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AFTI/F-16 FLIGHT TEST RESULTS AND LESSONS

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INTRODUCTION

The Advanced Fighter Technology Integration (AFTI)/F-16 Program is a technology development effort managed by the Advanced Development Program Office (ADPO), Flight Dynamics Laboratory (FDL), Air Force Wright Aeronautical Laboratories (AFWAL), Wright-Patterson AFB, Ohio. The overall objectives of this joint Air Force, NASA, Navy, and General Dynamics Corp. program are to develop and demonstrate technologies and alternatives for future fighter aircraft design. These objectives are to be accomplished in several phases. This paper addresses the results of the first phase – the digital flight control system (DFCS).

The digital flight control system phase consisted of the development and flight testing of a triplex, asynchronous, multimode, digital flight control system which was integrated with improved avionics. Flight testing was conducted by the AFTI/F-16 Joint Test Force from the Dryden Flight Research Facility at Edwards AFB, California, from July 10, 1982, through July 30, 1983. A total of 118 flight test sorties were flown, totaling 177.2 flight hours.

This paper summarizes the flight test program and addresses several design issues of general interest. The paper begins with a brief description of the test vehicle, its flight control modes, and the flight envelopes in which testing was accomplished. It further summarizes flight test results by addressing benefits experienced in flight control task-tailoring, handling qualities in mission tasks, aircraft structure considerations, digital flight control system performance, and human factors. The last section addresses several design issues relevant to future fighter aircraft.

THE TEST AIRCRAFT

The AFTI/F-16 is a modified full-scale development NF-16A aircraft. Modifications included incorporation of an asynchronous operation, triplex digital flight control system, which provided multiple in-flight-selectable flight control laws, including six-degree-of-freedom decoupled aircraft motions. Twin canards were mounted from actuators in each side of the lower lip of the engine inlet, 15° off the vertical. A fuselage dorsal fairing was added to provide room for test instrumentation and additional avionics. New and modified cockpit controls and displays included a redesigned sidestick controller incorporating eight switches, a linear motion throttle with a twist action controller for vertical decoupled motion, a conventional optics wide-field-of-view head-up display, two multipurpose display cathode ray tubes, and a voice command system providing voice actuation of selected cockpit switches.

Eight distinct cockpit-selectable control laws were implemented with the digital flight control system. Each set of control laws (control modes) was "task-tailored" for the intended mission. Decoupled control motions were included with selected control modes, as shown in table 1.

Each of the decoupled-mode pitch axes was implemented with a "maneuver enhancement" version of the corresponding standard-mode pitch-axis command mechanization. Maneuver enhancement was accomplished by tailoring symmetrical flaperon and horizontal tail motions to achieve the desired pitch response. Trailing-edge flaperon motion was designed to minimize steady-state drag at a given flight condition (scheduled flaps), while simultaneously quickening g response or improving tracking (maneuvering flaps). Maneuvering flaps were optimized for either flightpath maneuver enhancement (FPME) or pitch-rate maneuver enhancement (PRME).

The pitch axis of the decoupled air-to-air mode was a unique mechanization of variable gains. Pitch command gains varied as a function of the pitch-rate error signal (commanded versus actual). For large changes in pitch command, command gains were increased to improve pitch-rate and load-factor response. Desirable fine-tracking handling qualities were to be achieved with lower command gains for smaller pitch command changes.

Six-degree-of-freedom decoupled motions were produced by combined deflections of two similarly oriented control surfaces (fig. 1). In the vertical axis, combined deflections of flaperons and horizontal tails were used with different control laws to produce decoupled direct lift, pitch pointing, or vertical translation (fig. 2). Vertical decoupled motions were controlled using the throttle twist controller. Combined deflections of vertical canards and rudder were used with different control laws to produce the directional decoupled motions of direct sideforce (flat turn), yaw pointing, and lateral translation (fig. 3). Rolling moments produced by directional control surface deflections were countered by roll control surfaces to provide directional decoupling. Directional decoupled motions were controlled on the conventional rudder pedals.

Figures 4 and 5 show the final flight envelopes achieved for handling qualities evaluations. During preliminary evaluations, it was determined that, except for the standard normal control mode, the decoupled control modes showed more potential for improved mission performance. Envelope expansions of the standard modes for bombs, air-to-air guns, and air-to-surface guns were discontinued at that time. Although there was often more than one set of control laws implemented and evaluated in the AFTI/F-16 for each mission task, only the results of the "best" control laws evaluated are reported in this paper.

FLIGHT TEST RESULTS

Task Tailoring

The effort to optimize control laws for individual mission tasks was highly successful. Using the production F-16 aircraft as a baseline for comparison, pilots cited marked improvements in handling qualities for nearly all tasks. These tasks included air-to-air and air-to-ground missions, as well as formation flying and approach and landing. It was apparent that the control laws had been developed with accurate prioritization of the control parameters used for individual mission tasks.

In the process of identifying the "best" control laws for each task, it became clear that control law optimization for one task did not carry over to another task. During preliminary evaluations, several control laws were investigated for potential utility. Many control laws were evaluated intentionally for tasks for which they were not designed. In every case, the task-tailored control law was identified as having superior handling qualities for that task. In many cases, the converse was also true. Task-tailored control laws often demonstrated unacceptable handling qualities in tasks for which they were not tailored.

The full benefits of task tailoring could not have been realized without multiple control modes. Handling qualities improvements over the production F-16 aircraft in nearly all tasks indicated that significant benefits are to be gained in the task-tailoring approach. Handling qualities improvements were, however, associated with distinct control modes, and each of these control modes demonstrated less desirable handling qualities in tasks for which they were not tailored. This indicated that a single control mode could not have been tailored for multiple missions without compromising handling qualities for some or all of the mission tasks.

Air-to-Air Handling Qualities

The decoupled air-to-air flight control mode employed pitch-rate maneuver enhancement tailored to facilitate air-to-air weapon delivery. The mode exhibited superior nose-pointing capability, reliable predictability, and precise small-amplitude high-frequency control. Although the concept of weighting feedback variables, such as load factor and pitch rate, was not new, it appeared to offer consistent improvement over simpler control law structures. The basic control law concept employed in the air-to-air task-tailored control law suggested generic structure which should be observed by any fighter.

The differential weighting of pitch rate as a function of pitch-rate error attempted to address the requirement of large tracking errors for immediate movement of the flight-path vector, which requires significant overshoot of pitch rate. Small errors, however, necessitate high-frequency attitude adjustments and are more closely controlled with minimum pitch-rate overshoot. The AFTI/F-16 air-to-air control law attempted to infer which type of tracking error existed by categorizing feedback pitch-rate error. Regardless of the variable used to deduce the magnitude of the tracking error, the capability to switch between the two pitch-rate responses suggested that the AFTI/F-16 aircraft is a paradigm for any fighter when judged from the flying qualities point of view.

The decoupled capabilities of pitch and yaw pointing did not demonstrate the same unequivocal utility as the longitudinal coupled control law. Although difficult to ascertain when pitch-pointing authority was saturated, the mode appeared quite controllable in terms of response rise time, linear movement and small overshoot of final position. Controllability notwithstanding, target tracking handling qualities were not improved over sole use of coupled longitudinal control on the conventional sidestick. For small corrections, yaw pointing permitted better azimuth error correction than lateral stick only. Limited pointing and yaw-rate authorities restricted its use for larger corrections and higher line-of-sight-rate targets typical of high-aspect gunnery (table 2). Pedal forces were rather high for a vernier controller. Bank attitude became harder to control with larger yaw-pointing angles. It was occasionally difficult to avoid overcontrol in the lateral axis, expecially for small, quick inputs with large aft stick inputs. Yaw pointing appeared to obviate this lateral difficulty and represented its chief advantage.

Air-to-Ground Handling Qualities

Flightpath maneuver enhancement was incorporated in the decoupled bombs control mode to improve precision in flightpath control and alleviate gust upset. An additional feature of automatic trim compensation relieved the pilot from having to make trim corrections for pitch-attitude changes (dive angle) and for airspeed changes (zero speed stability). The result was excellent air-to-ground and strafe pipper stability, precise control, and improved ride quality. All combined to reduce pilot workload and improve mission performance.

The primary decoupled motions evaluated for the air-to-ground tasks were flat turn and direct lift. Although smooth and precise air-to-ground tracking corrections could be made using direct lift on the throttle twist controller, the same task could be accomplished equally well using only coupled longitudinal control on the conventional sidestick. The use of flat turn in the bombing and strafing tasks provided the significant advantage of reducing the directional correction problem from two control axes to one. Conventional control requires use of the roll and pitch axis to make directional corrections. Often the dynamics of bomb fall lines, pendulum effects, and/or gravity drop (strafe pippers) cause unpredictability in pipper motion while making corrections using the roll axis. Flat turn eliminated that unpredictability by allowing corrections to be made using a direct pipper tracking path to the target. The result was a quicker and more accurate weapon solution.

Handling Qualities in Formation

The standard normal mode was intended for use in navigation and formation flying tasks. Handling qualities were satisfactory for small pitch inputs generally representative of aerial refueling and mild maneuvering in close formation. Pilots preferred the aerial refueling handling qualities of the AFTI/F-16 aircraft over the production F-16 aircraft, primarily because of a perceived improvement in open-loop pitch stability. For larger pitch inputs, however, a somewhat unpredictable response was discovered which the pilots described as a vertical "heaving."

This description of aircraft motion suggests that the blended motion of trailing-edge flaps in this mode may have been responsible for the undesirable response. In close formation, relative change in pitch attitude may be a more precise pilot cue for position control than load factor. The use of maneuvering flaps to increase weighting of load factor in pitch response may lead to unpredictability in formation flying.

Translations were primarily evaluated for close-formation and aerial refueling tasks. The mechanization of lateral and vertical translation gave the pilot acceleration controllers and was found to be peculiar. With any input, the pilot was commanding an acceleration and, when released, a deceleration. Mechanization with translation rate control would have been more intuitive. The control surface deflection for vertical translation produced considerable drag, which complicated the fore and aft positioning task. The vertical positioning task was more easily accomplished using coupled longitudinal control on the conventional sidestick. It was projected that, with a rate controller, lateral translation could offer benefits in the aerial refueling task.

Approach and Landing Handling Qualities

Handling qualities of the AFTI/F-16 aircraft during approach and landing were significantly better than those of the production F-16 aircraft. The pitch-rate command system provided precise pitch-attitude control with exceptional hands-off pitch stability. With reduced workload in pitch-attitude control, pilots perceived correlated improvements in flightpath and angle-of-attack stability. The overall result was improved aircraft control and landing performance.

These improvements were apparent for both front-side and back-side control techniques. When flying the front-side technique, for which flightpath was the primary control parameter, precise pitch attitude control reduced effort spent in establishing and maintaining flight path leaving more time for control of airspeed and angle-of-attack using the throttle. Using the back-side technique, for which angle-of-attack was the primary control parameter, pitch attitude stability tended to reduce angle-of-attack variation allowing more time for control of flight path control using power. The Navy project pilot conducted a comparative evaluation of carrier approach handling qualities between the AFTI/F-16 and the production F-16 aircraft. From this high gain back-side technique evaluation, he concluded that the AFTI/F-16 demonstrated better handling qualities.

Degraded Modes

An analog independent backup unit flight control system was incorporated in the AFTI/F-16 aircraft to offer a safe recovery capability in the event of generic digital flight control system failures. Although the backup unit was tested throughout the Mach-altitude envelope of the digital flight control system, testing was limited to benign maneuvering. No high-angle-of-attack testing or landings were accomplished in the backup mode. The independent backup unit performed as it was designed, and flight test results matched well with simulation. The only significant discrepancy was a tendency for lateral-directional pilot-induced oscillation at Mach 1.2 and 30,000 ft.

The AFTI/F-16 digital flight control system architecture included control law reconfigurations for complete loss of certain types of sensor information. These seven reconfiguration control laws were not tested in flight.

Structures

Flight testing demonstrated the advantages of digital flight control systems for exploiting aircraft structure envelopes. Without expensive or complicated analog or mechanical systems, the flight control law gain structure essentially "mapped" the structural capability of the aircraft by limiting surface motions as a function of flight condition. Performance was improved by taking advantage of that structural capability over a large portion of the flight envelope. This did, however, significantly increase the flight test matrix since there was no one "worst case" flight condition below which structural loads could be assumed acceptable. Where flight test loads did not match predicted loads, changes could be made in software (instead of making expensive hardware changes) to improve structural "mapping."

The predictions for structural loads during unique decoupled motions were inadequate. Decoupled maneuvers produced horizontal tail loads and vertical tail support structure loads which were higher than predicted. This required not only control law changes, but modification to the vertical tail support structure and further horizontal tail static testing to verify the adequacy of the structures without reducing aircraft performance. These higher-than-predicted loads indicated the need for improved structural design techniques for decoupled motions.

Digital Flight Control System Performance

In the course of 118 test sorties, a total of 38 in-flight fault declarations were annunciated by the digital flight control system (table 3). At no time did the system automatically degrade to either a reconfiguration mode or the analog independent backup unit. All of these fault declarations occurred during periods of system development and flying qualities envelope expansion. No anomalies occurred during dedicated handling qualities evaluation flights. This performance indicated that, like hardware, a software envelope can be established in which continued reliable operation can be expected.

During less than 13 months of flight testing, there were 13 DFCS operational flight program (OFP) software releases (Fig. 6). These incorporated 129 changes, involving approximately 12,000 words of computer code.

Human Factors

The AFTI/F-16 program has addressed several new issues and techniques for improving the pilot's ability not only to fly but also to manage a fighter weapons system. Among others were the questions of (1) mechanization of flight controllers for decoupled motions, (2) improved pilot-vehicle-interface (PVI) avionics, (3) mission phase switchology for easy transition between mission tasks, and (4) introduction of voice-commanded switch actuations.

A fair handling qualities evaluation of decoupled motions demands that flight controllers be mechanized to be intuitive and to maximize positive transfer of previously learned skills. Use of the rudder pedals for control of directional decoupled motions was successful. Indeed, by the end of the flight test program, pilots found themselves unconsciously applying flat turns in the bombing task when it was not required to meet the objectives of the test maneuver.

This transfer was not as successful, however, with the throttle twist controller for vertical decoupled motions. The problem was compounded in that, unlike the rudder pedals, conventional control on the pitch stick could not be replaced with decoupled motion and retain gross maneuvering capability. The result was implementation of two controllers that provided simultaneous control in similar (vertical and/or pitch) axes. Recognizing that the decoupled motions controlled on the throttle twist were designed for small vernier corrections, vertical decoupled motions were evaluated with the pilot consciously attempting to make small, high-frequency corrections using the throttle twist controller, while attempting to make larger amplitude, lower frequency corrections using the conventional sidestick. The results were discouraging in that pilots encountered difficulty in recognizing approaching saturation of left-hand decoupled motions and integrating the saturation away with the right hand. There was also some indication that right-handed pilots tended to use their left hand less actively for high-gain tracking corrections than did the left-handed pilot (one of the five project pilots was left-handed). It was concluded that the use of two controllers in similar axes for the same task only increased workload and did not improve task performance. Each task could be accomplished just as well (if not better) using only the conventional sidestick controller.

Improvements in pilot-vehicle-interface avionics were beneficial and considered necessary for management of sophisticated aircraft systems. With multiple complex aircraft systems, such as multimode flight control systems, multimode radar, threat warning, and a variety of stores and stores management options, efficiency in displays and pilot interface becomes essential for keeping workload at a tolerable level. Two multipurpose displays (with integrated switchology for systems interface) and a conventional optics, wide-field-of-view (instantaneous 15° x 20° (total 25°) for AFTI/F-16, versus 9° x 13° (total 20°)) for production F-16) head-up display provided that interface capability. Of particular benefit was the capability to display flight control system fault status. Although mechanization and display symbology warranted improvement, the pilot was offered detailed information on the "health" of the digital flight control system.

The transition between types of mission (such as from air combat to ground attack) was made very handily through mission phase switchology. Through a single switch action, the pilot could configure all the avionics systems and the flight control laws for the mission phase. This was considered very beneficial since configuration of individual subsystems was cumbersome.

The AFTI/F-16 program included the first developmental testing of a voice command system on a fighter aircraft. The system was flown on 87 test sorties and was tested by five pilots. Two independent contractors provided voice processors for flight testing. The objectives of the testing were to determine how word recognition rate was affected by (1) cockpit noise levels and (2) physiological stress produced by increased g loads. Of 4137 word recognition attempts, 2615 were tests of varying noise conditions, 1161 were tests of varying load factor conditions, and 361 were in the active mode where pilots activated switchology by voice during mission tasks. These data were used to develop system recognition algorithms throughout the test program.

Varying cockpit noise levels were produced by changes in airspeed and altitude conditions and environmental control system settings (fig. 7). Tests were conducted at normal load factors from 1 to 5. All quantitative tests were conducted with the pilot looking forward in the cockpit with no planned additional cockpit tasking. The systems were tested mainly in the verify mode where no actual cockpit switch actions were taken as a result of a recognized word.

Test results are presented in figures 8 and 9. The overall recognition rate was 78 percent. These figures include all the data collected during flight tests. Therefore, they do not delineate improvements made in recognition algorithms and improvements in recognition rates as pilots became more familiar with the system. Results indicated that recognition rates were essentially independent of cockpit noise levels and that there was only minor degradation with load factors up to 5. Brief qualitative evaluations of voice command systems indicated potential for workload reduction by use of voice command systems in fighter cockpits.

DESIGN IMPLICATIONS

Degraded Flight Control

The AFTI/F-16 architecture reflects at least four design ramifications of general interest. The first issue examines transition between flight control mode. Highly augmented aircraft such as the F-16 rely on flight control system "intelligence" to inhibit aircraft responses. Indeed, the flight envelopes of all recent fighters are limited by their flight control systems. Unstable aircraft obviously require closed-loop feedback control to provide conventional stability and control. Increasing dependence on the flight control system to provide air-craft performance and safety requires classical tradeoff decisions when the system is mechanized with digital computers.

Traditionally, software engineers have argued for simplicity in the generic software failure recovery mechanization. The IBU of the AFTI/F-16 aircraft generally follows guidelines for simplicity. In fact, the IBU was originally conceived with no pitch-rate feedback in the longitudinal axis. Even though the AFTI/F-16 aircraft is slightly unstable longitudinally, it was initially believed to be more important to keep the IBU simple than to minimize pilot control tasks. The emphasis on simplicity was generally motivated by the desire to maximize IBU reliability by minimizing complexity as well as the cost of covering a remote failure mode. The augmentation required by aircraft like the AFTI/F-16 encourages reexamination of the benefit of simple, degraded flight control modes such as the IBU.

The AFTI/F-16 aircraft requires angle-of-attack limiting to prevent post-departure deep stall. Simulation suggests that the IBU reduced capability to recover from spins or deep stalls. The automatic yaw-rate limiting of the primary flight control system renders the AFTI/F-16 extremely spin resistant. In the IBU, however, the simulation indicates that stopping yaw rate requires considerable altitude, thus suggesting a smaller envelope may be necessary for safe aircraft operation should the aircraft degrade to IBU. A similar constraint has been encountered with the IBU at high airspeed. During aeroservoelastic testing, one pilot found insufficient lateral stability in IBU at Mach 1.2; therefore, he reselected the standard normal mode and recommended not flying faster. Even though the AFTI/F-16 aircraft is longitudinally stable supersonically, selecting a single fixed gain for fighter aircraft such as the AFTI/F-16 over their entire flight envelope may not be possible.

Analytically, there are at least two parts to the solution of optimum tradeoff between degraded-mode complexity and envelope-protection capability. First, consider transitioning from normal to degraded flight control. Transitions can be characterized by discontinuous step inputs or outputs. Additionally, the failures that cause transition are usually assumed to be random. The second part of degraded-mode flight addresses whether the flight can be successfully continued or what constraints must be observed during abort and recovery.

The more difficult decisions occur with respect to transition flight. Degraded modes in the AFTI/F-16 aircraft accommodate discontinuous inputs or outputs satisfactorily, and the techniques are generally known. The assumption that one could "drop" into IBU at any time, however, presents the possibility of some adverse events. Transition to IBU while flying a maximum angle of attack implies an unfortunately high probability of departure. Similarly, degrading to IBU at high airspeed suggests that the pilot must attempt to slow down in an unstable airframe pilot system. Under such circumstances the costs of simplicity in modes like the IBU are very high during random transitions to degraded flight control. Highly augmented aircraft such as the AFTI/F-16 are penalized rather severely by simplicity in modes like the IBU during the relatively brief transition period. Development of the IBU reflected several compromises between simplicity and adequate coverage; Fig. 10 illustrates the significant increase in complexity of the final design as compared with the initial design. Degraded-mode simplicity is not sufficient justification when it prevents flight-envelope protection during the transition to backup flight control. After reversion to a backup mode, however, the lack of envelope limiting during mission abort is much less costly, because the pilot can be asked to constrain the aircraft to more benign conditions.

For the case of AFTI/F-16 aircraft, angle-of-attack limiting would be beneficial, particularly during IBU transition. Similarly, if a single fixed gain is not sufficient to provide acceptable stability over the entire envelope, the backup systems should include additional gains. Morever, the primary system should automatically update the appropriate backup gains for the current dynamic pressure conditions of the airplane. This provision would solve stability problems associated with any fixed-gain system to which the aircraft can default at any time. It is not necessarily as important for the backup system to maintain equivalent envelope protection during mission abort and recovery. The pilot can be asked to constrain angle of attack to safe values during abort. Similarly, he can maintain airspeeds and altitudes appropriate to a fixed-gain control mode such as the IBU. It is feasible to postulate several gains that a pilot could select as he decelerated and descended to land. The only constraint to maximizing opportunities for simplifying backup systems during the recovery phase is that pilot workload or distraction may prematurely require a minimum level of augmentation during the abort/recovery phase. The IBU included pitch-rate feedback in partial response to cover pilot workload constraints.

System Complexity

A second architectural characteristic that significantly affected our experiences reflected the integrated nature of the system. The AFTI/F-16 is complex in terms of the number of system components and the permutations on component configuration. The large number of system configurations and their extensive interaction produce rather subtle consequences. It is frequently very difficult to explicitly know or test all the system effects of pilot actions in the real-time cockpit environment. Several discretes were required to indicate a specific component problem, and several components drove the same discrete. The AFTI/F-16 employs an architecture in which a single discrete may indicate multiple system conditions and, conversely, several discretes are often required to indicate a single system configuration or degradation. The multipurpose displays (MPDs) are frequently sequential interfaces with the flight control system, stores, or fire control computers where the pilot's eventual interaction with the system is a function of a series of key strokes whose system effects change based on the "page" displayed on the MPD at the time of option selection. Frequently, a time history of failure annunciations is required to accurately identify a specific failed component. Although the AFTI/F-16 system is not stochastic, it is often no more clearly deterministic at the time one is trying to anticipate system response to pilot-controllable options.

Such a cockpit differs subtly from more traditional pilot-vehicle interfaces where system discretes are largely dedicated to single, fixed functions. For example, failure annunciator lights are usually dedicated to single component condition in more conventional cockpits. In the AFTI/F-16 cockpit, those same lights may be used in combination with five-digit numerical fields on the MPD to indicate a specific flight control system failure or configuration. The salient characteristic of a system with such configurational flexibility is that cause and effect is deduced from a set of multivalued system displays that both pass information to the pilot and represent pilot commands to the system.

In the real-time cockpit environment where decisions are frequently required within a few minutes, it is often problematical whether the plot has the information, total system knowledge, or time to analyze and consciously acknowledge all ramifications of his interaction with the operating system. The real-time decisionmaking constraints of systems sush as the AFTI/F-16 can be addressed by increasing the dimensions of the pilot-vehicle interface with color presentations, audible tones, and voice actuation of system discretes. However, the systems still rely on the pilot to organize the system information, recognize inductive patterns in the system status, and deduce logical cause and effect relationships. The AFTI/F-16 may provide an early opportunity to evaluate "expert systems" in the real-time cockpit environment. A pilot-vehicle interface constructed around an expert-system architecture avails itself of a fundamental symbiosis. Human beings are unmatched pattern recognizers. Computers, their information structures, and certain mathematical algorithms have demonstrated equally peerless capability to search extensive graphs, trees, and other prestored lists. An expert system in the real-time cockpit of an aircraft like the AFTI/F-16 promises to use the strength of both pilot and computer. Not the least advantage of such a system would be its capability to partition decisions and system information into equivalent sets. Such partitioning would allow bounded decisions to be made without knowledge of the total system's response at the time of decision. Thus, expert systems may be powerful aids in solving the type of problems faced in the AFTI/F-16 real-time cockpit.

Simplex Information in Redundant Systems

A third ramification of system design that has proved interesting is the user's percepton of system reliability. The design goal of the AFTI/F-16 triple-redundant dual-fail-operate system required extraordinarily autonomous channels and a very powerful interchannel switching protocol to allow degradation to the last good channel. When the consequences of asynchronism are summed with this intrasystem autonomy, the operating flight control system often appears as a series of partially autonomous components that compete for aircraft control. Much of the interchannel independence arises from both unsynchronized interchannel skew and the requisite intrasystem autonomy of a triplex dual-fail-operate system.

It is important to distinguish the effects of asynchronism from last-good-channel operation. The AFTI F-16's asynchronous interchannel protocol created system states where single channels drove discretes and displays at the pilot-vehicle interface. Such simplex information is most important when it issues from the last good channel. Asynchronism, however, caused the display of false simplex channel information while the redundant set was still functional. Such annunciations diminish the perception that the system is highly reliable because it is composed of multiple identical channels – all doing the same "thing" – at least as long as there are no "real" faults in the system.

Unfortunately, the disagreeable impact of this architecture on perceptions of reliability causes difficulty in measuring the advantages of the capability to degrade to the last good channel and to operate asynchronously. Interchannel comparison varies between the extremes of bit-by-bit comparison and force summing across the power ram of an actuator. Even though AFTI/F-16 computers do not explicitly ascertain whether the other members of the operating set are performing the same operation, program development, nonetheless, shows continued localized synchronization. AFTI/F-16 channels do not employ dedicated hardware or software to communicate states to redundant channels and wait for acknowledgment; they "synchronize" by increasing interaction rates, or voting system states, or both. Interchannel differences are reduced by voting control law switch states, which control integrators and gains by interacting sufficiently fast or by exchanging status information in a timely fashion. As long as no errors exist, redundant systems cannot function reliably unless the implicit interchannel comparisons are sufficiently small to enable the system to behave as identical command paths. This requirement is independent of which synchronizing algorithms are used to achieve sufficient interchannel tracking. Furthermore, those same algorithms should not enable simplex information at the pilot-vehicle interface while a redundant set remains.

A graphic example of how dramatically the perception of reliability can suffer from permitting simplex information at the pilot-vehicle interface while redundant channels remain occurred during flight test. Although no failure had occurred, the pilot received messages that two of the channels had detected each other failed. With each channel in a different state, the actuators eventually selected a command. The pilot was unable to ascertain system configuration. It is important to recognize that the problem is not that the system failed to provide sufficient aircraft control. Such inconsistent simplex information erodes users' perceptions that the redundant system is operating reliably and will continue to do so in future confusing failures.

In summary, the AFTI/F-16 incorporates very powerful simplex channel capabilities to enable the system to degrade to the last good channel. Although the architecture retained this feature, reliability requirements, forced additional localized interchannel tracking by voting system states and increasing interaction rates. Regardless of asynchronism, or last-good-channel capability, displaying single-channel information with no failures in the redundant system diminishes subjective estimates of total system reliability. Neither architectural characteristic should enable single-channel interaction at the pilot vehicle interface during redundant channel operation.

Single Failure Propagation in Redundant Systems

A fourth issue, which is tangentially related to the characteristic discussed above, expands the fidelity of the interface between redundant core elements of the system and simplex peripheral components such as avionics. The AFTI/F-16 aircraft shares common trends in system design where the critical core elements are replicated in order to render sufficient reliability. The triplex flight control computers represent such strategy. A significant development to note, however, is that the redundant set of processors is embedded in a set of simplex units, such as the fire control or air data computer. Similarly, although the stores management computer is partially dual redundant,the protocol for switching between redundant halves frequently failed to take advantage of that capability and simplex failures were propagated.

The interface between the redundant core of the triplex flight control computers in the AFTI/F-16 aircraft must be meticulously delineated, documented, and understood so that failures in the simplex subset of the system are not unequivocably accepted and replicated by the redundant subset of the system. The authority and criticality of simplex inputs to the integarated system are substantial in the AFTI/F-16 and will probably increase in the future.

The AFTI/F-16 aircraft experienced a failure in the stores computer, which exemplifies the subtle but critical value of the interface between the redundant core and the simplex (in this case, the duplex that failed to use its redundancy) subset of the total AFTI/F-16 system. Functioning as a bus controller for the bus conveying flight control mode requests to the flight control mode requests. In less than 3 min, the AFTI/F-16 changed flight control modes more than 800 times! The flight control computers received control mode change requests from a simplex bus controller that appeared to function as a random-number generator. The flight control computer changed control modes whenever it received an actual mode request. The unscrutinized replication of a simplex input as critical as flight control mode lead to a rather dramatic breakdown of reliability in the redundant subset of the AFTI/F-16 system.

Analysis of this type of failure suggests that responsibility for assessing the validity of simplex data resides in the redundant subset, not the generating single-string component. Generally, the complex fault-detection logic is already resident in the redundant subset. Although duplicate information will not be available for fault detection, resonability checks can still be executed on simplex data. Since failure-detection algorithms typically reside in the redundant set, it seems consistent to include simplex data inputs in these kinds of data validity certifications.

The redundant subset responsibilities for operand validity follow from a second architectural characteristic in that the level of sophistication in failure-detection algorithms should be appropriate to the criticality of the data. Data criticality is defined by system use and generally cannot be determined prior to system definition. Frequently, an avionics system is an operational unit and is not susceptible to modification of the failure-detection algorithms because the data are to be used in a more critical function than intended when the unit was fabricated. Additionally, loading such failure detection in the redundant subset provides the same fault tolerance to hardware failures that is provided to other replicated processes.

The final point to be made in this context is that testing should especially emphasize the redundant simplex interface. Once signal-string component errors propagate across the redundant core boundary, their effects become more insidious, because redundancy no longer covers their effects. Understanding failure propagation behavior across the redundant simplex interface is roughly equivalent to single-point failure analysis and shares much of its importance.

CONCLUSIONS

The capability for improved mission effectiveness becomes ever more critical as enemy threat capabilities increase. Improvements can be attained by providing the pilot with the best flight control laws for the task at hand. This was demonstrated in the AFTI/F-16 aircraft using a multimode digital flight control system designed to optimize handling qualities for individual mission tasks. Without task-dedicated control law design, the full benefit of control law tailoring could not have been realized. This strongly suggests the need for multiple flight control mode capablity in future mulitrole fighter aircraft.

Direct side force with zero sideslip has been isolated as a decoupled motion which promises to significantly improve air-to-ground mission performance. Its implementation on conventional rudder pedals, even with limited authority, can offer pilots a simple, intuitive initiation to an easier way to solve the directional problem in bombing and strafing.

As the systems management function becomes a larger portion of the piloting task, improvements must be made in the management tools. Integrated avionics must include efficient and comprehensive pilot displays and system controls, including multiple display units with well integrated display symbologies and methods for display of head-up information over a wider field of view.

Voice command systems offer potential for reducing the pilot's workload with "hands-on" control of a variety of onboard systems from transducer codes to flight control modes. Further implementation of onboard synthesized voice and interactive operation may allow head-out access to critical information not displayed visually. Carefully conceived voice systems may help to contain increases in cockpit workload as avionics subsystems become increasingly complex.

Each of the four design ramifications discussed in this paper isolates an independent aspect of vehicles such as the AFTI/F-16. Our experiences have suggested higher penalties associated with failure to cover transitions to degraded mode flight. The costs of simplicity for a highly augmented vehicle are outstripped by costs of aircraft requirements for envelope limiting during the transition to degraded flight control. It is more important to provide envelope protection during transition than to constrain the backup system to be the simplest system that allows aircraft recovery. Aircraft control deteriorates so rapidly with unstable airframes that the advantages of backup simplicity are quickly overshadowed by risks of aircraft loss or severe operational constraints imposed to enable safe transition to backup.

The complex nature of the AFTI/F-16 cockpit suggests rather fundamental constraints that may imply architetures as radical as admitting expert systems to integrate the pilot-vehicle interface.

The capability to degrade to the last good channel and asynchronous interchannel tracking suggest the advisability of suppressing simplex channel information while a redundant set remains functional. Just as the actual reliability of redundant set operation was improved by localized synchronization, the user's perception of system reliability is improved by preventing single-channel interaction at the pilot-vehicle interface during redundant set operation.

The final issue discussed above suggests that regardless of information source, the redundant subset should logically be the location of information validity checks. Simplex error propagation across the redundant simplex interface should be emphasized during failure modes and effects testing.

As user's we have been exposed to several interesting design ramifications that suggest basic constraints that may be useful for future design efforts.

Table 1. Task-tailored flight modes, including decoupled motion (six degrees of freedom).

	Standard modes	Decoupled modes
Normal	SNRM g command	DNRM FPME Vertical translation Lateral translation
Bombs	SASB g command Flat turn	DASB FPME Directional lift Flat turn
Air-to-air guns	SAAG Pitch-rate command Flat turn	DAAG PRME Pitch pointing Yaw pointing
Air-to-surface guns	SASG Pitch-rate command Flat turn	DASG PRME Pitch pointing Yaw pointing

FPME	Flightpath maneuver enchancement
PRME	Pitch-rate maneuver enchancement

Table 2. Decoupled Motion with Maximum Control Authorities. 1-g flight, impurities included.

Motion	Authority	Flight Conditions	
		Airspeed (KCAS)	Altitude (ft)
Flat turn	Lateral g 0.90 g Yaw rate 7.0 Deg (122.2 Mils/s	500	10,000
Direct lift	Normal g -1.7 g	480	9,500
	Pitch rate 2.2 Deg/s/38.4 Mils/s	440	21,200
Yaw pointing	Sideslip 9.0 Deg/157.1 Mils	277	20,200
	Yaw rate 9.0 Deg/s/157.1 Mils/s	220	30,500
Pitch pointing	ΔAOA 8.0 Deg (139.6 Mils)	240	31,500
	Pitch rate -4.9 Deg/s/-85.5 Mils	450	21,000
Lateral	Lateral g 0.95 g	480	20,500
	Lateral velocity 38.3 knots	400	9,000
Vertical	Normal g -1.10 g	480	20,500
	Vertical velocity -25.1 knots	360	10,200

Table 3. DFSC Inflight fault detection.

38 fault declarations
Hardware
  Switch – 17
  Other a/c systems – 8

Software
  Design and mechanization – 10
  Unknown Cause

Pilot procedures
  Deselection of g-bias – 1

2 fault declarations not resetable inflight.

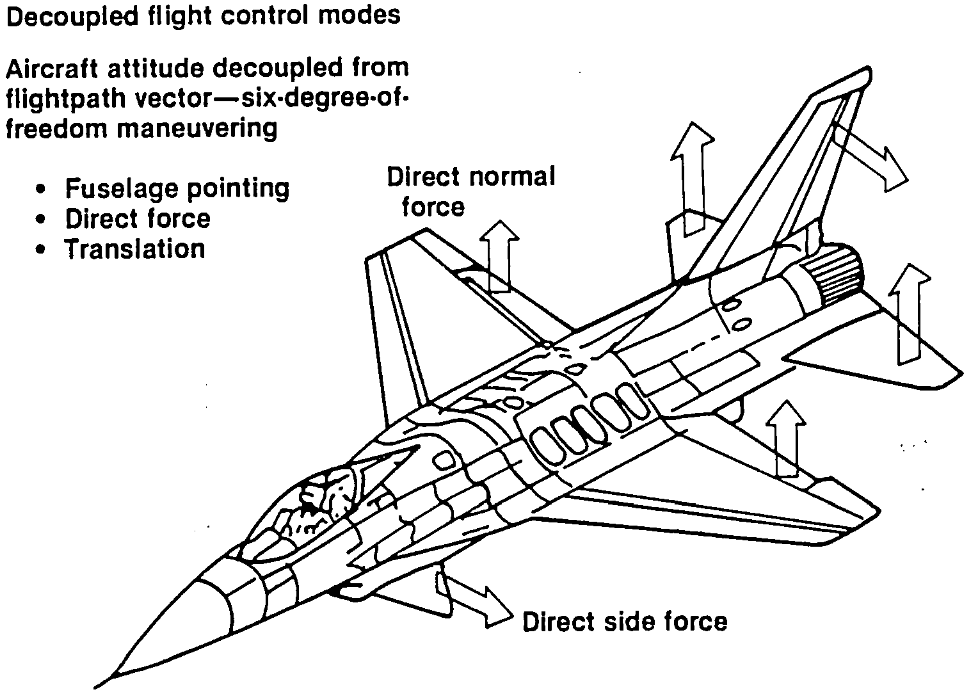


Fig. 1. Control surfaces producing decoupled motions.

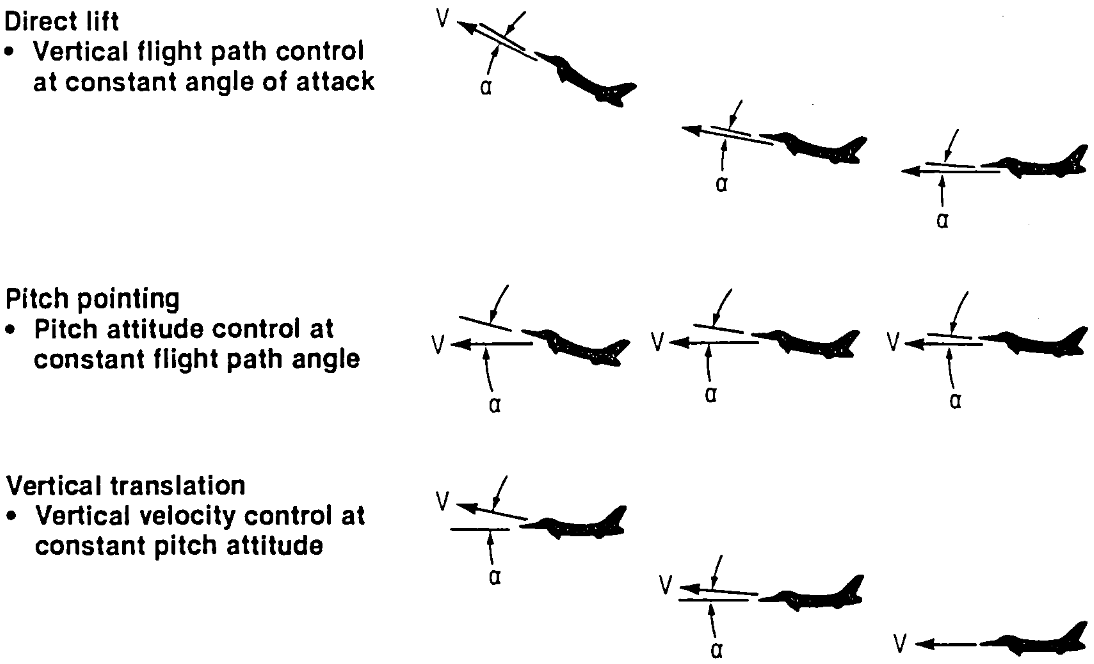


Fig. 2. Vertical decoupled motions. Thottle twist controller.

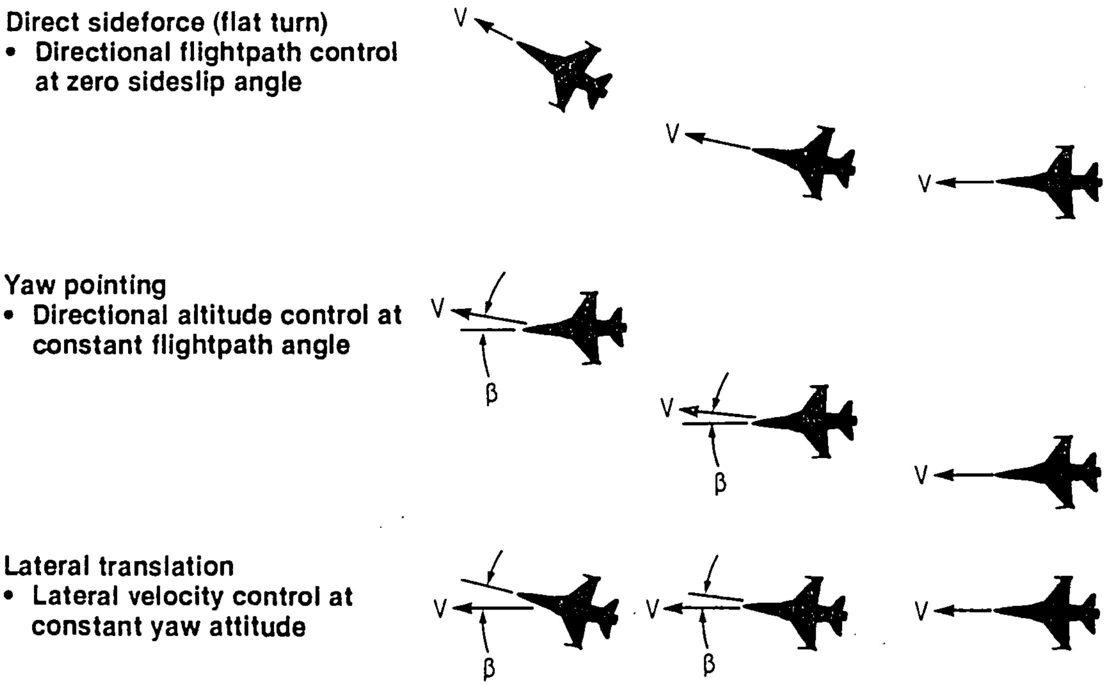
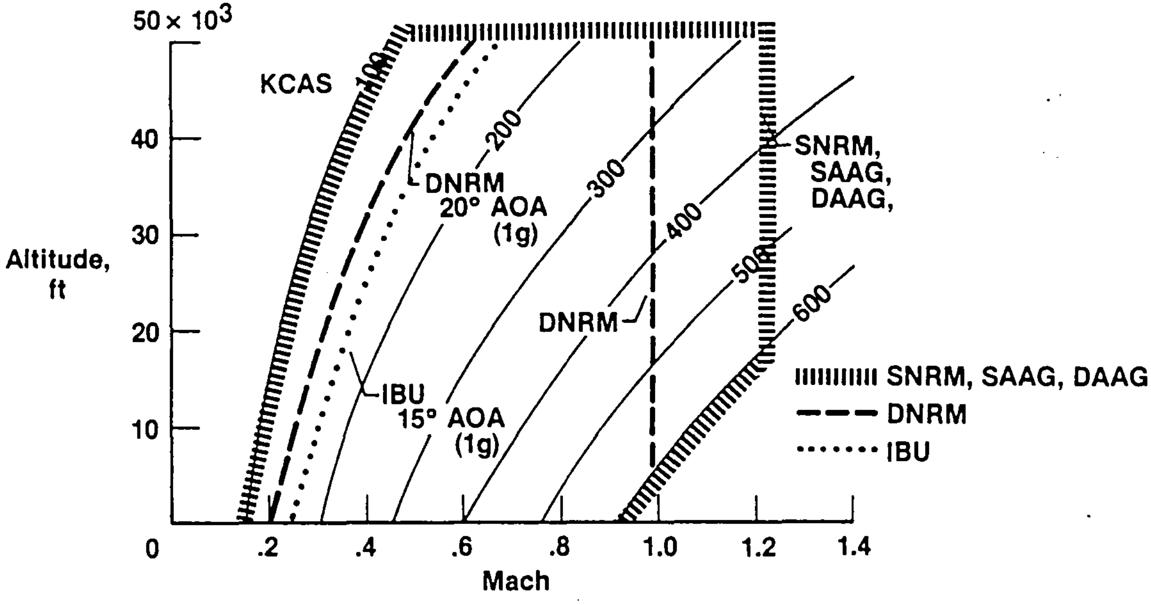
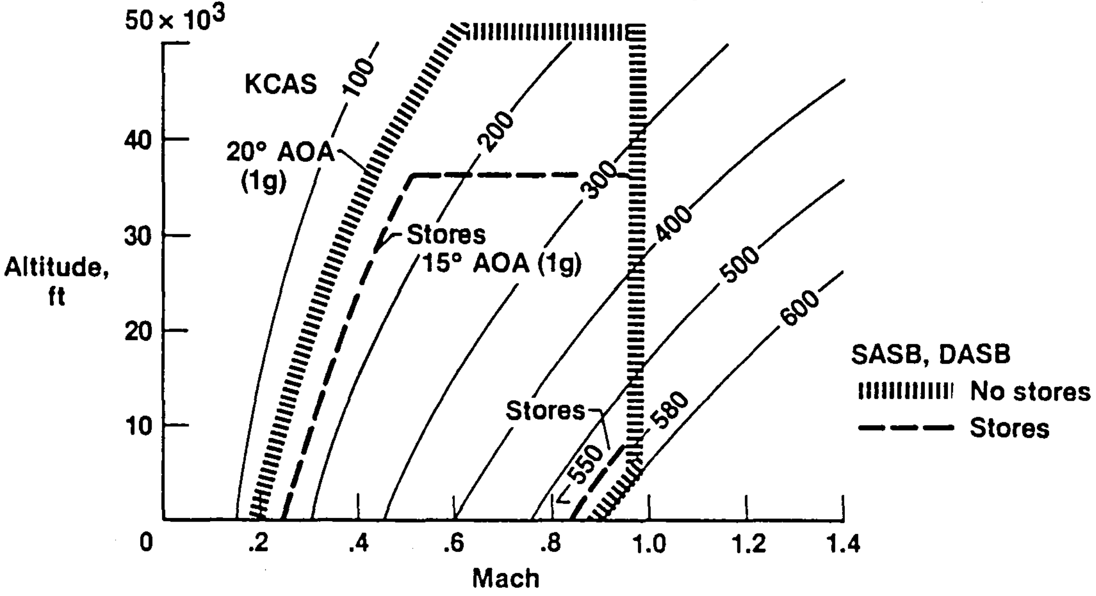


Fig. 3. Directional decoupled motions. Conventional rudder pedals.



- F-16 limits (9g, 25° AOA, etc.)
- Decoupled operations to 6g (release pedal for max roll)
- DNRM more restricted

Fig. 4. Flight envelopes for air-to-air modes.



- F-16 limits (9g, 25° AOA, etc.)
- Decoupled operations to 6g (release pedal for max roll)
- Combined decoupled operations to 4g

Fig. 5. Flight envelopes for air-to-ground modes.

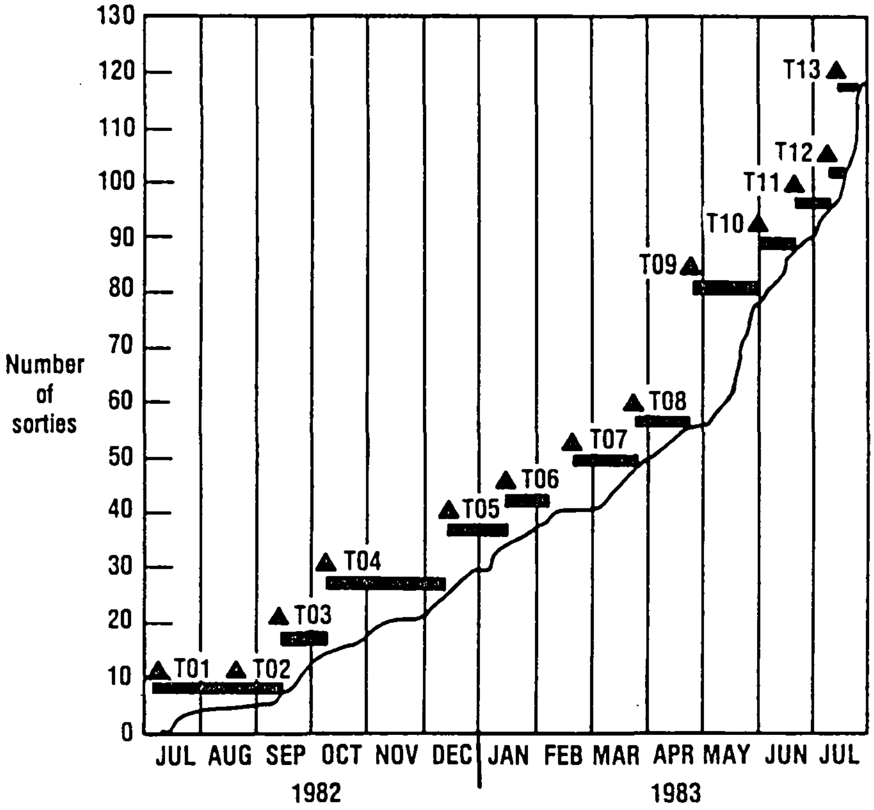


Fig. 6. Digital flight control system software control — software release summary.

Noise levels for flight test conditions.

Altitude/Airspeed	Environmental Control Setting	Sound Pressure Level
30K ft 304 KIAS	Auto cool	96dB
	Manual hot	100dB
20K ft 374 KIAS	Auto cool	99dB
	Manual hot	103dB
10K ft 448 KIAS	Auto cool	100dB
	Manual hot	108dB
5K ft 488 KIAS	Auto cool	105dB
	Manual hot	110dB

Fig. 7. Voice command system — noise levels for flight test conditions.

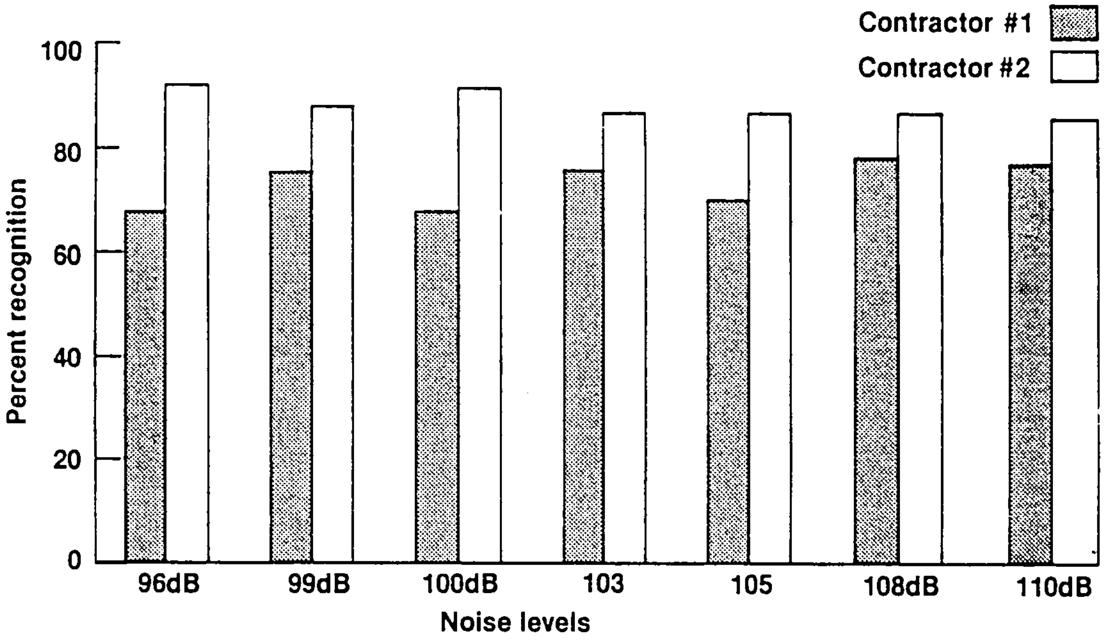


Fig. 8. Voice command system — in-flight recognition accuracy for noise condition.

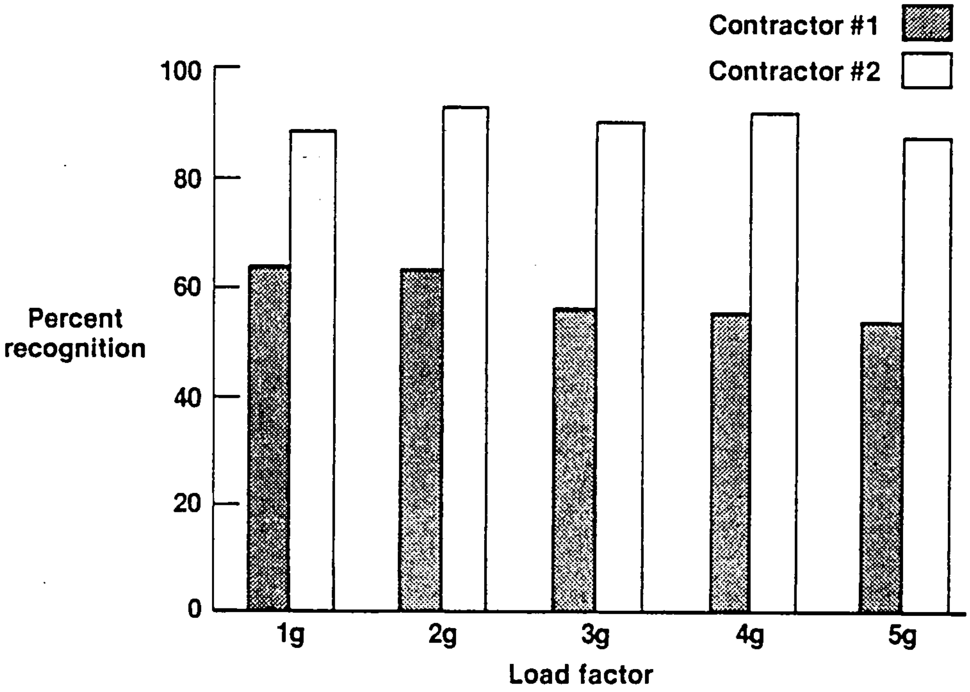
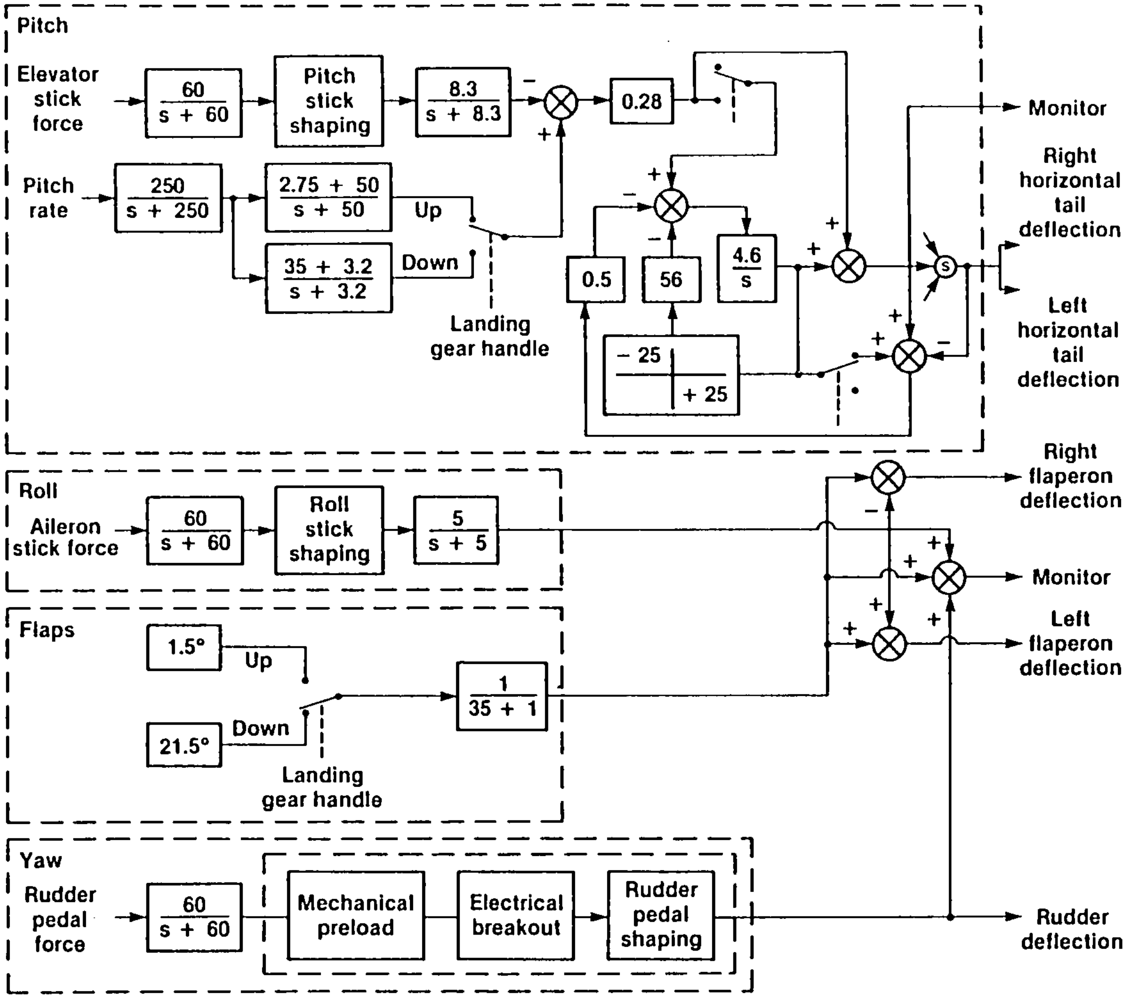
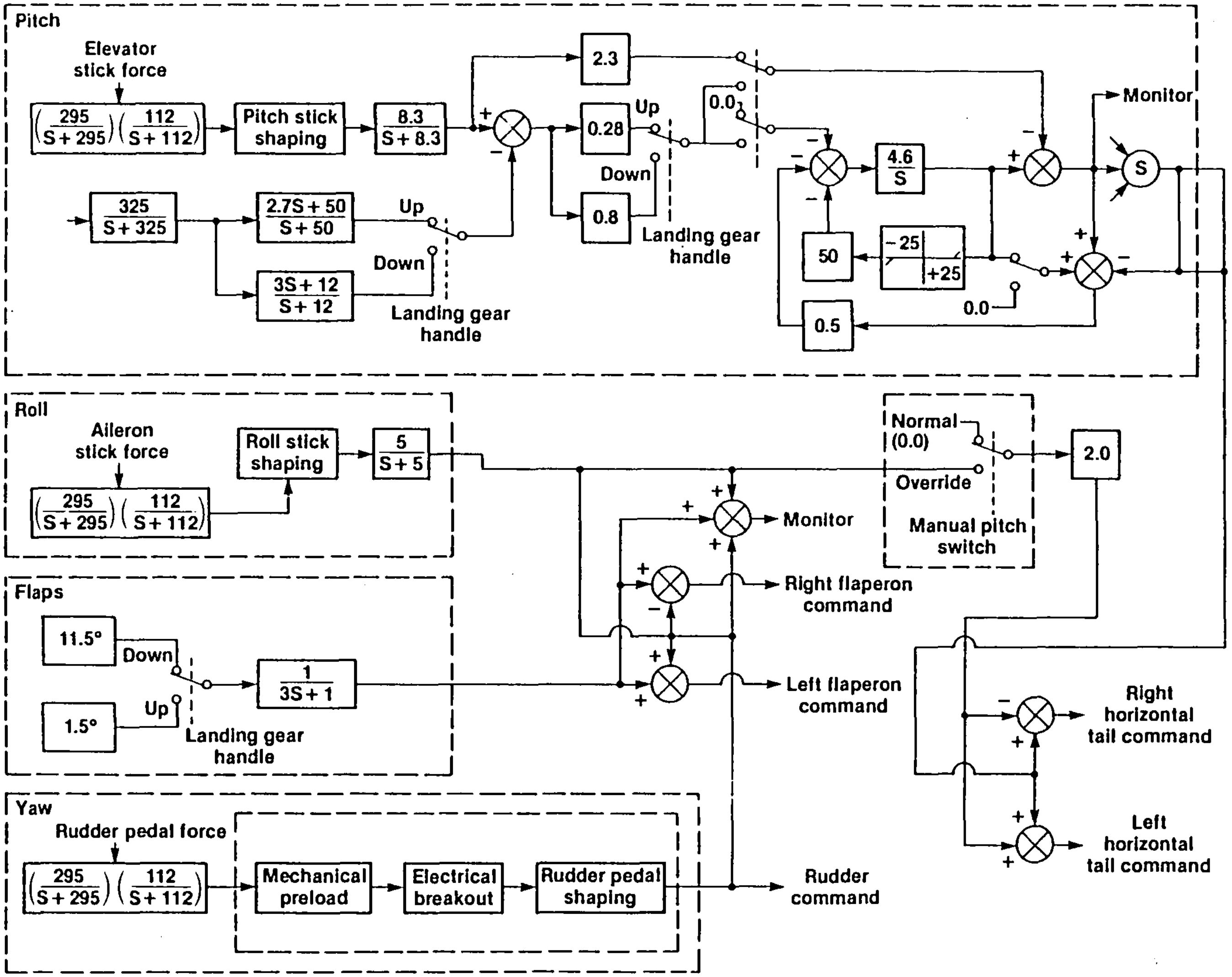


Fig. 9. Voice command system — in-flight recognition accuracy for load factor conditions.



(a) Original configuration.

Fig. 10. Independent backup unit.



(b) Final configuration.

Fig. 10 concluded.

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16. Abstract

Advanced fighter technologies are evolving into highly complex systems. Flight controls are being integrated with advanced avionics to achieve a total system. The advanced fighter technology integration (AFTI) F-16 aircraft is an example of a highly complex digital flight control system integrated with advanced avionics and cockpit. The architecture of these new systems involves several general issues. The use of dissimilar backup modes if the primary system fails requires the designer to trade off system simplicity and capability. This tradeoff is evident in the AFTI/F-16 aircraft with its limited stability and fly-by-wire digital flight control systems. In case of a generic software failure, the backup or normal mode must provide equivalent envelope protection during the transition to degraded flight control. The complexity of systems like the AFTI/F-16 system defines a second design issue, which can be divided into two segments: the effect on testing, and the pilot's ability to act correctly in the limited time available for cockpit decisions. The large matrix of states possible with the AFTI/F-16 flight control system illustrates the difficulty of both testing the system and choosing real-time pilot actions. The third generic issue involves possible reductions in the users' reliability expectations where false single-channel information can be displayed at the pilot-vehicle interface while the redundant set remains functional.

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