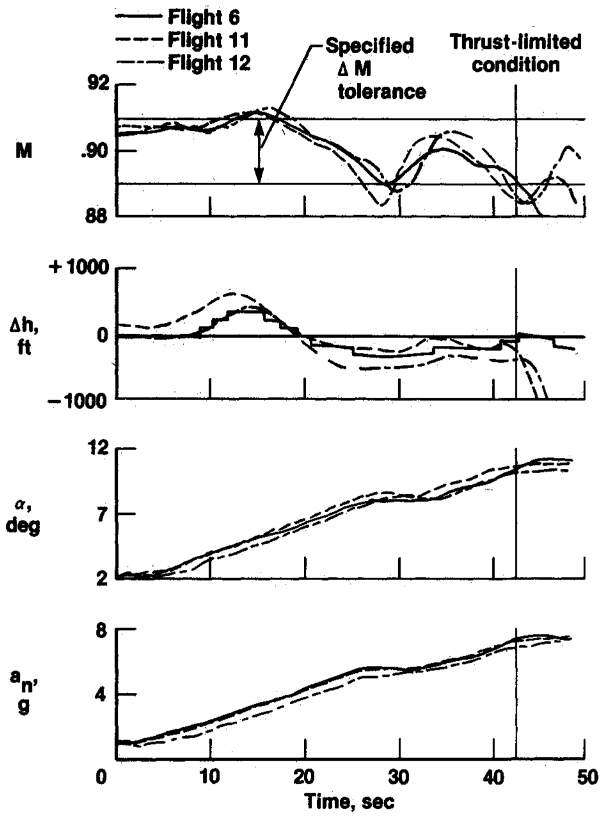

Fig 9 Comparison of three FTMAP flown windup turns at Mach 0 9 and 25 000 ft

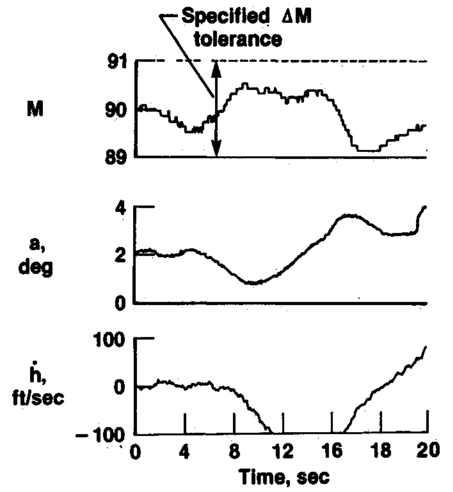

Fig. 10 FTMAP flown pushover pullup at Mach 0 9 and 25,000 ft

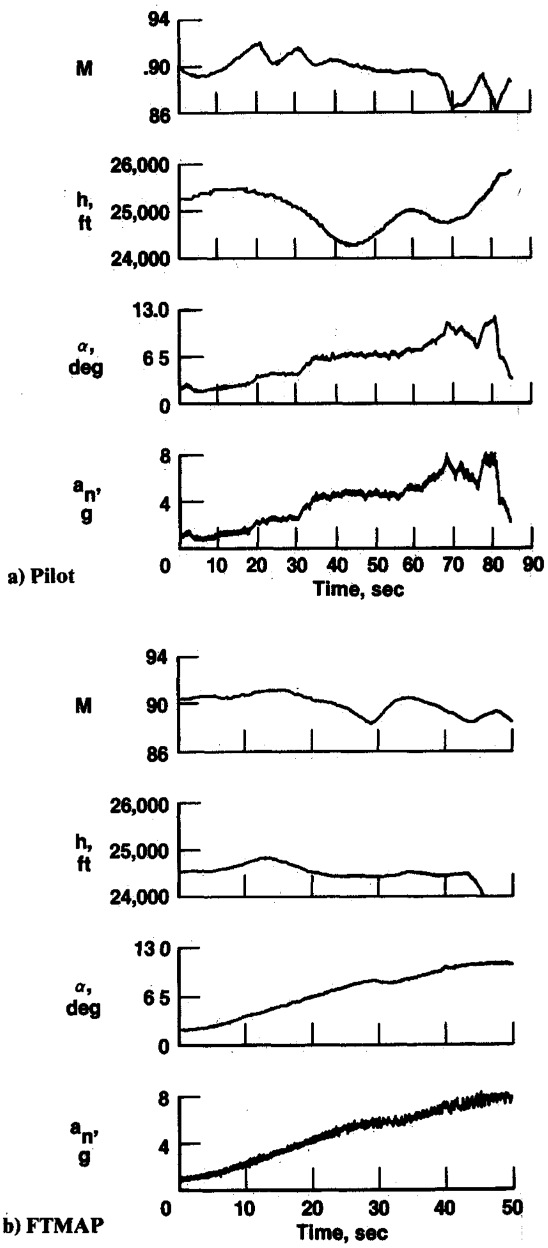

Fig 11 Comparison of pilot and FTMAP windup turn at Mach 0 9 and 25,000 ft

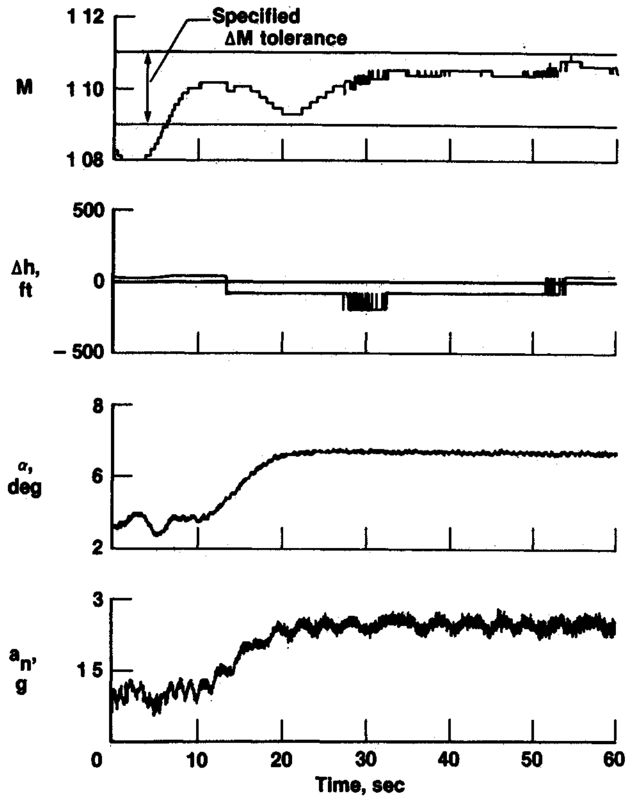

Fig 12 FTMAP flown windup turn at Mach 1 1 and 40,000 ft.

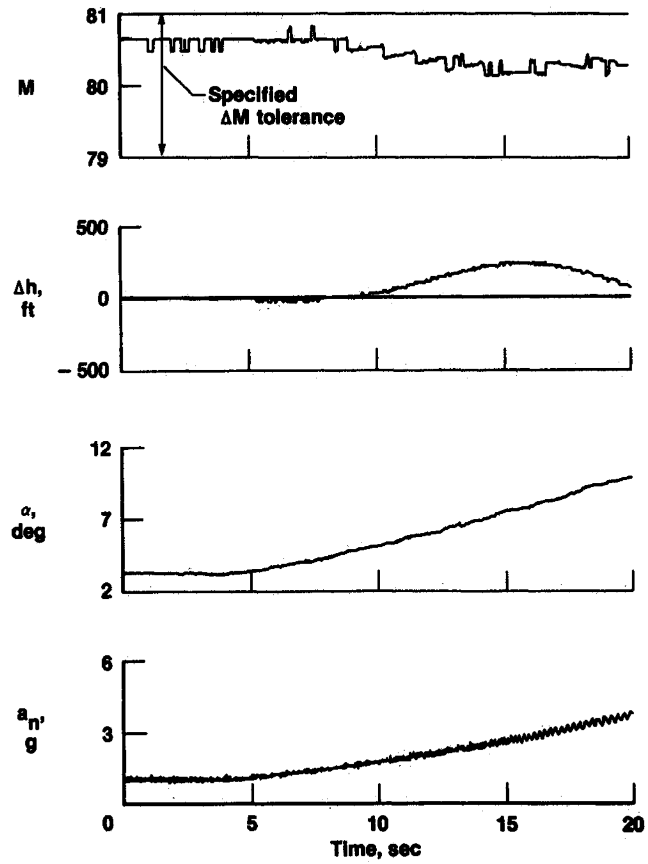

Fig 13 FTMAP flown windup turn at Mach 0.8 and a nominal altitude of 32,000 ft

amount of flight time is expended repeating maneuvers to obtain data of the requisite quality The application of an FTMAP minimizes such repetitions When quality data can be guaranteed on each maneuver, the quality of the data collected on the total flight program is improved

Figure 12 illustrates both the supersonic performance of the FTMAP and its ability to achieve and maintain a flight condition The maneuver is a normal acceleration commanded windup turn to $2g$ at an altitude of 40 000 ft and Mach 1 1 Once the $2g$ turn is achieved the FTMAP recovers Mach number to within the resolution of the data system This Mach number control is accomplished even though the maneuver is initiated at a $-0\ 02$ Mach number below the nominal condition The final flight condition is held almost without deviation for 40 s

Figure 13 shows time histories from an angle of attack commanded windup turn to 12 deg angle of attack This maneuver was performed at a nominal altitude of 32 000 ft and Mach 0 8 This maneuver again illustrates the capability of the FTMAP to control the HiMAT vehicle in a precise, predictable way The onset of angle of attack and normal acceleration is regular and constant Both Mach number and altitude are held to specified tolerances

The two maneuvers shown in Figs 12 and 13 are representative of the class of maneuvers in which the FTMAP excelled and for which all design specifications were met The common feature in these maneuvers is the absence of the transition from core engine to afterburner The supersonic maneuver shown in Fig 12 was performed entirely in the afterburner The subsonic maneuver shown in Fig 13 was performed using only the core engine The FTMAP flown maneuvers shown in Figs 9 and 11b began by using the core engine and then transitioned into the afterburner as the angle of attack increased (This transition occurred during the time when the slope of the angle of attack and normal acceleration time histories flatten out approximately 30 s into the maneuvers)

Concluding Remarks

An experimental flight test maneuver autopilot (FTMAP) was developed for and demonstrated using the highly maneuverable aircraft technology (HiMAT) vehicle. This application represents proof of a concept of an advanced flight test technique rather than a finished production system While the FTMAP performed exceptionally well, not all design goals were met to the specified tolerances However, even when those goals were not met the FTMAP proved capable of controlling the HiMAT vehicle to tolerances comparable to a pilot using normal piloting techniques

The stated goals of the FTMAP development were to increase the quantity and quality of the data obtained in flight test The expectation was that by providing precise, repeatable control of the HiMAT vehicle during certain prescribed maneuvers a large quantity of high quality test data could be obtained in a minimum of flight time In a very real sense, all of these goals and objectives were met The FTMAP increased the overall quality of maneuvers even when not achieving the performance specification The quantity of data was increased because the FTMAP performed maneuvers in less time than the pilot, and because once the FTMAP was operational maneuvers did not have to be repeated because of poor maneuver execution

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