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H-Dot Automatic Carrier Landing System for Approach Control in Turbulence

J. M. Urnes,* R. K. Hess,† and R. F. Moomaw‡
McDonnell Aircraft Company, St. Louis, Mo.
and
R. W. Huff§
Naval Air Test Center, Patuxent River, Md.

The Automatic Carrier Landing System (ACLS) provides a fully automatic approach and landing capability for high-performance carrier-based fighter aircraft. Approach path air turbulence produces significant touchdown error. Using power spectral density definitions of turbulence, a method to determine flight-path deviation due to turbulence and effects of changing system control laws to reduce dispersions and improve ACLS performance is presented. This technique, as applied to an F-4J ACLS fleet configuration, results in significant improvement using a vertical rate (H-Dot) reference in the autopilot control law. The F-4J H-Dot avionics mechanization was implemented and flight test results are discussed.

Introduction

THE Automatic Carrier Landing System (ACLS) incorporates the SPN-42 shipboard radar and computer and a data link to the aircraft autopilot for fully automatic approach and landings of high-performance carrier-based fighter aircraft.[1] The ACLS uses a shipboard computer to compute pitch and bank commands from space position and ship motion data, which are transmitted back to the aircraft via a radio frequency data link. A high-gain attitude-referenced autopilot is used to steer the aircraft in response to data link commands. An autothrottle (approach power compensation system) is also required, and is a separate system not interfaced with the autopilot or data link commands.

A large source of touchdown error is the turbulent air environment found in the approach path. The random turbulence components cause the aircraft to move off course vertically. This is shown in Fig. 1, which is an F-4J ACLS flight response in turbulent air with the present fleet flight control configuration. Another effect unique to the carrier approach is the wind pattern found immediately behind the carrier fantail, which usually, but not always, consists of a downdraft and associated decrease in airspeed. This effect, termed the ship burble, varies between ships and is also dependent on the wind-over-deck angle. Figure 2 shows simulated flight response through a burble, which causes a 6 ft drop below the glideslope and consequent touchdown 125 ft short of the ideal touchdown point. As shown in Fig. 3, there is not much margin for error on a carrier landing zone; the four arrestment cables are about 32 ft apart. The current SPN-42 counteracts the burble by adding a nose-up pitch command at the final portion of the approach. This command is tailored to the ship, and will effectively counteract the burble shown in Fig. 2. This open-loop command, however, will cause overshoot of the arrestment cables (or bolter) if the ship burble is not present or has a shape different than the compensated design.

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*Unit Chief, Guidance & Control Mechanics. Member AIAA.
†Lead Engineer, Guidance & Control Mechanics. Member AIAA.
‡Senior Engineer, Guidance & Control Mechanics.
§Head, Landing Aids, Section B.

Gain Optimization Design Method

To analyze the effects of turbulence on ACLS flight-path control and to design improved control laws, an optimization technique was developed using power spectral density (PSD) definitions of the turbulence and resulting flight-path errors. A computer program of the F-4J airframe, autopilot, autothrottle, and SPN-42 control equations was created using a Laplace matrix equation format, and then the PSD and root mean square (rms) of the path deviation were calculated. Cramer's rule[2] is used to define a numerator and denominator matrix for a desired transfer function. For determining path following in turbulence, the desired transfer function is vertical displacement vs vertical turbulence. The computer program solves for the determinant polynomials of the denominator and numerator matrices. These polynomials are factored and the damping ratios and natural frequencies of the complex roots are calculated. The normalized PSD of the desired parameter is calculated by multiplying the gusts spectra by the airframe/autopilot/SPN-42 transfer function response to gusts. An example of this for vertical gusts is

$$\Phi_H(\omega) = \left| \frac{H(j\omega)}{W_g(j\omega)} \right|^2 \Phi_{W_g}(\omega) \qquad \frac{\text{ft}^2}{\text{rad/s}} \qquad \text{(PSD of vertical displacement)}$$

where Φ is power spectral density, W_g is vertical gust velocity, ω is frequency in rad/s, H is vertical displacement in feet, and $H(j\omega)/W_g(j\omega)$ is the airframe/autopilot/SPN-42 transfer function response to gust.

Both the ACLS system specification (AR-40A)[1] and MIL-8785B[3] definition of turbulence were used. For example, the vertical turbulence PSD is defined as:

$$\Phi_{W_g}(\omega) = \frac{716}{(11.22)V_0}\left[\frac{1}{1+(100\omega/V_0)^2}\right] \qquad \text{AR-40A}$$

$$\Phi_{W_g}(\omega) = \frac{375}{\pi V_0}\left[\frac{1+3(375\omega/V_0)^2}{[1+(375\omega/V_0)^2]^2}\right] \qquad \text{MIL-8785B}$$

where V_0 is the trim velocity.

Because Φ_H is normalized, the net rms of vertical displacement is calculated by integrating the PSD

$$\sigma_H^2 = \sigma_{W_g}^2 \int_0^\infty \Phi_H(\omega)\,\mathrm{d}\omega \quad \text{ft}^2 \qquad \text{(square of rms of vertical displacement)}$$

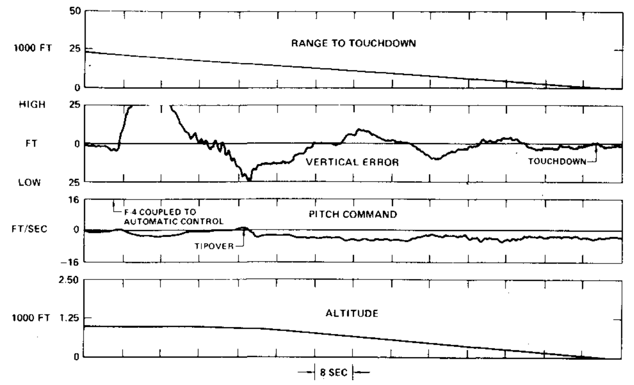


Fig. 1 F-4J ACLS flight test approach in turbulent air (turbulent day).

The actual PSD can be obtained by multiplying the normalized PSD by the square of the gust rms. The actual rms is determined by multiplying the normalized rms by the value of the gust rms. (A 3.35 ft/s rms of turbulence was used for this study.) The PSD definition of the gust spectra may also be used to generate a time-history simulation of the turbulence, which is then used in a time-history simulation of the ACLS/airframe to evaluate proposed changes to the system.

An optimization process was then applied to the present and alternate F-4J ACLS and autothrottle control laws. Each configuration was optimized by successively changing selected system gains by a value of ±10%, and recalculating the new rms value. If the rms is reduced at least by a required amount (usually a minimum of 0.5%), the corresponding gain is updated and held until the remaining gains have been tested. At the same time, damping of all the roots of the closed-loop characteristic equation is computed and must remain greater than a specified level (0.35 in lateral, 0.30 in pitch). Failure to pass either the damping or improvement test results in the gain being fixed for the remainder of the run. The process is repeated until all of the selected gains are held constant. A typical run is shown in Table 1. This example is optimizing the SPN-42 gains and F-4J autothrottle gains; the autopilot configuration is being maintained in its baseline form (pitch-attitude command). The net rms of vertical deviation at the pilot's station was reduced from 4.32 to 1.44 ft rms of vertical turbulence (AR-40A definition). This improvement is due to reducing the autothrottle angle-of-attack gain K_α and increasing the autothrottle normal acceleration gain K_{n_z}, permitting the SPN-42 proportional and rate (first derivative) gains to be increased.

System Design Results Using Optimization Method

Table 2 shows the results of the optimization process applied to several candidate F-4J control law configurations.[4] A 3.35 ft/s rms vertical gust definition was used. The MIL-8785 gust definition gave similar results. Optimizing the SPN-42 shipboard computer gains (configuration 1) resulted in small improvement, indicating that the present F-4J ACLS has already been tuned to maximum performance in turbulence. Revision of the autothrottle gains (configuration 2) provides improvement, but is subject to pilot acceptability of throttle motion. The most significant improvement is realized by changing the autopilot control law from pitch attitude command to vertical rate command, giving a decrease of rms touchdown error from 70 ft to only 12 ft. The vertical rate, or H-Dot, control law also greatly decreases the flight-path errors due to the ship burble, as shown in the time-history simulated response in Fig. 4. This approach resulted in a touchdown error of only 16 ft long, which is a significant improvement over the 125 ft short using the present F-4J ACLS without SPN-42 open-loop compensation (Fig. 2). This H-Dot configuration was selected for flight test evaluation.

Another potentially large source of touchdown error is the motion of the ship's flight deck. To minimize deviations in both longitudinal touchdown error and the effect of touchdown sinking speed with respect to the flight deck, the landing system must be capable of accurately driving the aircraft to follow the vertical motion of the touchdown point during the final portion of the approach. To accomplish this, the motion of the deck is calculated in the SPN-42 computer, and a deck motion compensation (DMC)[1] is used to filter the calculated deck position to provide the proper shaping to bring the vertical motion of the aircraft flight path in phase with the deck motion. This mode, termed "deck chasing," is activated during the final half-mile of the approach. This requirement means that the ACLS closed-loop altitude response must have a wide bandpass; the desired frequency response shall have less than 100 deg phase lag at 1 rad/s to permit deck motion compensation with the DMC filter. This requirement also had to be included in the gain optimization process.

The results of the PSD control law optimization process appeared very promising; however, three key questions

Table 1 Optimization process—F-4J autothrottle and shipboard SPN-42 computer gains

		SPN-42 gains				Autothrottle gains				
Pass	Rms of vertical displacement at pilot station	R, first derivative (gain 1)	A, second derivative (gain 2)	I, integral (gain 3)	P, proportional (gain 4)	K_{n_z} (gain 5)	K_δ (gain 6)	$K_{\alpha i}$ (gain 7)	K_α (gain 8)	$K_{\Delta\alpha}$ (gain 9)
Initial	4.321	1.18	1.00	0.0666	1.00	−60.0	−1.25	0.660	3.96	1.50
1	3.886	1.30	1.10	0.0599	1.10	−66.0	−1.25	0.594	3.56	1.50
2	3.551	1.43	1.21	0.0539	1.21	−72.6	−1.25	0.535	3.21	1.50
3	3.223	1.57	1.33	0.0480	1.33	−80.0	−1.25	0.480	2.89	1.50
4	2.931	1.73	1.46[b]	0.0432	1.46	−88.0	−1.25	0.432	2.60	1.50
5	2.673	1.90	1.46	0.0389[a]	1.61	−96.8	−1.25	0.389	2.34	1.50
6	2.442	2.09	1.46	0.0389	1.77	−106.0	−1.25	0.350	2.11	1.50
7	2.224	2.30[b]	1.46	0.0389	1.94	−117.0	−1.25	0.315	1.90	1.50
8	2.074	2.30	1.46	0.0389	2.14	−129.0	−1.25	0.284	1.71	1.50
9	1.930	2.30	1.46	0.0389	2.36	−142.0	−1.25	0.255	1.54	1.50
10	1.789	2.30	1.46	0.0389	2.60	−156.0	−1.25	0.230	1.39	1.50
11	1.652	2.30	1.46	0.0389	2.86	−171.0	−1.25	0.207	1.25	1.50
12	1.524	2.30	1.46	0.0389	3.14	−188.0[a]	−1.25	0.176	1.12[b]	1.50
13	1.437	2.30	1.46	0.0389	3.45	−188.0	−1.25	0.167	1.12	1.50

[a] Failed to improve rms more than 0.5%. [b] Damping becoming unacceptable.

Table 2 Results of optimizing F-4J ACLS control laws

Configuration	Autothrottle control law, n_z	Autopilot control law	Gains optimized	Rms vertical displacement at pilot's station (3.35 ft/s gusts), ft	Rms along deck touchdown dispersion (3.35 ft/s gusts), ft
Present	AOA	Pitch attitude	–	4.32	70
1	AOA	Pitch attitude	SPN-42	3.85	64
2	AOA	Pitch attitude	SPN-42 autothrottle	1.44	23.5
3	AOA	Vertical rate	SPN-42 autopilot	0.74	12
4	AOA	Vertical acceleration and pitch attitude	SPN-42 autopilot	1.52	25

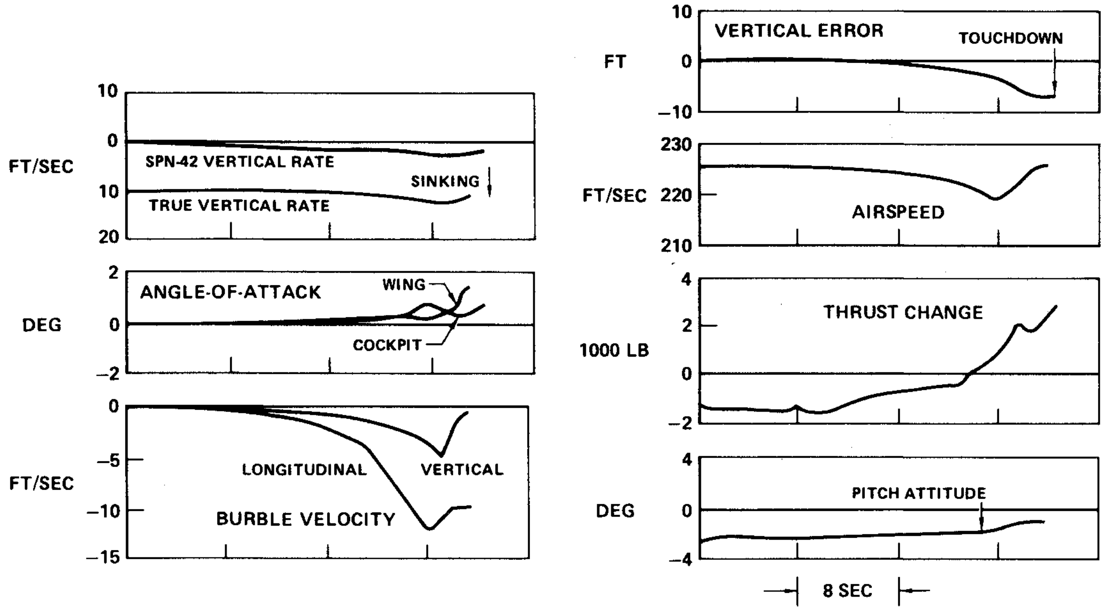


Fig. 2 F-4J simulated approach through the ship burble.

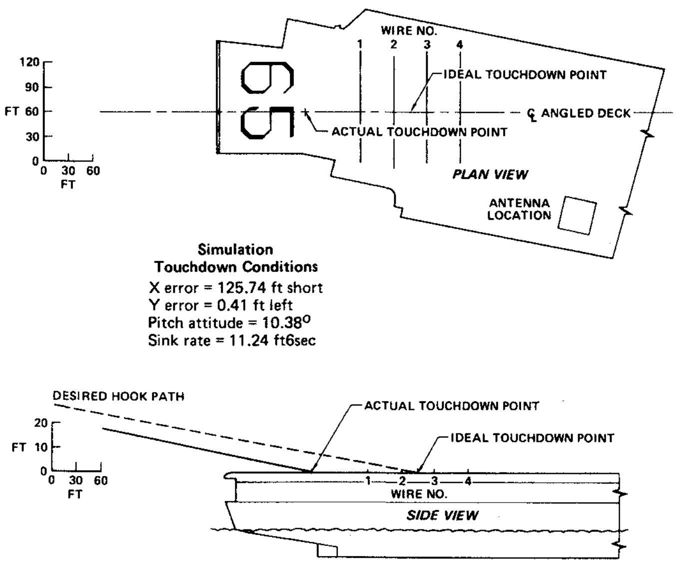


Fig. 3 Carrier deck landing zone geometry and F-4J simulated approach through ship burble if no SPN-42 open-loop compensation is used.

remained to be answered:

1) Do the PSD turbulence definitions accurately predict the true environment?

2) Does the airframe/flight control system/autothrottle in turbulence and the H-Dot solution in the true environment function as effectively as the simulation?

3) Can an H-Dot feedback be mechanized in the hardware which would have satisfactory dynamic response with minimum lag and good noise characteristics for the high gains necessary for ACLS?

To obtain answers to these questions, the next phase of avionics modification and flight test of the H-Dot ACLS commenced.

Hardware Implementation and Flight Tests

Implementing the H-Dot control law in the F-4J (Ref. 5) was initially accomplished using the ASN-70A vertical reference set, which presently has an interface with the autopilot coupler for another F-4 flight mode. The gain was increased and an acceleration feedback path added in the ASN-70A unit for possible use during the flight test program. The ASN-70A vertical rate ($\dot{h}$) signal is derived from baro altitude and vertical acceleration. The autopilot coupler was modified to accept commands from the ASN-70A during

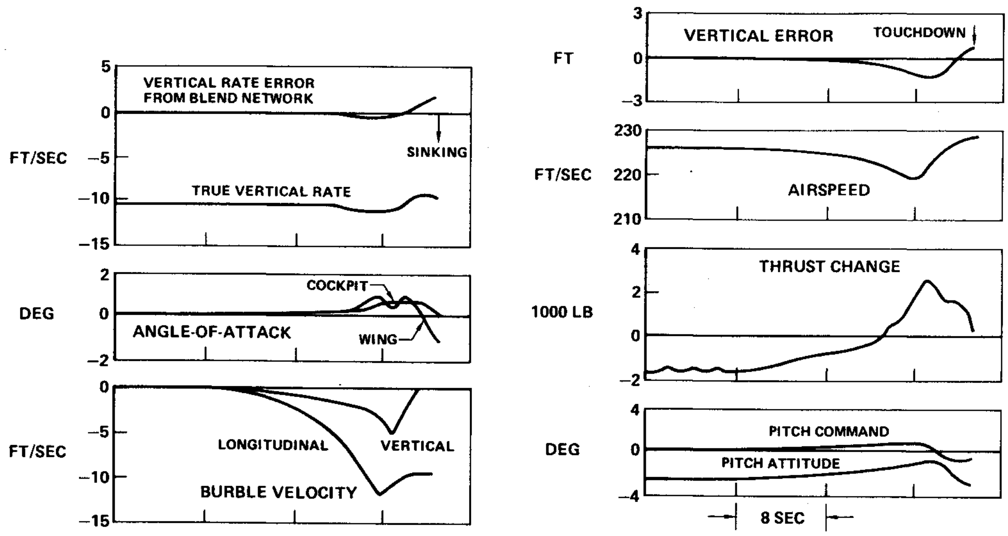


Fig. 4 F-4J ACLS simulated approach through the ship burble using the initial H-Dot control law modification.

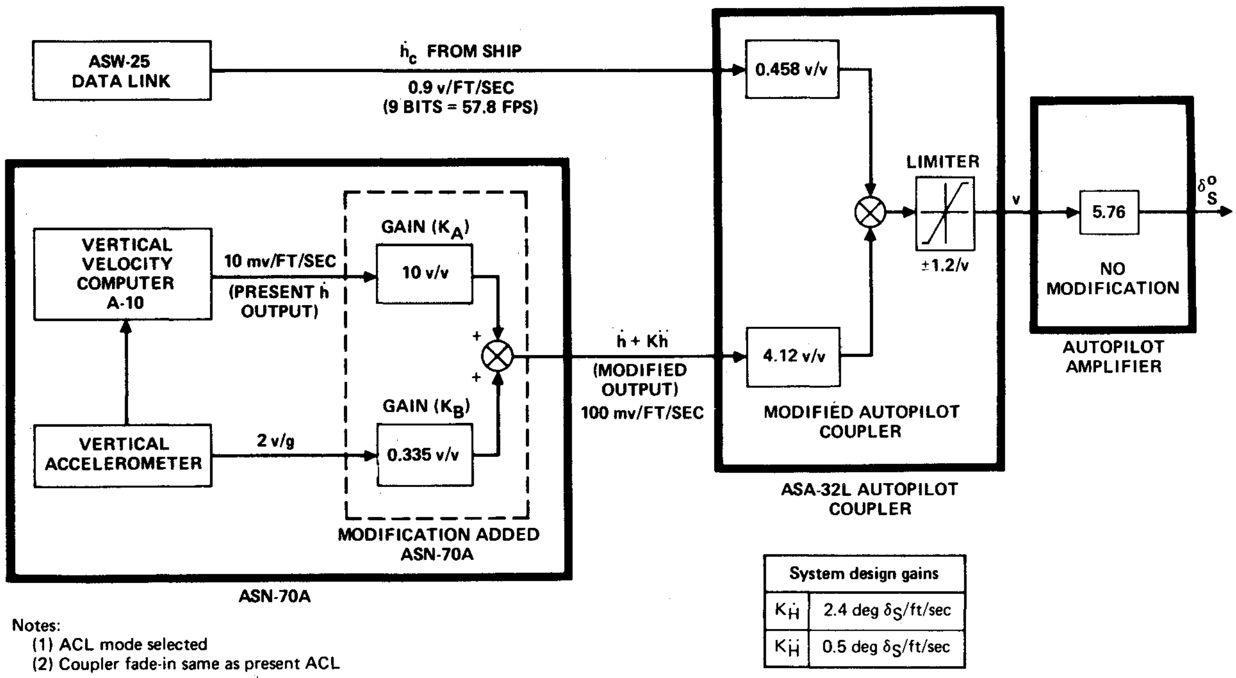


Fig. 5 F-4J H-Dot ACLS avionics modification initial configuration.

ACLS operation. Figure 5 shows the H-Dot hardware modifications. This system was flown in an F-4J test aircraft, and resulted in significant improvement. Figure 6 is the flight response under turbulent conditions and was flown in the same test period as the response in Fig. 1. Vertical error is greatly reduced throughout the approach. However, the pitch rate and stabilator response exhibited oscillations during the glide slope portion of the approach. This was traced to the barometric altitude signal used to derive the vertical rate, which could not smoothly follow the decreasing altitude and exhibited small step changes in altitude. Even though this signal is smoothed by the vertical accelerometer in the H-Dot derivation in the ASN-70 computer, command errors to the stabilator were generated due to the very high gains necessary for ACLS control.

A second H-Dot mechanization was then implemented,[6] which used no barometric altitude but instead derived vertical rate from the SPN-42 measured vertical error and the onboard vertical accelerometer. This configuration uses a blending network in the autopilot coupler and is shown in Fig. 7. The configuration does not require an Inertial Navigation System (INS) vertical rate signal, and can be implemented on any Navy aircraft equipped with an accelerometer sensor. This H-Dot control law incorporates proportional, rate, and acceleration gains; the gain optimization process was again used, with results shown in Table 3. Initial gain values were selected to provide stable closed-loop control. The optimization process increases the $K_{\dot{H}}$ and $K_{\ddot{H}}$ gains before the damping criteria stops the run. The K_H gain is decreased by the optimization process. However, when this gain configuration was evaluated for the deck-chasing DMC requirement, the phase lag was excessive and did not meet the 100 deg max. at 1 rad/s. Consequently, the K_H gain was increased to satisfy the DMC requirement with only a small increase in rms deviation and a slight decrease in damping ratio (see Table 3). The final gains implemented are shown in Fig. 7. An autopilot coupler was modified and flight tested.

Initial flight tests indicated good response in turbulence, but the closed-loop frequency response was not sufficient to permit operation with the DMC filter. Consequently, the

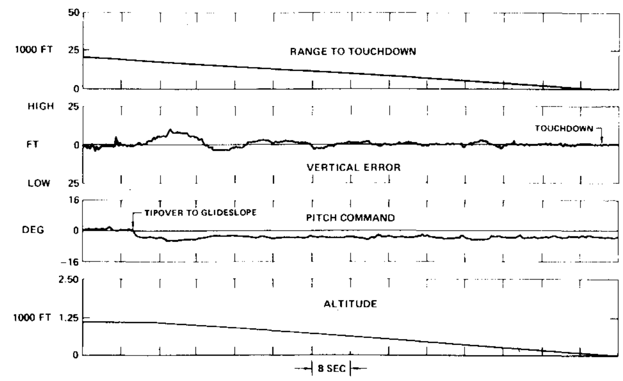


Fig. 6 F-4J ACLS flight test approach in turbulent air using the initial H-Dot control law modification (turbulent day)—baro altitude/accelerometer-derived vertical rate.

gains were revised and some lead compensation added in the SPN-42 computer. These lead terms are activated at a range of 7500 ft, reaching full value at 2500 ft. To minimize noise due to the lead terms, a range-scheduled α filter is used, having a gain of 1/16 or lag of 0.775 s at ranges greater than 4000 ft, then increasing to 1/8 (or a lag of 0.374 s) at 2500 ft range. This was the final optimized form of the H-Dot ACLS.

Flight Tests Aboard USS Independence

The system was flown aboard the USS Independence in November 1978 with excellent results. All 43 automatic approaches flown with the H-Dot system resulted in touchdowns in the required deck landing zone, the majority being the desired third-wire landings. This test period aboard the Independence demonstrated the excellent potential of the H-Dot ACLS control techniques, and further verified the gain optimization process using the power spectral density technique.

F-4J ACLS approaches were also flown on the Independence using the present attitude reference system, and data from the flights compared with the simulated time-history response in turbulence for the present and H-Dot systems.

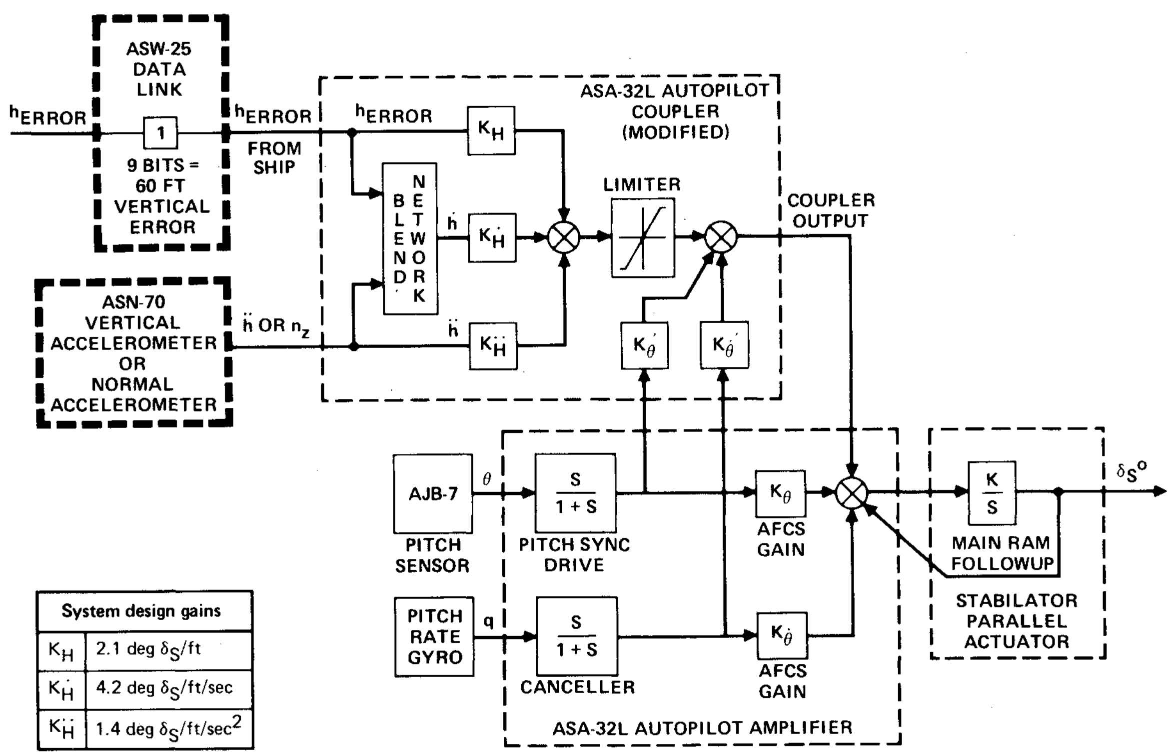
Figure 8 shows a simulated ACLS approach using the present pitch attitude command control law. The random turbulence model derived from the AR-40A PSD definition was included. A similar F-4J flight test approach from the Independence is shown in Fig. 9. A good comparison exists between simulated and flight test data. Figures 10 and 11 show simulated and flight test ACLS approaches using the H-Dot ACLS. The H-Dot system provides much tighter glide path control than the pitch attitude system, which verifies the original predictions from the PSD optimization process.

H-Dot System Performance in Severe Wind Shear

Another test of the H-Dot concept is performance under severe wind shear conditions. The wind profiles used are based on wind conditions experienced at JFK airport on June 24, 1975.[7] On that day, three aircraft (DC-8, L-1011, and B-727) experienced extreme wind conditions and out-of-control situations during the landing approach, with the loss of the 727 aircraft. The MCAIR simulation was used to compare the present attitude reference fleet ACLS with the H-Dot system.

The F-4J ACLS computer simulation was revised to incorporate a land-based approach, using a 3.5 deg glide slope. An F-4J in the full-flap power approach configuration was simulated, together with an autothrottle set to maintain the approach speed at 18.3 units angle of attack. Approaches commenced at 4.5 n.mi. from the runway. The wind shear patterns were programmed as a function of range from the runway. Figure 12 shows the response during the final 7000 ft, where the wind patterns are a decreasing headwind combined with a sharp vertical downdraft. The present ACLS drops 140 ft below the commanded glide slope, then recovers, but aborts the landing. The autopilot pitch command limiter is activated throughout the recovery, which prevents the aircraft from rotating into stall. Full military power (100% rpm) is applied by the autothrottle, which is the limit of the autothrottle command authority. After the initial recovery (20-24 s), there is not enough time to change the pitch attitude to steer the aircraft back to the glide path, and the landing is aborted.

By contrast, the H-Dot automatic approach system has little difficulty with the wind shear, dropping only about 7½ ft below the glide slope and quickly recovering to complete the



System design gains	
K_H	2.1 deg δ_S/ft
$K_{\dot{H}}$	4.2 deg δ_S/ft/sec
$K_{\ddot{H}}$	1.4 deg δ_S/ft/sec^2

Fig. 7 F-4J H-Dot ACLS avionics modification—H-Dot signal derived from the SPN-42 vertical error and an aircraft accelerometer.

Table 3 Optimization process: F-4J H-Dot coupler gains

Pass	$K_{\ddot{H}}$	$K_{\dot{H}}$	K_H	Rms of vertical displacement at pilot's station	Key roots: Natural frequency	Key roots: Damping
Initial	0.66	2.00	0.84	1.930	0.38	0.74
					1.10	0.20
1	0.72	2.21	0.76	1.662	0.34	0.66
					1.20	0.24
2	0.80	2.41	0.68	1.491	0.31	0.59
					1.30	0.26
3	0.88	2.67	0.60	1.360	0.29	0.54
					1.40	0.28
4	0.96	2.95	0.54	1.260	0.26	0.50
					1.40	0.28
5	1.06	3.25	0.50	1.189	0.25	0.47
					1.50	0.28
6	1.16	3.57	0.44	1.119	0.23	0.45
					1.60	0.28
7	1.28	3.91	0.40	1.069	0.22	0.43
					1.70	0.28
8	1.40	4.31	0.36	1.028	0.20	0.42
					1.80	0.27
DMC revision	1.40	4.20	2.10	1.149	0.36	0.74
					1.60	0.26

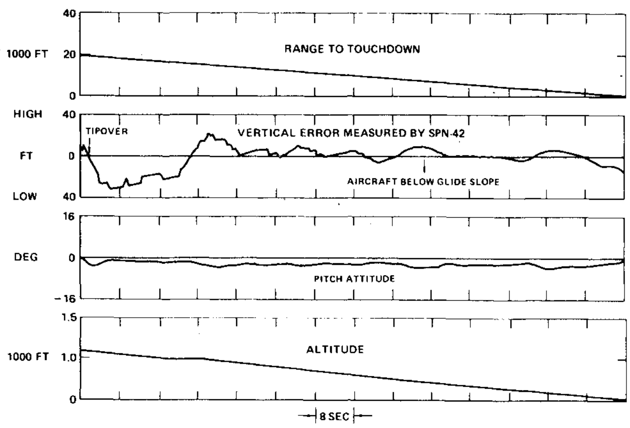


Fig. 8 Simulated F-4J ACLS coupled approach: present fleet system, wind gusts (3.35 ft/s 1σ), carrier burble.

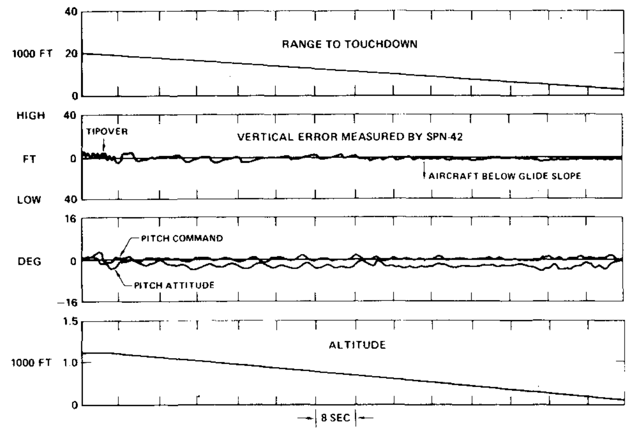


Fig. 10 Simulated F-4J ACLS coupled approach—modified H-Dot system, low gains, wind gusts (3.35 ft/s 1σ), carrier burble.

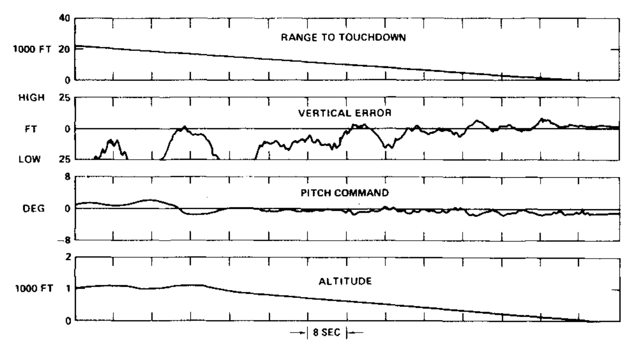


Fig. 9 F-4J ACLS approach on the USS Independence—flight-path response using the current ACLS pitch attitude control law.

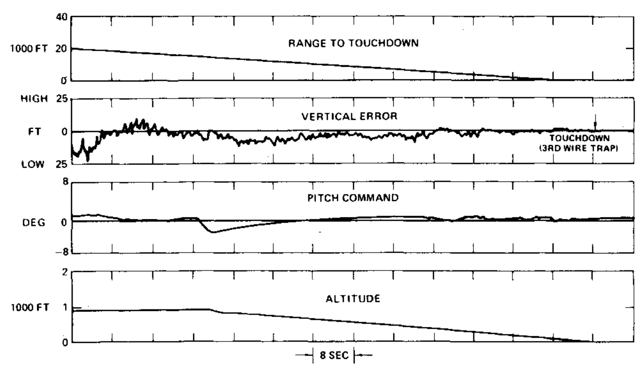


Fig. 11 F-4J approach on the USS Independence—flight-path response using the H-Dot control law. Vertical rate derived from the SPN-42 vertical error and the aircraft accelerometer.

landing. Angle-of-attack deviation is only about 1 unit (equivalent to 1 deg), and the autothrottle requires less than full power. The big advantage of the H-Dot ACLS over the present ACLS is the faster nose-up attitude response immediately after encountering the wind shear. The 2-s delay in establishing attitude recovery with the present ACLS is critical and causes a large sink rate to develop, with the subsequent pull-out maneuver close to stall. The H-Dot system also contains a pitch limiter, which was not activated during the recovery.

Application of H-Dot System Concepts to Other Fleet Aircraft

In order to further investigate the potential of the H-Dot ACLS control techniques, computer simulation studies were

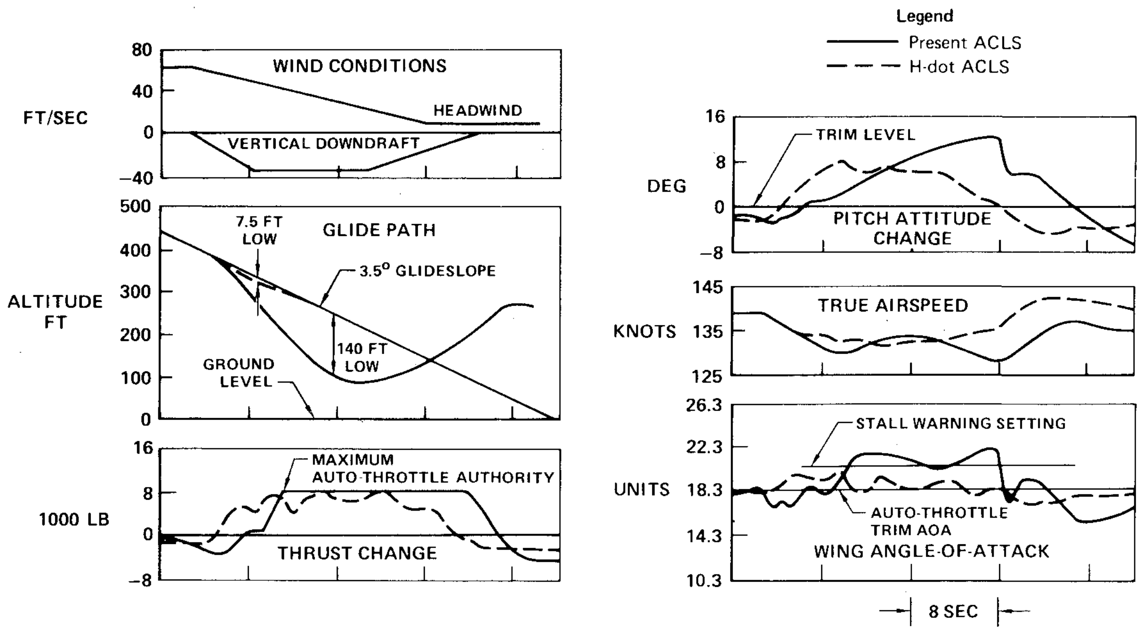


Fig. 12 Comparison of simulated automatic approaches through severe wind shear conditions.

Table 4 Standard deviation (ft) of longitudinal touchdown error from simulation studies with turbulence and burble—no ship motion

AFCS system	Aircraft type A-7E	F-14A	S-3A
Standard pitch command ACLS	39.4	54.7	53.1
Initial H-Dot modification (baro-altitude/accelerometer-derived H-Dot)	14.2	23.7	21.3
Current H-dot modification (SPN-42 vertical error/ accelerometer-derived H-Dot)	15.9	21.6	22.0

conducted to develop H-Dot systems for the A-7E, F-14A, and S-3A aircraft. The A-7E and F-14A aircraft simulations at NASA Ames Research Center[8,9] and the Lockheed S-3A aircraft simulation[10] were utilized for these studies. As shown in Table 4, an approximate 2.5:1 improvement in longitudinal touchdown dispersions was obtained for all three aircraft. Projects are under way to investigate the feasibility of implementing R&D H-Dot systems for flight test on all three aircraft.

Conclusions

Both simulation analyses and flight test results show that the power spectral density optimization process accurately predicts and corrects for flight-path errors due to turbulence, and that the hardware implementation can be achieved to give excellent Automatic Carrier Landing System control. Time-history simulation emulates the true response due to approach turbulence, and can be used to assess performance prior to flight testing.

Further application of the power spectral density optimization process can be made on any closed-loop system control of aircraft flight path involving turbulence, such as low-altitude high-speed gust alleviation, V/STOL landing approach, and conventional automatic landing systems.

Acknowledgment

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