Development of the F/A-18A Automatic Carrier Landing System

J.M. Urnes* and R.K. Hess†
McDonnell Aircraft Company, St. Louis, Missouri

The F/A-18A Automatic Carrier Landing System integrates the aircraft flight control system, throttle control system, inertial navigation sensors, and shipboard SPN-42 tracking radar and computer system to achieve fully automatic approach control to the carrier deck in all weather conditions. Accurate touchdown position and sink rate must be achieved under varying conditions of visibility, deck motion, air turbulence, and ship air wake downdraft. Design analysis of this integrated digital control system is described, including digital synthesis methods used and projected performance under wind and deck motion conditions. Two shipboard trials have verified the high touchdown accuracy potential of the system, resulting in along-deck touchdown dispersion of only 19 ft for 91 automatic landings.

Introduction

THE Navy Automatic Carrier Landing System (ACLS) is an integrated control system incorporating an SPN-42 shipboard tracking radar and digital computer to measure the aircraft position and calculate pitch and bank steering commands for transmission to the aircraft via a radio data link. The aircraft flight control systems are designed to couple these commands to the aircraft autopilot and, together with an Approach Power Compensation System (APCS), provide automatic flight and thrust control to touchdown. The design goal of the ACLS is to relieve the carrier fleet pilot in landing the high-performance fighter aircraft under conditions of low-visibility weather, night visibility, deck motion due to high seas, and approach path air turbulence by providing automatic control of flight path and approach velocity. This paper describes the design criteria and analysis methods used to develop the ACLS for the latest Navy tactical fighter, the F/A-18A Hornet.

System Design Criteria

Navy specifications and past experiences in ACLS flight development were used to define design guideline criteria and anticipate possible development problem areas. Key concerns were as delineated below.

ACLS Autopilot Flight Path Response

The autopilot/autothrottle combination must have a flight path response bandwidth of at least 1.2 rad/s to achieve good glide slope control and permit commanded flight path alteration for compensation of vertical motion of the deck. Vertical path rate and position frequency response to commanded inputs should meet the AR-40 specifications.[1]

Minimum Path Errors in Turbulence

Random gusts and the carrier air wake are the largest sources of ACLS touchdown error. Control law design should minimize flight path errors due to turbulence.

Minimum Effects of Radar Tracking Noise

Control gain amplification between the tracking radar sensor and the flight control system control surface commands can cause excessive control surface activity in the presence of tracking noise.

Structural Mode Excitation

The high system gains inherent with flight coupled carrier landing systems can cause resonant aircraft surface actuator oscillations due to aircraft motion sensor output coupling with aircraft structural bending modes.

Digital Processor and Data Transmission Delays

Time delays in forward path data computation and transmission delay from either ship to aircraft or onboard feedback signals can cause low stability margins.

Control System Interaction

Subsystems used in the integrated system may interact adversely when linked together in the Automatic Carrier Landing System. An example is thrust/flight control response coupling which can decrease integrated ACLS system stability.

Flight Safety

Failure in motion sensors, data link transmission, or the SPN-42 ship radar can cause large transients before the pilot can regain control. Failure detection and command limiters must protect against excessive failure transients and automatically disengage the coupled control.

These design guideline criteria and key concerns were addressed in the integrated flight control system design, using analysis programs and development procedures tailored to determine if the required performance was achieved.

Inner Loop Design

The ACLS autopilot uses an inner loop control law configuration specifically designed with dynamic response capability to give rapid flight path response when integrated with the Inertial Navigation System (INS) vertical rate and acceleration feedback signals. Figure 1 is the block diagram of the pitch ACLS autopilot. The pitch inner loop, which uses the same components as the Control Augmentation System (CAS) primary pilot flight mode, is shown as four-channel notation. Quad redundant pitch rate sensors and actuator control are integrated with quad command limiters; the limiter values are selected to permit satisfactory ACLS control while still providing flight redundant protection in the presence of possible large signal failures from the nonredundant sensors and data link transmissions used in the ACLS.

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*Section Chief, Guidance and Control Mechanics. Member AIAA.
†Lead Engineer, Guidance and Control Mechanics.

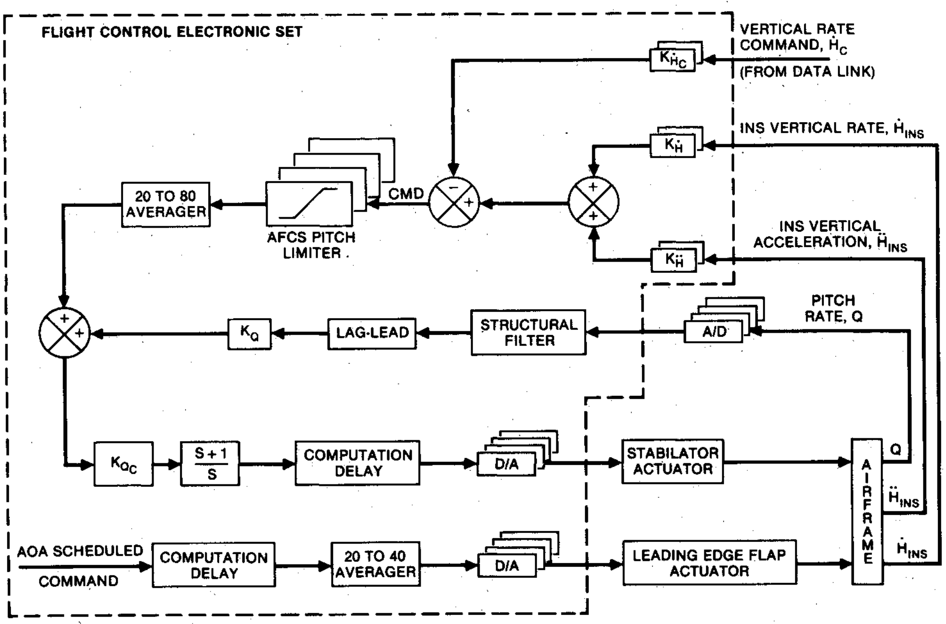

Fig. 1 F/A-18A flight computer quad redundant capabilities incorporated in ACLS flight mode design.

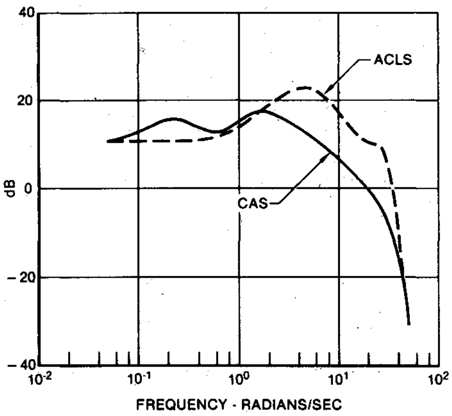

Fig. 2 Pitch rate to command frequency response of flight computer inner loop tailored to lead response during ACLS operation.

Dynamic response characteristics of pitch rate to command of the inner loop (Q/CMD in Fig. 1) is shown in the Bode frequency response in Fig. 2. The INS rate and acceleration feedback and gains are deactivated. The APCS is engaged. The ACLS mode has a higher gain amplitude in the 2-30-rad/s frequency range; this provides the necessary lead response to achieve high flight path bandpass when the INS vertical rate feedback is closed around the inner loop. Attempting to achieve this lead response using lead-lag filter compensation the command path will amplify noise present on the command signal. This noise can be traced to SPN-42 radar position tracking errors and subsequent digital sampling as the tracking signal traverses the SPN-42 computer, data link, and transmission to the command limiters. The inner loop lead effect is achieved using a lag-lead filter on the pitch rate feedback signal. A higher forward path integrator gain (a factor of 11 times the gain in CAS mode) is used in the ACLS mode to ensure a flat, low-frequency response, rapid trim in turbulent conditions, and accurate pitch rate response to the command limiter setting (3 deg/s).

The roll inner loop is similar to pitch, except that no integrator is used. Quad roll inner loop command limiters are set at 11 deg/s roll rate.

Structural Mode Interaction

Adverse interaction of the rate gyro feedbacks with structural bending modes can cause high-frequency resonant oscillations. The feedback signals from the rate gyros command surface motions which reinforce the structural bending motion at the rate gyro locations. The higher rate gains necessary for ACLS operation can result in mode excitation while the CAS primary system with its low gains is stable. Second-order filters were used in ACLS mode for both pitch and roll rate gyro feedback paths, with the break frequency set at 5.7 Hz, which will provide the same rate feedback gain as the equivalent CAS gain at the lowest structural mode frequency (9.3 Hz). This established the structural mode gain margin already flight proven in previous CAS development and provided the necessary increased low-frequency gains to achieve good ACLS control. This method thus eliminated adverse effects of the lowest frequency structural mode and all higher structural mode frequencies. The filter dynamics were then included in setting the remaining ACLS gains. No structural mode problems were encountered in the F/A-18A ACLS flight development.

Integration with the INS and Data Link Receiver

The F/A-18A avionics, like other current technology Navy aircraft, incorporates a 1553 multiplex data bus to transmit digital data between the avionics sensor and computer units. For the ACLS integration, this bus transmits command data sent from the ship and also vertical rate and acceleration signals from the Inertial Navigation System computer to the flight control computer via the AYK-14 mission computer. Significant delays occur due to this interface and computation; these delays vary from 80 to over 200 ms due to the asynchronous operation of each system component. Consequently, analysis programs having the properties to investigate effects of these delays were used in the ACLS synthesis. Figure 3 shows the pitch control interface, with the range of delays and system sample rates. These were incorporated in a sample data analysis program, together with linear definitions of the aircraft equations of motion, flight control actuators, engine dynamics, and digital control laws.

The analysis program synthesizes multiple input and multiple sample rate systems in the Z domain providing Z-plane and equivalent S-plane roots for stability assessment. Nyquist analysis techniques used in previous analog autopilot control law designs at McDonnell Aircraft Company can be directly applied using the program. This results in complete fidelity of synthesized aircraft dynamic response operating with sampled data control systems. Historically, the open loop form using Nyquist theory has been used in analog system design to set closed loop gains with no reduction in system order necessary to interpret the results. Typical ACLS pitch control system order is greater than 35. The resulting Bode response definition has become a cornerstone in the Navy ACLS specification[1] and flight certification procedures at the Naval Air Test Center. For these reasons, the digital synthesis program incorporating Nyquist analysis methods was used in F/A-18A ACLS design.

The Bode response of the ACLS mode avionics, autothrottle and flight control system should meet Navy specification[1] guideline requirements and thereby result in satisfactory response when controlled by the SPN-42 radar and ship computer. Figure 4 illustrates this specification and the computed predicted frequency response. The actual response can be precisely measured in flight using the data link to command sine waves of the desired frequency. Typical flight measured response points also shown in Fig. 4 show close correlation with the computed predicted Nyquist Bode response. It should be noted that the Vertical Rate Command ACLS system incorporated in the F/A-18A uses vertical rate response as the primary requirement.[1] Previous specifications,[2] based on pitch attitude command requirements, were superseded for the F/A-18A control law design.

Integration with the Shipboard ACLS Components

Figure 3 shows the digital characteristics of the ACLS vertical control system including the shipboard SPN-42 radar and computer components. This system was simulated using the digital analysis program and was evaluated and verified for performance in a time history analysis program containing all system actuator, aerodynamic, engine, and sensor nonlinearities. These analyses were used in conjunction with gain optimization for turbulence and deck motion to arrive at final system design gains.

The Nyquist technique has been a powerful tool in predicting not only system stability but also time response from a single plot. An additional concern using integrated digital systems is the effect of time delay. This is illustrated in assessing values of the vertical path gain K_H in Fig. 5. This Nichols plot shows both the open- and closed-loop frequency response of the vertical position change to vertical command of the tracking radar beacon point on the aircraft ($H_{BEACON}/H_{COMMAND}$). All digital interface time delays and encoder sample rates are included. Effects of both the best and worst time delays described in Fig. 3 are shown in Fig. 5. Using an equivalent second-order approach, the time constant and damping can be estimated from the closed-loop frequency response 90 deg phase locus. Variations in stability and time response due to different values of the gain K_H or digital time delays thus can be directly evaluated.

Figure 6 illustrates the computed and flight vertical path frequency response including the effects of average interface

Table 1 ACLS gain optimization process.

K_H	$K_{\dot{H}}a$	$K_{\ddot{H}}$	rms H_{BEACON}/W_{GUST}, ft	Improvement, %	Denominator roots and damping, ω_N/ζ	
0.6	1.0	0.25	0.55	–	1.74/0.27	2.67/0.33
0.66	1.0	0.25	0.55	−0.3	1.73/0.23	2.70/0.33
0.54	1.0	0.25	0.55	−0.1	1.75/0.31	2.65/0.34
0.6	1.1	0.25	0.47	14[a]	1.94/0.33	2.5/0.30
0.6	1.1	0.275	0.46	2.6	1.84/0.37	2.6/0.26
0.6	1.21	0.275	0.40	14[a]	1.98/0.46	2.55/0.19
0.6	0.99	0.275	0.54	−18	1.67/0.30	2.74/0.30
0.6	1.1	0.3025	0.45	2.3	1.75/0.40	2.71/0.24
0.6	1.1	0.333	0.44	1.9	1.67/0.43	2.81/0.22
0.6	1.1	0.366	0.435	1.6	1.60/0.45	2.9/0.1998
0.6	1.1	0.30	0.45	−2	1.76/0.40	2.7/0.24

[a] Vertical rate feedback gain $K_{\dot{H}}$ is the major factor for minimizing vertical glide path error of the F/A-18A in turbulence.

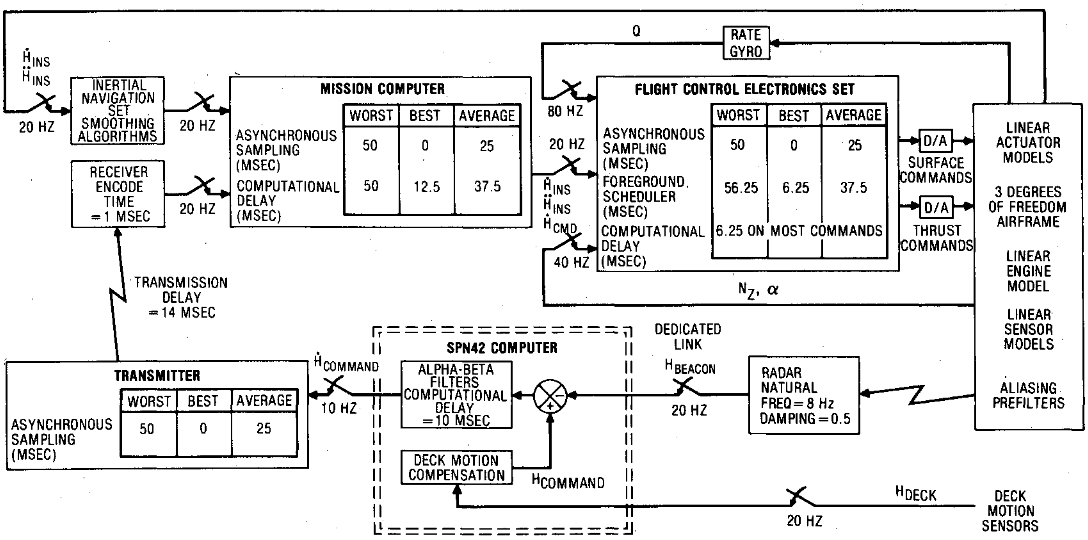

Fig. 3 Variable time delays inherent in the F/A-18 ACLS are synthesized in a digital analysis program.

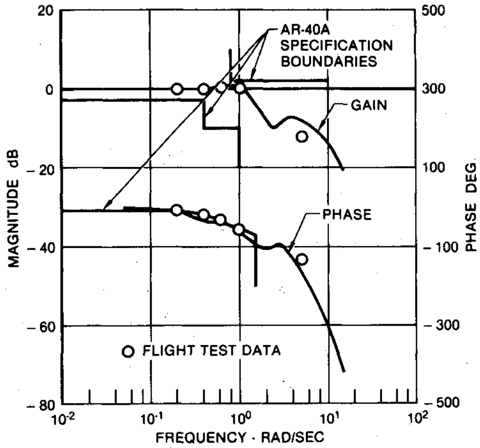

Fig. 4 Frequency response of vertical rate to vertical rate command ($\dot{H}/\dot{H}_{COMMAND}$). Comparison of simulated and flight measured F/A-18A ACLS autopilot response.

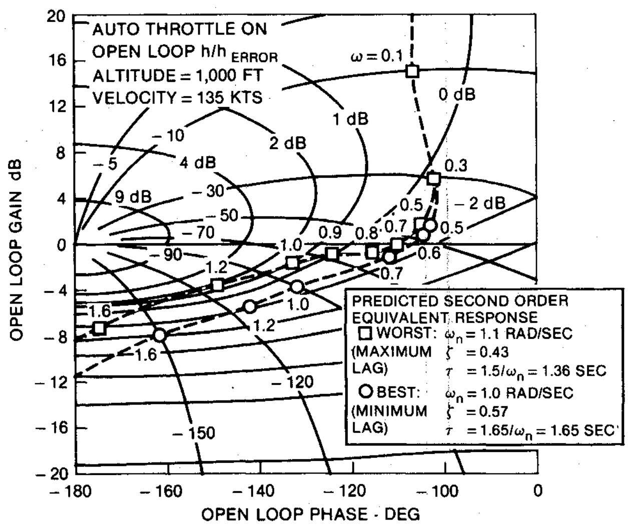

Fig. 5 Nyquist analysis techniques used to investigate vertical position to vertical position error response with effects of digital system transmission time lag delays.

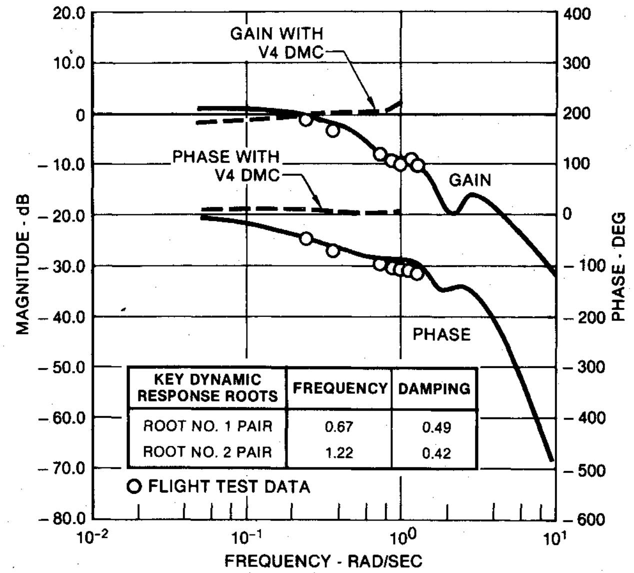

Fig. 6 Frequency response of vertical path position change to vertical path command (H_{BEACON}/H_{DECK}), with and without Deck Motion Compensation.

time delays shown in Fig. 3. The solid line plots shown in Fig. 6 represent the gain and phase vertical position change to a commanded change at a given frequency. The circles represent flight data points measured in flight test sine wave command tests. The dashed lines are the vertical position frequency response with compensation for deck motion inserted in the command path. This compensation will be further discussed in a later section.

Integration with the Approach Power Compensation System

The F/A-18A Approach Power Compensation System automatically controls thrust to maintain a reference angle of attack during the carrier approach, thus effectively controlling the proper approach velocity. The autothrottle can be used independently of ACLS. Different gain values are used for the manual and ACLS modes.

The APCS contains feedback gains from normal accelerometer, pitch rate, stabilizer position and bank angle in addition to angle of attack error. The manual mode pitch rate gain is 2.7 times higher than the ACLS mode; this provides fast throttle response to pilot stick commands. Use of this higher gain with ACLS results in a 50% degradation in the flight path mode damping, which could be alleviated by reducing autopilot vertical rate gain at the expense of path holding in turbulence. However, for the final design, pilot opinion for good approach path control resulted in a configuration with different gains for the ACLS and manual modes of APCS. Selecting optimum APCS gains for ACLS performance objectives provides the best integrated system response and should not be compromised.

Control Law Design for Minimizing Path Errors in Turbulence

A gain search technique developed during analysis of the F-4J aircraft[2] was used to analyze the effects of turbulence on ACLS flight path control for the F/A-18A. A power spectral density (psd) definition of the turbulence was used to drive a frequency domain representation of the F/A-18A airframe, autopilot, autothrottle, and SPN-42 control equations including equivalent digital transport delays, asynchronous sampling delays, computational delays, and zero-order hold delays. For determining path following performance in turbulence, the desired transfer function is vertical displacement path error output to vertical turbulence input. The normalized psd and rms of this desired parameter are calculated for different gain configurations until an optimum solution is reached. An example of this process for the optimum glide path in turbulence is shown in Table 1. K_H represents the glide path position error gain; $K_{\dot{H}}$ and $K_{\ddot{H}}$ the vertical rate and acceleration feedback gains from the aircraft INS. Each system gain is varied $\pm 10\%$; if the path error is reduced at least 0.5% and the system damping remains above a required level, the revised gain is held, then tested again on the next pass. It should be noted from Table 1 that the vertical rate feedback gain $K_{\dot{H}}$ is much more significant in reduction of vertical glide path error than either the path position or acceleration gains, giving a 14% reduction for the 10% gain increase. The inner loop pitch rate gain K_Q was not permitted to vary in this process because of the possibility of introducing adverse interaction with the aircraft structural bending modes, as previously discussed. Increasing K_Q could increase system damping so as to permit further increases in $K_{\dot{H}}$ and $K_{\ddot{H}}$; however, it may not be possible to implement the resulting configuration due to the structural properties of the aircraft. Table 1 also illustrates the effects of the turbulence gain optimization process on system damping. Final ACLS design gains were selected using a combination of the turbulence optimization process and Nyquist stability theory accounting for the digital delay effects.

In addition to random turbulence, the carrier-based aircraft is required to fly through the ship's air wake (burble), consisting of a downdraft combined with a decrease in airspeed just behind the carrier fantail. Response for the F/A-18A in the burble was simulated and compared with a simulated F-4J fleet system which does not incorporate the turbulence-minimizing vertical rate feedback. The results are presented in Fig. 7. The F/A-18A remains closer to the commanded glide path than the F-4J and recovers from the burble more quickly. Power is applied by the APCS as the aircraft transverses the ship burble, and is then reduced in the case of the F/A-18A while the power is further increased for the F-4J attitude command flight control system. This is because the F-4J is much further below the commanded glide slope and thus continues to receive large nose-up commands, with the consequent power on commands. In the case shown, the F-4 touches down about 100 ft short; the F/A-18 about 8 ft long. This illustrates the significance of using vertical path rate feedback in ACLS glide path control design.

Response in random turbulence was evaluated with simulation and monitored during flight test. During the course of ACLS land-based flight testing, several periods of heavy to severe turbulence were encountered during ACLS approaches flown at the Naval Air Test Center, Patuxent

Table 2 Phase of deck at commencement of simulated ACLS Deck Motion Compensation

Simulated flight condition	Longitudinal touchdown, ft	Sink rate, ft/s
± 4 ft heave, $\omega = 0.6$ rad/s		
Phase = 0 deg	3.0 short	11.0
Phase = 90.0 deg	18.6 short	11.3
Phase = 180.0 deg	0	10.3
Phase = 270.0 deg	1.7 short	10.8

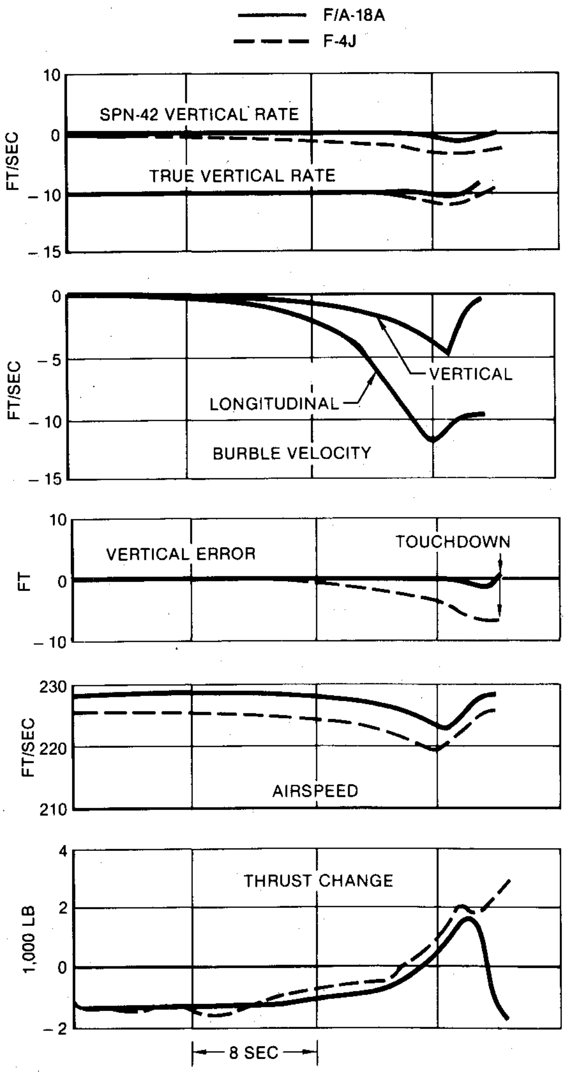

Fig. 7 F/A-18A ACLS response due to ship burble compared with the fleet F-4J response.

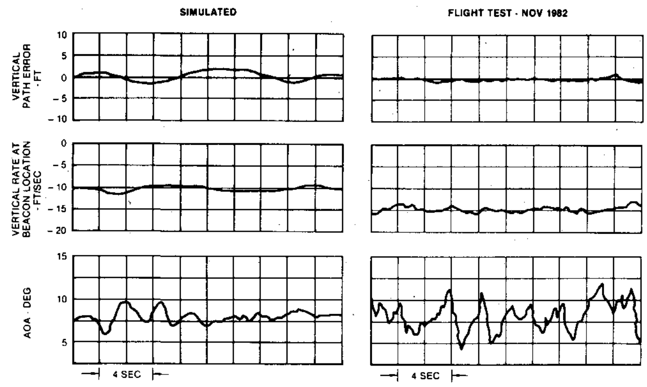

Fig. 8 F/A-18A ACLS glide path errors due to turbulence. Simulated vs flight measured response.

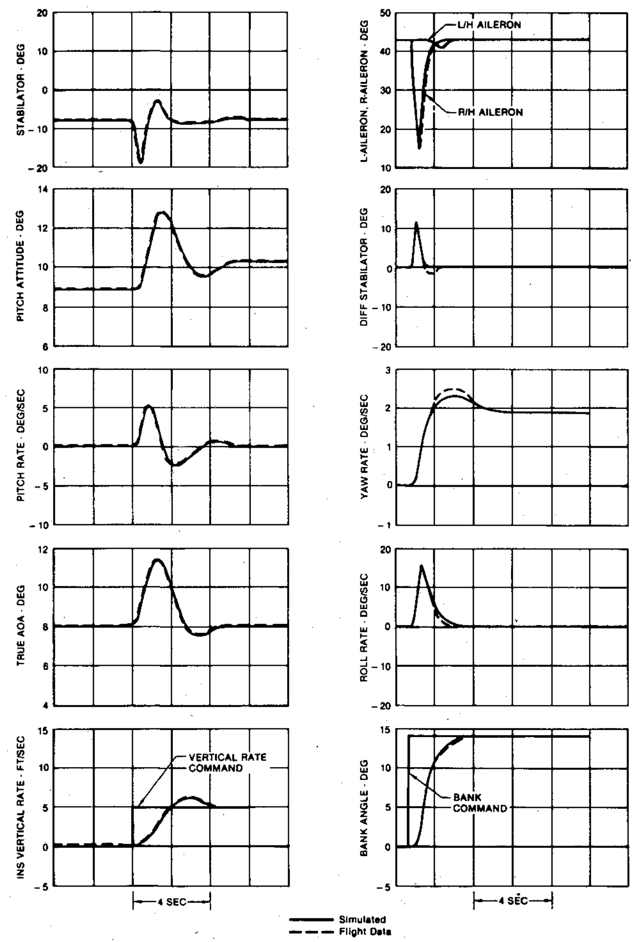

Fig. 9 F/A-18A ACLS flight measured step response to open-loop data link step commands compared with simulated predicted design response.

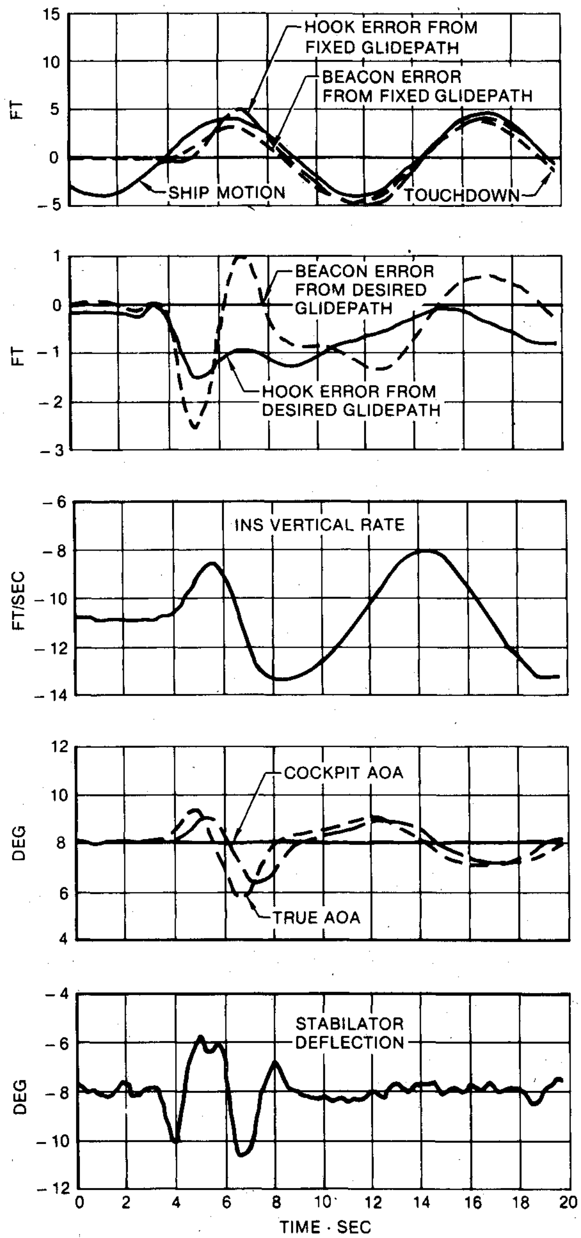

Fig. 10 F/A-18A simulated Deck Motion Compensation.

River, Md. A comparison between the analytical response of the aircraft in simulated turbulence flight and actual response in severe turbulence is shown in Fig. 8. Even in the severe turbulence, the standard deviation from the glide path was less than 1 ft.

Initial Flight Testing at NATC

The performance of the F/A-18A during ACLS control was verified during flight test evaluation at the Naval Air Test Center (NATC), Patuxent River, Md. The flight tests were designed first to measure the dynamic response of the aircraft systems, followed by similar tests with the entire integrated ACLS system active using a SPN-42 radar located at the test center. Hardover pitch and bank data link commands were used to test system limiters. Predicted response from simulation was used to verify flight measured response.

Both frequency response and step response tests were used to check the aircraft systems response (open loop ACLS response). Figure 4 shows the resultant frequency response comparison. A comparison of the simulated and flight test step responses to 5-ft/s vertical rate commands and 14-deg bank commands are shown in Fig. 9. Close agreement between these simulated and flight test results is noted. This comparison was made at NATC observing telemetry data, resulting in a go-ahead to engage the Approach Power Compensation System and the autopilot for an automatic approach to touchdown on the very first ACLS test flight (Jan. 8, 1982).

Automatic Landing on a Heaving Carrier Deck

The aircraft must arrive at the touchdown point with the proper sink speed and position in space to closely match the position and vertical motion of the carrier deck touchdown zone. There are usually four arresting cables, spaced evenly across the touchdown zone. Ideally, the aircraft hook should impact the deck midway between No. 2 and No. 3 arresting cables with a sink speed of 10-14 ft/s. The carrier deck may be pitching, heaving, and rolling; the ACLS is designed to command the aircraft to follow the heaving motion to minimize along-deck touchdown errors and prevent excessive landing gear loads due to high sink rate. This path matching control must be achieved over the 10-13-s time interval prior to touchdown. If large corrections were to be commanded immediately prior to touchdown, excessive aircraft attitude and sink rate changes might occur, resulting in possible structural damage to the aircraft at touchdown.

In order to correct the aircraft flight path for the deck heaving motion, a Deck Motion Compensation (DMC) control law is incorporated in the SPN-42 shipboard computer, located as shown in Fig. 3. The DMC provides an additional altitude command to the vertical error measured by the stabilized SPN-42 radar. This additional command, in effect, predicts the future path of the deck in the form to account for the inherent altitude control lag of the combined closed-loop aircraft/APCS/SPN-42 system. The DMC utilizes lead compensation added to the deck position measurement sensors to achieve this objective. The combined aircraft/APCS/SPN-42 system vertical position dynamic lag can be measured in the frequency domain for the closed-loop frequency response of aircraft vertical position to vertical position command (or $H_{\mathrm{BEACON}}/H_{\mathrm{COMMAND}}$ in Fig. 3); this is shown as the solid line plot in Fig. 6. Carrier deck motion frequencies are typically between 0.2 and 0.8 rad/s. DMC lead control is added between the deck motion sensors and the vertical position command ($H_{\mathrm{COMMAND}}/H_{\mathrm{DECK}}$) to cause the frequency response of aircraft vertical position to deck vertical position to maintain nearly unity gain and minimum phase over the range of deck motion frequencies. The frequency response with the DMC correction is also shown as the dashed line plot in Fig. 6; this is the response of $H_{\mathrm{BEACON}}/H_{\mathrm{DECK}}$ (see Fig. 3).

The DMC control law was derived by the Carrier Suitability Branch at the Naval Air Test Center using flight measured frequency response data. This was measured using sinusoidal vertical position commanded changes inserted in the SPN-42 system located at NATC. Data points from the flight measurement are shown in Fig. 6, which can be compared with the simulated theoretical response. Use of the DMC succeeds in placing the frequency response of commanded vertical position close to unity gain and zero phase between the frequencies of 0.1 and 0.8 rad/s.

The aircraft is commanded to a stabilized glide slope until reaching a range that is about 13 s from touchdown. At this point, the ACLS transitions to the deck motion compensation mode, and a rapid path correction is required to achieve the steady-state path matching to the deck motion prior to touchdown. This transition can be seen in the simulated time history response of an F/A-18A ACLS approach to an aircraft carrier with a moving deck (deck frequency = 0.6 rad/s, ±4 ft deck amplitude) shown in Fig. 10. During the final 13 s, the aircraft follows the stabilized fixed glide path plus the deck motion, moving to be in phase with the deck motion within one cycle. A table of simulated touchdown points for ACLS approaches with deck motion is given in Table 2. The phase of the deck motion was varied by 90 deg for each

Table 3 F/A-18A USS Eisenhower ACLS test results

Wind-over-deck magnitude, knots	Relative wind direction, deg <347	347-353	354-000	>000
>30	No data	$N^a=4$ $X_H{}^b=35.9$ $X_M{}^e=13.8$	$N=5$ $X_H=13.7$ $X_M=-9.8$	$N=2$ $X_H=7.1$ $X_M=-6.2$
24-30	$N=8$ $X_H=30.1$ $X_M=17.3$	(Nominal) $N=11$ $X_H=23.0$ $X_M=12.6$	(I)[c] $N=10$ $X_H=20.8$ $X_M=-5.4$	No data
<24	$N=2$ $X_H=15.6$ $X_M=1.3$	(II)[d] $N=5$ $X_H=19.4$ $X_M=-17.7$	$N=8$ $X_H=25.8$ $X_M=-9.1$	$N=2$ $X_H=0.4$ $X_M=11.3$

[a] N = Number of samples.
[b] X_H = Standard deviation of longitudinal hook touchdown position (calculated for hook-up touch-and-go) relative to ideal value.
[c] I – Probable condition with ship making its own wind.
[d] II – Probable condition with low wind-over-deck recovery.
[e] X_M = Mean value of hook touchdown position; positive for aircraft beyond ideal touchdown point.

successive approach. All of the touchdowns are close to the desired point. Note also the small variation in touchdown sink rate for the four deck conditions shown in Table 2.

ACLS Shipboard Trials

During the ACLS evaluation on the USS Eisenhower in January 1983, approaches were flown in a variety of wind conditions and ship speeds to evaluate the F/A-18A ACLS performance thoroughly. A matrix of wind direction and speed together with touchdown results is shown in Table 3. Overall results indicated a mean touchdown approximately 6.3 ft beyond the target touchdown with a standard deviation of 22 ft. The standard deviation remained constant for landing with measurable deck motion. Nine approaches were flown with 3-7 ft peak-to-peak deck motion during the Deck Motion Compensation portion of the approach. For these nine passes, the mean was 2.9 ft short of the target with a standard deviation of only 21.8 ft. For comparison, the F-4 fleet configuration ACLS has a standard deviation of slightly less than 40 ft.

A second sea trial ACLS evaluation was conducted in March 1984 on the USS Constellation. Deck motion as large as 7 ft was present. The along-deck touchdown mean value was measured at 10 ft beyond the target touchdown point; for these 28 landings, the standard deviation was only 14.2 ft.

Flight Safety

The F/A-18A uses quad redundant pitch and bank command limiters to protect the aircraft against large transients should failures occur in nonredundant INS, data link, or shipboard SPN-42 system components. These limiters allow a maximum of 3 deg/s of pitch rate and 11 deg/s of roll rate in response to hardover commands. This allows the pilot time to recognize abnormal response and regain manual control. Monitors will disengage the entire autopilot if the angle of attack exceeds 14 deg or is less than −6 deg, or if the bank angle exceeds 70 deg. Detected failures in subsystem INS, data link, or shipboard systems will automatically disengage the autopilot. Exceeding coupled control path error boundaries measured by the SPN-42 radar will cause an automatic downgrade to manual control. At any time the pilot can regain manual control by applying either 5 lb pitch stick force or 3½ lb lateral stick force. He also can regain manual control by depressing a switch located on the control stick.

Results

1) For the F/A-18A Automatic Carrier Landing System, both the flight control inner loop and autothrottle subsystem were configured with optimized control gains different from those gains considered optimum for manual flight approaches.

2) Time delays as large as 250 ms can occur due to the nonsynchronous architecture of linking the ACLS avionics components with the 1553 multiplex bus. Use of Z transform analysis techniques adapted to conventional Nyquist criteria accurately synthesized the integrated characteristics of the system, and provided the design method for analytic determination of the ACLS flight and throttle control laws.

3) Air turbulence is the dominant source of glide path and touchdown errors in ACLS control. Excellent path holding capability was achieved by incorporating high gain vertical path rate feedback.

4) Adverse effects of the SPN-42 radar tracking noise were minimized by avoiding inner loop lead-lag filters in the forward command path.

5) Inner loop pitch rate control was designed to provide significant lead response in order to minimize the time constant of the total system flight path response with the autopilot INS vertical rate feedback active.

6) Roll-off filters on rate gyro feedback signals were included to preclude structural mode coupling through the ACLS flight control system.

7) Quad redundant command limiters have been incorporated in the flight computer to minimize the transient due to failure of nonredundant system components and thereby permit safe takeover by the pilot.

8) Deck Motion Compensation design utilizing Nyquist frequency response techniques accurately compensates for the dynamic response lag inherent in altitude command control systems.

9) Along-deck touchdown dispersions are less than half of any previous Navy ACLS fighter, measuring 19.7 ft standard deviation for two carrier trials.

On June 19, 1984, the Naval Air Systems Command granted fleet certification of the F/A-18A ACLS, thus permitting operational use as the first Hornet carrier squadron deploys at sea.

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