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Piloted Simulation Study to Develop Transport Aircraft Rudder Control System Requirements

Phase 1: Simulator Motion System Requirements and Initial Results

March 2009

Final Report

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16. Abstract

This report documents Phase 1 of the Federal Aviation Administration piloted simulator study. The overall objective of this study was to provide guidance to develop rudder flight control system requirements. During the piloted simulator study, pilots flew through large lateral disturbances that required rudder inputs to augment the aileron.

The objective of this Phase 1 study was to determine the type of flight simulator required and, more specifically, the required lateral motion of the simulator. Once the appropriate type of simulator is determined, additional tests will be performed in Phase 2 of the piloted simulator study.

As a result of this study, it was determined that a simulator with large lateral travel should be used in future phases.

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LIST OF ACRONYMS

DER	Designated Engineering Representative
FAA	Federal Aviation Administration
FFT	Fast Fourier Transform
HM	Hinge moment
HQR	Cooper-Harper Handling Qualities Rating
KIAS	Knots indicated airspeed
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
PFD	Primary flight display
PIO	Pilot-induced oscillation
RMS	Root mean square
V_{MC}	Minimum controllable airspeed
VMS	Vertical Motion Simulator
YD	Yaw damper

EXECUTIVE SUMMARY

The Federal Aviations Administration piloted simulator study is designed to provide guidance to develop rudder flight control system requirements. During the piloted simulator study, pilots flew a flight simulator through large lateral disturbances that required rudder inputs to augment the aileron.

This report represents Phase 1 of this piloted simulator study. The goal of Phase 1 was to determine the type of flight simulator required and, more specifically, the required lateral motion of the simulator. Once the appropriate type of simulator is determined, additional tests will be performed in Phase 2 of the piloted simulator study.

As a result of this study, it was determined that a simulator with large lateral travel should be used in future phases.

1. INTRODUCTION.

This report describes the results of the first phase of piloted simulator evaluations to develop rudder flight control system requirements for up-and-away flight.

Rudder size and travel are typically defined by Federal Aviation Administration (FAA) requirements for minimum controllable airspeeds following an engine failure (V_{MC}) and crosswind limits for takeoff and landing. The rudder authority that results from these requirements can impose excessive loads on the vertical stabilizer at high airspeeds. Therefore, rudder travel is limited as airspeed increases. The method used to limit rudder travel can have an impact on handling qualities and the tendency to overcontrol and can vary significantly among and within manufacturers.

The overall objective of this program was to develop data that the FAA could use to develop criteria for rudder flight control systems that ensure safe handling qualities by minimizing the tendency for overcontrol.

Three test phases have been developed to accomplish the objective:

- Phase 1—Determine the required lateral motion of the simulator necessary to obtain valid pilot opinion for aggressive rudder control, and obtain initial results for variable gearing, variable stop, and force limit rudder control system designs. Piloting tasks for this phase were designed to guarantee aggressive rudder use.

- Phase 2—Using a simulator that meets the requirements defined in Phase 1, conduct detailed experiments to determine criteria for transport aircraft rudder control systems. Piloting tasks for this phase are designed to guarantee rudder use. Analyze the results to formulate tentative criteria for rudder flight control systems in transport aircraft.

- Phase 3—Validate the Phase 2 results using more realistic piloting tasks where rudder use is based on pilot judgment and technique. The results will be used to validate and, if necessary, refine the criteria developed in Phase 2.

The Phase 1 test plan [1] was updated to reflect all changes that were made while checking out and running the simulation experiment described in this report. The Phase 2 and Phase 3 test plans are given in references 2 and 3. The Phase 2 test plan was updated to reflect the results of this study.

The simulation evaluation was perfomed using the National Aeronautics and Space Administration (NASA) Ames Research Center Vertical Motion Simulator (VMS). This facility was selected because it has more lateral travel (±20 ft) than any other existing simulator, and lateral motion would be expected to affect the pilot's rudder use.

The VMS simulator motion gains were optimized for the tasks to provide the maximum motion without hitting stops. An additional set of motion gains were used to simulate a Hexapod simulator, typical of those used for most airline training. This was done so the results of a full motion and Hexapod motion could be compared. No comparisons were made without motion because there was no intent to conduct the Phase 2 and Phase 3 studies on a fixed-base simulator.

The goal of this research was to develop criteria for a rudder control system design that minimized the likelihood that a pilot would overcontrol or experience pilot-induced oscillation (PIO) in the directional axis. There have been a number of accidents and incidents where pilots misused the rudder control, most notably an Airbus A300-600 accident when the vertical stabilizer failed as a result of excessive rudder inputs in a wake vortex encounter [1]. Other rudder-related accidents are summarized in appendix D.

No attempt was made to optimize the rudder flight control system design, as it was agreed that the manufacturers have a good understanding of what is required for good directional handling qualities for takeoff and landing [1]. Given that the rudder control on transport aircraft is used almost exclusively for takeoff and landing tasks, the rudder control system parameters are optimized for that flight regime. In most cases, the rudder size and deflection is based on providing sufficient control power to handle engine-out conditions as well as setting limits on crosswinds for landing.

At the low airspeeds used for takeoff and landing, there is no danger of overstressing the aircraft with excessive rudder use, and full deflection is provided to achieve the necessary control power. At higher airspeeds, the control power is no longer required, and rudder travel is limited to reduce the possibility of overstressing the vertical stabilizer.

The present research was aimed at developing criteria for rudder flight control systems in the presence of various methods to limit rudder travel at high airspeeds.

A detailed analysis of three different rudder control system designs is given in appendix A.

2. DESCRIPTION OF EXPERIMENT.

2.1 MATH MODEL.

The simulated aircraft consisted of a generic transport model that was located at the NASA Ames Research Center simulation facility. The model was used in research studies involving transport aircraft in the past and was well accepted by the subject pilots as a realistic simulation. Several pilots with transport aircraft experience flew the model during checkout for the present study, and all agreed that it was representative of a medium-sized, twin-engine transport aircraft at the test flight condition. The test flight condition consisted of cruise flight at 250 knots indicated airspeed (KIAS) at 2000 ft altitude. This flight condition was similar to what existed in an Airbus A300-600 accident wherein the vertical stabilizer failed. The National Transportation Safety Board (NTSB) accident report [4] indicated that pilot overcontrol of the rudder was the primary cause of the accident.

All aspects of the model were held constant during the experiment except for the rudder flight control system. As described in appendix A, the rudder flight control system was systematically varied, while the available rudder control power was constrained to be constant, to the extent that was possible with differing control systems.

2.2 SIMULATOR MOTION SYSTEMS.

The VMS motion system parameters (e.g., gains and washouts) were tuned to maximize the lateral travel without hitting stops. Different motion gains were used for the yaw and roll tasks. A tradeoff study was done to determine the best compromise between the size of the disturbance input and the motion gains and washouts.

The final motion gains were classified as “Good Fidelity” in a rating system used by the VMS simulation staff.

Motion system parameters were available for viewing by the experimenter for each run for a typical run with full VMS motion, as shown in figure 1.

Figure 1. Display of Motion System Parameters and Performance for Typical VMS Run (Yaw Task)

The green trace shows the simulator bank angle versus lateral displacement and indicates that the full lateral travel was used during the yaw task.

Figure 2 shows the same display for the motion of the simulated Hexapod for the same task. As expected, the lateral travel of the simulator cockpit was substantially less for the simulated Hexapod.

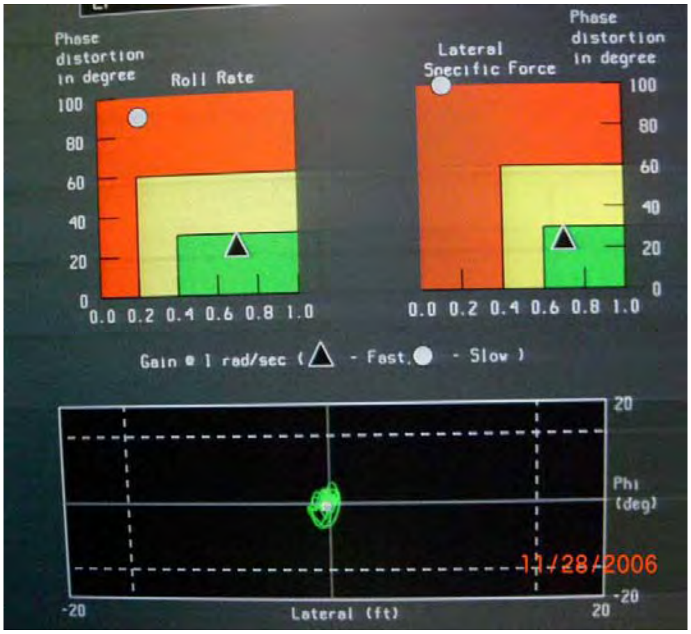


Figure 2. Display of Motion System Parameters for Typical Simulated Hexapod Run

2.3 SIMULATION ENVIRONMENT.

Standard transport cockpit flight controls were provided in the simulator cockpit, consisting of a transport-style yoke with maximum travel of ±90° and rudder pedals with a maximum travel of ±3.5 inches. Throttles were consistent with a twin-engine transport aircraft.

The primary flight display (PFD) that was provided in the simulated generic transport cockpit is shown in figure 3.

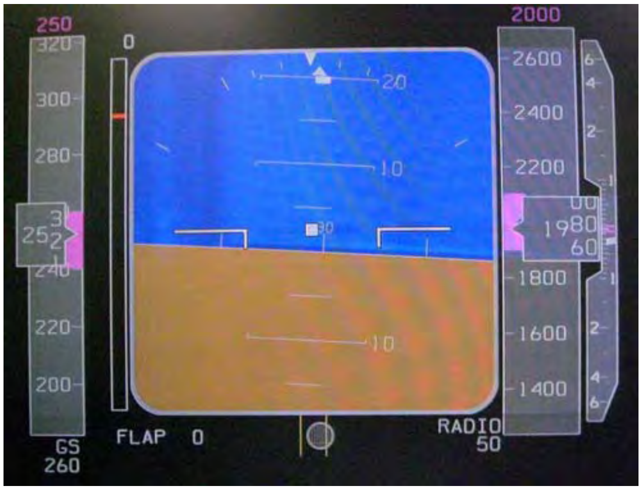


Figure 3. The PFD Used in Rudder Simulation

Sideslip was displayed in the usual way with the “doghouse” symbol at the top of the display. It was also displayed with the more compelling sideslip ball at the bottom of the display. Most pilots used the ball exclusively. One ball deflection was scaled to 0.10 lateral g, which is the conventional scaling for this type of display. The top indicator was scaled so that 0.10 lateral g corresponded to a rectangle edge being aligned with one of the lower corners of the triangle. The displayed lateral accelerations were referenced to a point slightly aft of the cockpit and 58 ft in front of the center of gravity (i.e., location of the inertial reference system in the electronics bay). The acceleration displays were lagged by a first-order filter with a 0.5-second time constant.

The magenta airspeed and altitude bugs were tailored so that the edge of desired performance existed when one edge of the square bug was aligned with the opposite edge of the white box surrounding the digital airspeed or altitude display. This made it easy for pilots to determine if they were within the specified desired airspeed and altitude performance during the task. Desired performance was specified as maintain airspeed at 250 kt ±10 kt and altitude at 2000 ft ±100 ft.

The outside visual scene consisted of an airport and buildings, as shown in figure 4.

Figure 4. Outside Visual Scene

It was found that having the aircraft lined up with a runway was useful for holding heading during the large rolling gust inputs. However, there was no task that related to using the runway for landing, and runway alignment was not part of the task.

There were a number of displays that allowed the experimenters to be aware of what the pilot was doing during the tasks. Two of the displays are shown in figure 5.

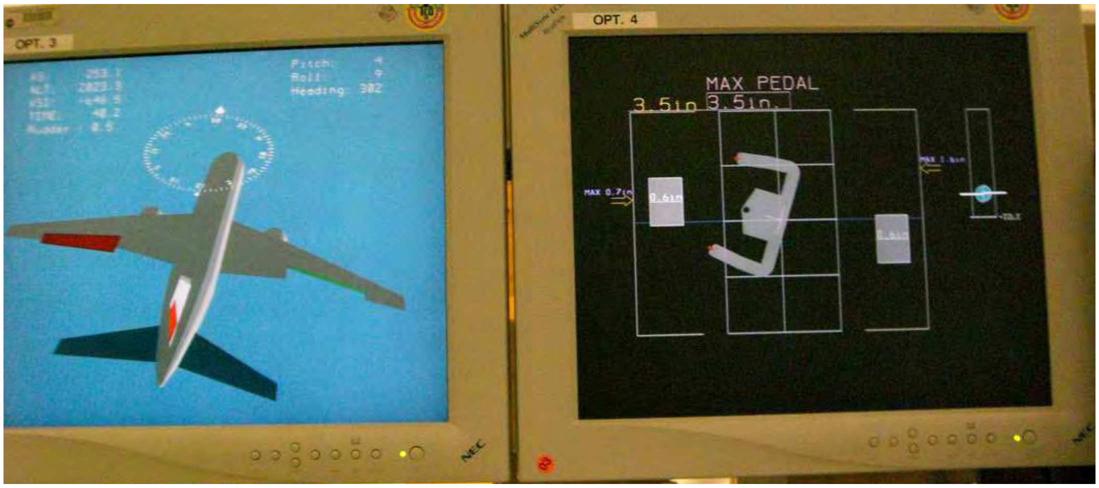


Figure 5. The VMS Experimenter Displays for Rudder Study

The display on the left provided an indication of aircraft attitude and control positions. The display on the right showed the control wheel deflection, rudder pedal deflection, and the thrust lever positions. The maximum pedal position (pedal stops) was also displayed.

2.4 PILOTING TASKS.

The current protocol for transport aircraft training is to use rudders for crosswind landings and engine-out on takeoff and landing, but not for rudder up-and-away. One exception is that pilots are allowed to use rudder up-and-away to assist in controlling the aircraft if out of aileron control power following a gust or wake vortex upset.

This training was strongly reinforced after the A300-600 vertical stabilizer failure on American Airlines Flight 587. Nonetheless, some pilots are more prone to using rudders aggressively than others. This study took the position that in the unlikely event the rudder is used in an aggressive manner while in up-and-away flight, it should result in predictable aircraft response with no tendency for overcontrol or PIO.

There are no real-world tasks that require precision rudder control while in up-and-away flight, which presented a challenge for developing appropriate piloting tasks to test rudder control at high airspeeds. As noted in section 1, rudder travel is progressively limited as airspeeds increase above those used for takeoff and landing. Therefore, it is not useful to study the effects of rudder control system design in the presence of reduced rudder travel for a takeoff or landing task. Using takeoff and/or landing tasks (e.g., engine-out, crosswind, and lateral offset) was therefore rejected for this study.

Two piloting tasks were developed: a yaw tracking task and a roll tracking task.

2.4.1 Yaw Task.

The yaw tracking task consisted of a sum-of-sine waves that was inserted into the model as random-appearing lateral gusts, as illustrated in figure 6.

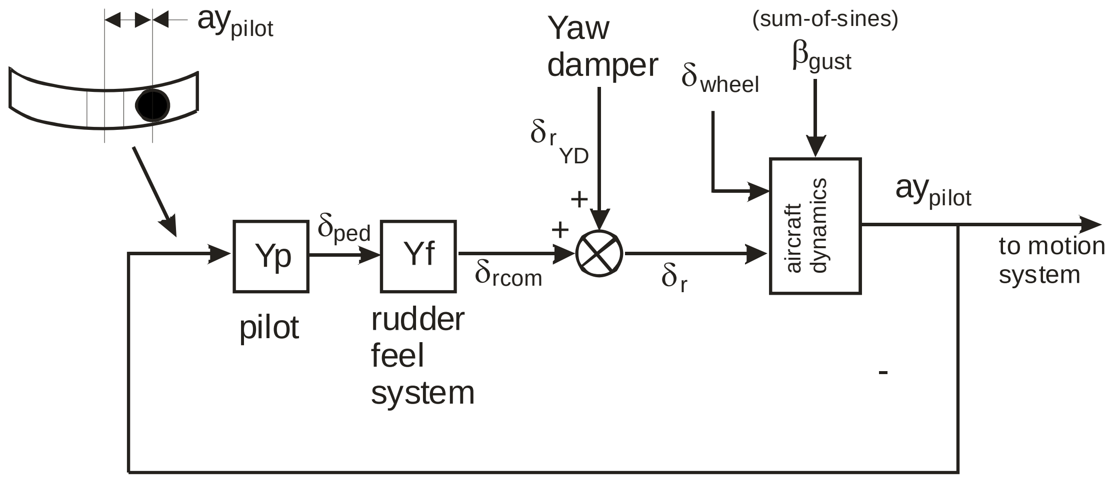


Figure 6. Pilot-in-the-Loop Representation of Yaw Task

The pilot was instructed to minimize sideslip using rudder. The desired and adequate performance standards for this task are given in the pilot briefing in appendix C. The primary task was to keep the sideslip indicator within 1/2 unit (ball or triangle) most of the time. Occasional excursions beyond this were briefed as acceptable.

The yaw task was not intended to be a realistic piloting task; its primary role was to force the pilot to use rudders in an aggressive manner. The rationale for this was that the rudder control should result in predictable responses if used aggressively, and should not result in overcontrol or PIO tendencies. It was also included to take quantitative measurements of pilot behavior in a yaw tracking task. By taking pilot describing functions, it was possible to quantify rudder tracking behavior, and thereby determine if there were differences that can be attributed to the motion system used and/or the type of rudder flight control system employed.

2.4.2 Roll Task.

The roll tracking task consisted of a random-appearing, sum-of-sine wave inputs into the roll axis, as illustrated in figure 7. These had the appearance of rolling gusts that might occur in a wake vortex upset. The magnitude of the inputs was set to momentarily exceed the lateral control power during the peaks of the disturbance. This was done to encourage the subject pilots to use rudder to compensate for the lack of aileron control power.

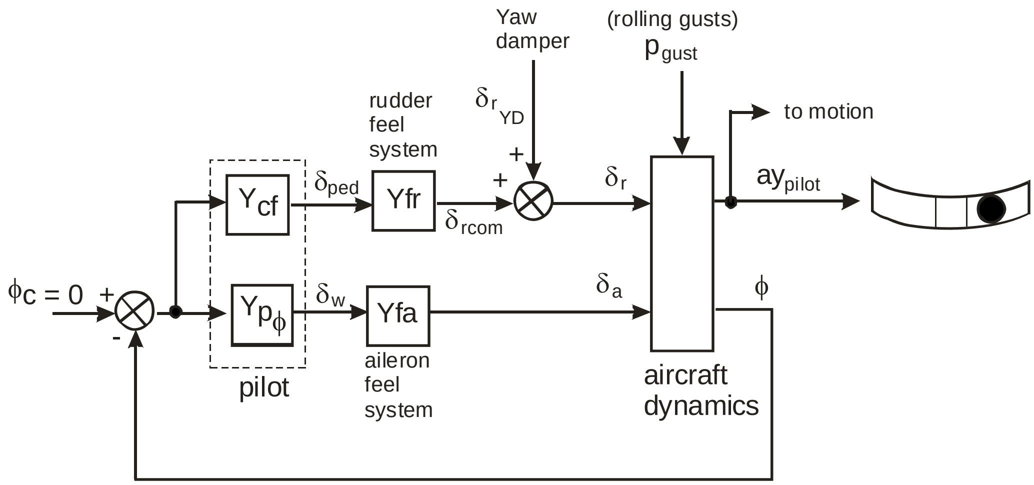


Figure 7. Pilot-in-the-Loop Representation of Roll Task

There was no attempt to simulate an actual wake vortex encounter with the roll tracking task. However, all pilots agreed that the task was a realistic simulation of a wake vortex upset. The pilots were briefed that this was not a roll control study, and that the focus was on rudder control. They were asked to focus on the rudder use to augment roll control when assigning subjective pilot ratings.

All runs were made at an airspeed of 250 KIAS and an altitude of 2000 ft in VMC conditions. Desired and adequate performance standards used in the task are given in the pilot briefing in appendix C.

Some thrust lever activity was required to keep airspeed in the desired range, which was ±10 kt about the 250 KIAS target speed. The increased thrust requirement during the runs was a result of the increased drag that resulted from large control inputs required to accomplish the task.

2.4.3 Sum-of-Sine Wave Inputs.

The governing equation for the sum-of-sine wave inputs used in the simulation was:

$$X_C = \sum_{i=1}^{n} K_{SF} A_i \sin(\omega_i t + \phi_0)$$

where n = 7. The values for frequency and amplitude of the input sine waves for each task are given in table 1.

Table 1. Sum-of-Sine Waves Parameters

Sine Wave No.	Yaw Axis (side gust inputs)			Roll Axis (roll gust inputs)		
	Ai (v_{gust}) ft/sec	No. of Cycles	ω_i rad/sec	Ai (p_{gust}) deg/sec	No. of Cycles	ω_i rad/sec
1	-35	2	0.19947	-9	3	0.2992
2	35	5	0.49867	-9	4	0.39893
3	35	9	0.8976	9	7	0.69813
4	17.5	14	1.39626	4.5	18	1.79519
5	-7	24	2.39359	-1.8	30	2.99199
6	7	42	4.18879	-1.8	40	3.98932
7	2.8	90	8.97597	0.72	70	6.98131

K_{SF} is a scale factor that allowed adjustment of the magnitude of all the input sine waves simultaneously. This was varied empirically during the simulator checkout with the result that the scale factor for the roll task was set to 1.0. For the yaw task, it was necessary to reduce the scale factor to 0.55 to avoid overdriving the motion system. All efforts were made to keep the motion gains as high as possible.

ϕ_0 is the initial phase angle, which was changed in increments of 60° for each run to make the sequence appear more random to the pilots. Each configuration was flown three times before being rated, and the phase angle was set to 0 for the first of these three runs (i.e., each configuration was rated with an initial phase angle of 0°, 60°, and 120°). In that way, each configuration was evaluated with identical disturbance inputs. This was done when it was found that some initial phase angles produced a more severe environment than others. The same initial phase angle was used for each of the seven sine waves in table 1.

The sum-of-sine waves input lasted 69.25 seconds for each run. The first 5 seconds was for warm-up (nonscored time) followed by 63 seconds of data collection. The inputs were terminated 1.25 seconds later.

As a side note, the frequencies in table 1 are calculated as a function of the number of cycles (N_i), and the scoring time (T_s = 63 sec) - $\omega_i = \dfrac{2\pi N_i}{T_s}$

2.5 EVALUATION SCENARIO.

The evaluation pilots were provided with one or more initial runs to become familiar with the handling qualities when presented with a new rudder flight control system. No disturbance inputs occurred during these familiarization runs, and the pilots were requested to focus on evaluation of the aircraft response to rudder inputs. All pilots were advised that the only possible configuration changes were to the rudder flight control system and the simulator motion system. All other handling qualities and simulation parameters remained constant throughout the experiment.

Test cases were presented to the evaluation pilots in random order and in the blind. As a result, each evaluation pilot saw the configurations in a different order. To the extent possible, test cases were repeated at random times during the experiment to check for consistency. This was done both randomly and by design if an unexpected rating was obtained for a given test case.

The scenario for each evaluation was as follows.

1. The simulator was put in Operate mode with no disturbance inputs.

2. The disturbance was initiated 5 seconds after the beginning of the run.

3. The data collection was initiated 10 seconds after the beginning of the run.

4. The data collection was terminated 63 seconds after initiation, and the disturbances were removed. The simulator was put into initial condition by the pilot after disturbances were removed.

5. Three repeat runs were accomplished per steps 1 through 4.

6. The pilot made comments and ratings per the provided scales and questionnaires.

The pilots were requested to issue ratings from the scales in figure 8a, respond to a questionnaire, and issue Cooper-Harper Handling Qualities Ratings (HQR) and Modified Cooper-Harper workload ratings. The modified workload rating scale was taken from reference 5.

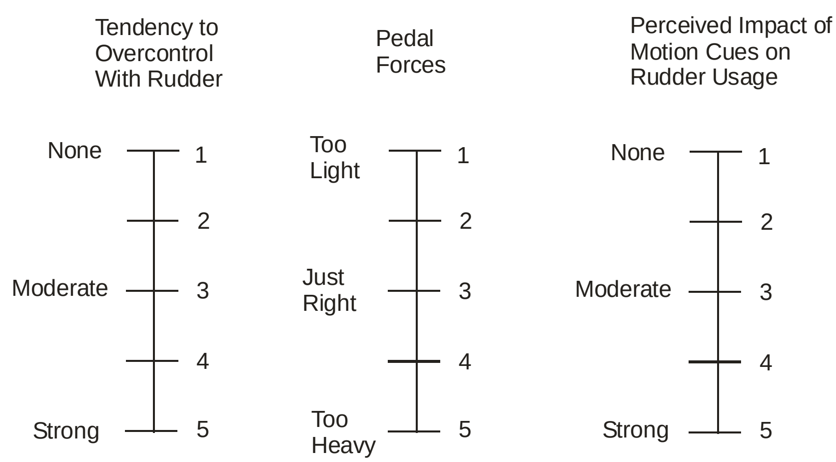


Figure 8a. Pilot Rating Scales

The pilot comments were guided by the above scales and the questionnaire shown in figure 8b.

QUESTIONNAIRE

1. Briefly describe any unusual rudder feel system characteristics and any other information that you consider necessary to support the ratings given above.

2. Did you hit rudder stops during the runs?

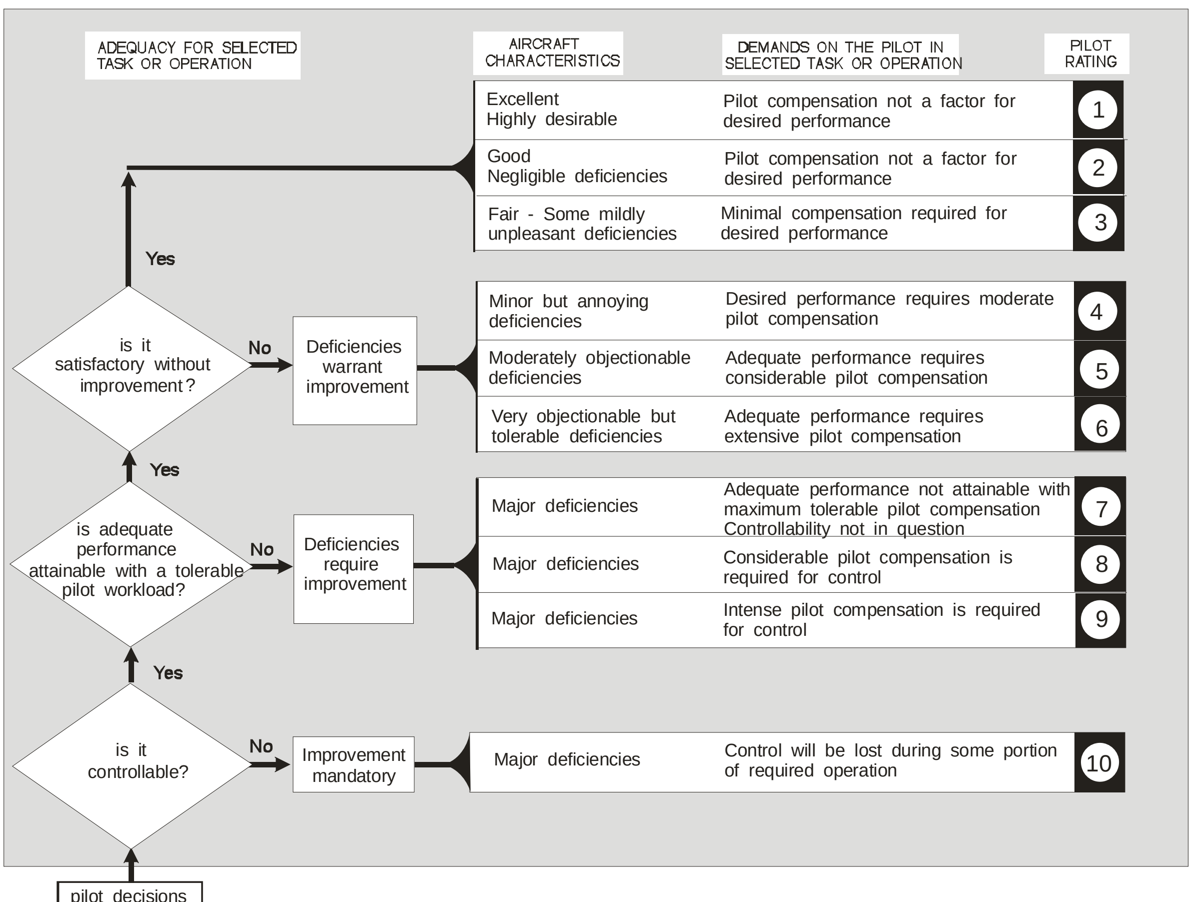
3. For FAA Pilots and DERs – In your opinion, is this rudder system certifiable for this task (yes or no)?

4. Assign Cooper-Harper Pilot Rating

5. Assign Modified Cooper-Harper Pilot Rating

Figure 8b. Questionaire

The standard Cooper-Harper HQR scale from reference 6 was used to evaluate handling qualities of each configuration with emphasis on response to rudder. This scale is shown in figure 9.



Cooper Harper Handling Qualities Rating (HQR) Scale (Ref. NASA TND 5153)

Figure 9. Cooper-Harper Handling Qualities Rating Scale

The Modified Cooper-Harper Rating scale (reference 5) was used to obtain an indication of pilot workload. This scale is shown in figure 10.

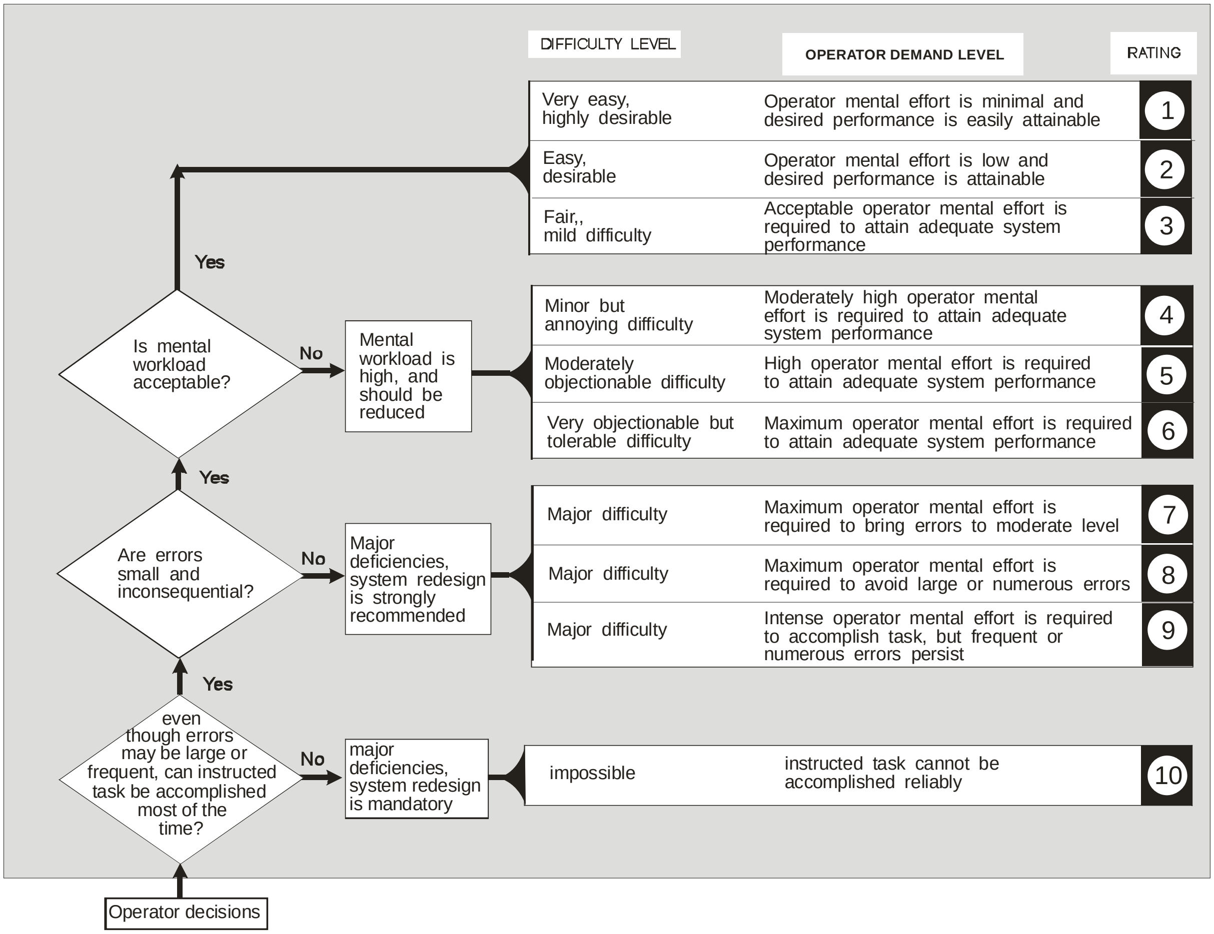


Figure 10. Modified Cooper-Harper Rating Scale for Pilot Workload

The pilot workload to accomplish the tasks was quite high, especially for the roll task. Simulator sessions were limited to 45 minutes or less for most pilots. Two pilots were always on hand so that one pilot could rest while the other performed the evaluations.

3. TEST CONFIGURATIONS.

3.1 FEEL SYSTEM DEFINITIONS.

Rudder flight control system definitions used in this study are shown in figure 11.

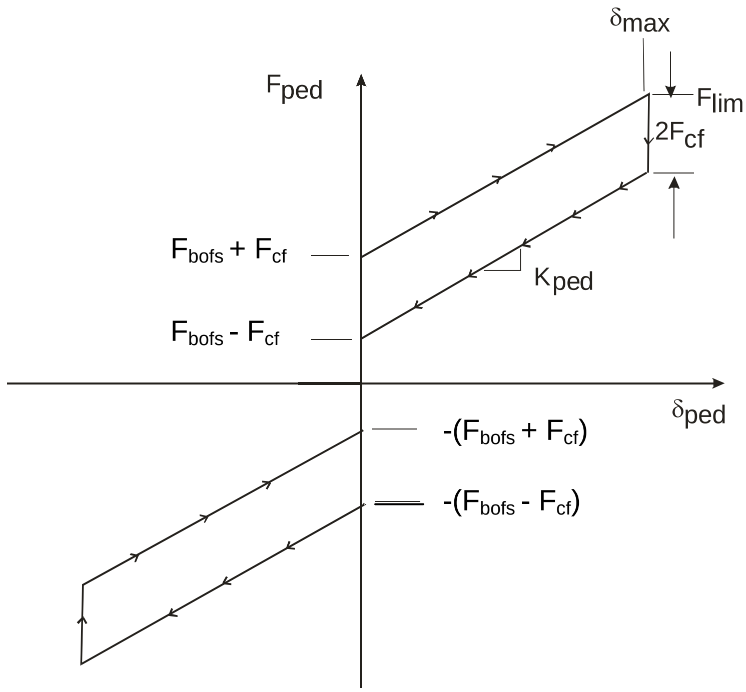


Figure 11. Definitions for Rudder Flight Control System

For the purpose of this simulation, the following definitions from figure 11 apply.

- Feel Spring Breakout (F_{bofs})—A constant force in a direction to return the rudder control to trim regardless of displacement. This is simulated with a large spring gradient over a small deflection, with the force held constant once that deflection is exceeded (e.g., see bottom of figure A-1 in appendix A).

- Couloumb Friction (F_{cf})—A constant force that is independent of displacement and in a direction opposite to the motion of the pedals - F_{cf}.

- Breakout Force (F_{bo})—The force required to initiate pedal motion. This is the sum of the feel spring breakout and Coulomb friction: $F_{bo} = F_{bofs} + F_{cf}$.

- Load-Feel Curve—Pedal force as a function of pedal displacement, which may be linear or nonlinear, as shown in figure 12. The slope of the linear load-feel curve in figure 11 is K_{ped} (lb/in.). A nonlinear load-feel gradient is typically used to provide good force cues for small pedal deflections in variable stop systems without requiring excessive forces to achieve large rudder deflections during engine out or crosswind landing operations. Load-feel curves are typically achieved with one or more centering springs and, where necessary, cams to achieve the nonlinear gradient. Both linear and nonlinear load-feel curves were studied in this experiment.

- Viscous Friction (F_{vf})—Force that is proportional to pedal velocity in a direction to resist pedal motion, i.e., the feel system damping. The work in reference 7 did not indicate a strong sensitivity in pilot opinion with respect to rudder feel system damping. The subject pilots in that experiment found the response was satisfactory without improvement (Cooper-Harper Handling Qualities (HQRs) ratings equal to or less than 3.5) for feel system damping ratios greater than 0.3. Tests with damping ratio of zero resulted in HQRs of no worse than 4.2. In this experiment, the damping ratio was held at approximately 0.5.

- Stop—A force that simulates the mechanical limit of travel. The stop is a constant for variable gearing systems and it varies with airspeed in variable stop systems. The VMS control loaders create a stop by increasing the force gradient to 200 lb/in. Some pilots were able to push through that force, and future tests should increase the gradient to a number representative of cable stretch.

- Flim—The pedal force necessary to move the pedals from trim to the stop. Trim was always zero pedal deflection for this experiment.

The pilot must input a force greater than the feel spring breakout force plus the Coulomb friction force ($F_{bofs} + F_{cf}$) before the rudder pedals move. The force required to keep the rudder pedals from returning to center is equal to or greater than ($F_{bofs} - F_{cf}$). These parameters were studied in reference 7 for landing tasks.

3.2 CONFIGURATIONS.

The variations in rudder system configurations to be tested are defined as follows:

- Variations in load-feel (shape and magnitude of rudder force versus pedal deflection)

- Low breakout and high breakout

- Variable stop scheduled with airspeed

- Variable rudder-to-pedal gearing (variable gearing)

- Force limit system that limits the amount of rudder hinge-moment that can be commanded by the pilot

- Block diagrams and detailed descriptions of each of the rudder system configurations tested herein are given in appendix A

3.2.1 Load-Feel Variations.

The load-feel curves for four different aircraft are shown in figure 12.

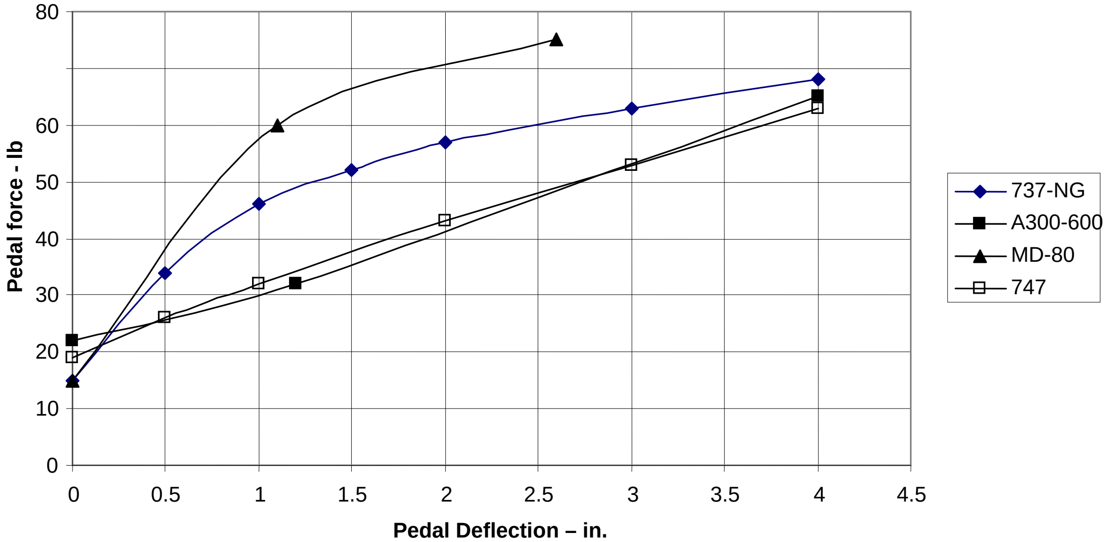


Figure 12. Load-Feel Curves Representative of Existing Aircraft

The load-feel curves shown in figure 12 include the effect of breakout. They represent three different approaches to rudder system design, as summarized below.

The A300-600 is a variable stop design and employs a high level of breakout and a nearly linear variation in pedal force versus deflection. This linear variation results in low levels of pedal force for maximum rudder as the stop is decreased with increasing airspeed. For example, at 250 kt, the pedal stop is at 1.2 inches, resulting in a force of only 32 lb to achieve maximum rudder deflection.

The McDonnell Douglas (MD)-80 employs a similar variable stop design as the A300-600, except the breakout is more moderate and the load-feel curve is highly nonlinear. This nonlinear variation results in significantly higher levels of pedal force for maximum rudder as the stop is decreased with increasing airspeed. For example, at 250 kt, the pedal stop is at 1.1 inches, resulting in a force of 60 lb to achieve maximum rudder deflection.

The Boeing 737 NG employs a force limit system and a nonlinear load-feel curve. The force limit system also results in a variable pedal stop with airspeed. At 250 kt, the pedal stop is 1.5 inches, resulting in 52 lb of force.

The B-747 employs a variable gearing system. The load-feel curve is linear and very similar to the A300-600.

Variable stop systems have been designed with linear and nonlinear load-feel curves[1]. Based on the available data from the NTSB report, it appears that Airbus has employed an essentially

[1] The load-feel curves in figure 12 are estimates based on limited data from reference 4 (3 points - breakout, pedal deflection, and force at 135 and 250 kt).

linear load-feel curve for the variable stop systems, whereas Boeing/Douglas tended to use a nonlinear load-feel curve for their variable stop designs.

The Boeing B-727, B-737, DC-10, and MD-11 aircraft employ the force limit design. Figure 12 indicates that the B-737 uses a nonlinear load-feel curve, which is taken as representative of this type of system. Note that mechanical implementations of the variable force design require variable pedal stops, very similar to the variable stop design (see appendix A).

Variable gearing systems have been employed by Boeing on the B-747 through B-777 series aircraft, as well as the A300 B2/B4. The B-747 has an essentially linear load-feel curve, and it is assumed that this is representative of variable gearing systems. That is because such systems do not require significant nonlinearities to achieve high pedal forces at reduced rudder deflections. That function is accomplished by reducing the pedal-to-rudder gearing.

3.2.2 Breakout Force.

The effect of breakout is expected to be important, especially for the linear load-feel design, because with that design the maximum force is not much greater than the breakout force. To isolate this effect, a low and high breakout version of each design was included in the tests.

Breakout is defined herein as the force required to initiate motion of the rudder pedals, and this is the convention that was used in the reference 4 NTSB report. Using this definition, F_{bo} is defined as the sum of the feel spring breakout plus Coulomb (static) friction. The feel spring breakout results from cable stretch. Since the spring does not move until the breakout force is applied, there is a deadband in the load-feel curves, which is calculated as follows: $\delta_{bo} = K_{CS} F_{bosp}$. In this experiment, the cable stretch coefficient (K_{CS}) was set to 0.005 in/lb.

Two levels of F_{bo} were used: 10 and 22 lb. These were taken as representative of the low and high values of breakout found on existing transport aircraft. The values of feel spring breakout (F_{bosp}) and static friction (F_{sf}) used to achieve the low and high breakout configurations are given in table 2.

Table 2. Rudder Feel System Constants

	Low Breakout	High Breakout
F_{bo} - lb	10	22
F_{bosp} - lb	6	12
F_{cf} - lb	4	10

Reference 7 shows that pilot opinion is sensitive to holdback force, which is defined as $F_{hb} = F_{bosp} - F_{cf}$. The ideal region of holdback force is given as between 0 and 8 lb, and table 2 shows that F_{hb} = 2 lb was used in this experiment.

3.2.3 Simulated Feel System Plots.

The linear and nonlinear generic load-feel curves used in this experiment are shown in figures 13-16. These plots include the effects of breakout and friction and were taken on the simulator by sweeping the pedals full travel in each direction (starting with the pedals at full travel in one direction).

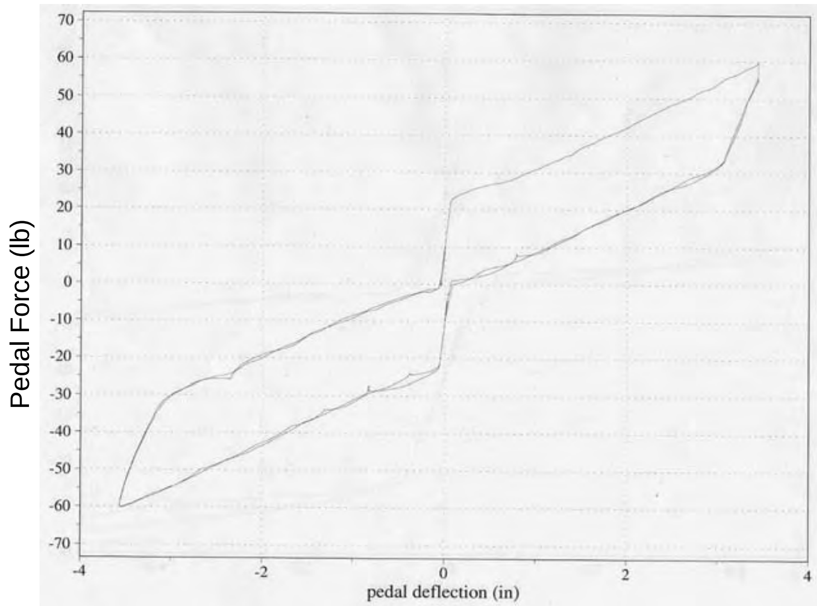


Figure 13. Linear Load-Feel With 22-lb Breakout

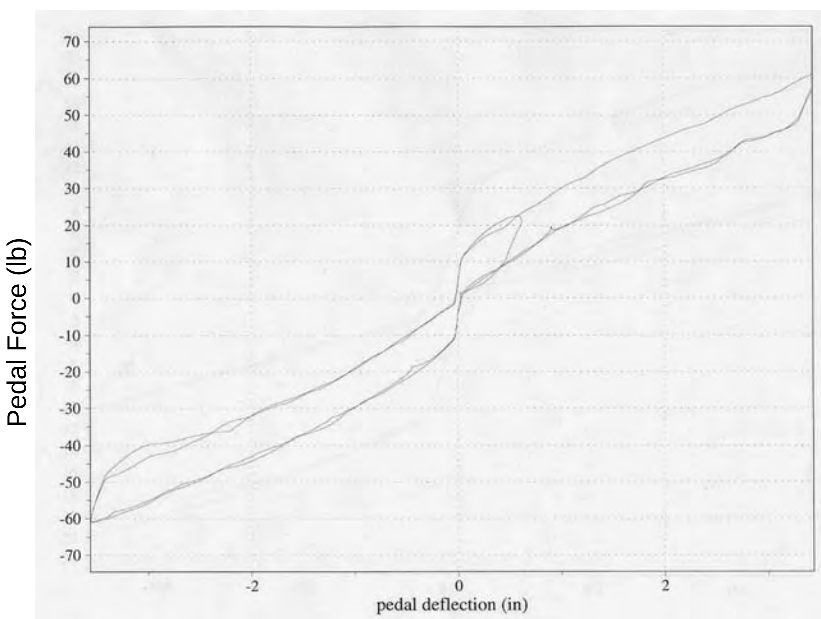


Figure 14. Linear Load-Feel With 10-lb Breakout

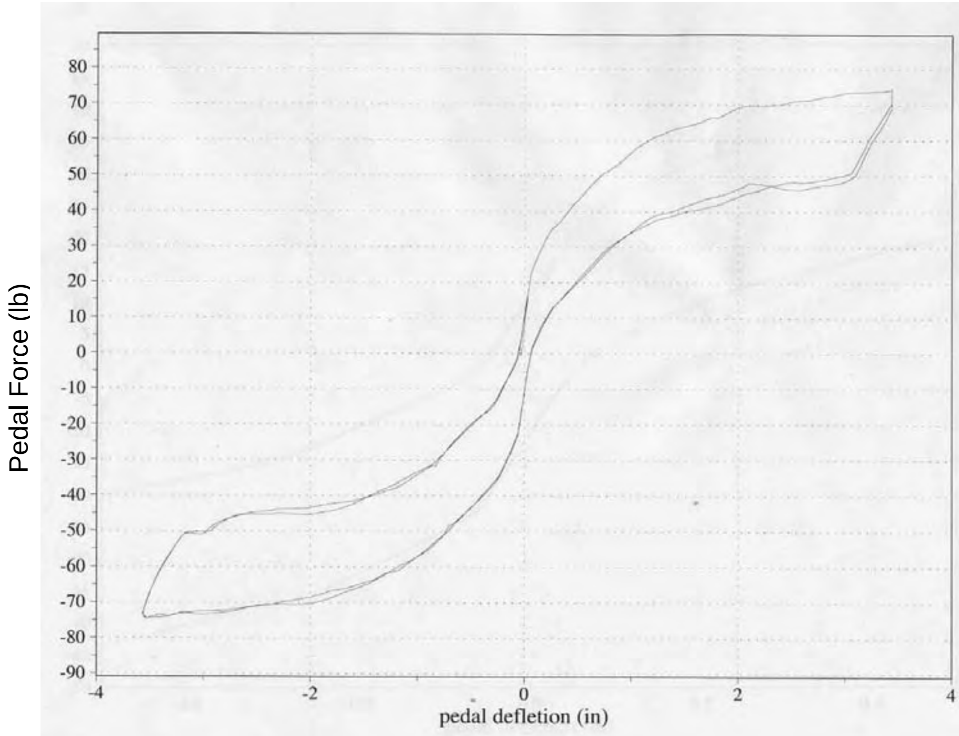


Figure 15. Nonlinear Load-Feel With 22-lb Breakout

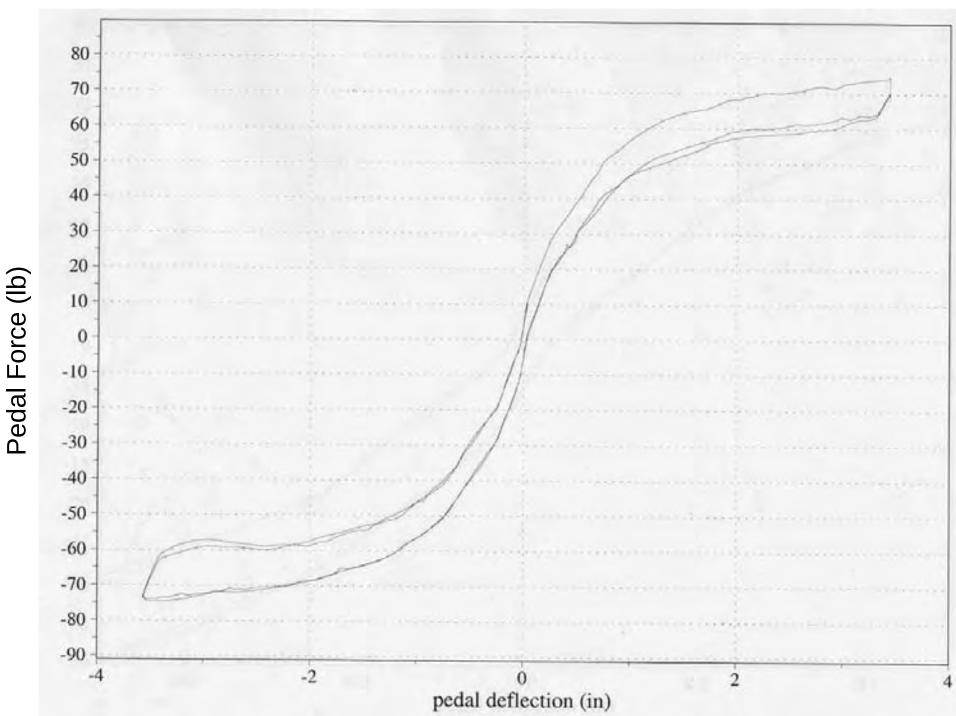


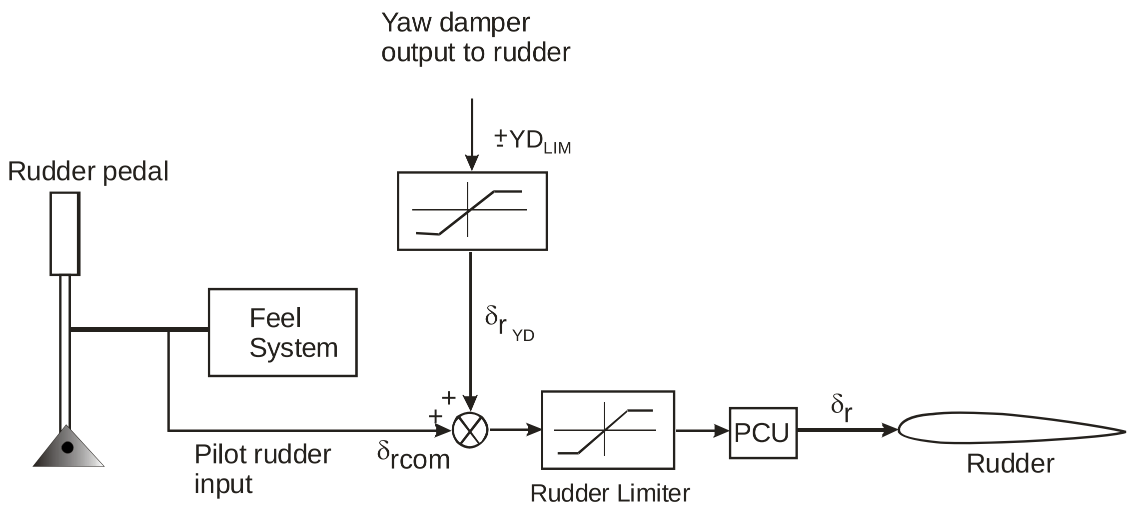
Figure 16. Nonlinear Load-Feel With 10-lb Breakout

For this experiment, the nonlinear load-feel curves are the same for the variable stop and variable gearing designs. This is done to isolate the effect of varying the rudder stop or the rudder gearing. Because there is precedent for a linear load-feel curve in some Airbus aircraft with variable stop rudder designs, such a linear load-feel curve is included in the experimental matrix for the variable stop design.

3.2.4 Yaw Damper.

A generic yaw damper (YD) was implemented for this simulation. A block diagram of the yaw damper is shown in figure A-8 of appendix A.

The yaw damper output was limited to ±3° for this simulation exercise. The limited yaw damper output was summed with the rudder deflection commanded by the pedals, and that value was passed to the rudder limiter. This is illustrated in figure 17 and is referred to as Yaw Damper A (YD A).



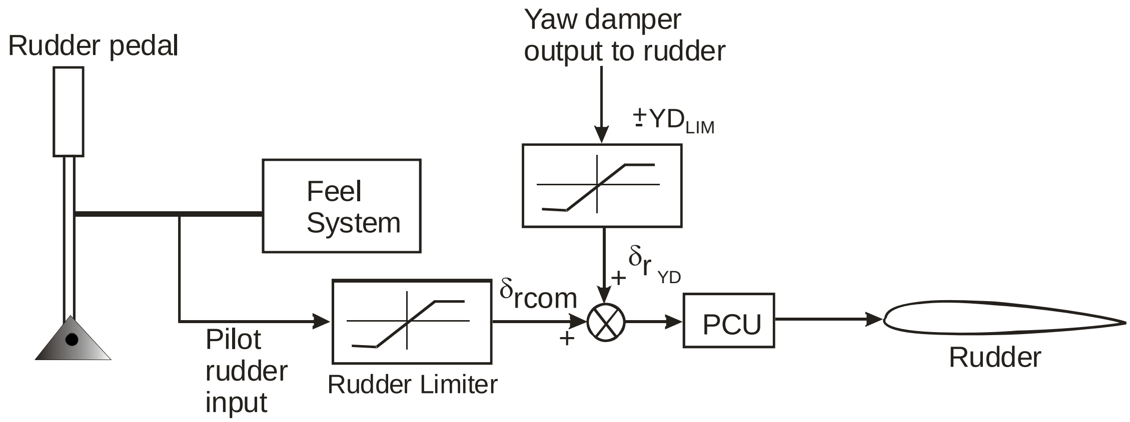
Note: Yaw damper input to rudder is restricted by magnitude of pilot input

PCU = Power control unit

Figure 17. Implementation of YD A

Yaw Damper B (YD B) was implemented to investigate the effect of summing the yaw damper command downstream of the rudder limiter as illustrated in figure 18.

With YD A, it is possible for the yaw damper to be rendered ineffective when the pilot rudder pedal input is large. That is because the rudder limiter limits the sum of the yaw damper and pilot input. The rudder is mechanically limited by variable stop and force limit designs, but not by the variable gearing design.



PCU = Power control unit

Figure 18. Implementation of YD B

With YD B, input to the rudder is unaffected by the size of the pilot input. The YD B implementation was investigated to determine if improved yaw damper operation can be achieved with YD B and if this improvement modifies the loads on the vertical stabilizer.

3.3 TEST CONDITIONS.

The configurations tested during this simulation experiment are given in table 3.

Table 3. Test Configuration Summary

Config	Approximate Maximum Pedal Travel (in.)	Load-Feel Curve Shape	Breakout (lb)	Coulomb Friction F_{cf} (lb)	Feel Spring Breakout F_{bosp} (lb)	K_{ped}	Rudder Control System	Yaw Damper
1	1.15	Linear	10	4	6	7.5	Variable stop	A
2	1.15	Nonlinear	10	4	6	7.5	Variable stop	A
3	1.15	Linear	22	10	12	7.5	Variable stop	A
4	1.15	Nonlinear	22	10	12	7.5	Variable stop	A
5	3.5	Nonlinear	10	4	6	Varies with airspeed	Variable gearing	A
6	3.5	Nonlinear	22	10	12	Varies with airspeed	Variable gearing	A

Table 3. Test Configuration Summary (Continued)

Config	Approximate Maximum Pedal Travel (in.)	Load-Feel Curve Shape	Breakout (lb)	Coulomb Friction F_{cf} (lb)	Feel Spring Breakout F_{bosp} (lb)	K_{ped}	Rudder Control System	Yaw Damper
7	1.15	Nonlinear	10	4	6	7.5	Force limit	A
8	1.15	Linear	10	4	6	7.5	Variable stop	B
9	1.15	Nonlinear	10	4	6	7.5	Variable stop	B
10	1.15	Linear	10	10	12	7.5	Variable stop	B
11	1.15	Nonlinear	10	10	12	7.5	Variable stop	B

Configurations 1 through 4 are intended to investigate the variable stop design with low and high breakout and linear and nonlinear load-feel. The linear load-feel results in a significantly decreased maximum force when the pedal throw is limited to 1.15 inches at 250 kt.

Configurations 5 and 6 represent the variable gearing design with low and high breakout and a nonlinear load-feel.

Configuration 7 is included to investigate the force limit design for comparison with the variable stop design in configuration 2. A review of the configurations in appendix A shows that the force limit and variable stop designs are similar, except the force limit design has about 0.7 inch of pedal motion with no rudder motion. This pedal motion occurs after 1.15 inches of pedal deflection, so the effective pedal stop is 1.65 inches. The force limit design results in variations in the maximum pedal travel, depending on sideslip (see appendix A), whereas the variable stop system does not.

Configuration 3 is representative of the A300-600 variable stop design, which incorporates an essentially linear load-feel curve. Configuration 1 represents that design with decreased breakout. Configurations 2 and 4 investigate the variable stop design with nonlinear load-feel curve (i.e., the approach taken by Douglas Aircraft Company) combined with low and high breakout forces.

For configurations 1 through 7, the yaw damper output to the rudder can be limited when pilot pedal inputs are large (version A), and configurations 8 through 11 investigate the alternative yaw damper design where such limiting does not occur (version B). The two yaw damper designs are discussed in detail in appendix A.

The yaw damper configurations are:

- Configuration 8—Configuration 1 with improved yaw damper
- Configuration 9—Configuration 2 with improved yaw damper
- Configuration 10—Configuration 3 with improved yaw damper
- Configuration 11—Configuration 4 with improved yaw damper

3.4 CASE IDENTIFIERS.

Each configuration in table 3 was tested using the full VMS motion and motion that simulated a Hexapod simulator.

A case identifier code was established as follows.

- The first digit is the configuration number from table 3.
- The second character is either H for Hexapod motion or V for full VMS motion.
- The third character is either B for yaw task (beta-gust) or P for rolling task (p-gust).

For example, case 2VB means configuration 2, VMS motion, and yaw (beta) task. The combination of 11 configurations, 2 motion systems, and 2 tasks resulted in 44 cases. It was decided to use only the VMS motion to evaluate the effect of an improved yaw damper. This reduced the total number of cases from 44 to 36.

3.5 TEST SUBJECTS.

Eleven test subjects performed formal evaluations in this program. The names and background of each of the pilots is as follows.

- Paul Desrochers — Airline Pilot, former Boeing Test Pilot, FAA Designated Engineering Representative (DER) Test Pilot, Type rated in most currently flying Boeing transport aircraft
- Brian Watson — FAA Test Pilot
- Gene Arnold — FAA Test Pilot
- Jim Moore — Airline Pilot—Type rated in numerous Boeing transports, active General Aviation Pilot
- Howard Pincus — Airline Pilot (retired)—Type rated in several Boeing transports, active General Aviation Pilot
- Rick Dunham — FAA Test Pilot
- Michael Sies — FAA Test Pilot

- Richard Duprey FAA Test Pilot
- John Hagen FAA Test Pilot—substantial helicopter background
- Roger Hoh DER Test Pilot, Type rated B-737, active General Aviation Pilot

4. RESULTS.

The primary objective was to determine the degree of lateral motion required to accomplish the criteria development in Phase 2. The secondary objective was to achieve initial insight into the effect of rudder control system characteristics on overcontrol tendencies, especially as such tendencies affect loads on the vertical stabilizer. To the extent possible, the results are presented in terms of these objectives.

When discrepancies existed between the Hexapod and VMS motion results, it was assumed that the VMS motion was more correct because it provided more cueing than the Hexapod motion. As outlined in the Phase 1 test plan [1], differences between the system with large motion and limited motion will be reason to down-select to the simulator with larger motion. The assumption that the simulator with larger motion provided more valid answers was tempered by evaluating the results against expected trends in the data, based on first principals of pilot-vehicle control.

A detailed spreadsheet containing all the pilot ratings and summarized comments is provided in appendix B.

All runs prior to run 94 were ignored for analysis because it was discovered that the cable stretch was not correctly implemented during those early runs. This was discovered when the evaluation pilots noted that the rudder control power seemed asymmetric. Investigation showed that the cable stretch was only active in one direction.

Based on comments from the evaluation pilots, there seemed to be more rudder authority for configuration 7 than the other configurations. An investigation of this showed that the hinge moment limit for the force limit system was set too high. This was reduced so the maximum rudder deflection at zero sideslip was approximately the same as for the other configurations. This was done at run 527. Therefore, all runs prior to 527 for configuration 7 were not included in the analysis, except to investigate the effect of increased rudder control power. Fortunately, there were not many evaluations of this configuration prior to run 527.

A total of 1105 runs were made by 11 evaluation pilots. In the following discussions of qualitative pilot ratings, a trial refers to one pilot's evaluation of a configuration, which always consisted of at least three runs. For the quantitative data, a trial consists of one run.

All the results are implemented with YD A unless otherwise noted.

4.1 QUALITATIVE PILOT RATING RESULTS.

Qualitative pilot rating results were obtained from the rating scales and questionnaires presented in section 2.5. To put these results in the context of FAA certification, the pilots were asked if they would certify the rudder control system to accomplish the task. It was emphasized that this decision was to be based on this task only and no other factors. Note that all but two of the test subjects were either FAA test pilots or FAA DER test pilots with Part 25 (airline aircraft) authorization (see section 3.5). Those results are shown in figure 19.

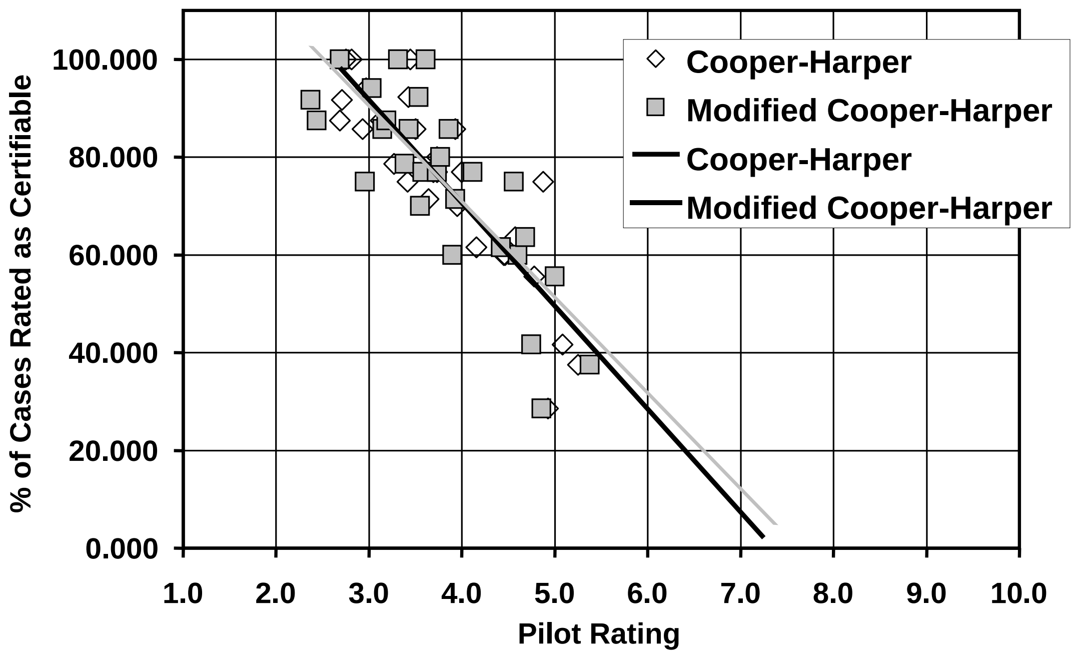


Figure 19. Correlation Between Cooper-Harper Ratings and Probability of Certification

The trend lines through the data are the results of a linear regression. A fourth-order fit shows the expected cumulative probability distribution for this type of data, as shown in figure 20.

Trend lines through the data in figures 19 and 20 indicate that an HQR of 5 is consistent with a 50% chance of getting certification approval for the task. This is consistent with results from a previous study where FAA test pilots were used to evaluate instrument approaches in a variable stability helicopter [8].

The results shown in figures 19 and 20 are useful for interpreting Cooper-Harper HQRs in terms of the probability of achieving FAA certification for accomplishment of the task for which the HQRs were obtained. Note that increasing the HQR from 4 to 6 results in a substantial decrease in the probability of certification from 80% to 30%.

The Modified Cooper-Harper workload rating results track the Cooper-Harper HQRs very closely, as shown in figure 21.

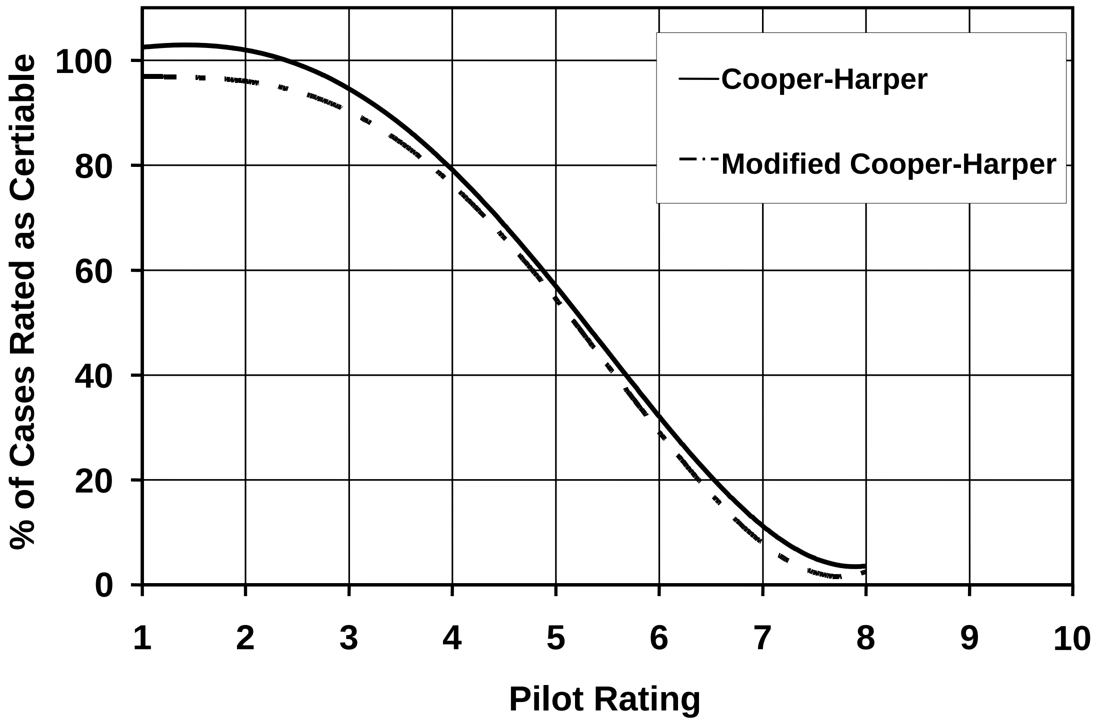


Figure 20. Percentage of Certifiable Rating vs Cooper-Harper and Modified Cooper-Harper Ratings—Yaw and Roll Tasks—Fourth-Order Fit of Data

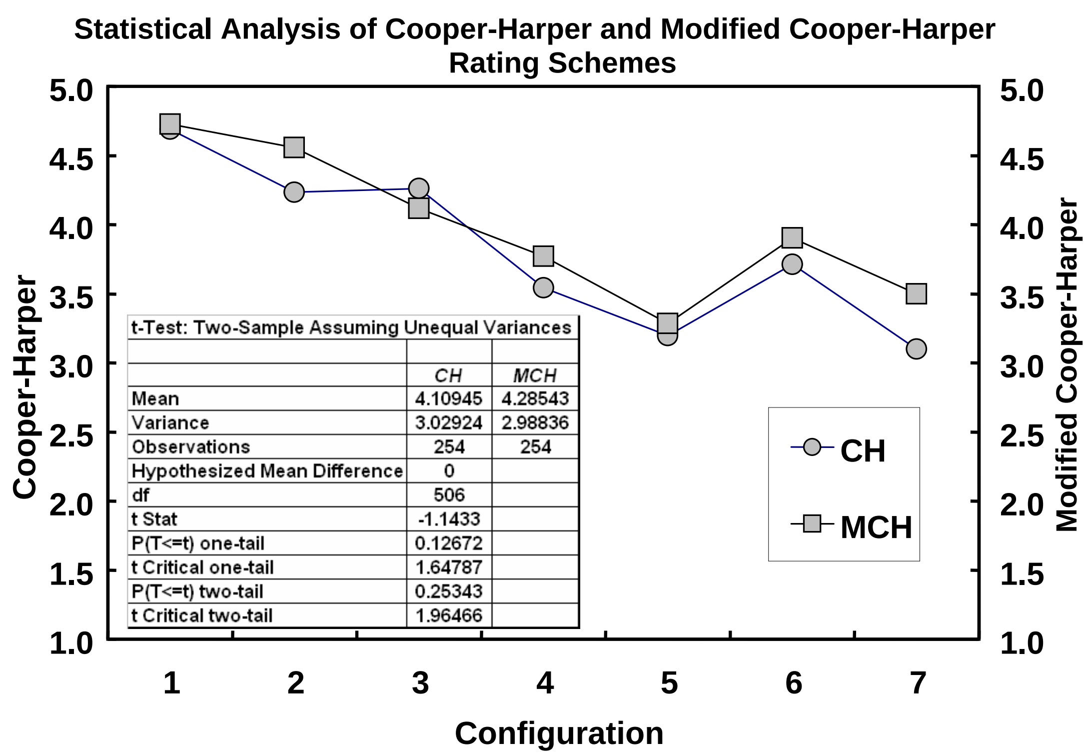


Figure 21. Comparison of HQRs and Workload Ratings

Statistical analysis of HQR data was performed to investigate differences in perceived pilot opinion using the Cooper-Harper rating scale and the Modified Cooper-Harper rating scale. To complete this task, a two-sample student's t-test assuming unequal variances was employed using Microsoft® Excel® Data Analysis ToolPak. A hypothesized mean difference of 0 between the means was selected, and the test was run at the 95% confidence level ($\alpha = 0.05$). The results in table 4 show that the *t critical* for the two-tailed distribution is greater than *t stat* with a 25% probability that the test is inconclusive. These results indicate that there is no significant statistical difference between perceived pilot opinion using the Cooper-Harper rating handling qualities scale and the Modified Cooper-Harper rating workload scale. On that basis, most correlations in this report are made using the Cooper-Harper Scale.

Table 4. Cooper-Harper and Modified Cooper-Harper Student t-Test Results

t-Test: Two-Sample Assuming Unequal Variances		
	Cooper-Harper	Modified Cooper-Harper
Mean	4.10945	4.28543
Variance	3.02924	2.98836
Observations	254	254
Hypothesized mean difference	0	
Df	506	
t Stat	-1.1433	
P(T<=t) one-tail	0.12672	
t Critical one-tail	1.64787	
P(T<=t) two-tail	0.25343	
t Critical two-tail	1.96466	

4.1.1 Pilot Rating Results for Roll Task.

4.1.1.1 Subjective Motion Cue Ratings—Roll Task.

The motion cue ratings from the figure 8a scale for each configuration and motion system are given in figure 22.

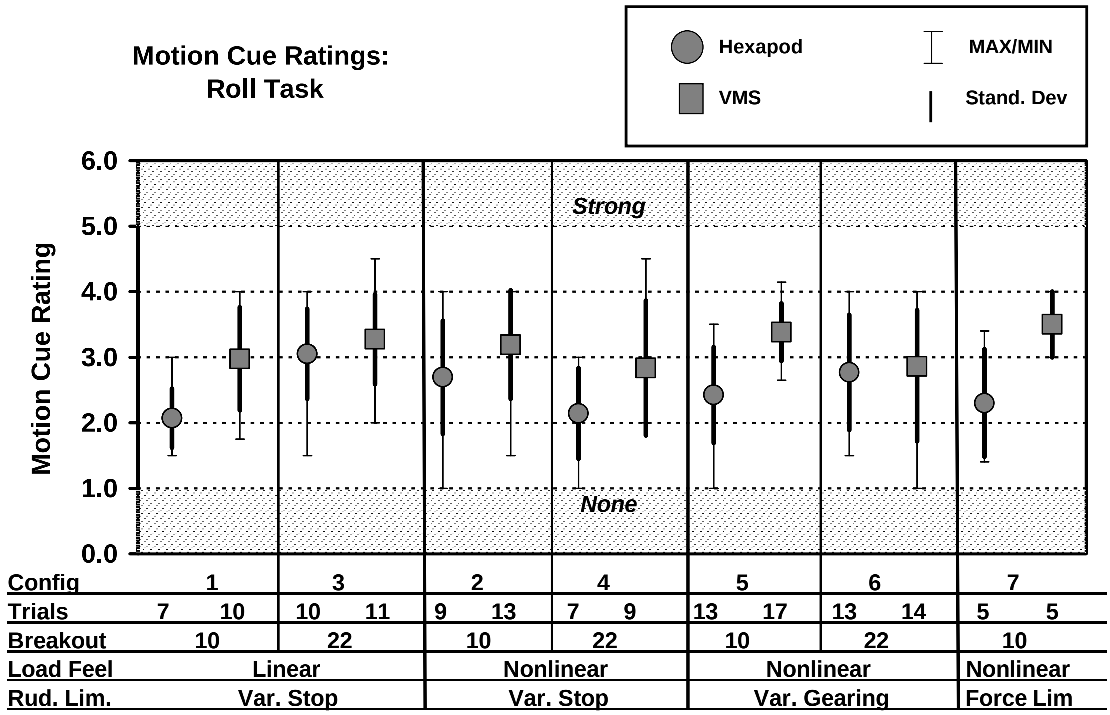


Figure 22. Motion Cue Ratings for Roll Task

Many results in this report are presented in the figure 22 format, which summarize the effects of both the configuration and the motion system. Each data point indicates the average, maximum/minimum, and standard deviation of the pilot ratings. The x-axis labels provide the number of trials run for that case and the pertinent rudder flight control system parameters associated with the case (breakout, linearity of load-feel, and type of rudder limiter).

The data in figure 22 indicate that where a difference existed, the VMS motion was rated as more compelling than the Hexapod motion. Section 4.1.2.2 explains that the perceived difference in motion cues between the Hexapod and VMS was slightly greater for the yaw task.

4.1.1.2 Tendency to Overcontrol With Rudder—Roll Task.

The overcontrol ratings that were obtained using the figure 8a scale are plotted in figure 23.

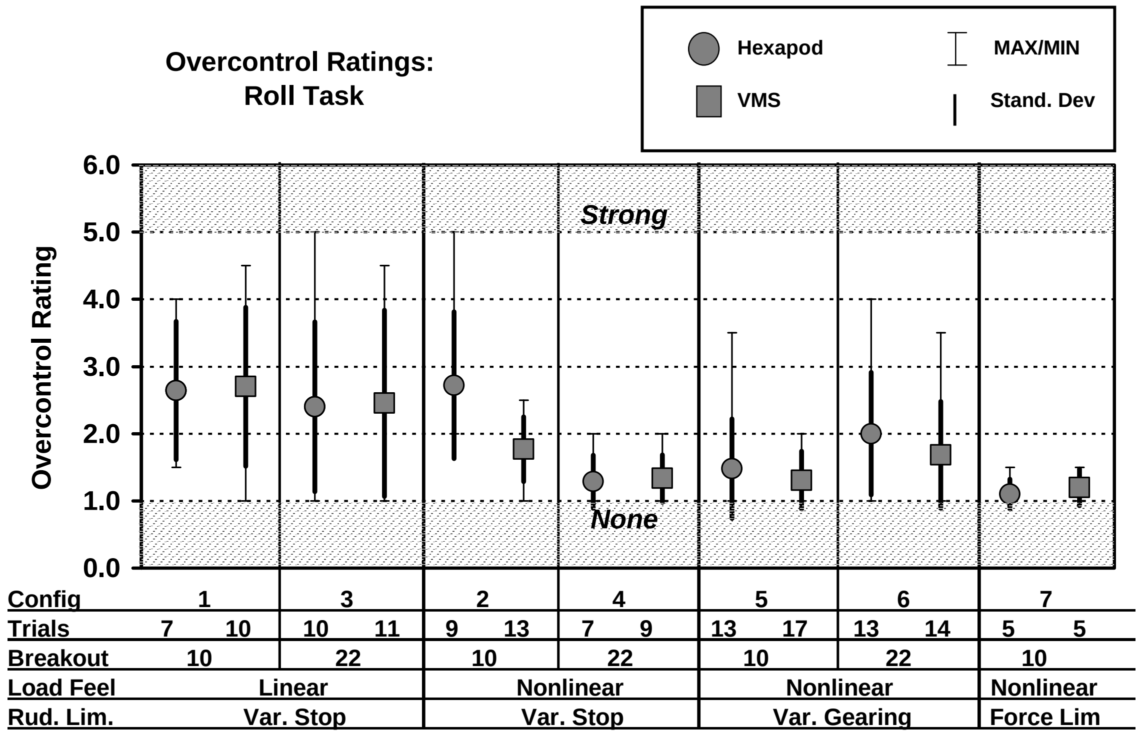


Figure 23. Overcontrol Ratings for Roll Task

The following conclusions may be drawn from the results presented in figure 23.

- The results for configuration 2 obtained with Hexapod motion indicate a perception of significantly greater tendency to overcontrol than the results obtained with VMS motion.

- Except for configuration 2, there was little difference in pilot perception of overcontrol between the two motion systems.

- The effect of breakout force on tendency to overcontrol was minimal for evaluations made with VMS motion.

- Evaluations with Hexapod motion showed that increasing the breakout from 10 to 22 lb on the variable stop nonlinear load-feel configurations resulted in a substantial decrease in the perceived overcontrol tendency.

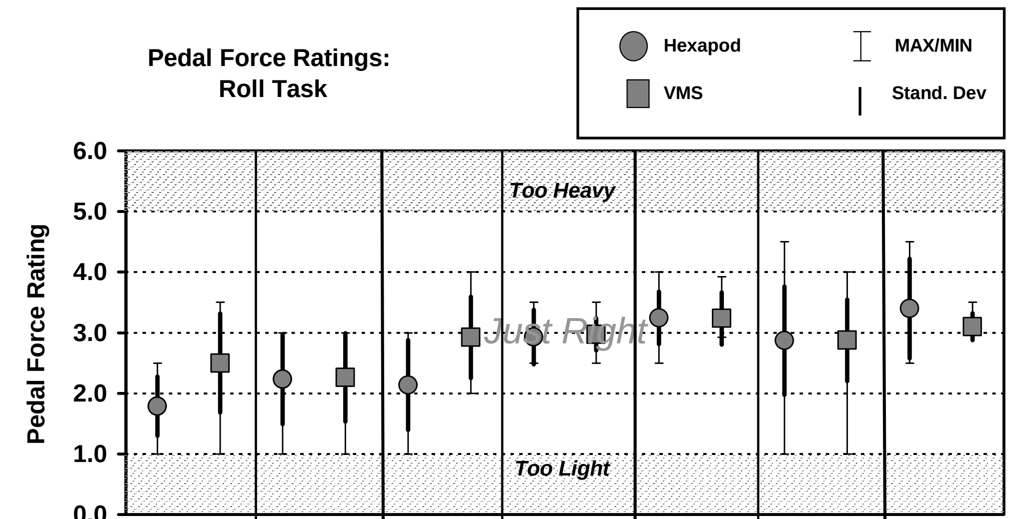
- Configurations with light pedal forces (linear load-feel) are seen to be more prone to overcontrol than those with heavier pedal forces (nonlinear load-feel). The 1σ variation is seen to be close to 4 on a scale of 1-5 for configurations 1 and 2, and at least one pilot rated the tendency to overcontrol at the maximum value of 5.

- Limited pedal travel did not result in a strong tendency for overcontrol when used in combination with a nonlinear load-feel system to provide increased pedal force cues. The only exception to this occurred with evaluations of configuration 2 using Hexapod motion, as noted above. When evaluated with VMS motion, this configuration was not perceived as being prone to overcontrol.

- The pilot commentary contained very little mention of PIO, nor did the time histories exhibit divergent tendencies that would indicate PIO.

<u>4.1.1.3 Perceived Pedal Forces—Roll Task</u>.

The subjective pilot opinions regarding pedal forces using the figure 8a scale are given in figure 24.



Config	1	3	2	4	5	6	7
Trials	7 10	10 11	9 13	7 9	13 17	13 14	5 5
Breakout	10	22	10	22	10	22	10
Load Feel	Linear		Nonlinear		Nonlinear		Nonlinear
Rud. Lim.	Var. Stop		Var. Stop		Var. Gearing		Force Lim

Figure 24. Ratings of Perceived Rudder Pedal Forces

The following conclusions may be drawn from the results presented in figure 24.

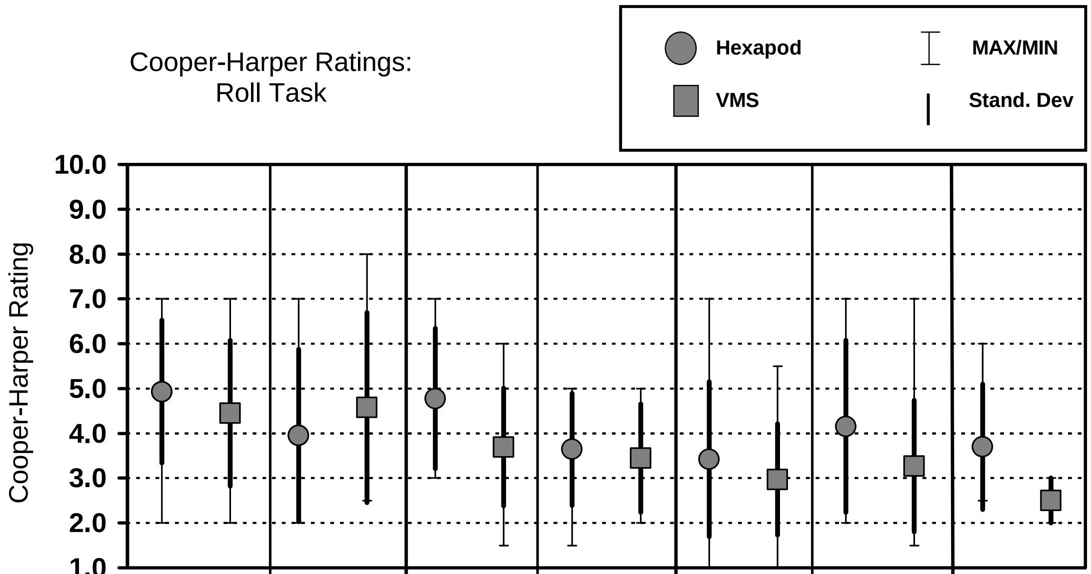
- The pedal force evaluations for configuration 2 were judged to be too light when evaluated on the Hexapod motion system and just right on the VMS motion system. This is probably related to the greater tendency to overcontrol configuration 2 with Hexapod motion that was noted in section 4.1.1.2. This trend is also seen for configuration 1.

- The pedal forces for the variable stop linear load-feel configurations were judged to be too light by most evaluators. One evaluator that liked these light forces had extensive helicopter background and therefore was used to very light pedal forces.

- The pedal forces for configurations with nonlinear load-feel were judged to be "just right" by most pilots. This was true for both the variable stop and variable gearing configurations.

4.1.1.4 Cooper-Harper HQR Results and Pilot Commentary—Roll Task.

The HQRs for the roll task are given in figure 25.



Config	1	3	2	4	5	6	7
Trials	7 10	10 11	9 13	7 9	13 17	13 14	5 5
Breakout	10	22	10	22	10	22	10
Load Feel	Linear		Nonlinear		Nonlinear		Nonlinear
Rud. Lim.	Var. Stop		Var. Stop		Var. Gearing		Force Lim

Figure 25. Cooper-Harper HQRs for Roll Task

The following conclusions may be drawn from the results presented in figure 25.

- Configurations with light pedal forces (linear load-feel) were rated worse than those with increased pedal forces (nonlinear load-feel). This trend is noticeably better defined for VMS motion than for Hexapod motion.

- The HQRs for all configurations except 3 are more degraded when evaluated with Hexapod motion than with VMS motion.

- The effect of breakout force (F_{bo}) was negligible for evaluations accomplished with VMS motion.

- For trials with Hexapod motion, increasing the breakout force noticeably improved the ratings for the variable stop configurations and degraded the ratings for the variable gearing configurations.

Based on the data in reference 7, increasing the breakout from 10 to 22 lb would be expected to degrade the ratings only slightly from HQR $\leq$3.5 to HQR = 4. The reference 7 data was for a landing task and may not apply to the aggressive roll task used in these tests.

The maximum and minimum ratings are seen to exhibit considerable variability between pilots (5 rating points from minimum to maximum, and a standard deviation of about $\pm$1.5 rating points). An examination of the pilot comments indicate that this accrues from a large variation in pilot preferences.

While most pilots did not like the very light forces associated with configurations 1 and 3, there were a few pilots that favored those very low pedal forces. One pilot was a former Army helicopter pilot and another was an airline pilot with extensive general aviation experience. These evaluators accounted for the surprisingly good HQRs at the lower end of the minimum and maximum lines. They also tended to account for the poor ratings at the upper end of the minimum and maximum lines for configurations 5 and 6, and complained about the high forces and large travel required to accomplish the task with those configurations.

Another caveat is that both the roll task and the yaw task required frequent and aggressive rudder activity. When doing this run after run, it might have been tempting to lean towards lighter forces and shorter throw simply because that is physically less tiring. As one pilot noted: “Systems that are hard to overcontrol require more effort to accomplish the task and conversely, systems that are easily overcontrolled are better to accomplish these tasks.”

Some examples of comments where pilots rated configurations 1 and 3 (variable stop with linear load-feel) as uncertifiable for the roll task are as follows:

- “Overcontrolling a lot. Turning down my gain. Not enough motion cues to figure out what is coming next (Hexapod). Over-responsive. On stops too often.”—1HP (HQR = 5)

- “Extremely light forces to get full travel”—1HP (HQR = 6)

- “Light forces were objectionable”—1VP (HQR = 7)

- “Big tendency to overcontrol”—3HP (HQR = 7)

- “All or nothing. Highest mental workload so far”—3VP (HQR = 7)

- “Significant out of sync aileron and rudder, Out of phase aileron and rudder often for large inputs. Barely controllable. Definitely not certifiable.”—3VP (HQR = 8).

A few pilots liked the variable stop with linear load-feel despite its tendency to overcontrol. Representative comments from this group are:

- “Tendency to overcontrol; could lead the ball with motion cues.”—3VB (HQR = 3)
- “Forces a little light but no unusual characteristics.”—3VP (HQR = 3)

- “Numerous time on stops, limited throw, but nice pedal pressure.”—3VP (HQR = 2.5

While most evaluators felt that the short-travel, higher pedal force configurations (2 and 4) were certifiable, a few did not. Those pilots complained mostly about the travel being too short, which led to overcontrol. Some examples are:

- “Travel too short”—2HP (HQR = 5
- “Tendency to overcontrol with rudder”—2HP (HQR = 6)
- “Overcontrol due to short pedal throw”—2HP (HQR = 7)
- “Limited travel caused some overcontrol”—4HP (HQR = 5.5)

Some examples of comments where pilots rated configurations 5 and 6 (3.5-inch travel with variable gearing and highest pedal forces) as uncertifiable or questionable are as follows.

- “Rudder system seemed nearly ineffective”—5HP (HQR = 7)
- “Too much pedal travel and force to get rudder”—5VP (HQR = 5.5)
- “Did not have enough rudder power”—5VP (HQR = 6)
- “Higher force with larger throw”—6HP (HQR = 6)
- “Heavy feel and travel too long”—6HP (HQR = 7)
- “Too heavy. Rating of 7 is due to heavy forces”—6VP (HQR = 7)

In a few cases, pilots noticed the nonlinear load-feel and felt that this was objectionable. In one case, this was deemed uncertifiable, and the pilot noted that “forces get lighter with increasing deflection”—6HP (HQR = 6). This comment suggests that a linear load-feel curve might alleviate some of the objections to the heavy forces with the variable gearing system. The Phase 2 experimental matrix [2] includes both linear and nonlinear load-feel curves for the variable gearing design.

There were essentially no comments related to PIO when debriefing each configuration for the roll task. One pilot noted a slight tendency to PIO configuration 6 with Hexapod motion (variable gearing—high breakout) and rated it HQR = 6 and uncertifiable. When given the same configuration with VMS motion, the pilot rated it HQR = 2.5 and certifiable, with no mention of PIO.

In summary, the objective of this work is to minimize the tendency for overcontrol and thereby minimize the forces on the vertical stabilizer. In that context, the above pilot commentary adds considerable insight to the Cooper-Harper ratings and reveals the following:

- Variable stop with linear load-feel systems (light pedal forces and short pedal travel—configurations 1 and 3) are prone to overcontrol.

- Variable stop with nonlinear load-feel systems (high pedal forces and short travel—configurations 2 and 4) are significantly less prone to overcontrol than configurations 1 and 3, but still have some overcontrol tendencies.

- Variable gearing with nonlinear load-feel systems (high pedal forces and long pedal travel—configurations 5 and 6) are resistant to overcontrol.

A summary of pilot commentary and ratings for each trial is given in appendix B.

4.1.1.5 Modified Cooper-Harper Workload Rating Results—Roll Task.

The Modified Cooper-Harper workload rating results are presented in figure 26.

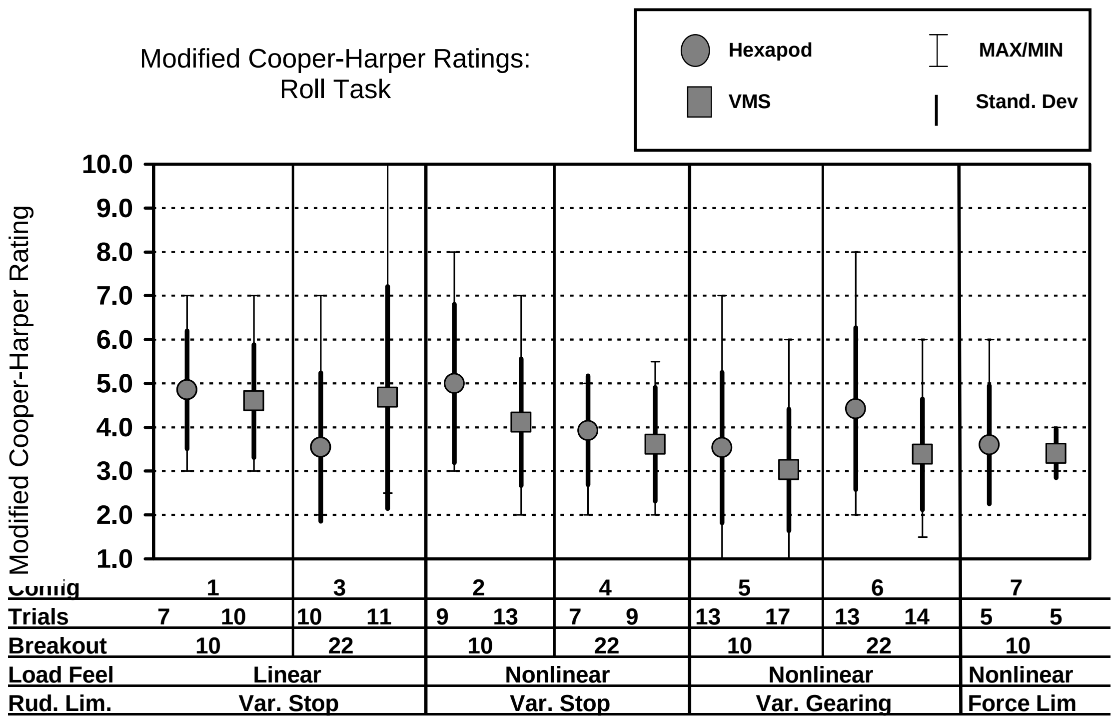


Figure 26. Modified Cooper-Harper Workload Rating Results—Roll Task

The results with the Modified Cooper-Harper workload rating scale are consistent with the results obtained the Cooper-Harper HQR scale that were shown in figure 25.

The trend in workload rating for VMS motion shows the low pedal force (linear load-feel—configurations 1 and 3) required consistently higher workload than the other configurations, and the variable gearing and force limit systems required the least amount of workload. This conclusion does not apply for evaluations with Hexapod motion, where the rating trends are quite different.

4.1.1.6 Correlation Between HQR and Proposed Criterion Parameters—Roll and Yaw Tasks.

Two criterion parameters that were suggested in the reference 4 NTSB report to predict overcontrol tendencies were evaluated using the data generated in this experiment. While this was not a primary objective of Phase 1, these metrics were evaluated to gain some insight to guide Phase 2.

$F_{bo}/F_{\lim} - F_{\lim}$ is defined as the force required to reach the rudder deflection limit, F_{bo} is defined as the sum of the feel spring breakout force (F_{spbo}), and Coulomb friction (F_{cf}) as defined in section 3.1.

It has been hypothesized that the rudder overcontrol that occurred in the American Airlines Flight 587 accident was related to the fact that the rudder pedal force to reach the limit of travel ($F_{\lim}$) was not much greater than the rudder pedal breakout force (F_{bo}) on the A300-600 accident aircraft (e.g., references 9 and 4).

The basic principals of manual control would predict that systems where F_{bo} is close in magnitude to $F_{\lim}$ would be prone to overcontrol because of the highly nonlinear nature of such a system, and the fact that there is only a small region of pedal force between zero and maximum rudder deflection.

Note that if $F_{bo} = F_{\lim}$, the effect is that of an on-off relay (all or nothing). Control system theory indicates that such systems will limit cycle at best and are unstable with any additional lag. Values of the $F_{bo}/F_{\lim}$ parameter are given for the aircraft reviewed by the NTSB in table 5.

It is notable that the Airbus variable stop designs have much larger values of $F_{bo}/F_{\lim}$ than all other aircraft reviewed, as shown in table 5. The large value of $F_{bo}/F_{\lim}$ is a result of using the variable stop design along with an almost linear force-feel gradient.

Table 5. Values of Parameters From NTSB Report

Rudder System	Aircraft	$F_{bo} / F_{\lim}$	$\frac{\delta_{r_{\max}}}{F_{\max} - F_{bo}}$
Variable gearing	A300 B2/B4	0.18	0.09
Variable stop	A310, A300-600	0.69	0.93
Variable stop	A320	0.59	0.56
Variable stop	A330, A340	0.71	0.73
Force limit	B-727	0.34	0.21
Force limit	B-737	0.30	0.11
Variable gearing	B-747	0.24	0.20
Variable gearing	B-757	0.20	0.09
Variable gearing	B-767	0.21	0.13
Variable gearing	B-777	0.30	0.21
Variable stop	DC-9	0.27	0.18
Variable stop	MD-80	0.25	0.18
Variable stop	B-717	0.31	0.29
Force limit	DC-10	0.15	0.25
Force limit	MD-11	0.15	0.27

The data in table 5 indicate that the Douglas/Boeing variable stop designs have an $F_{bo}/F_{\lim}$ that is consistent with the variable gearing and force limit configurations. This is a result of using a highly nonlinear load-feel curve.

Figure 27 shows that the results of this simulation indicate that $F_{bo}/F_{\lim}$ is not a good correlating parameter to predict overcontrol tendencies for the rudder control.

$\frac{\delta_{r_{\max}}}{F_{\lim} - F_{bo}}$ - This parameter is also suggested by the NTSB in reference 4. Large values of this parameter imply that it takes relatively little additional force above breakout to achieve the maximum rudder displacement. As noted above, $F_{\lim}$ is defined as the force required to reach the maximum rudder deflection, $\delta_{r_{\max}}$. The rationale here is similar to $F_{bo}/F_{\lim}$ in that good handling qualities and resistance to overcontrol or PIO require some minimum difference between the maximum force and the breakout force. This parameter accounts for rudder deflection explicitly and penalizes increased rudder control power due to larger maximum deflection. The $\frac{\delta_{r_{\max}}}{F_{\lim} - F_{bo}}$ parameter is shown for the aircraft reviewed by the NTSB in table 5. As with the $F_{bo}/F_{\lim}$ metric, the Airbus variable stop designs stand out with higher values than the rest.

A better parameter might substitute maximum sideslip or maximum lateral acceleration for maximum rudder in the numerator of $\frac{\delta_{r_{\max}}}{F_{\lim} - F_{bo}}$. This would better account for variations in rudder control power. However, for this experiment, the correlation with pilot ratings would be the same as for $\delta_{r_{\max}}$ because the rudder control power was held constant.

The Cooper-Harper HQRs are plotted against these proposed criterion parameters for the VMS and Hexapod motion, and for the roll and yaw tasks.

Cooper-Harper HQRs are plotted versus $F_{bo}/F_{\lim}$ and $\frac{\delta_{r_{\max}}}{F_{\lim} - F_{bo}}$ in figures 27 and 28, respectively, for the roll task with VMS motion.

The $F_{bo}/F_{\lim}$ value of configuration 1 falls very close to the value for configuration 6 in figure 27. A review of the pilot commentary (e.g., section 4.1.1.4) indicates that configuration 1 (light pedal force and short travel) was judged to be highly prone to overcontrol, and configuration 6 (high pedal force and long travel) was highly resistant to overcontrol. On that basis, $F_{bo}/F_{\lim}$ is judged to be a poor metric for estimation of overcontrol tendency, and it is not surprising that configuration 1 appears as an outlier when plotted versus this metric. Therefore, $F_{bo}/F_{\lim}$ has been rejected as a potential overcontrol metric.

$\frac{\delta_{r_{\max}}}{F_{\lim} - F_{bo}}$ is plotted versus Cooper-Harper HQR in figure 28.

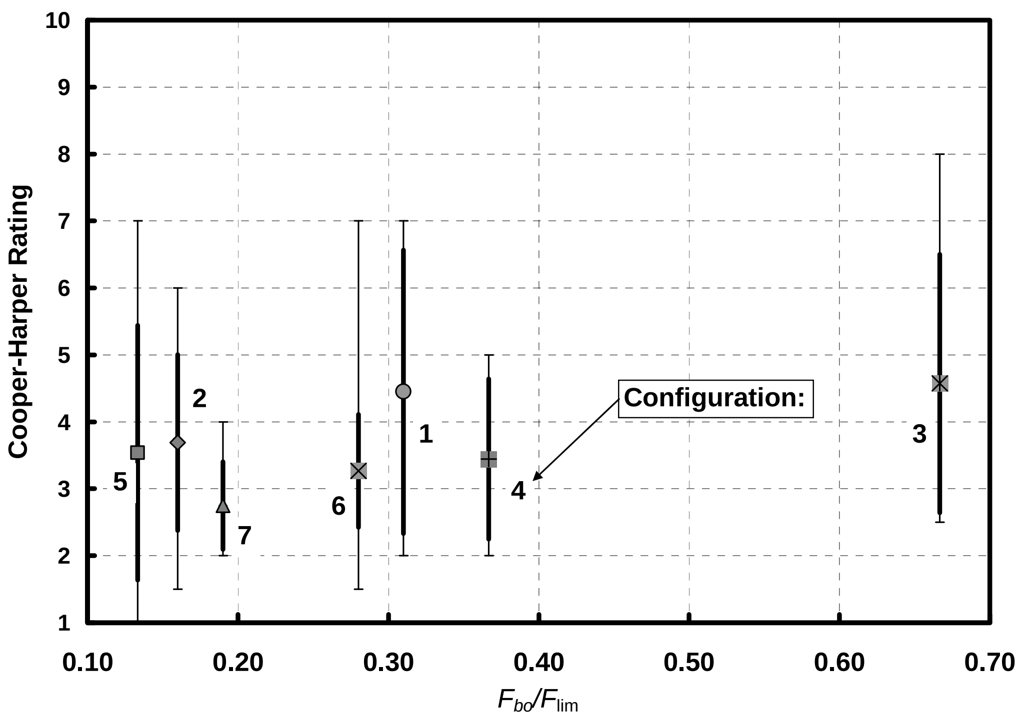


Figure 27. Cooper-Harper HQR vs $F_{bo}/F_{\lim}$—VMS Motion—Roll Task

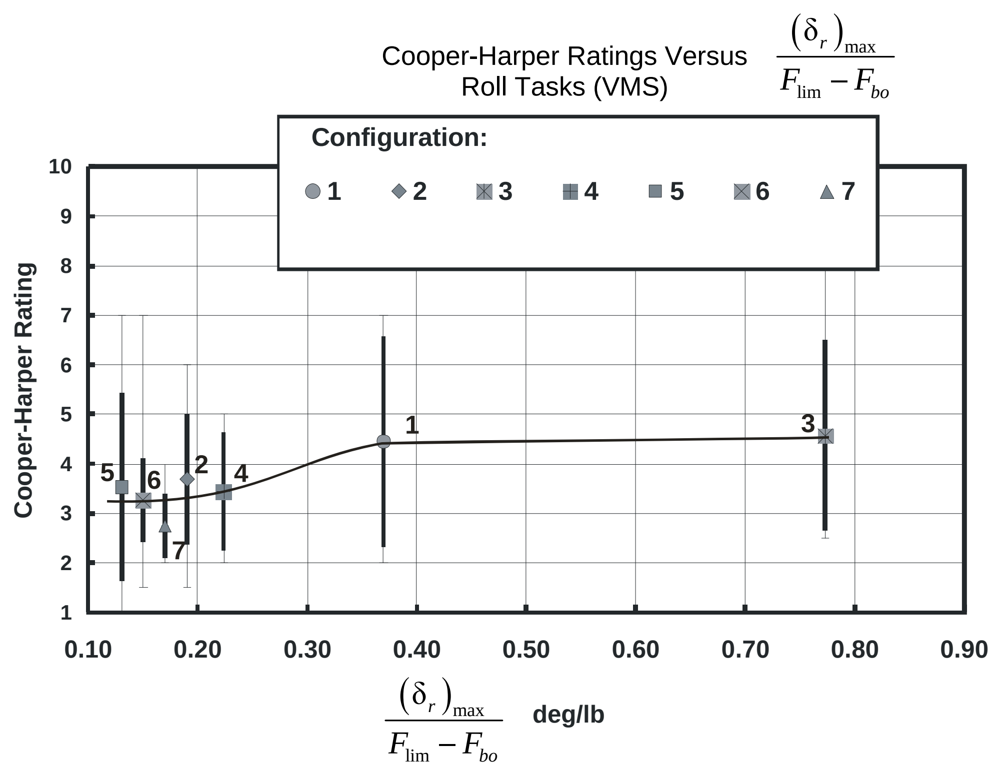


Figure 28. Cooper-Harper HQR vs $\frac{\delta_{r_{\max}}}{F_{\lim} - F_{bo}}$ —VMS Motion—Roll Task

The rating data in figure 28 exhibit the expected trend towards more degraded ratings with increasing values of $\frac{\delta_{r_{max}}}{F_{lim} - F_{bo}}$. As is often the case, the relatively small change in average HQR does not reflect the fact that there may be significant differences in the aircraft response characteristics. Referring to the correlation between HQR and probability of passing FAA certification that was shown in figure 20, the observed decrease in average HQR from 3.5 to 4.5 is seen to represent a significant decrease in the probability of successful certification.

Increasing the value of $\frac{\delta_{r_{max}}}{F_{lim} - F_{bo}}$ from 0.20 to 0.40 deg/lb results in an increase in HQR. However, further increasing this parameter did not result in additional degradation in handling qualities rating. This may be because most pilots pushed much harder than the 33-lb limit force, even though this extra effort had no effect on rudder deflection. It is suspected that the pilots were unaware that they were pushing far beyond F_{lim}, and most of the pedal force had no effect on rudder deflection. This would probably obscure the effect of F_{lim} on subjective pilot opinion.

It will be shown in section 4.2.1.4 that the average maximum pedal force during the roll task with 10-lb breakout was 80 lb and with 22-lb breakout was 120 lb, and that forces as high as 200 lb were measured with either value of breakout. These high forces relate to the sense of urgency that exists when rudder is necessary to augment limited aileron control power.

Cooper-Harper HQRs are plotted versus $\frac{\delta_{r_{max}}}{F_{lim} - F_{bo}}$ in figure 29 for the yaw task with VMS motion.

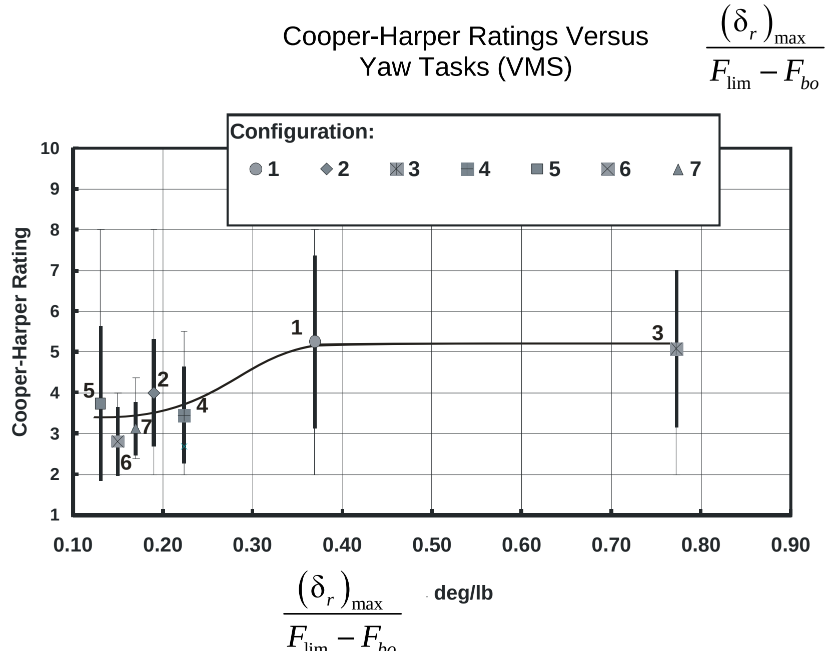


Figure 29. Cooper-Harper HQR vs $\frac{\delta_{r_{max}}}{F_{lim} - F_{bo}}$—VMS Motion—Yaw Task

The correlation between handling qualities ratings and $\frac{\delta_{r_{max}}}{F_{lim} - F_{bo}}$ for the yaw task with VMS motion is similar to the roll task, except the degradation in HQR with increasing values of $\frac{\delta_{r_{max}}}{F_{lim} - F_{bo}}$ is slightly more pronounced for the yaw task.

As noted for the roll task, the lack of degradation in HQR when increasing $\frac{\delta_{r_{max}}}{F_{lim} - F_{bo}}$ from 0.40 to 0.77 deg/lb is surprising, because increases in this parameter result in an increase in the nonlinearity of the response of rudder to pedal force inputs. Such highly nonlinear characteristics would be expected to be very objectionable for the yaw task, which consists of closed loop tracking with pedals.

The maximum forces applied by the pilots were considerably less than with the roll task, but still somewhat higher than the limit force of 33 lb. In section 4.2.2.4, the data shows an average maximum force of approximately 45 lb and peak maximum forces of 100 lb. As with the roll task, the use of such high pedal forces probably obscures the effect of F_{lim}.

Cooper-Harper HQRs are plotted versus $\frac{\delta_{r_{max}}}{F_{lim} - F_{bo}}$ in figure 30 for the roll task with Hexapod motion.

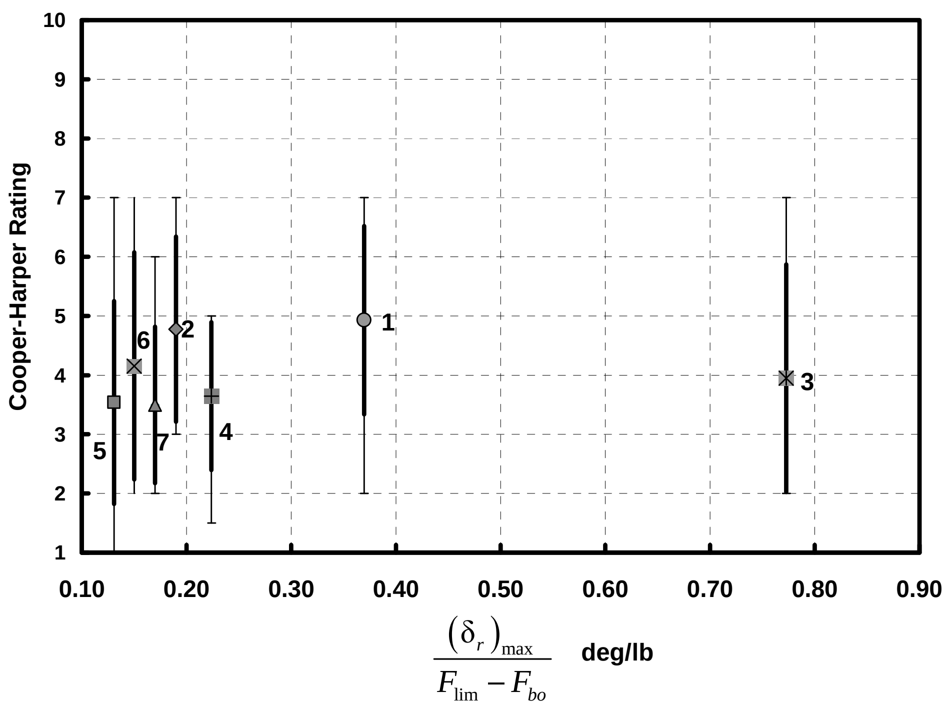


Figure 30. Cooper-Harper HQR vs $\frac{\delta_{r_{max}}}{F_{lim} - F_{bo}}$—Hexapod Motion—Roll Task

For the roll task with Hexapod motion, the data in figure 30 indicate that there is no correlation between the subjective pilot ratings and $\frac{\delta_{r_{max}}}{F_{\lim} - F_{bo}}$. This is dramatically different from the VMS results, which showed good correlation.

As discussed earlier, when a discrepancy exists between the results from Hexapod and VMS motion, it is assumed that the VMS motion is more correct because it provides significantly more cueing than Hexapod motion.

Cooper-Harper HQRs are plotted versus $\frac{\delta_{r_{max}}}{F_{\lim} - F_{bo}}$ in figure 31 for the yaw task with Hexapod motion.

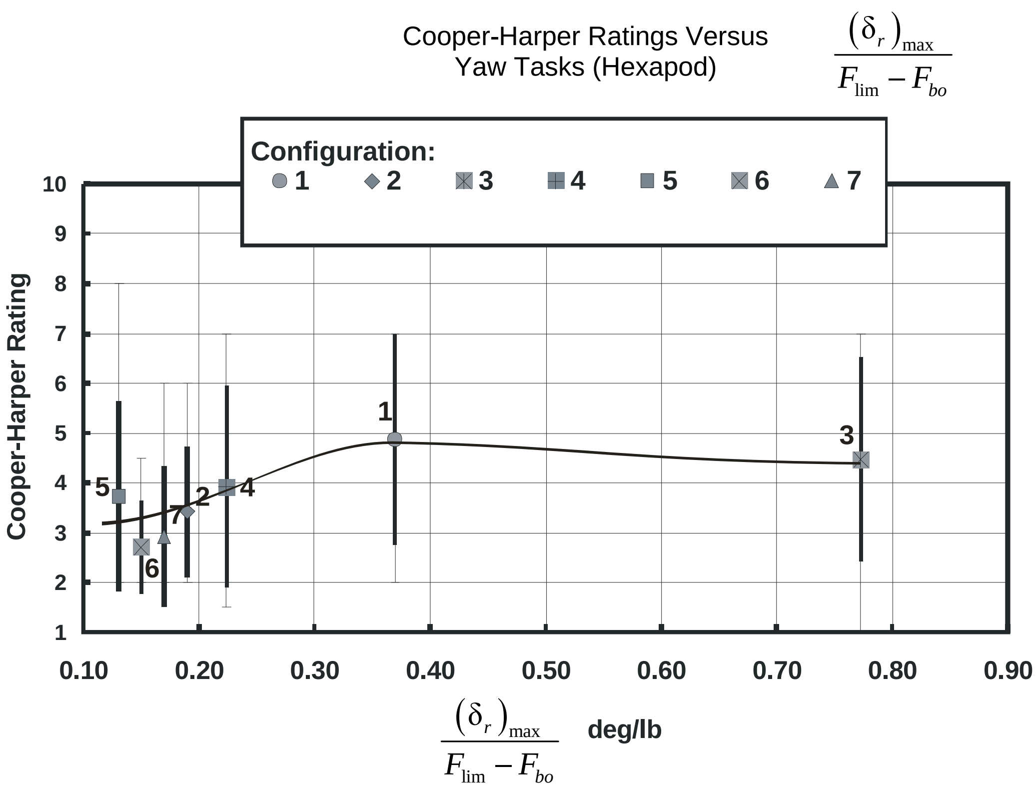


Figure 31. Cooper-Harper HQR vs $\frac{\delta_{r_{max}}}{F_{\lim} - F_{bo}}$ —Hexapod Motion—Yaw Task

For the yaw task with Hexapod motion, there is better correlation between the subjective pilot ratings and $\frac{\delta_{r_{max}}}{F_{\lim} - F_{bo}}$ than was exhibited for the roll task, albeit not as compelling as for VMS motion.

In summary:

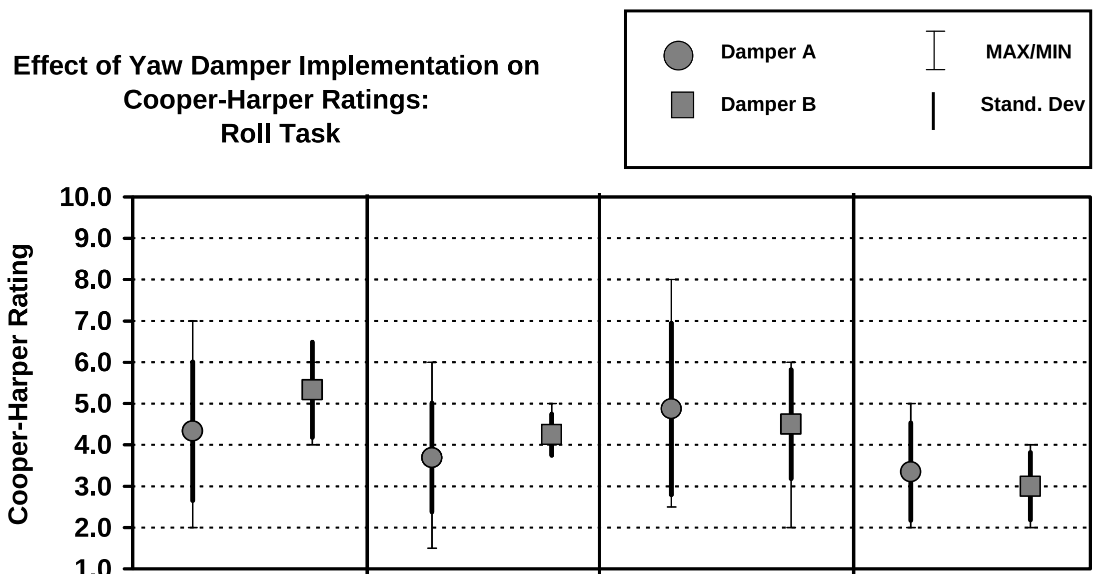
- The correlations from evaluations with VMS motion are significantly better than with Hexapod motion for the roll task and slightly better for the yaw task.

- The $F_{bo}/F_{\lim}$ parameter was not found to effectively separate configurations that are prone to overcontrol from those that are not, and was eliminated as a potential metric.

- The expected trend of degraded HQRs with increasing values of $\frac{\delta_{r_{\max}}}{F_{\lim} - F_{bo}}$ occurred, although it is less dramatic than expected. That is, there was an incremental degradation between 0.2 and 0.4 deg/lb, but further increases in the parameter did not result in the expected degradation in handling qualities.

4.1.1.7 Effect of Yaw Damper Implementation on Cooper-Harper Pilot Ratings—Roll Task.

The effect of inserting the yaw damper downstream of the rudder limiter was evaluated as discussed in section 3.2.4. Yaw damper evaluations were only accomplished with VMS motion. The effect of yaw damper implementation on Cooper-Harper ratings for the roll task is tabulated in figure 32.



Config	1	8	2	9	3	10	4	11
Trials	8	3	15	4	12	5	7	4
Breakout	10		10		22		22	
Load Feel	Linear		Nonlinear		Linear		Nonlinear	
Rud. Lim.	Var. Stop		Var. Stop		Var. Stop		Var. Stop	

Figure 32. Effect of Yaw Damper Implementation on Cooper-Harper HQR—Roll Task

As discussed in section 3.2.4, YD A was implemented upstream of the rudder limiter, and YD B was downstream of the rudder limiter.

These results do not indicate that YD B provided any improvement in handling qualities over YD A for the roll task. In fact, some degradation was observed when YD B was implemented on configurations 1 and 2.

4.1.1.8 Percent of Trials Rated as Certifiable for Roll Task.

A comparison of the certification decision (yes or no) for runs made with VMS motion versus runs made with Hexapod motion is shown in figure 33 for the roll task. In some cases, the evaluator gave an opinion of "uncertain." Those cases were classified as a "no" for plotting in figure 33.

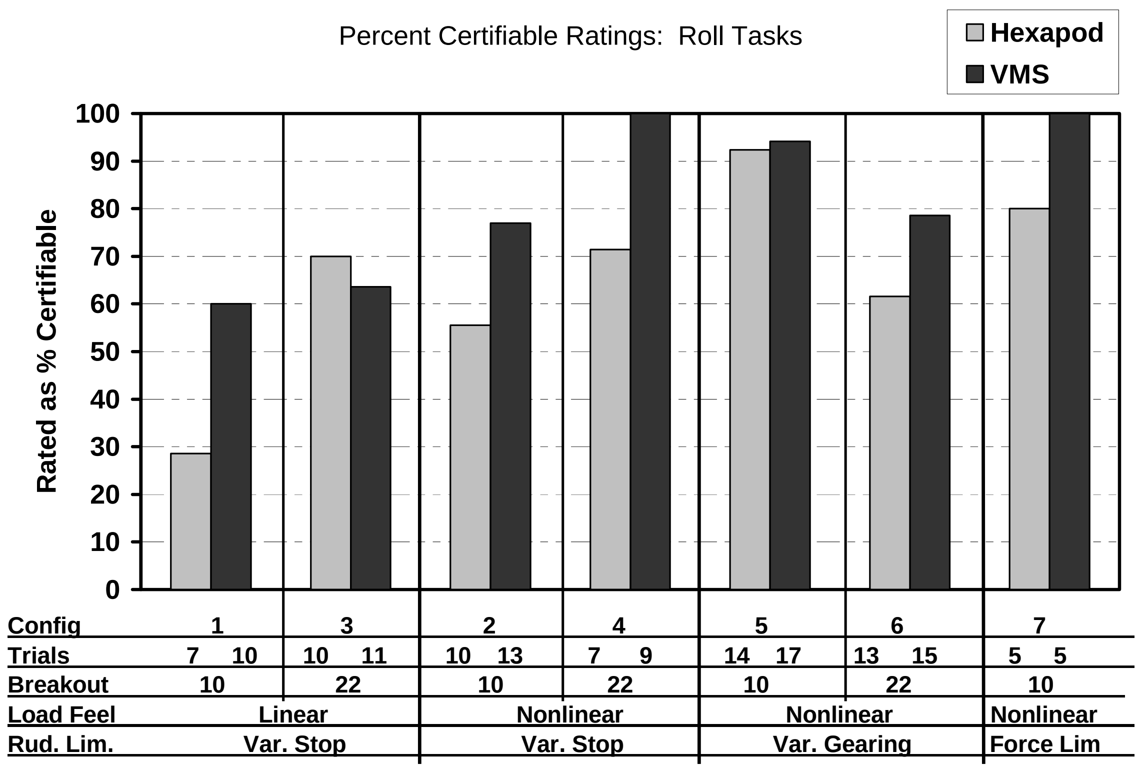


Figure 33. Percentage of Trials Rated as Certifiable for Each Configuration—Roll Task

These data indicate that there was a higher tendency to rate a configuration as uncertifiable with Hexapod motion than for runs with VMS motion. This may indicate that enhanced motion cues compensate for rudder system deficiencies.

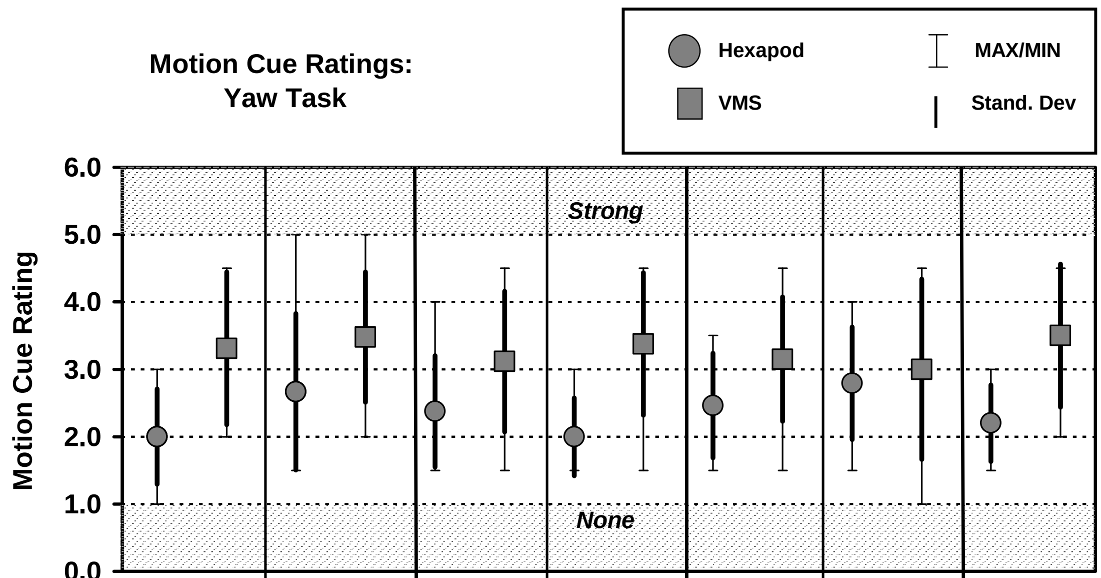
Surprisingly, the variable gearing configuration trials were not rated as 100% certifiable. A review of pilot commentary reveals that this was because the task required the pilot to continuously move the pedals through a large travel with moderately high forces. One pilot objected to the change in force with deflection as a result of the nonlinear load-feel curve. Future testing in Phase 2 should include a variable gearing linear load-feel configuration.

Conversely, the reason given for rating the variable stop configuration as uncertifiable was almost always related to overcontrol tendency. These effects were discussed in detail in sections 4.1.1.4 and 4.1.2.4.

4.1.2 Pilot Rating Results for Yaw Task.

4.1.2.1 Subjective Motion Cue Ratings—Yaw Task.

The pilot rating results for subjective motion cueing for the yaw task are given in figure 34.



Config	1	3	2	4	5	6	7
Trials	7 10	10 11	9 13	7 9	13 17	13 14	5 5
Breakout	10	22	10	22	10	22	10
Load Feel	Linear		Nonlinear		Nonlinear		Nonlinear
Rud. Lim.	Var. Stop		Var. Stop		Var. Gearing		Force Lim

Figure 34. Pilot Ratings for Perceived Impact of Motion Cues on Rudder Usage—Yaw Task

The results shown in figure 34 indicate that there was a consistent improvement in the perceived impact of motion cueing for evaluations using the VMS motion compared to the Hexapod motion. This is probably because the dominant motion for the yaw task was side acceleration, and therefore, lack of motion in that axis would be expected to be noticeable.

One pilot commented that when flying with VMS motion, the lateral acceleration was felt before the ball movement was detected, and that definitely had an impact on the pilot's rudder inputs.

The difference in ratings between Hexapod and VMS was somewhat greater for the variable stop configurations than for the variable gearing configurations. This probably indicates that there was more of a tendency to excite lateral motion with the variable stop designs where full rudder deflection is achieved with only 1.15 inches of rudder pedal travel.

4.1.2.2 Tendency to Overcontrol With Rudder—Yaw Task.

The pilot rating results for tendency to overcontrol with rudder for the yaw task are given in figure 35.

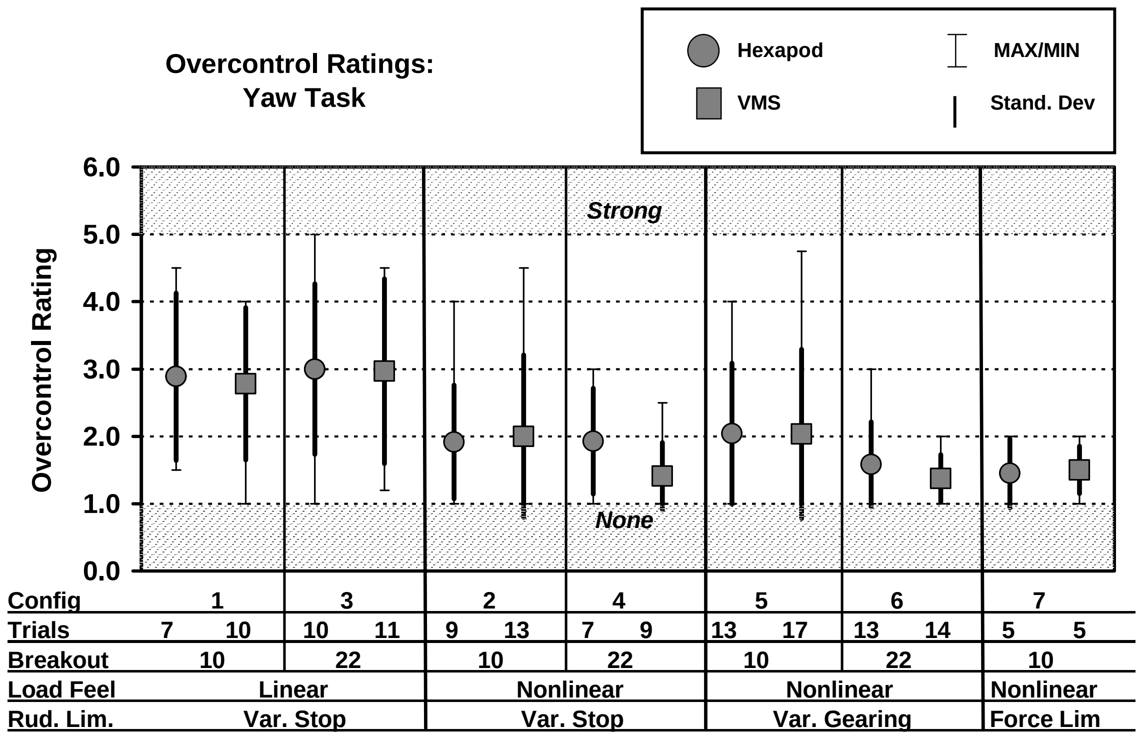


Figure 35. Pilot Ratings for Tendency to Overcontrol With Rudder—Yaw Task

The following conclusions related to ratings of overcontrol tendency with the yaw task may be drawn from the data in figure 35.

- There was very little difference in the ratings for VMS or Hexapod motion.

- The configurations with light pedal forces (linear load-feel) were rated as more prone to overcontrol with rudder than those with higher pedal forces (nonlinear load-feel). This trend is equally well-defined for evaluations with VMS and Hexapod motion.

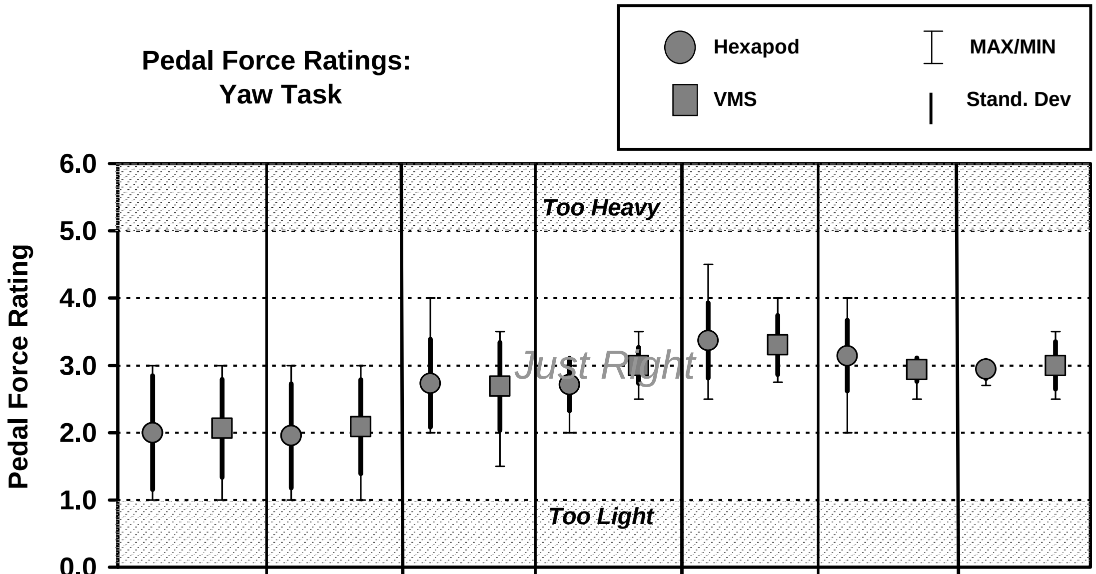
- There was no significant difference in the overcontrol rating data for short throw pedal travel (configurations 2, 4, and 7) and long throw pedal travel (configurations 5 and 6) as long as the load-feel was nonlinear (i.e., higher pedal forces).

- The effect of breakout force was negligible for the variable stop linear load-feel configurations.

- There was a slight decrease in the tendency for overcontrol with increasing breakout for the variable stop nonlinear configurations and the variable gearing configurations.

4.1.2.3 Perceived Pedal Forces—Yaw Task.

The pilot rating results for the perceived pedal forces for the yaw task are given in figure 36.



Config	1	3	2	4	5	6	7
Trials	7 10	10 11	9 13	7 9	13 17	13 14	5 5
Breakout	10	22	10	22	10	22	10
Load Feel	Linear		Nonlinear		Nonlinear		Nonlinear
Rud. Lim.	Var. Stop		Var. Stop		Var. Gearing		Force Lim

Figure 36. Pilot Rating for Perceived Pedal Forces—Yaw Task

The following conclusions may be drawn from the results presented in figure 36.

- There was no significant difference between the VMS and Hexapod motion systems related to pilot perception of pedal forces for the yaw task.
- The pedal forces for the configurations with linear load-feel were judged to be too light by most evaluators for the yaw task.
- The pedal forces for configurations with nonlinear load-feel were judged to be in the vicinity of “just right” by most pilots for the yaw task.
- Breakout force had essentially no impact on the pilot’s ratings of pedal force with either motion system for the variable stop linear load-feel configurations.
- Increasing breakout force caused a slight increase in pedal force rating for the variable stop nonlinear load-feel case with VMS motion and had no effect with Hexapod motion.
- Increasing the breakout force caused the ratings of pedal force to decrease slightly for the variable gearing configurations.

4.1.2.4 Cooper-Harper HQR Results and Pilot Commentary—Yaw Task.

The Cooper-Harper HQRs for the yaw task are given in figure 37.

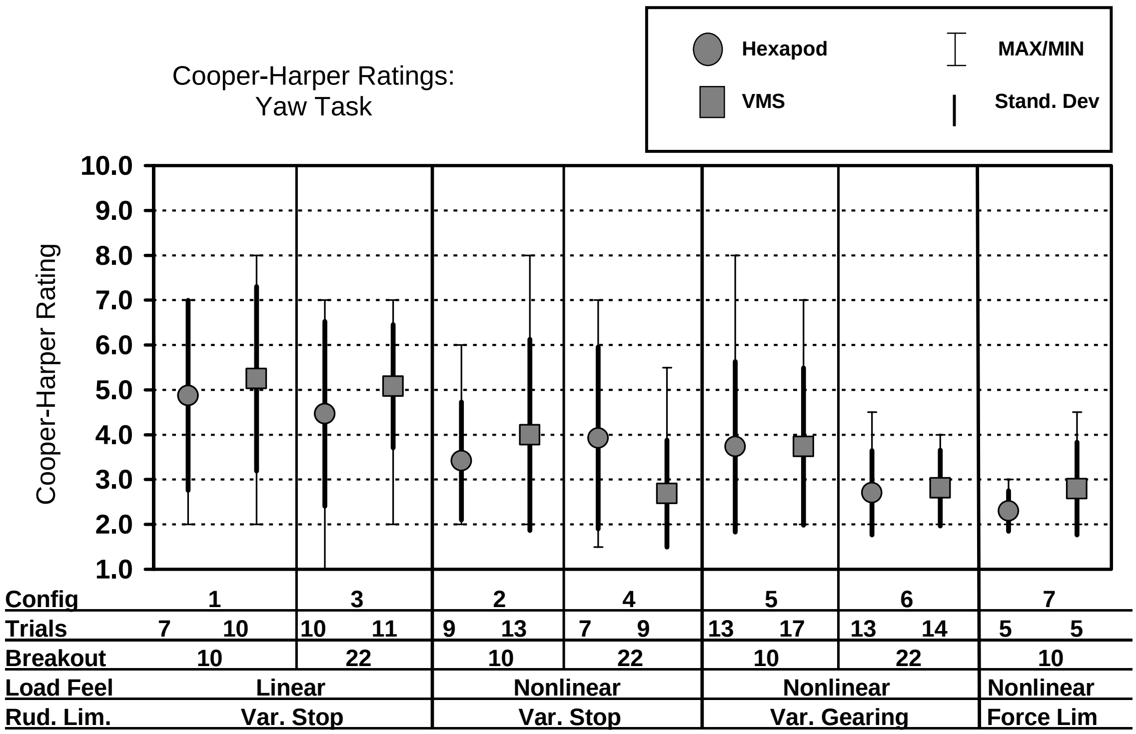


Figure 37. Cooper-Harper HQR—Yaw Task

The following conclusions were drawn from figure 37.

- There were differences in HQRs obtained with the VMS motion and Hexapod motion for all configurations except variable gearing. Configuration 4 produced the largest discrepancy ($\Delta HQR \approx 1.2$).

- Increasing the breakout force had no effect on the variable stop linear load-feel configurations with either motion system.

- With VMS motion, increasing the breakout force caused the ratings to improve for the variable stop nonlinear load-feel and variable gearing configurations.

- With Hexapod motion, there was no consistent trend in HQRs with increasing breakout.

Configurations with linear load-feel curves exhibited noticeably more degraded HQRs than those with nonlinear load-feel. Example pilot commentary where the pilots rated the linear load-feel cases as uncertifiable are:

- "Not appropriate for transport airplane."—1VB (HQR = 5)
- "Tendency to overcontrol with rudder."—1VB (HQR = 7)
- "High tendency to overcontrol."—3VB (HQR = 7)

Cases where configurations with nonlinear load-feel were rated as uncertifiable for the yaw task were almost always related to the high forces required to accomplish the rudder tracking task. Some examples are:

- "Rudder forces way too heavy."—5HB (HQR = 8)
- "Negligible response to small inputs."—5VB (HQR = 6)

The same pilot who gave the above comment for Case 5VB also gave the following comment on a repeat run during a subsequent session.

- "Strong tendency to overcontrol rudder especially at large pedal deflections."—5VB (HQR = 7)

This pilot clearly did not like the variable gearing configuration and rated it as ineffective in one instance and a strong tendency to overcontrol in another. This was the only trial where a variable gearing configuration was noted to have a tendency to overcontrol for the roll or yaw task.

There were only two pilot comments related to PIO. Both were for configuration 3 (variable stop and linear load-feel), and one referred to a slight tendency. Neither comment was accompanied by any evidence of divergence in rudder or sideslip angle. One PIO comment was for an evaluation with VMS motion and the other with Hexapod motion.

4.1.2.5 Modified Cooper-Harper Workload Rating Results—Yaw Task.

The workload ratings for the yaw task from the Modified Cooper-Harper scale are given in figure 38.

The trends observed for the Cooper-Harper handling scale in figure 37 are consistent with those observed for the Modified Cooper-Harper workload scale in figure 38, except that the discrepancy between the two motion systems is magnified for configurations 1 through 4.

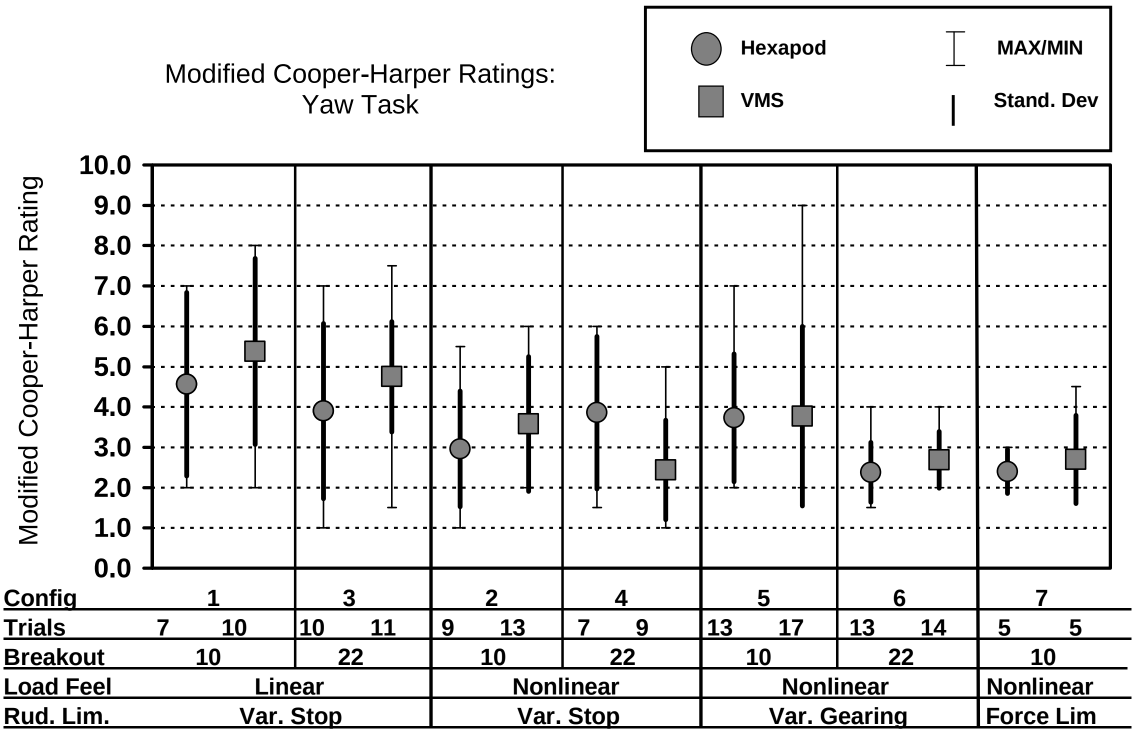


Figure 38. Modified Cooper-Harper Workload Ratings—Yaw Task

4.1.2.6 Comments on Rating Variability.

It is well known that there is significant variability among pilots as to what constitutes good handling qualities. This was very evident in this experiment where some pilots favored light forces and short pedal throw, while others thought those characteristics were completely unacceptable.

This variability among pilots was also true for simulator motion, wherein some pilots hardly noticed the significantly increased lateral motion provided by the VMS over the Hexapod, while others thought the motion cues were extremely important.

One pilot noted that the lateral motion was felt before the ball movement was detected with VMS motion. The pilot's comments regarding discrepancy between ball and motion needed to be taken in the context that motion was giving more immediate cues than the sideslip ball, which enhanced the ability to properly use the rudder.

A pilot with substantial experience as a transport test pilot gave significantly more degraded ratings for configuration 4 for Hexapod motion compared to VMS motion. As shown in table 6, these evaluations were made on two occasions during the test program, and therefore, the results are unlikely due to chance.

Table 6. The VMS Motion vs Hexapod Motion

Run	Case	HQR	Modified Cooper-Harper
48	4HP (Hexapod)	5	6
778	4VP (VMS)	2.5	3
992	4HP (Hexapod)	4	5
988	4VP (VMS)	2.5	2.5

For this experienced transport test pilot, the VMS motion resulted in considerably better ratings than Hexapod motion. As shown in figures 25 and 26, this trend is not observed for the average of all pilots wherein the effect of motion seems to be negligible for this configuration. When developing criteria in Phase 2, it is suggested that each pilot's rating trends be plotted separately so that important effects are not averaged out. The potential loss of important insight that can occur by averaging all ratings is discussed in reference 8.

The variability in pilot opinion is good reason for why a quantitative criterion is necessary to define what is an acceptable and safe rudder system and what is not. Otherwise, the decision to certify is left to chance and depends on the unique opinions and background of the chief test pilot for the company and the FAA certification project pilot.

<u>4.1.2.7 Effect of Yaw Damper Implementation on Cooper-Harper Pilot Ratings—Yaw Task</u>.

The effect of yaw damper implementation on the Cooper-Harper ratings given during yaw tasks is shown figure 39.

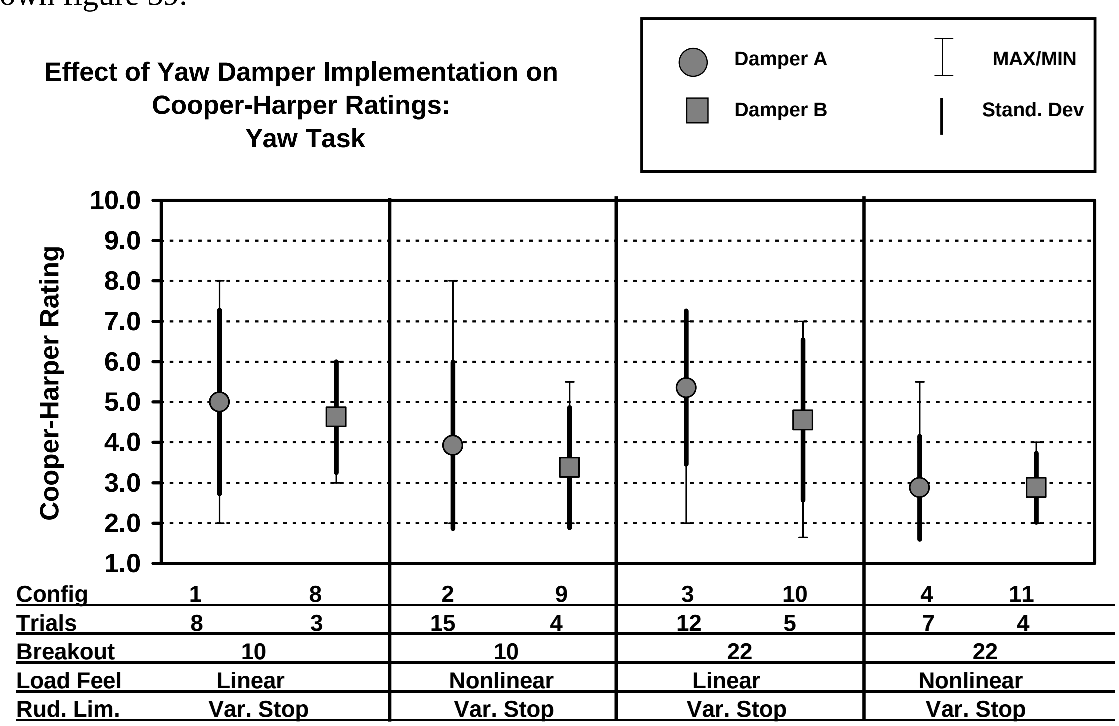


Figure 39. Effect of Yaw Damper Implementation on Cooper-Harper Ratings—Yaw Task

YD B is seen to result in a small but consistent improvement in HQR compared to the results for YD A for the yaw task. This improvement was not observed for the roll task (see section 4.1.1.7). This is probably because the yaw task occurred almost exclusively in the yaw axis where improved yaw damping would be most noticeable.

4.1.2.8 Percentage of Trials Rated as Certifiable for Yaw Task.

A comparison of the certification decision (yes or no) for runs made with VMS motion versus runs made with Hexapod motion is shown in figure 40 for the yaw task.

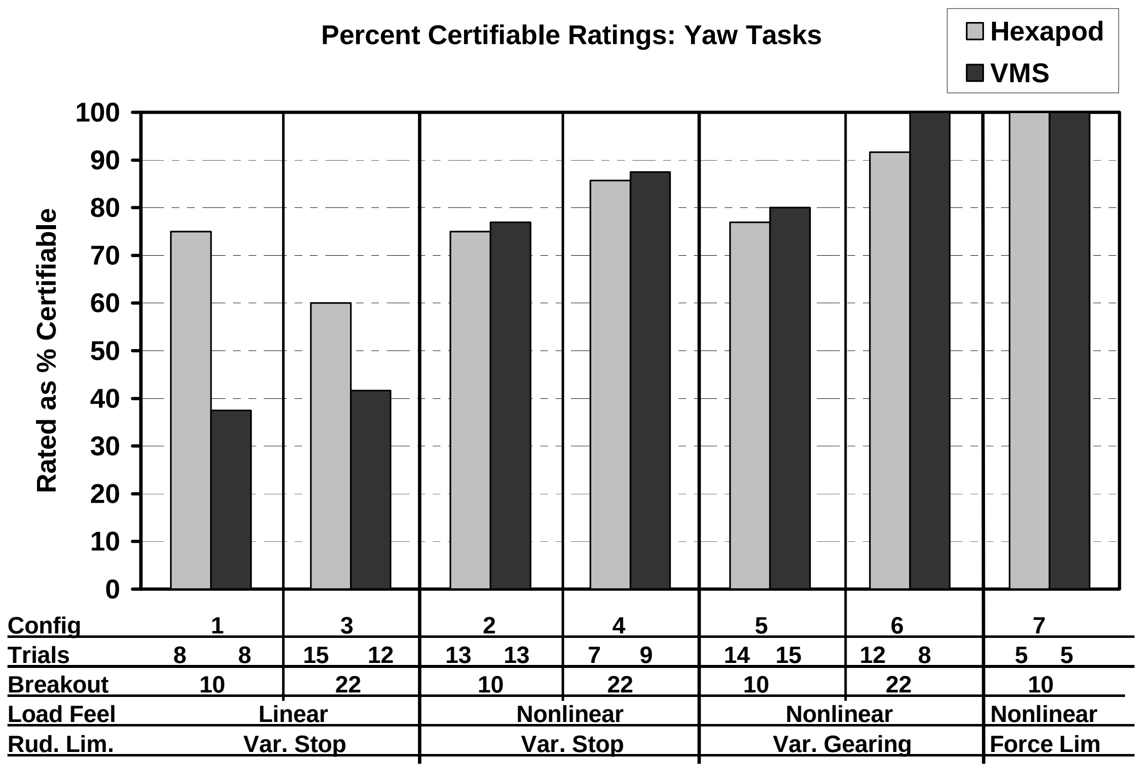


Figure 40. Percentage of Trials Rated as Certifiable for Each Configuration—Yaw Task

The variable stop systems with linear load-feel (configurations 1 and 3) indicate a more significant tendency to be rated as uncertifiable than configurations with nonlinear load-feel. That trend is much better defined with VMS motion than with Hexapod motion.

4.2 QUANTITATIVE DATA.

Quantitative data were taken on every run. These data are presented and analyzed in this section of the report.

Each plot indicates the number of trials involved in taking the average and standard deviation. For the quantitative data, one trial indicates a single run. This is different from the qualitative data presented above, where a trial consisted of three or more runs.

4.2.1 Roll Task.

4.2.1.1 Effect of Yaw Damper Implementation on Force on Vertical Stabilizer—Roll Task.

The effect of yaw damper implementation on the maximum force exerted on the vertical stabilizer for roll tasks is shown in figure 41.

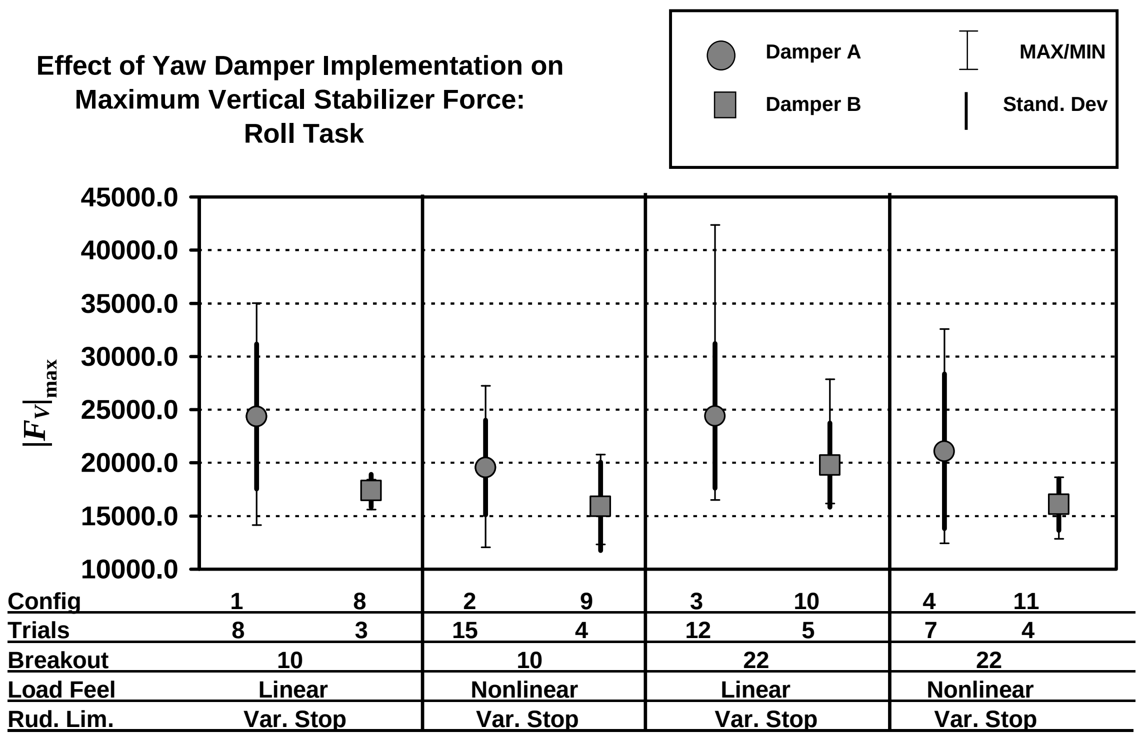


Figure 41. Effect of Yaw Damper Implementation on Maximum Vertical Stabilizer Force—Roll Task

These data indicate that YD B implementation (see section 3.2.4) is quite effective as a means to reduce the loads on the vertical stabilizer. This was not noticed by the evaluation pilots, as they indicated no advantage to the YD B versus YD A implementation in their ratings (section 4.1.1.7).

The YD B implementation effectively increases the control power of the yaw damper by allowing full authority (±3° in this simulation) even when the rudder is on or near the limit. It is hypothesized that the reduced vertical stabilizer loads are a result of more efficiently minimizing sideslip.

4.2.1.2 Maximum Rudder Surface Deflection—Roll Task.

The experimental design called for keeping the maximum rudder deflection constant to the extent possible for all tested configurations. The rudder control system block diagrams and descriptions in appendix A shows that the maximum commanded rudder deflection is 8.23° for the variable gearing system and 8.63° for the variable stop systems at the target airspeed of

250 KIAS. These values are decreased by cable stretch and then modified by the effect of the yaw damper, which can add or subtract 3°. If one assumes maximum pedal deflection and a yaw damper input of 3° in the same direction, the maximum possible rudder deflections were 10.38° for the variable gearing system and 8.63° for the variable stop systems with YD A (8.63° is the rudder limiter value at 250 KIAS). For YD B, the maximum deflection for the variable stop systems increases to 11.23°. YD B did not affect the maximum rudder deflection for the variable gearing systems.

The data in figure 42 indicate average values for the variable stop systems that are in the vicinity of the maximum possible value of 8.63° (YD A). The excursions above that value are because reduced airspeed resulted in increased rudder deflection. For example, decreasing airspeed from the target value of 250 to 240 KIAS caused the variable stop rudder limiter to increase from 8.63° to 9.4°. Airspeed excursions rarely exceeded ±10 kt.

The average of the maximum rudder excursions for the variable gearing systems was significantly less than the limit value of 10.38° at 250 KIAS. This is probably due to the long throw and moderately high pedal force required to achieve full deflection for this type of rudder control system.

The variable force system limits rudder deflection according to a hinge moment (HM) limit, as defined by the following expression (see appendix A).

$$\delta_{r_{\lim}} = \left[\left[\frac{HM_{\max} sign(\delta_{ped})}{KrV_{CAS}^2} - CH(\beta) \right] \frac{1}{C_{H_{\delta r}}} \right] \quad (1)$$

The rudder limit is seen to be a function of the hinge moment limit, $HM_{\max}$, and sideslip angle, β, where CH(β) is positive for positive sideslip, $C_{H_{\delta r}}$ is negative, and δ_{ped} is positive for left pedal. Therefore, positive sideslip angles produced by left pedal inputs will increase positive (trailing-edge left) rudder limit, resulting in increased control power. The hinge moment limit was initially set to 3947 ft-lb so that the rudder was limited to ±9° at zero sideslip angle. The hinge moment limit was later decreased to 3508 ft-lb so that the rudder was limited to ±8° at zero sideslip angle. The data in figure 42 only include runs for the lower hinge moment limit.

As shown in equation 1, when rudder is used to generate sideslip, the value of rudder limit will be greater than 8° for the force limit system. The data in figure 42 show that this is the case, and that the maximum rudder deflections for the variable force system (configuration 7) were higher than any of the other configurations, even though it was nominally limited to ±8° at 250 KIAS (at zero sideslip).

If a large sideslip angle is produced by the increased rudder deflection and the rudder is suddenly reversed, the force on the vertical stabilizer would be large. This was quite common for configuration 7, as will be shown in the following section.

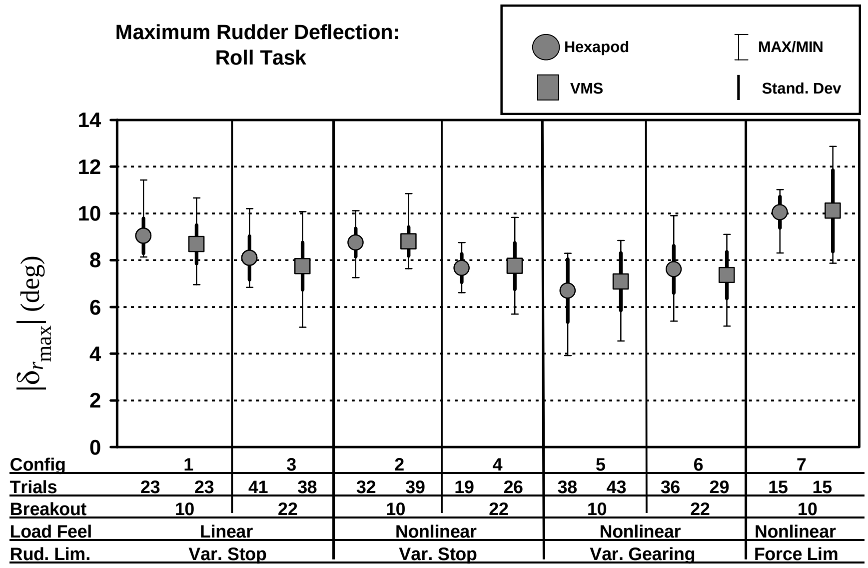


Figure 42. Maximum Rudder Deflection—Roll Task

4.2.1.3 Force on Vertical Stabilizer—Roll Task.

An approximation to the loads on the vertical stabilizer was calculated during the simulation runs. This calculation was based on the fact that the lateral force on the vertical stabilizer is a result of sideslip and rudder deflection.

$$F_{Y_{Vert}} \approx Y_\beta \beta + Y_{\delta_r} \delta_r = (C_{Y_\beta} \beta + C_{Y_{\delta r}} \delta r) \frac{S \rho_o V_{CAS}^2}{2} \qquad (2)$$

This expression assumes that the sideforce due to sideslip is due to the vertical stabilizer. This is a reasonable approximation for the purpose of this study.

Generic values of aircraft derivatives that are representative of large transport aircraft and a representative wing area (S) was used in equation 2 as follows:

$$C_{Y_\beta} \approx -0.211/\deg \; and \; C_{Y_{\delta r}} = 0.00651/\deg \qquad (3)$$

$$F_{Y_{Vert}} = [-0.034\beta + 0.01\delta_r] V_{CAS}^2 \qquad (4)$$

Where sideslip and rudder deflection are in degrees, airspeed is in ft/sec, $F_{Y_{vert}}$ is in lb, sideslip is positive with wind from the right, and rudder deflection is positive trailing-edge left (standard NASA sign conventions).

Equation 4 does not provide values for any single aircraft, but does give the correct proportions of force due to sideslip and force due to rudder deflection for a typical transport aircraft. By using this same expression for all the tested configurations, it is possible to compare the forces on the vertical stabilizer that result from different rudder flight control system mechanizations.

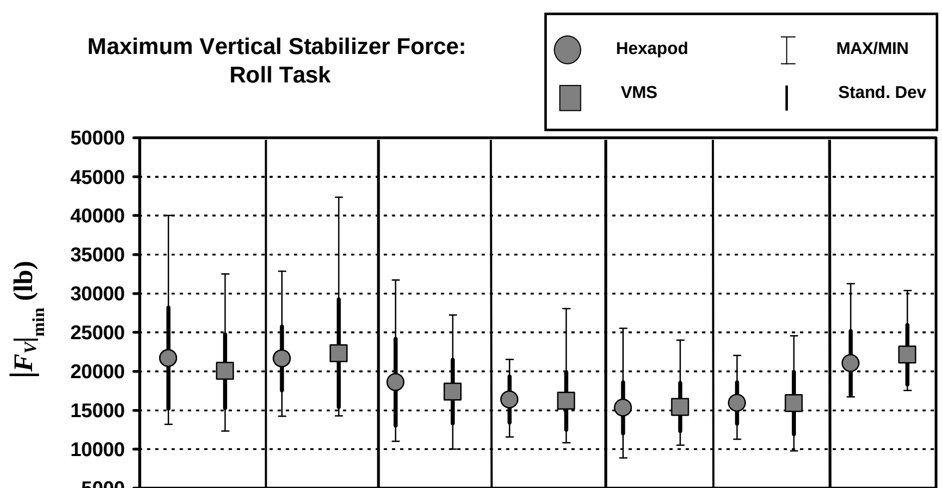
To put this in context, the sideslip (10°) and rudder deflection (-6°) for American Airlines Flight 587 at the time of failure at 250 kt, were input to equation 4, resulting in a force of 71,400 lb force on the vertical stabilizer. At a near maximum takeoff weight for the generic aircraft of 175,000 lb, this results in a lateral acceleration of 0.41 g. The NTSB data indicated a lateral acceleration of 0.38 g, indicating that equation 4 is a reasonable estimate of sideforce due to sideslip and rudder deflection.

The maximum force on the vertical stabilizer that occurred during each run for the roll task is summarized in figure 43.

These data indicate that the maximum force on the vertical stabilizer was essentially the same for the VMS and Hexapod motion systems for the roll task.

None of the data exhibit a force on the vertical stabilizer that approaches the 71,400 lb that occurred in the American Airlines Flight 587 accident with the Airbus A300-600. Given that the rudder was limited to approximately 8.5° for all configurations and the maximum A300 rudder deflection was only 6°, it can be surmised that the rudder control power for the generic transport used in this simulation was less than the A300. It is emphasized that there was no attempt to reconstruct the American Airlines Flight 587 accident scenario in this study.

The data in figure 43 indicate that the forces imposed on the vertical stabilizer for the roll task were substantially greater for the variable stop configurations with linear load-feel (configurations 1 and 3) than the variable gearing systems and variable stop systems with nonlinear load-feel. Configuration 3 is representative of the rudder system employed on the Airbus A300 aircraft that was involved in the American Airlines Flight 587 accident.



Config	1		3		2		4		5		6		7	
Trials	23	23	41	38	32	39	19	26	38	43	36	29	15	15
Breakout	10		22		10		22		10		22		10	
Load Feel	Linear				Nonlinear				Nonlinear				Nonlinear	
Rud. Lim.	Var. Stop				Var. Stop				Var. Gearing				Force Lim	

Figure 43. Maximum Force on Vertical Stabilizer—Roll Task

The force limit configuration (configuration 7) also exhibited a tendency to incur higher forces on the vertical stabilizer. This is because the force limit system allows greater rudder deflections when sideslip and rudder deflection are of the same sign (see equation 1). Larger rudder deflections result in larger sideslip angles and hence increase loads on the vertical stabilizer.

Given that the rudder deflections are limited by hinge moment and not by vertical stabilizer loads, it is important to ensure that the hinge moment limits are set considering the worst-case condition—rudder reversals at high sideslip angles. Alternatively, it may be desirable to limit rudder deflection based on a measurement of vertical stabilizer load.

The maximum load on the vertical stabilizer tends to occur following a rudder reversal at large sideslip angles. That is because following such a rudder reversal, the terms in equation 4 are added together, i.e., the force due to sideslip and the force due to rudder deflection are additive. This occurs when the pilot gets out of phase with the aircraft (rudder deflection of opposite sign from sideslip). This, in fact, was the scenario for American Airlines Flight 587.

Based on the above discussion, it is expected that forces on the vertical stabilizer will be large at large values of $|\beta - \delta_r|$, and this is confirmed by the data in figure 44. Large values of $|\beta - \delta_r|$ occur when the pilot rapidly puts in rudder to counter sideslip, causing the rudder deflection to be large and of opposite sign to sideslip before the sideslip has a chance to respond. This is more likely to happen if the pedal throw is short and the forces are light, e.g., configurations 1 and 3.

The data in figure 44 indicate that such reversals are common when countering large roll disturbances, and that there is a definite trend toward increasing force on the vertical stabilizer as $|\beta - \delta_r|$ increases. The ability to produce large values of this parameter increases with increasing rudder control power and or maximum rudder deflection (allowing large values of sideslip to be produced).

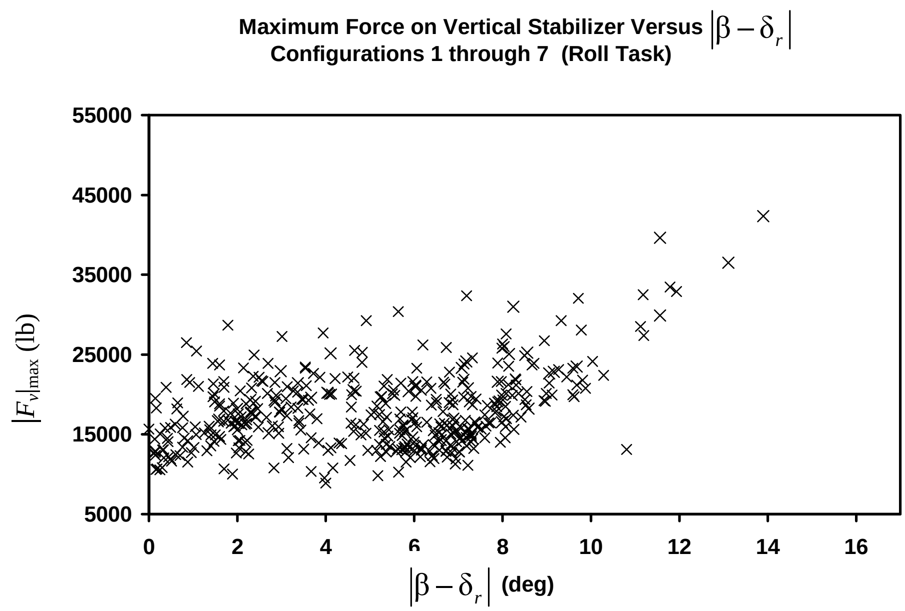


Figure 44. Maximum Force on Vertical Stabilizer vs $|\beta - \delta_r|$—All Configurations—Roll Task

The data in figure 43 indicate that the variable stop linear load-feel configurations (1 and 3) exhibited the highest forces on the vertical stabilizer (highest mean, 1σ, and maximum values). These cases also were rated as most prone to overcontrol, according to the pilots ratings and commentary (e.g., see sections 4.1.1.2 and 4.1.1.4).

The effect of rudder control power on forces on the vertical stabilizer can be investigated by comparing the results for configuration 7 (force limit system) with the two values of rudder hinge moment limit that were used during the simulation exercise. During the first 527 runs, the hinge moment limit was set to 3947 ft-lb. Pilot commentary indicated that configuration 7 had more rudder control power than the other configurations, so the hinge moment was reduced to 3508 ft-lb for all runs after 527.

With the hinge moment limit set to 3947 ft-lb, the maximum rudder at zero sideslip is 9°. Reducing the hinge moment limit to 3508 ft-lb reduced the rudder limit to 8° at zero sideslip.

A comparison of the runs with the two values of rudder limiter for configuration 7 are shown in figure 45.

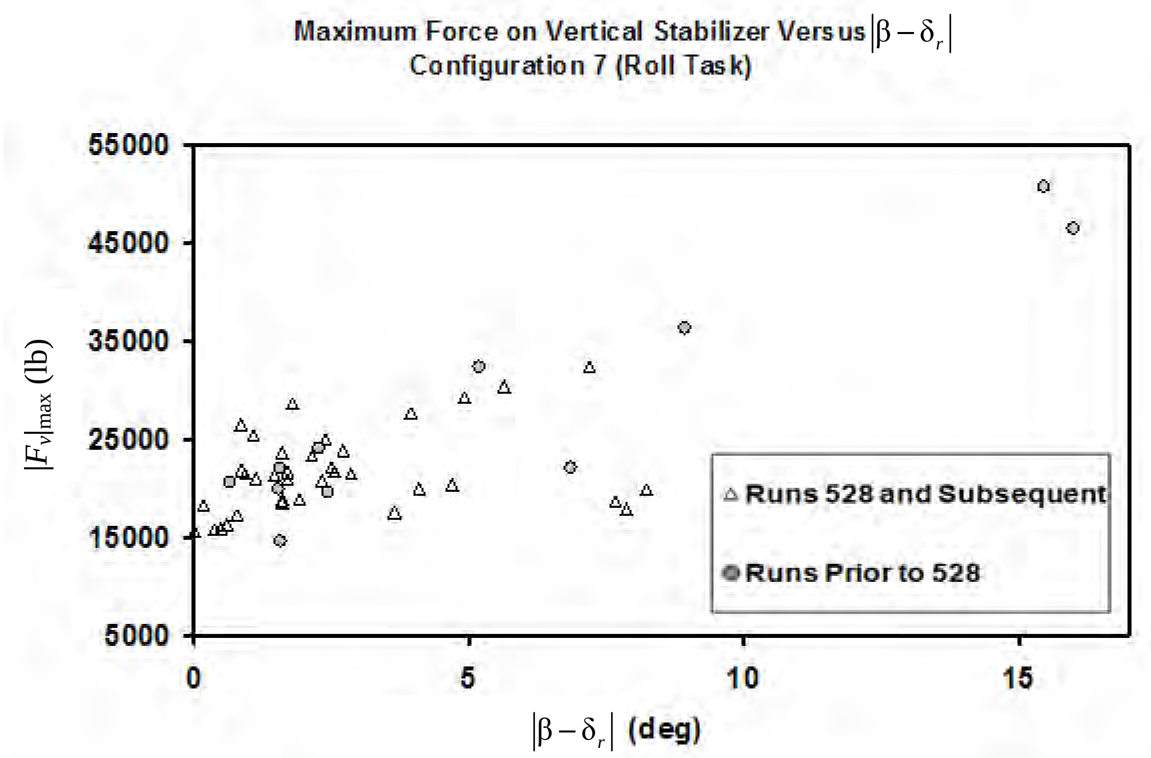


Figure 45. Effect of Increasing Rudder Control Power on $|\beta - \delta_r|$ and F_v

There were 32 runs with the decreased value of rudder limiter compared to only 11 runs with the increased limit. Nonetheless, three of the highest values of $|\beta - \delta_r|$ and vertical stabilizer loads were encountered during runs with the increased hinge moment limit.

This result indicates that small changes in rudder control power can have a large effect on the loads that are imposed on the vertical stabilizer for a rolling task.

One potential approach for developing the criteria in Phase 2 is to calculate the maximum achievable value of $|\beta - \delta_r|$ with rudder, and specify acceptable rudder systems as those where there is little or no tendency to approach that value. An alternative solution is to simply build the vertical stabilizer strong enough to withstand the maximum achievable value of $|\beta - \delta_r|$ at any airspeed.

4.2.1.4 Maximum Pedal Force and Deflection—Roll Task.

The maximum rudder pedal forces that were encountered for each run are tabulated and summarized for the roll task in figure 46.

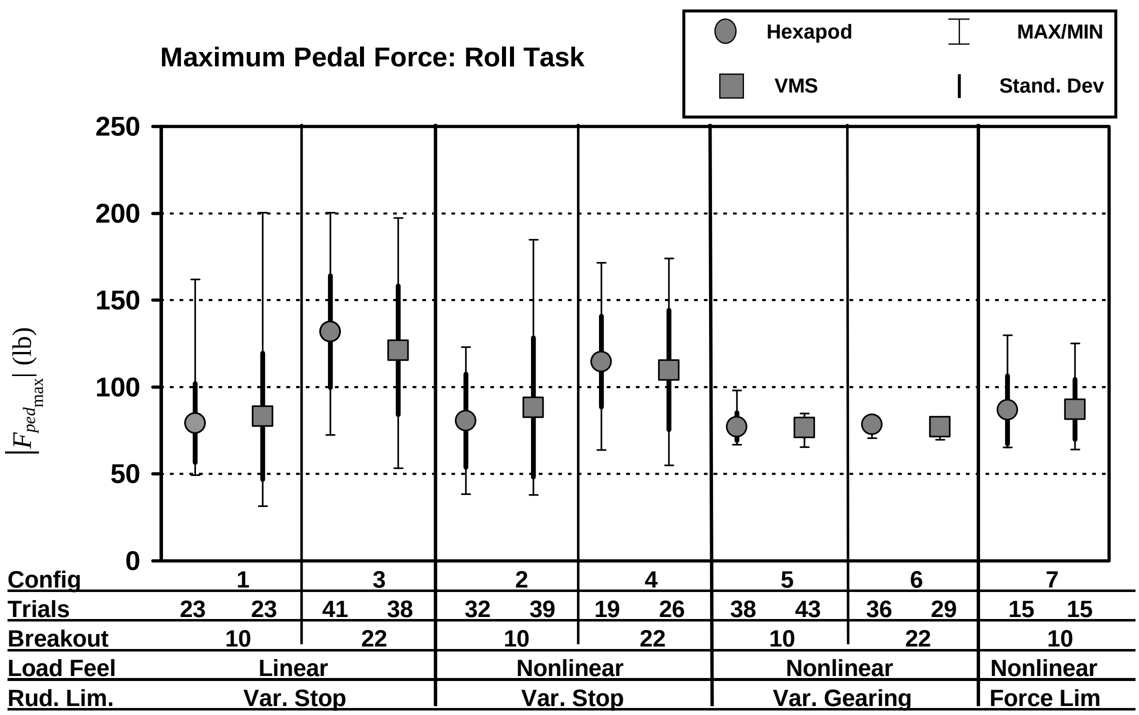


Figure 46. Maximum Rudder Pedal Forces—Roll Task

Comparing the cases that were run with VMS motion and Hexapod motion show that there was essentially no difference.

From the load-feel curves in section 3.2.3, the forces required to reach the pedal stop at an airspeed of 250 KIAS are summarized as:

- Configurations 1 and 3—33 lb at 1.15 inches of travel
- Configurations 2 , 4, and 7—60 lb at 1.15 inches of travel
- Configurations 5 and 6—72 lb at 3.5 inches of travel

A comparison of these limit forces with the forces that the pilots actually exerted on the pedals is given in figure 46, and indicates the following:

- The pilots used considerably more force than required to reach full rudder deflection for configurations 1 through 4 (variable stop). This was exacerbated by the higher breakout force configurations (configurations 3 and 4).

- The average forces applied were factors of between 2 and 4 over the required 33 lb for configurations 1 and 3.

- The maximum pilot forces used by the pilots were almost exactly that required to reach full travel for the variable gearing cases (72 lb).

- The maximum pedal forces applied by the pilots for configuration 7 were not significantly greater than the 60-lb force required to reach full travel. That is probably because the variable force configuration has inherently more control power as a result of the increased rudder deflection that can be achieved (see figure 42).

- The fact that the pilots used considerably more force beyond what was required is probably due to a sense of urgency that causes pilots to push harder on the pedals. This seemed to be exacerbated by the short travel (1.15 inches) of the variable stop systems. The longer travel of the variable gearing system (3.5 inches) provides more positive cueing to indicate that full rudder is being commanded, and that no more can be done.

The maximum pedal positions encountered for each run were tabulated and are summarized in figure 47.

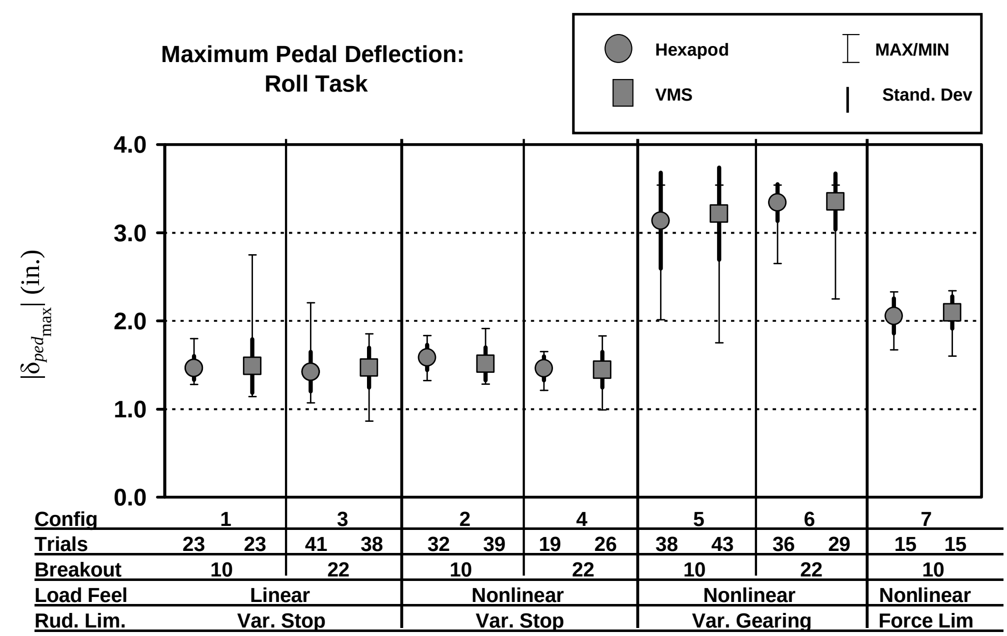


Figure 47. Maximum Rudder Pedal Position—Roll Task

A comparison between cases run with VMS motion and those run with Hexapod motion show that there was essentially no difference.

The low standard deviations for these cases show that there was little variability, indicating that nearly all the test subjects used full rudder pedal travel to augment roll control during these runs.

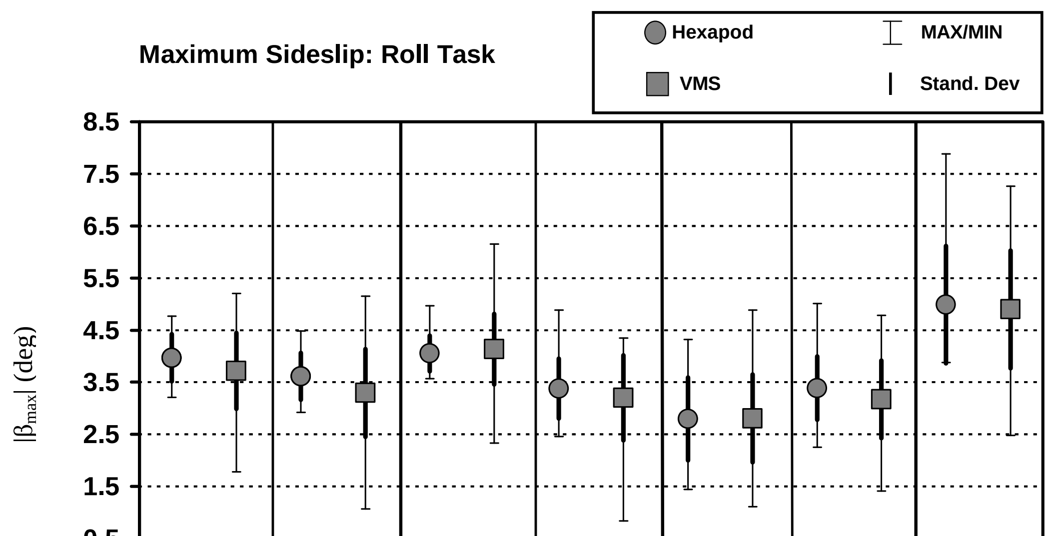
The variable stop cases were limited to 1.15 inches of pedal travel at 250 KIAS. Figure 47 shows that the average maximum pedal travel actually used was approximately 1.4 inches. The additional travel was due to cable stretch, resulting from the very high pedal forces that the pilots used (see figure 46).

The average maximum pedal deflections for the variable gearing cases were very close to the actual limit of 3.5 inches of travel.

The force limit configurations were limited to 1.07 inches of pedal travel, plus 0.7 inch to bottom the simulated servo-valve (total travel to limit of 1.77 inches). There was no rudder travel during the last 0.7 inch of pedal travel. One or two pilots noted this but did not feel that it was a deficiency. The data in figure 47 show that even after the 0.7 inch of unproductive pedal motion, the pilots pushed with additional force to stretch the cables and achieve an average maximum pedal deflection of approximately 2.0 inches.

4.2.1.5 Maximum Sideslip Angle—Roll Task.

The absolute value of maximum sideslip angle encountered for each roll task run was tabulated, as shown in figure 48.



Config	1		3		2		4		5		6		7	
Trials	23	23	41	38	32	39	19	26	38	43	36	29	15	15
Breakout	10		22		10		22		10		22		10	
Load Feel	Linear				Nonlinear				Nonlinear				Nonlinear	
Rud. Lim.	Var. Stop				Var. Stop				Var. Gearing				Force Lim	

Figure 48. Maximum Sideslip Angle—Roll Task

No consistent difference in maximum sideslip angle is observed between the runs with VMS motion and runs with Hexapod motion.

The largest values of maximum sideslip angle were achieved with the force limit system because of its inherently greater control power.

The variable gearing nonlinear load-feel systems exhibited the least amount of peak sideslip excursions.

4.2.1.6 Maximum Lateral Acceleration—Roll Task.

The maximum lateral acceleration encountered for each roll task run was tabulated and plotted, as shown in figure 49.

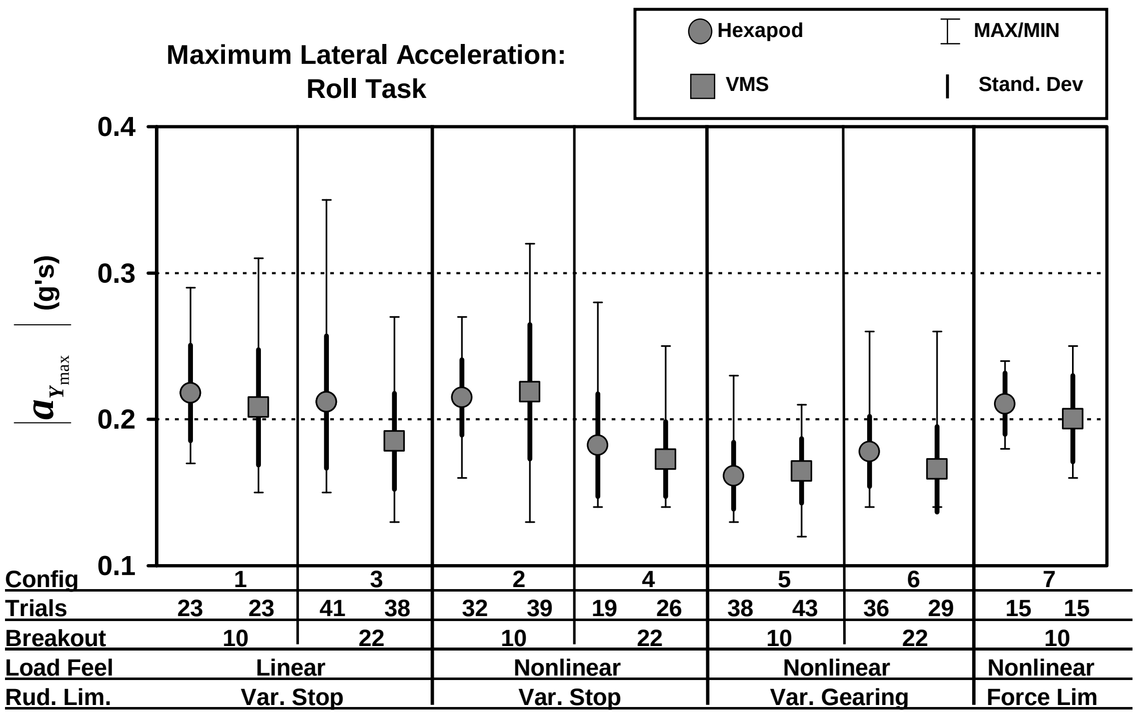


Figure 49. Maximum Lateral Acceleration—Roll Task

The maximum lateral accelerations achieved with the VMS motion were essentially the same as those achieved with the simulated Hexapod motion.

The peak lateral accelerations were greatest for the systems with linear load-feel and the nonlinear load-feel system with low breakout.

The variable stop system with high breakout exhibited approximately the same peak lateral accelerations as the variable gearing systems.

4.2.1.7 Time on Pedal Stops—Roll Task.

The time that the rudder pedals were against the stops during the roll task was measured and plotted, as shown in figure 50.

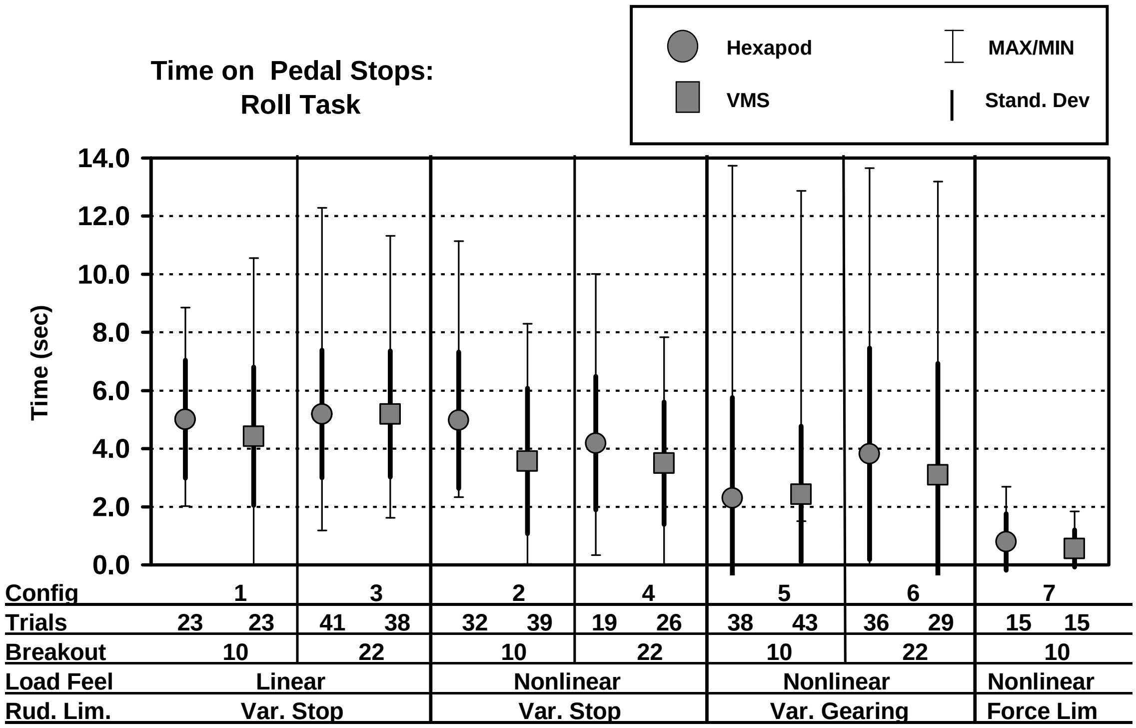


Figure 50. Time on Pedal Stops—Roll Task

There was no observed significant difference between the time on pedal stops for runs with VMS motion and runs with Hexapod motion.

The average time spent on the pedal stops was greatest for the variable stop linear load-feel systems as well as the variable stop system with nonlinear load-feel and low breakout.

The force limit system had the lowest tendency to spend time on the pedal stops for the roll task. This is especially dramatic when comparing the 1σ and maximum values. It is believed that this was because the force limit system has more inherent rudder control power (see section 4.2.1.3). With a more effective rudder, the pilot has less tendency to hold the pedal on the stops to augment roll control during large rolling gust events.

4.2.1.8 Root Mean Square Sideslip Angle—Roll Task.

The root mean square (RMS) sideslip angles during the roll task runs were calculated and plotted, as shown in figure 51.

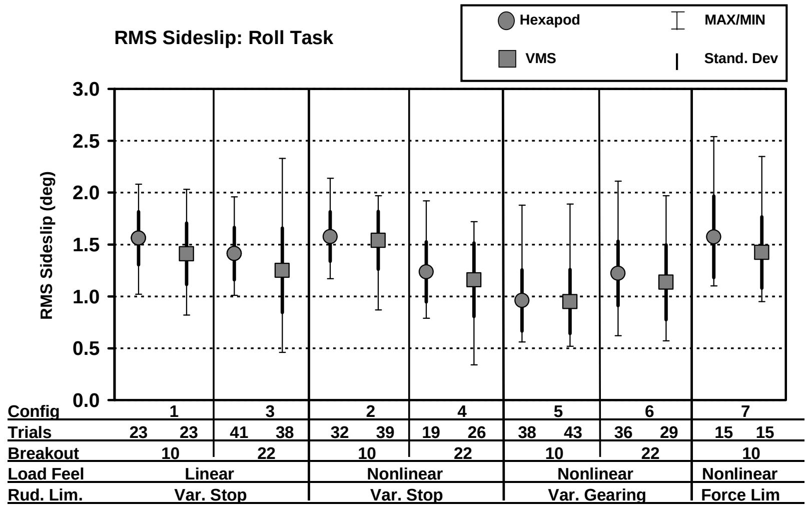


Figure 51. The RMS Sideslip Angles—Roll Task

There was no observed significant difference between the RMS sideslip angle for runs with VMS motion and runs with Hexapod motion.

The RMS sideslip angles were lowest for the variable gearing configurations and the variable stop configuration with 22 lb of breakout force.

4.2.1.9 The RMS Pedal Force—Roll Task.

The RMS rudder pedal forces encountered during roll tasks were calculated and plotted, as shown in figure 52.

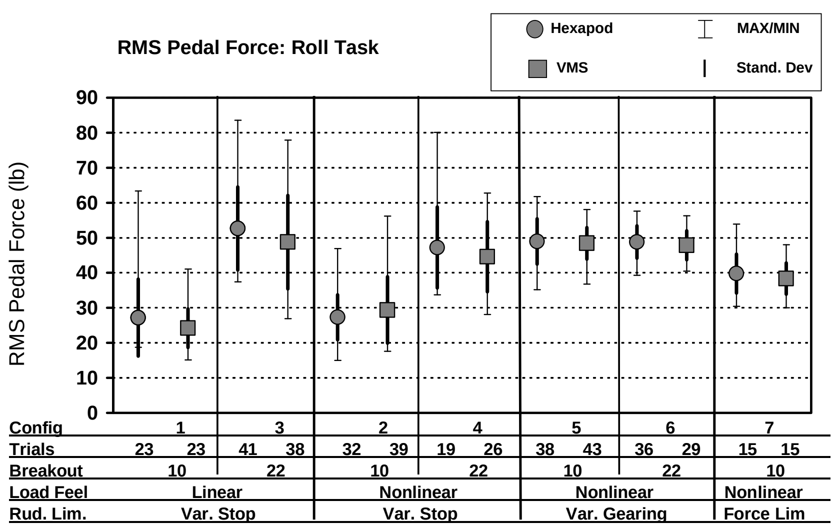
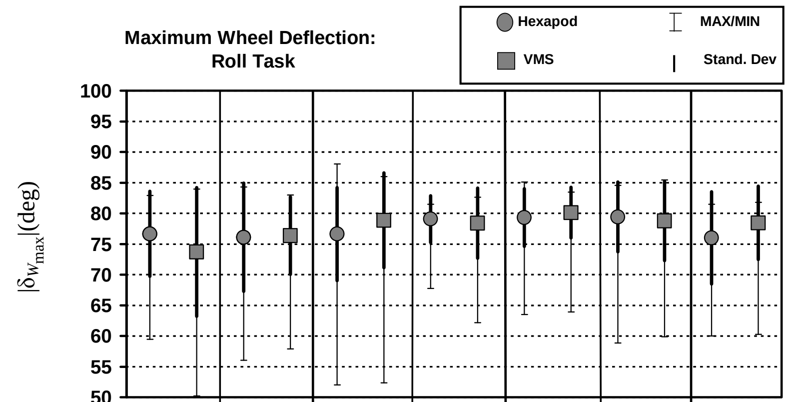


Figure 52. The RMS Rudder Pedal Forces—Roll Task

There was no observed significant difference between the RMS pedal force for runs with VMS motion and runs with Hexapod motion.

4.2.1.10 Maximum and RMS Wheel Deflection—Roll Task.

The maximum wheel deflections encountered during the roll tasks were tabulated, as shown in figure 53.



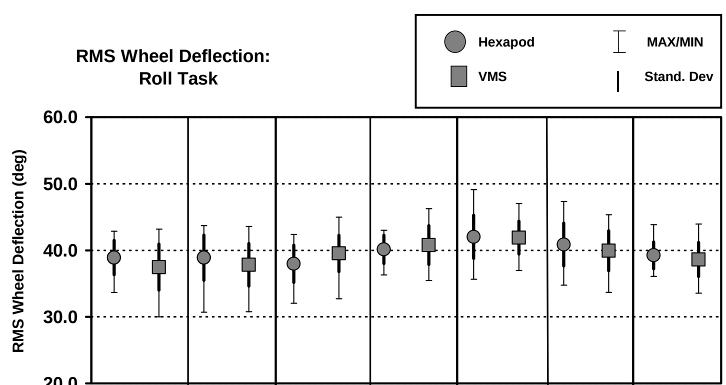
Config	1	3	2	4	5	6	7
Trials	23 23	41 38	32 39	19 26	38 43	36 29	15 15
Breakout	10	22	10	22	10	22	10
Load Feel	Linear		Nonlinear		Nonlinear		Nonlinear
Rud. Lim.	Var. Stop		Var. Stop		Var. Gearing		Force Lim

Figure 53. Maximum Wheel Deflection—Roll Task

The maximum wheel deflections were consistently near the wheel stop of 90°. This was expected because the rolling disturbance was sized so that the peaks exceeded the available roll control power with ailerons. This was done to force the pilots to use rudder to augment ailerons for roll control.

There was no observed significant difference between the maximum control wheel deflection for runs with VMS motion and runs with Hexapod motion.

The RMS wheel deflections for the roll tasks were calculated and tabulated, as shown in figure 54.



Config	1	3	2	4	5	6	7
Trials	23 23	41 38	32 39	19 26	38 43	36 29	15 15
Breakout	10	22	10	22	10	22	10
Load Feel	Linear		Nonlinear		Nonlinear		Nonlinear
Rud. Lim.	Var. Stop		Var. Stop		Var. Gearing		Force Lim

Figure 54. The RMS Wheel Deflection—Roll Task

There was no observed significant difference between the RMS control wheel deflection for runs with VMS motion and runs with Hexapod motion.

4.2.2 Yaw Task.

4.2.2.1 Effect of Yaw Damper Implementation on Force on Vertical Stabilizer—Yaw Task.

The effects of yaw damper implementation on the maximum force exerted on the vertical stabilizer is shown in figure 55.

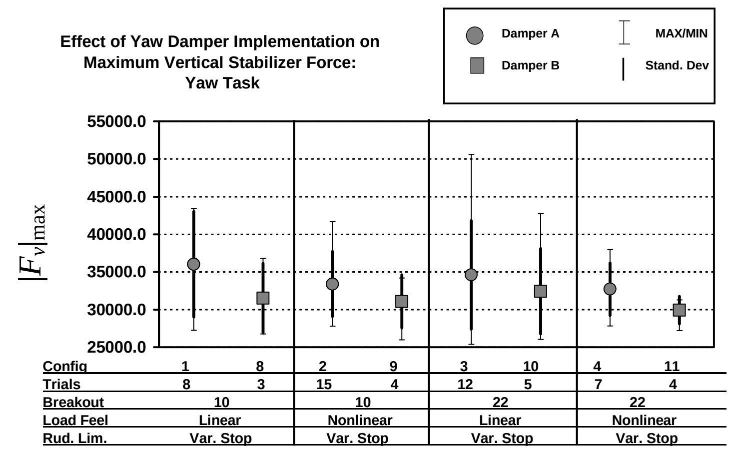


Figure 55. Effect of Yaw Damper Implementation on Maximum Vertical Stabilizer Force—Yaw Task

As with the roll task, YD B resulted in decreased loads on the vertical stabilizer. The yaw damper comparisons were only made with VMS motion.

4.2.2.2 Maximum Rudder Surface Deflection—Yaw Task.

The maximum rudder surface deflections encountered during yaw task runs were tabulated and plotted, as shown in figure 56.

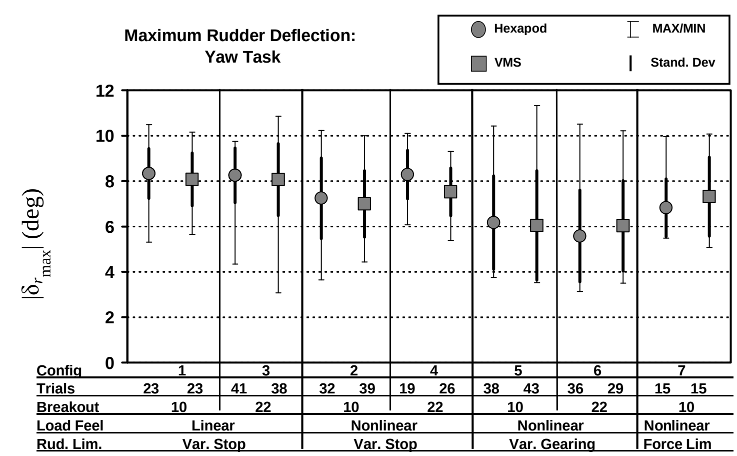


Figure 56. Maximum Rudder Surface Deflections—Yaw Task

There was no observed significant difference between the maximum rudder deflection for runs with VMS motion and runs with Hexapod motion for the yaw task.

The maximum rudder deflection was noticeably less for the variable gearing configurations than for the variable stop configurations. This was also true for the roll task.

4.2.2.3 Force on Vertical Stabilizer—Yaw Task.

Maximum forces on the vertical stabilizer encountered during the yaw task were tabulated and plotted, as shown in figure 57.

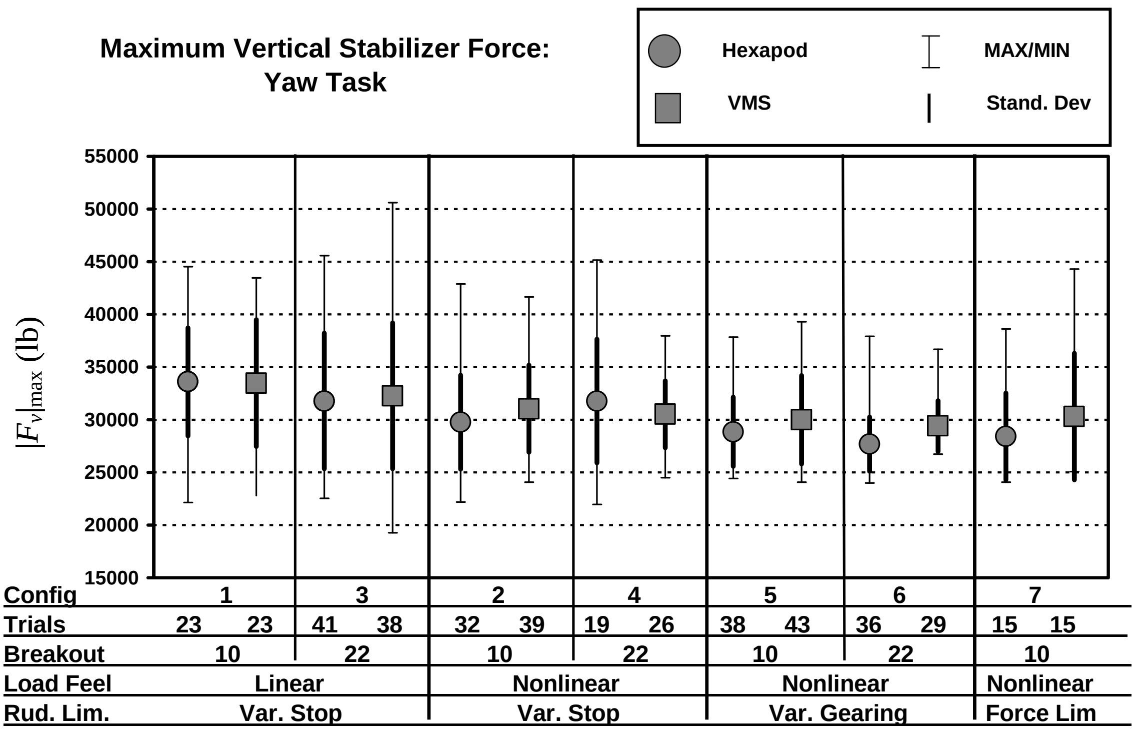


Figure 57. Maximum Vertical Stabilizer Force—Yaw Task

There was no observed significant difference between the maximum force on the vertical stabilizer for runs with VMS motion and runs with Hexapod motion for the yaw task.

The maximum force on the vertical stabilizer was greater for the variable stop systems with linear load-feel, than for the other systems, but not to the extent that this was true for the roll task.

The maximum force on the vertical stabilizer at rudder reversal was plotted, as shown in figure 58.

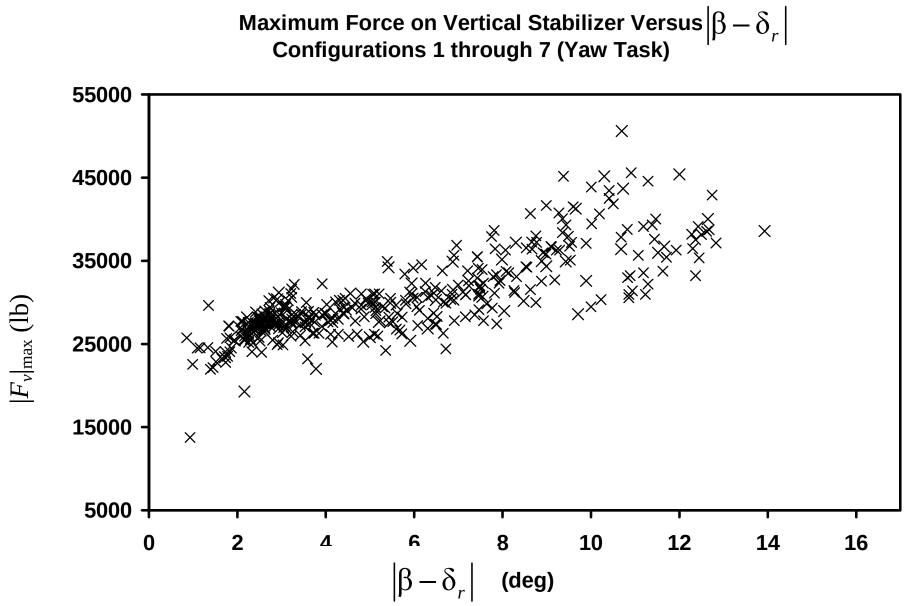


Figure 58. Maximum Force on Vertical Stabilizer at Rudder Reversal—Yaw Task

As with the roll task, the maximum force on the vertical stabilizer is highly correlated with $|\beta - \delta_r|$. This parameter is maximized when the pilot makes rapid rudder reversals at large values of sideslip. For the yaw task, such reversals are required by the task, so the correlation is better than shown by the roll task (section 4.2.1.3), where such reversals are a matter of pilot technique in using rudder to augment roll control.

4.2.2.4 Maximum Pedal Deflection and Force—Yaw Task.

Maximum rudder pedal deflections encountered during yaw tasks were tabulated, as shown in figure 59.

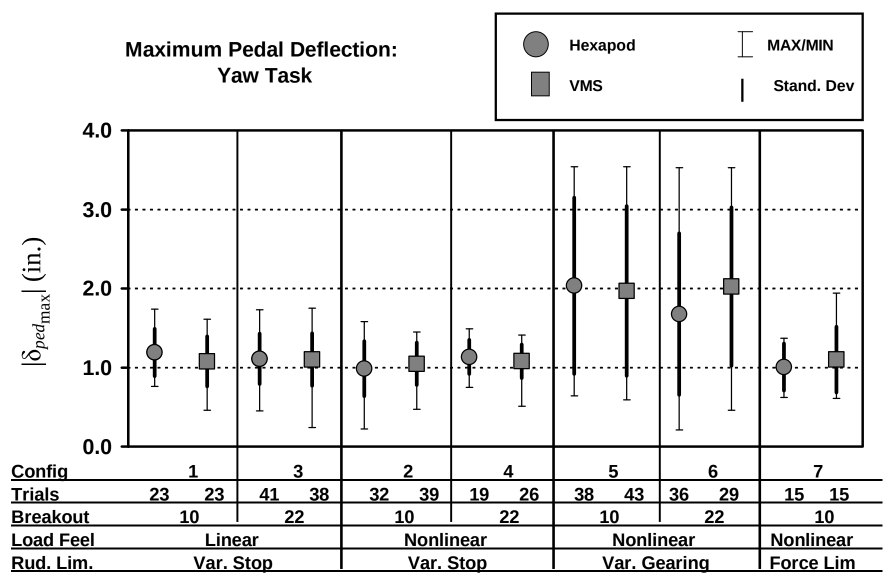


Figure 59. Maximum Rudder Pedal Deflections—Yaw Task

There was no observed significant difference between the maximum rudder pedal deflection for runs with VMS motion and runs with Hexapod motion for the yaw task.

The average maximum pedal deflections were at the pedal stop (1.15 inches) for the variable stop configurations and considerably below the stop (3.5 inches) for the variable gearing configurations. This was expected because the yaw task does not involve potential loss of control and, therefore, was less stressful to the pilot. This was indicated by the fact that the pilots did not have a tendency to push through the stops for the yaw task.

Maximum rudder pedal forces encountered during the yaw task were tabulated, as shown in figure 60.

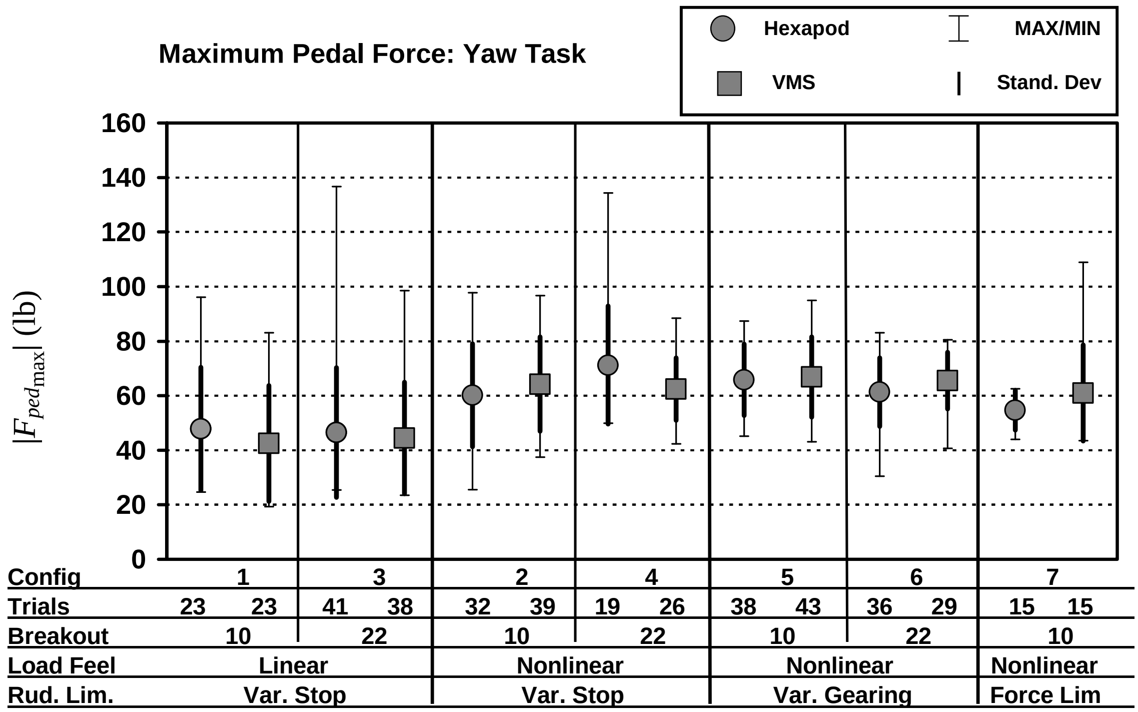


Figure 60. Maximum Rudder Pedal Forces—Yaw Task

There was no observed significant difference between the maximum pedal force for runs with VMS motion and runs with Hexapod motion for the yaw task.

The pedal forces were close to the rudder control system design limits for the yaw task. That is, the pilots did not continue to apply increasing force to the pedals once the stops were achieved.

4.2.2.5 Maximum Sideslip Angle—Yaw Task.

The maximum sideslip angles encountered during the yaw task were tabulated and plotted, as shown in figure 61.

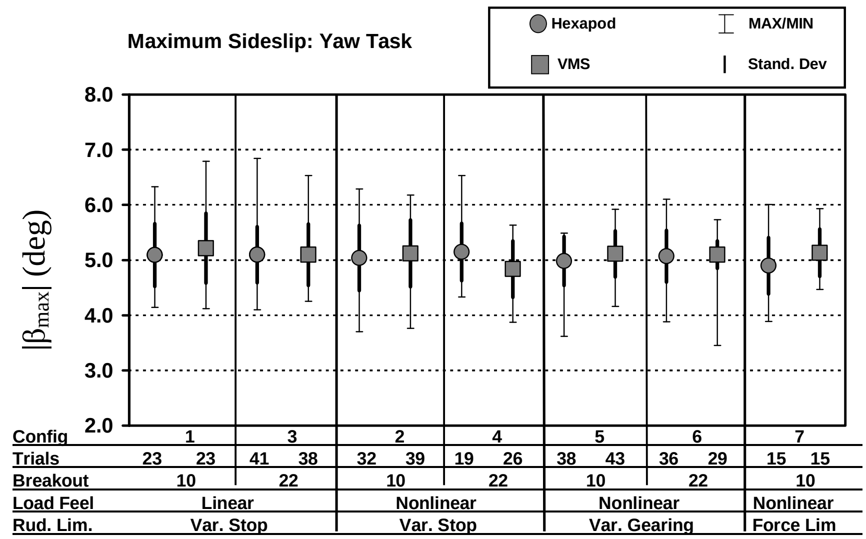


Figure 61. Maximum Sideslip Angle—Yaw Task

There was no observed significant difference between the maximum sideslip angle for runs with VMS motion and runs with Hexapod motion for the yaw task.

There was no observed significant difference between the maximum sideslip angle for the yaw task across all the tested configurations. This was expected because the maximum sideslip angle occurs immediately following the disturbance after which the pilot task is to reduce the sideslip angle. Therefore, unless there is a divergent PIO, the maximum sideslip angle is a function of the disturbance input.

4.2.2.6 Maximum Lateral Acceleration at Pilot Station—Yaw Task.

The maximum lateral accelerations encountered at the pilot station during the yaw task were tabulated, as shown in figure 62.

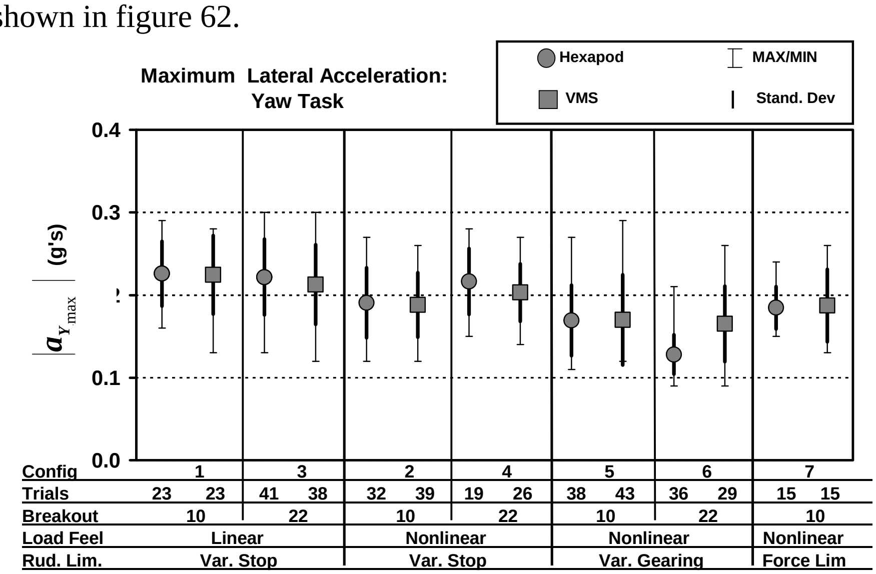


Figure 62. Maximum Lateral Acceleration—Yaw Task

There was no significant difference between the maximum lateral acceleration for runs with VMS motion and runs with Hexapod motion for the yaw task, with the exception of configuration 6. For this configuration, the lateral acceleration at the cockpit was noticeably greater with VMS motion than with Hexapod motion.

The variable gearing configurations tended to exhibit the lowest average levels of maximum lateral acceleration at the cockpit.

4.2.2.7 Time on Pedal Stops—Yaw Task.

The time that the rudder pedals were against the stops was measured and plotted, as shown in figure 63.

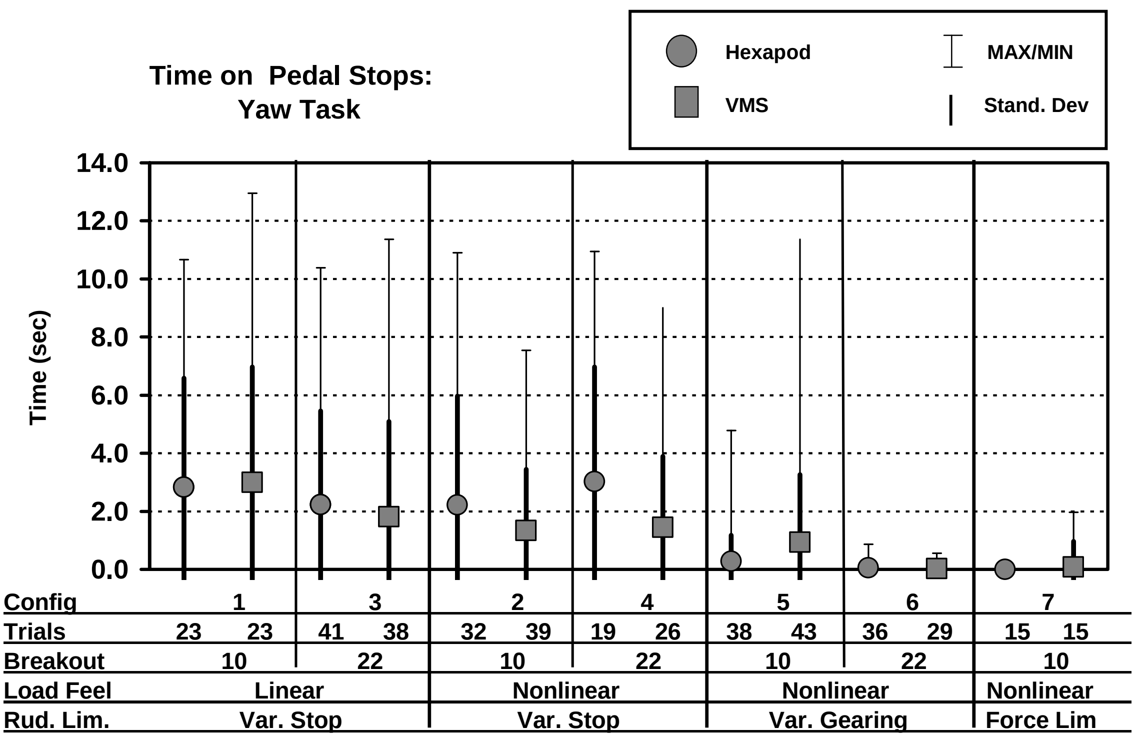


Figure 63. Time on Rudder Pedal Stops—Yaw Task

There was no observed significant difference between the times on the pedal stops for runs with VMS motion and runs with Hexapod motion for the yaw task.

The maximum and 1σ values indicate that there was significantly less tendency for the variable gearing and force limit systems to be on the pedal stops compared to the other configurations for the yaw task.

4.2.2.8 The RMS Sideslip Angle—Yaw Task.

The RMS sideslip angles encountered during the yaw task were tabulated, as shown in figure 64.

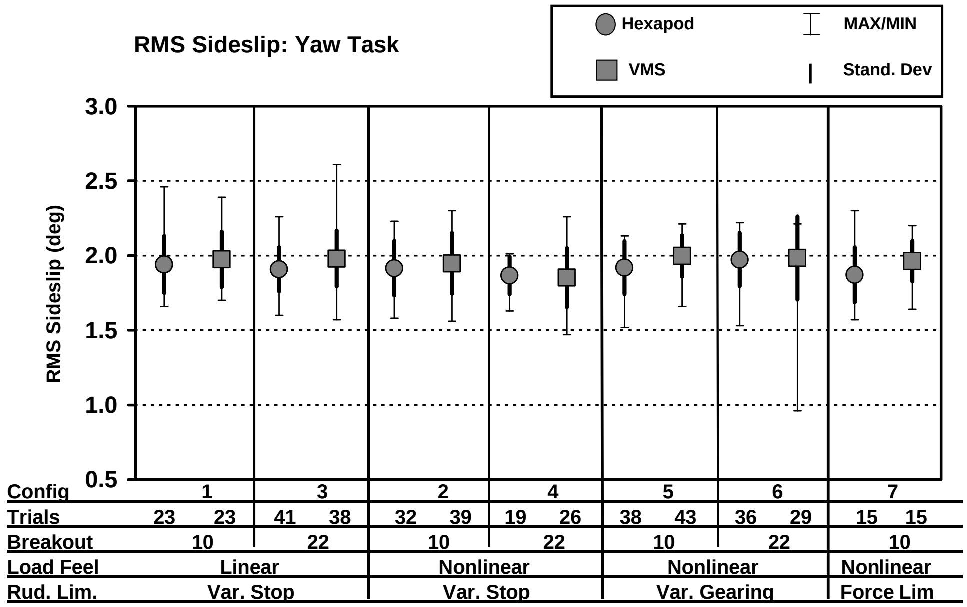


Figure 64. The RMS Sideslip Angle—Yaw Task

There was no observed significant difference between the RMS sideslip angle for runs with VMS motion and runs with Hexapod motion for the yaw task.

4.2.2.9 The RMS Pedal Force—Yaw Task.

The RMS rudder pedal forces encountered during the yaw task were tabulated, as shown in figure 65.

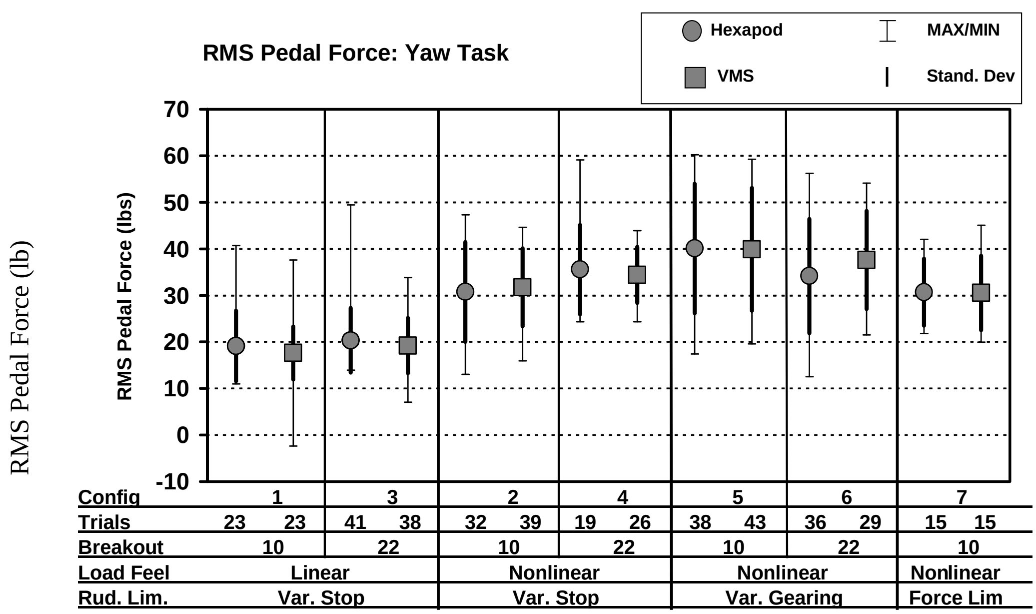


Figure 65. The RMS Rudder Pedal Forces—Yaw Task

There was no observed significant difference between the RMS pedal forces for runs with VMS motion and runs with Hexapod motion for the yaw task.

4.2.2.10 Maximum and RMS Wheel Deflection—Yaw Task.

The maximum wheel deflections encountered during the yaw task were plotted, as shown in figure 66.

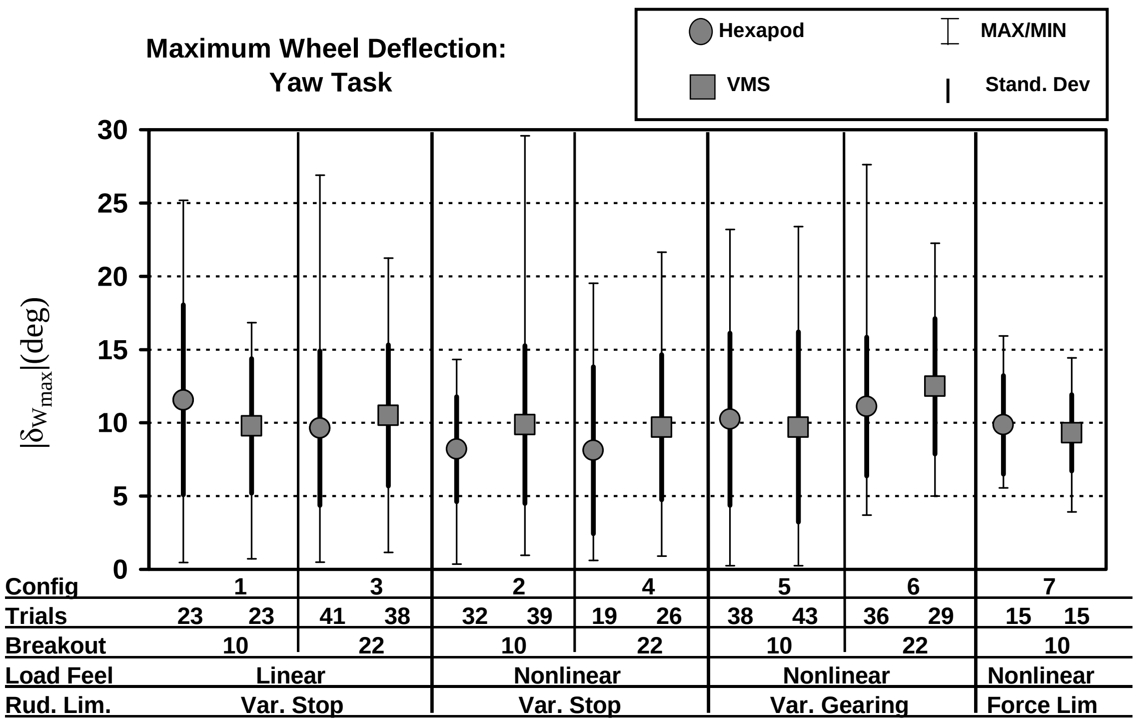


Figure 66. Maximum Wheel Deflection—Yaw Task

There was no observed significant difference between the maximum wheel deflection for runs with VMS motion and runs with Hexapod motion for the yaw task.

The RMS wheel deflections encountered during the yaw tasks were calculated and tabulated, as shown in figure 67.

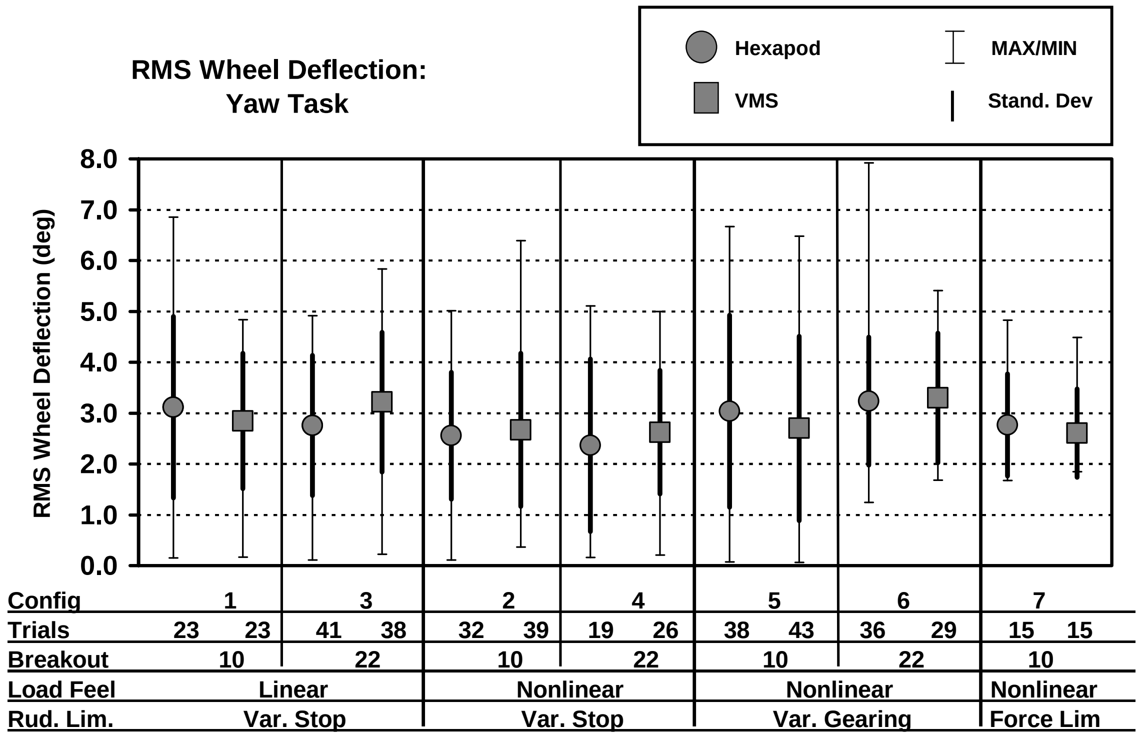


Figure 67. The RMS Wheel Deflection—Yaw Task

There was no observed significant difference between the RMS wheel deflection for runs with VMS motion and runs with Hexapod motion for the yaw task.

4.3 DESCRIBING FUNCTION RESULTS.

The yaw task was designed specifically to allow the measurement of pilot describing functions and thereby to quantify pilot rudder control activity. This assumes that the pilot is closing a loop on lateral acceleration (sideslip ball deflection), as illustrated in figure 6 where the pilot is represented as the transfer function, $Y_p = \frac{\delta_{ped}}{a_{y_{\mathrm{PILOT}}}}$.

Time histories of pedal and lateral acceleration at the pilot station were put through a Fast Fourier Transform (FFT) process to obtain the magnitude and phase of Y_p for all evaluations by all pilots. This resulted in a large amount of data, which was analyzed to determine the effect of varying the motion system and rudder system characteristics on Y_p.

As expected, there was some variability between pilots, but mostly, the data provided consistent results. A representative set of that data is given in figures 68 through 74. This data consists of a representative run for one subject pilot for each configuration, as evaluated with VMS motion and Hexapod motion. That pilot was selected because his commentary tended to reflect a high degree of sensitivity to simulator motion and because of his extensive background as a current airline pilot and transport aircraft test pilot.

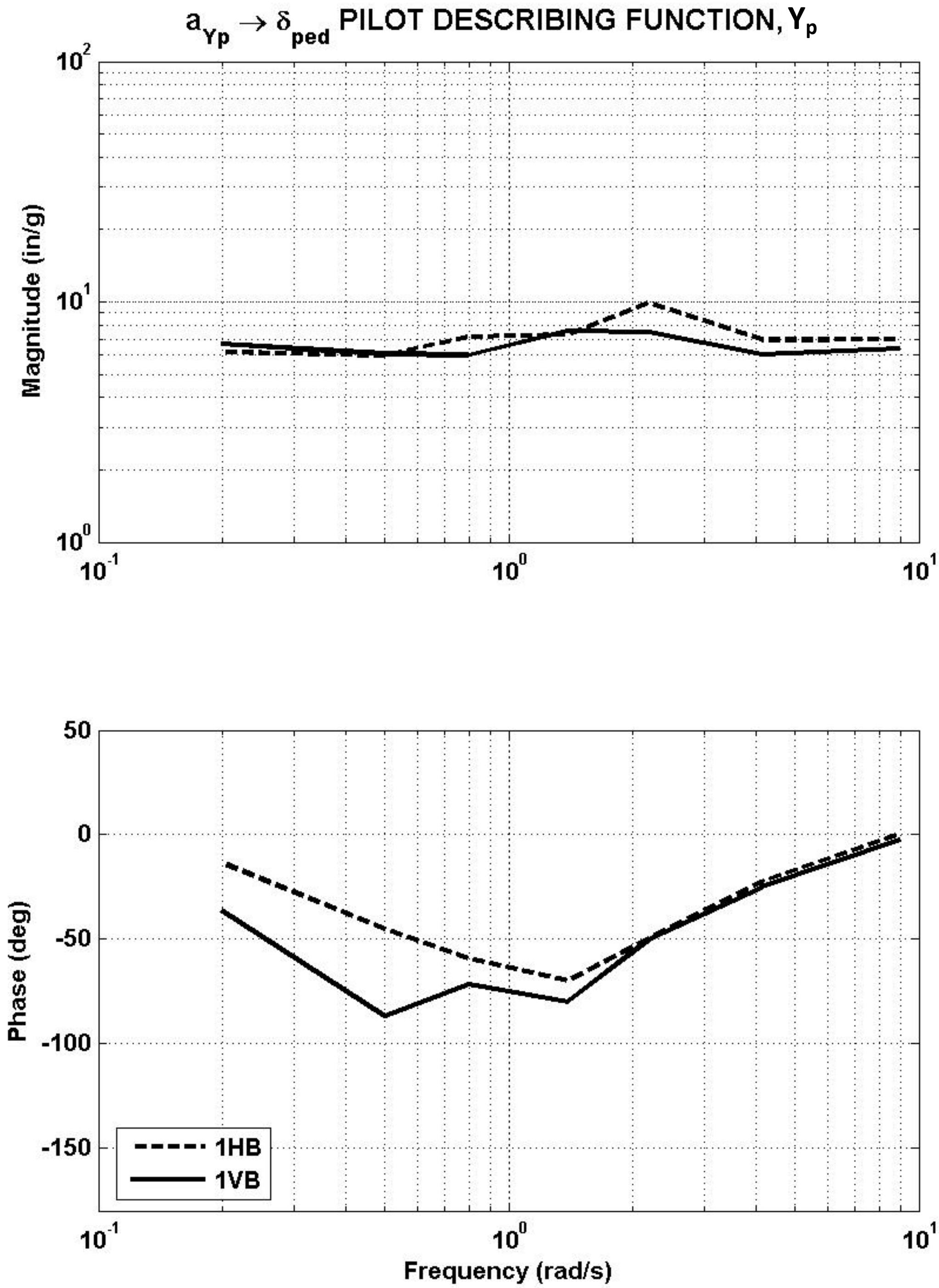


Figure 68. Measured Y_p for Configuration 1—VMS and Hexapod Motion

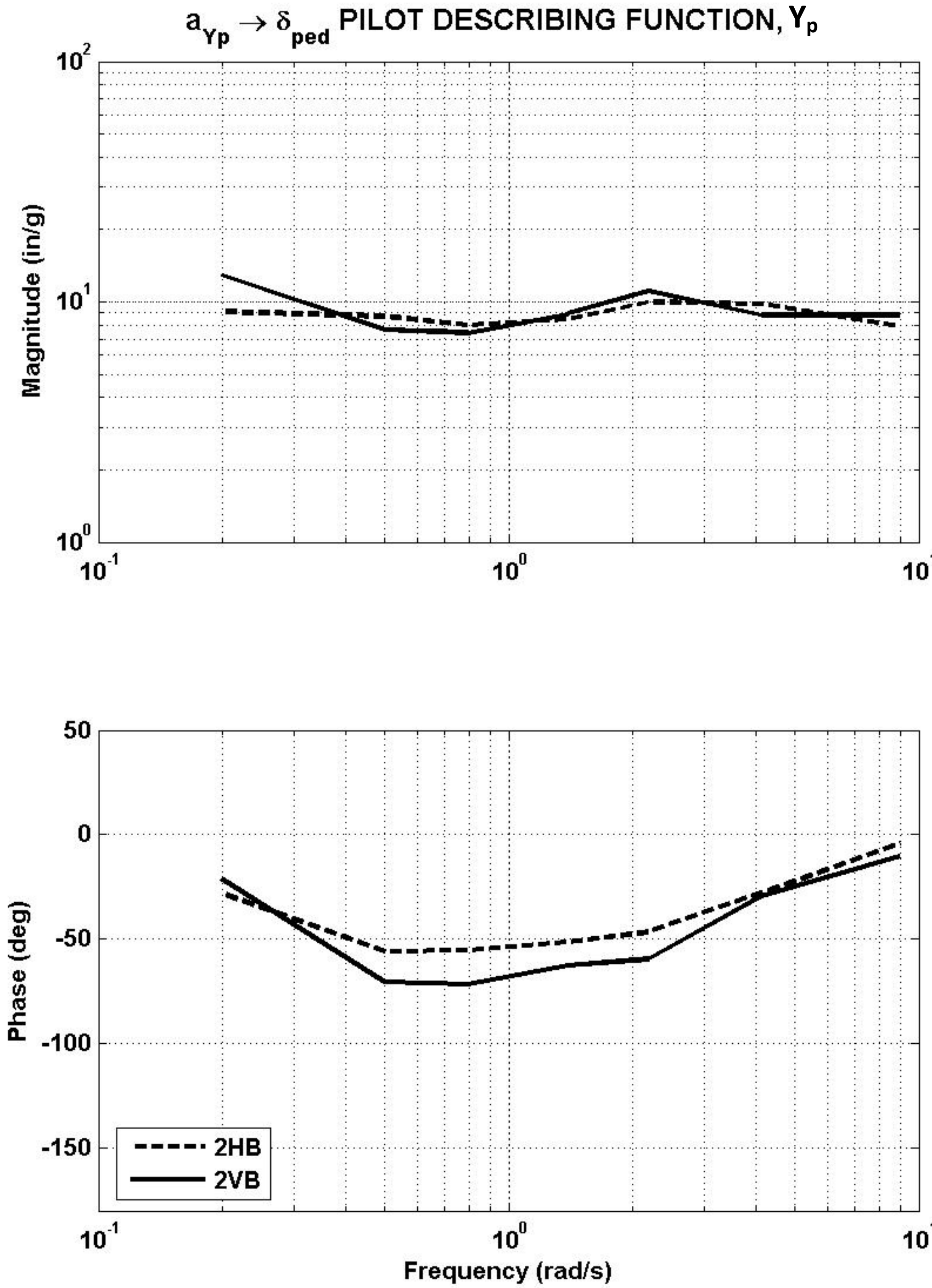


Figure 69. Measured Y_p for Configuration 2—VMS and Hexapod Motion

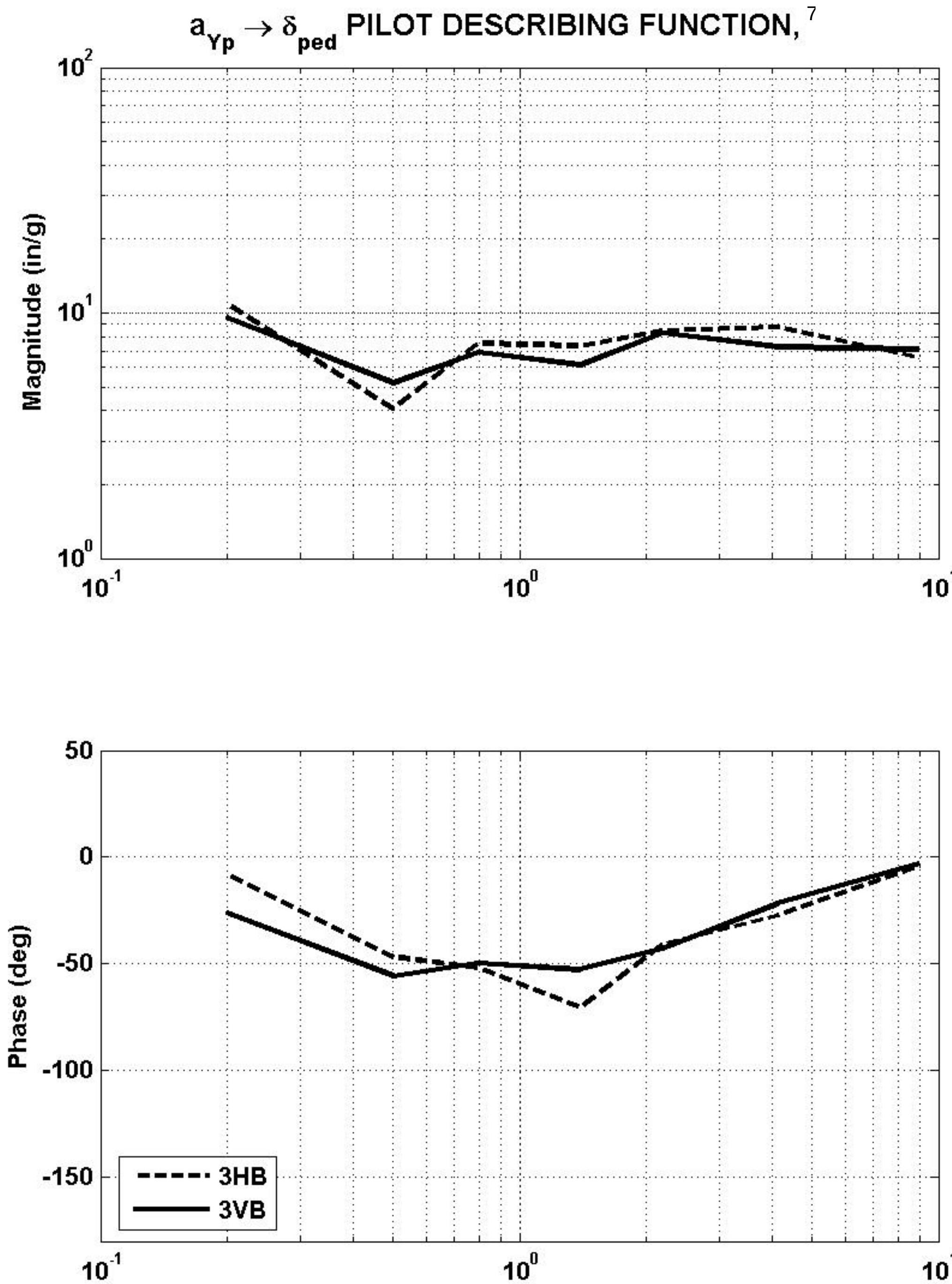


Figure 70. Measured Y_p for Configuration 3—VMS and Hexapod Motion

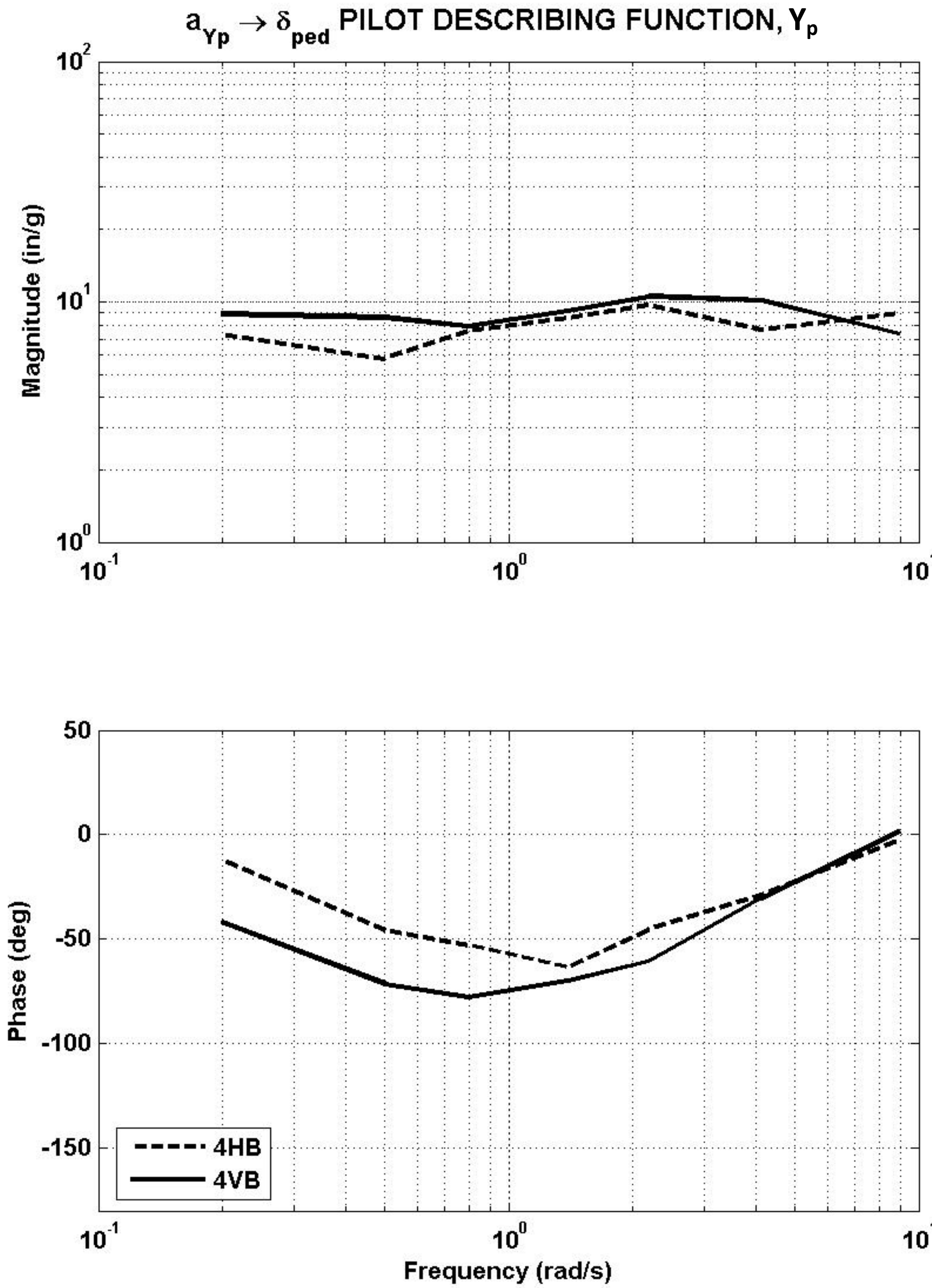


Figure 71. Measured Y_p for Configuration 4—VMS and Hexapod Motion

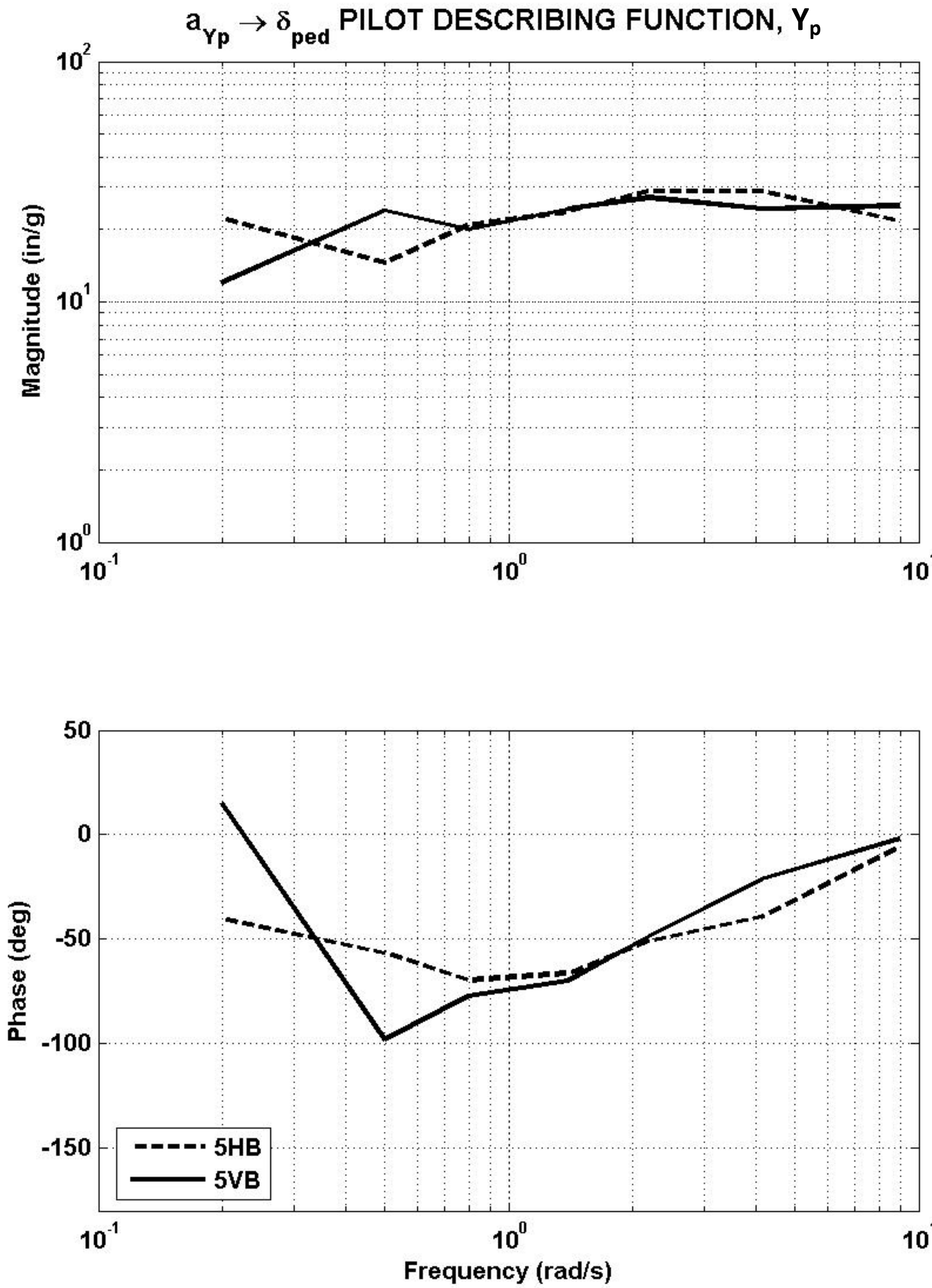


Figure 72. Measured Y_p for Configuration 5—VMS and Hexapod Motion

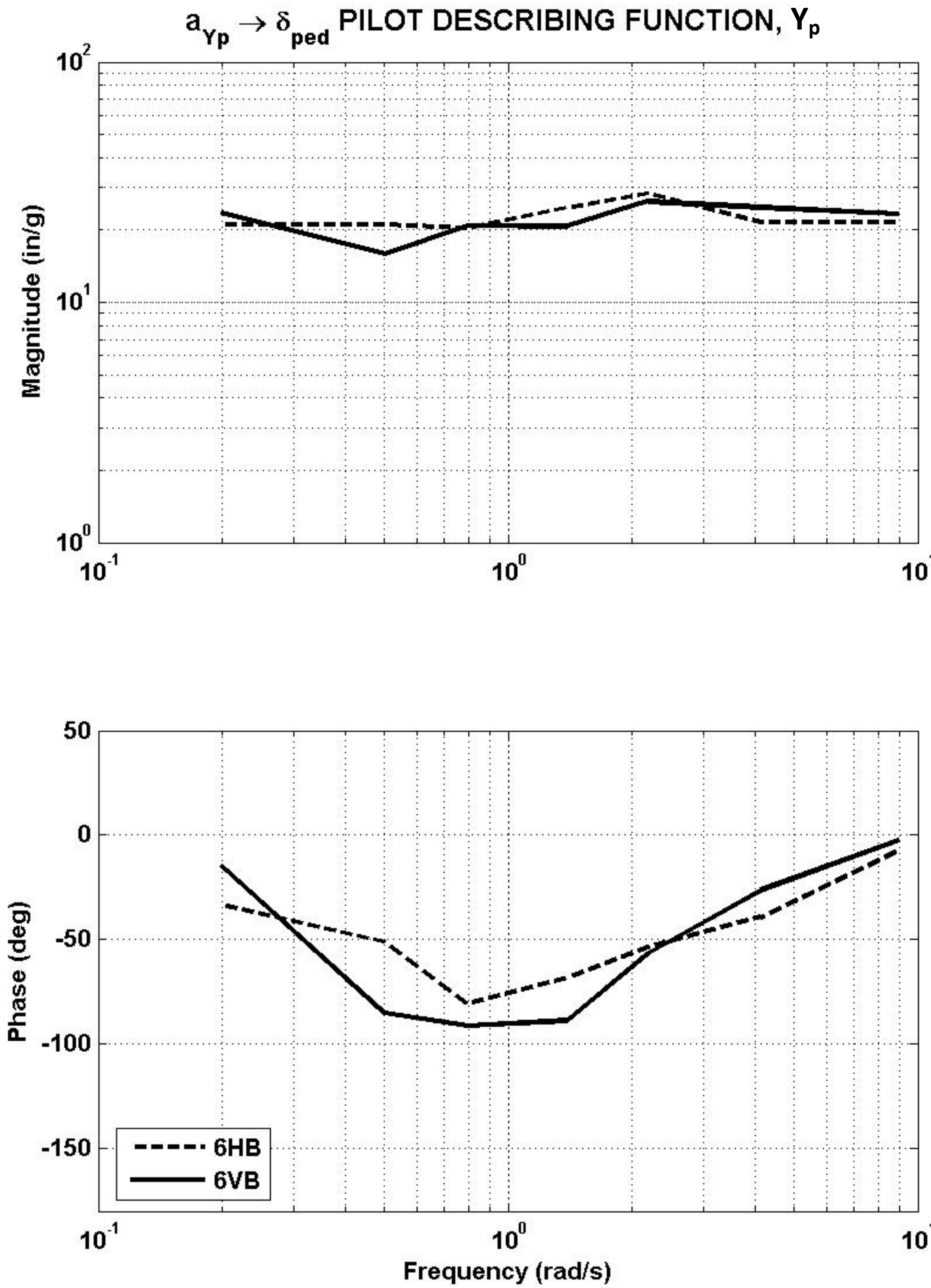


Figure 73. Measured Y_p for Configuration 6—VMS and Hexapod Motion

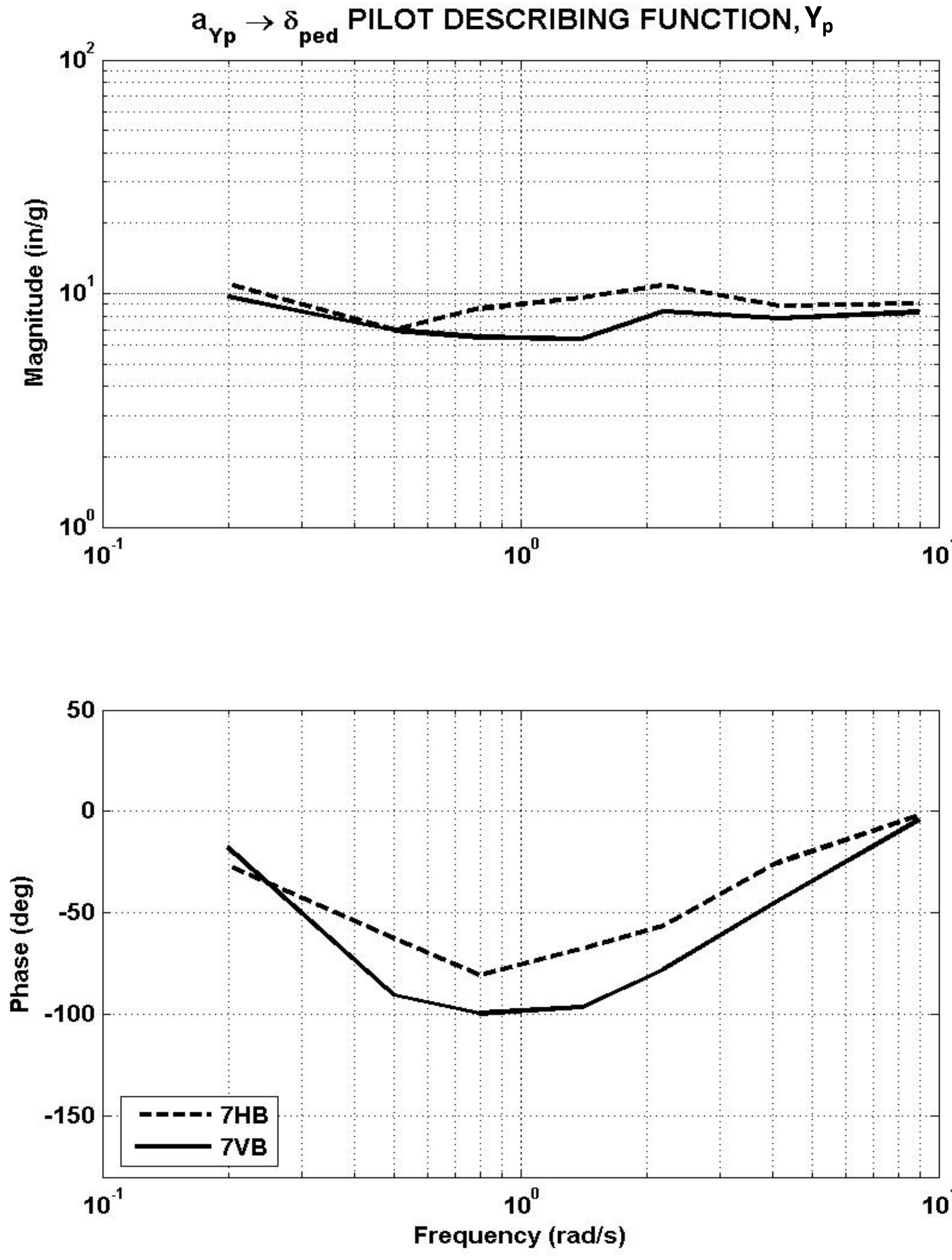


Figure 74. Measured Y_p for Configuration 7—VMS and Hexapod Motion

These data indicate that the pilot tracking behavior was essentially identical for evaluations with VMS motion and Hexapod motion for all the tested configurations. This result was observed to exist for all subject pilots, and is consistent with the quantitative measures discussed in previous sections, where there was no difference between the VMS and Hexapod motion results.

In all cases, the pilot acted as a pure gain with nearly constant magnitude across the entire frequency spectrum. Some pilots exhibited a "notch" with decreased tracking gain between approximately 0.5 and 2 rad/sec. All pilots exhibited the approximately 90° of phase dip in the frequency range between 0.2 and 10 rad/sec.

The magnitude plots indicate the amount of pedal that the pilots used as a function of ball displacement (a_y). The gain used in the above plots varied with configuration as follows.

- Configurations 1 and 3—0.7 inch of pedal for one ball displacement (0.1 g)
- Configurations 2 and 4—0.85 inch of pedal for one ball displacement
- Configurations 5 and 6—2.5 inches of pedal for one ball displacement

As expected, the variable gearing configurations 5 and 6 required a much higher pilot gain in terms of pedal displacement.

In no case was there any tendency for Y_p to exhibit a resonant peak that might indicate a tendency for PIO.

5. SUMMARY OF RESULTS.

5.1 SIMULATOR MOTION SYSTEM RESULTS.

A comparison of subjective pilot rating results between VMS and Hexapod motion indicated that:

- VMS motion provided more compelling cues for rudder usage than Hexapod motion based on a motion cue rating scale.

- Subjective pilot ratings obtained from evaluations with VMS motion resulted in more consistent and explainable trends than subjective pilot ratings obtained with Hexapod motion. This result was observed for the Cooper-Harper HQRs, Modified Cooper-Harper workload ratings, ratings of tendency to overcontrol, and decision to certify.

- The perceived effect of varying breakout was judged to be different when evaluating with VMS than with Hexapod motion.

Pilot describing function data for the yaw task showed no difference in rudder pedal closed-loop tracking behavior between VMS and Hexapod motion.

A comparison of quantitative data that resulted from runs using the VMS motion with results from Hexapod motion indicated that the following parameters exhibited no significant differences.

- Maximum load on the vertical stabilize
- RMS and maximum pedal force and deflection
- RMS and maximum rudder surface deflection

- RMS and maximum control wheel deflection
- Maximum sideslip and lateral acceleration
- Maximum time on pedal stop

In summary, the pilot's subjective evaluations produced more consistent trends when evaluated with the increased VMS motion compared to evaluations with the more limited Hexapod motion. However, there was no significant difference between the results obtained with VMS motion from those obtained from Hexapod motion for quantitative measures or measured pilot tracking behavior with pedals.

5.2 RUDDER CONTROL SYSTEM RESULTS.

The Cooper-Harper ratings along with pilot commentary show that

- variable stop systems with linear load-feel (light pedal forces and short pedal travel—configurations 1 and 3) were most prone to overcontrol.

- variable stop systems with nonlinear load-feel (high pedal forces and short travel—configurations 2, 4, and 7) were significantly less prone to overcontrol than variable stop with linear load-feel, but still exhibited some overcontrol tendencies.

- variable gearing systems with nonlinear load-feel (high pedal forces and long pedal travel—configurations 5 and 6) were most resistant to overcontrol.

In most cases, the variable gearing configurations were rated favorably. However, some pilots objected to the high forces and rapid variation in pedal force with deflection and, consequently, rated these systems poorly. Phase 2 tests will include linear load-feel in combination with the variable gearing design for rudder limiting.

In nearly all cases, the pilot commentary did not indicate a tendency for PIO. This is supported by pilot describing function data, which did not exhibit characteristics that would indicate PIO tendencies (e.g., resonant peaks in pedal activity).

Correlation of HQRs with $\frac{\delta_{r_{\max}}}{F_{\lim} - F_{bo}}$ (with VMS motion) indicate that higher values of this parameter led to degraded handling qualities.

$F_{bo}/F_{\lim}$ was rejected as a valid criterion parameter because it did not separate configurations rated to be highly prone to overcontrol from those that were shown to be resistant to overcontrol.

Configurations rated as prone to overcontrol exhibited higher forces on the vertical stabilizer than those rated as not prone to overcontrol. However, the force limit configuration was rated as resistant to overcontrol but exhibited high vertical fin forces due to increased inherent control power.

High forces on the vertical stabilizer are correlated with large values of $|\beta - \delta_r|$. Large values of this parameter result from overcontrol with pedals to produce large sideslip followed by a rapid rudder reversal.

Implementing the yaw damper downstream of the rudder limiter allowed full yaw damper authority even when the rudder was at or near its limit of travel. This noticeably reduced the loads on the vertical stabilizer. It also improved the HQRs slightly for the yaw task, but not for the roll task.

A review of pilot commentary and ratings indicates that there are no cues that indicate to the pilot when excessive loads are being imposed on the vertical stabilizer. For example, the force limit system was well liked by the pilots (good HQRs), yet this configuration resulted in high vertical stabilizer loads on par with the variable stop—linear load-feel cases for the roll task.

6. CONCLUSIONS.

A simulator with large lateral travel similar to the National Aeronautics and Space Administraton Ames Research Center Vertical Motion Simulator should be employed in Phases 2 and 3 to accurately predict subjective pilot opinion of workload, handling qualities, and overcontrol tendencies.

A Hexapod simulator could be employed to predict quantitative measures such as forces on the vertical stabilizer.

A criterion to ensure that pilots do not overload the vertical stabilizer should take into account that high vertical stabilizer loads occur when $|\beta - \delta_r|$ is large. Conditions that lead to large values of $|\beta - \delta_r|$ are:

- Large sideslip that can be generated with a powerful rudder
- Tendency for inadvertent rapid rudder reversal

The data indicated that some configurations are more susceptible to rapid rudder reversal than others. The challenge is to set a limit on what is acceptable and what is not. Ideally, the strength of the vertical stabilizer should depend on susceptibility to rudder reversal, but that relationship may be difficult to quantify.

7. REFERENCES.

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APPENDIX A—RUDDER FLIGHT CONTROL SYSTEMS

Generic versions of the three types of rudder flight control systems that were studied are given in this appendix. It is intended that these representations of rudder systems will be used for all three phases of testing.

The generic rudder flight control systems discussed in this appendix do not include the effects of structural compliance. If the pilot applies approximately 50 lb of force to the pedal on a typical transport rudder flight control system, structural compliance accounts for approximately 2% of the total pedal travel, which is judged to be insignificant for the purpose of this experiment.

A.1 VARIABLE GEARING.

Figure A-1 shows a block diagram that simulates a generic variable gearing system.

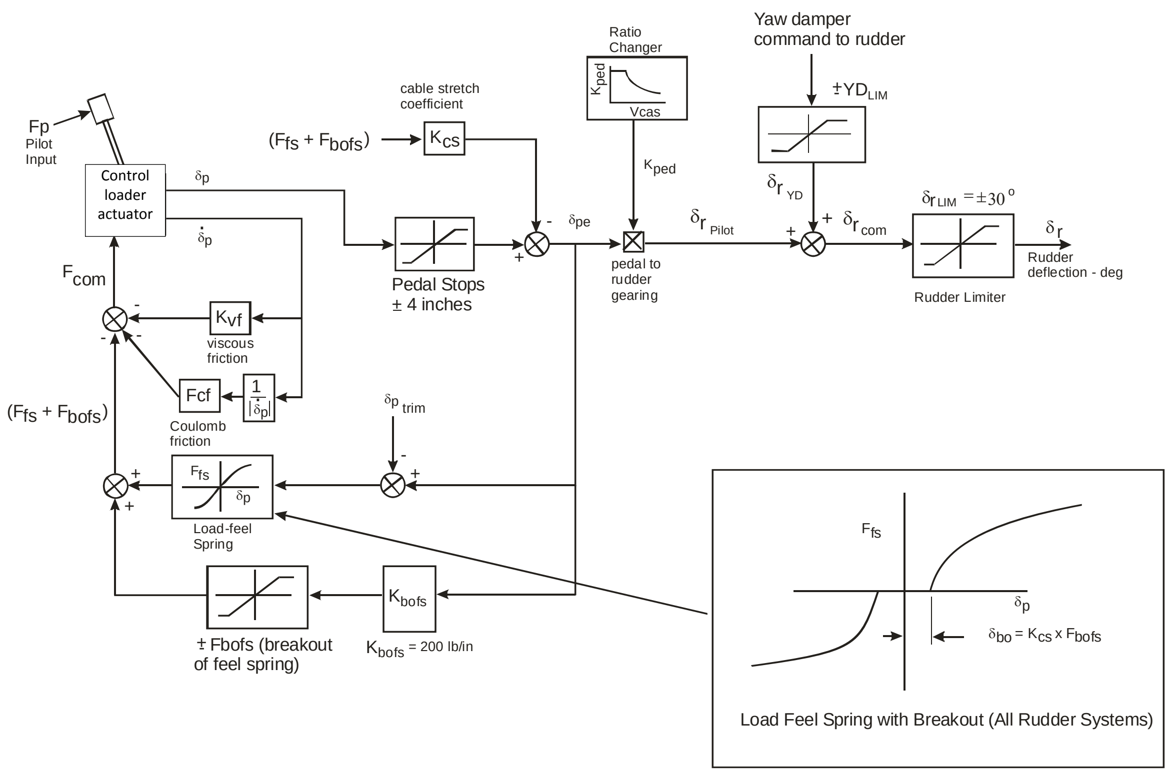

Figure A-1. Generic Variable Gearing Rudder System

The force command to the control loader actuator (F_{com}) is the sum of the viscous friction, Coulomb friction, load-feel spring, and breakout of the load-feel spring. Pedal motion occurs when the pilot force is not equal to F_{com}.

The pedal stops are achieved within the control loaders by increasing the spring force to a very large value. This is constant for the variable gearing system, but it is a calculated variable in the variable stop and force limit systems.

Note that because K_{bofs} is a large number (100 lb/in), the feel spring breakout is a constant (F_{bofs}) for pedal deflections above approximately 0.10 to 0.20 inch (F_{bofs} / K_{bofs}) and has the sign of the pedal deflection.

Cable stretch is accounted for as a result of the sum of the feel spring and feel spring breakout forces. This assumes that the rudder feel spring is located at the aft end of the aircraft near the rudder. δ_{ped} is the effective pedal travel, which is defined as the pedal travel that contributes to moving the rudder. It is always slightly less than the actual pedal travel due to cable stretch.

A provision for rudder trim is included in the model to show where it will be included in later tests. For the pilot tasks used in this experiment, there is no need for rudder trim, so it may be excluded.

Variable gearing systems reduce the rudder control gearing (K_{ped} = ratio of rudder travel-to-pedal travel) as a function of airspeed or dynamic pressure. As a result, the total pedal travel does not change, but the gradient of rudder surface deflection-to-pedal travel decreases as airspeed increases.

Note that the rudder is not mechanically limited, its maximum travel being "limited" solely by the reduced gearing between pedal and rudder. The variable gearing is usually accomplished by means of a mechanical ratio changer (e.g., a variable lever arm). Since the yaw damper is always in series with the pedals (i.e., yaw damper does not cause pedals to move), the yaw damper servo effectively sums with the output of the ratio changer. Consequently, the sum of the yaw damper input and pilot pedal motion can cause the rudder to momentarily exceed its theoretical limit. The advantage of this is that the yaw damper continues to perform its function regardless of the magnitude of the pilot input. The disadvantage of such a system is that a hardover failure could cause the rudder to move full travel (30°) at any airspeed. As noted in reference A-1 (section 1.6.2.2), the motivation for Airbus to change from a variable gearing system in the A300B2/B4 to a variable stop system in the A300-600 was that "it was less complex and had less severe failure modes."

The rudder pedal limits for the variable gearing system are fixed at ±4 inches. Rudder limiting is achieved by reducing K_{ped} as a function of airspeed. The schedule of K_{ped} versus calibrated airspeed is made such that the rudder deflection at full pedal is identical to the variable stop system at full pedal at the same calibrated airspeed. The difference between the systems for this experiment is that full pedal will be 4.0 inches for the variable gearing system and 1.2 inches for the variable stop and force limit systems.

The variation of maximum rudder deflection as a function of airspeed is typically inversely proportional to the square of calibrated airspeed, i.e., dynamic pressure. The generic curve in figure A-2 reflects this relationship with minor adjustments based on a review of available data for Douglas/Boeing and Airbus.

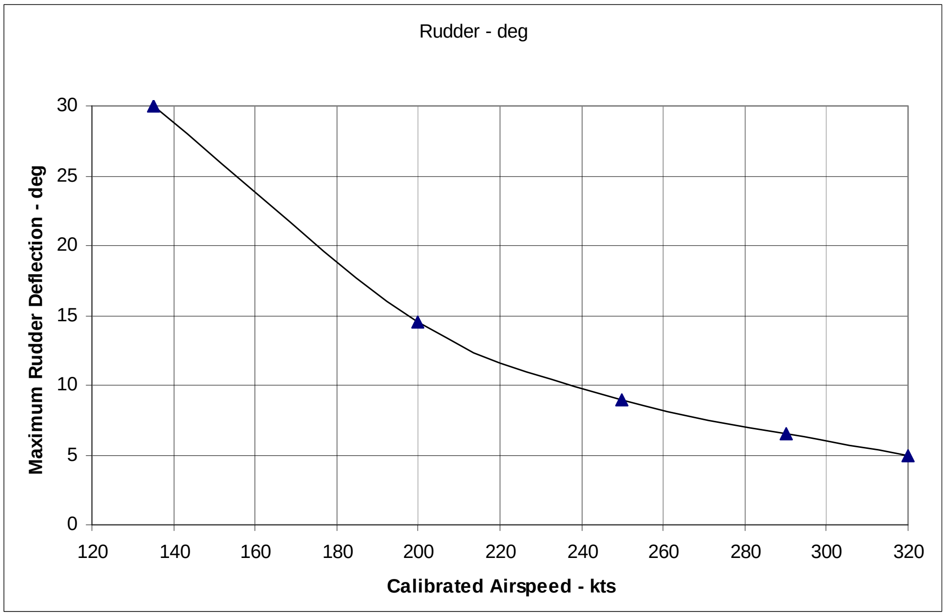

Figure A-2. Limit on Rudder Travel as a Function of Calibrated Airspeed—Variable Gearing

The pedal deflection at airspeeds below 135 kt is based on a pedal-to-rudder gearing of K_{ped} = 7.5 deg/in. This gearing is calculated to produce 30° of rudder deflection when the pedal is deflected 4.0 inches (i.e., $K_{ped} = \delta_{r_{max}} / 4$). At calibrated airspeeds above 135 kt, $\delta_{r_{max}}$ is reduced (figure A-2), and the resulting variation in K_{ped} with airspeed is shown in figure A-3.

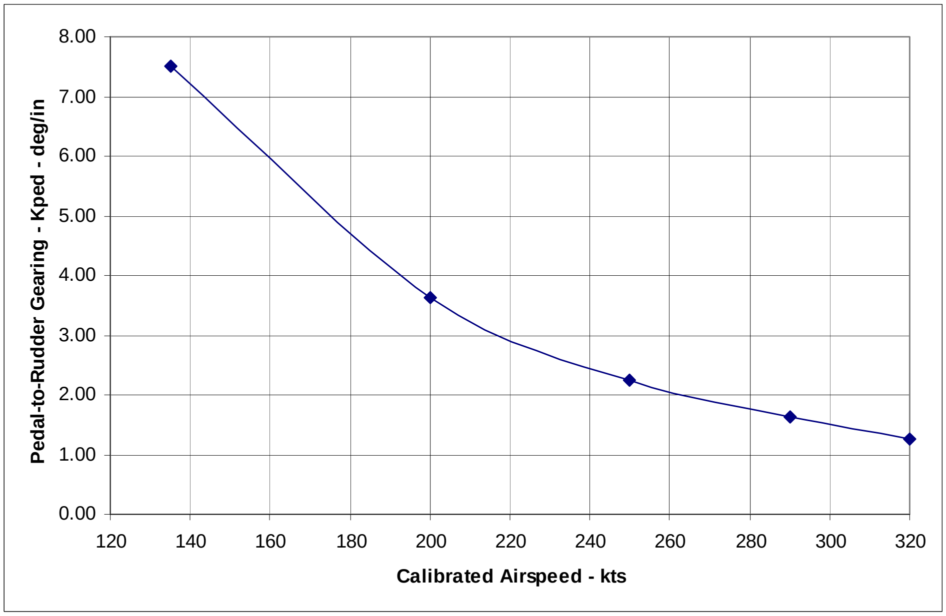

Figure A-3. Variation of K_{ped} With Airspeed—Variable Gearing

In this experiment, airspeed was nominally constant at 250 kt. Nonetheless, the nonlinear ratio changer is necessary to account for the effect of changes in the pedal-to-rudder gearing with airspeed changes during the run.

A.2 VARIABLE STOP.

In this design, the rudder pedals and rudder surface are mechanically limited as a function of airspeed. The control gearing between rudder surface and rudder pedal (K_{ped}) remains constant.

Figure A-4 shows a block diagram that simulates a generic variable stop system.

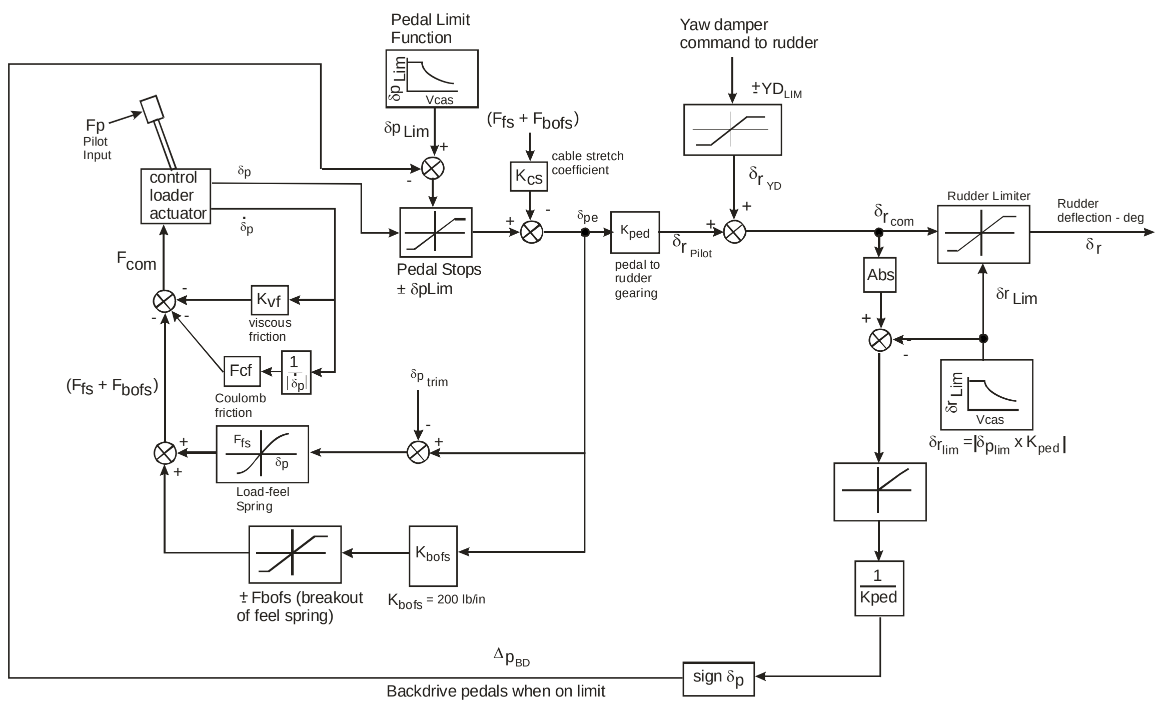

Figure A-4. Generic Variable Stop Rudder Control System

The pedal stop is a calculated variable in this mechanization. The A300-600 variable stop function is achieved by means of a mechanical limit on rudder travel that is varied as a function of airspeed. The commanded rudder position ($\delta_{r_{com}}$) is determined by the sum of the pilot's rudder pedal input ($\delta_{p_{pilot}}$) and yaw damper command ($\delta_{r_{YD}}$). Since $\delta_{r_{\lim}} = \delta_{p_{\lim}} \times K_{ped}$, the only way for $\delta_{r_{com}}$ to exceed the rudder limit is via yaw damper inputs that occur simultaneously with a large pedal input. According to reference A-1, yaw damper inputs that cause the rudder limit to be exceeded result in the pedal being pushed aft while the rudder position remains constant on the limit. This is simulated by the Δp_{BD} input to the control loader in figure A-4. This is not shown as a force input to denote that it cannot be resisted by the pilot because the hydraulic system forces are very high.

The variation of maximum rudder deflection with airspeed is identical to that used for the variable gearing system. The variation of pedal deflection limit with calibrated airspeed was achieved by dividing the rudder deflection by the constant K_{ped} = 7.5 deg/in to achieve the result shown in figure A-5.

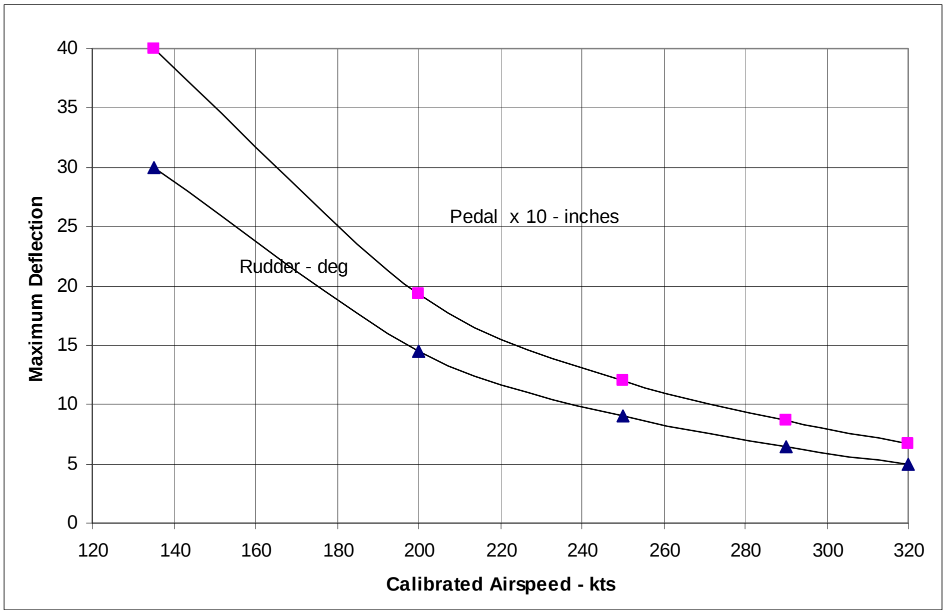

Figure A-5. Reduction in Pedal and Rudder Deflection With Airspeed—Variable Stop

The maximum rudder deflection plot shown in figures A-2 and A-5 was adjusted slightly to achieve a maximum pedal of 1.2 inches at 250 kt for the variable stop system (value common to A300-600, A300B2/B4, A310, A330-300). The maximum pedal deflection of the MD-80 and MD-90 at 250 kt is 1.1 inches.

A.3 FORCE LIMIT.

The force limit rudder system is intended to prevent excessive loads on the vertical stabilizer and rudder. Typically, this is done by limiting the rudder hinge moment (H_{M_r}), which is assumed to be proportional to the loads on the vertical stabilizer and rudder. The rudder hinge moment is given as:*

$$H_{M_r} = S\bar{c}\frac{\rho_0}{2}V_{CAS}^2 C_{Hr}(\delta r,\beta) \qquad \text{(A-1)}$$

Where S = rudder area, $\bar{c}$ = mean aerodynamic chord of rudder, ρ_0 = sea level air density = 0.00238 slug-ft^2, V_{CAS} is the calibrated airspeed, and C_{Hr} is the rudder hinge moment coefficient,

*The total force on the vertical stabilizer is a result of rudder deflection and sideslip. Limiting the rudder hinge moment to a value that limits rudder deflections that would exceed the allowable loads on the rudder mitigates the chances of exceeding the limit loads. However, the rudder hinge moment is an indirect measure of load on the vertical stabilizer, and it may be possible to exceed the allowable load due to certain combinations of sideslip and rudder deflection, with an operational force limit system.

which is a function of rudder deflection and sideslip angle. It is important to note that β is the aerodynamic sideslip angle, i.e.,

$$\beta = \beta_{inertial} - \beta_{gust}$$

where $\beta_{inertial}$ = track angle—heading angle

The force limit system usually operates by providing a method to bypass hydraulic fluid around or through the actuator piston, such as by drilling an orifice in the piston. This bypass is set so that the actuator will stall at some level of reactive force (i.e., rudder hinge moment divided by lever arm). Once the actuator stalls, the pilot can move the control valve by increasing pedal deflection until the control valve bottoms. However, when the actuator is stalled, the inflow of hydraulic fluid is equal to the flow through the orifice, and therefore, the actuator piston does not move, and hence, the rudder does not move. Inherent in this design is the fact that the rudder pedal must move through some stroke, $\Delta\delta_p$, (typically about 0.7 inch) before the control valve bottoms. The rudder surface does not move during that interval. Once the control valve bottoms, additional force on the pedals is transmitted directly to the rudder surface. Because the aerodynamic loads are sufficiently high, this is equivalent to a hard stop.

Simulation of a generic force limit rudder flight control system is accomplished with the block diagram shown below in figure A-6.

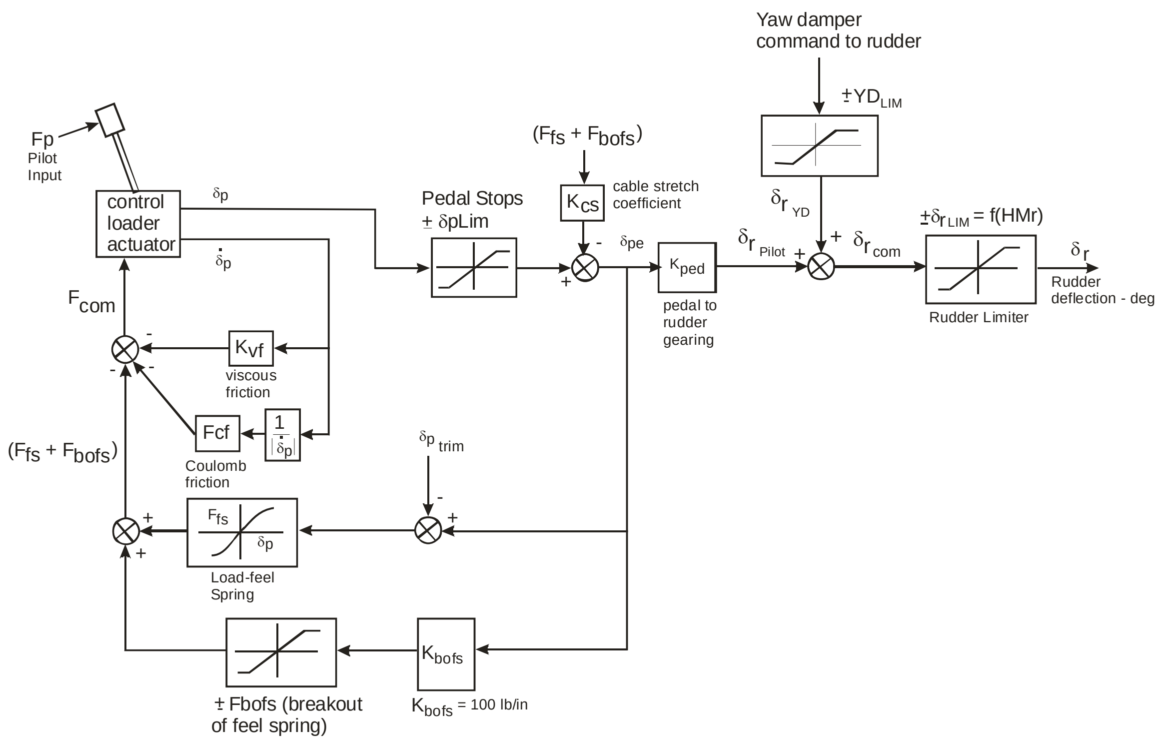

Figure A-6. Generic Force Limit Rudder Control System

The pedal stops are variable in this mechanization, and are a function of rudder hinge moment. Note that if the aircraft is accelerated with a large rudder deflection, the effect should be to backdrive the pedals (as the value of the pedal limiter is reduced). This should be verified during simulator checkout.

The commanded rudder is the sum of the pilot pedal input and yaw damper. A combination of large pedal input and yaw damper activity could cause hinge moment limiting and render the yaw damper ineffective. For mechanical implementations of this system, it would not be practical to sum the yaw damper input downstream of the rudder limiter. However, for a fly-by-wire implementation, it would be possible to set limits only on the portion of the input due to pedal, leaving the yaw damper to operate independent of pedal input.

As long as the rudder hinge moment (HM_r) is equal to or less than the maximum specified hinge moment ($HM_{r\max}$), the rudder deflection is proportional to the pedal input according to the control gearing, K_{ped}. When the rudder hinge moment increases above $HM_{\max}$, the rudder actuator stalls, resulting in an effective rudder deflection limit, $\pm\delta_{r_{\lim}}$. The calculation of the rudder limit is derived in equation A-2. The pedal stop limiter is set to allow the pedal travel required to reach the rudder limit, and then to bottom the servo valve, $\Delta\delta_p$. Therefore, the pedal limiter is set as follows:

$$\delta_{p_{\lim}} = \frac{1}{K_{ped}}\delta_{r_{lim}} + \Delta\delta_p sign(\delta p) \qquad \text{(A-2)}$$

For this series of experiments, the rudder travel to bottom the control valve ($\Delta\delta_p$) shall be set to 0.7 inch.

The rudder limit ($\delta_{r_{\lim}}$) is set by calculating the rudder deflection that results in $HM_{r\max}$ as follows. The rudder hinge moment coefficient corresponding to $HM_{r\max}$ is

$$CH_{r_{\max}}(\beta, \delta_r) = \frac{HM_{r_{\max}}}{KrV_{CAS}^2} \qquad \text{(A-3)}$$

where

$$Kr = \frac{1}{2} S\bar{c}\rho_o$$

S = area of rudder, and $\bar{c}$ = mean aerodynamic chord of rudder

The rudder hinge moment characteristics to be used in this simulation are a generic representation of large transport aircraft rudders. The variation of hinge moment with sideslip tends to be highly nonlinear, as shown in figure A-7.

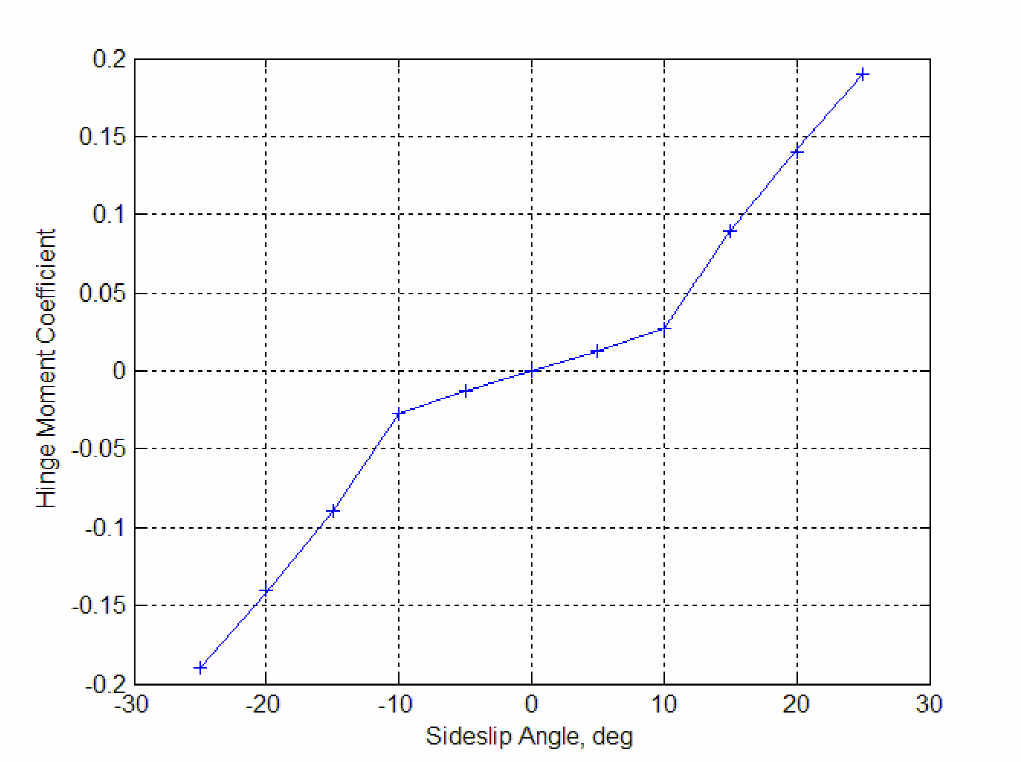

Figure A-7. Generic Variation of Rudder Hinge Moment With Sideslip

The plus signs in figure A-7 indicate the results of a fifth-order polynomial fit to the solid line as follows.

$$CH(\beta) = [4.9\times10^{-7}\left|\beta^5\right| - 3.21^{-5}\beta^4 + 7.16\times10^{-4}\left|\beta^3\right| - 6.04\times10^{-4}\beta^2 + 0.0186\left|\beta\right|]sign\beta \quad \text{(A-4)}$$

where β is in degrees. The variation of the hinge moment with rudder deflection is well represented as a linear function for rudder deflection angles less than 20° as follows:

$$CH(\delta_r) = C_{H_{\delta r}}\delta_r \quad \text{(A-5)}$$

where $C_{H_{\delta r}}$ = -0.0091/deg

The total hinge moment is:

$$CH(\beta,\delta_r) = CH(\beta) + CH(\delta_r) = CH(\beta) + C_{H_{\delta r}}\delta_r \quad \text{(A-6)}$$

The maximum hinge moment occurs when the rudder is on its limit:

$$CH_{r\max}(\beta,\delta_r) = CH(\beta) + C_{H_{\delta r}}\delta_{r_{\lim}} = \frac{HM_{r_{\max}}}{KrV_{CAS}^2} \quad \text{(A-7)}$$

Finally, solving for the rudder limit:

$$\delta_{r_{\lim}} = \left[\frac{HM_{\max} sign(\delta_{ped})}{KrV_{CAS}^2} - CH(\beta) \right] \frac{1}{C_{H_{\delta r}}} \; (V_{CAS} \text{ in ft/sec and } \delta_{r_{\lim}} \text{ in deg.}) \qquad \text{(A-8)}$$

where $CH(\beta)$ is calculated from the fifth-order polynomial in equation A-4. Recall that the pedal deflection when the rudder is at the limit is calculated from equation A-2.

The value of the rudder hinge moment limit ($HM_{\max}$) is set to 3508 ft-lb* so that the rudder limit is nominally 8° (at zero sideslip), to be consistent with the variable gearing and variable stop configurations at 250 KIAS. Kr = 0.27 lb sec^2/ft for the generic rudder configuration used in this experiment.

Recall from equation A-2 that the rudder reaches its limit at 0.7 inch of pedal ($\Delta\delta_p$) before the pedal reaches its limit. At the 250 KIAS used in this experiment, the rudder limits at 1.2 inches of pedal travel, and the pedal continues to move an additional 0.7 inch. As a result, the final 35% of pedal travel occurs with no response from the rudder ("unproductive pedal travel" = 0.7 inch). Comparison with the variable stop configuration with the same pedal travel (compare configurations 7 and 2) will determine if this is good, bad, or not important.

Unproductive pedal travel will be further investigated as discussed in section 4.3.2.

Equation A-8 shows that, for the force limit system, the rudder limit depends on the hinge moment limit and aerodynamic sideslip angle. For example, if the pilot applies and holds a positive (left) rudder-pedal input, a positive sideslip results. From figure A-7, this results in a positive hinge-moment coefficient, which from equation A-8 causes a higher value of rudder limit ($C_{H_{\delta r}}$ is negative) than would occur with a variable stop system, i.e., more control authority. However, if there is a positive sideslip (tending to cause a left roll rate), and the pilot uses negative (right) rudder to decrease the sideslip and thereby reduce the left roll response, the sideslip term in equation A-8 subtracts from the $HM_{\max}$ term, resulting in a decreased rudder limit compared to the variable stop system. This scenario was what existed at the time of structural failure of the vertical stabilizer in the American Airlines Flight 587 accident, so it is possible that a force limit system would have prevented the failure. This is especially true because the combination of positive sideslip and negative rudder deflection is additive in terms of aerodynamic load on the vertical stabilizer and rudder.

A.4 GENERIC YAW DAMPER.

All large aircraft employ a yaw damper. A generic yaw damper that is representative of large aircraft is required to investigate the interaction between the pilot's rudder use and the yaw damper. Since the primary purpose of a yaw damper is to damp the dutch roll mode and enhance turn coordination, all yaw dampers have similar dynamic response characteristics. Therefore, a

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* A value of 3947 ft-lb was used for all runs prior to run 528. This was reduced when pilots noted that the configuration had more control power (rudder was limiting at 9°).

single, generic yaw damper that accomplishes that function is adequate for this study. Such a yaw damper is shown in the block diagram in figure A-8.

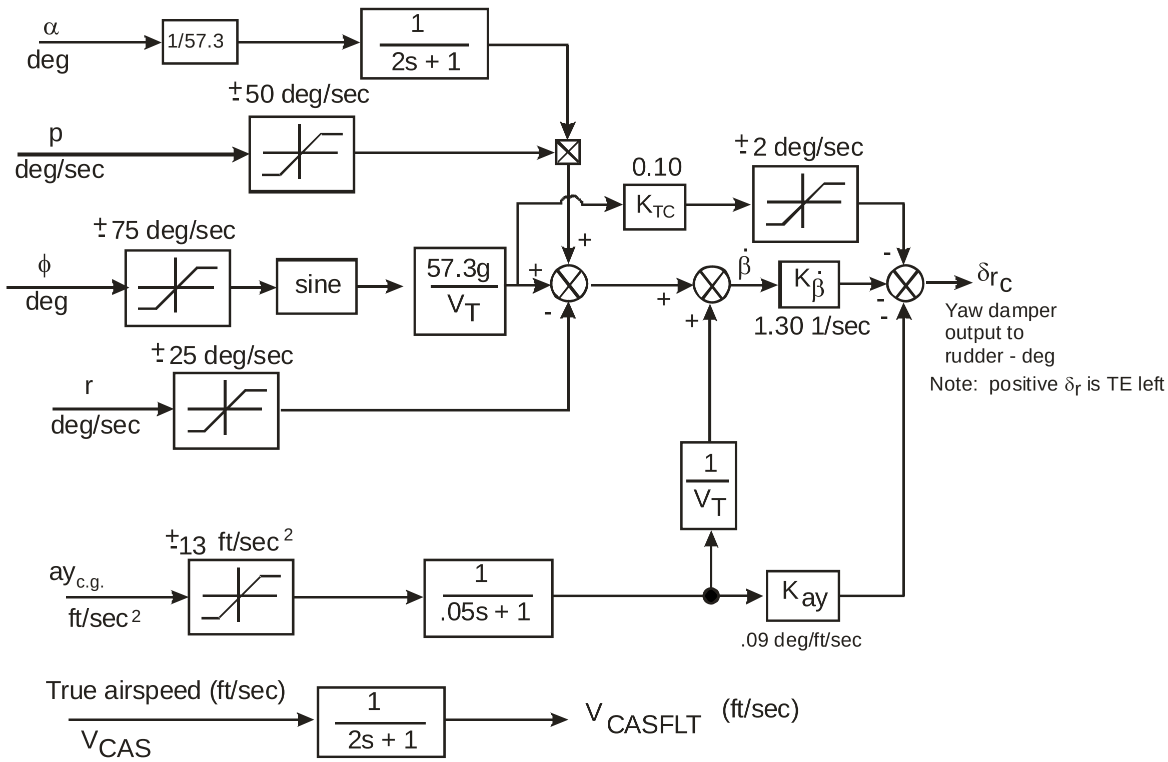

Figure A-8. Generic Yaw Damper

This commonly used yaw damper design is essentially a feedback of sideslip rate to rudder, where sideslip rate is calculated as:

$$\dot{\beta} = \frac{ay_{c.g.}}{V_T} + \frac{g}{V_T}\sin\phi - r_{stab}$$

where V_T = true airspeed, and $r_{stab} = r\cos\alpha - p\sin\alpha \approx r - p\alpha$.

As shown in the rudder control system block diagrams, the yaw damper authority is limited for each rudder system design. This limit is usually inversely proportional to airspeed above some reference airspeed. For example, reference A-1 notes that the A300-600 is limited to ±10° at and below 165 kt and to 10 (1-165/V_{CAS}) at airspeeds above 165 kt. This works out to 3.4° at 250 kt. By comparison, the Boeing 737NG limits the yaw damper travel to ±3° at 250 kt. The yaw damper limit was fixed at ±3° for this simulation study.

The YD A and YD B implementations (discussed in section 3.2.4) are incorporated into the variable stop and force limit rudder flight control system designs, as shown in figures A-9 and A-10.

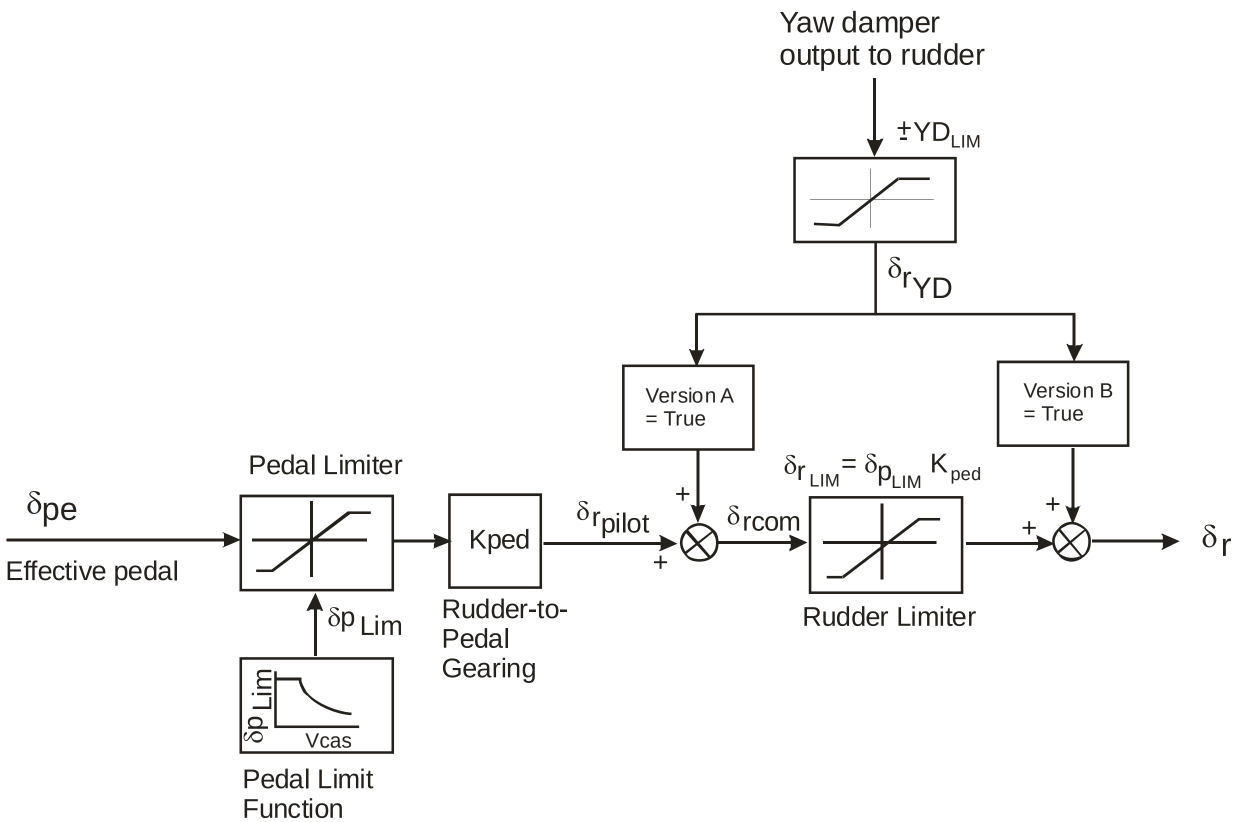

Figure A-9. Variable Stop System With YD A and YD B

With this mechanization, there is the possibility that the pilot's rudder command could saturate the rudder limiter so that the YD A becomes ineffective. For that reason, the test matrix includes YD A and YD B for each of the variable stop system configurations.

The block diagram in figure A-10 illustrates how YD B would be integrated with a force limit system.

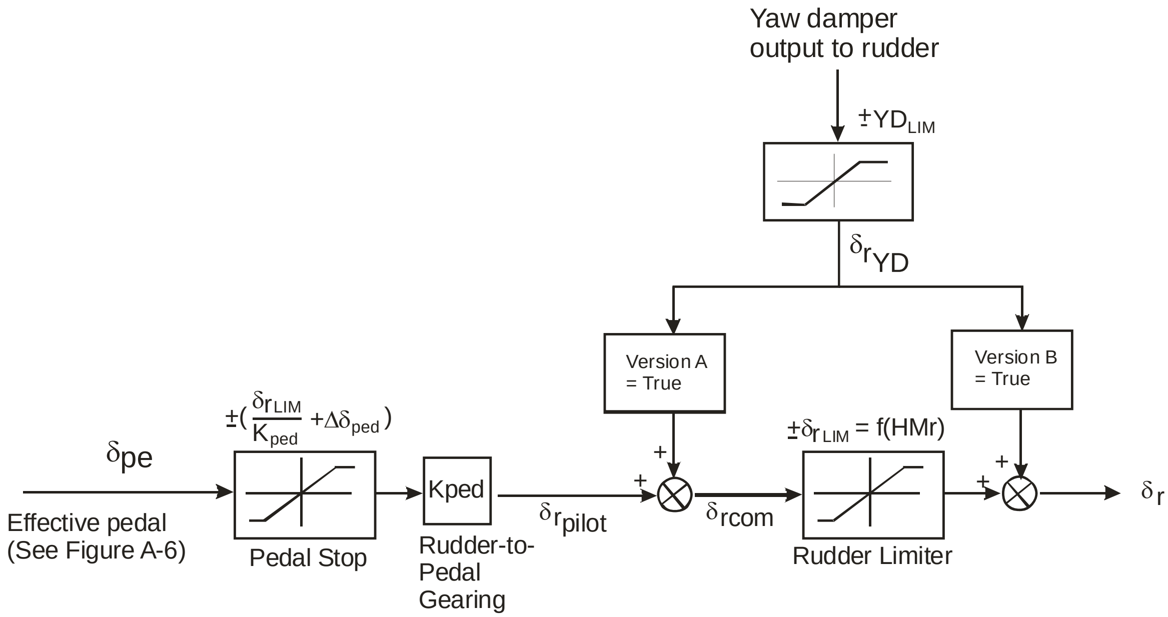

Figure A-10. Force Limit System With YD A and YD B

A.3 REFERENCES.

A-1. Anon, "In-Flight Separation of Vertical Stabilizer American Airlines Flight 587 Airbus Industrie A300-605R," N14053 Belle Harbor, New York, November 12, 2001, NTSB/AAR-0404, PB2004-910404, Notation 7439B, October 12, 2004.

APPENDIX B—DETAILED PILOT RATINGS AND COMMENTS

The raw pilot rating data and a summary of pilot comments made after each run are provided in table B-1. A detailed run log is included in table B-2.

Table B-1. FAA Rudder Simulation

Run No.	Config. No.	Case ID	Pilot	Overcontrol Scale	Pedal Force Scale	Motion Cue Scale	Certifiable	CH Scale	MCH Scale	Max Fy	In/Out	
										lb		
6-9	4	1VP	BW	2	2	3	-	4	5	19457	10:35	
9-11	19	5VB	BW	1	3	3	yes	2	2	29535		
12-14	10	3HP	BW	2	2	2	-	6	7	24562		
15-17	14	4HP	BW	2	3	2	no	9	8	20486		Good feel but pedal travel is inadequate
18-20	21	6HB	BW	3	3.5	1.5	-	4	3	31306	11:25	
21-23	7	2VB	BW	2	3.5	4	-	3	3	33196	11:38	Siffer but easily controllable
24-26	28	7VP	BW	1.5	3	3.5	yes	2	2	30942		Most realistic - hit stop on purpose once to see travel
27-29	2	1HP	BW	3	1.5	2	no	8	6	19643	12:08	Too light - throw is to small
30-32	23	6VB	BW	1	3	2	-	2	2	29624	13:38	No stops
33-35	12	3VP	BW	2	2	3	no	7	8	19311		Light rudder feel hit stops several times
36-38	13	4HB	BW	3.5	3.5	2	-	6	6	29473		short throw and heavy weight
39-41	17	5HB	BW	4	4	2	-	5	5	28566		**Repeat this Large input at beginning no stops
42-44	20	5VP	BW	1.5	2	2	no	9	8	18940	14:14	Spongy stops several times
45-47	5	2HB	PD	1.5	3	2	yes	3	4	34125		Benign - adequate
48-50	14	4HP	PD	2.5	2	1.5	yes	5	6	21827		Too much time on stop forces felt light
51-53	20	5VP	PD	1	3	4	no	6	7	20130		Did not have enough rudder power Too much time on stop
54-56	25	7HB	BW	3	3.5	2	yes	4	3	33425	3:05	No unusual characteristics - no rudder stops
57-59	22	6HP	BW	1	2	3	no	9	9	15912		Spongy - linear to stop Hit stop several times Time for rudder to become effective
60-62	19	5VB	BW	1	3	4	yes	2	2	27532		No unusal feel
63-65	25	7HB	BW	4	2.5	2	yes	5	6	19975		Tendency to overcontrol occurs at small bank angles
66-68	1	1HB	BW	4	1.5	2	no	8	9	32464		Light forces on pedals -
69-71	11	3VB	BW	4	2	2	no	7	7	34945		Nothinng unusual - light feel No stops
72-74	24	6VP	BW	1	3	3	yes	2	2	14380		Nothing unusual
75-77	17	5HB	BW	2	3.5	3	no	4	3	29021	4:15	Good feel for first 1/4 travel, then seemed ineffective

78-80	3	1VP	BW	3	2	3.5	yes	4	3	33245	8:35	Light rudder control. Did not hit stops
81-83	18	5HP	BW	1	2.5	3	-	5	5	19320		Left rudder more effective than right Hit right rudder stops - not enough roll control power with aileron and rudder
84-86	5	2HP	BW	4	3	2	no	7	8	32197		Overcontrol due to short rudder pedal throw. Hit stops due to short throw.
87-89	15	4VB	BW	3	3.5	3	-	4	4	33751		Tendency to overcontrol with rudder - motion cues were good
90-93	6	2HP	BW	3	3	2	NA	9	8	22760	9:20	Seems like bias on left rudder - tendency to hit stops on right side. Cable stretch error caused assymetry - Fixed at this time.
94-96	27	7VB	BW	2.5	3	2	yes	2	2	31414	10:45	Nothing unusual Did not feel stops Would like to have had better motion cues.
97-99	9	3HB	BW	4	2	1.5	NA	5	4	31539		Overcontrol during rudder reversals Hit stops once or twice - light rudder pedal forces reason for ratings
100-102	16	4VP	BW	2	3	2	yes	3	3	16086		Ran out of rudder and aileron several times "need more rudder" Nothing unusual on feel
103-105	8	3HB	BW	2	3	2	yes	3	2	13788		No unusual characteristics - hit stops mostly on right side
107-109	20	5VP	BW	2	2.5	2	yes	3	3	15061		Repeat - More rudder stops on right then left
110-112	18	5HP	BW	1	2.5	1	no	7	7	25532		Rudder system seemed nearly ineffective - hit stops often, stomped on pedal to see if effective
113-115	14	4HP	BW	1	2.5	2	NA	5	4.5	16641		Throw of pedal too short - hit stops several times Mostly right
116-118	13	4HB	BW	3	3	1.5	yes	2	2.5	33804		Did not hit stops
119-121	15	4VB	BW	1.5	3	4	yes	2	1	31195		No stops - Need more right rudder - have more control authority to the left.
122-124	13	4HB	GA	2.5	2.5	1.5	marginal	5.5	6	40770	3:20	Using ball - not motion. Rudder pedal motion very limited. Did not like that. Hit stops a lot
125-127	24	6VP	GA	2	3	2	yes	3	5	17756		Am relying on motion cues to some extent, but attitude is primary. No unusual rudder characteristics Roll axis HQR=5
128-130	4	1VP	GA	4.5	1	2.5	no	7	7	25903		Tendency to overcontrol. Liimited range of motion and light forces were objectionable.

131-133	19	5VB	GA	4.75	4	2.75	no	7	7	39118	8:15	Strong tendency to overcontrol rudder especially at large pedal deflections. Good throw. Forces a little higher than desirable
134-136	6	2HP	GA	4	1.25	2.75	no	7	8	28519		On-off rudder (either full or none) - undesirable. Low aileron authority. Seemed to be a delay in rudder taking effect to augment roll. Hit stops a lot
137-139	11	3VB	GA	4.4	2.75	2.75	no	7	7	38562		Very limited rudder authority. Reasonable forces. High tendency to overcontrol. Strong nonlinerity.
140-142	20	5VP	GA	1	3	3	yes	4	3	18563		Good range of motion for pedal. Forces felt good. Minimal tendency to overcontrol, lag in roll resp to rudder
143-145	19	5VB	GA	4.5	2.75	1.5	no	6	7	38734	9:15	**Repeat - Large deflection, reasonable forces. Large breakout, negligible response to small inputs. Discussion of task here.
146-148	26	7HP	GA	1.5	3.25	3	yes	4	3	50827	10:10	Nothing objectionable. Did hit rudder stops.
149-151	28	7VP	GA	1	3.25	3.5	yes	2.5	2.5	36397		Forces okay. Felt pretty good about this system.
152-154	25	7HB	GA	4	4	2	no	6	7	43711		Large initial force - high breakout was a significant problem. Tendency to overcontrol with rudder
155-157	27	7VB	GA	4.5	4	3.5	no	7	8	50367	11:15	Breakout forces too high - strong tendency to overcontrol - hit stops often
158-160	17	5HB	PD	1.5	3.5	1.5	yes	4	4	37220	11:25	No tendency to overcontrol, Pedal forces just fine but breakout a little high, too much throw with not enough happening first inch of pedal
161-163	20	5VP	PD	1.25	3.5	4	yes	4.5	5	21182	11:50	Touch high on forces and breakout,
164-166	1	1HB	GA	4.5	1.5	1.5	yes	7	7	40104	13:05	Light forces for breakout and full deflection. Very definite tendency to overcontrol when making large deflections. Used lead compensation
167-169	4	1VP	GA	3	1.5	2.5	no	5.5	5	32493		Light forces and tendency to overcontrol,
170-172	3	1VB	GA	3	2	2	no	7	8	39321		Tendency to overcontrol with rudder
173-175	2	1HP	GA	2.5	1.5	2	no	6	5	36728	13:55	Extremely light forces to get full travel
176-178	18	5HP	PD	1.25	3.5	1.5	yes	4	5	19931	14:00	Big throw, heavy forces, would like all rudder a little sooner for this task
179-181	19	5VB	PD	1.25	3.5	4	yes	4	4	39322	14:25	No stops, forces a little high

182-184	9	3HB	GA	3	1	2	no	7	7	40031	14:35	Light breakout and light rudder forces, continually putting in full amplitude forces, limited authority to center ball, on stops 70 to 80% of time
185-187	12	3VP	GA	4.5	1	3	no	8	10	42359		Significant out of sync aileron and rudder, Out of phase aileron and rudder often for large inputs. Barely controllable Definitely not certifiable
188-190	19	5VB	GA	3	4	1.5	no	7	9	37138	15:15	High rudder breakout of 15 to 20 lb, Nonlinear gradient, Full rudder 50% of time
191-193	16	4VP	RH	1.5	3	3	yes	3	4	12453		Limited travel not noticeable due to good force characteristics
194-196	7	2VB	RH	1.5	3	4	yes	3	3	35068		Limited travel not noticeable due to good force characteristics
197-199	17	5HB	GA	2.5	4	1.5	maybe	4	5	37855		High force that flattens out. Large breakout. Hit stops occasionally
200-202	5	2HB	GA	2.5	3.5	1.5	no	6	5.5	38168		Very limited control authority. Tracking more managable than some. Not certifiable because of small travel from breakout to stop
203-205	17	5HB	GH	3	4	2	yes	5	5	28898	8:35	Nothing unusual - Task is extreme
206-208	19	5VB	GH	2.5	4	2	yes	5	5	31068		Nothing unusual
209-211	4	1VP	GH	1.5	3	1.75	yes	5	4.5	14162		Getting desired performance but full wheel is very high workload Nothing unusual about rudder. Did not use rudder much - did not need it.
212-214	8	2VP	GH	1.5	3	1.5	yes	4.5	5	14152	9:15	Do not use rudder much. Very little rudder travel but did not impact task. Two hands, full wheel, = high workload
215-217	7	2VB	GA	1.5	3	1.5	yes	4	4.5	37611	9:25	Definitely more managable than yesterday's configs. Moderate forces, could moderate to some degree.
218-220	8	2VP	GA	1.5	3	2	yes	4.5	4	25805		Limited throw, but could modulate rudder due to forces, Only hit stops occasionally
221-223	10	3HP	GA	1.5	2	1.5	yes	5	4.5	32882		5 due to light forces and limited motion. In that context tracking was managable.
224-226	21	6HB	GA	1.5	4	1.5	yes	4.5	4	37913	10:13	Large throw, heavy forces, personnally perfer less force,
227-229	1	1HB	GH	2	3	2	yes	5	3	33271	10:20	Limited travel. Like light rudder forces. Nothing adverse about limited travel. Definitely certifiable

230-232	20	5VP	GH	2	4	2	yes	5	5	19054		Forces seemed too high durinng fam run but good during run. Did not hit stops. Desired perfomance but workload is high.
233-235	11	3VB	GH	2	2.5	2	yes	5	5	28593		Unusual with limited travel and light forces. Light forces helps with this task. No big tendency to overcontrol
236-238	18	5HP	GH	1.5	4	2	yes	5	5	16931	11:15	Hit longitudinal motion stops. For this task forces are heavy but okay. No unusual rudder characteristics
239-241	14	4HP	GA	1.5	3.5	1.5	yes	5	5	19705	11:25	Very limited rudder travel. Medium forces. Full aileron rudder to help. Rudder certifiable, ailerons not certifiable for this task.
242-244	23	6VB	GA	2	3	1.5	yes	4	4	33728		Medium forces (comfortable). Liked rudder feel characteristics. No stops
245-247	22	6HP	GA	1.5	3	1.5	yes	2.5	3	17153		Very large throw, high breakout. Like that rudder system. Hit stop once or twice. Able to modulate rudders fairly good.
248-250	15	4VB	GA	2.5	3	1.5	maybe	5.5	5	37949	12:08	Prefer longer range of deflection caused some overcontrol and tendency to hit stops. Maybe on cert due to limited travel.
251-253	16	4VP	GA	1.5	3	2	yes	5	4.5	28062	13:15	Very limited travel. Marginally certifiable
254-256	40	10VP	GA	2	1.5	1.5	no	5.5	5	27854		YD or something helping me out quite a bit. Forces too light, throw too limited, Certifiable borderline no.
257-259	36	9VP	GA	2	3.5	2	yes	5	4	20784		Definitely more managable with this YD. Ball excursions noticeably less. Hit stops quite a bit. YD helped roll upsets. Rudder and aileron were in phase most of the time. Certifiable=borderline yes
260-262	35	9VB	GA	2.5	3.5	1.5	no	5.5	5	34201		Not much delta between breakout and max deflection. Tendency to overcontrol sllightly. Hit rudder stops quite a bit. Not certifiable - overcontrol
263-265	39	10VB	GA	3.5	1.5	1.5	no	7	7	42724	14:10	Limited deflection. Light breakout not much force to stop. Tend to overcontrol
266-268	3	1VB	GH	2	1.5	2	no	5	4.5	31043		Breakout forces too light, and low breakout. Did not hit stops. Rudder gradient to low to be certifiable. Light forces good for this task however.

269-271	13	4HB	GH	1.5	3	2	yes	5	5	31025		Large breakout, good gradient - not a big factor in this task.
272-274	12	3VP	GH	1.5	3	2	yes	5	5	16507		Yaw task now seems easy compared to roll. Pedal feel is very good
275-277	16	4VP	GH	1.5	3	2	yes	5	5	13687	15:45	Little high on breakout, gradients nice - definitely certifiable Best rating is 5 because of wheel on stops
278-280	25	7HB	RH	1.5	3	3	yes	3	3	37289	15:50	Forces and displacement in good region.
281-283	30	8HP	RH	3.5	1.5	1.5	no	6	7	19157		Forces too light - mental workload to keep from manhandling rudder
284-286	40	10VP	RH	3.5	1.5	3	no	6	7	16176		Same as above
287-289	19	5VB	RH	1.25	3	4	yes	3	3	29184	16:30	Like this rudder system a lot.
290-292	5	2HB	JM	2	3	3	yes	2	2	29671	11:10	No unusual characteristics
293-295	21	6HB	JM	1	3	3	yes	2	2	27079		No Unusual characteristics
296-298	8	2VP	JM	1	4	2.5	yes	2.5	3	19730		Resistance seems the same all the way to the stop. Limited travel, forces a little bit heavy
299-301	23	6VP	JM	1.5	3	3.5	yes	1.5	1.5	28282	12:10	No unusual char.
302-304	22	6HP	HP	2	2.5	3	yes	3	4	20977	13:40	No unusual char. Hit stops once or twice
305-307	7	2VB	HP	4.5	2	4	no	7	6	34924		Too light - hit stops a few times - Re cert I would not want to fly an airplane that felt like that
308-310	24	6VP	HP	2.5	3	3	yes	2	3	19366		Nothing unusual
311-313	6	2HP	HP	3	2.5	3	yes	3	4	20056	14:20	Nothing unusual
314-316	22	6HP	JM	3	4.5	3	no	7	8	13997	14:25	Heavy feel, travel too long, hit stops
317-319	7	2VB	JM	2	1.5	2.5	no	7	5	28257		Travel too short and resistance too light
320-322	24	6VP	JM	1	4	2	no	7	6	12560		Too heavy. Rating of 7 is due to heavy forces
323-325	6	2HP	JM	2	2	2.5	no	5	6	16804	15:13	Travel too short
326-328	5	2HB	HP	2	2	3	yes	2	2	32157		326 recorded as 325 Nothing unusual about this rudder system.
329-331	21	6HB	HP	3	3	3.5	yes	2	2	28962		Nothing unusual
332-334	8	2VP	HP	2.5	3	3.5	yes	4	5	19085		Nothing unusual - hit rudder stops a few times
335-337	23	6VP	HP	3	3	4	yes	2	2	29997	15:57	Nothing unusual - hit rudder stops a few times
338-340	9	3HB	JM	1	3	5	yes	1	1	27540		Nothing unusual

341-343	18	5HP	JM	1.5	3.5	2	yes	3	3	15953		Excessive roll forces (31 lbs max at 80 deg wheel). Pedal travel too long. Did not hit stops . Not my favorite one.
344-346	19	5VB	JM	2	3	3	yes	3	3	27711	14:35	Nothing unusual Erronously recorded this as runs 344 to 347. Error propagated to end of day. Note on voice recorder
347-349	20	5VP	HP	1.5	3	4	yes	1	1	17214		Nothing unusual
350-352	12	3VP	HP	3.5	2.5	3	no	8	8	25134		Felt jerky and rough on rudders hit stop once or twice
353-355	10	3HP	HP	2	2.5	3.5	yes	3	2	21919	17:05	Nothing unusual. Roll forces seem too high and this could affect ratings.
356-358	17	5HB	HP	4	2.5	2.5	yes	5	4	27622	8:10	Overly sensitive to rudders Did not seem to hit stops
359-361	9	3HB	HP	3.5	2	3	yes	5	4	28861		Little light on rudder but okay
362-364	18	5HP	HP	2.5	3	3	yes	2	2	15944		No unusual characteristics. Motion problem at 08:45. LOOK AT WHEEL GRADIENT
366-368	9	3HB	JM	5	1	4	no	7	6	27702	9:25	START WITH LOWER WHEEL GRADIENT HERE. 20 LB MAX WHEEL (Repeat as many cases as possible))
369-371	18	5HP	JM	1	3	2.5	yes	1	1	16322		Pretty good feel
372-374	19	5VB	JM	1.5	3	3	yes	2	2	27046		No unusual characteristics
375-377	11	3VB	JM	1.2	2.8	2	yes	2	2	25397		No unusual characteristics
378-380	20	5VP	HP	2	3	3.5	yes	2	1	15516		No unusual characteristics
381-383	12	3VP	HP	3	2.5	3.5	yes	3	3	23334		Forces a little light but no unusual characteristics
384-386	10	3HP	HP	3.5	3	3	yes	2	2	20109		
387-389	17	5HB	HP	3	4.5	3.5	no	8	7	30535	10:45	Rudder forces way too heavy
390-392	20	5VP	JM	1	4	4.5	yes	3	2	12967	10:50	Nothing abnormal
393-395	12	3VP	JM	1	2.8	3	yes	2.8	3	21432		Forces a tiny bit too light
396-398	10	3HP	JM	1	2.8	3	yes	2	2	26194		Like this one a lot.
399-401	17	5HB	JM	1	3.5	3	yes	2	2	27385	11:30	Forces a little heavier than last run.
402-404	9	3HB	HP	2.5	2	4	yes	3	2	27396	12:45	Nothing unusual
405-407	18	5HP	HP	1	3	3	yes	1	1	16278		One of the better ones
408-410	19	5VB	HP	2	2.8	3.5	yes	3	2	29467		
411-413	17	5HB	HP	2	2.8	3.5	yes	2	3	27183	13:25	Repeat -

414-416	11	3VB	JM	1.5	2.5	4	yes	2	2	26849	13:30	Repeat - Little light feeling on rudder
417-419	5	2HB	JM	1	4	2	no	5	2	24579		Throw too short and forces too heavy - task seemed easy.
420-422	21	6HB	JM	1	3.5	2.5	yes	2	2	24485		Task seems much easier
423-425	8	2VP	JM	2	3.5	3	yes	2	3	12670		Task still seems easier
426-428	11	3VB	HP	3	2	3	yes	6	4	28180	14:10	No unusual rudder feel aside from light forces - barely certifiable due to light forces
429-431	5	2HB	HP	2.5	2.8	4	yes	3	2	27279		No unusual rudder
432-434	21	6HB	HP	2	3.2	4	yes	3	2	27444	14:45	Nothing unusual
435-437	1	1HB	RD	2.6	3	3	yes	2.5	2.5	35010	8:20	Nothing unusual "fam run"
438-440	4	1VP	RD	3.5	2.5	3.5	yes	2.5	4	23303		Nothing unusual - 3.5 on overcontrol is because I hit the stops
441-443	5	2HB	RD	1.5	3	2	yes	2	2.5	32251		Like the feel and performance
444-446	21	6HB	RD	2	4	4	questionable	4.5	3	28109		Pedal forces a little too heavy
447-449	8	2VP	RD	2.5	3	4	yes	3	4.5	20431	9:15	Like the feel and did hit rudder stops
450-452	1	1HB	MS	1.5	2.5	3	yes	3	2.5	35319	9:20	Fam runs then start with 1 and 4. Nothing Unusual Did not hit stops
453-455	4	1VP	MS	2.5	3.5	3	yes	3	3	25893	10:00	Nothing unusual Did not hit stops
456-458	23	6VB	RD	1.5	3	4	yes	2.5	3	27630	10:05	Characteristics good. Did not hit stops.
459-461	22	6HP	RD	3	2.8	3.5	questionable	5.5	4.5	16281		Tad sluggish. Did hit stops once.
462-464	7	2VB	RD	2	3.5	4	yes	2.5	2.5	33419		Characteristics stiff, but no problems. Did not hit stops.
465-467	24	6VP	RD	3.5	3	2.5	no opinion	5	4.5	18418		Characteristics OK. Did not hit stops. Throw too great. Tendency to forget I have rudder in with long throw and delay taking out
468-470	6	2HP	RD	2	3	4	yes	4	3	19778	10:55	Like rudder feel Did hit rudder stops "Hate long throw rudder systems"
471-473	22	6HP	MS	2	3	4	yes	2	3	17812	11:00	First impression - I like it-really nice. Like long rudder throw and light feel. Felt like a 6-axis simulator (Hexapod).
474-476	7	2VB	MS	1	3.5	2.5	yes	2	2	30267		Does not feel like 6 axis simulator. Motion cues not consistent with the ball. Motion cue seemed behind ball.
477-479	24	6VP	MS	1.5	3	4	yes	3	2.5	24582		Feels like combination of 6-axis and VMS

480-482	6	2HP	MS	2	3	3.5	yes	3	3	33462	11:47	Hard to overcontrol. Good motion cues. Felt like combination of hex and VMS
483-485	18	5HP	RD	3.5	3	3.5	yes	4	4	15146	13:00	Throw is pretty long. Motion effect quite noticeable.
486-488	9	3HB	RD	4.5	2.8	2.5	no	6	2.5	35463		Tend to overcontrol Rudder PIO Did not hit rudder stops A little too loose.
489-491	19	5VB	RD	2.8	3	3	yes	4	3	28172		Felt a tad loose but not by much.
492-494	11	3VB	RD	3	2.5	3.5	questionable	4	3	34234		Tendency to PIO a little
495-497	20	5VP	RD	2	3	3.5	yes	3	4.5	24002		I like that one. Good characteristics. Forgot to let rudder out on one occasion
498-500	12	3VP	RD	3.5	2.8	4	questionable	4	3	31009	14:00	Sensitive rudder. Did hit rudder stops Little light on force
501-503	5	2HB	MS	1	3	1.5	yes	3	1	29521		Motion cues did not match up with ball. Rudder is good
504-506	21	6HB	MS	1	3	3.5	yes	2.5	1.5	27734		Nothing unusual Still having problem correlating motion, visual, and ball (Found ay followup is zero starting at run 500
507-509	8	2VP	MS	2	4	3	questionable	5	5	20134		Ayp folloup on strip chart working this run. Did not like rudder. Want more throw and less resistance. Felt like I was not getting enough rudder authority.
510-512	23	6VB	MS	1.5	3	4	yes	2	2	30603	14:50	Can feel requirement to lead ball from motion cue. Good discussion of motion cue here.
513-515	10	3HP	RD	2.5	2.5	3.5	yes	2.5	3	22258	15:05	Little light on rudder Hit stops a couple times
516-518	17	5HB	RD	1.5	3	3.5	yes	2	2	28740		Good rudder
519-521	4	1VP	RD	2	2.5	3	yes	4	4	25997		Like throw. Little light on force
522-524	26	7HP	RD	1.5	3	3.5	yes	2	3	24146		Like this rudder system
525-527	27	7VB	RD	1.8	3	3.5	yes	2	2	30455	15:40	Like rudder setup. Motion real good
528-530	21	6HB	MS	1.5	3	2	yes	3	2.5	27995	15:50	Like light touch and full throw NOTE: reduced Hmmax on case 7 from 3947 to 3508 to keep drmax at 8 deg.
531-533	8	2VP	MS	1	3	4	yes	1.5	2	21411		Hit force gradient at just about where I needed it to help aileron.
534-536	23	6VB	MS	1.5	3	4.5	yes	2	3	27655	16:23	Motion real good - ahead of ball. First cues were off the motion, then ball.
537-539	25	7HB	RD	2	2.7	3	yes	2	2	26711	16:30	Nothing unusual

540-542	2	1HP	RD	2.5	2	1.5	questionable	4	4	22600		Rudder force a little light
543-545	28	7VP	RD	1.5	3	3.5	yes	3	3	25441		Like rudder setup. Hit stops a few times
546-548	21	6HB	RD	2	3	3	yes	2	3	29741		No problem with rudder.
549-551	24	6VP	RD	1.5	3	3.5	yes	4	4	16534	17:10	Did not like long rudder throw.
552-554	20	5VP	MS	1	3.5	4	yes	2.5	2.5	20061	8:20	Like the long throw, rudder forces a little heavy. Hit stops a few times.
555-557	12	3VP	MS	1.5	3	4	yes	2.5	2.5	19873		Stops numerous, limited throw but nice pedal pedal pressure.
558-560	10	3HP	MS	1.5	3	2.5	yes	2	2.5	22174		Limited throw, nice and light, stops a few times.
561-563	17	5HB	MS	3.5	3.5	2	questionable	6	5.5	28623		Slight tendency to overcontrol, got out of synch with ball; no stops; rather not certify
564-566	9	3HB	MS	2	3	2	yes	2.5	2	31370	10:05	Stops in synch with ball helping to reduce overcontrolling tendency.
567-569	9	3HB	PD	2.5	1.5	4	yes	4.5	4	44566	10:10	Short throw and very light. Some tendency to overcontrol
570-573	18	5HP	PD	1.5	4	2.5	yes	5	4	18698		Large throw, heavy forces. Hit stops but much less than last run.
574-576	19	5VB	PD	1	3.5	4	yes	3	2.5	32005		Large throw, high forces, liked it better the more I flew it
577-579	11	3VB	PD	3.5	1.5	5	questionable	6	7	41269	10:55	Very slight PIO. Light breakout, light forces, limited throw.
580-582	18	5HP	MS	1.5	3.5	2.5	yes	4.5	5	23914	11:15	Liked to have lighter rudder forces but not as bad as some; rud stops coordinated with aileron.
583-585	19	5VB	MS	1	3.5	4.5	yes	2	2	29893		Good system, slightly lighter forces would improve; no stops on the rudder
586-588	11	3VB	MS	1.5	3	4	yes	3	1.5	28683		Tendency to overcontrol; could lead the ball with motion cues
589-591	26	7HP	MS	1	4.5	2.5	no	6	6	27708		Not a favorite; cross control several times; rudder stops couple times each run
592-594	27	7VB	MS	1.5	3.5	4.5	yes	3	2	26657	12:05	Liked the system and stops; may have hit stops but not sure
595-597	20	5VP	PD	1	3	3	yes	2	3	23131	12:10	No unusual characteristics. Hit stops but it seemed appropriate

598-600	12	3VP	PD	4.5	1	4.5	no	7	7	29912	12:30	All or nothing. Highest mental workload so far. Stop-to-stop - too much or not enough. Pushed thru stops (stretched cables).
601-603	28	7VP	MS	1	3.5	3	yes	3	4	30386	13:30	Nothing unusual
604-606	13	4HB	MS	1	3	3	yes	1.5	1.5	28004		Nothing unusual, very responsive; liked this very much
607-609	14	4HP	MS	1	3	2.5	yes	1.5	2	20353		Really nice system. Hit stops a couple times.
610-612	15	4VB	MS	1.5	3	3.5	yes	2	1.5	30226		Motion cues as good as ball; nothing unusual; stops only a few times; nice system
613-615	25	7HB	MS	2	3	2	yes	3	3	25656	14:18	All ball for cue; reasonably good; never got to stops, good authority
616-618	20	5VP	PD	1	4	4	questionable	5.5	6	19086	14:24	Too much pedal travel/force to get rudder. Too much breakout. Not my favorite by a long shot
619-621	10	3HP	PD	5	1	3	no	7	7	22203		Way too light forces - low breakout. Big tendency to overcontrol. Throw is too small.
622-624	17	5HB	PD	1	3	1.5	yes	2.5	3	30989	14:55	Rudder good for this task. No stops.
625-627	2	1HP	MS	1.5	2.5	2	yes	2	3	19691	15:00	Nothing; light touch; stops when required but minimal motion cues
628-630	4	1VP	MS	1.5	3	3.5	yes	2	3	16810		Light touch; more motion cues; some stops but nothing unusual
631-633	3	1VB	MS	1.5	3	4	yes	3	2.5	27590		Good motion cues; slight tend overcontrol due to lite forces with foot even on other pedal; little pedal movement
634-636	16	4VP	MS	1	3.5	3	yes	5	5.5	19959		Difficult to overcontrol; can't get what you want right away; few stops
637-639	31	8VB	MS	2	2.5	4	yes	3	2.5	28747		Light touch and with less motion might overcontrol; instant response
640-642	39	10VB	MS	2	3	4	yes	3	2	28445	16:00	Light touch with slight tend to overcontrol
643-645	17	5HB	PD	1.5	3.5	2.5	yes	4	4	29996	16:05	Like throw and forces.
646-648	5	2HB	PD	4	2	3.5	questionable	5	5	33327	16:25	Short throw, slight lag and tend to overcontrol lowers CH ratings
649-651	40	10VP	MS	1	3	3.5	yes	2	2.5	20516	16:30	Limited throw, on stops with aileron but no tend to overcontrol
652-654	43	11VB	MS	1	3	4	yes	2	2	30656		Short throw and a few stops;

655-657	44	11VP	MS	1	3.5	3.5	yes	2	4	16635	17:05	Trade off as forces high which prevents you overcontrol; less likely to hurt the airplane but high workload v.v. lighter forces with tend to overcontrol can track better
658-660	21	6HB	PD	1	3	2.5	yes	2	1.5	27789	8:35	Very good for tracking task
661-663	8	2VP	PD	1.5	2.5	4	yes	3	3	20881		Fped>100 lb a few times- stretch cables. Short on throw but was able to make partial to full inputs as required.
664-666	23	6VB	PD	1	3	4	yes	3	3	36704		Good system for tracking - well behaved. Did not hit rudder stops (even if I tried)
667-669	22	6HP	PD	4	1	1.5	no	6	6	16982		Slight tendency to overcontrol/PIO. Goes away if I get off rudders. Low breakout and low forces.
670-672	7	2VB	PD	3.5	2	4	yes	5.5	6	33930	9:25	Good motion cues prevents me from needing large rudder inputs. Had to really turn my gains down to keep from overcontrolling.
673-675	14	4HP	RH	1.5	3	2.5	yes	3	3	14690	9:35	Limited throw, good gradient, several stops during larger disturbances
676-678	8	2VP	RH	1.5	3	4	yes	3	3	12071		Led inputs due to motion; limited throw with rudder on stops during large gusts
679-681	3	1VB	RH	3.75	1	4.5	no	7	7	38766		Forces light, motion system prevented overcontrol and aggressive inputs; stops all the time and too lite forces
682-684	20	5VP	RH	1	3	4	yes	2	3	15378		Long throw, nice force gradient; nothing - std rudder system; once on pedal stop on largest gust as appropriate
685-687	19	5VB	RH	1	3	4	yes	2	3	30237	10:35	
688-690	31	8VB	PD	3.5	1.5	4.5	questionable	6	5.5	33792	10:40	Very touchy. Good for task, but easy to overcontrol
691-693	3	1VB	PD	3.5	2	4.5	questionable	5	6	37215		Not appropriate for transport airplane. Errors higher than last run.
694-696	40	10VP	PD	4	2	3	yes	5	6	18874		Light forces result in my putting in too much rudder.
697-699	25	7HB	PD	1.25	3	1.5	yes	2.5	3	33017		Easy to develop right amount of rudder to do task
700-702	27	7VB	PD	1.5	3	4.5	yes	2	3	25977	11:35	Does good job for this task. Nowhere near any stops due to force.

703-705	39	10VB	PD	2	2	2.5	yes	5	5	33099	13:25	Force gradient too light. Too much sideslip for small pedal.
706-708	1	1HB	PD	2	1.5	1	yes	5.5	5.5	22397		Hit stops without realizing it due to light forces.
709-711	4	1VP	PD	3.5	2	4	questionable	6	6	35012		Not enough breakout. Unhappy with rudder control system. Difficult to be precise - too light.
712-714	44	11VP	PD	1.5	3	3.5	yes	3	3	18649		Seems better damped, does not respond as much to gusts. Probably a better yaw damper.
715-717	28	7VP	PD	1.5	3	4	yes	2	3	22138	14:15	Good force gradient. Liked it. Handled this task very well.
718-720	15	4VB	RH	1.5	3	4.5	yes	2	2	34526	14:30	Limited throw but good force gradient; no stops
721-723	9	3HB	RH	4.5	1	1.5	no	7	7	42519		high bo, low grad, poor characteristics; lack of motion made it worse
724-726	39	10VB	RH	3.2	1.5	4.5	no	5.5	5.5	31999	15:00	Tend to overcontrol less with more motion; no stops with ability to induce large oscill.; bo high, forces too lite, no stops
727-729	2	1HP	PD	4	1.5	2	questionable	5	6	23902	15:05	Overcontrolling a lot. Turning down my gain. Not enough motion cues to figure out what is coming next. Overresponsive - Too many stops
730-732	26	7HP	PD	1.5	3	2.5	yes	2.5	3	18555		Good run No unusual characteristics
733-735	35	9VB	PD	1	3	4.5	yes	2	2	32173		Fine rudder system. Low workload
736-738	28	7VP	PD	1.5	3	4	yes	2.5	3	21699		Nothing unusual
739-741	24	6VP	PD	1.5	3.25	3	yes	3	4	19375	15:55	Like throw on previous one better
742-744	23	6VB	RH	1.5	3	2	yes	2	2.5	29677	11:10	No unusual char. Did not hit stops.
745-747	11	3VB	RH	4.5	1.5	4.5	no	7	7	37190		Very limited throw, light forces, high break out. Did hit stops
748-750	1	1HB	RH	4.5	1	1.5	no	7	7	38850	11:45	Too light forces, small throw, low breakout. Did hit stops a lot.
751-753	6	2HP	RJD	5	1	3	no	7	7	26346	11:50	Less responsive rudder, Low breakout, light forces, hit stops a lot.
754-756	24	6VP	RJD	1.5	1	3	no	10	9	23294		Not enough rudder1/2 ball max, Like travel but forces were too light.
757-760	7	2VB	RJD	4	2	1.5	no	8	6	41657		Displacement short. Easy to hit stop. Short throw and ineffective rudder

761-764	22	6HP	RJD	2.5	2	3	no	6	7	22041	12:40	Rudder effectiveness more left than right. Forces get lighter with increasing displacement.
765-767	23	6VB	RJD	1	2.5	1	yes	4	2	33809	14:10	No overcontrol, forces too light near max, travel pretty good
768-771	8	2VP	RJD	2	2	4	no	5	7	27257		Short travel was irritant and easy to reach max; stops on occasion
772-774	21	6HB	RJD	1	2	2	yes	3	3	30235		Travel decent, forces a bit light; no stops
775-777	24	6VP	RJD	1	2	3	yes	4	3	22628	15:00	None; displacement good; forces light at full throw; stops several
778-780	15	4VP	PD	1.25	3	4	yes	2.5	3	31561	15:07	Short throw. On stop first run, but then learned not to do it. No unusual characteristics.
781-783	6	2HP	PD	2	2.5	2.5	yes	4	4	16179		Throw a little short and forces a little light for this task.
784-786	32	8VP	PD	3.5	1.5	3.5	questionable	6	6	18078	15:50	Way too light forces. On stops too much.
787-789	5	2HB	RJD	1	2	2.5	yes	3	3	42892	15:55	Forces too light; stops yes with high accel rates or large displacement-easy to hit stops
790-792	7	2VB	RJD	1	2.7	3	yes	3	2	40667		BO OK, gradient higher but not enough near end; stops occasional
793-795	17	5HB	RJD	1	3	3	yes	2	2	33573		BO not bad; forces non-linear; no stops
796-799	10	3HP	RJD	3	2	4	no	6	3	32054		Light forces with large phi slip to full rudder unintentionally
800-803	22	6HP	RJD	1	3	4	yes	2	2	21294		BO good, throw decent, forces little light, no stops
804-806	20	5VP	RJD	1	3	3	yes	2	2	21216	8:50	Feel system good, forces a bit heavier than others, bo nice, travel nice, some stops but appropropiately
807-809	8	2VP	RJD	2	2	3	no	6	6	20137		Lbeta not as good; workload higher and perf lower
810-812	12	3VP	RJD	1	1.8	3	yes	3	3	22652		BO very very low, touch pedal and changes one degree; even though short throw, rudder picked up wing and reduced work load
813-815	23	6VB	JH	1	3	3	yes	3	2	28575	10:00	None noted, no stops
816-818	8	2VP	JH	2	2	3	yes	4	3	20431		Short throw, continuous stops; light forces
819-821	21	6HB	JH	2	3	2	yes	2	2	27279		No; no stops
822-824	5	2HB	JH	2	2.5	2	yes	3	2	30042	10:55	None; no stops
825-827	12	3VP	RJD	1	2	3	yes	3	3	25089	11:00	NO unusual; stops number of times

828-830	11	3VB	RJD	3	1	3.5	no	7	5	50619		light forces; routinely hit stops
831-833	19	5VB	RJD	1	3	3.5	yes	2	2	28990		none; liked it, no stops
834-836	18	5HP	RJD	1	3.2	3.5	yes	3	3	19188		pretty nice; no stops unexpectedly
837-839	9	3HB	RJD	4	1	3.5	no	6	7	45568		short throws, often stops; difficulty keeping ball centered
840-842	15	4VB	RJD	1	3	3.5	yes	3	2	36290	12:00	no unusual except no idea near limit
843-845	25	7HB	RJD	1	3	2.5	yes	2	2	38607	13:07	Disregard run 843; none; BO higher(?); no stops
846-848	3	1VB	RJD	3.5	2.5	4	probably	5	5	41831		nothing out of ordinary; stops couple of time
849-851	13	4HB	RJD	2	2.5	2.5	yes	7	4	45168		didn't have feedback on hitting pedal stops;
852-854	27	7VB	RJD	2	2.5	3	yes	4.5	4.5	44313	13:50	Hit stops more to left; bo good, nothing peculiar
855-858	6	2HP	JH	2	2.5	1	yes	4	4	15585	13:55	short throw; stops yes
859-861	24	6VP	JH	1	3	1	yes	3	3	15338		like the throw; gradients & bo good
862-864	7	2VB	JH	1.5	3.5	2	yes	3	2	30001		heavier force; stops no
865-868	2	1HP	RJD	2.5	2	3	yes	5.5	5	40007	14:30	light forces, throw OK; stops yes and no idea I was getting there
869-871	3	1VB	RJD	4	1.5	3.5	no	8	8	43463		870 shouldn't count; stops yes a few intentionally
872-874	14	4HP	RJD	1	2.5	3	yes	4	5	21537		nothing stood out; stops almost always
875-877	28	7VP	RJD	1	3	3	yes	3	4	29267		nothing odd; stops all the time and knew when approaching
878-881	16	4VP	RJD	1	2.5	2.5	yes	3	4	18975		decent throw, some forces at end; number of stops
882-884	1	1HB	RJD	4	1	2	no	7	7	44554		light force, short throw, easy to hit stop chasing ball
885-887	26	7HP	RJD	1	3	3.5	yes	3	3	32385	15:40	displacement good, force good,
888-890	7	2VB	JH	1	2.5	3	yes	2	2	27789	15:45	very short throw, no stops
891-893	22	6HP	JH	2	3.5	3	no	6	6	15233		higher force with larger throw; stops yes
894-896	11	3VB	JH	4	2	3	no	5	6	31178		lo bo, low force, short throw, no stops
897-899	19	5VB	JH	1	3.5	3	yes	3	2	27094		mod bo, strong gradient, large throw, no stops
900-902	18	5HP	JH	1	3	2	yes	3	3	15846		feel system good, bo high, throw longer; no stops
903-905	9	3HB	JH	1	2	2	yes	2	2	27867		no unusual, light forces, good effectiveness, no stops
906-908	16	4VP	JH	1	3	2	yes	2	2	21543		nothing to note; occasional stops
909-911	27	7VB	JH	1	3	2	yes	2	2	26271	16:55	light bo but force gradient pretty good, stops soft and spongy

912-914	4	1VP	JH	1	2.5	2	yes	4	4	19671	8:15	LIGHT BO, LIGHT GRAD., SHORT THROW, FREQUENT STOPS
915-917	17	5HB	JH	1	3	2	yes	2	2	26561		large throw with high gradient but did not use much throw; no stops
918-920	14	4HP	JH	1	3.5	1	yes	3	3	15507		strong grad., short throw, frequent stops
921-923	25	7HB	JH	1	3	2	yes	2	2	26858	8:50	good force grad, mod throw, no stops
924-926	10	3HP	PD	3	1	3	questionable	6	5.5	21781	8:55	Not much motion but there was some. Very easy to hit the stop
927-929	16	4VP	PD	1.5	2.75	4.5	yes	2.5	2	15930		Strong motion cues on this one. Better yaw damper resulted in lower workload. Hit stops but appropriate.
930-933	36	9VP	PD	2	3.5	2.5	yes	4	5	17914	9:30	Higher breakout than last one. Did not go to stops many times Did not like it
934-936	28	7VP	JH	2	3	2	yes	4	4	23677	9:35	pleasant forces, light bo, reasonable grad., stops several
937-939	9	3HB	JH	2	2.5	1.5	yes	2	2	25934		light bo and grad with short throw, no stops
940-942	22	6HP	JH	1	4	3.5	questionable	6	5	14541		higher bo, high grad, high throw, some stops
943-946	10	3HP	JH	1	2.5	3.5	yes	4	4	21095		light grad, short throw, freq stops
947-949	12	3VP	JH	2	2.5	3	yes	4	4	20972	10:25	good grad, fairly short throw, frequent stops, but could use greater throw
950-952	43	11VB	PD	1	3	4	yes	2.5	3	30539	10:30	Force + motion helped keep me off stops.
953-955	5	2HB	PD	2	2	1.5	yes	4	4.5	32307		Not adequate motion - mostly visual. Short throw and forces a little light. Did not hit stops.
956-958	7	2VB	PD	1	3	4	yes	2	2.5	29910	10:57	Pedal throw feels good. Good motion cues, prevent me from using too much pedal. No tendency to hit stops - a good thing.
959-961	20	5VP	JH	1	3.5	2	yes	4	3	13776	11:00	First run after discussion re helo background. No stops anytime.
962-964	26	7HP	JH	1	2.5	1	yes	3	3	23896		pleasant forces, light bo, good grad., mod throw, no stops
965-967	1	1HB	JH	2	2.5	2	yes	2	2	30692		light bo, light grad, shorter throw, no stops
968-970	35	9VB	JH	1	3.5	3	yes	3	3	25967		mod bo, short throw, no stops
971-973	2	1HP	JH	1.5	2	2	no	5	4	20156	11:48	forces light but comfort, light bo, light grad, short throw, with numerous stops
974-976	39	10VB	JH	1.5	2	2	yes	2.5	2	26055	13:15	light bo, light grad, short throw; no stops

977-979	3	1VB	JH	1	3	2	yes	2	2	27248		light bo, med force gradient, short throw and didn't use that much rudder; no stops
980-982	26	7HP	JH	1	4	2	yes	4	3	21012		heavier, high bo, high grad, mod throw; no stops
983-985	15	4VB	JH	1	3.5	2	yes	2	2	27821		high bo, high grad, short throw; no stops; easy to use
986-988	40	10VP	JH	1	3.5	3	yes	4	3	16286	15:55	mod bo; mod force grad; stops few times but not strongly
989-991	9	3HB	PD	3.5	1.5	1.5	no	6	6	36298	14:03	Gradients too light. Throw too short.
992-994	14	4HP	PD	2	2.5	2.5	questionable	4	5	18522		Motion an indicator but little effect on rudder usage. Forces a bit light, but okay
995-997	20	5VP	PD	1	3	4	yes	2	2.5	13564		Could nail correct amount of rudder easily - nearly perfect
998-1000	15	4VP	PD	1	3	4.5	yes	2.5	2.5	32577	14:50	Compare to config 14. Short throw, could aggressively keep ball centered. Did a good job
1001-1003	13	4HB	JH	1	3	2	yes	2.5	2	27463	14:55	Mod bo, mod gradient, short to mod throw, did not feel stops
1004-1006	40	10VP	JH	1	2	3	yes	4	3	18335		light bo & grad, short to mod throw; stops once or twice
1007-1009	31	8VB	JH	2.5	2	2.5	yes	4	3	26760		light bo & grad with short throw; no stops
1010-1012	36	9VP	JH	1	4	2.5	yes	4	4	12306	15:32	hi bo, hi force, short throw; touch the stops
1013-1015	22	6HP	PD	1.5	2	2	yes	3	3	16391	15:37	Forces could be a little higher
1016-1018	12	3VP	PD	4.5	1	4	no	6	6	19628		YD study. Tell pilot what he is flying. Workload double from last run. Hard to nail precise amount of rudder needed. Hi breakout and low gradient leads to overcontrol
1019-1021	40	10VP	PD	2.5	1.5	4	questionable	5	5	20474	16:10	Cannot tell YD change from fam runs. During run, workload is lower. Much better behaved with this yaw damper. Hit stops less often than 3VP
1022-1024	44	11VP	JH	1	3.5	3	yes	4	3	12839	16:16	good & precise; higher bo with short to med throw; stops a couple of times not persistent
1025-1027	43	11VB	JH	2	2.5	2	yes	4	4	27213		Mod bo, mod gradient, short to mod throw, did not feel stops
1028-1030	32	8VP	JH	1.5	2.5	2.5	yes	4	3	15614	16:50	light to mod bo, lght to mod grad, short throw; felt stops a few times

1031-1033	13	4HB	PD	2.5	2	1.5	yes	4	6	36565	9:05	Feel I am a lttle behind it. Short throw and light to moderate forces led to overcontrol. Low motion cues are a factor. Lots of stops
1034-1036	15	4VB	PD	1	2.5	4	yes	2.5	3	30018		Perception is that I can track better.
1037-1039	11	3VB	PD	4	1	4	no	7	6	35174		Very hard to get interim rudder postion - rudder forces too light. Hit stops inadvertently and too soon.
1040-1042	39	10VB	PD	4	1	4	questionable	6	5	28465		Still very light feel. YDB smoother and overall workload was less than with YD A. On stops once or twice.
1043-1045	20	5VP	PD	1	3	3.5	yes	2	2	15868		Do to compare with Kcs=0. Told pilot case 5. Don't have to think about it - rudder very natural.
1046-1048	20	5VP	PD	1.5	3	3.5	yes	3	3	16783	10:10	KCS = 0. Initial impression is that this is NOT an improvement. Feels a little more sensitive. Hitting stops less in big gusts. Workload is higher - more sensitive and responsive - not needed
1049-1051	28	7VP	RH	1	3	3.5	yes	2	3	21868	10:20	harmonized forces, limit not a bother; nothing unusual; stops once or twice as appropriate
1052-1054	22	6HP	RH	1	3	2	yes	2	3	15304		large throw with nice forces; none - std throw and nicely tailored forces; stops only as necessary; larger throw physically works u harder but appropriate to large airplane
1055-1057	11	3VB	RH	4	1	4.5	no	7	7.5	43672		"back gain way down"; b.o. not much; unpredictable response; very lt force with lo gradient ; stops lots
1058-1060	2	1HP	RH	4	1	2	no	7	7	18242		lt forces & short throw; b.o. not as objectionable as previous; more predictable and almost an no/off system; stops all the time inadvertently
1061-1063	32	8VP	RH	4	1.5	3.5	no	6	6	18422		"feels like the same system" but it has YD B so dif YD hard to detect without advanced knowledge. Felt like less b.o.; stops inadvertently.
1064-1066	18	5HP	RH	1	3	2.5	yes	2	3	16196		conventional system; stops when desired
1067-1069	39	10VB	RH	4	1	4.5	no	7	7	36182	11:35	"feels like b.o. higher" - again, YD B manifests itself as a perceived change in b.o. lt K, shrt throw, no distinct back to more b.o.

1070-1072	4	1VP	RH	4	3.5	4	no	5.5	5.5	16033	12:45	LT forces, low b.o. which is a good thing; might be tuning up to these short throw systems
1073-1075	24	6VP	RH	1	3	3.5	yes	2.5	3	14943		long throw, mod hi forces, tend to stay out of loop; stops only when wanted to
1076-1078	31	8VB	RH	4	1.5	4	no	5.5	6	36804		short throw, lite force, easy to get carried away; not that much b.o.but that's not the issue; hit stops a lot inadvertently
1079-1081	35	9VB	RH	2.25	2.7	4	yes	3	2.5	31985	13:25	short throw but much better forces; no inadvert. Full throw as with the lite forces
1082-1084	22	6HP	PD	1.5	3	2	yes	3	3	13379	13:35	Long throw, good force gradient. Slight tendency to overcontrol on small inputs
1085-1087	24	6VP	PD	1.1	3	2	yes	2.5	2.5	15629		Similar to last one but without tendency to overshoot
1088-1090	6	2HP	PD	2.5	1.5	2	no	6	6	14420	14:07	Was a tendency to overcontrol with rudder
1091-1093	44	11VP	RH	2.3	2.5	2.5	yes	3	4	16211	14:10	short throw but forces good; not a bad system; stops on intention
1094-1096	27	7VB	RH	1.5	3	3.5	yes	2.5	2	35009		intermediate displacement, no unusual charact; no stops
1097-1099	36	9VP	RH	2.5	2.6	2	yes	4	4	12595		limited throw but good forces; stops yes but when required
1100-1102	43	11VB	RH	2.25	2.5	4	yes	3	3	31289	14:50	short throw, mod forces; stops only when wanted to
1103-1105	7	2VB	PD	1.5	2.75	4.5	yes	3	3	30755	15:55	short throw but good gradient. No stops.

Table B-2. Run Log

		Gordon Hardy		Paul Desrochers		Roger Hoh		Brian Watson		Gene Arnold		Jim Moore		Howard Pincus	
		Pilot GH		Pilot PD		Pilot RH		Pilot BW		Pilot GA		Pilot JM (6)		Pilot HP (7)	
Config #	Case ID	Run #	Case ID	Run #	Case ID	Run #	Case ID	Run #	Case ID	Run #	Case ID	Run #	Case ID	Run #	Case ID
1	1HB	227-229	1HB	706	1HB	748	1HB	66-68	1HB	164-166	1HB		1HB		1HB
2	1HP		1HP	727	1HP	1058	1HP	27 - 29	1HP	173-175	1HP		1HP		1HP
3	1VB	266-268	1VB	691	1VB	679	1VB	78-80	1VB	170-172	1VB		1VB		1VB
4	1VP	209-211	1VP	709	1VP	1070	1VP	6 - 8	1VP	128-130, 167-169	1VP		1VP		1VP
5	2HB		2HB	45; 646, 658	2HB	n/a	2HB	84-86	2HB	200-202	2HB	290-292, 417-419	2HB	326, 429	2HB
6	2HP		2HP	781, 1088, 1103	2HP	n/a	2HP	90-93	2HP	134-136	2HP	323-325	2HP	311	2HP
7	2VB		2VB	670, 956	2VB	194	2VB	21 - 23	2VB	215-217	2VB	317-319	2VB	305	2VB
8	2VP		2VP	661	2VP	676	2VP	103-105	2VP	218-220	2VP	296-298, 423-425	2VP	332	2VP
9	3HB		3HB	567, 953, 989	3HB	721	3HB	97-99	3HB	182-185	3HB	338-340, 366-368	3HB	359, 402	3HB
10	3HP	619	3HP	924	3HP	n/a	3HP	12 - 14	3HP	221-223	3HP	396-398	3HP	353, 384	3HP
11	3VB	233-235	3VB	577	3VB	1055	3VB	69-71	3VB	137-139	3VB	375-377, 414-416	3VB	426	3VB
12	3VP	272-274	3VP	598	3VP	745	3VP	33-35	3VP	185-187	3VP	393-395	3VP	350, 381	3VP
13	4HB	269-271	4HB	1,031	4HB	n/a	4HB	36-38	4HB	122-124	4HB		4HB		4HB
14	4HP		4HP	48-50, 992	4HP	673	4HP	15-17, 113-115	4HP	239-241	4HP		4HP		4HP
15	4VB		4VB	1034	4VB	718	4VB	87-89, 119-121	4VB	245-247	4VB		4VB		4VB
16	4VP		4VP	778, 927, 998	4VP	191	4VP	100-102	4VP	251-253	4VP		4VP		4VP
17	5HB		5HB	158; 622, 643	5HB	n/a	5HB	39-41	5HB	197-199	5HB	399-401	5HB	356, 387, 411	5HB
18	5HP	236-238	5HP	176; 570	5HP	1064	5HP	81-83, 110-112	5HP	176-179	5HP	341-343, 367-371	5HP	362, 405	5HP
19	5VB	206-208	5VB	179; 574	5VB	287, 685	5VB	9-11, 60-62	5VB	131-133, 143 -145, 188-190	5VB	344-346, 372-374	5VB	408	5VB
20	5VP	230-232	5VP	511,615,959,951,043	5VP	682	5VP	42-44, 107-109	5VP	140-142	5VP	390-392	5VP	347, 378	5VP
21	6HB		6HB	658	6HB	n/a	6HB	18 - 20	6HB	224-226	6HB	293-295, 420-422	6HB	329, 423	6HB
22	6HP		6HP	667, 1082	6HP	1052	6HP	57-59	6HP	245-247	6HP	314-316	6HP	302	6HP
23	6VB		6VB	664	6VB	742	6VB	30-32	6VB	242-244	6VB	299-301	6VB	335	6VB
24	6VP		6VP	740, 1085	6VP	1070	6VP	72-74	6VP	125-127	6VP	320-322	6VP	308	6VP
25	7HB		7HB	697	7HB	278	7HB	54-56	7HB	152-154	7HB		7HB		7HB
26	7HP		7HP	730	7HP	n/a	7HP	63-65	7HP	146-148	7HP		7HP		7HP
27	7VB		7VB	700	7VB	1094	7VB	94-96	7VB	155-157	7VB		7VB		7VB
28	7VP		7VP	715, 736	7VP	1049	7VP	24 - 26	7VP	149-151	7VP		7VP		7VP

= Case No H or V = Hex or VMS P or B = Pgust or Beta gust

APPENDIX C—PILOT BRIEFING

Excerpts from the written briefing sent to all pilots is given below.

VMS Protocol

All visitors to the NASA Ames Research Center must receive temporary visitor badges. Some government agency badges will suffice (e.g. FAA badge). Badging is conducted immediately adjacent to the main entry gate at Security. The security office will supply a map and directions to the VMS building. Parking is available adjacent to the VMS building.

A safety briefing for the operation of the VMS will be conducted prior to the first session of each test pilot by qualified personnel. An Authorization card must be completed and signed by the guest pilot. Pilots will be in constant communication with the simulator operators at all times via intercom. Rest breaks will be taken on an "as-needed" basis. In most cases, two subject test pilots may be scheduled simultaneously and will trade out testing on a daily schedule suited to their individual needs and time constraints. A pre-flight briefing and de-brief will be conducted by testing staff.

General

The simulated aircraft is a generic transport-category swept-wing twin-engined jet aircraft with a conventional planform. Weight is approximately 175,000 lb. with a nominal c.g. All other physical dimensions are not relevant to the study. The "cockpit" has a conventional yoke and rudder pedals, and the displays are a generic PFD with an EFIS version of "steam-era" engine gauges. There is no autopilot, flight director nor autothrottles. The initial flight condition is steady level flight at 250 KIAS, 2000' MSL on a heading of 300 degrees. Each task will take approximately 75 seconds. The pilot shall fly at least 3 consecutive tasks in the same configuration prior to assigning an opinion using the subjective rating scales and questionnaire in the appendix. The Scales will be available to the pilot in the VMS cab.

A large matrix of different directional control systems for each of the two motion capabilities of the VMS will be presented to the pilot at random. It is not necessary and perhaps undesirable for the pilot to know in advance the configuration that is being tested. Performance data for each run will also be recorded automatically by the simulation for analysis, and will not be revealed to the pilot after each run. This is to avoid interjecting any preconceived notions into the data.

Piloting Tasks

These semi-realistic piloting tasks are designed to require aggressive rudder use and are not necessarily indicative of real-world flying. The testing premise is in recognition that pilots of transport aircraft are almost exclusively trained to only use rudder for crosswind take-offs and landings, engine-out procedures and some flight control malfunctions. However, if in a critical situation and the pilot does have to use rudder aggressively, the aircraft response must be predictable, and there should be no tendency for overcontrol, PIO, or control surface reversals that could overstress the vertical stabilizer. The tasks are designed to force use of the rudder in order to expose deficiencies in aircraft handling qualities in the directional axis.

Each task will require a return to trim condition, and some pilot action will be required to set trim e.g. throttles. Cockpit displays are provided to assist in trimming.

Experiment #1: Yaw Gust

The task is to minimize lateral accelerations, as indicated by deviations of the sideslip indicator. This is to be accomplished in the presence of a series of random lateral gust disturbances, some of which are very large and will require aggressive rudder use. Due to aerodynamic dihedral effects, some roll will be encountered and should be countered with wheel. The lateral gusts will cause the sideslip indicator to move actively, and the pilot is required to recapture and contain the indicator to within desired and adequate performance standards. The pilot's rating should be based on his or her ability to reacquire and contain the ball after the gust. Gusts will be generated continuously throughout the data run after an initial 5 seconds quiescent period.

Two sideslip indicators are available. A legacy sideslip ball is located immediately below the PFD and the conventional EFIS "doghouse" display is located on the sky-pointer. Either symbol can be used, but our experience is that the sideslip ball is much easier to interpret and you are encouraged to use it as the primary indicator.

Performance targets are:

Task	Desired	Adequate
Primary	Sideslip Indicator deflection < ½ unit most of the time	Sideslip Indicator deflection < 1 unit most of the time
Secondary	Heading +/- 10 deg Altitude +/- 100' Airspeed +/- 10 KIAS	Heading +/-20 deg Altitude +/- 200' Airspeed +/- 20 KIAS

Please consider only the primary task when assigning pilot ratings. The intent of the secondary tasks is to maintain the flight condition constant and to avoid 100% fixation on the sideslip indicator. Some excursions of the sideslip indicator out of desired are inevitable. Consider your performance as desired if you are able to quickly bring the ball back to within tolerance.

It will be necessary to increase power slightly to avoid slowing down during the run. If you deviate significantly from desired performance on the secondary tasks, make additional runs as necessary to remain in desired performance most of the time. Occasional excursions out of desired are not considered to be a problem.

Experiment #2: Rolling Gusts

The task is to maintain heading in the presence of random rolling gusts, some of which are of sufficiently large amplitude so as to exceed the aileron control power of the test aircraft. In some gusts, rudder will be required to assist in roll control so that the bank angles do not become sufficiently large and/or sustained so as to exceed the heading tolerance of +/- 10 deg. Gusts will be generated continuously throughout the data run after an initial 5 seconds quiescent period.

Performance targets are:

Task	Desired	Adequate
Primary	Heading +/- 10 deg	Heading +/- 20 deg
Secondary	Altitude +/- 100’ Airspeed +/- 10 KIAS	Altitude +/- 200’ Airspeed +/- 20 KIAS

When assigning ratings, please consider only the primary task. If you deviate significantly from desired performance on the secondary tasks, make additional runs as necessary to remain in desired performance most of the time. Occasional excursions out of desired are not considered to be a problem.

Data

The data will consist of pilot ratings and commentary as well as quantitative data such as time histories and discrete parameters (e.g., RMS pedal deflection and maximum force on the vertical stabilizer). For this Phase 1 effort, the primary objective of the data analysis will be to determine the lateral motion that is necessary to obtain valid results using ground-based simulators. The secondary objective of the data analysis will be to obtain initial results for the most common types of rudder flight control systems used on transport aircraft.

Qualitative Pilot Ratings

Experience has shown that when systematically varying aircraft handling qualities, care must be taken to provide the necessary adaptation time to achieve a valid evaluation following a change in configuration. For example, after flying a series of runs with a good configuration, the pilot may initially have problems flying a new equally good configuration. That is because the pilot must adapt his or her control strategy to be compatible with the new configuration. Normally, full adaptation occurs in three runs. For that reason, the pilot ratings and commentary should only be taken after three or more runs have been accomplished.

Pilots will be asked to use the rating scales and the questionnaire that is given in the appendix after completion of a minimum of three runs. Since the tasks have been designed to require aggressive rudder use, it is expected that any deficiencies in the directional axis will be reflected in the ratings.

APPENDIX D—REVIEW OF RUDDER-RELATED ACCIDENTS AND INCIDENTS

D.1 Rudder Study Accident/Incident Categorization

Table D-1 shows a categorization of global aircraft accidents and incidents in which the rudder and/or its usage was identified in the documentation as a causal factor, or mentioned as a probable cause or contributing factor. Sources vary from detailed accident reports by the National Transportation Safety Board (NTSB) to vague information from foreign authorities and/or foreign accident databases. This study does not guarantee a comprehensive review of all data available, but rather a thorough investigation of data readily available and biased towards that produced by national review boards. In some cases, the originating agency had subdivided the events by causal factors, but most often by date or aircraft type.

The data itself had to be interpreted to categorize the potential errors and ensure that the rudder and/or its handling was a significant factor in the event. The decision as to whether increased/adequate training would have been beneficial in preventing the event is purely arbitrary by the authors, as is the interpretation of primary and secondary causal factors. Events are entered chronologically.

D.2 Categorization of Accidents and Incidents (full descriptions)

1. Lack of Adequate Cueing

    - Applied wrong rudder
    - Aileron-rudder coordination issues
    - Did not recognize need for rudder in a timely fashion
    - Did not recognize rudder mis-trim
    - Did not recognize inadvertent rudder input or need to remove rudder input

2. Poor Feel System Characteristics and Aircraft Dynamics

    - Over-control
    - Under-control—did not apply sufficient rudder
    - Rudder PIO

Table D-1. Summary of Rudder-Related Accidents and Incidents

Description of Event or Identifier	Type	Date	More Training Required	1. Lack of Adequate Cueing					2. Poor Feel System Characteristics/Dynamics		
				Wrong Rudder	Ail-Rudder	Late Rudder	Rudder Mis-Trim	Inadvert. Rudder	Over-Control	Under-Control	Rudder PIO
Incorrect rt rud actuator caused force imbal & non-linear displacement. MX.	TU134	6/24/03	Y							P	
American Flt 587 – lrg ampl & incorrect rud deflect out of phase with a/c in wake turb	A300-6	11/12/01	Y					S	P		S
Fail to maintain dir control after engine failure.	BAE J-3101	5/21/00	Y			P				S	
Rud jam full on taxi; after t/o yawed left and crashed.	IL114	12/5/99	Y					P			
Rud trim runaway caused upset at a/p disconnect. Limit load exceeded on recovery by pilot.	A300-6	11/99	Y						P		
Uncommand rudder motion and high rudder forces -YD	A300-6	5/11/99						P			
Sim e/o t/o; lt wing hit runway	ERJ-145	2/11/98	Y			P					
American Flt 903 – a/c stalled in hld entry with subs'q'nt lrg amp rud inputs	A300-6	5/12/97	Y		S				P		
Sudden left yaw at rotation caused left wing impact	B18	2/22/97	Y			P					
Dir cntl problem on t/o roll; airborne, yawed right and descended into frzn lake.	C-208	1/3/97	Y				P				
Uncommand No.2 t/r deployed at 90' AFL; a/c yawed rt until hit building	F-100	10/31/96	Y			P					

P = primary; S = secondary

Table D-1. Summary of Rudder-Related Accidents and Incidents (Continued)

Description of Event or Identifier	Type	Date	More Training Required	1. Lack of Adequate Cueing					2. Poor Feel System Characteristics/Dynamics		
				Wrong Rudder	Ail-Rudder	Late Rudder	Rudder Mis-Trim	Inadvert. Rudder	Over-Control	Wrong Rudder	Ail-Rudder
Loss of rudder control on final; Y/D hardover but pilot overcontrol on recovery	737-200	6/10/96							P		
Wake turb behind 757 on app; added "pwr and full rud" for recovery	MD-80	04/96	Y						P		
Loss of dir cntrl with e/o after t/o	B58	9/27/95	Y			P					
PIO induced with gsty x-wnd and x-cntrl of surfaces in C3	A320	4/27/95	Y		P						
"Uncomm'd" rudder h'over on app with sub stall	B-737-3	9/8/94		P							
G/A with 3 successive stalls; loss of control with repetitive rudded inputs (src:NTSB)	A310	9/94	Y						P		
Plt applied wrong rud dur sim e/o t/o	B-737-2	3/8/94	Y	P							
On g/a, plt resisted a/p and upon diseng pitched up, stalled 4 times with large amp surface inputs all axes	A310-3 (Interflug)	2/11/91	Y		S				S		
Full rud trim on t/o; aborted late and left prep surface	B-737-4	9/20/89	Y				P				
Rudder "jerk" at 250 KIAS caused 1.11 limit load	A300-6	5/89						P			
No.4 eng "hung" @ idle at alt with a/p eng. Plt lost cntrl at a/p diseng.	B-747SP	2/19/85	Y		S	P					

P = primary; S = secondary

Table D-1. Summary of Rudder-Related Accidents and Incidents (Continued)

Description of Event or Identifier	Type	Date	More Training Required	1. Lack of Adequate Cueing					2. Poor Feel System Characteristics/Dynamics		
				Wrong Rudder	Ail-Rudder	Late Rudder	Rudder Mis-Trim	Inadvert. Rudder	Over-Control	Wrong Rudder	Ail-Rudder
Wrong rud input 10 s following eng failure and 4 s correct rudder;	DC9-14 (Midwest Express)	9/6/85	Y	P							
Lost dir cntl on sim e/o t/o	LR35	12/20/84	Y			P					
Sim e/o at t/o; airborne, a/c entered spin and crashed	F-27	2/8/80	Y			P					
Uncommand rudder h'over	IL14	4/5/77						P			
A/c yawed and crashed on 3/eng g/a following rudder act support fail	B-720 (Western Airlines)	3/31/71	Y			P					
Rudder lock eng; crashed on t/o	IL18	6/5/70									
Sim e/o t/o; plt applied wrong rudder	HS-125	7/20/70	Y	P							S
On g/a, No. 4 left at idle but hyd fail prevent gear & flap ret	B-707	7/26/69	Y			P					
Rudder lock eng; crashed on t/o	IL18	8/27/66									
Crash on t/o with rud cntrls crossed by MX	TU104	10/25/62									
Rud cntl malf caused yaw, slip and roll; crashed	B-707	3/1/62									P?
Crew rpt "rud locked"; a/c crashed after two landing attempts; spin	C46	5/16/48	Y								
SUMMARY		34 events	25	4	4	10	2	4	7	2	3

P = primary; S = secondary

Sources:
NTSB
FAA
NASA Safety Reporting System
Spanish Civil Aviation Authority Accident Investigation Board
Canadian Aviation Safety Board
Air Accident Investigation Branch (UK)
Aviation Safety Network
Airclaims