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ACTIVE CONTROLS FOR RIDE SMOOTHING

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INTRODUCTION

Active controls technology offers great promise for significantly smoothing the ride, and thus improving public and air carrier acceptance, of certain types of transport aircraft. Recent findings which support this promise will be presented in the following three pertinent areas:

1. Ride quality versus degree of traveler satisfaction
2. Significant findings from a feasibility study of a ride smoothing system
3. Potential ride problems identified for several advanced transport concepts

RIDE QUALITY AND TRAVELER SATISFACTION

Aircraft Motion Characteristics

Large differences in ride smoothness can exist for transport aircraft as illustrated in figure 1, where levels of vertical acceleration are presented for three vehicles as a function of percent time that acceleration levels are exceeded. The data shown for airplanes A and B are averaged values of measurements obtained in the passenger compartment about every 2 minutes between takeoff and landing during many flights onboard scheduled passenger service in the eastern seaboard region of the United States.

For airplane C, data from which averaged values were obtained are much more limited, but are considered representative of cruise flight conditions for present-day large jet transports. Table I lists approximate values of several factors for the aircraft believed to influence the levels of vertical response. Acceleration levels for airplane C are favorably minimized by high wing loading, by wing sweep, by low tail volume coefficient, and by high cruise altitude. For the two smaller aircraft which have somewhat similar properties, the vertical acceleration levels for airplane B are significantly lower than for airplane A, probably because of the higher cruise altitude of these studies. The question arises as to how to interpret data such as presented in figure 1 in terms of passenger satisfaction. Before design goals can be established for application of active controls to ride smoothing, information is needed concerning the influence of ride quality on traveler acceptance and use of vehicles.

Comfort Factors and Criteria

Subjective response to motion has been studied in some detail to establish tolerance-limit criteria (e.g., ability to perform a specific task under adverse environmental conditions, exposure-time limit allowable in a high-vibration environment, etc.). In the area of the ride comfort, which involves much lower magnitude motions, meaningful information is limited and criteria are not well established. To fill a need in this area, NASA has under way considerable research concerning ride quality and traveler satisfaction. The effort described in reference 1 involves both field measurements to identify important factors (e.g., motion, vibration, etc.) and to develop approximate criteria, and laboratory and research aircraft experiments under closely controlled conditions to establish a good understanding of all factors involved. Much of the field measurement effort has been carried out as part of a traveler acceptance study by the University of Virginia under NASA grant. The study with some of the findings is decribed in reference 2. Information from that part of the study which addresses motion environment and passenger response will be used in the next few figures to illustrate how evaluation can be made of the ride quality. The study also provided the data for figure 1.

During flights on air carriers and research aircraft, simultaneous recordings were made of reactions of test subjects as well as of aircraft motion environment in all six degrees of freedom. Correlation of extensive data from a number of differenct aircraft indicated that ride comfort, while influenced by many factors, is particularly affected by vertical and lateral accelerations. Based on just these two factors, initial criteria have been developed of passenger ride comfort response. These criteria are presented in figure 2. Lines of approximately equal comfort rating are shown as a function of lateral and vertical acceleration. A five-unit descriptive scale of comfort rating was employed with terms ranging from Very Comfortable to Very Uncomfortable. Test subjects were about twice as sensitive to lateral accelerations as to vertical accelerations. In figure 3, acceleration values measured onboard airplane A are superimposed on the same scale. Of a total of 409 points, 25 points, which correspond to 6 percent, lie in the zone between Very Uncomfortable and Uncomfortable. An additional 46 percent falls in the region between Uncomfortable and Neutral. Thus, more than one-half the time, passengers could be expected to rate the ride as significantly less than Comfortable. Ride rating, however, does not tell the whole story. In surveys of passengers made at the end of trips, many passengers indicated, even after a ride rated as Uncomfortable, willingness to repeat the same trip. Figure 4 presents these results expressed as the variation in overall trip ride comfort rating with percent of passengers satisfied. For this figure, the word "satisfied" is defined as willingness expressed by the passenger to buy another ticket on the same aircraft and to experience the same ride. As would be expected, passenger satisfaction decreases substantially as the ride becomes progressively less comfortable, until only 25 percent were satisfied for a ride rated as Very Uncomfortable. Thus, passenger satisfaction can be related to ride comfort, which in turn can be related to the vertical and lateral acceleration environment.

Satisfaction Assessment of Aircraft

Figure 5 presents estimated traveler satisfaction characteristics derived from vertical and lateral acceleration data for the three aircraft discussed previously. Satisfaction is expressed in terms of percent travelers satisfied as a function of flight time percentile ranked by ride smoothness, with the smoothest periods of flight occurring at 0 percentile, and the roughest periods at 100 percentile. The term "traveler" is used rather than "passenger" to point out that about 5 percent of all travelers will not be satisfied in riding an aircraft no matter how smooth the ride may be. For this reason, airplane C, which is considered to have excellent ride characteristics when cruising in smooth air, is shown to be satisfactory under the best of conditions to only 95 percent of all travelers. For this aircraft, the ride quality continues to be quite favorable to the 90-percentile time point where about 90 percent of all travelers would be satisfied. In contrast, airplane A would be satisfactory to only 50 percent of all travelers at the 90-percentile time point and to slightly less than 80 percent of all travelers at the 50-percentile time point. While the trends indicated are considered significant, a note of caution needs to be interjected concerning the simplistic approach used to estimate traveler satisfaction. Actually, there are a number of factors other than vertical and lateral acceleration known to influence ride quality to some degree. Examples include disturbances in rolling motion, terminal-area maneuvers, visual cues, cabin temperature, and seat size. As more is learned in studies concerning these factors, the approach just described for estimating satisfaction can be refined to provide more precise evaluations.

Considerations for Application of Ride-Smoothing System

The trends shown in figure 5 indicate that, in terms of traveler satisfaction, the relative improvement possible by addition of an active-control system would be more modest for airplane C than for either airplane A or B. In addition to information as shown above, a decision to incorporate a ride-smoothing system into an aircraft involves a number of other considerations. Questions such as the following three are examples:

> What is the ride-environment conditioning of the passengers who will be using the aircraft? For residents in undeveloped regions, the ride of a DHC-6 could be a big improvement over the ride of an off-road mode of transportation, while for residents of a metropolitan area, seasoned by smooth rides on long-range, heavy aircraft, equally good rides could be expected of smaller short-haul aircraft used by the connecting feeder lines.
>
> Will increase in revenue from additional travelers gained by ride smoothing offset the increased costs of the active-control system? Carriers serving low-density markets may generate little, if any, additional business by ride smoothing, whereas air carriers serving high-density markets may generate considerable extra revenue by attracting customers from competitors whose aircraft have a poorer ride.

Is there a public responsibility to make the ride acceptable to the greatest possible number of travelers? Perhaps carriers serving the public should be obliged to conform to minimum comfort standards as well as to requirements concerning safety or to the amount of service given cities on their route structure.

Answers to the above questions will depend to a significant degree on detailed information on the active-control systems required for ride smoothing.

RIDE-SMOOTHING SYSTEM FEASIBILITY STUDY

Concurrent with subjective studies of ride quality, a feasibility study was carried out of an active-control system for the de Havilland DHC-6 aircraft for NASA by the Wichita Division of The Boeing Company assisted by de Havilland Aircraft of Canada, Limited. The objective was to examine the feasibility of developing and certificating a ride-smoothing-control system for a typical small feeder line aircraft known to have a ride environment not equal to that found on larger, high-wing-loading jet transports. The DHC-6 was selected for study not only because it has a low wing loading and is oftentimes operated extensively in low-altitude turbulence, but also because it is the only STOL vehicle presently certificated and extensively used by air carriers in this country. Its capability to carry out steep-angle climbouts and descents and to perform short-radius, terminal-area maneuvers makes suitable the study of ride-quality situations reasonably typical of those which may be encountered by subsequent advanced STOL/RTOL transports. An example application of this nature is the Canadian STOL Demonstration Program between Ottawa and Montreal, where modified DHC-6 aircraft are being used to obtain passenger acceptance data as well as to study and refine systems operations in advance of introduction of the new and larger DHC-7 STOL transport aircraft now being built for such service.

Description of System Studied

Quite a bit of information having general application to ride-smoothing systems was obtained from the feasibility study. Highlights of this general information will be presented herein; detailed description of the study and findings are presented in reference 3. Investigation of active controls was limited to only vertical and lateral ride smoothing, as preliminary study indicated response to turbulence to be acceptably low for the other degrees of freedom. The aerodynamic surfaces considered in the system are shown in figure 6 and include portions of the existing ailerons, elevators, and rudder as well as all-new spoilers. Consideration of additional surfaces could not be accommodated within the scope of the study. Ride control of each degree of freedom was treated independently. Simplified block diagrams showing feedback loops are presented in figure 7 for the vertical control system and in figure 8 for the lateral control system. Details such as transfer functions are not shown. System effectiveness was determined as reduction of acceleration response to a random turbulence intensity with an exceedance probability of 0.01 which was established as a gust velocity of 2.1 meters per second (rms) for the design flight conditions.

Ride-Control Effectiveness

In the area of effectiveness, the most important finding was the requirement for relatively large direct-lift and direct-side-force surfaces located near the airplane center of gravity. As shown by the bar charts of figure 9, significant reductions in vertical acceleration response were obtained with wing flaps retracted during both climb and cruise conditions. The elevator surfaces contributed only a modest amount to this reduction. For the landing approach condition, new spoilers had to be employed to even achieve the less-than-adequate reductions shown. Design techniques need to be developed for integrating large, direct-lift surfaces for ride smoothing into wing-flap systems. Use of rudder surfaces for reducing lateral response was somewhat effective in the aft section of the passenger cabin, but was ineffective ahead of the cabin midpoint. Efficient (high side-force/drag) direct side-force surface configurations need to be provided at a fore-and-aft location near the airplane center of gravity. Some technology for such surfaces was generated in the development of the General Purpose Airborne Simulator (GPAS) and the Total In-Flight Simulator (TIFS) research aircraft.

Aircraft Stability, Control, and Handling Qualities

In this area, a ride-smoothing system can be designed which is satisfactory. Considerable attention must be given, however, to various potential problems in order that the system be tailored to minimize adverse effects. In the feasibility study, problems which had to be resolved involved the aircraft low-frequency longitudinal mode, the very-low-frequency phugoid mode, the Dutch-roll mode, and the lateral-directional spiral mode. A detailed control system synthesis and performance analysis is required to examine various trade offs. During the study, problems also had to be resolved in aircraft handling qualities such as one where adding the active-control system caused a loss of effectiveness of the elevator to relatively sharp inputs. In this case, satisfactory short-period handling quality was achieved by introducing a crossfeed signal to the system to initially cancel the ride-control signal which opposed the acceleration, and then to wash out at the same rate as the ride-control signal. Use of ground based simulators is appropriate to study and help resolve handling problems.

Reliability and Safety

No major problems in reliability are anticipated for the ride-smoothing system. Since use of the system is not critical to the well being of the aircraft, the system can be deactivated if malfunctions occur. The main concern involves transient problems which could arise at the time of any malfunction. The worst problem envisioned would be hard-over deflection of an aerodynamic surface used in the active-control system. If sufficient authority is provided by the aircraft control system to control vehicle motions caused by such a deflection, safety can be maintained. Such authority would be a reasonable requirement for system certification. A fail-soft design control system, such as devised in the feasibility study, can also be incorporated for additional protection. The particular system studied contained dual signal channels with two stages of monitoring between channels for failure detection. An unfavorable comparison of channel signals would switch off the ride control signals.

System Components

Ride-smoothing hardware requirements are not considered to tax the present state of technology. Appropriate sensors, electronic elements, servosubsystems, and actuators are in production. The size and capacities of these components are not necessarily matched to detailed requirements, and modifications of existing designs may be required to obtain appropriately tailored articles. Aerodynamic requirements do require innovation, as discussed earlier, to develop configurations to efficiently produce aerodynamic forces through the center of gravity in both vertical and lateral directions.

Weight, Power, and Volume Requirements

Weight and power demands of a ride-smoothing system should not seriously burden the aircraft. Findings of the feasibility study indicated the total additional weight would amount to less than 2 percent of the aircraft gross weight. Additional power requirements of the system would amount to no more than 0.3 percent of the aircraft total engine power. Requirements for larger aircraft would not be expected to exceed these percentage values. Only a small additional volume is needed, but volume requirements in local regions near aerodynamic control surfaces may require special consideration, particularly if an existing aircraft is being retrofitted with a ride-smoothing system.

System Costs

Cost information is lacking because no detailed cost analysis has been carried out. Based on the findings presented above, system development and certification will require considerable effort which will be somewhat independent of aircraft size. Where the system is incorporated into the initial design of an all-new aircraft, the additional costs estimated for the system design through prototype flight tests and certification could range from 2 to 5 percent of the total costs. The additional cost would be expected to be higher if a system were to be designed and retrofitted into an existing vehicle. These higher costs result because of the probability of significant modification, requalification, and retesting of existing systems and structures. Estimated production costs for the system in terms of aircraft production cost could range from about 1 percent for large jumbo transports to as much as 4 or 5 percent for very small transports. Ride smoothing may be included as a feature of a multipurpose active-control system which performs other functions as well, such as gust-load alleviation. Design and checkout of an appropriate multipurpose system would require considerable effort, possibly greater than the sum of efforts required for individual systems.

Maintenance and Repair

Specific maintenance information is lacking until a ride-smoothing system is put into service. Considerable experience has been obtained, however, on a closely related active-control, fatigue-reduction system, described in reference 4, which was applied to the United States Air Force B-52G and B-52H fleet of 280 aircraft. For this application, system performance and maintenance experience has been excellent and well within guideline limits. Since an active-control, ride-smoothing system is essentially a state-of-the-art system competitive with control systems used on modern transport aircraft, maintenance should be similar to that required for current control systems.

Time Required for System Implementation

Little, if any, additional time would be needed if the decision to proceed is made at the beginning of an all-new aircraft project. For retrofit of a ride-smoothing system into an existing aircraft, the total time required is estimated to range between 2 and 3 years.

POTENTIAL RIDE PROBLEMS FOR ADVANCED TRANSPORT CONCEPTS

A number of advanced transport concepts are in various stages of technology development. Sufficient information is presently available to identify potential problems in ride quality for some of these concepts. Since only a qualitative assessment can be made of each problem, the exact role to be played by ride-smoothing systems cannot be exactly defined at this time. A description of potential problems is given for six vehicle concepts.

Large, Low-Wing-Loading Aircraft

One attractive concept, described in reference 5, for achieving STOL/RTOL capability in transports for medium- to high-density market short-haul use, involves the combination of low-wing-loading, mechanical-flap configurations with an active-control, gust-load alleviation system to minimize structural weight. Because of the relatively large wing area, response to vertical gusts can be expected to produce a ride which is less than satisfactory. Use of an active-control system will probably be required not only for gust-load alleviation, but for ride smoothing as well.

Powered-Lift Aircraft

Powered-lift concepts, which involve internally or externally blown flaps, can produce usable maximum-lift coefficients of two to three times those for current transports as described in references 6 and 7. Such high-lift capability is attractive for providing STOL/RTOL performance with high-wing-loading transports. For such configurations, engine-out control requirements will probably dictate the need for a relatively large vertical tail surface. Use of a large tail introduces a potential problem of uncomfortably large responses of the passenger compartment to lateral gusts. Use of an active-control system to reduce this lateral response is anticipated.

Terminally Configured Vehicles

Technology is being developed in the form of advanced display guidance and control systems together with new flight paths and operating techniques which can be applied to advanced aircraft specifically configured to more efficiently use the airspace in terminal areas and, thus, help relieve airside traffic congestion (ref. 8). The flight maneuver techniques are anticipated to involve relatively tight turns and abrupt decelerations which could introduce ride-quality problems, particularly if aggravated by oscillating motions of the aircraft due to air turbulence. In order that the maximum degree of planned flight maneuvers can be utilized, use of active-control systems may be required to minimize the random motion environment.

Supersonic Aircraft

The need to achieve efficient operations in supersonic-cruise flight leads to a configuration requirement for long, slender, and relatively limber fuselage configurations. Use of such configurations is anticipated to introduce problems of motion response in the passenger compartment to aeroelastic inputs during high-speed descent from cruise altitude, and to runway roughness inputs during taxi, take-off, and landing rollout. The magnitude of motion responses will depend on the fuselage structural dynamic characteristics and can be expected to vary considerably down the length of the passenger compartment. Problems may be of sufficient magnitude to warrant use of active-control systems to minimize motion. Solution to problems could lead to the need for a system of somewhat unconventional design.

Civil Helicopters

Significant effort is being directed toward providing advanced technology for large civil helicopter transports suitable for short-haul operations. Based on experience with large military vehicles, ride-quality problems can be anticipated from oscillating aerodynamic inputs associated with the rotating blades. These inputs result in vertical and lateral responses at discrete frequencies of the passenger compartment. The need for an active-control, rotor-feedback system to reduce responses is anticipated.

CONCLUDING REMARKS

A review has been given of the potential use of active-control systems for ride smoothing. Substantial differences in ride quality which can exist between transport aircraft have been illustrated, and a technique has been described for assessing these differences and the need for ride smoothing in terms of traveler satisfaction. Results from a ride smoothing feasibility study have been used to provide a generalized assessment of active-control systems for this purpose. The assessment, which includes effectiveness, reliability, maintainability, and costs, indicates that no major technical problems exist and that significant ride smoothing can be achieved within the present state of the art. Evaluation has been made of six advanced transport concepts to identify potential ride-quality problems and possible requirements for active controls. The next major step indicated for advancing ride smoothing technology is system application, demonstration, and evaluation for an aircraft in regular service.

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TABLE I - AIRCRAFT PROPERTIES AFFECTING RIDE QUALITY

	Airplane A (20 passengers)	Airplane B (29 passengers)	Airplane C (219 passengers)
Maximum take-off weight, N (lb)	55,600 (12,500)	104,000 (23,400)	1,490,000 (334,000)
Maximum wing loading, N/m^2 (lb/ft^2)	1,400 (30)	1,920 (40)	5,270 (110)
Wing sweep angle, degrees	0	0	35
Horizontal tail volume coefficient	0.94	1.02	0.63
Approximate cruise altitude of study, m ft	900 (3,000)	1,800 (6,000)	9,000 (30,000)

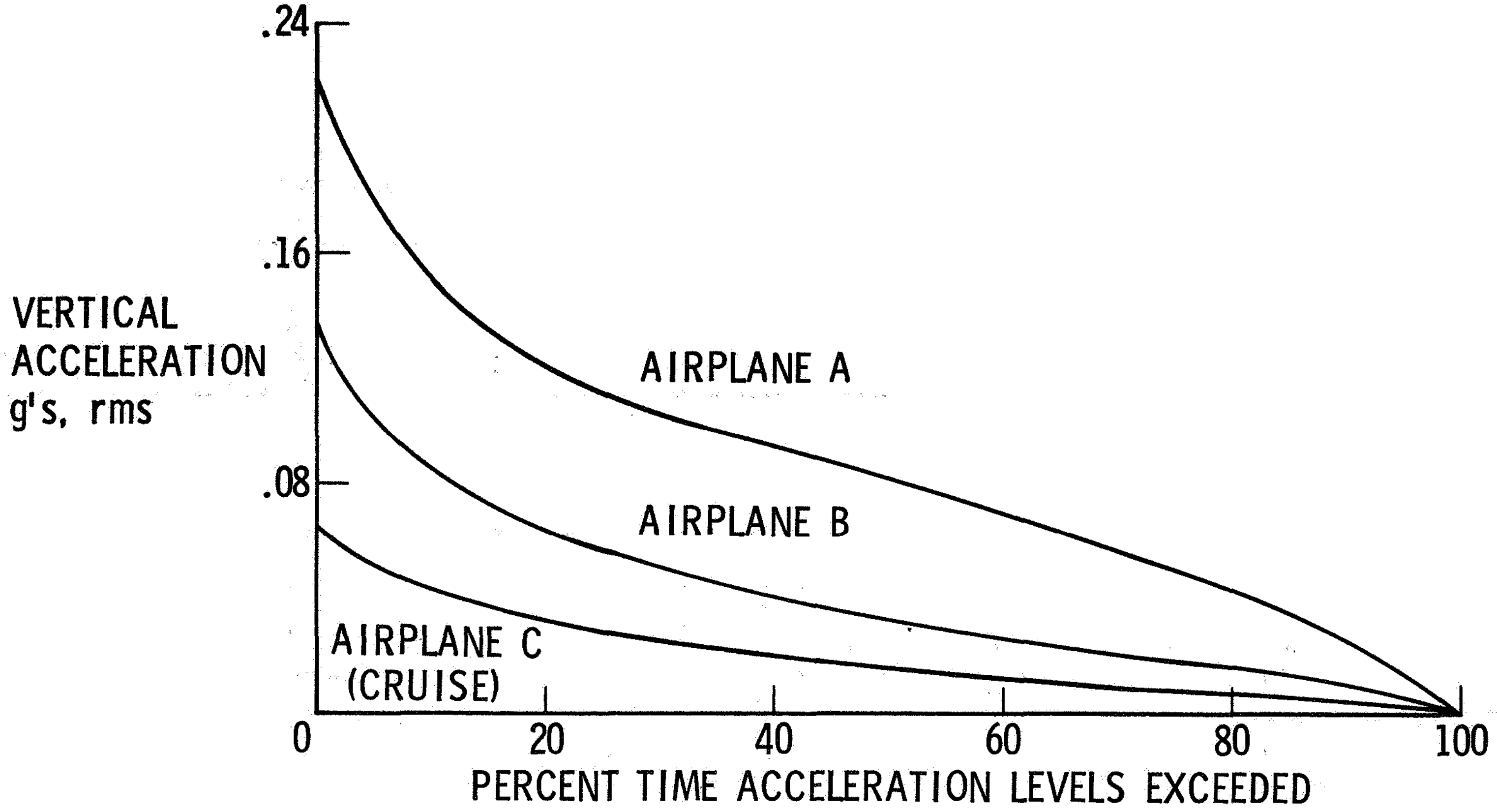

Figure 1. Example differences in aircraft motion characteristics for vertical acceleration.

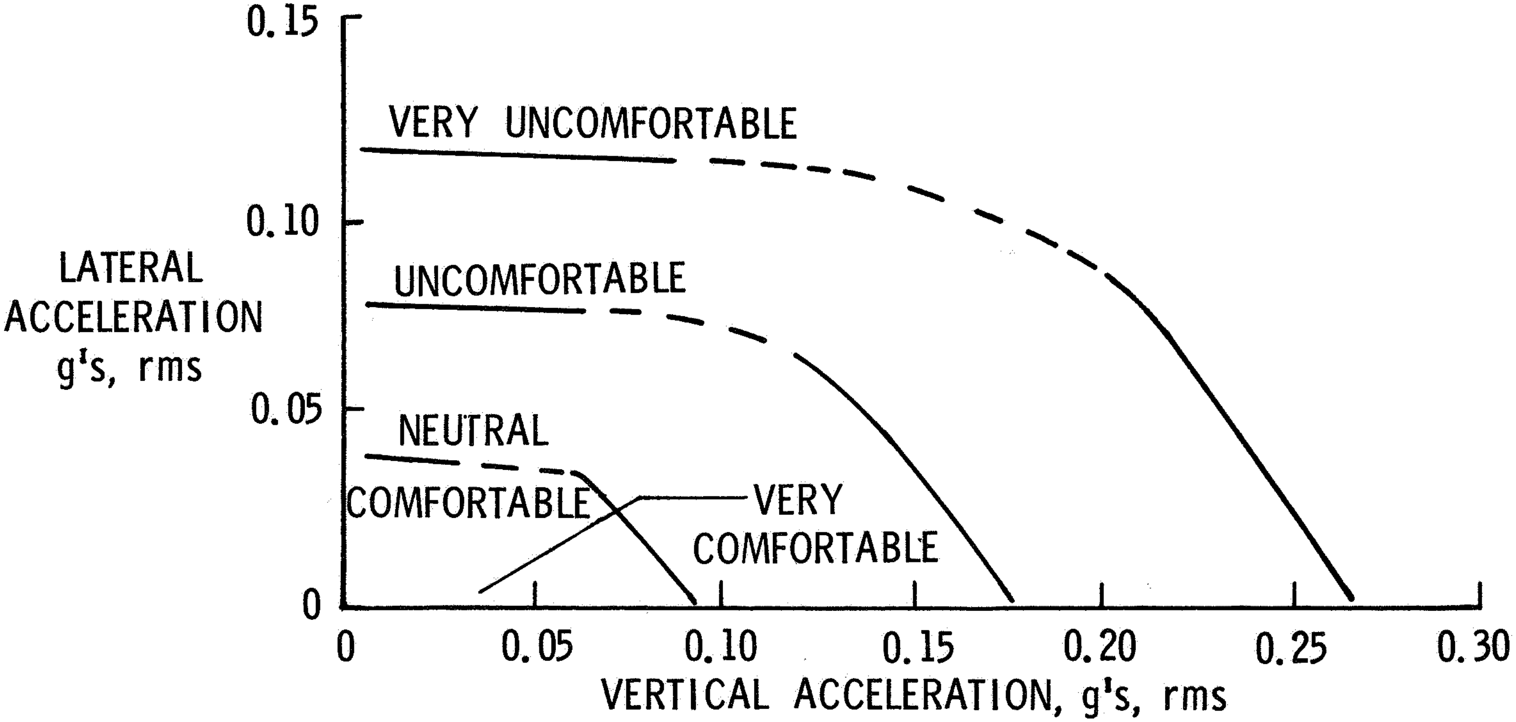

Figure 2. Significant comfort factors and initial criteria from airline and research aircraft.

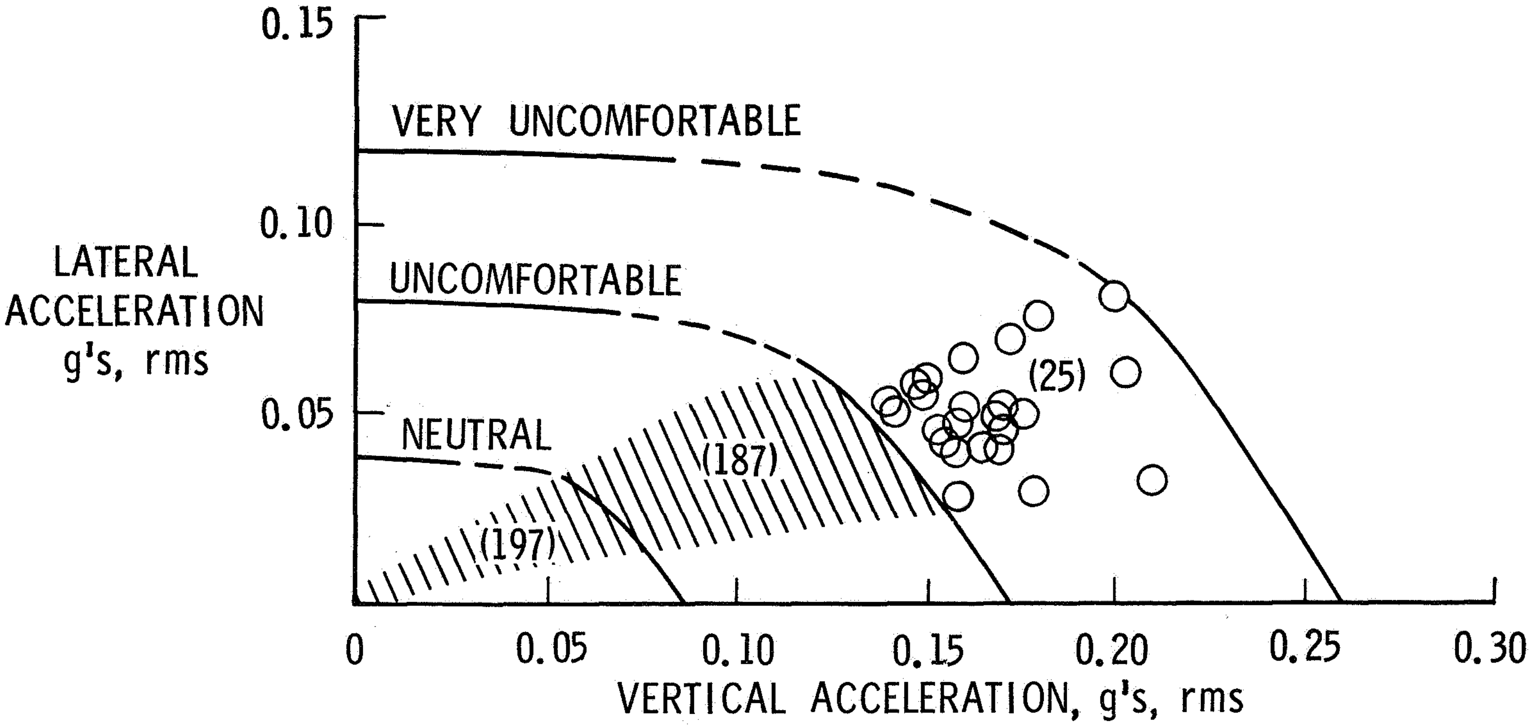

Figure 3. Comfort criteria applied to airplane A measurements (409 data points).

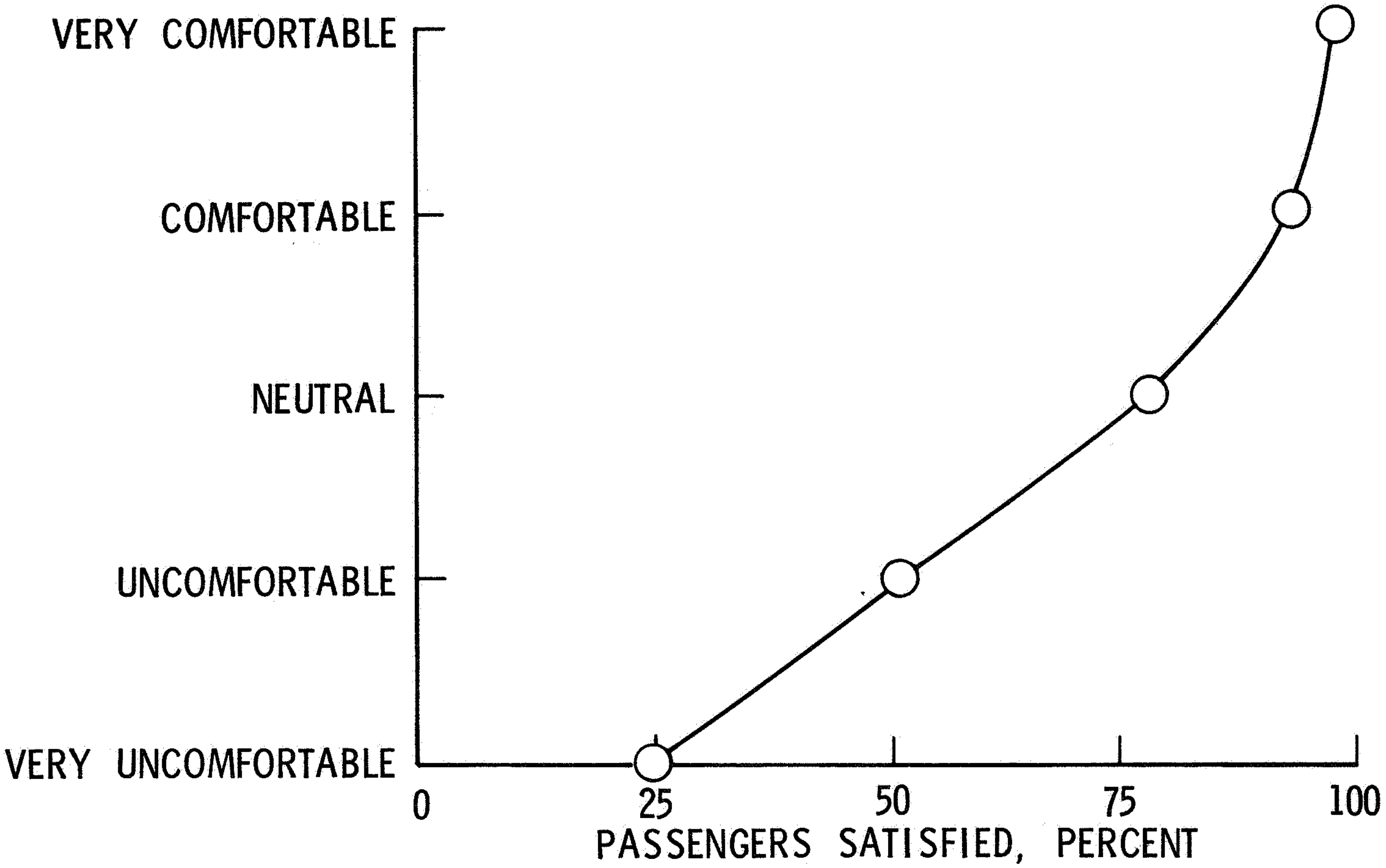

Figure 4. Relationship between comfort rating and passenger satisfaction.

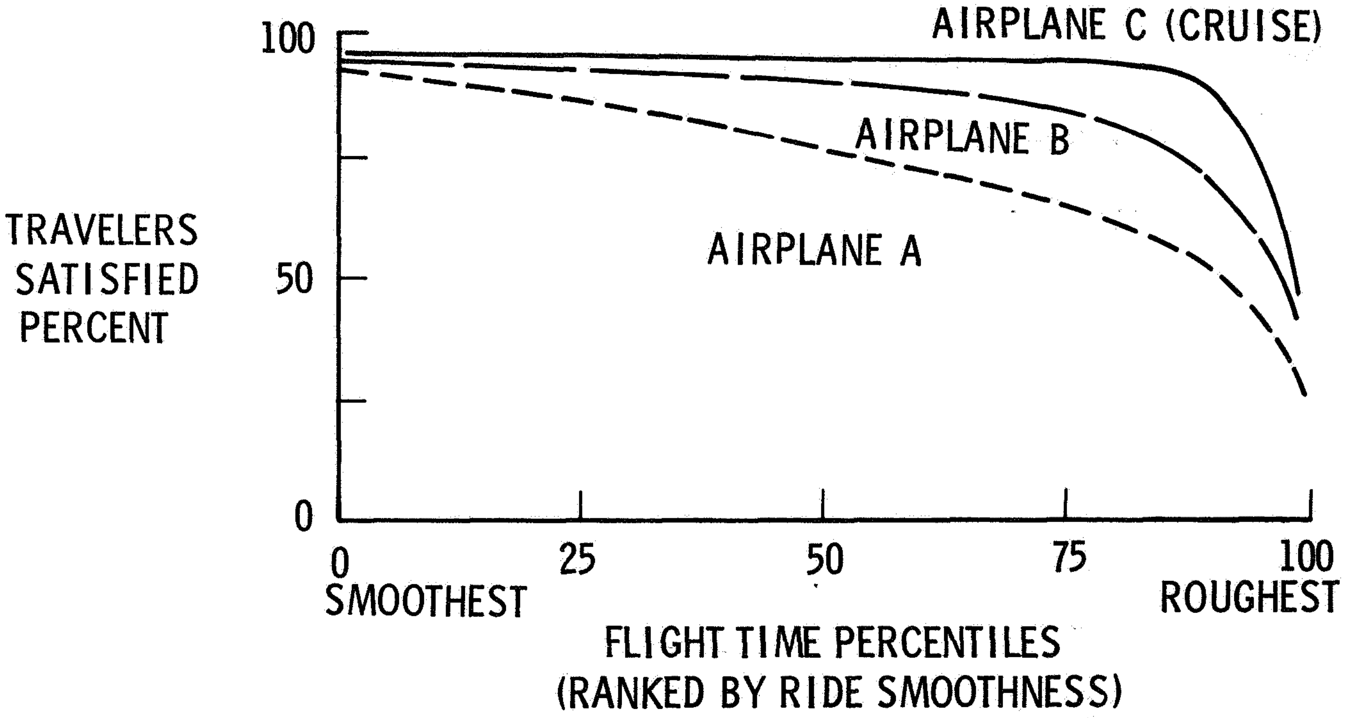

Figure 5. Estimated traveler satisfaction of three aircraft.

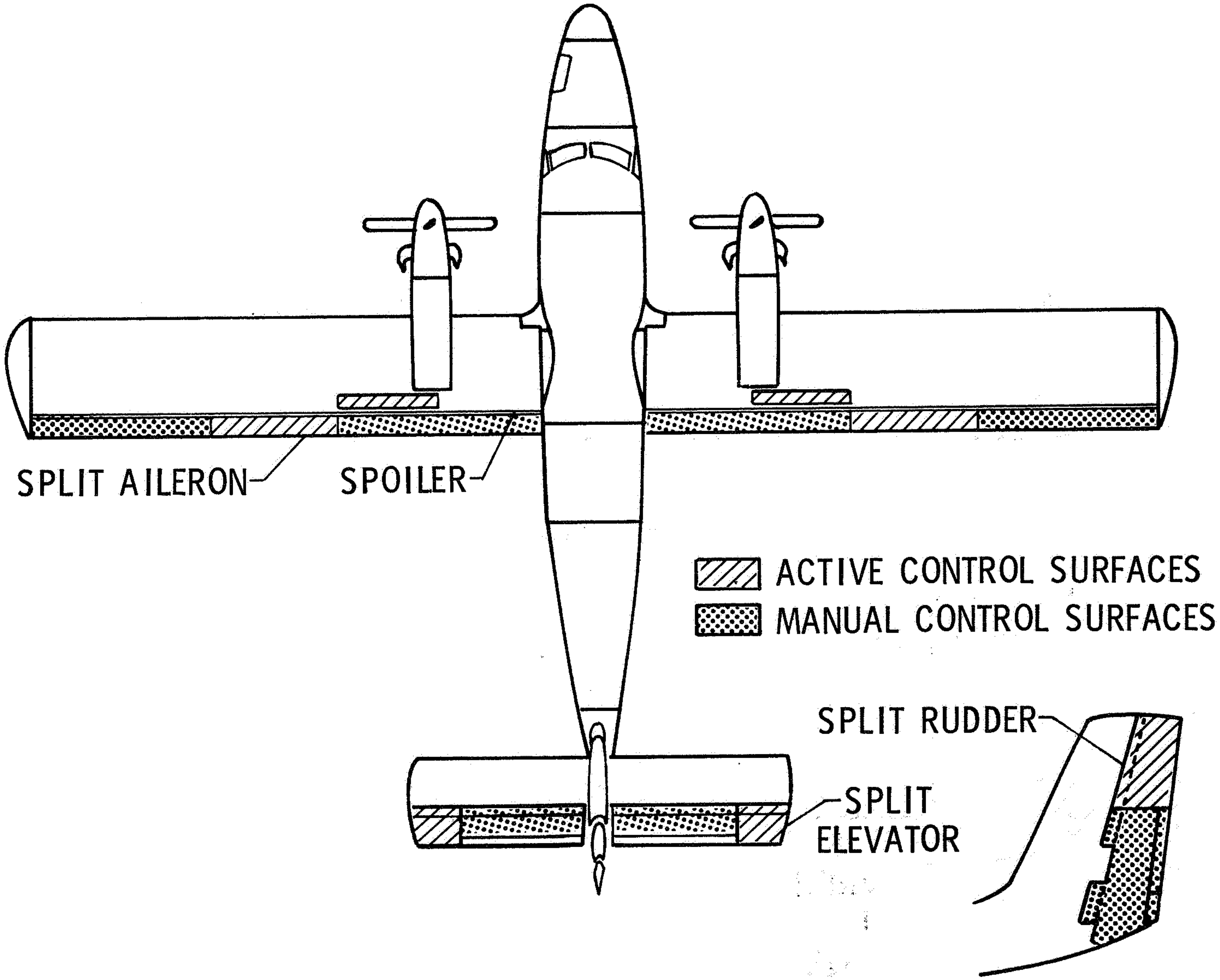

Figure 6. Active control surfaces studied on DHC-6 aircraft.

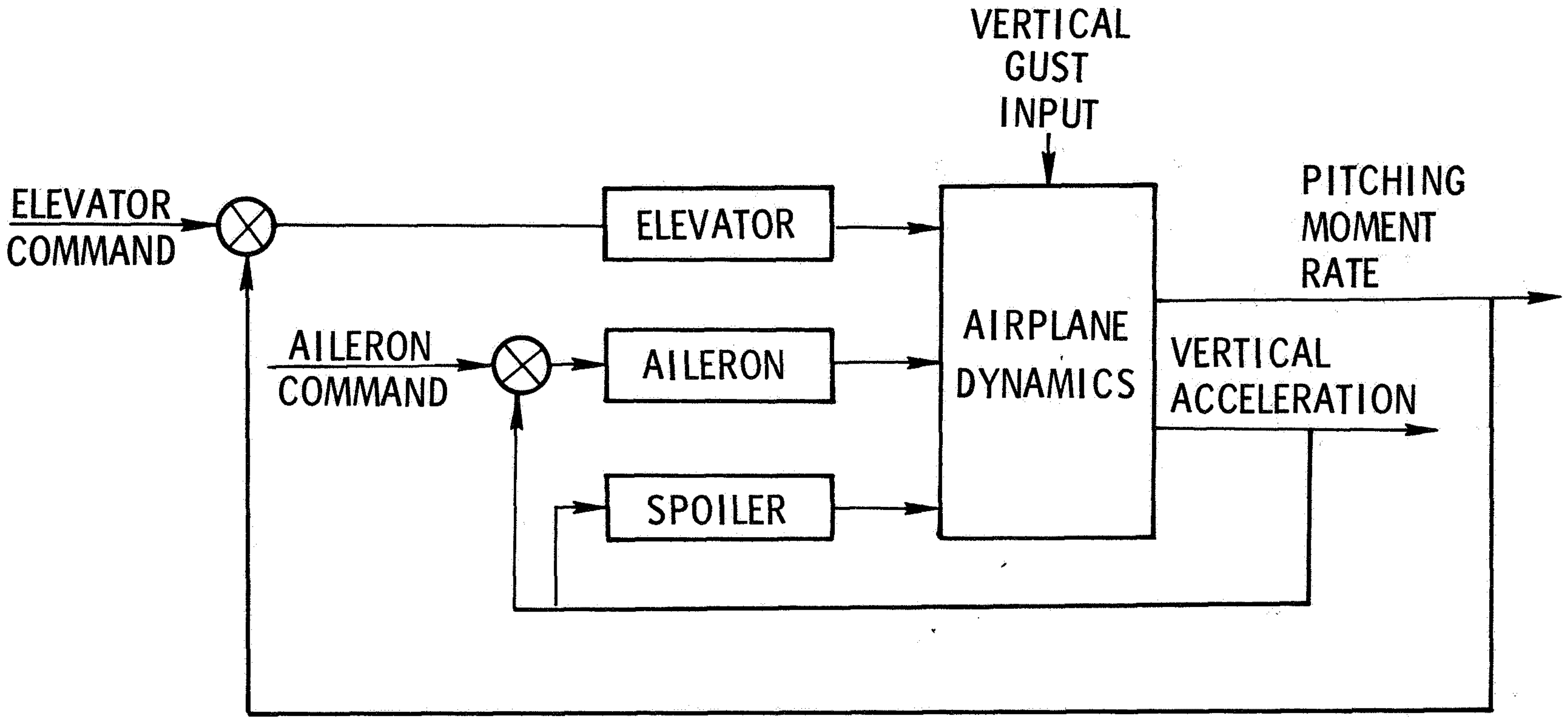

Figure 7. Block diagram of vertical ride-control system from DHC-6 study.

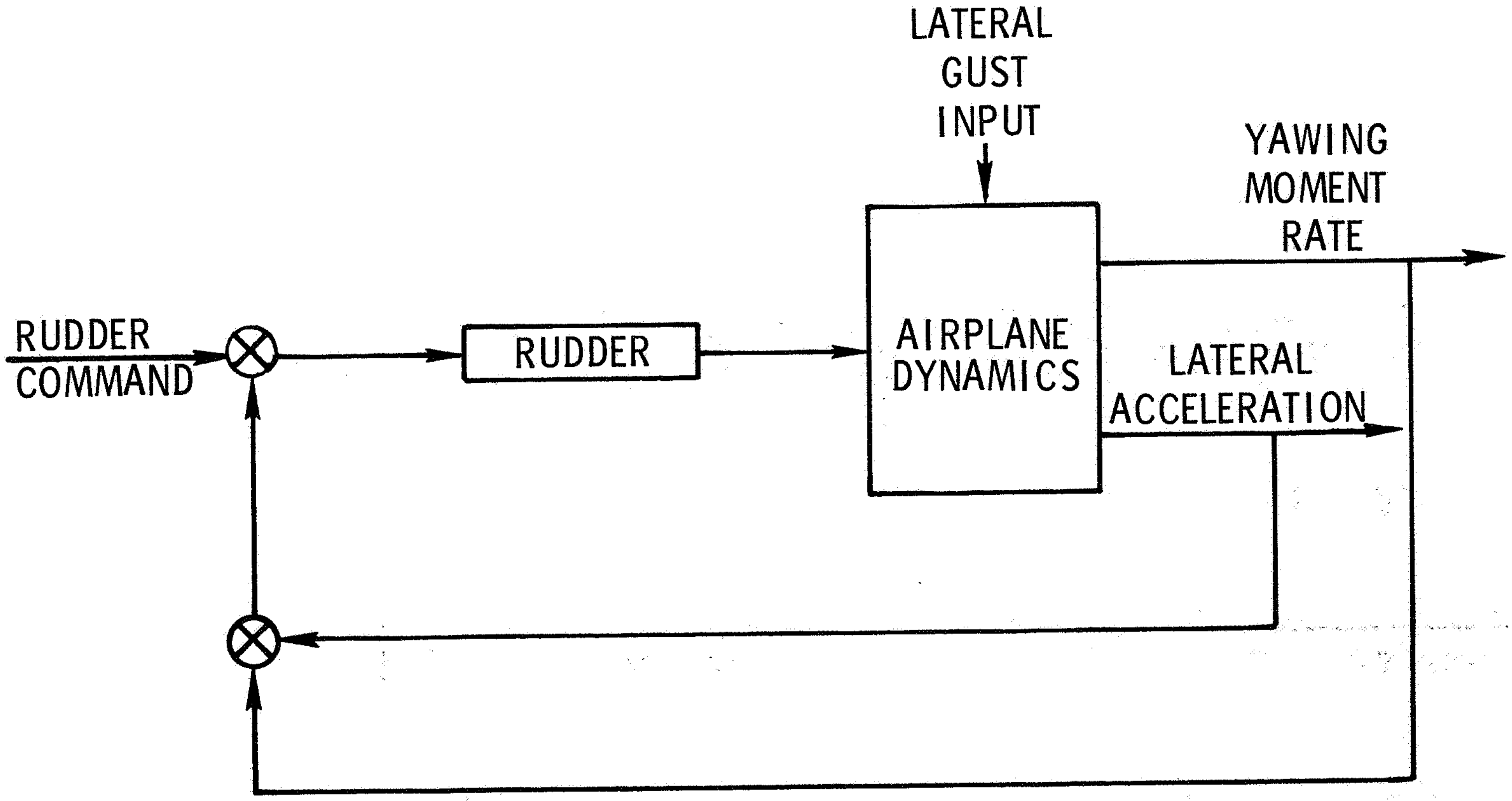

Figure 8. Block diagram of lateral ride-control system from DHC-6 study.

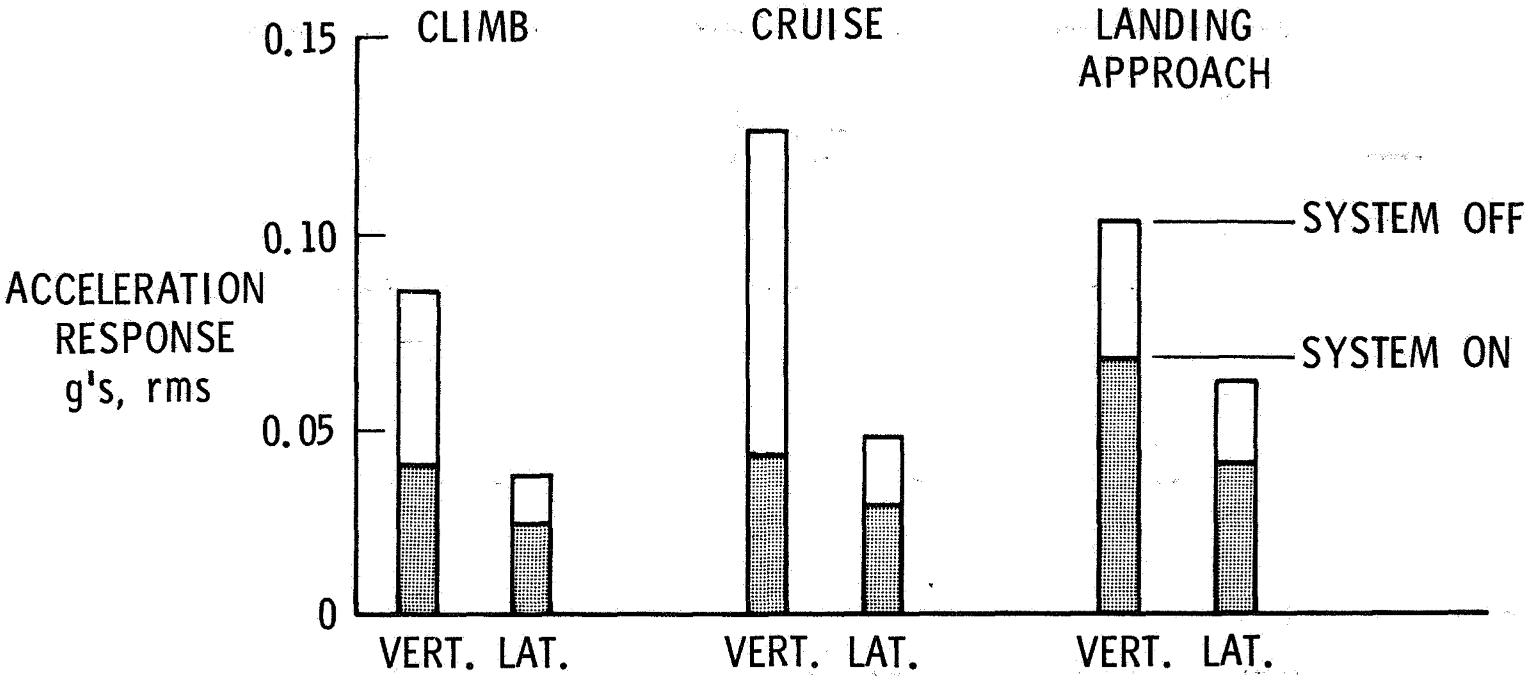

Figure 9. Effectiveness of ride-control system in terms of aft cabin response to 2.1 m/sec gusts.