Prospects for Low Wing-Loading STOL Transports with Ride Smoothing

R. B. HOLLOWAY,* G. O. THOMPSON,† AND W. J. ROHLING‡
The Boeing Company, Wichita, Kansas

Airplanes with low wing-loadings provide STOL capability without reliance on auxiliary propulsion or augmented lift, but require a ride smoothing control system to provide acceptable passenger comfort. A parametric study produced a configuration having a 0.35 thrust-to-weight ratio and a 50 psf wing loading, which satisfied specified mission requirements and airworthiness standards. A ride-smoothing control system (RCS) synthesis was then performed which consisted of ride quality criteria definition, RCS concept trades, and analysis of RCS performance benefits at significant flight conditions. Within the limitations of the study it is concluded that this is a viable approach to STOL airplane design.

Introduction

HIGH cruise speeds have been a goal of most commercial STOL studies. This requirement, with a desire for high cruise efficiencies and passenger ride comfort, has resulted in airplanes designed with high wing-loadings. To achieve STOL capability, these configurations rely on auxiliary propulsive systems or augmented lift systems which must be carried throughout the mission for use only on takeoff and landing. These designs are sensitive to propulsion system failures which affect safety of flight in most cases.

The low wing-loading concept relies on the flight control system to provide satisfactory ride and accepts some reduction in efficiency during high speed cruise. This STOL capability is provided with simple, flight proven, aerodynamic concepts. Such an airplane could be certified to present Federal Aeronautical Regulations.

Engine thrust required for takeoff is less for lower wing loadings. Since none of the lift is provided by the propulsion system, a propulsion system failure will not cause a sudden loss of lift. The low thrust requirement also reduces takeoff and sideline noise. However, low wing-loading causes a larger than necessary wing for cruise which reduces cruise efficiency.

At comparable speeds, low wing-loading airplanes are more gust responsive than high wing-loading airplanes. To provide acceptable passenger ride comfort, a ride smoothing control system is required. A system failure in a turbulent environment would require a slower speed to maintain satisfactory comfort.

Configuration Definition

An unrefueled range of 750 naut miles composed of three 250 naut-mile segments was chosen as the primary mission design objective, as shown in Fig. 1. Airplanes sized for the primary mission were recycled to determine their size compatibility with a 1000 naut mile alternate mission.

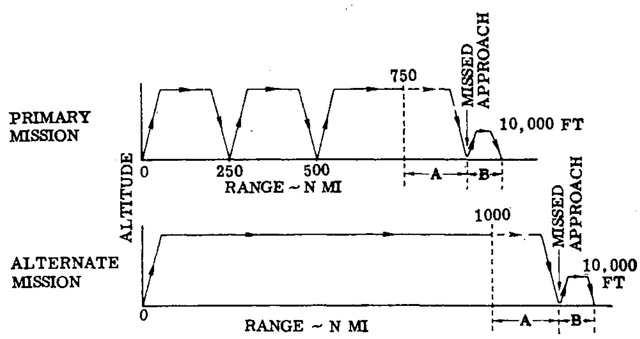


Fig. 1 Mission rules.

The airplanes were sized for the reserve requirements shown as distances A and B in Fig. 1. Distance A indicates a ½ hr continued cruise and descent to sea level followed by a missed approach. Distance B is 100 naut miles, composed of a climb to 10,000 ft, cruise and descent to an alternate field.

Takeoff and landing allowances were: taxi-out time = 3 min, takeoff time = 1 min, landing time = 1 min, and taxi-in time = 3 min.

The takeoff and landing requirement was for a 2000 ft F.A.R. field length. Payload was set at 130 passengers (18 first class and 112 economy class). The cruise speed objective was to be as near $M = 0.8$ as possible.

The lower than usual aspect ratio of six was selected since a high aspect ratio would result in a large span for the large area and the reduced lift curve slope somewhat improves the ride. Also, this configuration cruises at low lift coefficients where drag due to lift is not important to cruise efficiency. By utilizing supercritical wing technology, the sweep of the flap hinge can be zero for maximum flap effectiveness while maintaining high critical Mach numbers for cruise.

Estimated engine performance was based on projected 1975 technology which included turbine temperatures of 2900° R and compressor pressure ratios of 24. The operating rules for certification type analysis were based on Tentative Airworthiness Standards.[1]

The high lift system is a full-span double-slotted trailing-edge flap with a matched leading-edge flap (Fig. 2). The trailing-edge flap is a dual purpose surface that performs as a conventional double slotted flap for takeoff and landing. Deflection for takeoff is 20° and for landing 30°. The aft segment of the double slotted flap is controlled by a high band-pass actuator for use by the ride control system (RCS). The

Presented as Paper 72-64 at the AIAA 10th Aerospace Sciences Meeting, San Diego, Calif., January 17–19, 1972; submitted February 1, 1972; revision received May 11, 1972. This work was sponsored by the NASA Langley Research Center under contract NAS1-10410. Additional team members producing this work are: G. E. Bergmann, G. E. Hodges, R. L. Morris, and L. H. Pasley.

Index categories: Aircraft Gust Loading and Wind Shear; Aircraft Configuration Design; and Aircraft Handling, Stability, and Control.

* Chief, Technology Research; Wichita Division. Associate Fellow AIAA.

† Chief, Flight Controls Staff; Wichita Division. Member AIAA.

‡ Chief, Aerodynamics Staff; Wichita Division. Member AIAA.

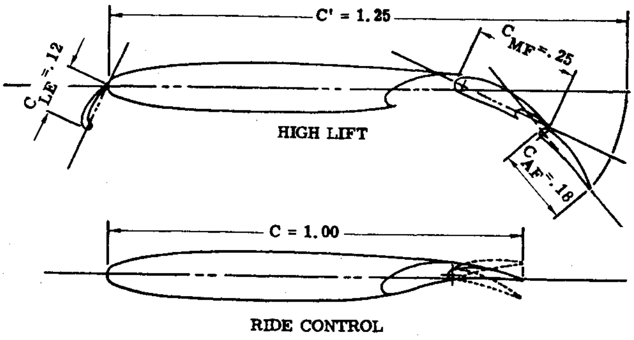


Fig. 2 Flap system.

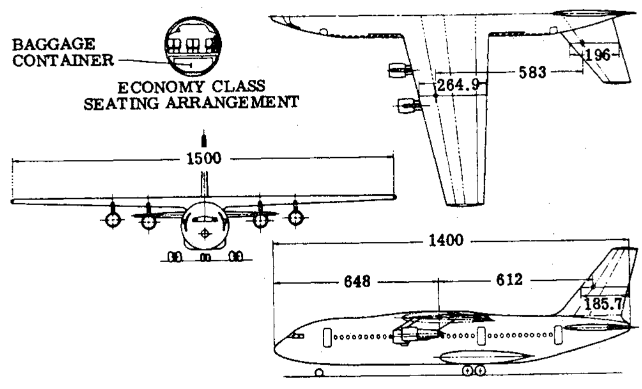


Fig. 4 Low wing-loading STOL study vehicle.

estimated maximum authority required of the aft flap segment for ride smoothing is $\pm 10°$ from its nominal position.

A simple parametric study was performed to define the configuration which would satisfy the mission requirements and airworthiness standards. A composite of these requirements is presented as a function of wing loading and thrust-to-weight ratio in Fig. 3. The takeoff requirement is for a 2000 ft F.A.R. field length. The takeoff climb requirements and the balked landing requirements are established for the most critical engine inoperative. The landing field length includes 67% conservatism. The cruise requirement is for a bypass ratio 4 turbofan engine (determined from sizing studies) at a Mach number of 0.75 at 30,000 ft altitude.

The configuration selected for the ride quality studies had a sea level static thrust-to-weight ratio = 0.35, and a maximum gross weight wing loading of 50 psf. This configuration has a good match between takeoff and cruise thrust requirements, which would not be the case for a higher cruise speed.

The study airplane configuration is shown in Fig. 4. The fuselage represents current wide body philosophy, incorporating a twin-aisle which aids rapid loading and unloading. The flight controls are conventional aerodynamic surfaces with minimum augmentation. Longitudinal controls consist of a 30% chord elevator and a low-rate all movable stabilizer. The directional axis is controlled by a large chord rudder on a conventional vertical tail. Lateral control is provided by wing mounted spoilers, which are also used for landing roll airbrakes.

It was assumed early in the study that an all movable vertical tail might be required to provide control power adequate for lateral ride smoothing. This dictated the low horizontal tail shown on the configuration in Fig. 4. As the study progressed it became obvious that the rudder would provide satisfactory authority for lateral ride smoothing.

As indicated in Fig. 5, a cruise altitude of 30,000 ft results in the lightest airplane that can reach 0.75 Mach number for cruise with a thrust/weight less than 0.35 when referenced to sea level static takeoff rated power. For low bypass ratio engines, the engines are sized by the takeoff requirement. As bypass ratio is increased, the engines become sized by the cruise thrust requirement due to the thrust lapse-rate characteristics of the engine.

As shown in Fig. 6, gross weight is extremely sensitive to cruise Mach number above Mach 0.75. The small block time advantage between Mach 0.7 and 0.75 may not be enough to merit the additional weight. A block time savings is indicated for cruise Mach numbers higher than 0.75. This is due to the lower climb times with the higher thrust/weight required to fly faster than Mach 0.75. However, it is questionable as to whether the resulting weight penalty would be economical. A more extensive configuration development could further refine the selected airplane by optimizing for economy.

The Direct Operating Cost (DOC) of the light wing-loading STOL airplane is shown in Fig. 7. The DOC was calculated

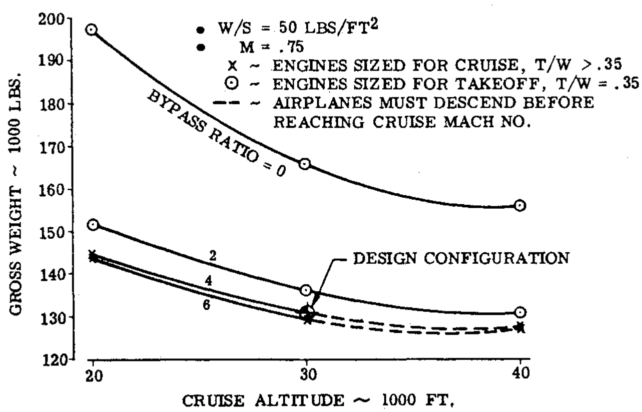


Fig. 5 Sizing study.

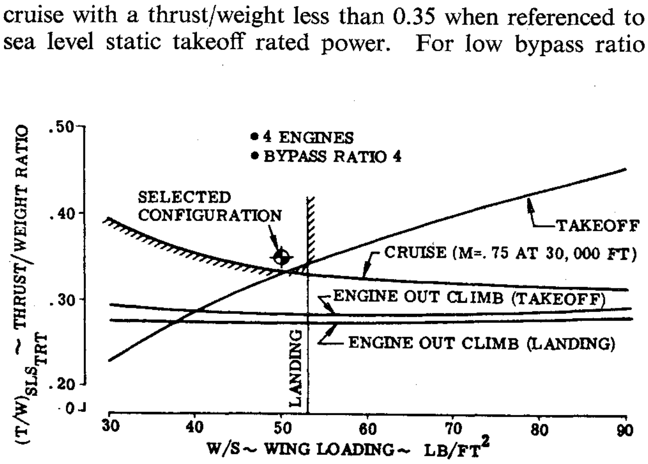


Fig. 3 Thrust and wing loading requirement.

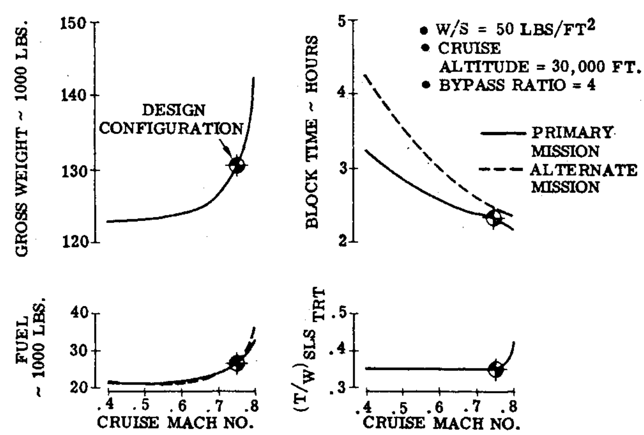


Fig. 6 Configuration sensitivity to cruise speed.

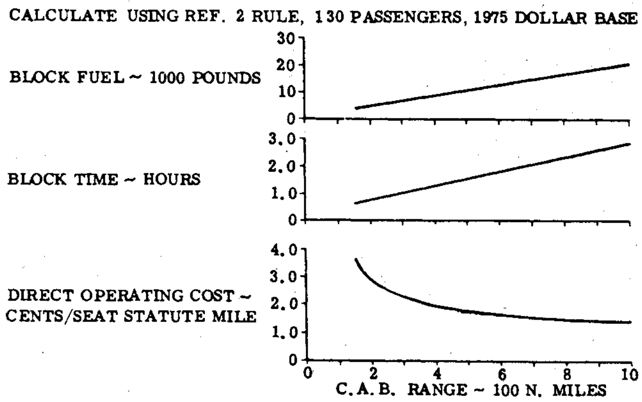


Fig. 7 Light wing loading STOL economics.

using the Eastern Air Lines DOC formula, with costs inflated to 1975 dollars.[2] DOC comparisons to other airplanes were not available; however, limited comparisons indicate that the DOC's of the present airplane are comparable to those of other STOL airplanes.

The trend of today's advancements in engine technology is toward smaller, lighter and more efficient propulsion packages. Engines used for this study were assumed to be 1975 reflections of this trend which is advantageous from the engine efficiency standpoint but not necessarily compatible with minimum engine noise. A critical point for STOL noise is the sideline. Data for 1000 ft sideline are shown in Fig. 8.

Ride Control System Definition

The ride control system (RCS) synthesis consisted of three elements: ride quality criteria definition, system conceptual trades, and analysis of RCS performance benefits at three selected flight conditions.

The three flight conditions shown in Table 1 were selected to provide a reasonable variation of conditions within the STOL flight envelope. Wing loading was held constant at 46 psf. A cruise condition was selected since a significant portion of flight time occurs at this condition. The most severe ride occurs at high speed descent, where the airplane is sensitive to turbulence. During landing approach with corresponding low dynamic pressure, large control surface deflections are required to produce aerodynamic forces and moments sufficient for ride smoothing purposes.

Small perturbation, linear, rigid body equations of motion with six degrees-of-freedom were used in the airplane mathematical models. Random turbulence and discrete 1-cos gusts were used to define surface rate and displacement limit

Table 1 Flight condition definition

Flight conditions	Weight	Altitude	Mach no.	Velocity	Wing loading
Cruise	120,000 lb	30,000 ft	.75	283 Kcas	46 lb/ft^2
Descent	120,000 lb	15,000 ft	.75	370 Kcas	46 lb/ft^2
Landing approach	120,000 lb	50 ft	.12	79 Kcas	46 lb/ft^2

effects. Random atmospheric turbulence was modeled with a von Kármán power spectral density function.

Four aerodynamic control surfaces were considered: full-span trailing-edge flap, elevator, spoiler, and rudder. The 30% chord elevator and 18% chord rear segment of the full-span, double slotted flap were used in the longitudinal RCS. The 40% chord rudder was used in the latest RCS.

The probability of exceeding a specified rms gust velocity varies as a function of altitude as shown by the constant exceedance probability curves in Fig. 9. An exceedance probability level of 10^{-3} was selected for this study. Corresponding rms gust velocities for the selected cruise, descent, and landing approach conditions are 5.6, 8.2 and 9.8 fps, respectively.

Criteria for determining STOL aircraft ride qualities were based on passenger compartment vertical and lateral linear accelerations. Based on results of ride quality moving base simulator tests and a review of Boeing commercial transport acceleration levels, acceptable acceleration criteria for a 10^{-3} exceedance probability turbulence were set at 0.11 g's vertically and 0.055 g's laterally. The lateral acceleration criterion was set at one-half the vertical criterion since tests have indicated that, at rigid body frequencies, humans are approximately twice as sensitive to lateral oscillations as vertical oscillations.

The longitudinal ride control system developed during the synthesis consists of two feedback loops: c.g. vertical acceleration driving the aft segment of the full-span trailing-edge flap, and pitch angular rate driving the elevator. A block diagram is shown in Fig. 10. The acceleration feedback provides ride smoothing, and the pitch rate feedback provides satisfactory handling qualities. A high-pass filter in the acceleration feedback improves phugoid mode stability and a low-pass filter in the elevator feedback provides proper phasing for handling qualities.

Although no attempt was made during this study to define gain scheduling requirements, it may be necessary to schedule gains as a function of flight condition.

During cruise and descent, the synthesized lateral ride control system (Fig. 11) uses aft body lateral acceleration and yaw rate feedback signals driving the rudder to provide ride smoothing and satisfactory handling qualities. At landing approach, lateral acceleration feedback produces excessive

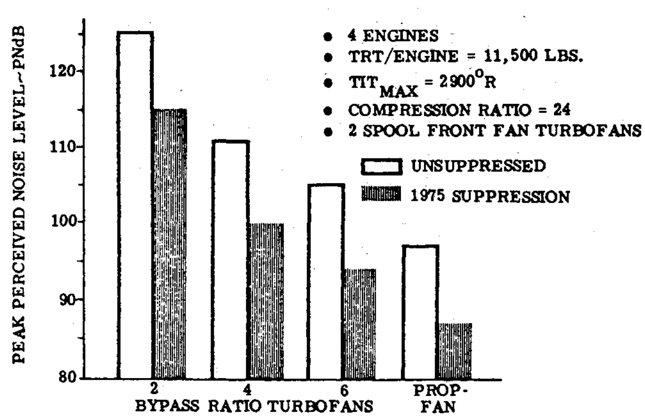


Fig. 8 Takeoff noise at 100 ft sideline.

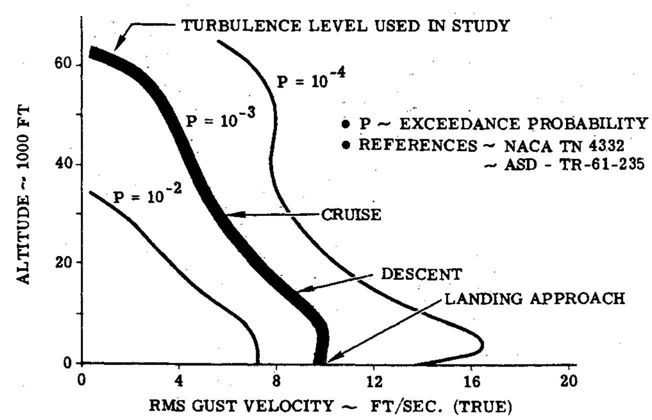
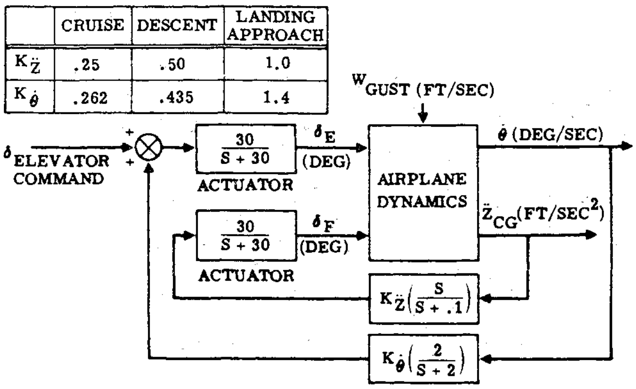


Fig. 9 Turbulence level criteria.



	CRUISE	DESCENT	LANDING APPROACH
$K_{\ddot{Z}}$	.25	.50	1.0
$K_{\dot{\theta}}$	.262	.435	1.4

Fig. 10 Longitudinal ride control system.

spiral mode divergence and is, therefore, not used at this condition. A high-pass filter in the acceleration loop minimizes this effect at cruise and descent conditions. In the yaw rate loop a high-pass filter washes out steady-state signals, providing satisfactory coordination during turns.

Although gain scheduling will probably be required, no attempt was made to establish gain scheduling requirements because of the limited scope of the study.

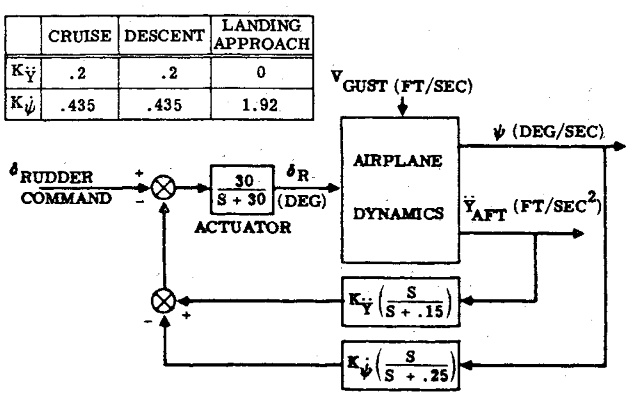
Passenger compartment vertical and lateral accelerations at the three selected flight conditions (cruise, descent and landing approach) are illustrated in Figs. 12, 13 and 14. Acceleration levels are for rms gust velocities corresponding to an exceedance probability of 10^{-3}. At the cruise condition, "airplane without RCS" vertical acceleration fails to meet the criteria, although the lateral acceleration criteria is met at all passenger compartment locations. (Fig. 12.)

The high-speed descent condition (370 KCAS at 15,000 ft) was selected for analysis because of the severity of the ride at this condition. With a gust velocity of 8.2 fps, the "airplane without RCS" has a c.g. rms vertical acceleration of 0.28 g's and an aft body rms lateral acceleration of 0.11 g's. (Fig. 13.)

At the landing approach condition, the "airplane without RCS" aft passenger compartment has a rms vertical acceleration of 0.22 g's and a rms lateral acceleration of 0.067 g's. (Fig. 14.) With the RCS, vertical and lateral accelerations meet the criteria at all passenger compartment locations, for all three flight conditions (Fig. 12, 13, 14).

Figure 15 illustrates vertical and lateral acceleration time histories at the descent condition with and without the RCS in random vertical and lateral turbulence. At the descent condition, the RCS reduces rms vertical acceleration levels 72% and rms lateral acceleration levels 60%.

Although the RCS was not designed to reduce airplane angular rates, it significantly reduces roll, pitch and yaw rates at the three flight conditions investigated, as shown in Fig. 16.



	CRUISE	DESCENT	LANDING APPROACH
$K_{\ddot{Y}}$	.2	.2	0
$K_{\dot{\psi}}$	.435	.435	1.92

Fig. 11 Lateral ride control system.

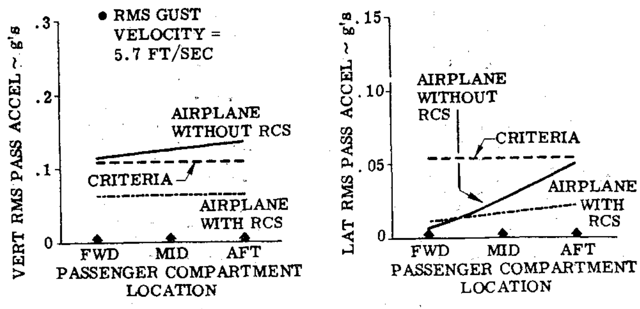


Fig. 12 Passenger ride quality during cruise.

Longitudinal handling qualities were evaluated at the three flight conditions using the airplane pitch rate response criteria contained in SST design requirements. (Fig. 17.) At all three conditions, the "airplane without RCS" meets the criteria. Adding acceleration feedback for ride smoothing degraded airplane response. Therefore, pitch rate feedback was required for satisfactory longitudinal handling qualities.

Lateral handling qualities were evaluated based on rigid body characteristic root requirements contained in MIL-F-8785B (ASG) dated Aug. 7, 1969 (Table 2). All lateral

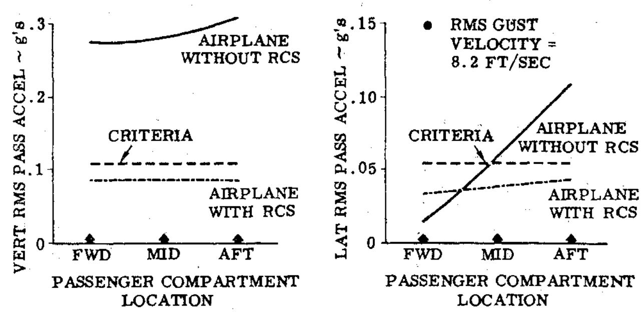


Fig. 13 Passenger ride quality during descent.

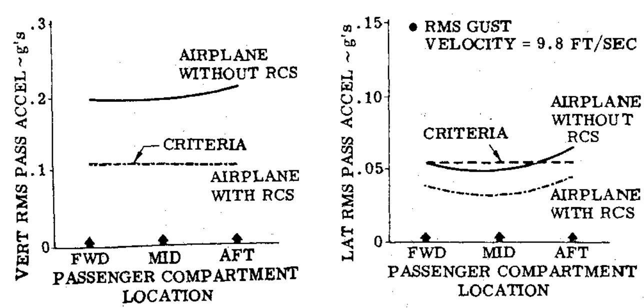


Fig. 14 Passenger ride quality during landing approach.

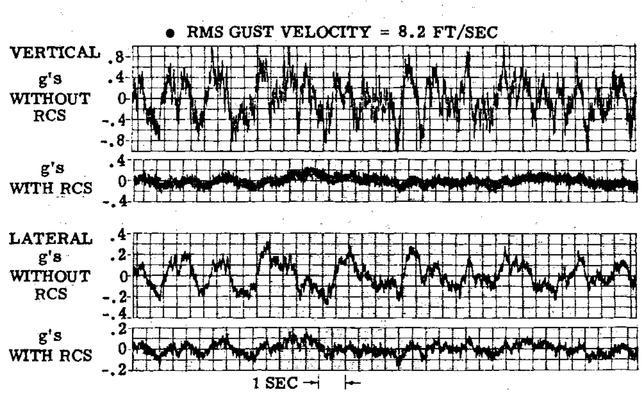


Fig. 15 Aft passenger acceleration response to random turbulence during descent.

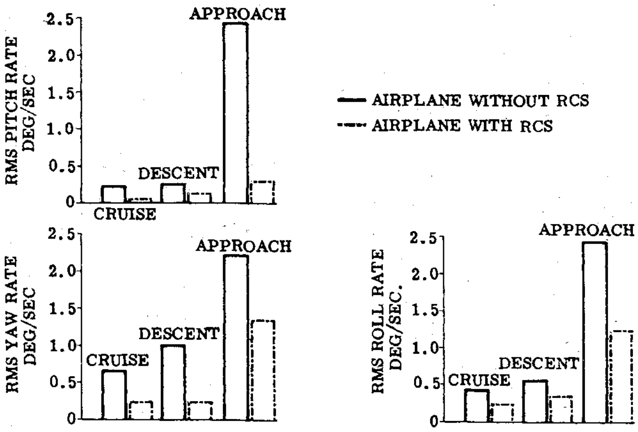


Fig. 16 Airplane angular rates.

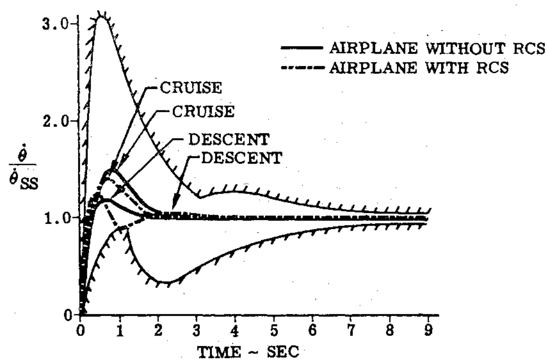


Fig. 17 Longitudinal handling qualities.

criteria are met except for spiral mode time-to-double-amplitude at the landing approach condition. The spiral mode time-to-double-amplitude at this condition is 8.2 sec compared to a requirement of 20 sec or greater. Future studies will consider the feasibility of roll feedback to eliminate this handling qualities deficiency.

Three-sigma control surface deflection and rate requirements for a 10^{-3} exceedance probability turbulence level were determined for the three flight conditions. The approach condition requires maximum control surface deflection and rates. At this condition a flap deflection of $\pm 9°$, a rudder deflection of $\pm 8°$ and a flap rate of 100°/sec are required. (Fig. 18.)

These requirements are based on an actuator bandpass of 30 rad/sec. Lowering the actuator bandpass reduces the rate requirement. For the descent condition shown in Fig. 19, for example, an actuator bandpass of 10 rad/second and a corresponding maximum flap actuator rate of 45°/sec provide satisfactory vertical acceleration reductions.

Effects of flap displacement and flap rate limits on acceleration reductions were determined at the descent condition for a

Table 2 Lateral handling qualities[a,b]

Flight condition	Dutch roll mode: Damping ratio ξ	Dutch roll mode: Damping factor $\xi\omega_N$	Roll mode time const. (sec)	Spiral mode time to double ampl. (sec)
Cruise	>.19	>.35	<1.4	>20
Descent	>.19	>.35	<1.4	>20
Approach	>.08	>.20	<1.0	>20

[a] Criteria (MIL-F-8785B).
[b] Airplane with RCS satisfies lateral handling quality criteria except during approach the spiral mode time to double = 8.2 sec.

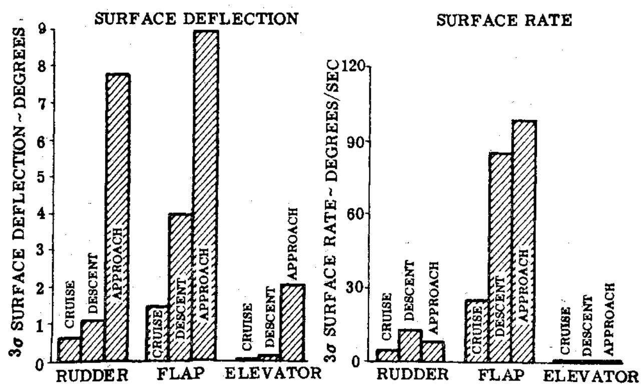


Fig. 18 RCS control surface deflection and rate requirements.

1-cos discrete gust with a peak velocity of 60 fps. (Fig. 20.) Frequency of the gust was adjusted to provide maximum acceleration (2.8 g's) without the RCS.

With the RCS the peak acceleration is reduced to less than one g with flap displacements of $\pm 10°$ and flap rates of $\pm 30°$/sec, as shown in Fig. 20.

Potential Problems

This study was based on a linear analysis using a rigid body airplane mathematical model with an ideal single channel flap mechanization. Several areas not considered could present potential problems and should be investigated further.

Structural flexibility may make it difficult to reduce the accelerations to the extent indicated with a rigid body model.

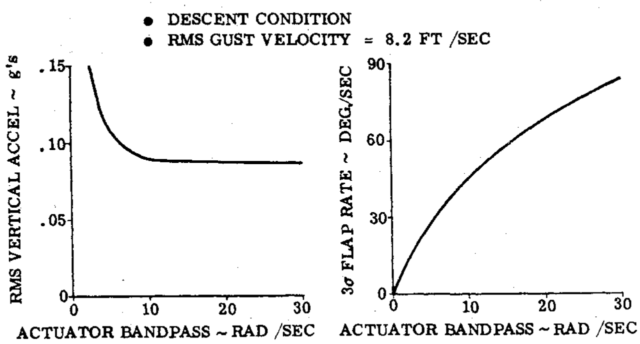


Fig. 19 Effect of flap actuation bypass.

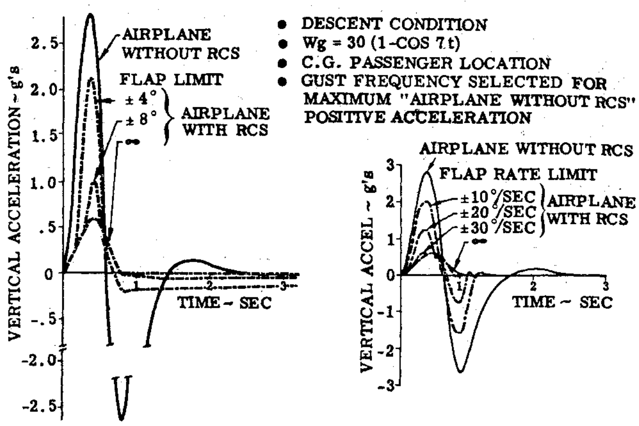


Fig. 20 Passenger acceleration response to 1-cos gust.

Adequate structural mode stability may limit system ride smoothing performance.

Control system nonlinearities during severe turbulence can cause excessive structural loading and reduced stability. Based on nonlinear analyses, design criteria must be defined to prevent this possibility.

This study assumed that the flap rear segment can be driven in retracted and extended positions. Potential problems associated with mechanizing a high response, aft segment full-span double-slotted flap should be considered. Related areas for study include redundancy, hydraulic power, and flap segment requirements.

Although the primary objective of the RCS is to provide ride smoothing, handling qualities and maneuvering requirements must be satisfied within the airplane operational flight envelope. Compatibility of these two functions must be thoroughly analyzed.

Conclusion

Keeping in mind the potential problems noted, this brief study indicates that a low wing-loading STOL aircraft with a ride control system provides satisfactory ride qualities and competitive high-speed performance. Further studies and flight tests should be conducted to analyze potential problems in depth and to obtain additional confidence in the concept.

References

[1] Sliff, R. S., "Tentative Airworthiness Standards For Powered Lift Transport Category Aircraft," FAA Flight Standards Service, Aug. 1970, D.O.T., Washington, D.C.

[2] Stater, R. S. and Hazen, S., "Operational Requirements and Guidelines For V/STOL Systems," E-482, Aug. 1970, Eastern Air Lines.

[3] Press, H. and Steiner, R., "An Approach To The Problem Of Estimating Severe And Repeated Gust Loads For Missile Operations," TN-4332, Sept. 1958, NACA, Langley Aeronautical Lab., Langley Field, Va.

[4] Neuls, G. S., et al., "Optimum Fatigue Spectra," ASD-TR-61-235, April 1962, United States Air Force, Aeronautical Systems Div., AFSC, Wright-Patterson Air Force Base, Ohio.

AUGUST 1972 J. AIRCRAFT VOL. 9, NO. 8

Application of the Head-Up Display (HUD) to a Commercial Jet Transport

J. Michael Naish*
Douglas Aircraft Company, Long Beach, Calif.

Previous work with HUD is extended by solving problems of installation in a commercial jet transport, and by demonstrating a high order of accuracy in manual control. Spatial aspects of the symbol format are organized to accord with principles promoting a balanced flow of information from the pilot's superimposed visual fields. Alternate installations are compared in DC-9 flight tests, an overhead mounting being found less prone to glare effects. Temporal aspects of the format are optimized by determining empirical relationships between gains and performance measures, for one test pilot, and conditions are chosen which enable subsequent users consistently to demonstrate equivalence between manual and automatic methods of flight control. Consequently, a new basis is suggested for evaluating an all-weather approach system.

Introduction

The original purpose of the Head-Up Display (HUD) was simply to supply information during visual flight without reducing the ability to see the outside world. But it was found, in the course of development for military airplanes, that the system was used with greater accuracy than a conventional flight instrument system.[1] The level of tracking accuracy was sufficient to allow comparison with an automatic flight control system, as indicated by Morrall,[2] and this suggested the possibility of an alternate method of all-weather approach and landing. Preliminary investigation with an experimental display installation, a small group of pilots, and in one type of commercial jet transport showed that full manual landings could be made in simulated category III conditions.[3] These results were promising, but needed to be confirmed; and it was clearly necessary to provide a more generally acceptable installation.

Although there is little difficulty in the military field, it is an immediate problem in commercial application to find room for the display equipment. A reflecting collimator has to be installed without affecting the view through the windshield, and without disturbing or obscuring the panel instruments. In the preliminary work it was sufficient to strap the display unit directly to the glareshield, ignoring interference with the forward view. But a more satisfactory method is now needed for production purposes.

Confirmation of the previously observed level of tracking accuracy, for a larger group of pilots, implies an optimum presentation, in which all aspects of the display are matched

Received January 27, 1972; revision received May 1, 1972. This work was performed at the Douglas Aircraft Company under the Independent Research and Development Program of the McDonnell Douglas Corporation. HUD equipment was kindly loaned by Elliott Automation and an experimental flight director computer by Sperry (Phoenix).

Index Categories: Navigation, Control, and Guidance Theory; Safety; Aircraft Flight Operations.

* HUD Coordinator. Associate Fellow AIAA.