Experience with Flight Test Trajectory Guidance

Eugene L. Duke,* Michael R. Swann,† Einar K. Enevoldson,† and Thomas D. Wolf‡
Dryden Flight Research Facility, NASA Ames Research Center, Edwards, California

A system that provides the test pilot with flight test trajectory guidance is presented. In use, this system has resulted in discernible improvements in the ease and accuracy with which pilots have approached and maintained the desired flight test conditions or trajectories. This paper describes the use of the guidance system in several past flight programs, including the F-111 TACT program, the F-15 airframe/propulsion system interaction program, the F-15 cone transition and boundary-layer experiments, and the Space Shuttle tiles flight test program.

Nomenclature

a_n = normal acceleration, g
H = altitude, ft
K_H = multiplier for altitude error
K = multiplier for angle-of-attack
K_α = multiplier for angle-of-attack-error
K_θ = multiplier for pitch attitude error
K_ϕ = multiplier for bank angle error
M = Mach number
P = roll rate, deg/s
q = dynamic pressure, psf
R = Reynolds number
s = Laplace operator, s^{-1}
X1,X2,X3 = internal guidance algorithm parameters (Fig. 12)
α = angle of attack, deg
β = angle of sideslip, deg
Δ = error: difference between target (or reference) and actual value for a parameter
θ = pitch attitude, deg
ϕ = bank angle, deg

Subscripts

test = variable specified as a test condition
ref = variable used as a reference level to aid in achieving a test condition

Introduction

THE quality of flight test data is often measured by the accuracy and steadiness of the flight test maneuver. Typically, the test pilot, knowing the desired flight test condition, applies indicator and position error corrections with the help of sensitive flight instruments. However, this piloting technique is subject to error, limits the variety of maneuvers that may be performed, and often generates inaccurate data. For this reason, there is a need for a system that will permit the pilot to converge rapidly and accurately on steady-state flight test conditions or predetermined trajectories.

This paper presents the evolution of a system providing the pilot with flight test trajectory guidance to aid the gathering of flight test data. The concept of providing the pilot with flight direction is not new: landing information is routinely displayed on the localizer/glide-slope bars of attitude/direction indicators; earlier programs presented simple error signals to the pilot. Flight direction is provided to the pilot for weapons delivery. However, the idea of providing an integrated signal to guide the pilot to a precise flight test condition or along a complex flight test trajectory is unique in its application. This guidance system is based on the computed differences between the actual and the desired flight test conditions, which are displayed to the pilot in a simple integrated format. Figure 1 illustrates the elements of this system in its most evolved form: Flight direction, derived from error signals via a guidance algorithm, guides the test pilot to the flight test condition or trajectory.

The guidance system is particularly beneficial for those tasks that require the pilot to integrate information from multiple instruments; for instance, a high-g level turn demands the assimilation of normal acceleration, altitude, altitude rate, bank angle, and roll rate information to control pilot stick position. Under normal circumstances, the pilot must read one instrument for each parameter to accomplish this; the flight test trajectory guidance system performs this assimilation and displays the combined signal to the pilot. In use, the system has resulted in improvements in the ease and accuracy with which pilots approach and maintain the desired flight maneuver.

The guidance system has been used in the F-111 TACT program, the F-15 airframe/propulsion system interaction program, the F-15 cone transition and boundary-layer experiments, and the Space Shuttle tiles flight test project.

Because virtually all work with flight test trajectory guidance has been directed towards satisfying specific project requirements, almost no effort has been expended quantifying the improvements gained with this technique. The continued development and use of the system has been based on pilot opinion and subjective engineering judgments of quality improvement. Some of the preliminary results of a simulator comparison of maneuvers with and without the guidance system are presented; a qualitative comparison is made of the results from the Shuttle tiles tests, which illustrates differences in data obtained in flight.

System Concept

Flight test trajectory guidance systems are piloting aids designed to reduce complex or unusual tasks to simpler, familiar ones. Despite the variety of highly specific maneuvers and trajectories required in the test programs cited, the piloting task in each was identical: to center the needles on a display, such as the one used for the F-15 cone experiments (see Fig. 2). The main element of the system is the guidance

Presented as Paper 81-2504 at the AIAA/SETP/SFTE/SAE/ITEA/IEEE 1st Flight Testing Conference, Las Vegas, Nev., Nov. 11-13, 1981; submitted Dec. 9, 1981; revision received Jan. 11, 1983. This paper is the work of the U.S. government and therefore is in the public domain.

*Aerospace Engineer. Member AIAA.
†Aerospace Research Pilot.
‡Simulation Engineer.

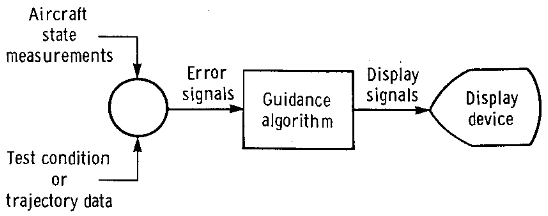

Fig. 1 Flight test trajectory guidance system elements.

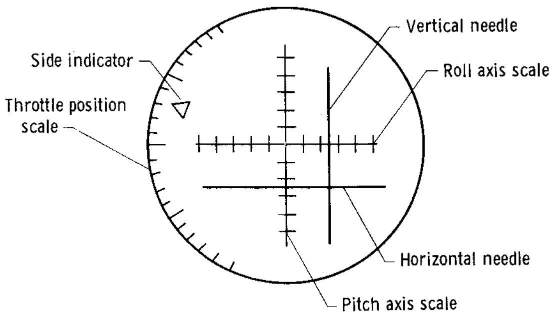

Fig. 2 Generic pilot display device.

algorithms. The algorithms synthesize information from a variety of sources, reducing complex and diverse information to two or three signals. The outputs of the algorithm, when displayed to the pilot, provide simple cues on how to position the stick or throttle. The research test pilot performs the function of connecting an autopilot into the control system. In fact, the guidance system/pilot combination is analogous to autopilot in many ways, particularly in the development of the guidance algorithm outer-loop control laws.

The localizer/glide-slope-type pilot display illustrated in Fig. 2 is typical: The horizontal and vertical needles provide pitch and roll axis information, respectively, and the side indicator, if activated, provides throttle information. All signals are error-type signals, and the piloting task is to zero all three needles on the display instrument.

Thus the most complex test condition or trajectory is reduced to a tracking task, a "fly-to" problem, in which the pilot applies aft stick to lower the horizontal needle, right stick to move the needle to the left, or less throttle to move the side indicator down. In fact, for every application of this technique when a given needle or side indicator is active, the display presents the pilot with a task separated into a pitch, roll, and velocity axis which is to be controlled by longitudinal stick, lateral stick, and throttle, respectively.

Simulation Study

A simulator study was undertaken to evaluate pilot performance with and without the guidance system. The study was conducted using students from the Air Force Pilot School as subjects.

The simulation was a detailed engineering model of an F-15 with a full-envelope nonlinear aerodynamic model, a complete control system model, and a first-order lag thrust model with afterburner sequencing. The simulator itself was fixed-based with no visual system. The simulator crew station realistically modeled that of the aircraft, having a stick and pedal force-feel system which matched the characteristics of the aircraft. An actual F-15 throttle quadrant was used.

The subjects were asked to fly a level turn at an altitude of 20,000 ft, a Mach number of 0.4, and an angle of attack of 19 deg. This flight condition was selected for its difficulty, which was due to the coupling of the longitudinal and lateral axes. The tolerance for altitude was ± 500 ft, Mach number ± 0.03, and angle of attack ± 1.5 deg. Data runs were begun off-condition so convergence time could be evaluated.

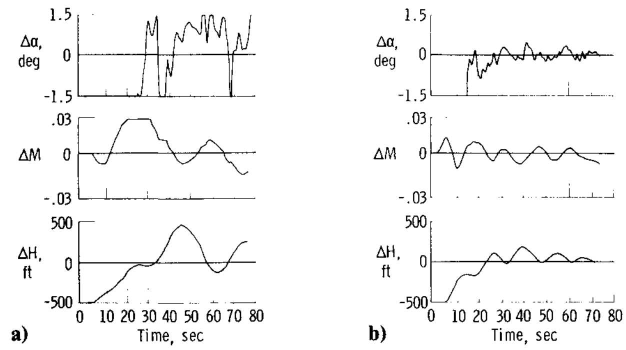

Fig. 3 Simulator comparison of level turn: a) Without flight trajectory guidance. b) With flight test trajectory guidance.

Figure 3 shows a typical set of results from a single test subject. Preliminary evaluation indicated that all subjects performed better with the flight test trajectory system than without it and that convergence time was less. The pilot rating of the task was favorable (one to two numbers lower using the Cooper-Harper rating system).

Technique Development

Flight test trajectory guidance began during the transonic aircraft technology (TACT) program. The TACT aircraft was an F-111 modified with a supercritical wing designed for transonic maneuvering. An interest in energy maneuverability emphasized precise performance measurements at flight conditions which included level turns at partial power throughout a matrix of constant altitudes, constant Mach numbers, and constant angles of attack. In addition to performance measurements, the wing boundary layer is surveyed for sustained periods. This maneuver was difficult to stabilize within the desired flight condition tolerances.

Consequently, a guidance system was developed and implemented. Analog hardware aboard the TACT aircraft provided the computation and display. The pilot display consisted of the pitch and bank steering bars on the attitude indicator (see Fig. 4). The horizontal bar was driven by a signal derived from the equation $K_\alpha(\alpha - \alpha_{\text{test}})$, and the vertical bar was driven by a signal derived from the equation

$$K_H(H - H_{\text{test}}) + K_\theta(\theta - \theta_{\text{ref}}) + K_\phi(\phi - \phi_{\text{ref}})$$

The gains used in these equations were determined during simulation sessions involving the pilot and a controls engineer rather than by use of any analytic technique. Parametric variations of the individual gains were assessed on the simulator, and the combination of gains which indicated best task accuracy with acceptable piloting sensitivity was then implemented for flight evaluation. Several iterations of the simulator and flight evaluation cycle were required to produce the final guidance algorithm.

The horizontal bar was used to indicate angle of attack error. The vertical bar was used to hold a desired altitude while turning at a constant load factor. The desired load factor determined the reference bank angle; reference pitch attitude was derived in flight.

Although this system was generally beneficial, onboard, analog computation had several limitations. Real-time corrections for sensor position errors were too complex to be implemented; in fact, the complexity of the required algorithm was limited by the onboard hardware. The analog system was subject to drift. The reference pitch attitude for a specific condition could only be determined in flight because the guidance algorithm was inflexible and no TACT simulation was available and all gains had been determined on a F-15 simulation. The calibration and checkout of a display required the exercise of the actual display hardware in a

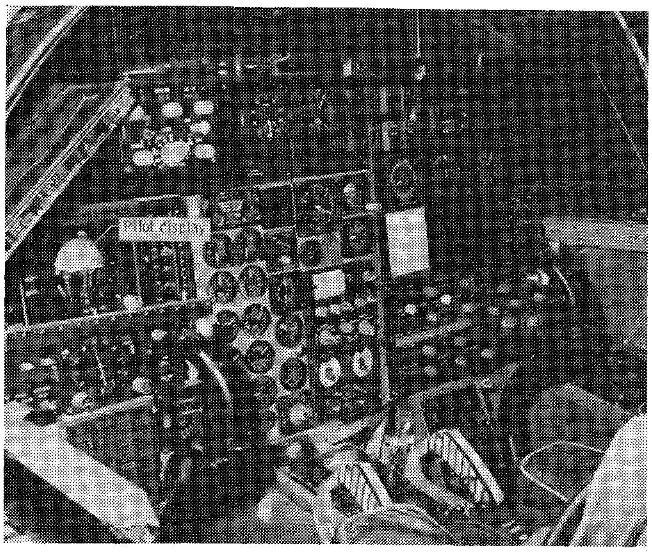

Fig. 4 TACT aircraft cockpit showing pilot display.

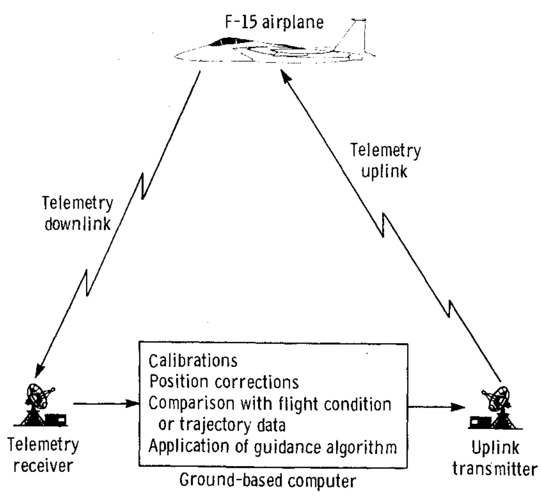

Fig. 5 Flight test trajectory guidance system used on F-15 airplane.

dynamic, pilot-interactive environment that could only be achieved in flight. Even though overall flight time for the program was reduced, setup and calibration time for a new flight condition was still extensive.

In spite of the deficiencies of the guidance system used in the TACT program, the potential of this flight test technique was clearly recognized. Favorable responses from both the pilots and engineers provided the impetus for further efforts toward refinement. Accordingly, a flight test trajectory guidance system was used in the F-15 airframe/propulsion system interaction program.[1-3]

To eliminate some of the problems encountered during the TACT program, computation of the guidance algorithms for the F-15 airframe/propulsion interaction program was transferred to a ground-based digital computer (see Fig. 5). The raw data input for the guidance system came from the aircraft instrumentation system. The data were downlinked to the computer, where the measured parameters were calibrated and corrected for position errors. The corrected data were compared with the desired flight test condition or trajectory, and error signals were generated. The guidance algorithm then converted these signals to sets of proportional signals—either simple error-type or the more complex flight test guidance, depending on the sophistication of the algorithm and the complexity of the maneuver. The sets of signals were uplinked to the aircraft for pilot display.

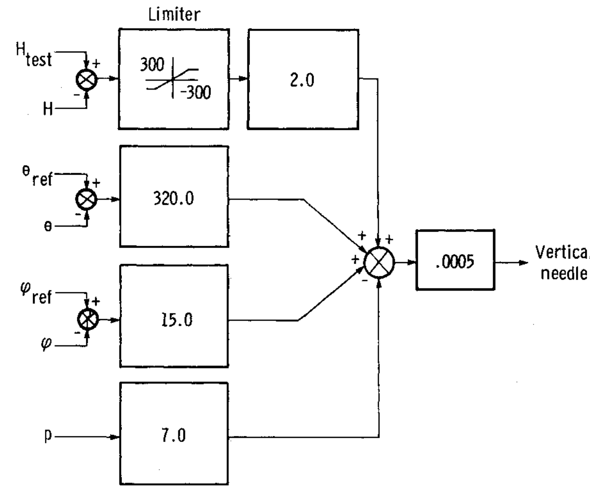

Fig. 6 Guidance algorithms used for F-15 airframe/propulsion system interaction program.

The program objective was to compare wind tunnel and flight measurements of the drag resulting from the airframe/propulsion system interaction in order to better predict such drag on future fighters. To match wind tunnel conditions, the F-15 had to be flown to extremely close tolerances. The flight condition was repeated if the desired tolerances were not achieved. The tolerances of the flight condition were as follows: $M = \pm 0.01$, $\alpha = \pm 0.25$ deg, and $\beta = \pm 0.25$ deg. Altitude was selected to provide the highest ambient pressure while obtaining compatible flight conditions.

The algorithm used for the pilot display was similar to that used in the TACT program. The horizontal needle displayed angle-of-attack error. The vertical needle displayed altitude and pitch attitude error (for altitude control), with a bank error signal and roll rate term for load factor control. A roll rate feedback term was added to the algorithm for the bank steering bar to damp pilot lateral inputs (see Fig. 6). An additional, highly sensitive indicator was used to monitor Mach number. The flight condition was specified as an angle-of-attack, altitude, and Mach number combination; angle of sideslip was required to be zero. The display was calibrated so that when the vertical and horizontal needles were within one tick mark of the center, the aircraft was within the tolerances of the flight condition. The pitch and bank reference attitudes were determined by piloting a real-time simulation of the F-15 to the test condition. A test engineer in the control room entered the test condition and reference attitudes into the ground-based digital computer.

These developments in the flight trajectory guidance system improved the accuracy and steadiness of the maneuver and dramatically reduced the pilot's perceived workload. The flight test procedure was simpler because information that was normally communicated by voice was now displayed to the pilot. For many of the flight conditions, angle of attack and angle of sideslip were within desired tolerances on the first flight, reducing the need to repeat flights.

Algorithm development for the program was still "cut-and-try," requiring long simulation sessions that involved research pilots and engineers. The logistics of transferring an algorithm from the development computer to the flight support computer required translation from one computer language to another. Further, the main algorithm developed for the F-15 program had deficiencies: The level-turn guidance algorithm required prior knowledge of θ_{ref} and ϕ_{ref} for each flight condition; the stability and response time of the algorithm was sensitive to the accuracy of the selected ϕ_{ref}; and the algorithm was limited to left turns. Nonetheless, with the exception of specific guidance algorithms developed later, the system and operational techniques employed in this function remained essentially unchanged in subsequent projects.

Follow-On Applications

The flight test results of two programs are significant in that they were important applications of flight test trajectory guidance and demonstrated that high-quality flight data can be obtained using this technique. The results of these flight programs encouraged the improvement of the flight test trajectory guidance system.

F-15 Cone Experiments

The flight test trajectory guidance system was used in two experiments with a 5-deg semiangle cone, which was sting-mounted on the nose of an F-15 airplane (see Fig. 7).[4] The objective of the program was to compare wind tunnel, flight, and numerical simulation results to provide a fundamental understanding of the mechanism of three-dimensional separated flows in general and to yield performance criteria

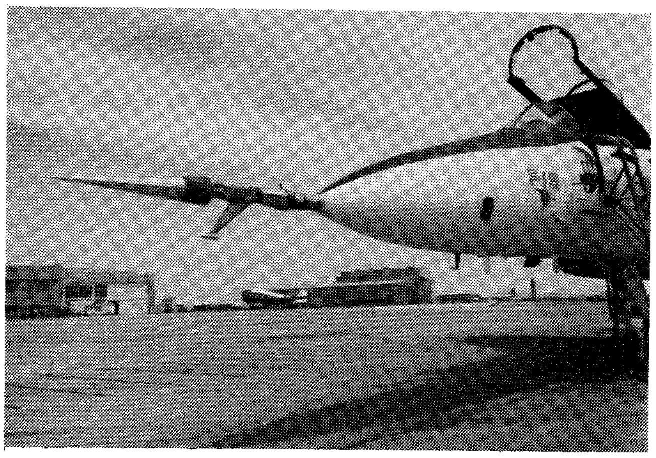

Fig. 7 F-15 airplane with 5-deg cone sting-mounted on nose.

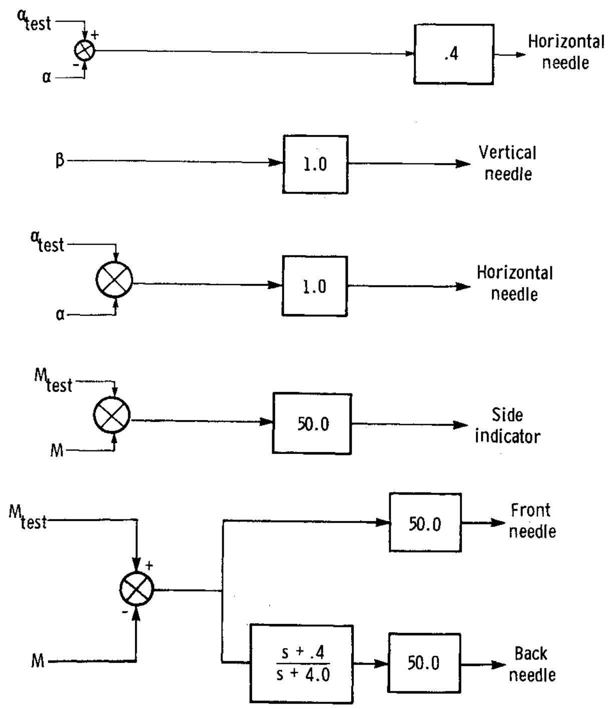

Fig. 8 Algorithms used for pilot displays in F-15 cone experiments: a) M, and b) compensated M.

for a common forebody shape used in the design of supersonic flight vehicles. The piloting task required that true Mach number, Reynolds number, and angle of sideslip of the cone be maintained within wind tunnel tolerances for sustained periods.

The aircraft was flown with the autopilot engaged in attitude-hold. The autopilot, modified with pilot-controlled vernier biases on the reference pitch and bank attitudes, allowed very small attitude corrections. The flight condition of the cone was sensed by a combined pitot-static/flow-direction hemispherical probe mounted on a dogleg from the sting support; position errors were determined by wind tunnel calibration. Mach number, angle of attack, and angle of sideslip were calibrated in real time by the ground-based computer, and deviation from the flight condition was computed. The algorithms used to compute the errors are shown in Fig. 8a; the algorithm used to compute the compensated Mach error is shown in Fig. 8b. These errors were displayed on on two cockpit indicators (see Fig. 9).

The Mach error display had two needles: The front needle represented Mach error only, and the back needle indicated filtered Mach error. The front needle indicated whether the pilot was within tolerance; the back needle showed the trend in Mach number. Thus, when both needles were centered, the aircraft was well within Mach tolerance.

In the simulator display development, the lead/lag Mach error behaved like a flight-path accelerometer. But, in flight, it was discovered that the Mach error display was subject to significant lag, which caused the compensated Mach error to behave like the uncompensated Mach error in the simulator. However, the problem was not in the approach, but in the modeling: Air data sensor lags had not been modeled in the simulation. Consequently, the three-axis error display shown in Fig. 9 was used.

The aircraft was flown with the autopilot engaged in the attitude-hold mode. To provide the pilot with sensitive controls, the axes normally controlled by pilot stick position were controlled using vernier dials located slightly aft of the throttle quadrant. Still, the primary task required of the pilot was to zero the needles on the error display.

Since the pitch attitude required for level flight is constant at constant speed and is independent of bank angle within the linear region of the lift curve, the roll vernier was used to control angle of attack. To maintain pitch attitude as roll attitude varied, the pitch attitude-hold mode varied angle of attack. The pitch vernier, in turn, was used for small adjustments in altitude rate.

A typical maneuver at a Mach number of 1.8 started at an angle of bank of approximately 20 deg. The angle was increased to 60 deg as fuel weight decreased, requiring a greater load factor to maintain angle of attack. Even with the error

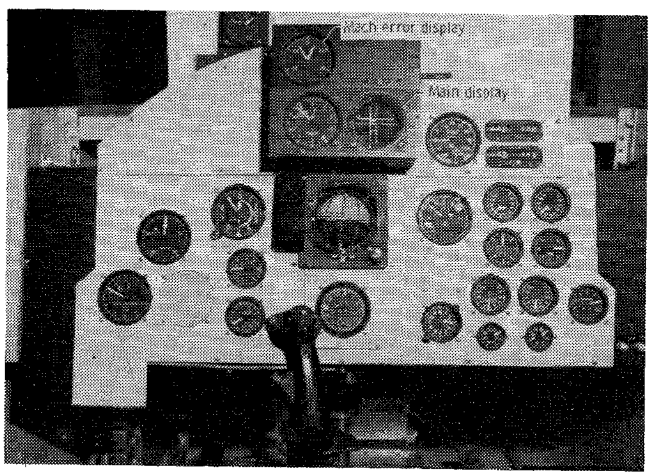

Fig. 9 F-15 airplane simulator instrument panel showing pilot displays used for cone experiments.

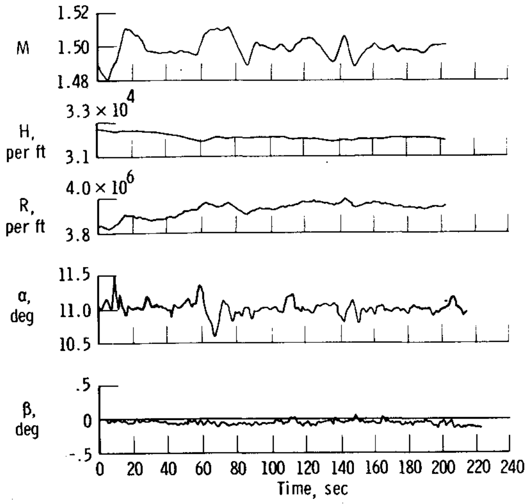

Fig. 10 Time history of typical F-15 cone experiments maneuver.

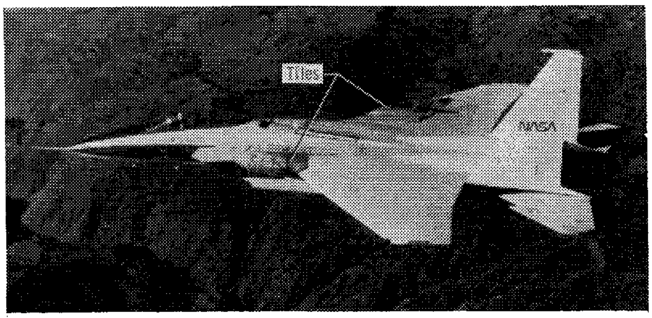

Fig. 11 F-15 airplane with Shuttle tiles mounted on wings.

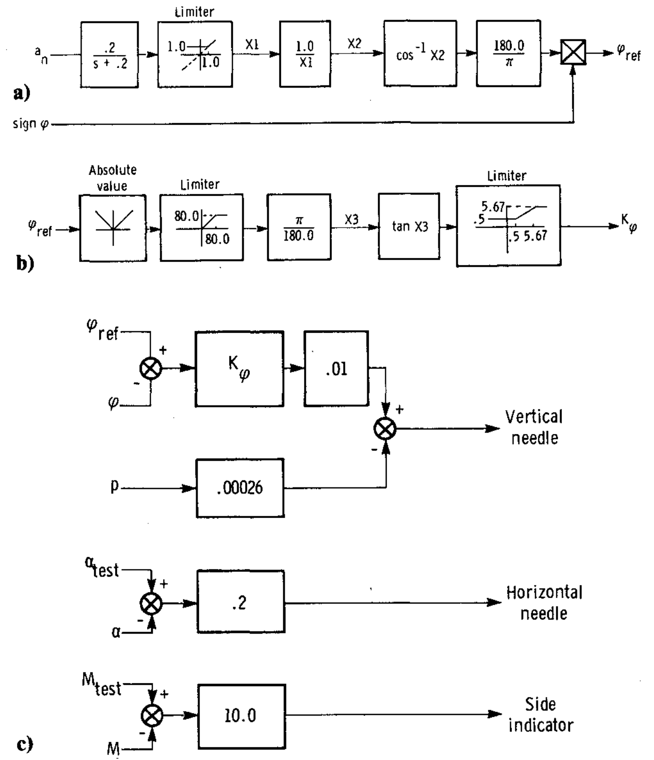

Fig. 12 Algorithms used for Shuttle tiles tests: a) Reference bank angle. b) Bank angle gain. c) Guidance.

displays, this was a complicated task. The resultant tolerances were similar to those obtainable in wind tunnels: $M = 0.02$, $\alpha = \pm 0.2$ deg, and $\beta = \pm 0.2$ deg. Figure 10 illustrates the quality of the data from a typical flight.

Shuttle Tiles Tests

The Shuttle tiles tests program was conducted to demonstrate the performance of the Space Shuttle protection tile and gap filler system in a high dynamic pressure environment up to 1.4 times the design limit. The program also verified the airloads acting on the tile and gap filler.[5] An F-15 aircraft was flown as a carrier vehicle in the tests. The Shuttle tile test articles were affixed to various locations on the F-15 carrier aircraft to best simulate the contours and flow patterns on the Orbiter at the most critical locations (wing glove, wing leading edge, vertical stabilizer leading edge, window post, elevon trailing edge, and wing elevon cove). The F-15 aircraft (see Fig. 11) was equipped with a flight test trajectory guidance system to assist the pilot. All tests required the carrier vehicle to fly trajectories related to the predicted STS-1 (Space Transportation System, Flight No. 1) launch conditions. These trajectories were specified as an altitude and Mach number profile. The F-15 was also used for trajectories that had both angle of attack and Mach number specified as a function of altitude.

The guidance algorithms used to drive the F-15 display for the latter tests are shown in Fig. 12. The Mach number error display was used for the altitude and Mach number trajectory. For both types of trajectories the aircraft altitude was used to compute a target Mach number from a table stored in the ground-based computer; this target Mach number, M_{test}, was then compared to the measured Mach number to generate the displayed signal. For those tests in which an angle of attack was specified as a mission parameter, the vertical and horizontal needles were activated. Deviation from the desired angle of attack was displayed on the horizontal needle. Because the target angle of attack was not in general, the trim angle of attack, the aircraft had to be flown at a nonzero bank angle, resulting in a normal acceleration greater than 1*g*. This normal acceleration was used to compute both a reference bank angle and bank angle gain (Fig. 12) used in the algorithm driving the vertical needle. Holding the active needles within one tick mark of the zero condition was the primary piloting task in the F-15 for both types of trajectory profiles. The format was the same as in the display systems described earlier—vertical bar for roll axis, horizontal bar for pitch axis, and side indicator for throttle position information.

The Mach number and altitude profiles were flown wings level in a steady climbing or diving maneuver. When angle of attack was specified, the flight path was a climbing or descending spiral with varying bank angle. The trajectory guidance system was a valuable aid for both maneuvers, freeing the pilot from the Mach scheduling task. The more complicated angle-of-attack, Mach number, and altitude profiles were made significantly easier with the display. For both types of missions, the use of flight test trajectory guidance allowed the pilot to keep the target parameters well within the desired test tolerances.

Flight data from two flights are compared in Fig. 13. In both cases the pilot used a guidance display. One set of data is from a Mach number and altitude specified profile; the other set is from a mission requiring both Mach number and angle of attack to be scheduled as a function of altitude. The second profile would normally be a considerably more difficult piloting task; however, with the guidance display, the pilot is able to fly both profiles to the same accuracies. This comparison illustrates how a task can be simplified and made more manageable for the pilot. The accuracies to which these trajectory profiles were to be flown would not have been achievable using conventional piloting techniques and, furthermore, the number of flight test maneuvers required to acquire these data was significantly less than normally expected.

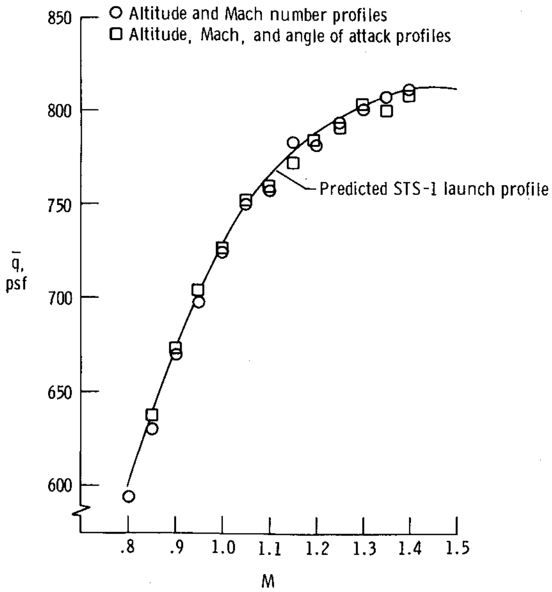

Fig. 13 Comparison of altitude, Mach, and angle-of-attack profiles for F-15 Shuttle tiles.

Concluding Remarks

By integrating the mission parameters into a simple display format, the pilot is able to monitor the flight conditions much better than by scanning several instruments. Even in their least complicated form, such as the simple error display computations, these flight test trajectory guidance algorithms allow the pilot to directly concentrate on the flight requirement of establishing and maintaining the aircraft at the required test conditions without having to concentrate on the details of those conditions.

The benefits of flight test trajectory guidance have been demonstrated in flight. This pilot-aiding flight test technique is of general application in flight test and provides increased capability by allowing data to be collected to demanding tolerances. More maneuvers can be flown per flight, more accurate data can be obtained, and more difficult maneuvers can be executed.

References

[1] Nugent, J., Taillon, N.V., and Pendergraft, O.C. Jr., "Status of a Nozzle-Airframe Study of a Highly Maneuverable Fighter," AIAA Paper 78-990, July 1978.

[2] Webb, L.D., Whitmore, S.A., and Janssen, R.L., "Preliminary Flight and Wind Tunnel Comparisons of the Inlet/Airframe Interaction of the F-15 Airplane," AIAA Paper 79-0102, Jan. 1979.

[3] Burcham, F.W. Jr., Meyers, L.P., Nugent, J., Lasagna, P.L., and Webb, L.D., "Recent Propulsion System Flight Tests at the NASA Dryden Flight Research Center," AIAA Paper 81-2438, Nov. 1981.

[4] Peake, D.J., Fisher, D.F., and McRae, D.S., "Flight Experiments with a Slender Cone at Angle of Attack," AIAA Paper 81-0337, Jan. 1981.

[5] Meyer, R.R. Jr., Jarvis, C.R., and Barneburg, J., "In-Flight Aerodynamic Load Testing of the Shuttle Thermal Protection System," AIAA Paper 81-2468, 1981.