Appendix A: Wind Model

The turbulence power spectral density function used in the analysis is given by

$$\Phi(\Omega) = \sigma_G^2 \frac{L}{\pi}\left[\frac{1 + \frac{8}{3}(1.339L\Omega)^2}{[1 + (1.339L\Omega)^2]^{11/6}}\right]\frac{(\text{fps})^2}{\text{rad/ft}} \quad \text{(A1)}$$

where $\Omega = \omega/V$ = reduced frequency (rad/ft), V = aircraft velocity (fps), L = characteristic length (ft), σ_G = rms gust velocity (fps), and

$$\int_0^\infty \phi(\Omega)d\Omega = \sigma_G^2$$

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Automatic Flight Control System for Automatic Terrain-Following

F. M. Krachmalnick,* G. J. Vetsch,† and M. J. Wendl†
McDonnell Douglas Corporation, St. Louis, Mo.

This paper discusses the design, simulation, and flight testing of an automatic flight control system (AFCS) developed under Project 666A‡ to provide an automatic terrain-following capability in a supersonic, fighter-bomber type of aircraft. Functional operation and features of the high performance, very reliable fixed-gain AFCS are described. Excellent terrain-following performance using AFCS hardware integrated with a flight simulator was achieved in a six-degree-of-freedom simulation program. Radar system failure effects on terrain-following performance and flight safety were studied and documented for Air Force review. Comparisons of flight test and simulation study results show very close correlation. The 666A AFCS will provide the high performance and high degree of reliability required to perform the automatic terrain-following task. Further flight test development and evaluation of the automatic terrain-following system will be performed by the Air Force at Wright-Patterson Air Force Base.

I. Introduction

Background and Goals of 666A Program

McDONNELL, General Electric, and Texas Instruments were selected by the U. S. Air Force to participate in the Project 666A Automatic Terrain-Following Program. This program was conducted at McDonnell from June 1965 through December 1966. The goals of Project 666A were to develop and demonstrate an automatic terrain-following capability in the vertical plane, and to provide precise lateral control for guidance and navigational course direction in the horizontal plane of a high-performance, fighter-bomber type of aircraft, such as the McDonnell F-4.

Responsibilities of Associate Contractors

Texas Instruments Inc. was responsible for the design, development, and fabrication of the AN/APQ-101 Forward Looking Radar and the Terrain-Following Computer. General Electric was given responsibility for the design and fabrication of the AFCS hardware, performing analytical design studies, accomplishing flight-worthiness tests of the AFCS hardware, and for participating in the flight test evaluation of the AFCS.

McDonnell's primary responsibilities in the 666A program were 1) to participate in the design and development of the 666A Automatic Flight Control System (AFCS), 2) to install and integrate the AFCS and radar into the aircraft, and 3) to perform the flight test evaluation of the AFCS. This paper summarizes the results of analysis, simulation, and flight test accomplished in developing and evaluating the AFCS for use in providing the automatic terrain-following capability. Simulations and flight tests were conducted to determine that the performance of the AFCS met the specified design requirements.

II. 666A Automatic Flight Control System (AFCS)

The 666A AFCS was designed to provide the high degree of performance and reliability required for automatic terrain-following in the sensitive low-altitude, high-speed (LAHS) environment.

Features of the 666A AFCS

The 666A AFCS provides the following features in pitch, roll, and yaw channels.

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* Section Manager, Guidance and Control Mechanics. Associate Fellow AIAA.

† Senior Engineer, Guidance and Control Mechanics.

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Pitch channel

Pitch channel features are as follows:

1) High performance throughout the F-4 flight envelope, using fixed gains in all control modes of operation. Conventional autopilots in current service aircraft utilize air data computers to control the gain-changing functions. In more recent years, the concept of adaptive gain changing has appeared more promising for providing improved and uniform handling qualities. The use of either type of gain-changing technique has resulted in a reduction in reliability and an increase in maintenance time for the automatic flight control system. The 666A AFCS uses *fixed gains* in all control modes of operation, and, therefore, the reliability and ease of maintainability of the AFCS should be vastly increased.

2) Nearly invariant stick force per g and nearly uniform dynamic response handling qualities characteristics throughout the entire flight envelope.

3) Three channels of identical sensors and electronics with voting to provide failure detection and correction for the electronics and the three main ram feedback signals from the stabilator actuator.

4) Fail-operate capability in the electronics with a calculated mean time between failures (MTBF) in excess of 50,000 hr, based on a 5-hr mission that includes 1 hr of automatic terrain-following.

5) Fail-operate, fail-neutral operation of the stabilator actuator. Dual servo actuators with electrical feedback and an electrical "model" provide failure detection and correction.

6) Control augmentation and normal acceleration command inputs.

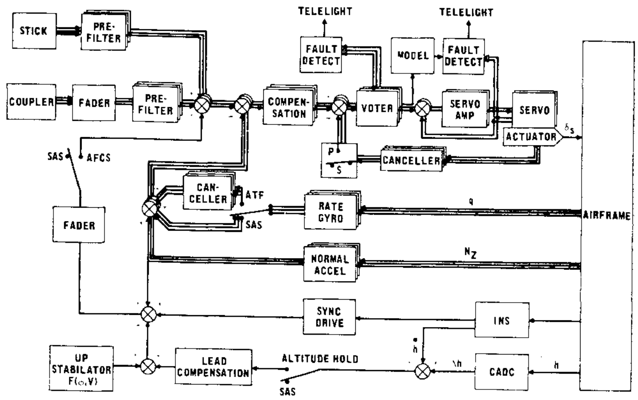
7) Blended pitch rate and normal acceleration feedback.

8) Series or parallel servo actuation with automatic trim available in both servo modes. Both servo configurations were incorporated into the AFCS to provide a test article for evaluating which configuration would provide the better performance relative to handling qualities and terrain-following.

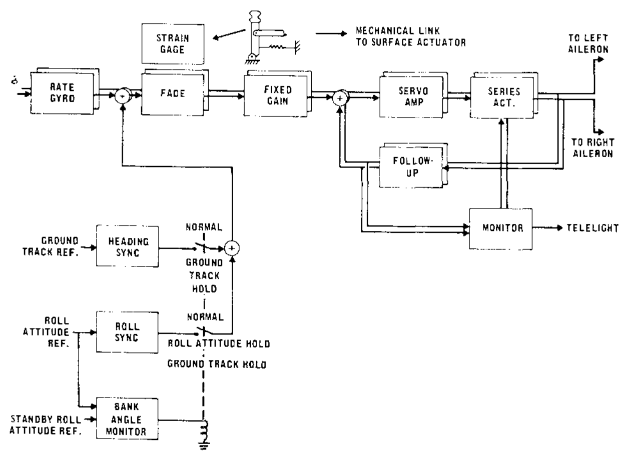
Automatic trim is used to unload the servo in the parallel mode and to effectively increase the deflection authority in the series mode. The automatic trim motor rate in the F-4 is approximately 1 deg/sec of equivalent stabilator rate and is commensurate with safety-of-flight criteria established for the aircraft.

Roll and yaw channels

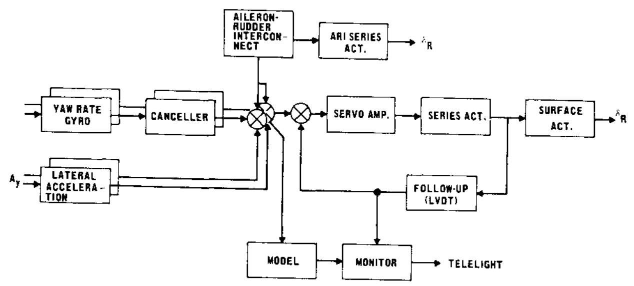
The lateral channels are virtually unchanged from the production F-4 AFCS except with respect to safety considerations. Roll channel features are 1) dual sensors, electronics and series actuators with a monitor used to provide failure detection and shutdown, 2) reduced servo authority from $\pm 7.5°$ to $\pm 3°$ aileron and fast-centering time (changed from present 3 to 10 sec to 0.3 sec), and 3) fixed gains in all modes of operation. Yaw channel features are 1) dual sensors and electronics to provide an active channel and "model" channel to enable failure detection and shutdown and 2) fixed gains in all modes of operation.



a) Pitch axis



b) Roll axis



c) Yaw axis

Fig. 1 Automatic flight control system block diagrams.

666A Program AFCS Modes of Operation

The modes of AFCS operation are 1) stability (control) augmentation, i.e., pitch, roll, and yaw short-period damping and lateral turn-coordination; 2) pilot assist (with control stick steering), a) pitch: attitude hold, altitude hold, and b) roll: attitude hold, ground track hold; and 3) automatic terrain-following, i.e., automatic pitch path control using either manual stability-augmented lateral control or automatic ground track hold as may be selected by the pilot.

Functional Description of AFCS

The requirement stipulated by the U.S. Air Force for the AFCS design was that no single malfunction, whether in the automatic flight control or in other systems, such as the hydraulic and electrical supplies, will generate a situation that requires immediate and/or precise action by the pilot to avoid disaster. This requirement was applicable to all modes of operation and all channels of control.

Pitch channel

The function of the pitch channel of the AFCS is to provide acceptable flight path response in the automatic terrain-following mode and satisfactory handling qualities in the stability (control) augmentation and pilot assist modes. A functional block diagram of the pitch axis is presented in Fig. 1a.

All sensors and electronics of the inner loop, as well as the signals from the stick force transducer and the terrain-following coupler, are provided in triplicate to increase the reliability of this channel. The voter on the electronics and the three main ram feedback signals insures that the outputs applied to the servo amplifiers and to the model are good signals, despite any one failure occurring in any of the three channels of the electronics preceding the voter. A failure is detected and indicated to the pilot in the form of a light on the telelight panel.

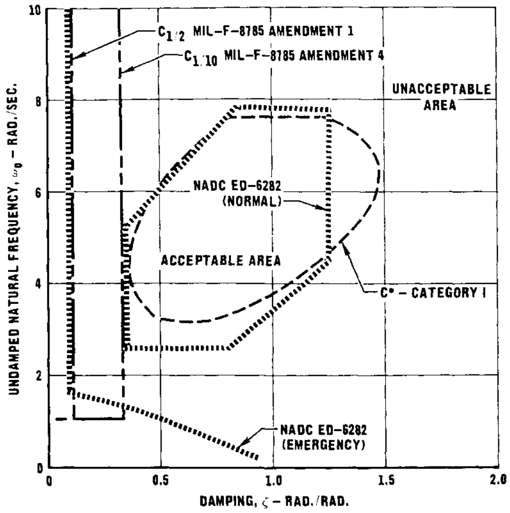


Fig. 2 Longitudinal handling qualities criteria.

A second voter is utilized to detect any failure of the outputs of the auxiliary rams of the servos. Deviations above a set tolerance among the two auxiliary ram position signals and the model electrical output are detected, the failed channel is shut down, and the failure is indicated to the pilot. A second failure in either the model or a remaining servo ram channel causes a center lock mechanism to cam the servo ram to its null position. This centering action prevents a servo hardover in the event of a second failure. Series or parallel servo operation is available for pilot selection in all modes.

Blended pitch rate and normal acceleration are used as feedbacks to all input commands with the exception of automatic terrain-following where pitch rate feedback is cancelled to accommodate the ride control and g-limits of the automatic terrain-following (ATF) command computer. The attitude command signal is derived from the Inertial Navigation System (INS) and the altitude command signal from the central air data computer (CADC). An up-stabilator signal as a function of bank angle and velocity is commanded in these modes to preclude loss in attitude and altitude during turns.

Roll channel

The function of the roll channel of the AFCS is to reduce roll-yaw coupling by utilizing roll damping to alleviate disturbance-induced roll rates while providing good roll response to pilot commands. The functional block diagram of this mode is provided in Fig. 1b. Roll attitude hold and automatic ground track hold are provided as the pilot-assist modes. The servo ram position outputs are continuously compared and if the difference exceeds 50% of full servo stroke, the prescribed tolerance, a fail light is illuminated in the telelight panel, and the roll stability augmentation mode is disengaged. In the terrain-following mode, either the stability augmentation or automatic ground track hold mode may be selected. The automatic ground track mode incorporates a bank angle monitor, which compares the INS roll attitude signal with the roll attitude signal derived from a separate miniature vertical gyro source, used with the forward looking radar, to provide an increase in reliability for the roll signal. If these two signals differ by more than 5 deg of bank angle, the automatic ground track hold mode will not engage. This mode will also not engage if either roll attitude source indicates a bank angle exceeding 15 deg.

Yaw channel

The function of the yaw channel is to improve Dutch-roll damping and directional stability of the basic aircraft. The functional block diagram of this channel is presented in Fig. 1c. Monitoring consists of comparing the yaw servo position with the electrical output of an electronic model representative of the servo loop dynamics with the shutdown technique being identical to that used in the roll channel. Incorporating the lateral accelerometer provides automatic turn-coordination in this mode. Aileron-to-rudder interconnect is incorporated to preclude adverse yaw due to aileron deflections at low-speed flight conditions.

III. AFCS Analysis and Simulation Results

Analysis

Since the lateral and directional channels of the 666A are functionally similar to those of the current F-4 (FC8) AFCS, major emphasis was placed on the analysis of the longitudinal channel. The design philosophy of the 666A AFCS is based on a modified sensitivity concept whereby the necessary control system compensation is systematically chosen to minimize system sensitivity to plant variations and to random disturbance inputs. The synthesis technique used in the design of the fixed-gain system results in network compensation, which, when combined with the aircraft (plant) open-loop, frequency response characteristics, insures stability margins above a prescribed minimum throughout the flight regime. The manner in which the system constraints and plant variations are assimilated and used in obtaining an optimum compensation loop definition is unique to this technique. The design process allows efficient use of the digital computer facilities for processing the routine calculations involving airframe dynamics and influential feedback parameters, such as the canceller time constant and the blended normal acceleration to pitch rate feedback gain ratio.

In addition to meeting stability requirements, the pitch channel was designed essentially to meet the performance criterion proposed by the Naval Air Development Center (NADC) in NADC-ED-6282, and the stick force per g gradient required by MIL-F-8785. Since the primary use of the AFCS was in the LAHS flight regime for accomplishing the automatic terrain-following task, the fixed-gain longitudinal system design was directed such that the handling qualities would meet the NADC criterion for the LAHS flight conditions, which include the flight regime from 0.8 Mach to $V_{\max}$ for altitudes below 15,000 ft. Special emphasis was placed on tailoring the system to meet this criterion as closely as possible for the higher altitude and low q flight conditions. The NADC criterion is compared with the MIL-F-8785 and the Boeing C* criterion in Fig. 2 in an equivalent second-order frequency and damping ratio format. For evaluating the 666A AFCS, the NADC criterion was converted to a normalized

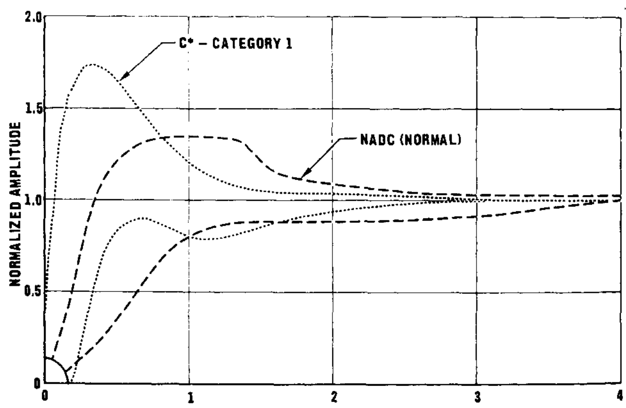


Fig. 3 Normalized time history response envelopes of acceptability. Note: 1) Normalized amplitude for C* criteria is $N_{z_p} + 12.4\,\dot{\theta}$; 2) normalized amplitude for NADC criteria is N_{z_p} at $V > 400$ fps, $\dot{\theta}$ at $V < 400$ fps, where N_{z_p} is in g's and $\dot{\theta}$ is in rad/sec.

time history envelope of performance acceptability and is presented along with the C* time history envelopes in Fig. 3. Such envelopes enable meaningful comparisons of augmented aircraft responses, which may be slightly nonlinear or of higher order, to be made with the criteria.

The NADC proposed revision to MIL-F-8785 specifies that the longitudinal short-period dynamic oscillations of normal acceleration, in equivalent damping and frequency, be used for comparison with the criterion requirements. McDonnell has extrapolated the NADC criterion to reflect the measure of pilot's response to the blend of pitch rate and normal acceleration as sensed at the pilot's seat location. For aircraft velocities above 400 fps, the responses used for cirterion comparison should be normal acceleration measured at the pilot's seat; for velocities below 400 fps, pitch rate responses should be used for criterion comparison; and for velocities in the vicinity of 400 fps, both pitch rate and normal acceleration at the pilot location (N_{z_p}) responses should fall within the criterion envelope.

Three-Degree-of-Freedom Simulation Results

In summarizing the results obtained from a three-degree-of-freedom simulation, the longitudinal system response characteristics are compared with the NADC criterion using 1) series or parallel servo modes, 2) normalized pilot seat response N_{z_p} to step inputs of stick force command in the stability augmentation (SAS) mode, and 3) normalized pilot seat response N_{z_p} for step inputs of normal acceleration command from the terrain-following radar.

Stability augmentation system (SAS) and automatic terrain-following system (ATFS)

Early in the study, it was found that an increase in the AFCS speed of response was needed to attain sufficient augmented aircraft performance improvement at the higher altitude flight conditions to meet the NADC specification requirements. Changes to the SAS and ATFS compatible with AFCS hardware were made. These changes included a modified forward-loop compensation network, a shorter canceller time constant, the addition of a normal accelerometer structural filter, and an increase in the normal acceleration N_z to pitch rate $\dot{\theta}$ feedback gain ratio. The original AFCS design utilized an N_z to $\dot{\theta}$ feedback gain ratio of 3:1 in units of g/deg/sec. In the course of McDonnell's analytical studies, system configurations were studied, using N_z to $\dot{\theta}$ feedback ratios of 3:1, 4.5:1, and 9:1. A comparison of the responses for the ATF parallel mode with the NADC criteria is shown in Fig. 4 for a weight of 37,200 lb with the c.g. at 30.8% $\bar{C}$. As can be seen, the system with the 9:1 gain ratio provided the best system responses for meeting the criterion envelope. The stability margins are considered satisfactory for all three system configurations.

Results obtained from both the subsequent six-degree-of-freedom simulation study, incorporating 666A AFCS hardware and the fixed-base flight simulator, and from flight testing indicated that the final system design should be changed to incorporate the 4.5:1 ratio. This change was necessary because of compatibility problems that existed between the force balance artificial longitudinal feel system used in the F-4 aircraft and the integrated servo-actuator in the parallel mode configuration.

Stability augmentation system responses to step inputs of stick force command for both the parallel and series servo configurations are compared with the NADC criteria in Fig. 5 for the final system design incorporating the 4.5:1 N_z to $\dot{\theta}$ gain ratio. For the most part, the normalized pilot seat normal acceleration responses for the high q LAHS flight conditions studied fall within the NADC envelope of acceptability. The responses shown for the lower q flight conditions are considered satisfactory with the use of a fixed-gain system. Of course,

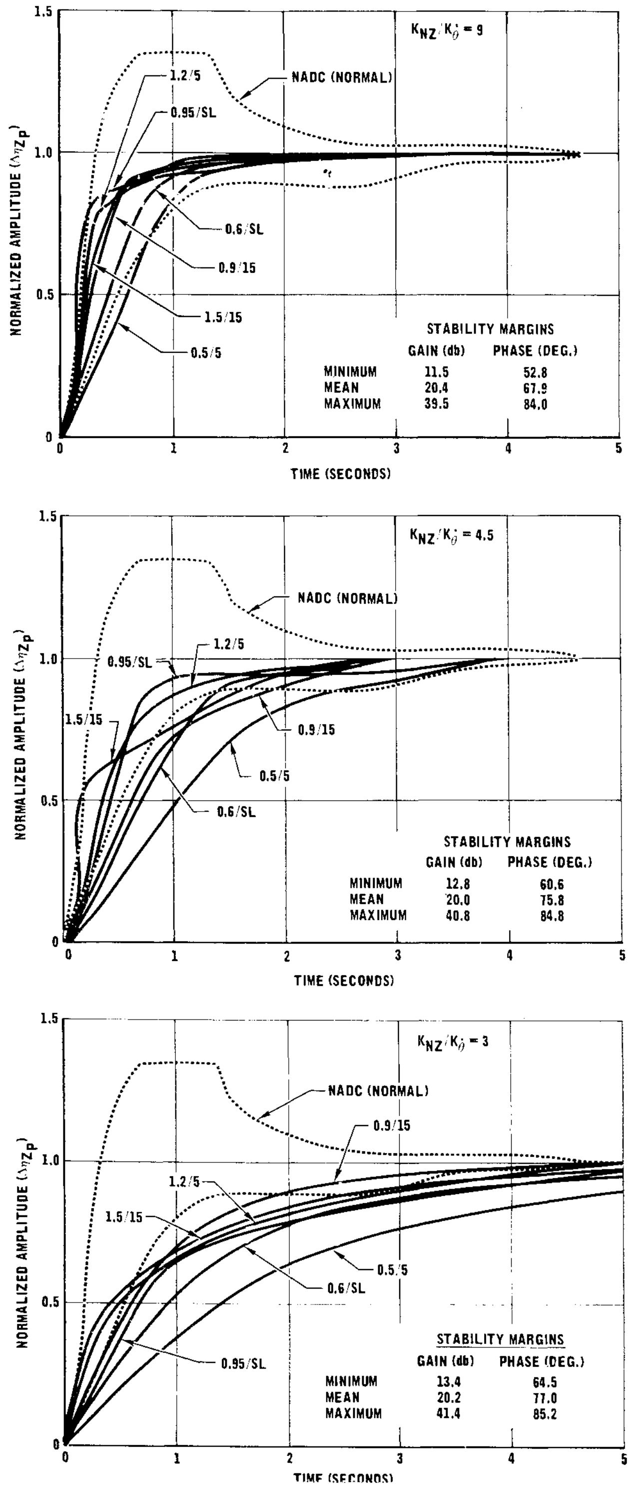


Fig. 4 Comparison of aircraft response with NADC criteria—ATFS parallel servo mode.

some compromise in response time at the low q and high-altitude flight conditions had to be made using a fixed-gain system in lieu of a self-adaptive gain changing or air data gain-scheduled system. However, this compromise is considered justified when this slight reduction in performance is weighed against the increase in system reliability and decrease in complexity and maintenance time gained by deletion of the three-channel, gain-changing function. Because for this program the primary mission usage of the AFCS is in the low-altitude, higher q regions compatible with automatic terrain-following flight, the design of optimum system performance was tailored to this portion of the F-4 flight envelope. The stability margins for the SAS mode are considered adequate to insure

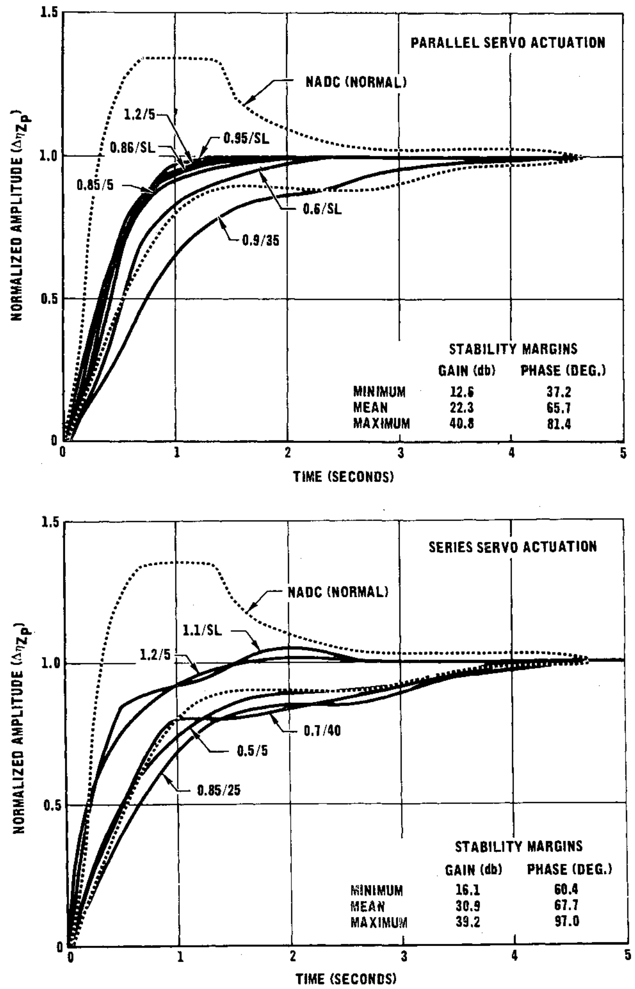


Fig. 5 Comparison of aircraft response with NADC criteria—SAS mode ($K_{N_z}/K_{\dot\theta}$ = 4.5).

stability in the presence of hardware tolerance variations and nonlinearities.

Responses for the final system design to simulated radar step command inputs in the automatic terrain-following mode for the parallel servo configuration are compared with both the NADC criterion and C* criterion in Fig. 6. Because of the concept similarity of the two criteria, similar evaluation results are obtained from comparison of the normalized time history responses with the two criteria as shown in Fig. 6. The fixed-gain ATF mode provides acceptable transient responses for all the LAHS flight conditions.

Attitude and altitude hold

The dynamic characteristics and stability of the outer-loop modes of attitude and altitude hold were also studied in this phase of the program. The performance of the attitude and altitude hold modes as studied was found to be much improved over that obtainable with the production F-4 AFCS, and both modes yielded adequate stability margins at all flight conditions studied.

Stick force per g characteristics

The 666A AFCS was designed to meet the stick force per g specification requirements of MIL-F-8785. The stick force gradient, shown plotted vs aircraft velocity in Fig. 7, meets the specification requirements. As a result of the use of integration in the inner loop for both the parallel and series servo configurations, the stick force gradient of the basic aircraft is very nearly masked. The extent to which this masking is possible during a maneuver is dependent on the deflection authority and follow-up trim motor rate allowed in the series servo mode and on the servo stall torque and the amount of mismatch between the stick force gradient of the basic aircraft and the stick gradient desired for the control augmentation system in the parallel mode configuration. In the F-4 aircraft, this mismatch notably increases with increasing Mach number because of the spring constant characteristics of the bellows in the force balance system, which produces forces proportional to dynamic pressure.

Stability margins

A notable result was obtained from this analysis as related to system stability margins. Referring to Fig. 8, it can be seen that the gain margins for the final system design are low for the high q regions and high for the low to medium q regions, whereas the phase margins manifest an opposite characteristic.

The gain margin trend is readily explainable. In a self-adaptive or air-data, gain-scheduled system, the forward-loop gain is very nearly inversely proportional to the surface effectiveness parameter. With a fixed-gain system, the gain is limited to the maximum value that can be tolerated for stability reasons, i.e., where the surface effectiveness is the highest, occurring generally in the high q region. Consequently, the gain margins with a fixed-gain system are maximum for the low to medium q region where the surface effectiveness parameter is low.

The phase margins are observed to be lowest in the low to medium q region. The AFCS system dynamics in this portion of the flight envelope of the F-4 aircraft generate root loci branches that are nearer to the origin and closer to the imaginary axis than those same branches generated for the

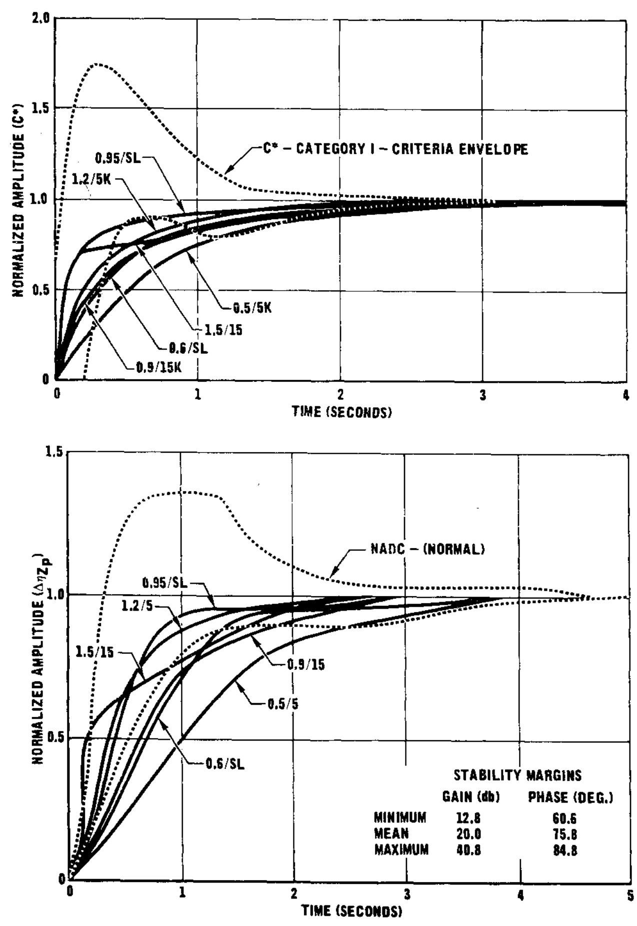


Fig. 6 Comparison of aircraft response with NADC and C* criteria—ATFS parallel servo mode ($K_{N_z}/K_{\dot\theta}$ = 4.5).

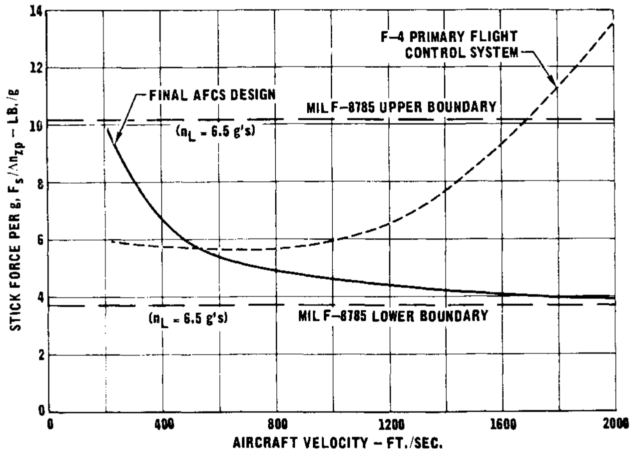


Fig. 7 Stick force per *g* gradient characteristics.

high q region. This characteristic is typical of stability-augmented aircraft in the high-speed, fighter/interceptor category, such as the F-4. With a fixed-gain system, where large gain margins exist in the low q flight regime, the phase margins are even lower than with gain-scheduled systems. This characteristic is due to the fact that the phase margins are a function of the system gain and the proximity of this root locus branch to the imaginary axis. The phase margins approach values that are very nearly determined by the location of the basic aircraft poles in this portion of the flight regime. Therefore, the phase margins are minimum at the low q region and maximum at the high q regions as depicted in Fig. 8.

Six-Degree-of-Freedom Analog Simulation Results

In addition to the three-degree-of-freedom analysis, a six-degree-of-freedom, large perturbation man-in-the-loop, terrain-following analog simulation was performed. The purposes of this simulation were 1) pilot evaluation of all AFCS control and pilot-assist modes using AFCS hardware, 2) pilot evaluation and documentation of terrain-following performance for the AFCS/radar/airframe combination under manual and automatic control, and 3) limited evaluation of simulated system failures.

Description of simulation

A functional block diagram of this simulation is presented in Fig. 9. This simulation incorporated a six-degree-of-freedom airframe, AFCS hardware, a radar simulator, and a fixed-base flight simulator.

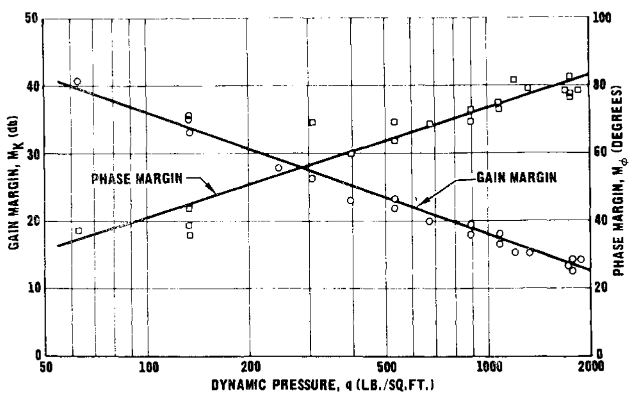


Fig. 8 SAS stability margins—parallel servo mode ($K_{N_z}/K\dot{\theta}$ = 4.5).

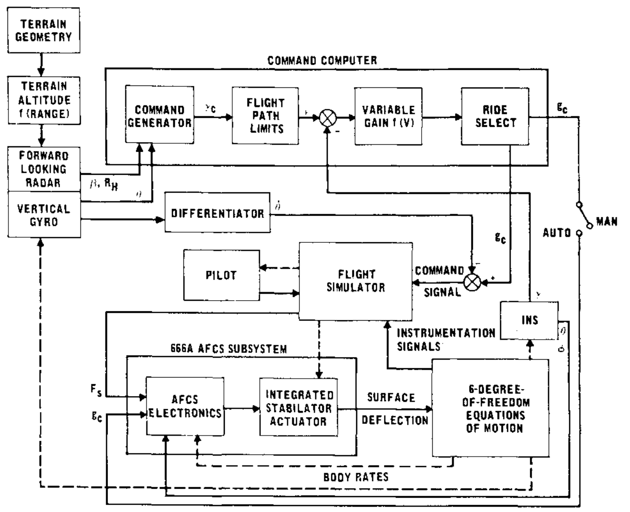


Fig. 9 Terrain-following simulation functional block diagram.

Terrain-following performance

Typical terrain-following performance achieved utilizing the simulated radar and AFCS hardware is shown in Fig. 10. Both automatic and manual terrain-following performance for the 0.9 Mach number flight condition are illustrated. (Clearance altitude is classified.)

It is noted that very little difference exists between the manual and automatic terrain-following performance, and both are considered excellent. McDonnell has determined that, for short-duration flights, the human pilot utilizing an optimized command display can equal the performance of an automatic system. However, as the time duration of terrain-following flight increases and/or other cockpit duties are imposed, the human pilot's performance becomes grossly degraded.

The third profile shown in Fig. 10 has been called the "ideal profile." This curve represents the best possible terrain-following performance that can be achieved at 0.9 Mach number within the constraints imposed on the aircraft for the terrain-following mode, i.e., limitations on load factor, climb and dive angles, and level flight over peaks and flat terrain.

Evaluation of failure effects

As a part of the six-degree-of-freedom simulation, a failure analysis was conducted to examine the effect of failures that were basic to the aircraft, the AFCS, and terrain-following radar. These random failures were imposed upon the aircraft while pilots were "flying" the flight simulator at low-altitude flight conditions. The response of the airframe to the failures and the ability of the pilots to take corrective action quickly enough to avoid collision with the ground were

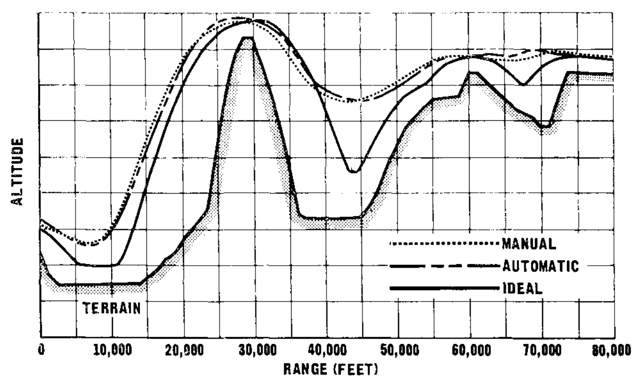


Fig. 10 Terrain-following performance.

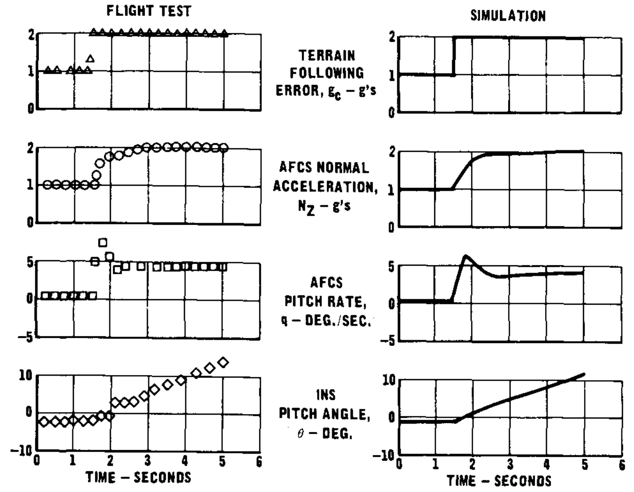


Fig. 11 Flight test and simulation results comparison—ATFS parallel servo mode. $M = 0.95$, $h = 5000$ ft.

evaluated. The results of these tests showed that the pilots experienced little difficulty in detecting and correcting for failures that were indicated by the illumination of a failure-warning light. However, certain failures that did not result in the illumination of a failure-warning light went undetected, and collision with the simulated terrain occurred.

As an example, one of the nonindicating failures that can occur is an electrical open or hard-over on the normal acceleration command (g_c) output of the terrain-following computer. No failure-detection logic is provided for this nonredundant circuit. The only means of failure detection for the pilot is the monitoring of the E^2 situation display and the flight instruments. Although modification of the radar computer was outside the scope of this program, all such potential failures were documented for Air Force review.

IV. Flight Test Results

Description of Flight Test Program

Flight test evaluation of the 666A AFCS was initiated on October 6, 1966 and completed in December 1966. Only 17 flights were required to evaluate the AFCS. All flight testing was accomplished at St. Louis. Further flight test development and evaluation of the automatic terrain-following system will be performed by the Air Force at Wright-Patterson Air Force Base following McDonnell's program.

AFCS flight evaluation

The test pilots who flew the aircraft during the AFCS flight test program carefully evaluated the characteristics of the stability (control) augmentation system. This concept of augmented control would be utilized as the normal control system of the aircraft if this system were used for a production aircraft. Reversion to the present mechanical-hydraulic control system would be used for back-up if failure of the SAS occurs. Therefore, special attention was given to evaluating the handling qualities provided by the SAS concept of control.

The performance of the outer-loop modes of operation including attitude and altitude hold was also evaluated during the flight test program. Simulated radar step command inputs were used to verify proper terrain-following mode operation.

The results of these flight tests were compared with those of the six-degree-of-freedom simulation. Typical results of representative parameter comparisons are shown in Fig. 11. The aircraft parameter responses to a maximum pull-up command with the terrain-following mode engaged and the parallel actuator selected are presented in Fig. 11. Very close correlation between the simulation and flight test results was achieved. From such comparisons with flight test recordings and from pilot comments, the following significant results were realized:

1) Aircraft response during maneuvering in the SAS mode with the pitch actuator in the series or parallel configuration was considered satisfactory with deadbeat damping at all flight conditions.

2) Over-all performance obtained with the pitch actuator in the parallel configuration was considered superior in both the SAS and ATF modes. The series servo deflection limit and the low automatic trim rate used in the F-4 aircraft resulted in a lower pilot opinion rating of the series servo operation.

3) Aircraft response to the 2 g normal acceleration command with the system in the ATF mode was demonstrated satisfactorily during operation in both pitch actuator servo modes.

4) Altitude hold mode performance was demonstrated successfully throughout the aircraft flight regime.

5) Pilots confirmed their preference for nearly constant stick force per g handling characteristics throughout the flight envelope.

6) The near-zero stick-force-per-V handling characteristics were found to be acceptable by the pilots.

7) Pilot comments indicated that it was difficult to discern improvement in aircraft handling qualities provided by the stability (control) augmentation system at the low q flight conditions because of the large stick deflections that were required for commanding maneuvers.

In addition, a number of modifications to the system were accomplished in the process of performing these flight tests, and several areas requiring improvement were defined. Major items are summarized as follows:

1) As originally configured, the pitch stability augmentation mode could not be used for takeoff because of the operation of the automatic trim follow-up in the series mode and because of the main-ram follow-up canceller driving the surface hard-over in the parallel mode when stick forces were applied. Since the series *damping* mode is desired for takeoff, modifications were made to disable series auto-trim when weight is on the main gear in order to provide for automatic removal of the trimming function when the aircraft is on the ground. Time limitations precluded incorporation of feasible changes to the hardware to facilitate takeoff with the system using the parallel servo configuration.

2) With the stability (control) augmentation system engaged and the series actuator selected, application of stick force by the pilot resulted in adverse stick force and stick motion because of the series automatic trim. This condition was eliminated by making the trim inoperative when stick force is applied. This change resulted in the series actuator bottoming whenever large stabilator deflections are commanded. No increase in series servo authority was made to alleviate this problem during this program.

3) Pitch and roll attitude hold operation was satisfactory for straight and level flight and during maneuvering at small bank angles. Normal acceleration transients occurring during pilot-commanded pitch maneuvers performed in turning flight were eliminated by varying the outer-loop fader time constant as a function of bank angle.

4) The use of limited authority series servo and automatic trim follow-up employing slow trim rates significantly increases the system response times for large input commands. Faster response times can be obtained using either a parallel servo or a series servo with large authority.

5) Significant reduction in stick motoring was achieved by lowering the feedback gain ratio. The small level of stick motoring or "nervousness" that still exists in the parallel servo mode was considered objectionable for precise manual terrain-following.

6) Small pitch attitude changes were difficult to accomplish in the series servo mode because of a combination of low frictional forces in the control system and a relatively slow force build-up from the automatic trim. This condition could be improved by lowering the force breakout level in the stick force transducer. Since this adjustment for the triply redundant transducer was a factory adjustment, this modification was not evaluated during the flight test program.

7) The lack of a manual pitch trim capability for trimming the aft stick force during a turn with the stability (control) augmentation system engaged was considered unacceptable. Consideration was given to installing an integrating amplifier, which could be controlled by a manually actuated trim switch, to provide this capability. The output of this amplifier would be summed into the AFCS bridge to provide a voltage equivalent to the output of the stick force transducer. In this manner, the pilot force can be relieved to 0 during a turn. However, this modification could not be readily made in the AFCS hardware and therefore, was not accomplished.

8) Poor stall recovery characteristics were present in both pitch actuator modes. In series mode, the stick remains fixed following a stall condition. In parallel mode, the servo moves the stick aft to oppose the nose-down pitch rate following a stall. This problem is inherent in all stability (control) augmentation systems of this type. No attempt was made during the flight test program to incorporate system changes to alleviate this condition.

Since these undesirable characteristics of the AFCS do remain, further development would be necessary before implementing it as a production system. On the other hand, the system as it exists at the completion of the flight test program is considered suitable for development test flying of automatic terrain-following systems. This system will provide satisfactory flying qualities and the necessary reliability for low-altitude, high-speed flight.

V. Conclusions and Recommendations

Engineering knowledge and technology have been enhanced as a result of the 666A program in the areas of advanced automatic flight control system synthesis techniques, handling qualities, and flight testing. The following major program conclusions were reached:

1) Simulation and flight test results indicate that the 666A AFCS as it exists at the completion of the flight test program will provide the high performance and high degree of reliability required to accomplish the automatic terrain-following task in the YRF-4C test aircraft.

2) The 666A AFCS fixed-gain longitudinal channel performance and handling qualities satisfactorily meet the NADC and C* criteria for the low-altitude, high-speed environment.

3) The simulation studies a) significantly reduced the flight test development time, b) were instrumental in determining and defining necessary AFCS modifications to enable the AFCS to meet the specified requirements, and c) permitted pilot evaluation of all AFCS modes of operation, cockpit instruments and displays, and terrain-following performance.

4) The redundant solid-state circuitry with electronic majority-voting logic provides undegraded system performance following the occurrence of an in-flight sensor or electronic system failure.

5) The 666A integrated actuator hardware, which features failure detection and correction logic, provides high reliability for operation throughout the flight envelope.

6) The characteristics of the existing aircraft primary flight control system and power supplies should be included in the early design phase of the AFCS to minimize the mechanical and electrical incompatibility and mismatch that could produce significant system operational problems.

The following recommendations are made:

1) Failure analysis studies should be performed on automatic flight control systems operating in the LAHS environment. Adequate precautions must be taken in the system design stages to prevent situations where any one single malfunction in the aircraft power systems, the AFCS, or terrain-following radar requires immediate and/or precise action by the crew to avoid disaster.

2) Although the 666A limited-authority series servo operation is considered sufficiently reliable for LAHS operation, it is recommended that future systems, which employ full-authority series servo operation in the pitch axis, be made even more reliable. Hardover failures occurring with large authority series servos cannot be overpowered. Reliability must be very high to insure the necessary margin of safety to avoid disaster.

3) In future aircraft designs incorporating combinations of mechanical backup control systems and electronic control augmentation systems, it is recommended that the mechanical system design possess the nearly constant stick force per g characteristics desired by the pilots. Such a design will facilitate interfacing of the stability (control) augmentation system with the basic manual control system of the aircraft.