# Direct Lift Control for Improved Automatic Landing and Performance of Transport Aircraft

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**Direct lift control (DLC) has been integrated into the L-1011 All Weather Landing System design to enhance the performance and safety capabilities of this Category III aircraft. The merits of the improved aircraft behavior achieved with DLC not only provide a higher degree of performance capability for a large vehicle of this nature, but are also firmly reflected in many subtle areas relating to the design, safety margin, and reliability of a complex, fail operational all weather landing system. The result in terms of influence on autoland system design, problems and limitations that constrained the design, and resulting improvements in performance and safety characteristics are the subject of this paper.**

## Nomenclature

$\dot{h}$ = altitude rate
$\ddot{h}$ = vertical acceleration
$\dot{h}_e$ = altitude rate error
$\dot{h}_{RL}$ = lagged radio altitude rate
$h_r$ = radio altitude
$HWS$ = head wind shear
$MAC$ = mean aerodynamic chord
$TWS$ = tail wind shear
$\delta h_c$ = stabilizer command
$\Delta\theta$ = change in pitch attitude
$\dot{\theta}$ = pitch rate
$\mu a$ = glideslope deviation

## I. Introduction

THE Astronics Division of Lear Siegler Inc., in conjunction with Collins Radio Co., is developing and producing the automatic flight control system for the Lockheed L-1011 commercial transport. The L-1011 is currently being flight tested at the Lockheed flight test facility, Palmdale, Calif. The L-1011 avionics system has been designed for Category III autoland certification, although initial FAA certification will be for Category II.

In order to meet rigid Category III safety and performance requirements, a quadruple channel fail-operational integrated autopilot/flight director system has been developed. This system utilizes direct lift control (DLC) for both manual and automatic control during the approach and landing phase. This paper discusses the use of DLC with the L-1011 all weather landing system to achieve improved performance and safety. DLC, which is incorporated as part of the basic aircraft design and is used during all approach land modes of control, manual or automatic, has become an integral part of the total flight control system design.

Extensive work conducted throughout the industry has verified the fact that DLC provides a very effective means of 1) improving aircraft flight response both by providing instantaneous lift prior to aircraft rotation and cancelling opposing lift from the elevator surfaces, and 2) reducing the aircraft response to external disturbances by using the DLC surfaces to oppose such activity. This means, in effect, that DLC provides higher pitch axis control bandwidth without additional demand from the conventional pitch control surfaces. The merits of this improved aircraft behavior are not only to provide a higher degree of performance capability for a large vehicle of this nature, but are also firmly reflected in many subtle areas relating to the design, safety margin, and reliability of a complex, fail operational all weather landing system. The result in terms of influence on autoland system design to problems and limitations that constrained the design, and resulting improvements in performance and safety characteristics, are the subject of this paper. The scope will be a survey of the consideration relating to the integration of DLC into the system and resulting system configurations and performance and safety capabilities.

## II. Investigations

### Basic DLC Principles

The general use of DLC has been discussed in numerous technical publications. DLC is implemented through the use of high lift devices on the wings which are capable of providing instantaneous (direct) lift to the aircraft. This lift capability can be used independently or it can be used together with the normal lift through rotation which is created by deflection of the tail surfaces. The latter becomes a very effective means of improving flight path response, particularly for large aircraft which are inherently very sluggish due to the large moment of inertia and large flight path time constant. Due to practical limitations such as available lift, drag, and buffeting, DLC is normally used to provide short term or high-frequency lift modulation where the tail surfaces are used for long term control, pitch stabilization, and trim. DLC can also provide effective means for attenuating undesirable aircraft activity in the lift axis by sensing these activities and opposing them with the DLC devices. Figure 1 shows typical normal acceleration response with and without DLC; conventional concepts are shown in Fig. 2. These basic DLC techniques are applied as well to the L-1011 landing system design.

### Design Considerations

The development of the automatic flight control system for the L-1011 and the integration of the DLC system had several interesting and unique aspects. Some of these were: 1) DLC

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Index categories: Aircraft Performance; Aircraft Handling, Stability, and Control; and Aircraft Landing Dynamics.

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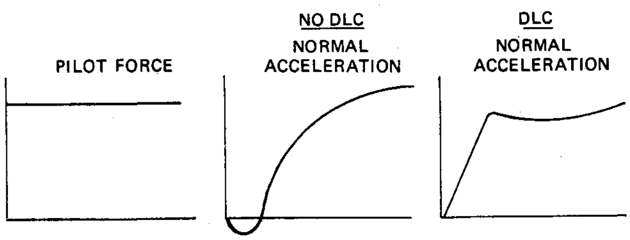


**Fig. 1 Normal accelerometer step response.**

was included in basic aircraft design. 2) DLC is required and will be certified for all approach land AFCS modes: a) fully automatic, b) pilot manual with visual reference, and c) pilot manual with flight director reference. 3) Since DLC was available, additional autoland performance and safety margins were specified. 4) A fail operational autoland system was required which included the DLC implementation. 5) The system must perform acceptably without DLC.

A summary of the DLC system design constraints and objectives is shown in Fig. 3. A discussion of the important factors in each area, their impact on the design and the solution to each problem area is included in subsequent sections. Performance and safety characteristics relating to the design objectives are also described. Several of the factors were not evident at the beginning of the development program, but became apparent as an understanding of the total integration problem grew.

### Design Constraints

#### *Aircraft Characteristics*

The L-1011, as illustrated in Fig. 4, uses four inboard spoiler panels for DLC. During DLC operation, the spoilers are biased upward and driven symmetrically. Extension of the DLC surfaces occurs at the same time that final approach flaps are extended and, as a result, the static lift changes from the two surfaces tend to cancel. The selection of the optimum spoiler arrangement for DLC was, of course, the result of extensive analysis, design and pilot-in-the-loop simulator studies conducted by the aircraft and AFCS manufacturer. The dominant aircraft characteristics which dictated the design were lift authority and pitching moment. The drag effect is small and, in fact, causes a slight increase in plugoid damping.

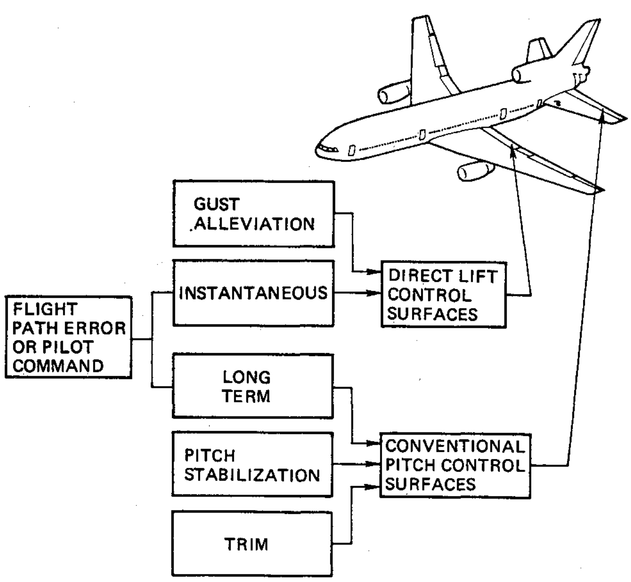


**Fig. 2 Conventional DLC and pitch axis control concept.**

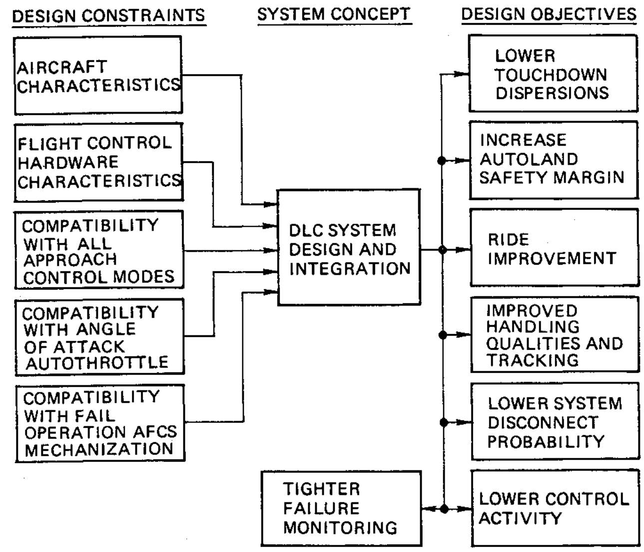


**Fig. 3 DLC design and system integration for a Category III aircraft.**

#### *Limited Authority*

The DLC authority is limited due to airframe buffet produced by large spoiler deflections. Also, the lift effectivity diminishes with larger spoiler angles. Approximately $\pm 0.1$ g lift is available with the present configuration which was determined to be adequate for good DLC performance.

#### *DLC Induced Pitching Moments*

The lift produced by spoilers will either cause nose up or nose down pitching moment, depending on whether the center of pressure is located forward or aft of the aircraft center of gravity. The pitching moment is also dependent on the downwash caused by the stabilizer. For a swept back wing, the pitching moment generated by the spoilers changes for different spoiler pairs along the wing span; the inboard spoilers tend to produce relatively positive pitching moment.

The nose-up pitching moment causes a rotation of the airplane and an increase in angle-of-attack which generates additional lift. A small effect is beneficial; however, large pitching moments will negate the basic purpose of the DLC which is the separation of pitch and heave motions.

The nose-down pitching moment reduces the angle-of-attack and hence the lift. A small nose-down effect can be tolerated. However, if the effect is large, the lift decrease due to pitch down motion can exceed the initial lift increase due to spoiler retraction and the steady-state airplane lift will be less. This effect is illustrated in Fig. 5 which shows the normal acceleration response to a combined spoiler step for various degrees of adverse spoiler pitching moment. (Note: Steady-state DLC input is washed out).

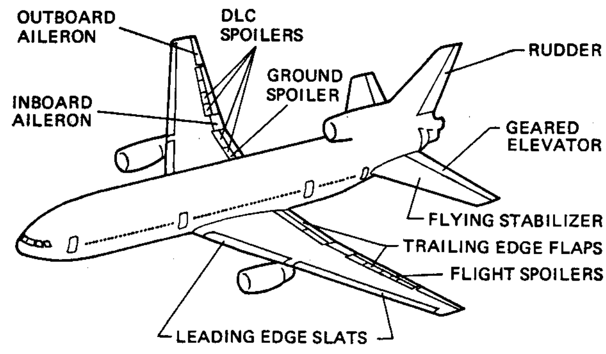


**Fig. 4 Control surface arrangement.**

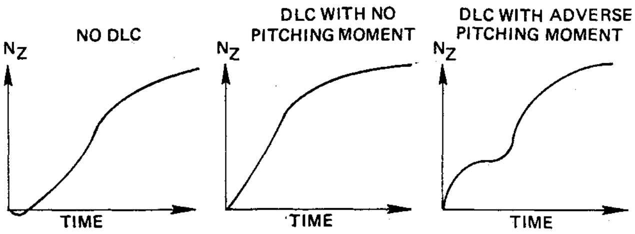


**Fig. 5 Effects of adverse spoiler pitching moment on acceleration response.**

This undesirable phenomenon does not only effect the sample step response, but lends itself to an over-all performance deterioration in all areas influenced by DLC. Using crossfeeds from the spoiler to the pitch surfaces could be used to compensate for this adverse moment but the net result in loss of lift and increased system complexity is not warranted. Also, many of the benefits of DLC to be discussed later would be negated. The best solution is to select lift surfaces so that the moment is very small. As a result, the four inboard panels are being used.

### Flight Control Hardware Characteristics

#### *DLC Spoiler System Nonlinearities*

The spoiler surfaces are also used for roll and speed brake inputs. Their total travel is five times that allowed for DLC input. Hence, even an over-all reasonable magnitude of nonlinearity such as a backlash in the linkage and servo system appears large for DLC operation. The DLC nonlinearities do not pose any limit cycling problems; therefore the control laws were optimized to minimize adverse effect of these nonlinearities on performance.

#### *Slew Rate*

Slew rate or DLC rate limits are the most critical actuator parameter problems. In order for DLC to be effective for gust compensations, a minimum rate of the order of 30°/sec is required for most lift devices. If DLC were only required to augment the pilot response, a lower slew rate could be tolerated.

#### *Bandwidth*

Actuator or control bandwidth is not a significant problem. This is primarly because the DLC devices produce little or no moment and therefore do not contribute to aircraft stability or instability. A total bandwidth between the DLC command and surface response of less than 0.15 cps is probably acceptable. The attenuation of the control frequencies can be compensated for by a higher gain, provided that the actuator slew rate is high enough.

### DLC Mechanization

Compatibility of the DLC configuration with all approach control modes is not only important to achieving an efficient mechanization, but is also an important factor in obtaining pilot acceptance. It was further found that aircraft motion cues with DLC for manual and automatic approach land control should be similar to conventional aircraft control so to ease pilot monitoring and training and ensure pilot confidence in the system performance. Therefore, every effort was made to develop a DLC implementation which is common to the fully automatic system and the basic (Autopilot Off) manual control system. The technique employed was to use an electrical pitch control to spoiler crossfeed with suitable gain and filtering to satisfy the requirements of both the autopilot and manual control modes. The next step was to design the automatic control system to be compatible with this simple DLC mechanization and still provide optimum performance.

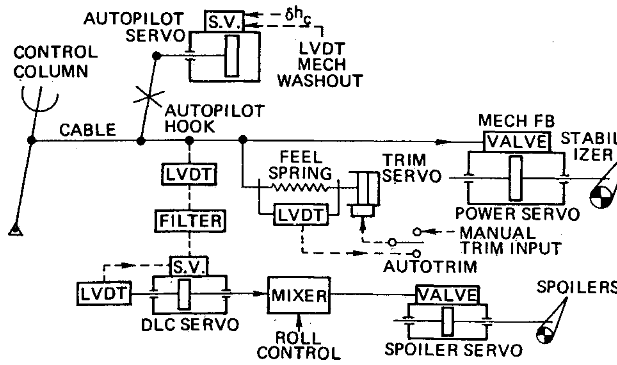


**Fig. 6 Pitch autopilot-DLC system mechanization.**

The DLC mechanization for manual and automatic modes is identical and is shown in Fig. 6. The input to the DLC servos is provided by a crossfeed from the column position transducers. The filter consists of washout, lag and lead-lag networks. The washout is required to prevent saturation of the limited authority surfaces and to eliminate steady-state trim offset. The washout time constant should be such that the initial lift increase from the DLC fades out when the lift increase from the angle-of-attack change caused by the tail surface command becomes effective. The lag prevents the over-sensitivity caused by instantaneous lift buildup due to DLC surface deflection; the input should be filtered. The filter is also necessary to limit the inner loop system bandwidth to that required for gust alleviation.

The filter and crossfeed gain were optimized during pilot-in-the-loop simulator studies where consideration of pilot comments, tracking accuracies, pilot induced oscillations (PIO) prevention, and aircraft response cues were the influencing factors. The spoiler servos are hydromechanical and have built-in mechanical feedbacks. The inputs are applied by a linkage system which is driven by summation of DLC and aileron servo system outputs.

In the automatic mode the column transducer (LVDT) output is a function of the stabilizer command ($\delta h_c$) applied to the pitch servo system. The $\delta h_c$ is provided by the pitch autoland computations. As previously indicated, the optimum use of DLC for automatic control is highly dependent on the pitch autoland control law scheme. Since the basic objective of the pitch autoland system is to control the aircraft in the vertical axis, and since DLC provides an instantaneous means of control, it follows that the autoland system should be configured to most effectively provide this vertical control. The configuration developed, as shown in Fig. 7, utilizes glide

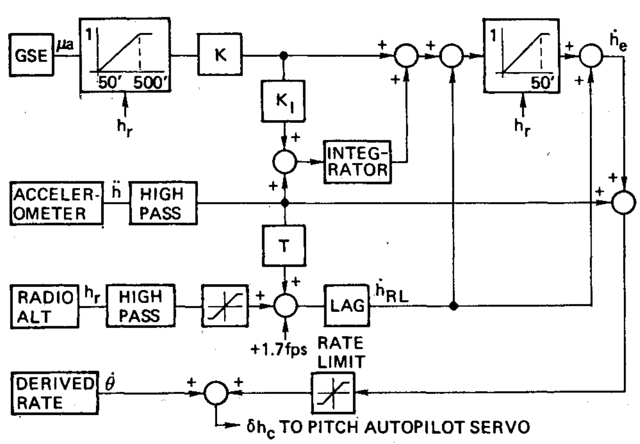


**Fig. 7 Simplified autoland configuration.**

slope, altitude and normal acceleration information for vertical control, and only pitch rate added for short term pitch damping. This system utilizes the high bandwidth well stabilized altitude rate error to command a longitudinal surface deflection rather than a vehicle pitch attitude; as a result, the system bandwidth is not limited by the vehicle for flight-path time constant.

This basic altitude rate ($\dot{h}$) control system is similar in nature to the LSI L-102 autoland system being successfully used on French Caravelles. No switching is required between track and flare modes. Exponential flare is provided. The L-1011 flare mode always commands constant touchdown sink rate irrespective of the sink rate prior to flare and the precise control provided by DLC, even in the presence of turbulence, enables it to follow the command closely.

Since pitch attitude feedback is not used, it is possible to use the simple DLC crossfeed mechanization. If a basic pitch attitude system were used it would be necessary to separate it from the DLC system, which would result in a significant increase in system complexity. This is because the phasing of the normal pitch attitude feedback would cause the spoilers to behave incorrectly when the aircraft is exposed to vertical turbulence and, in fact, the result could be to amplify the aircraft activity rather than to suppress it. Further, the attitude feedback requires higher pitch rate feedback gain to maintain sufficient short period damping and natural frequency; hence the altitude response will be slow unless the outer loop gains were increased or a path integrator was used for flare, which would further reduce the system bandwidth. Instead, washed-out normal accelerometer feedback is used which provides the required pitch damping and the gust alleviation signal for the spoilers. The acceleration ($\ddot{h}$) feedback to the stabilizer is lagged to reduce the high-frequency column and stabilizer activity and the hydraulic flow requirements. The lead-lag network in the DLC input path allows high frequency input to the DLC only. It is also used to minimize the effect of nonlinearities such as backlash in the DLC spoiler system; hence it eliminates the need for extra precision servos and linkages which are costly.

The accelerometer is located forward of the CG at a distance so that resulting pitch attitude acceleration feedback has a beneficial effect. Also, it is tilted forward to minimize the coupling with the aircraft longitudinal axis. Again, the pilot monitoring and training tasks are simplified due to similar aircraft motions under automatic manual control. In addition the pilot can monitor the DLC operation with the same flight director and column cues as are used for monitoring the stabilizer operation. Separate instruments and controls are not necessary. With this higher bandwidth provided by DLC, more filtering of ILS beam noise is also possible.

### Redundancy Considerations

The requirement for a safe, reliable four-channel fail-operational system imposed many rigid requirements on the autoland control law definition. This meant that the system must be as simple as possible because each must be mechanized four times and must be allowed minimum tracking errors between the computational channels. Features of the autoland control laws shown in Fig. 7 which simplify the redundancy and safety problems are: 1) A minimum number of sensors: Pitch attitude, acceleration, radio altitude, and ILS glide slope error are used. The use of low reliability air data computations is not required. 2) All sensor outputs are washed out except glide slope error which utilizes path integrator. This means that the effects of sensor nulls and offsets are eliminated; as a result, much closer tracking between redundant channels is achieved. 3) Continuous operation between glide slope and flare means minimum complexity and the ability to predict a successful operation during flare rather than having to switch in an unused control law during this critical phase. 4) A common output ($\delta h_c$) for pitch and DLC control surfaces.

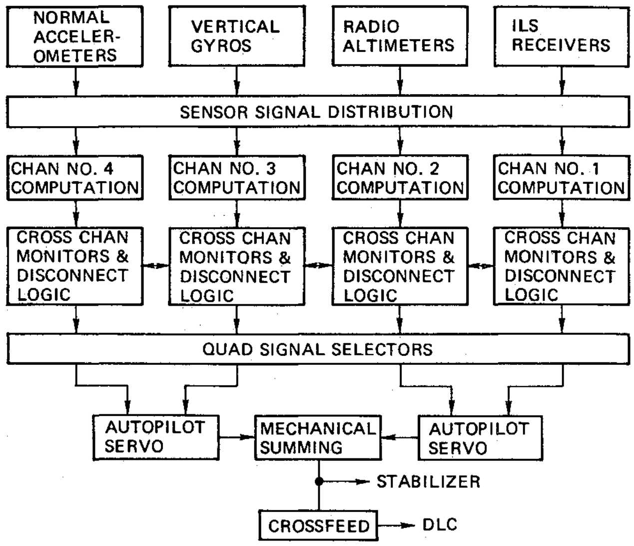


**Fig. 8 Quad channel redundancy configuration.**

The last feature can best be appreciated by realizing the complexity of a quad channel fail operational system. A generalized block diagram of the L-1011 configuration is shown in Fig. 8. If separate DLC computations were required it would also mean that another complete set of cross channel comparators, disconnect logic, and quad signal selectors would increase the system complexity by about 30%. Further, there is little certainty that the DLC channels would track the pitch control channels; therefore it may be difficult to realize any advantage from DLC and, in fact, it may not even work. As a result, it is very important that the system be mechanized around the single DLC crossfeed and that only feedbacks that are compatible with pitch control and DLC surfaces are used.

### Compatible with Angle-of-Attack Approach Autothrottle

The angle-of-attack speed control system is utilized for the approach-land mode because it allows for a fixed margin against stall and has lower throttle activity during aerodynamic turbulence. A simplified schematic is shown in Fig. 9. When an angle-of-attack autothrottle is used together with a DLC system, an undesirable coupling exists between airspeed control and the flight path control. For example, if the DLC surfaces are actuated to cause an increase in lift, the total aircraft angle-of-attack becomes less, and assuming the pitch attitude does not decrease, the aircraft begins to climb. However, the autothrottle sees this decrease in angle-of-attack as an increase in airspeed and calls for a decrease in thrust rather

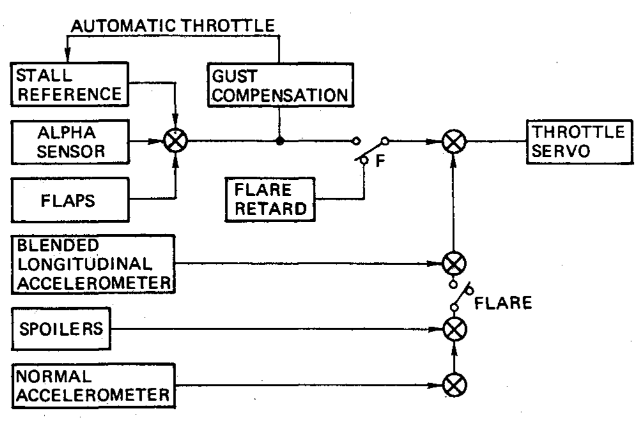


**Fig. 9 Simplified angle-of-attack autothrottle configuration.**

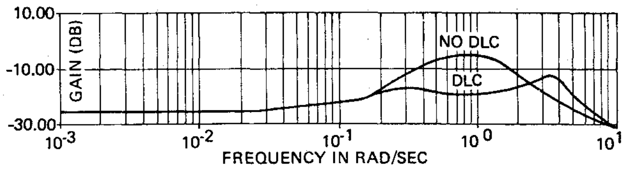


Fig. 10 Frequency response plot.

than the required increase. The coupling problem was eliminated by cross feeding the DLC position into the speed control system and by using a suitable value of washout in the DLC crossfeed.

## III. Discussion

### Performance Results

As discussed in the introductory portion of this paper, the benefits from DLC are achieved from 1) compensating for the limitations in basic aircraft bandwidth and response characteristics, and 2) by reducing the aircraft activity during external disturbances. This effect is illustrated in Fig. 10, which is a frequency response plot of aircraft altitude rate to vertical gust disturbances. It can be seen that the aircraft activity, in the frequency range of importance, is substantially reduced with DLC. A power spectrum density plot shown in Fig. 11 illustrates a factor of four reduction in the aircraft energy absorbed from the gust with the DLC operative.

It should be pointed out that the system shown without DLC was designed to provide acceptable performance alone with optimum performance being achieved with DLC added. In other words, with DLC available it was possible to compromise on the bandwidth of the basic system so that the normal pitch control activity could be minimized. However, the comparative results presented in this study were obtained with different system configurations that were optimized both with and without DLC, making it possible to obtain a realistic assessment of the advantages gained with DLC. Therefore, the degree of performance improvement is by no means exaggerated and would in fact be greater if DLC were simply disabled.

The gross improvement which involves the total scope of design areas remains substantial. By using this philosophy it was possible to optimize the system in light of all of the design objectives. The primary contribution of DLC to each of these objectives is illustrated in Fig. 12. Certainly it is not possible to clearly attribute meeting each design objective to one or two of the benefits indicated since all aspects are highly interrelated. However, the most directly influencing factors are indicated.

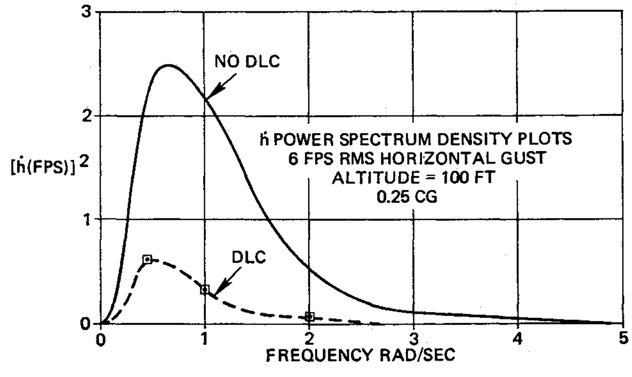


Fig. 11 Power spectrum density plot.

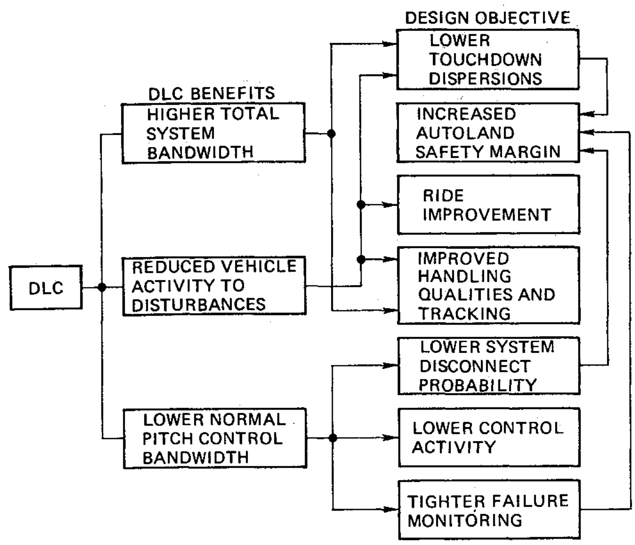


Fig. 12 DLC design objectives.

### Performance Studies

Autoland certification of the L-1011 system will be based on statistical performance and safety analyses and flight test evaluation. The flight test evaluation will be used to confirm the results of the simulation studies, but because of practical limitations, will not cover the scope of situations that can be considered analytically.

The analytical evaluation criteria being established for autoland certification was also used in optimizing the L-1011 autoland system design. The system optimization criteria was based on Category III performance and safety requirements, pilot acceptability and hydraulic power requirement. Performance and safety requirements and associated evaluation criteria consist of the following.

#### *Performance*

Principal longitudinal autoland requirements affecting DLC design include: 1) Good tracking and touchdown performance. On $2\sigma - 95\%$ probability basis: sink rate at touchdown $<2.8$ fps; longitudinal touchdown dispersion $<1000$ ft total. 2) Adequate stability margin. 3) Low control column activity: 0.5 in. rms, $2\sigma$ basis. 4) Hydraulic power requirement: 2 deg/sec rms, $2\sigma$. 5) Pilot acceptance.

#### *Safety*

The probability of a hazard situation arising during the approach land phase must be extremely remote. The hazardous situation may arise due to various conditions such as landing short of the threshold, exceeding the landing gear stress limit, tail scraping due to excessive pitch up, etc. Therefore, the system must be designed to minimize the probability of a hazardous situation under the three following conditions: 1) Fault free system performance under extreme environmental conditions (i.e., wind gusts, bad ILS beams). 2) Failures in the autoland system. 3) Nuisance disengagement of the system at a critical phase (i.e., flare) due to external disturbances and/or system tolerances.

### Evaluation Techniques

A flow diagram of the performance and safety studies conducted is shown in Fig. 13. The deterministic and stochastic disturbances used included: 1) turbulence, horizontal and vertical; 2) wind shear and constant winds; 3) beam noise and beam angle variations; 4) sensor and computations tolerances; 5) terrain profile and runway slope; and 6) aircraft variations.

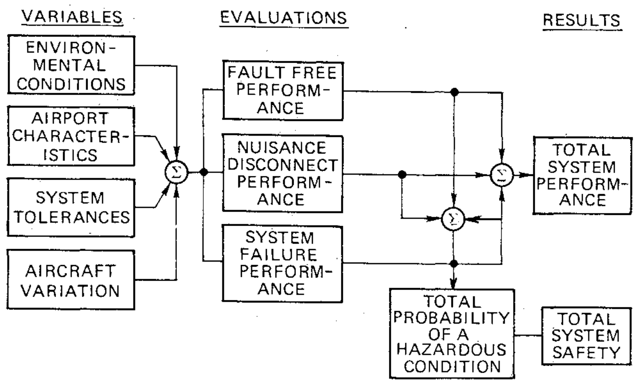


**Fig. 13 Autoland safety and performance system evaluation studies.**

The turbulence model was based on the Dryden form and was supplied by Lockheed. Most of the statistical studies were conducted by using high speed analog simulation techniques. Thousands of simulated landings were made in the presence of various levels of disturbances and then the results were combined, with proper weighting factor for the disturbance levels, by using multiple integration technique. All probable system failures and failure sequences were also considered.

### Detail Performance Results

Detailed performance results obtained from the L-1011 AFCS development and certification studies are shown in Table 1, which shows performance under normal (95.5% probability) conditions, and Table 2 which represents performance under extreme or low probability conditions defined by LCC.

*Nominal Performance ($2\sigma$—95% Probability)—Touchdown Dispersions*

Touchdown dispersions covering 95.5% of the landings studied as shown by items 1, 2 and 3 in Table 1 are significantly reduced with DLC. Particularly significant is the reduction

**Table 1 Statistical performance summary ($2\sigma$—95.5% probability level)**

| | With DLC | Without DLC | Requirement Design |
|---|---|---|---|
| 1) Descent rate at touchdown, fps | <2.6 | <5.0 | <2.8 |
| 2) Touchdown range dispersion, total ft | <650 | <900 | <1000 |
| 3) $\Delta\theta$ deg at touchdown | <2.2 | <3.0 | — |
| 4) Surface rate activity, deg/sec, rms | 1.7 | 1.8 | <2 |
| 5) $N_z$ at c.g., GS rms ($h$ beam = 1000 ft) | 0.094 | 0.150 | — |
| 6) Column activity, rms inches | 0.4 | 0.7 | 0.5 |
| 7) Pitch attitude activity deg, rms | 0.7 | 1.3 | — |

**Table 2 Statistical performance summary**

| | With DLC | Without DLC |
|---|---|---|
| 1) Probability sink rate at touchdown exceeding stress limit | $4 \times 10^{-9}$ | $10^{-5}$ |
| 2) Probability of landing short of threshold | $2 \times 10^{-8}$ | $5 \times 10^{-6}$ |
| 3) Cross-channel monitor levels (degrees) | 1.2 | 2.0 |

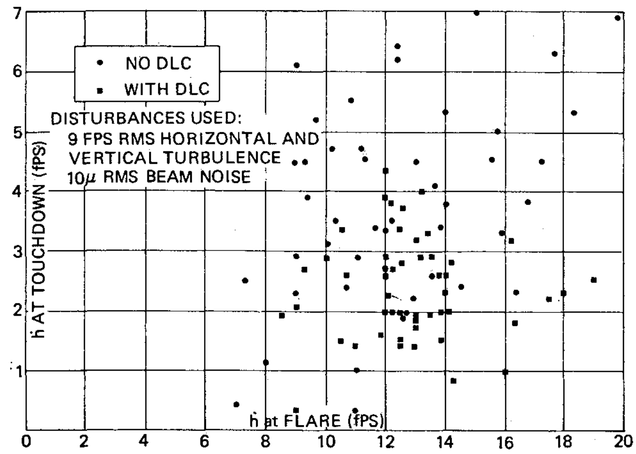


**Fig. 14 $\dot{h}$ touchdown vs $\dot{h}$ at flare.**

in descent rate at touchdown by a factor of two while at the same time the longitudinal dispersions are reduced by 50%. The pitch attitude variation and the column activity are also considerably lower. It must be noted that the performance achieved without DLC is compatible with Category III requirements. However, with DLC the touchdown performance is improved and the pilot acceptability and passenger comfort level are enhanced due to reduced aircraft activity.

The plots showing $\dot{h}$ at touchdown vs $\dot{h}$ at flare for 50 statistical landings under extreme wind conditions are shown in Fig. 14 for DLC and no DLC cases. They dramatically illustrate the control capability available with DLC. Typical altitude vs range traces for different beam angles and with FAA specified wind shear and constant winds are shown in Figs. 15–17.

*Ride Improvement*

The significant reduction in descent rate activity shown in Figs. 10 and 11 and the 50% lower acceleration shown in Table 1 indicates a vast improvement in ride comfort. Other studies have shown that the reduction in rms descent rate and altitude deviation at 1000 feet beam height are in excess of 50%.

*Pilot Handling Qualities*

Extensive analytical and simulator studies were performed to examine the possible manual DLC mechanizations. As discussed earlier, electrically coupled DLC mechanization

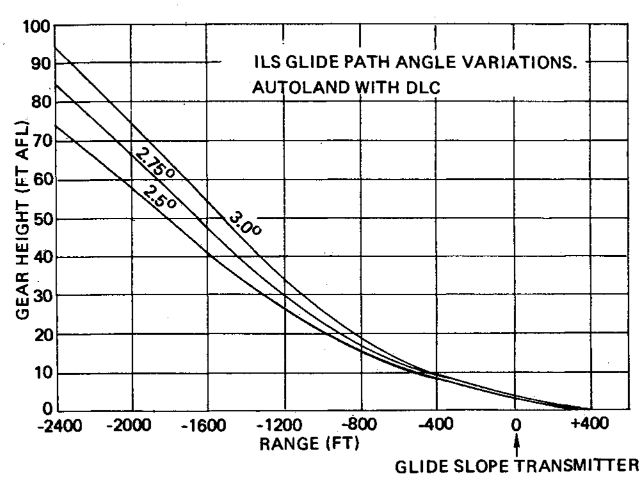


**Fig. 15 ILS glide path angle variation.**

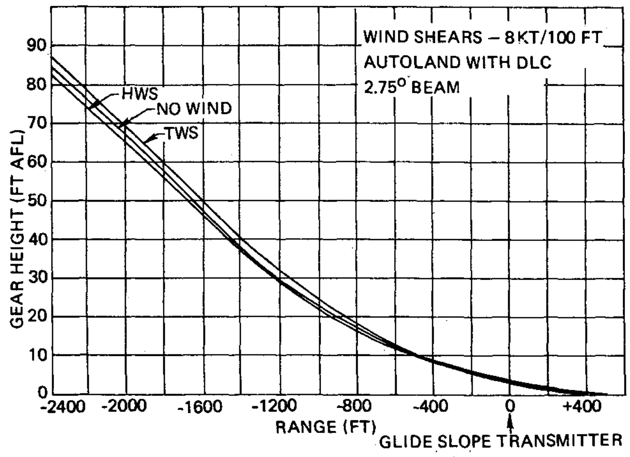


Fig. 16 Wind shear.

shown in Fig. 6 was selected. Separate DLC mechanization was considered undesirable due to requirements for separate control and display.

The pilot-in-the-loop simulator studies verified that the use of spoilers during landing approach quickens the short term altitude response of the airplane. The quickening allowed the pilots to recognize the airplane response to control inputs faster, thus allowing him to fly a tighter control loop resulting in smaller tracking deviations. The effects of spoiler pitching moments were also evaluated during these studies and the results indicated that with an adverse pitching moment greater than an equivalent of 5% *MAC* the positive benefits of DLC were in fact negated. Further, it was found that with an excessive adverse moment the control motion travel was significantly increased, thus increasing the pilot workload.

Once the proper selection of DLC surfaces were made and the manual DLC system was optimized, the following areas of improvement during manual approach and landing were realized: 1) an improvement in composite pilot rating from 3.5 to 2.5 on the Cooper scale; 2) a 40% reduction in pilot tracking error and pilot workload during approach; 3) a 30% reduction in touchdown dispersions; and 4) by proper selection of DLC filters and gains: a) the tendency toward pilot induced oscillations (PIO) can be reduced, b) the system is acceptable for both manual visual and manual flight director control, and c) important aircraft and control motion cues during approach and flare are essentially the same as a conventional non-DLC system.

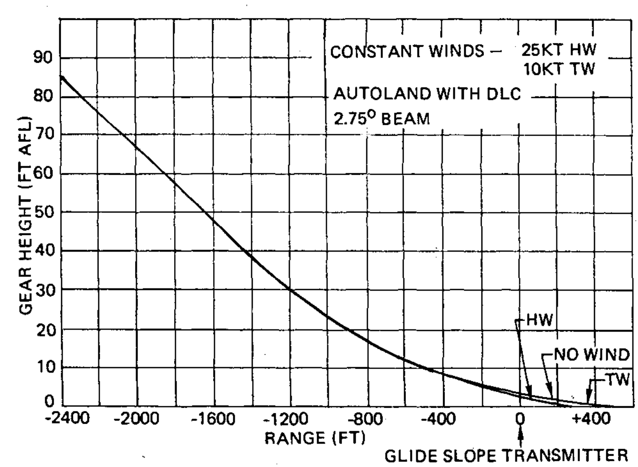


Fig. 17 Constant winds.

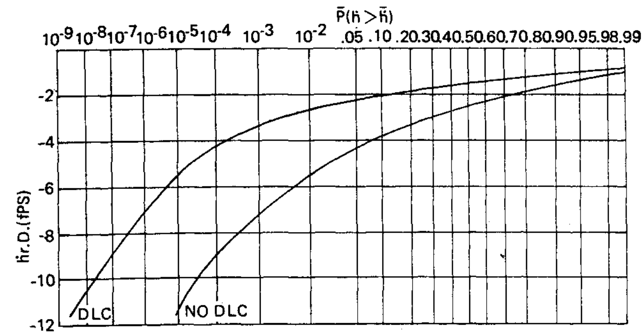


Fig. 18 Descent rate at touchdown.

*Performance with Extreme Disturbances*

Typical performance data is shown in Table 2 where the system with DLC shows large improvements in terms of safety. The probability of exceeding the gear stress limit is roughly 3000 times lower and the probability of landing short of the runway is about 250 times lower. To achieve the same performance without DLC it will be necessary to put operational restrictions on wind speed to about 25 knots. Another alternative will be to increase gains in the pitch computation. However, it will cause greatly increased aircraft and surface activity, and the system nonlinearities and the monitoring safety requirements will pose greater problems.

Other data showing typical exceedance probability levels for the sink rate and range at touchdown are shown in Fig. 18 and 19 for both DLC and non-DLC configurations. Data of this type is used for optimizing the system as well as for obtaining probability numbers contributing to the total system safety computation. Table 2 also shows that the cross channel comparator levels can be reduced from 2.0 to 1.2° stabilizer with DLC. Further, because the system is operating at a higher bandwidth, a greater amount of filtering can be done on the cross channel monitoring signals. This contributes to a significant increase in safety performance in terms of reduced disengage probability and higher probability of detecting failures.

The tracking error between the redundant pitch computation channels is also greatly reduced due to lower pitch channel gains and larger filter systems possible due to DLC. Thus lower monitor comparator levels resulting in better protection against failures, particularly slow runaways and opens, are possible without increasing the nuisance disconnects. The inability to detect these failures will considerably increase the possibility of multiple failures which can be disastrous. Almost three times larger command activity and comparator levels will be required if attempts are made to achieve the identical touchdown performance without DLC.

Again, the smaller pitch commands allows closer tracking between the servos and lower servo comparator levels. Servo nuisance disconnects have been a major contributor in reducing the reliability of the many existing redundant systems. As pointed out earlier, the DLC tracking and monitoring are greatly eased with the mechanization selected. The DLC

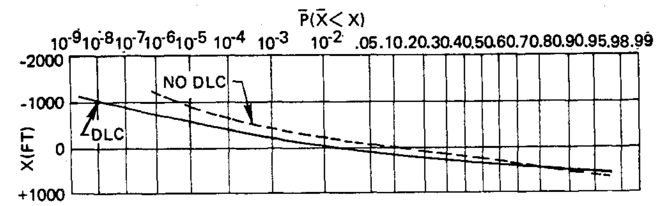


Fig. 19 Range at touchdown.

control laws and servo are in-line monitored and have fail-operational capability. However, failure studies were conducted by disabling monitors. The results have shown that due to limited DLC authority ($<\pm 0.1$ g peak) the failures have very small effect on landing safety except in the presence of very heavy turbulence.

*Control Activity and Hydraulic Flow*

It has been pointed out before that with the use of DLC the dynamic limitations caused by the aircraft short period mode can be overcome; hence large filters such as on the glide slope receiver and normal accelerometer feedback can be used. Also, since the pitch control is now mainly used for trim changes, lower gains in the pitch control loops can be used with the higher forward loop integral gain. Thus, by using DLC, both the gain and the high frequency content of the input to the pitch servo system can be reduced.

Obviously, the column and stabilizer activity, particularly the high frequency content, are reduced. It also allows use of low bandwidth and a less precise servo system which requires less flow. Hence the pitch servo system size, weight and cost are greatly reduced, and the changes in autoland performance due to servo variations are small. Also, the lower actuator bandwidth and flow limit provide more attenuation to the undesirable inputs caused by aircraft bending modes which are likely to be at lower frequencies for big transports such as the L-1011.

## IV. Conclusion

The improved basic aircraft behavior that can be gained from DLC can provide a general increase in over-all performance and safety capabilities of a Category III automatic landing system and, at the same time, can simplify many design and integration problems. The analytical and simulator studies have shown that with the present L-1011 DLC mechanization the nominal manual and automatic landing performance is improved by at least a factor of two. The safety of automatic landing in the presence of gusts is enhanced by about 1000 times. These benefits are achieved with lower gains and larger filters in the pitch computations, which help to lower the channel tracking errors and monitor comparator levels while providing improved safety against failures. Also, the pitch servo system bandwidth and flow requirement are reduced, which results in cost and weight savings. The pilot monitoring and tracking tasks are simplified due to similar aircraft motions under automatic and manual control, and the need for separate controls and displays for DLC are eliminated. To gain all these advantages it is necessary to ensure that the pitching moment associated with the lift, particularly the nose down, is small. If an angle-of-attack speed control system is used, care must be taken to eliminate the coupling between it and the DLC.

## Afterword

### Flight Test Results

At the time this paper was submitted, a large number of automatic and manual landings had been made with DLC operation. Lockheed and airline pilots have confirmed the performance trends described in this paper and have strongly recommended the use of DLC. Typical comments are: "The performance is an order of magnitude better with DLC," and "The aircraft and control column activity is reduced to almost 50% with DLC." They are also pleased with the general autoland performance without DLC.