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A Piloted Simulator Evaluation of Transport Aircraft Rudder Pedal Force/Feel Characteristics

Eric C. Stewart
Langley Research Center, Hampton, Virginia

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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NOMENCLATURE

V	airspeed, knots
h	altitude above runway, ft
β	angle of sideslip, deg (positive to right)
P_{xy}	cross spectra (lb-deg/sec/Hz) of pedal force and heading
E_f	final steady crosswind component, knots
ψ	heading relative to runway centerline, deg (positive for nose right)
E_o	initial steady crosswind component, knots
a_{y_ps}	lateral acceleration at pilot's station, g units (positive to right)
Y	lateral displacement from runway centerline, ft (positive to the right)
θ	pitch attitude, deg (positive nose up)
δ_p	rudder pedal deflection, inches (positive to left)
F_p	rudder pedal force, pounds (positive to left)
E	total crosswind (combined steady and random winds), feet/second (positive from right)
AGL	above ground level
B	breakout force, (e.g. +/-10 pounds)
b_i	coefficients of response surface equation, i=1,2,3….10
CCD	Central Composite Design (of experiments)
C-H	Cooper-Harper
FAA	Federal Aviation Administration
$h_{\copyright}$	altitude at which the crosswind shear is initiated, ft
IFD	Integration Flight Deck (Langley Simulator)
M	maximum pedal force (force at maximum pedal travel, (e.g. +/-100 lbs, positive to the left)
NTSB	National Transportation Safety Board
PIO	pilot induced (or involved) oscillation
PR	pilot rating using Cooper-Harper pilot rating scale
PS	peak values of cross spectra for frequencies greater than 0.2 Hz
r	yaw rate, deg/sec (positive to the right)
Stdev	standard deviation
X	limits of pedal travel (e.g. +/- 2 inches),
X_1, X_2, X_3	Normalized axes of Central Composite Design
Δt	time increment during wind shear, seconds

ABSTRACT

A piloted simulation study has been conducted in a fixed-base research simulator to assess the directional handling qualities for various rudder pedal feel characteristics for commercial transport airplanes. That is, the effects of static pedal force at maximum pedal travel, breakout force, and maximum pedal travel on handling qualities were studied. An artificial maneuver with a severe lateral wind shear and requiring runway tracking at an altitude of 50 feet in a crosswind was used to fully exercise the rudder pedals. Twelve active airline pilots voluntarily participated in the study and flew approximately 500 maneuvers. The pilots rated the maneuver performance with various rudder pedal feel characteristics using the Cooper-Harper rating scale. The test matrix had 15 unique combinations of the 3 static pedal feel characteristics. A 10-term, second-order equation for the Cooper-Harper pilot rating as a function of the 3 independent pedal feel parameters was fit to the data. The test matrix utilized a Central Composite Design that is very efficient for fitting an equation of this form. The equation was used to produce contour plots of constant pilot ratings as a function of two of the parameters with the third parameter held constant. These contour plots showed regions of good handling qualities as well as regions of degraded handling qualities. In addition, a numerical equation solver was used to predict the optimum parameter values (those with the lowest pilot rating). Quantitative pilot performance data were also analyzed. This analysis found that the peak values of the cross power spectra of the pedal force and heading angle could be used to quantify the tendency toward directional pilot induced oscillations (PIO). Larger peak values of the cross power spectra were correlated with larger (degraded) Cooper-Harper pilot ratings. Thus, the subjective data (Cooper-Harper pilot ratings) were consistent with the objective data (peak values of the cross power spectra).

INTRODUCTION

Directional handling qualities of transport airplanes have long been neglected compared to longitudinal and lateral handling qualities. As a result, the Federal Aviation Administration's (FAA) quantitative certification requirements for rudder pedal feel characteristics are very limited [ref. 1]. For example, the maximum pedal force is limited to 150 pounds, but there is no requirement for breakout force or maximum travel. U.S. military handling qualities specifications [ref. 2], include a quantitative limit on the breakout force (no more than 14 pounds). However, there are still no guidelines as to the optimum combinations of the quantitative parameters describing the rudder pedal feel characteristics or the sensitivity of the handling qualities to off-optimum combinations. The lack of comprehensive criteria was highlighted in a recent National Transportation Safety Board (NTSB) accident report on a fatal accident of a commercial transport that revealed the possibility that certain combinations of travel and breakout forces, while not specifically covered in the certification requirements, might help induce PIOs [ref. 3]. One of the recommendations of that NTSB accident report was for the FAA to include a certification standard for safe handling qualities in the yaw axis. To develop this new certification standard, a systematic handling qualities research program is needed. Recent studies [ref. 4 and 5], have begun to fill the need for data to base the certification standards on. However, more research is needed to develop criteria to apply to a practical system. Other work [ref. 6], has developed some simple indexes that define maximum limits of pedal feel characteristics. However, optimum characteristics and sensitivity to changes about the optimum are not specified. In addition, these indexes are demonstrated using the results from desktop simulations of limited realism.

The present study is intended to be an additional step in the development of a directional handling qualities database and the production of preliminary estimates of acceptable pedal feel characteristics. Tests were conducted in a fixed-base simulator for a medium-sized commercial transport with two engines mounted under the wings. An artificial piloting task that required multiple rudder pedal inputs was developed specifically for the purposes of this research. Twelve volunteer airline pilots performed the artificial maneuver, which consisted of a simulated manual approach to a runway in a crosswind with random turbulence. A severe random lateral wind shear was introduced near the ground that ordinarily would cause the pilot to execute a go-around. However, the pilot was instructed to neither execute a go-around nor attempt a landing. Instead, the pilot was instructed to level off at about 50 feet above the ground, correct any lateral offsets from the runway centerline, and then track the remaining runway in a de-crabbed, cross-controlled state. After each maneuver the pilot rated the airplane handling qualities using the Cooper-Harper (C-H) pilot rating scale.

A simple and highly effective test matrix called a Central Composite Design (CCD) was used to minimize the number of simulation tests required. This design is efficient when used with a 10-term, second-order response surface equation with three independent research variables [ref. 7]. With this test matrix each maneuver was conducted with one of 15 unique combinations of maximum force, breakout force, and maximum travel. The maximum force was varied between 30 and 150 pounds; the breakout force was varied between 3 and 50 pounds, and the maximum travel was varied between ±1 and ±4 inches.

The ten coefficients of the response surface equation estimating the C-H rating as a function of the three research variables were determined in a least squares sense. The ten terms included a constant, the linear variations of the three research variables, their interaction terms, and their squares. The equation was then used to produce contour plots of constant pilot ratings as a function of two of the parameters with the third parameter held constant. These contour plots showed regions of good handling qualities as well as regions of degraded handling qualities. In addition, a numerical equation solver was used to predict the optimum parameter values (those with the lowest pilot rating).

To supplement the subjective C-H pilot ratings, quantitative data such as tracking error and pilot inputs were recorded and analyzed. Various measures of pilot performance and Pilot Induced Oscillation (PIO) tendencies were explored. The most fruitful measure was the peak value of the cross power spectra between pilot input such as pedal force and airplane response such as heading. A response surface equation of the same form as that for the C-H ratings was used to produce contour plots and optimum parameter values using the same procedures used for the qualitative C-H ratings. The quantitative peak cross spectra data were in general agreement with the qualitative C-H ratings.

Description of Simulator

The Langley Integration Flight Deck (IFD) fixed-based simulator, shown in Figures 1 and 2, was used for all tests reported in this paper. The simulator represented a medium size commercial transport with two engines mounted under the wings and a weight of approximately 180,000 pounds. A conventional wheel and column control, rudder pedals, and twin engine throttles were provided. The simulation used a high fidelity, 6-degree-of-freedom, non-linear math model similar to that in a Level D commercial transport training simulator. Included in the simulation were non-linear models of the cable and hydraulic actuator systems for the pitch, roll, and yaw controls. In addition, a conventional yaw damper for transport airplanes was simulated to suppress the lightly-damped Dutch roll response. The entire simulation was solved on a digital computer in real-time at a rate of 50 times per second. A representative time history of the transient directional response to a ramped, full rudder input is shown in Figure 3. These responses probably have an effect on the results of this study and should be compared to the responses of other simulation studies of directional handling qualities. They can also be used with the pilot ratings obtained in this study to estimate proposed handling qualities indexes [ref. 6].

Figure 1. Exterior view of fixed-base Langley Integration Flight Deck (IFD) Simulator.

Figure 2. Interior view of Langley IFD simulation cockpit. (Stereo) speakers were designed to provide a lateral acceleration cue.

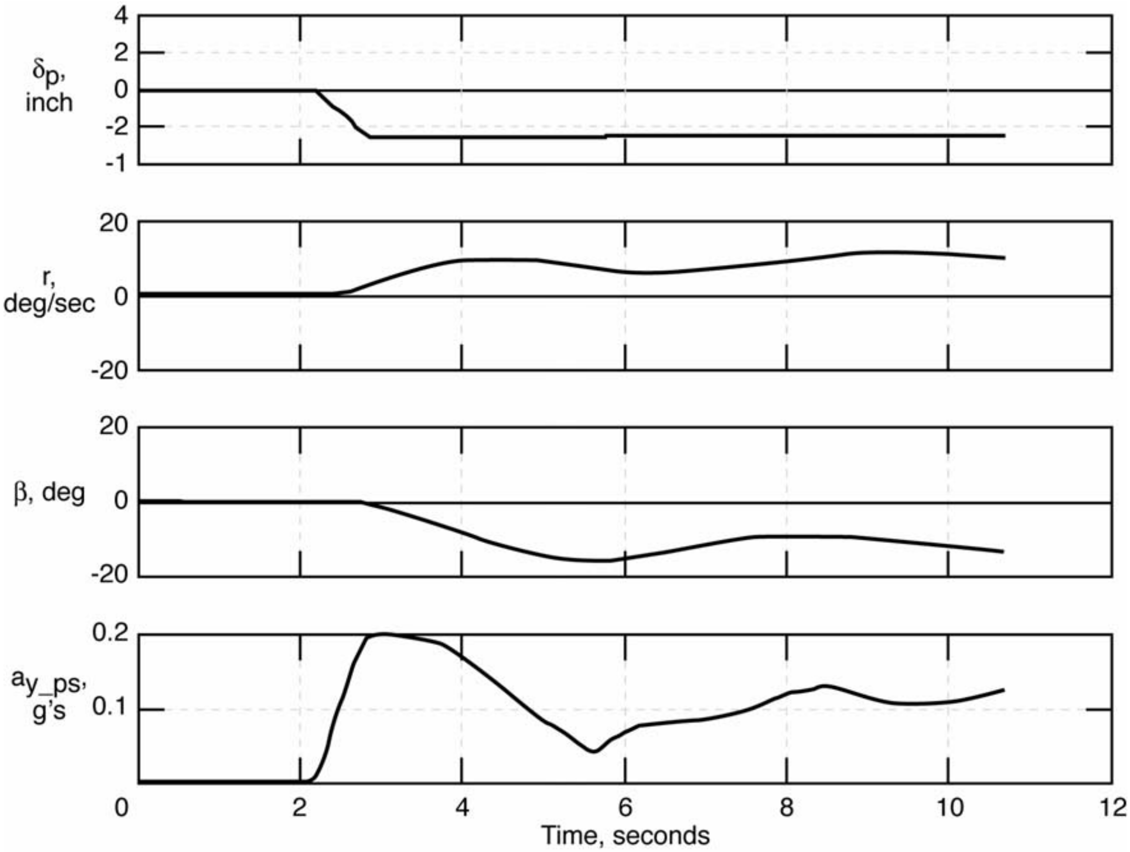


Figure 3. Transient response to a ramped, full rudder input at the test flight condition with Control Loader Combination #8.

The out-the-window visual scene was driven by a computer-generated-image system with an approximate 200-degree field of view. The average pure transport delay in the visual channel was determined to be approximately 72 ms. The visual database of the scene represented the Dallas/Fort Worth airport and its surrounding terrain. The study utilized runway 36L, which is 13,400 feet long and 150 feet wide. The visual database included all runways, taxiways, airport structures, and buildings. All tests were conducted in a simulated daylight environment with full visibility.

Hydraulic control loaders were provided for the wheel and column and varied the forces according to non-linear models of airspeed and other airplane and control system states. For the nearly-constant flight conditions of the present tests, the quasi-static control forces of the column and wheel are shown in Figures 4 and 5.

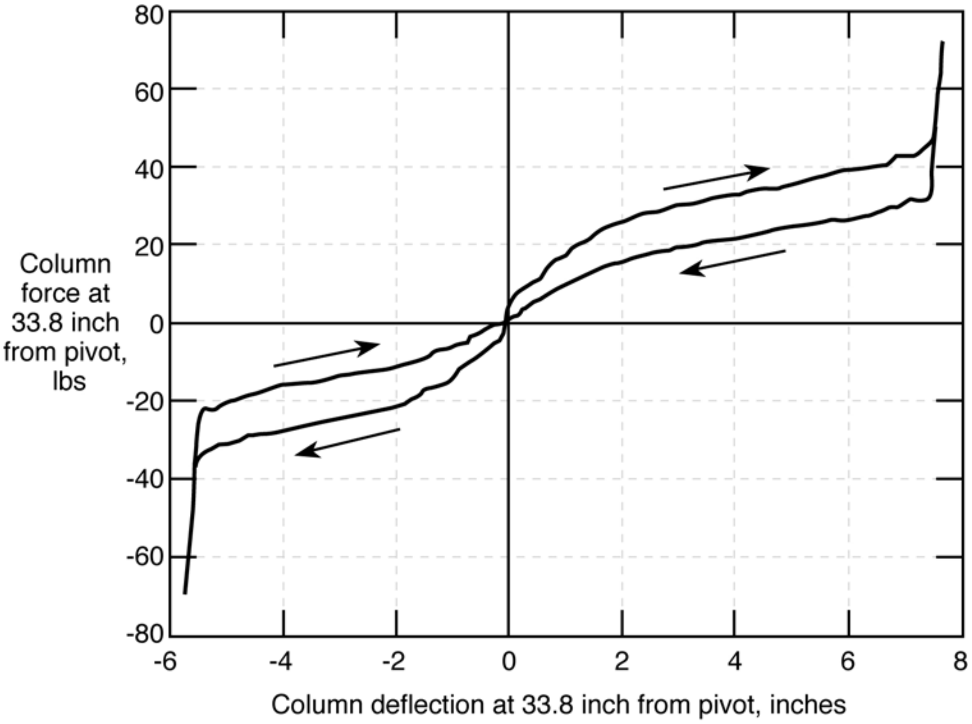


Figure 4. Quasi-static column forces.

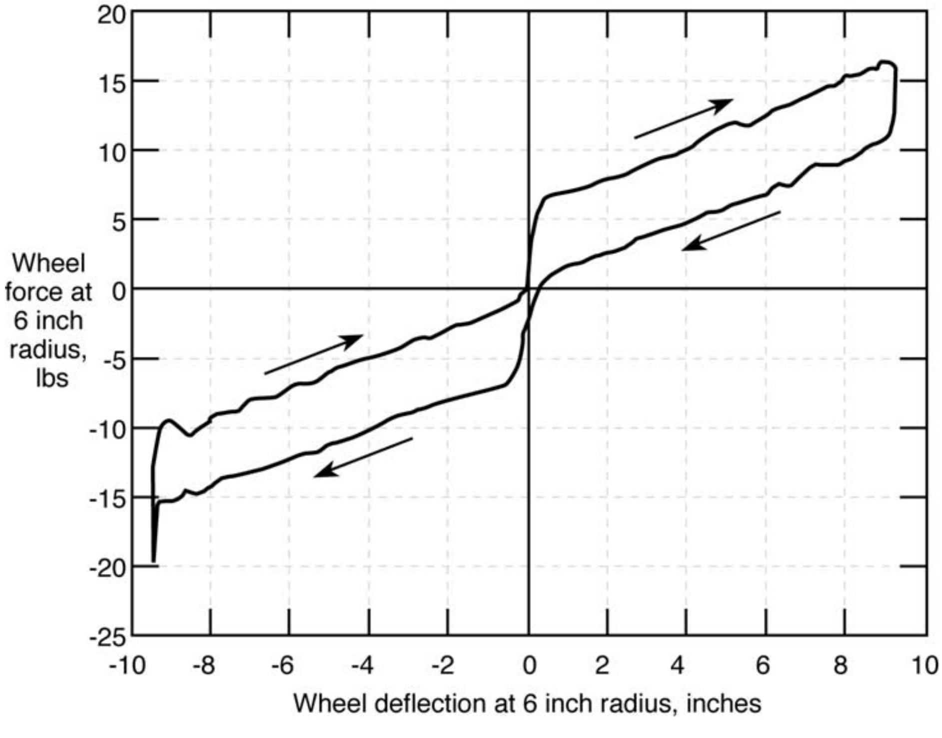


Figure 5. Quasi-static wheel forces.

Hydraulically-loaded rudder pedals were used for directional control. The pedals were actuated through slots in the cockpit floor rather than from the side or from above as in some commercial transport airplanes. The floor under the pedals was covered with carpet. The slots and carpet presented a potential resistance to pedal inputs compared to the smooth metal floor underneath the rudder pedals in most commercial transports. The pilots were advised to place their feet high on the pedals to eliminate any interference. The maximum force, breakout force, and maximum travel of the rudder pedals were varied from run to run but, unlike the wheel and column, were constant during a given run regardless of changing airspeed and flight conditions. The simulated pedal/rudder control system included a ratio changer to compensate for speed changes. The simulated mechanical gearing between the pedal and rudder ratio changer was modified so it changed whenever the pedal travel was changed in the course of the experiment. That is, the simulated mechanical gearing was programmed to change simultaneously with the changes in pedal travel so that the maximum rudder deflection normally attainable through the ratio changer was unaffected. In this way, only the pedal travel changed while the maximum rudder available at any given airspeed was a constant.

In an attempt to compensate for the lack of motion cues, an experimental sound system using stereo speakers mounted on the pilot's seat on either side of his/her head was installed, as shown in Figure 2. The sound level of a constant-pitch tone was made proportional to the lateral acceleration at the pilot's station. For zero acceleration there was no sound; but when the simulated pilot's station was accelerating to the right, the sound level increased in the right speaker; and when accelerating to the left, the sound level increased in the left speaker.

Data recordings (e.g. control inputs, attitudes, etc.) were made at 10 samples per second. Video and audio recordings of the pilot's actions and comments were also made.

TEST SUBJECTS

All the pilots who served as test subjects were volunteers who were paid a small stipend and expenses to participate. All were active airline pilots (either captain or first officer) with widely ranging levels of experience as seen in Table 1. The pilots were all currently flying airplanes with column and wheel controls similar to those in the simulator.

Table 1. Test Subjects

- All active airline pilots operating equipment with wheel/column controllers
- 7 males and 5 females
- 4 captains and 8 first officers
- Individual Total Hours: 5,500 to 20,000, average = 11,000
- Individual Hours in command: 500 to 18,500, average = 5,000
- 6 with military flying experience and 6 without military flying experience

Tests

Development of Research Maneuver: Several maneuvers were studied during extensive preliminary tests (data not shown). These maneuvers were flown by NASA research engineers who were qualified to fly transport airplanes. The goal was to develop a maneuver that required rudder pedal inputs and was amenable to pilot ratings. Standard, operationally-relevant maneuvers such as engine failures did not produce much rudder pedal activity other than a steady input. An artificial, one-degree-of-freedom, yawing disturbance was studied and rejected because it was very unnatural. The selected maneuver, described below, was a compromise between an operationally realistic maneuver and a completely artificial maneuver.

It became apparent during the tests that the C-H pilot ratings were dependent on the severity of the wind shears and whether the wind shears reversed direction. For consistency, it was decided to base the subjective C-H pilot rating analysis on only medium wind shears. However, it was feared that the pilots would learn to react in a mechanical (open-loop) manner if they were repeatedly exposed to only medium wind shears. Therefore, lower and higher wind shears were retained to prevent the pilots from learning how much input was needed for the medium wind shears. The result was that the test matrix size had to be doubled from 18 to 36 data runs per pilot. Only the pilot ratings for the medium wind shears will be presented. However, quantitative data will be presented for all the wind shears.

<u>Research Tests</u>: All research test sessions were conducted from 8:00 am to 4:30 pm local time. The test session started with a 1-hour briefing covering the program background, a description of the simulator, the research variables, the maneuver, and the C-H rating scale. After the briefing, the test subjects were given a 1-hour familiarization/practice period in the simulator. All test subjects flew the simulator in the left seat regardless of whether they currently were a captain or a first officer. The first runs during this practice period were conducted with a nominal combination of rudder pedal characteristics. A combination is defined by three numbers (M, B, X) where M is the maximum force in pounds, B is the breakout force in pounds, and X is the maximum travel in inches. For the nominal combination, M = 90 lbs, B = 26.5 lbs, and X= 2.5 inches or expressed as coordinates (90, 26.5, 2.5). A generic figure depicting the three research variables is presented in Figure 6.

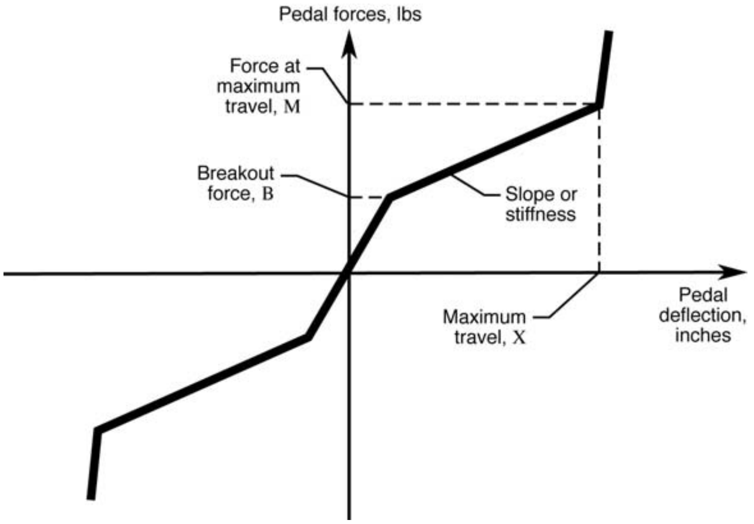


Figure 6. Illustration of the three static pedal parameters (M, B, X). Note that the slope around the origin has been greatly reduced for illustrative purposes.

Approximately six practice approach and tracking maneuvers were performed starting with no steady winds or random turbulence, then adding winds and turbulence, and ending with a severe lateral wind shear described below. After the six practice maneuvers with the nominal pedal feel characteristics, the test subjects were given five additional runs with some of the most extreme pedal feel characteristics. However, for these five additional practice runs, a steady track angle maneuver at a constant altitude of 1,700 feet above ground level (AGL) was used rather than the research approach and runway tracking maneuver. For these maneuvers the test subjects were instructed to make slow, full-travel pedal inputs while keeping the wings fairly level. In this way, the test subjects experienced the full range of maximum pedal forces, breakout forces, and travel that would comprise the research test matrix. After the practice period, the actual research maneuvers were conducted. The test subjects were given a break after about one hour in the simulator or when they or the researcher felt tired.

Test Matrix: The test matrix for the independent variables is presented in Table 2. It was arranged according to a Central Composite Design (CCD) [ref. 7]. Fifteen unique combinations of rudder pedal feel characteristics were tested, but the nominal combination (90, 26.5, and 2.5) in the center of the matrix was used four times so that there were a total of 18 test conditions. Measurements of the pedal characteristics for quasi-static inputs were made on the simulator for these 15 combinations and are shown in Figure 7.

Table 2. Test Matrix

(Control loader combinations are designated by the numbers in the shaded blocks)

		Force at Max Travel, lbs																								
		30.0					47.1					90.0					132.9					150.0				
		Breakout Force, lbs					Breakout Force, lbs					Breakout Force, lbs					Breakout Force, lbs					Breakout Force, lbs				
		3.0	9.7	26.5	43.3	50.0	3.0	9.7	26.5	43.3	50.0	3.0	9.7	26.5	43.3	50.0	3.0	9.7	26.5	43.3	50.0	3.0	9.7	26.5	43.3	50.0
Max Travel, inches	1.00													1												
	1.43							2		3								4		5						
	2.50			6								7		8to11		12								13		
	3.57							14		15								16		17						
	4.00													18												

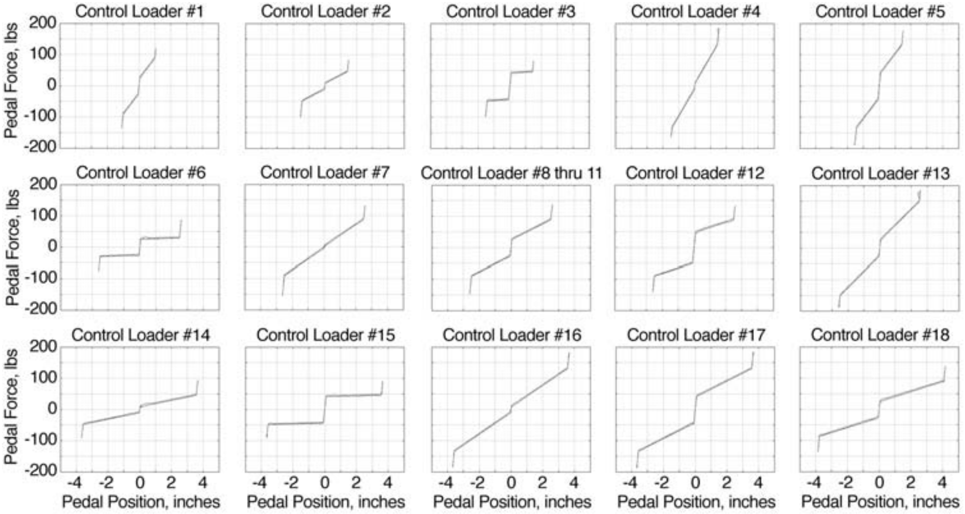


Figure 7. Measured quasi-static pedal forces for the 15 unique combinations tested. Coulomb friction = 1 lb and viscous friction = 1 lb/(in/sec).

An explanation for the choice of the values in the test matrix is better understood by examining Figure 8. This pictorial representation of a generic CCD test matrix for three independent variables places the origin at the center of the selected range of each of the three independent variables—in this case at 90, 26.5, and 2.5. The coordinates are then normalized so that the normalized coordinates of the origin are 0, 0, and 0 and the extreme values are ± 1.4. The six extreme values are symmetrically placed on the plus and minus coordinate axes. The eight corners of the box are then placed at the appropriate combinations of ± 1. This test matrix is efficient for fitting the 10-term response surface equation shown later in the Data Reduction section.

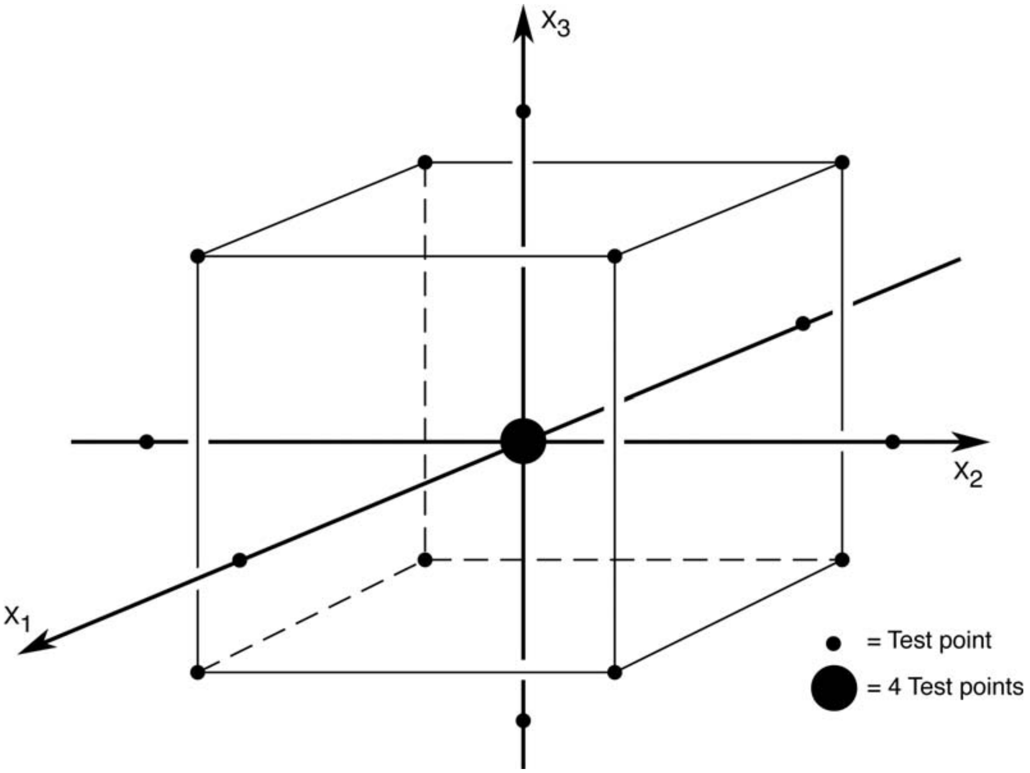
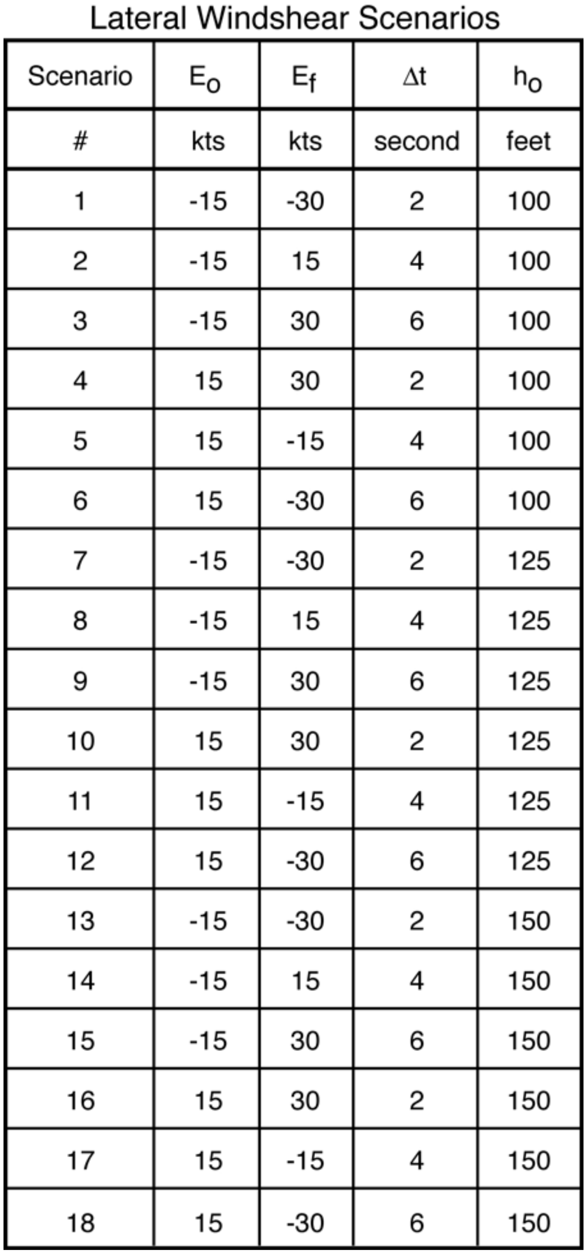


Figure 8. Pictorial representation of a central composite design with 3 independent parameters (normalized).

There were also 18 different combinations of wind shears, as shown in Table 3. These wind shears were selected during the maneuver development phase of the research (described above) because they were severe, but not unrealistic. The wind shear combinations were defined by three numbers: (1) the initial crosswind, E_o, (+15 kts or -15 kts), (2) the final crosswind, E_f, (+15 kts, -15kts, +30 kts, or -30 kts), and (3) the altitude, h_o, at which the transition from the initial to final crosswind began (100 feet, 125 feet, or 150 feet). The rate of change during the transition was a constant 15 kts/2 seconds. The wind shears are illustrated in the 6 time histories in Figure 9, which have generic time scales not related to the three altitudes at which the shears were actually initiated. Table 3 reveals that six wind shear scenarios had a 15 kts change in cross winds, six wind shear scenarios had a 30 kts change in the cross wind, and six wind shear scenarios had a 45 kts change in cross wind. The 30 kts-change wind shears are referred to herein as the “medium wind shears” and are used for the pilot ratings presented later.

Table 3. Wind Shear Scenarios



Lateral Windshear Scenarios

Scenario	E_o	E_f	Δt	h_o
#	kts	kts	second	feet
1	-15	-30	2	100
2	-15	15	4	100
3	-15	30	6	100
4	15	30	2	100
5	15	-15	4	100
6	15	-30	6	100
7	-15	-30	2	125
8	-15	15	4	125
9	-15	30	6	125
10	15	30	2	125
11	15	-15	4	125
12	15	-30	6	125
13	-15	-30	2	150
14	-15	15	4	150
15	-15	30	6	150
16	15	30	2	150
17	15	-15	4	150
18	15	-30	6	150

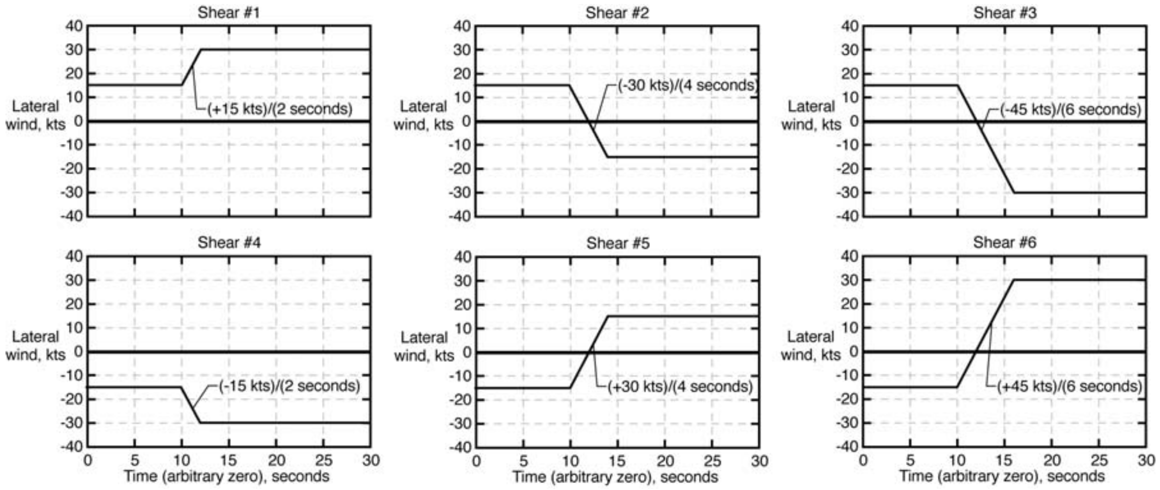
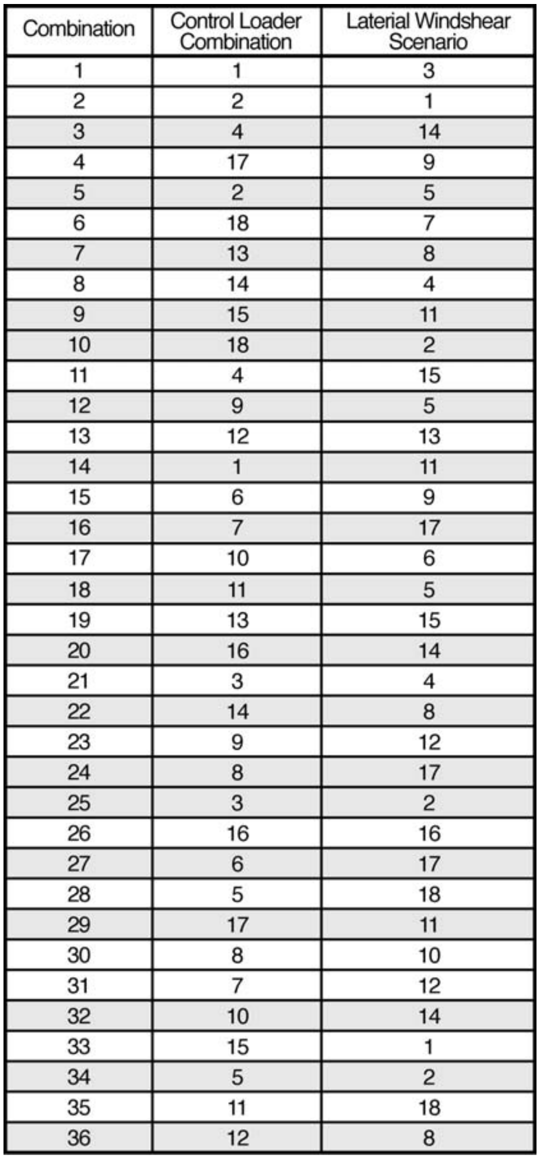


Figure 9. Lateral wind shear scenarios (Time scales are generic and not related to the actual time used in the tests).

The 18 research variable combinations and 18 wind shear scenarios were randomly presented to the pilots so that they could not predict which combination was going to be presented for a given simulation run. In addition, each pilot was presented with a different combination of research variable combinations and wind shear scenarios so that any interaction due to the order of presentation would be averaged out for all 12 pilots. Each pilot flew a total of 36 maneuvers (each pedal feel combination was flown twice, but with different wind shears). A typical run sequence for one pilot is shown in Table 4. The pilot rating (qualitative) data are presented for only the medium wind shear scenarios (+15 kts to -15 kts or -15 kts to + 15 kts). The other wind shear scenarios were primarily intended as "fillers" to keep the pilots from recognizing the pattern of the medium wind shears. However, the quantitative data are presented for all the wind shear scenarios.

Description of Research Maneuver: The maneuver started at an altitude of about 1,700 feet AGL, stabilized with the wings level on the minus 3-degree glide slope to runway 36L, and yawed into the +15 kts initial crosswind. The airplane was in the landing configuration (flaps fully extended and the landing gear down) at an air speed of 130 kts. The yaw damper was on, but the auto throttles were off. The pilot was instructed to continue the approach as if to make a landing and to yaw out of the wind ("decrab" using cross controls) at an altitude of 400 feet AGL. Between 150 and 100 feet AGL the wind shear was introduced. Although, in general, the approach was no longer stabilized and would ordinarily have demanded a go-around, the pilots were instructed not to execute a go-around or to attempt a landing. Instead they were instructed to level off at about 50 feet AGL and correct any lateral offsets back to the runway centerline. From that point on they were to continue tracking the centerline of the runway at 50 feet AGL and the nominal airspeed of 130 kts using column and throttle inputs. They were instructed to keep the airplane's nose aligned with the runway centerline and keep the lateral displacement small so they could have made a landing if they had been required to (neglecting the fact there would not have been sufficient distance to stop on the runway after they landed). This maneuver required holding cross controls for several seconds while they transited the entire length of the runway after which the maneuver was terminated. The pilots were instructed to ignore the possibility of wing scrapes on the runway. Moderate random turbulence was constantly superimposed on the steady winds and wind shears. This turbulence required the pilots to constantly make small corrections that were especially important while tracking the runway centerline.

Table 4. Typical Run Sequence
(Shaded combinations were used for C-H ratings)



Combination	Control Loader Combination	Laterial Windshear Scenario
1	1	3
2	2	1
3	4	14
4	17	9
5	2	5
6	18	7
7	13	8
8	14	4
9	15	11
10	18	2
11	4	15
12	9	5
13	12	13
14	1	11
15	6	9
16	7	17
17	10	6
18	11	5
19	13	15
20	16	14
21	3	4
22	14	8
23	9	12
24	8	17
25	3	2
26	16	16
27	6	17
28	5	18
29	17	11
30	8	10
31	7	12
32	10	14
33	15	1
34	5	2
35	11	18
36	12	8

<u>Cooper-Harper Pilot Ratings</u>: None of the pilots who participated in this study had any previous experience using the C-H rating scale, shown in Figure 10 [ref. 7]. Therefore, they were trained on the use of the scale during the initial briefing period. They were told to rate the total task including the longitudinal, lateral, and directional tasks but with emphasis on the directional task. It is recognized that rating the entire task can introduce scatter in the C-H ratings, but it was also important to account for the effects of the directional handling qualities on the other axes.

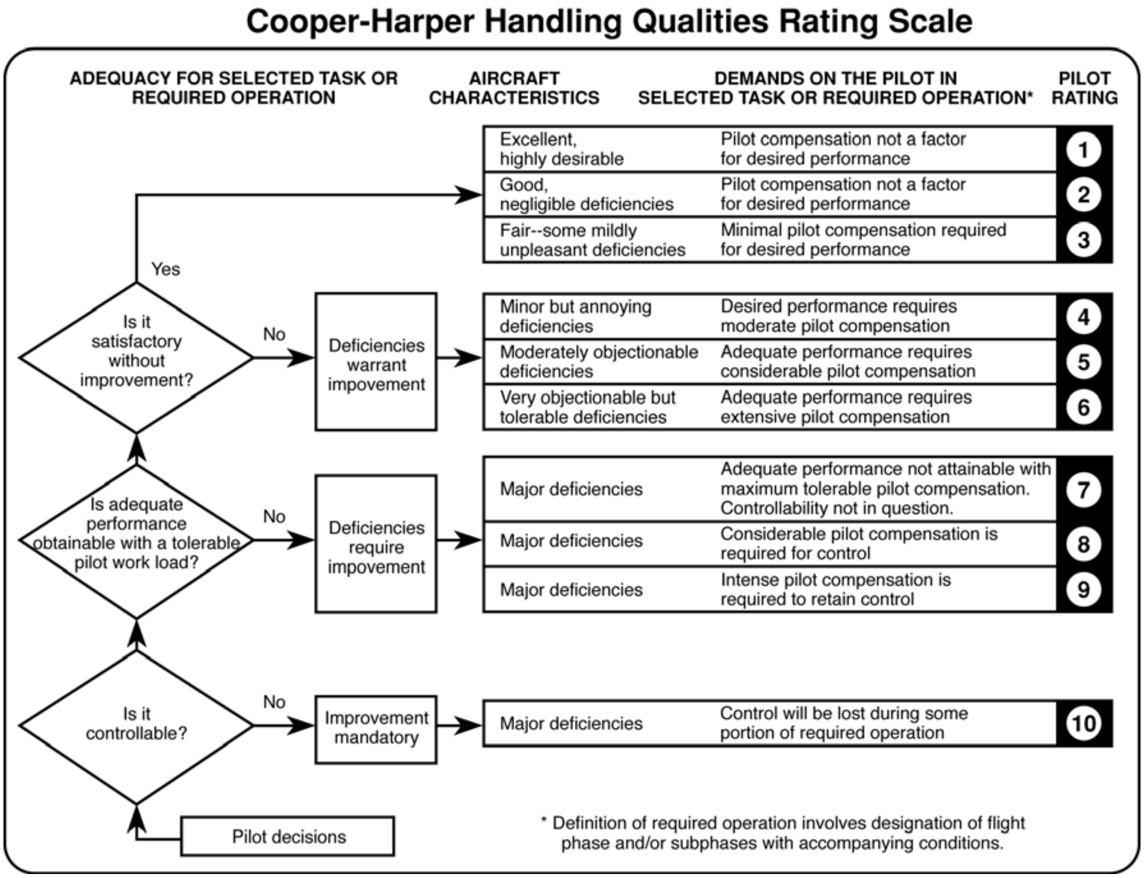


Figure 10. Cooper-Harper (C-H) pilot rating scale.

The pilots were given a definition of “adequate performance” on the rating scale, i.e., “(1) returning the airplane back to the runway centerline (after the destabilizing wind shear) and stabilizing the lateral drifts and heading within the first half of the runway, (2) tracking down the second half of the runway close enough to the centerline so that a landing could have been made (without consideration of the runway remaining for stopping), and (3) maintaining the heading of the airplane aligned close enough to the centerline of the runway so that a landing could have been made.” Likewise, the pilots were given a definition of the words “satisfactory without improvement” on the rating scale, i.e.,: “an airplane that you, as a hypothetical chief test pilot in the development of this airplane, would recommend for production and operation for the complete life-cycle of the airplane.” The pilots were told to use their own judgment as to what was a “tolerable” workload and the correct adjective (“minimal,” “moderate,” “considerable,” etc.) to modify the words “pilot compensation.”

For the purposes of this research, and due to the test subjects’ lack of experience with the C-H scale, the emphasis was not on the absolute pilot ratings, but rather on the sensitivities of pilot ratings to the pedal force-feel characteristics. The ratings that were given should be much more reliable in predicting relative merits between different combinations of the pedal feel parameters. Therefore, the ratings should be accurate in predicting optimum combinations of the parameters and the sensitivity to off-optimum combinations.

Data Reduction

The data can be analyzed and interpreted in different ways. For example, an analysis based on the highest C-H pilot rating for each control loader combination might be of interest. Alternately, an analysis based on the largest variability in the C-H pilot ratings might be of more interest. For this report, the emphasis is on the average C-H pilot rating for each control loader combination. But this emphasis should not hide the fact that there were large variations in the pilot rating between pilots for the same control loader combination. The same comments apply equally well to the quantitative measurements of pilot performance and airplane response.

One way to address the variation in pilot ratings is to fit an equation to the data. For example, the C-H pilot ratings for the medium wind shears were used to determine, in least squares, the ten coefficients of the following equation (referred to herein as the response surface equation)

$$PR(M,B,X) = b_1 + b_2M + b_3B + b_4X + b_5MB + b_6MX + b_7BX + b_8M^2 + b_9B^2 + b_{10}X^2 \quad \text{(EQ. 1)}$$

A set of ten coefficients was determined from the pilot ratings of Pilot #1; the combined pilot ratings of Pilots #1 and #2; the combined pilot ratings for Pilots #1, #2, and #3; and so forth up to the combined pilots ratings for all 12 pilots. Comparisons of the predictions of pilot ratings (PR) for these groups of pilots were made from these sets of coefficients to determine the number of pilots needed to converge on consistent estimates of $PR(M,B,X)$.

An additional analysis was conducted on the quantitative performance data to measure the tendency toward a directional PIO. Cross spectra of the pedal force (pilot input) and the airplane heading (airplane response) were calculated. The peak value of these spectra for frequencies greater than 0.2 Hz was examined as a possible indicator of a PIO tendency. An equation of the same form as EQ. 1 was used to reduce these data.

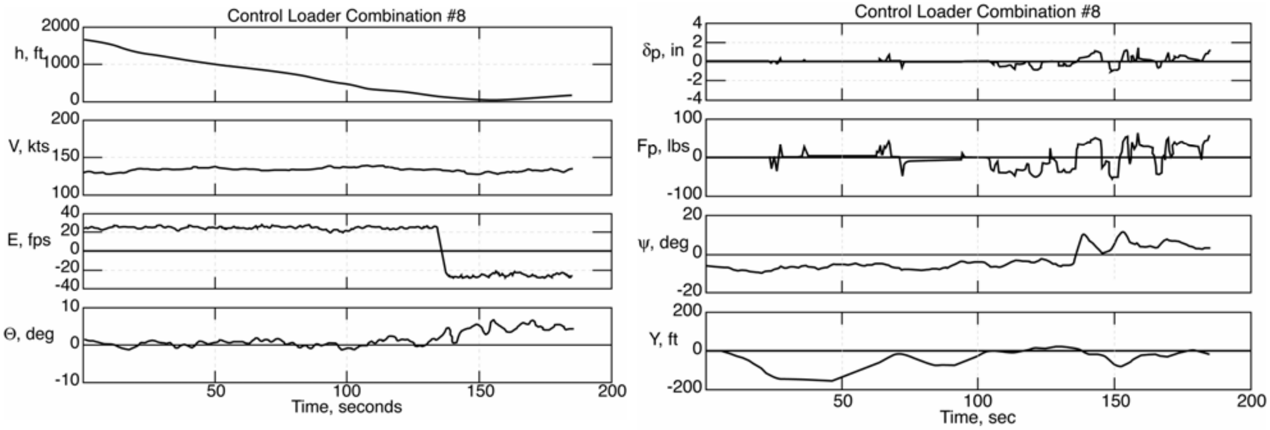
$$PS(M,B,X) = b_1 + b_2M + b_3B + b_4X + b_5MB + b_6MX + b_7BX + b_8M^2 + b_9B^2 + b_{10}X^2 \quad \text{(EQ. 2)}$$

However, in this case and explained earlier, the data from all wind shears and not just the medium wind shears were used.

The response surface (EQ. 1 and EQ. 2) is versatile for interpreting and summarizing the data. The pilot ratings (PR) and peak spectra values (PS) can be calculated for any combination of the three independent variables M, B, and X. This makes it possible to construct contour plots as a function of any two of the variables M, B, and X while the third variable is held constant. The equations can also be used to find the combinations of M, B, and X that give the best (minimum) pilot rating or peak spectra values. That is, using an equation solver, the best combination of M, B, and X can be determined. If one (or two) of the parameters is constrained to a fixed value (or fixed values), the constrained optimum values of the other two (or one) parameters can be determined. For example, if X is constrained, the optimum values of M and B can be readily determined. Finally, the sensitivity of PR or PS to changes in M, B, and X about a design point can be determined by simply varying the parameter of interest while holding the other two parameters fixed.

RESULTS AND DISCUSSION

Time histories of a typical maneuver are presented in Figure 11, which shows little rudder activity before the wind shear at about 130 seconds. When the airplane was over the runway (after approximately 140 seconds), the pilot in this case was able to track the centerline fairly well. However, the pilot did not completely perform the decrab maneuver at 400 feet AGL (at approximately 100 seconds) as instructed, nor did the pilot perfectly align the heading with the runway after the wind shear when tracking the runway centerline. An examination of other time histories (not shown) showed this was a fairly typical response. That is, the pilots often failed to completely decrab the airplane while occasionally they decrabbed too much causing the nose of the airplane to be pointed slightly to the downwind side of the runway. The simulator, like a real airplane, lacked a positive visual cue of the heading making it difficult for the pilots to judge their actual heading. That is, the wide windshield field of view provided no ready reference for heading. Another possible reason for the partial decrab maneuvers is that in ordinary commercial transport airplane operations, the pilots can use a large crab angle at touchdown because of the strength of the landing gear on transport airplanes.



a. Longitudinal parameters

b. Directional parameters

Figure 11. Typical time histories of a research maneuver for control loader combination #8.

In contrast, the view of the runway centerline provided a positive cue of the lateral position error, and operational landings have to be made near the runway centerline. When the pilots failed to completely decrab, their pedal forces were reduced. When they decrabbed too much, their pedal forces were increased over those required for a complete decrab in which the airplane was pointed directly down the runway. More important, the poor visual heading cues probably reduced the number of small corrective rudder inputs made by the pilots. An artificial, head-up, pointer on the horizon might have given the pilot the needed heading reference to more fully reveal any hidden tendencies to directional PIOs using the present evaluation maneuver.

Pilot Ratings: The C-H pilot ratings for medium wind shears for all pilots are presented in Table 5 and plotted in Figure 12. There were wide variations in the C-H pilot ratings for a given control loader combination. For example, for control loader combination #6, Pilot #1 gave a rating of 1 and Pilot #9 gave a rating of 10. Control loader combination #6 had a breakout force of 26.5 pounds, but a maximum force of only 30, which Pilot # 9 said was too light. Pilot #9 was not able to stabilize the lateral position causing the pilot to make large pedal inputs in opposite directions as the runway centerline was overshot. At the same time, the airspeed got low and the angle of attack large so that the pilot actually touched down on the runway instead of maintaining the desired 50 feet AGL. Since the pilot could not control the lateral position and maintain altitude, combination #6 was given a rating of 10.

Table 5. Cooper-Harper Pilot Ratings

	Pilot Number															
Control Loader Combination	1	2	3	4	5	6	7	8	9	10	11	12	Max	Min	Average	Stdev
1	5	7	8	2	6	7	2	5	7	5	4	6	8.00	2.00	5.08	1.88
2	4	8	5	2	5	5	4	4	4	3	2	2	5.00	1.00	3.42	1.38
3	2	6	8	5	5	5	4	8	4	5	3	5	8.00	1.00	4.58	2.07
4	4	8	8	5	6	7	6	8	6	5	5	3	8.00	3.00	5.75	1.48
5	5	7	8	3	4	9	10	5	8	5	3	5	10.00	3.00	6.08	2.39
6	1	4	8	2	4	4	2	4	10	6	3	3	10.00	1.00	4.58	2.81
7	1	5	8	3	3	1	4	2	3	5	2	4	8.00	1.00	3.17	1.95
8	1	3	3	2	6	3	3	4	4	4	3	5	6.00	1.00	3.33	1.37
9	1	1	4	2	3	3	4	5	7	4	2	4	7.00	1.00	3.33	1.72
10	1	2	2	2	3	3	4	4	3	3	3	2	4.00	1.00	2.67	0.89
11	1	3	8	3	3	4	5	2	2	2	2	2	8.00	1.00	2.92	1.98
12	2	4	8	7	4	7	8	5	5	5	3	9	9.00	2.00	5.83	2.17
13	4	4	8	2	5	7	4	5	9	5	3	9	9.00	2.00	5.50	2.28
14	2	3	8	5	3	5	4	4	8	1	3	4	8.00	1.00	4.08	2.19
15	2	8	4	6	5	4	1	8	5	4	4	1	8.00	1.00	3.83	2.08
16	2	8	2	2	3	3	1	1	7	4	2	1	7.00	1.00	2.42	1.73
17	4	5	4	4	3	2	7	5	2	9	3	5	9.00	2.00	4.33	2.02
18	1	1	3	3	5	2	4	2	6	2	2	3	6.00	1.00	2.83	1.53

Max	5	8	8	7	6	9	10	8	10	9	5	9
Min	1	1	2	2	3	1	1	1	2	1	2	1
Average	2.39	3.22	5.94	3.33	4.22	4.50	4.28	4.50	5.56	4.28	2.89	4.06
Stdev	1.50	2.53	2.46	1.61	1.17	2.18	2.32	2.04	2.38	1.78	0.83	2.31

Note: Only pilot ratings for medium wind shears (wind shear scenarios 2, 5, 8, 11, 14, and 17 in Table 3) are shown. The shaded area is the center of the test matrix where M, B, and X are constant (90 lbs, 26.5 lbs, and 2.5 inches, respectively).

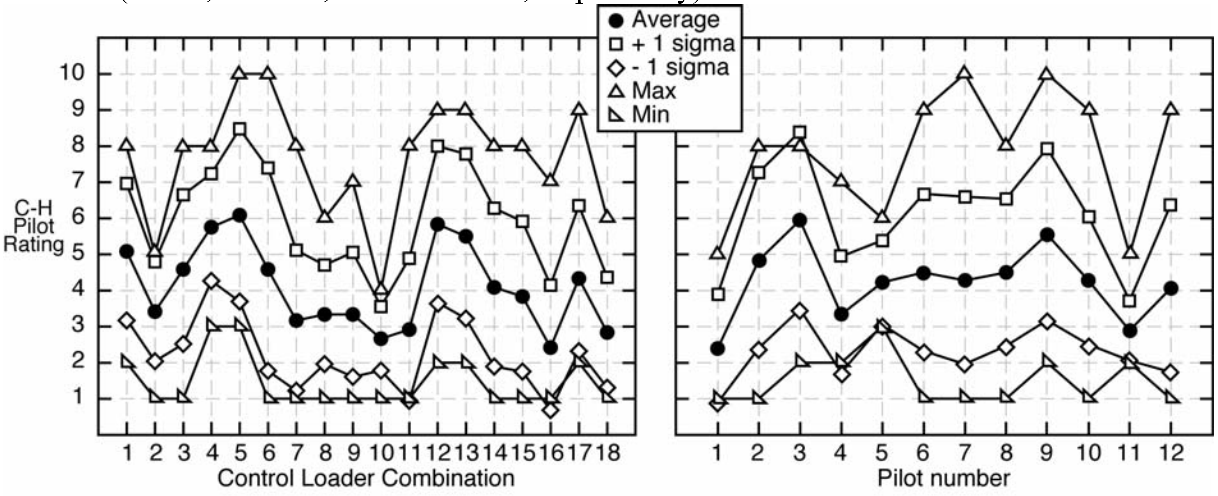


Figure 12. Summary of pilot ratings showing the averages and variations about the average.

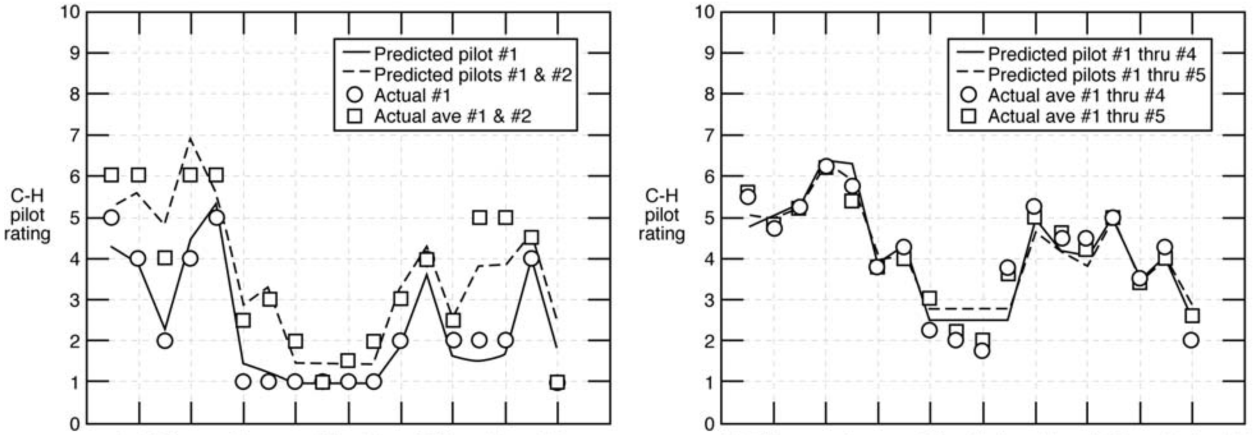
The other control loader combination that was rated a 10 by Pilot #7 was control loader combination #5 (133, 43.3, and 1.43). Pilot #7 said this combination's forces were too heavy and the travel was too short with the result so there was no indication where the rudder was located. The pilot also got high and fast with a large, unstabilized angle of attack, roll attitude, and lateral position error. Therefore, the pilot felt momentarily out of control and gave a pilot rating of 10.

Both combinations with a pilot rating of 10 demonstrate the coupling between the rudder pedals and the lateral and longitudinal tasks. That is, when the rudder pedals do not feel right, the pilot can become saturated with the directional task. As a result, the pilot momentarily ignores the lateral and longitudinal tasks causing large errors to develop in those axes.

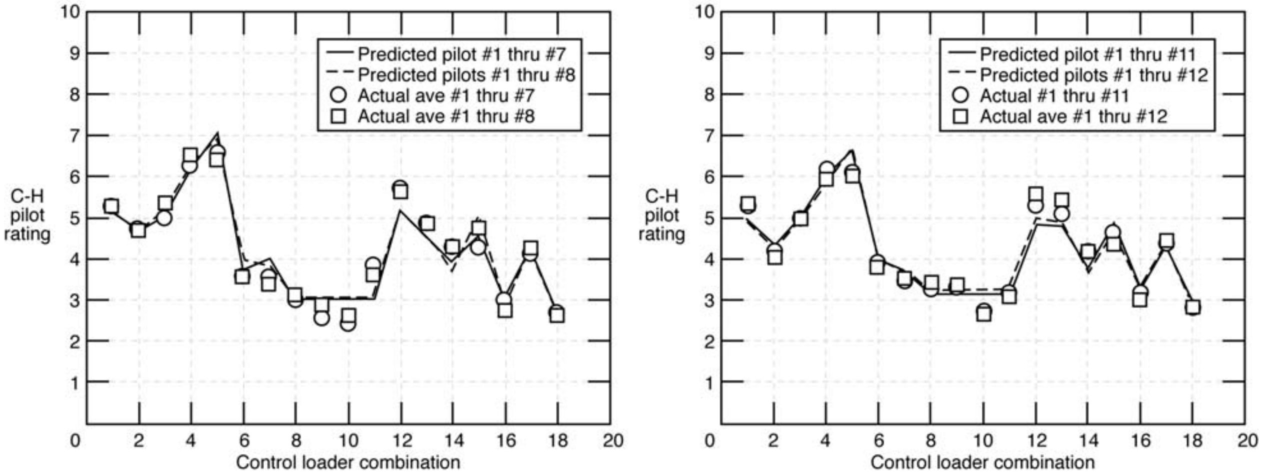
The variation for a given pilot for the same control loader combination was also large — as much as 5 C-H rating units. This can be verified by referring to Table 5 for Pilots #3 and 9 for control loader combinations #8 through 11. Control loader combinations #8 through 11 were all M=90 lbs, B=26.5 lbs, and X=2.50 inches. Finally, there were large differences between pilots. For example, Pilot #1 had an average rating for all 18 control loader combinations tests of about 2.4 while Pilot #3 had an average rating of about 6.0.

Many of these variations in pilot ratings were probably due to wide-ranging differences in pilot skill level and experience, shown in Table 1. But, as noted above, there were also substantial differences in the pilot ratings and performance for a given pilot for the same experimental condition. It appeared that many of these latter differences were due to the essentially open-loop pedal inputs to initially counter the wind shears. That is, when the wind shear was encountered, the pilot made a rather large step pedal input not really knowing what the pedal forces and travel were. After the large step input, the pilot needed to hold a steady pedal input and make small multiple inputs about that steady input. If the pilot's first (open-loop) step input was close to the average value actually needed, the remaining task was much easier and the performance was better. Alternatively, if the pilot's first step input was either too big or too small, the pilot often unsuccessfully searched for the correct input for the rest of the run.

Equation 1 for PR was fit to the ratings of different pilot combinations, and the resulting predictions are shown in Figure 13. In the upper left corner of Figure 13 the predictions for the ratings of Pilot #1 are compared to the predictions for the combined ratings of Pilots #1 and #2. As the data for more pilots are added, the difference due to each additional pilot gets smaller as can be seen from the other three plots in Figure 13. The change between consecutive pilots appears to be about the same for Pilots #1 through 7 compared to Pilots #1 through 8 (lower left plot) and Pilots #1 through 11 to Pilots #1 through 12 (lower right plot).



a) Difference between Pilot #1 and Pilots #1 and #2 b) Difference between Pilot #1 thru #4 and Pilots #1 thru #5



c) Difference between Pilot #1 thru #7 and Pilots #1 thru #8 d) Difference between Pilot #1 thru #11 and Pilots #1 thru #12

Figure 13. Effect of additional pilots on response surface equation predictions and average C-H pilot ratings.

Also, the worst control loader combinations were #4 and #5 as shown in Figure 13 because they consistently had the highest values. The best combination was #18, but it was not much better than #16 or the nominal combinations #8 through #11.

The estimated values of the coefficients for the combined data of all 12 pilots are presented in Table 6. These values were used to make the following predictions, but the fundamental information is included in these coefficients. That is, the equation can be used directly to calculate the pilot rating for any combination without reference to Figure 13 or the contour plots that follow.

Table 6. Estimated Coefficients for Response Surface Equation for C-H Pilot Ratings

b1	b2	b3	b4	b5	b6	b7	b8	b9	b10
7.12966	-0.02491	-0.09033	-1.17499	5.79E-05	-0.01089	0.00348	0.00033	0.00197	0.27947

The cumulative average C-H pilot rating for all 18 pedal feel combinations is shown in Figure 14. As the data for more pilots are added to the average, the average effectively reaches a constant value of approximately $PR = 4.3$ after 4 to 6 pilots. This result is consistent with the lower 2 plots in Figure 13 and indicates if the goal is to predict the average pilot rating — that six test subjects will be sufficient.

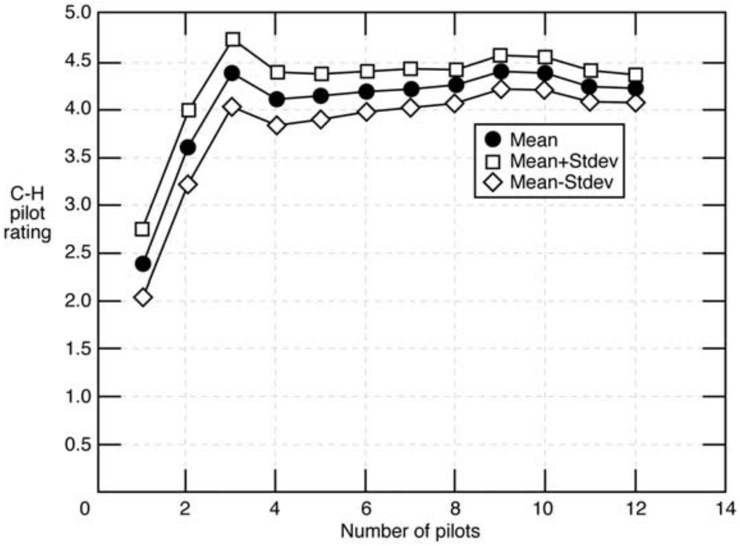


Figure 14. Mean pilot ratings as more pilots are added to the calculations.

Assuming that the C-H rating for all 12 pilots is the best estimate of the true handling qualities, the difference, or error, in using a smaller number of pilots is shown in Figure 15. For example, the error in the average pilot rating for the data of the first six pilots was less than 0.1 C-H rating unit. The corresponding maximum errors in the average rating for all the individual pedal feel combinations were approximately ±0.5 C-H rating units. These results suggest that ratings from only six pilots were needed to arrive at a consistent estimate of the handling qualities.

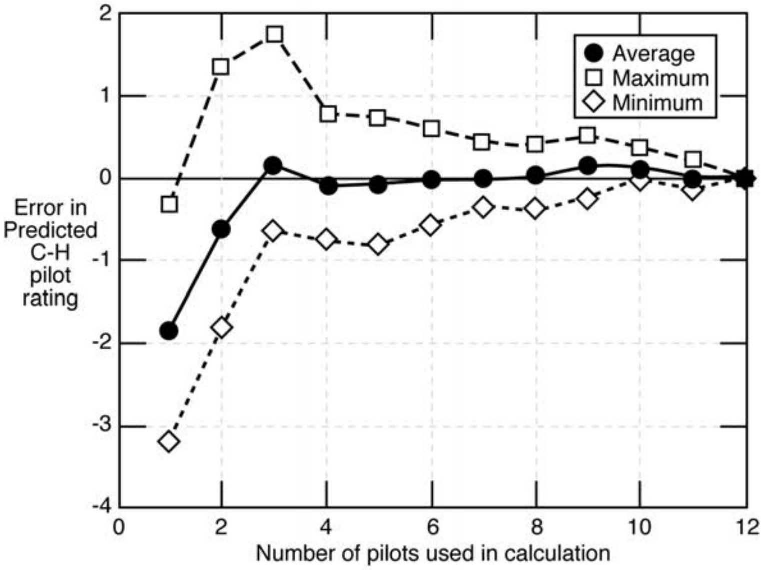


Figure 15. Errors in the predicted C-H pilot ratings assuming the predicted ratings for all 12 pilots are correct.

The response surface equation was used to populate the test matrix in Table 7. From this table, it is apparent that, in general, the pilots preferred longer travels, medium breakouts, and medium maximum forces. These observations will be confirmed in the contour plots that follow.

Table 7. Predicted C-H Pilot Ratings

		Force at Max Travel, lbs																								
		30.0					47.1					90.0					132.9					150.0				
		Breakout Force, lbs					Breakout Force, lbs					Breakout Force, lbs					Breakout Force, lbs					Breakout Force, lbs				
		3.0	9.7	26.5	43.3	50.0	3.0	9.7	26.5	43.3	50.0	3.0	9.7	26.5	43.3	50.0	3.0	9.7	26.5	43.3	50.0	3.0	9.7	26.5	43.3	50.0
Max Travel, inches	1.00													4.9												
	1.43							4.2		5.0								5.8		6.7						
	2.50			3.9								3.7		3.2		5.0								4.9		
	3.57							3.7		4.6								3.3		4.4						
	4.00													2.9												

The maximum force-breakout force contours of constant pilot rating are presented for three different values of maximum travel shown in Figures 16, 17, and 18. It should be noted the contours in the corners of these plots are extrapolations from the actual control loader combinations tested. The coordinates of the actual test points projected on the plane of the figure are plotted to illustrate the amount of extrapolation. The minimum (best) pilot rating decreases from 3.8 to 2.7 as the maximum travel increases from 1.5 to 3.5 inches. The breakout force at the minimum pilot rating is nearly independent of travel and has an approximate value of 18 to 21 pounds. On the other hand, the maximum force at the minimum pilot rating increases from about 62 to 95 pounds as the travel increases from 1.5 to 3.5 inches.

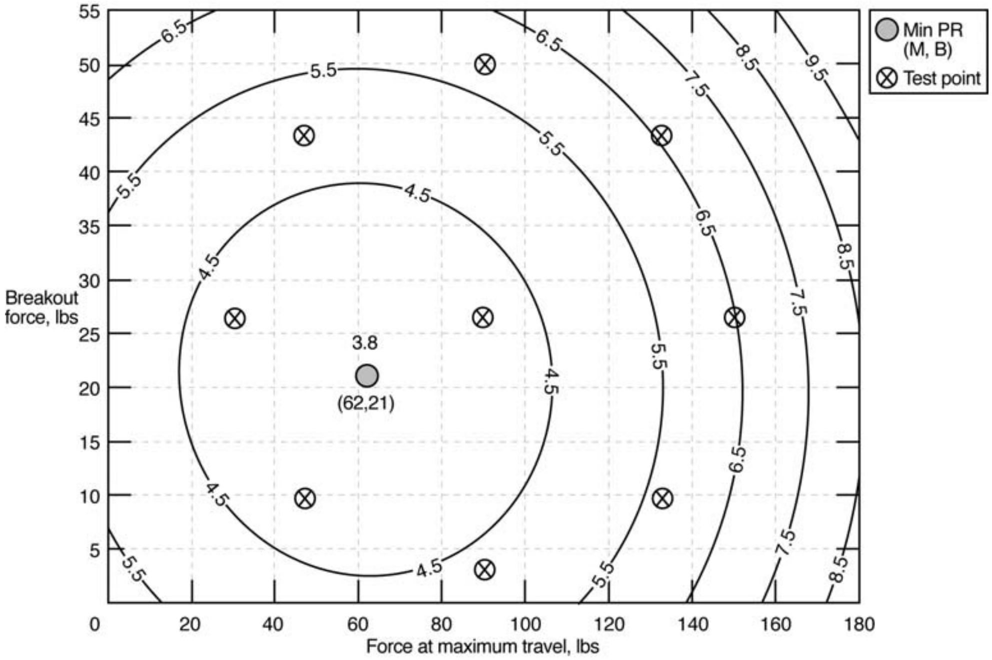


Figure 16. Contours of C-H pilot ratings for a maximum travel of 1.5 inches.

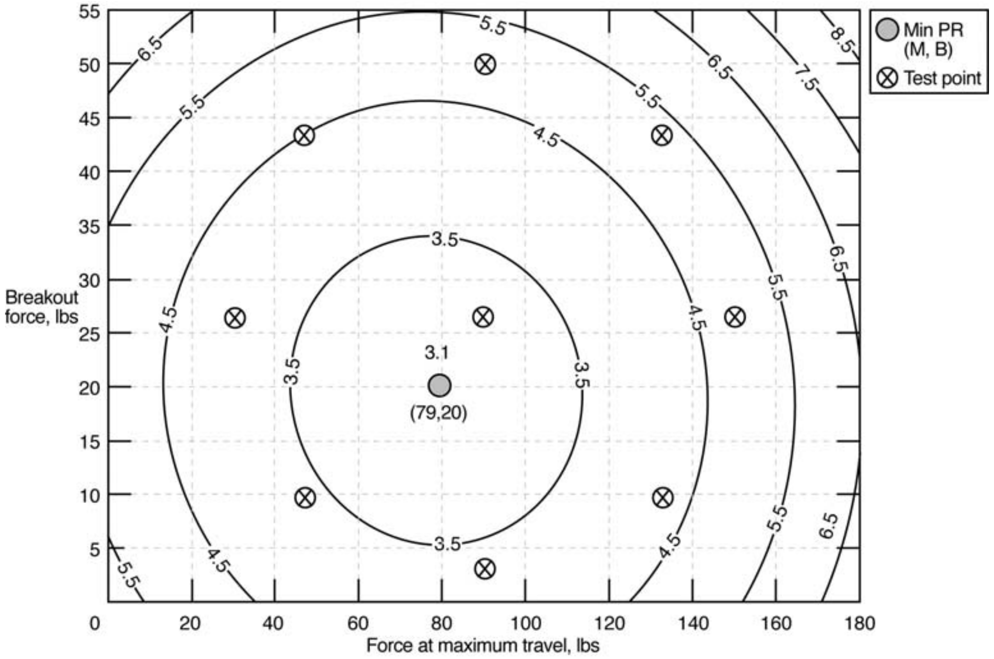


Figure 17. Contours of C-H Pilot Ratings for a Maximum Travel of 2.5 inches.

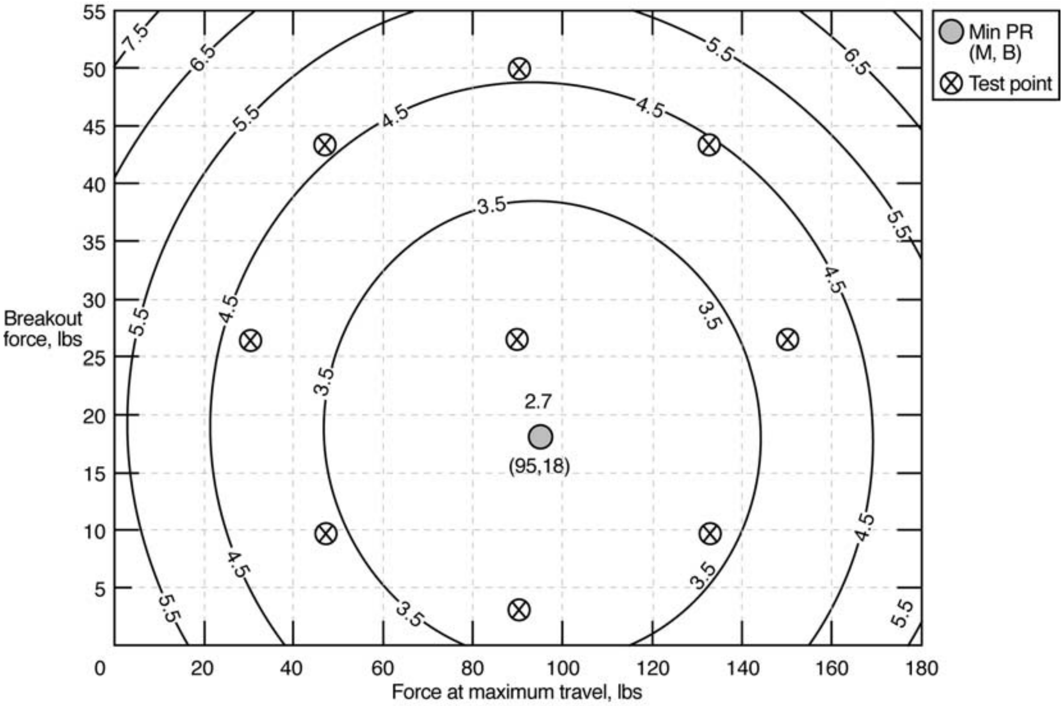


Figure 18. Contours of C-H Pilot Ratings for a Maximum Travel of 3.5 inches.

Figure 19 provides an alternate illustration of the effect of travel. For the nominal breakout force of 26.5 pounds, the minimum pilot rating occurs very near the high end of the travel tested. It would probably have been desirable to have tested to slightly larger travels than the current hardware was capable of producing.

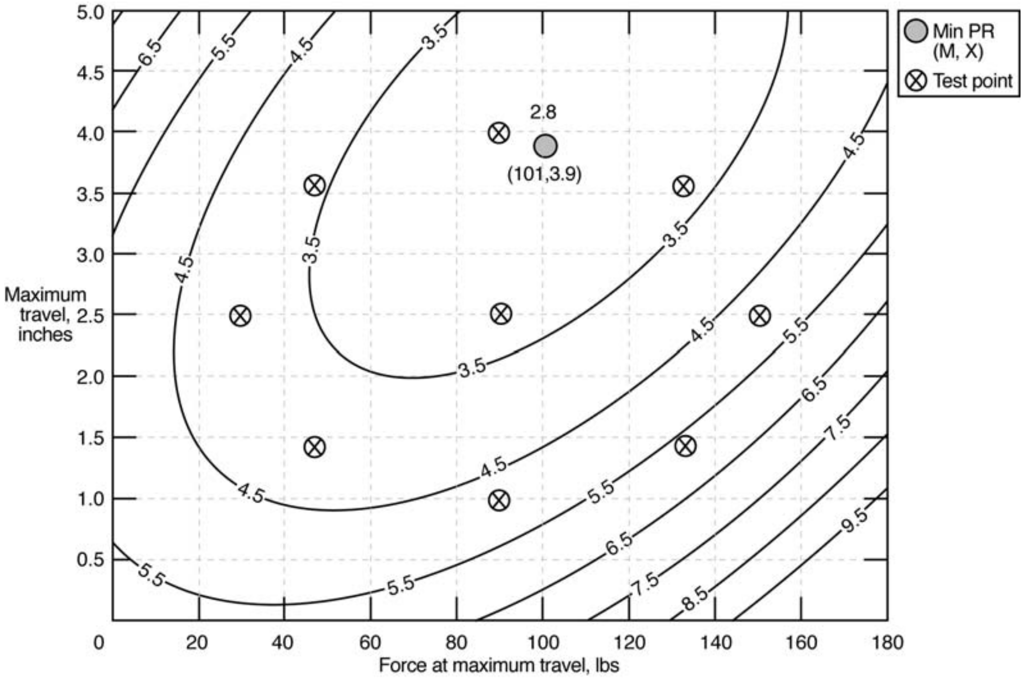
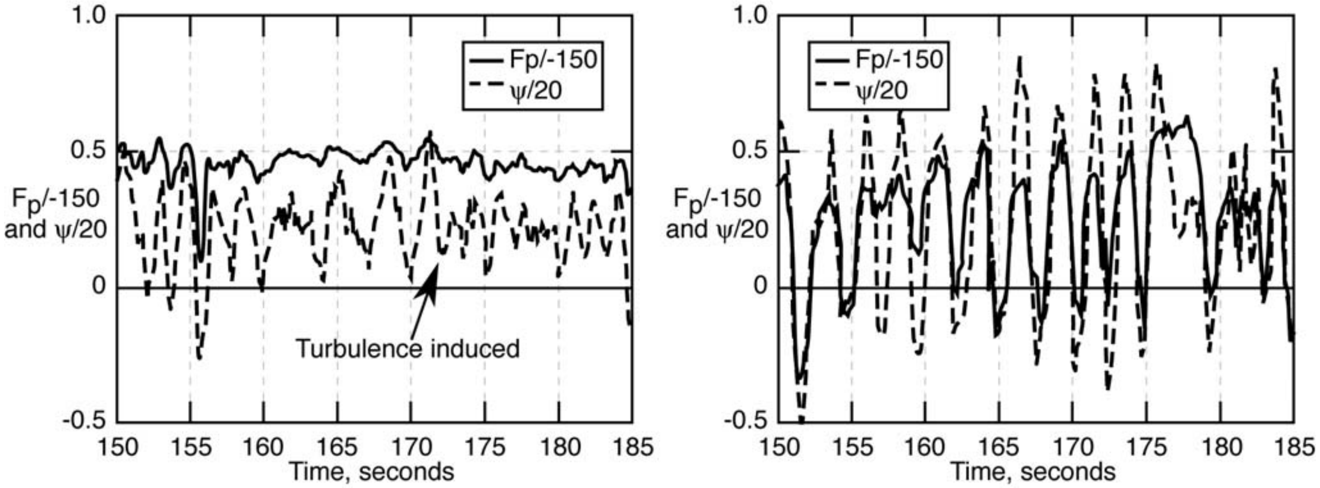


Figure 19. Contours of C-H Pilot Ratings for a Breakout Force of 26.5 pounds.

It is possible that during the initial practice runs with the fixed set of nominal pedal characteristics (M=90 lbs, B=26.5 lbs, and X=2.5 inches), the pilots developed a preference for this combination. An indication of this possible preference is the fact the optimum breakout force was 18 to 21 pounds while the maximum allowable breakout force is 14 pounds [ref. 2]. Further experiments will be required to determine the effect of the nominal practice conditions on the final result.

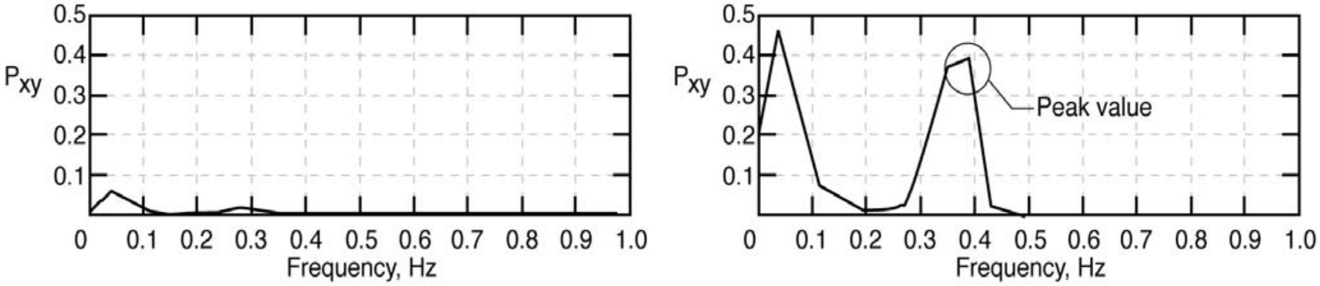
PIO Tendencies: Two time histories are presented in Figure 20. The time histories on the right show an oscillation at the same frequency in both the pedal force and the airplane heading while the time history on the left shows practically no oscillation in the pedal force and a turbulence induced oscillation in the heading. In both time histories the pedal force is divided by -150 and the heading by 20 to make them have approximately the same relative magnitude and to ensure positive values correspond to the same direction (nose right). The Dutch roll frequency was about 0.14 Hz and the observed oscillation frequency was about 0.4 Hz. Therefore, it appears that the pilot was inducing the observed oscillation although it was not a divergent oscillation.



a) No pilot induced oscillations b) Pilot induced oscillations

Figure 20. Time Histories Comparing Pilot Induced Oscillation (PIO) Tendencies.

Cross power spectra between the pedal force and heading for the same two maneuvers are shown in Figure 21. A cross power spectra indicates a correlation between two parameters at a given frequency. Unless another factor was causing both the pedal force and heading to oscillate at the same frequency, it can be assumed that the pilot's pedal force was causing the heading to oscillate—a PIO. The spectrum on the left shows practically no peak while the one on the right shows a definite peak at about 0.4 Hz indicating a tendency toward a PIO. A short program was written to capture the peak value of the spectra for frequencies greater than 0.2 Hz from the data files. The 0.2 Hz lower limit was imposed to eliminate large-scale, deliberate maneuvers.



a) No pilot induced oscillations b) Pilot induced oscillations

Figure 21. Cross Power Spectra Comparing Pilot Induced Oscillation Tendencies.

The program extracted the peak values for all research runs for all pilots. So, unlike the pilot ratings, the peak values were extracted for all wind shears and not just the medium wind shears used for the subjective pilot ratings. The results of this extraction process are presented in Table 8. The peak values are multiplied by 100 for better readability. An examination of this table indicates large variations similar to those for the pilot rating data. The reasons for these variations are probably the same as those discussed earlier for the pilot rating data.

The coefficients of EQ. 2 for PS were computed for the numbers in Table 8, and the results are shown in Table 9. These coefficients were used to make all the following predictions.

Table 8. Peak Values of Cross Spectra

	Pilot															
Control Loader Combination	1	2	3	4	5	6	7	8	9	10	11	12	Max	Min	Average	Stdev
1	0.96	1.74	9.52	3.64	12.12	17.42	4.85	11.07	0.62	4.79	3.37	11.20	17.42	0.07	3.98	4.78
1	0.12	0.62	0.50	1.25	1.33	0.10	1.12	4.54	0.35	3.88	0.43	0.07				
2	3.13	1.18	8.70	2.11	17.97	9.29	1.45	4.27	19.37	5.37	1.32	0.69	19.37	0.18	4.57	5.70
2	1.08	0.54	1.24	1.70	16.45	4.48	1.41	2.97	1.13	3.30	0.24	0.18				
3	1.32	3.19	3.42	11.95	39.61	38.19	2.01	22.38	4.76	7.53	1.70	1.74	39.61	0.11	6.67	11.16
3	0.27	0.11	0.26	10.65	0.66	1.15	0.44	4.53	2.97	0.75	0.14	0.26				
4	0.78	2.01	6.21	1.32	49.18	32.81	5.63	3.98	5.59	8.06	1.86	3.44	49.18	0.22	6.35	11.33
4	0.22	0.47	4.29	1.00	8.45	10.90	0.25	3.41	0.31	0.39	0.75	1.16				
5	2.30	2.09	1.02	2.21	14.44	6.59	2.24	8.83	2.05	23.28	2.53	3.29	23.28	0.15	4.03	5.53
5	0.42	0.61	0.37	1.60	0.15	6.09	0.36	0.71	1.28	11.54	0.75	2.05				
6	0.20	0.44	0.65	12.34	5.30	4.35	0.46	2.25	1.82	3.27	0.44	0.27	12.34	0.07	1.65	2.73
6	0.07	0.11	0.08	3.86	0.64	1.02	0.12	0.50	0.76	0.39	0.18	0.08				
7	1.41	0.88	2.43	5.61	4.78	20.04	0.26	1.83	0.64	1.36	2.45	1.20	20.04	0.04	2.23	4.05
7	0.91	0.23	0.93	2.32	1.48	3.09	0.12	0.15	0.55	0.13	0.04	0.69				
8	0.46	1.24	4.73	3.37	4.84	6.98	11.80	3.46	2.42	3.25	0.27	1.65	11.80	0.06	2.27	2.71
8	0.25	0.62	2.15	1.51	0.08	0.06	0.85	0.97	1.00	2.01	0.15	0.32				
9	1.03	3.72	2.60	4.97	19.40	19.88	0.48	4.74	0.77	9.56	0.91	0.23	19.88	0.04	3.30	5.51
9	0.13	0.71	0.24	3.39	0.16	0.04	0.13	1.93	0.43	3.04	0.64	0.17				
10	0.77	0.64	1.68	0.97	19.63	5.88	1.12	6.86	0.59	2.04	0.50	1.12	19.63	0.09	2.17	4.10
10	0.09	0.14	1.60	0.78	0.47	0.18	0.44	3.40	0.43	1.98	0.13	0.61				
11	0.55	0.80	0.61	2.24	4.00	14.17	1.52	6.44	2.25	0.82	4.43	0.69	14.17	0.01	1.83	3.07
11	0.43	0.47	0.22	0.65	1.25	0.01	0.30	1.02	0.26	0.30	0.25	0.20				
12	0.20	0.54	2.19	2.62	5.22	25.75	1.52	9.10	0.45	1.41	2.79	1.73	25.75	0.02	2.98	5.44
12	0.11	0.22	0.14	0.89	0.31	8.06	0.84	4.99	0.02	1.34	0.73	0.36				
13	0.51	1.35	5.69	1.31	21.86	5.57	0.45	5.11	1.74	2.01	0.35	2.47	21.86	0.07	2.77	4.66
13	0.17	0.08	1.76	0.76	9.32	0.07	0.36	0.59	1.71	1.70	0.27	1.22				
14	0.45	0.37	2.36	6.28	2.51	33.53	2.63	21.12	2.74	4.58	0.30	0.80	33.53	0.01	3.80	7.69
14	0.01	0.23	1.18	0.71	0.30	6.15	0.18	1.04	0.20	2.47	0.29	0.70				
15	0.11	5.37	0.88	8.14	0.63	0.34	0.16	2.29	0.22	8.70	0.27	1.62	8.70	0.04	1.40	2.45
15	0.04	1.41	0.12	0.35	0.50	0.07	0.10	1.47	0.22	0.32	0.21	0.07				
16	0.16	1.84	1.85	2.60	2.32	18.30	0.78	1.93	0.98	4.26	1.54	2.26	18.30	0.15	2.54	4.36
16	0.15	0.19	1.40	0.18	1.92	13.99	0.38	0.59	0.31	0.74	0.16	2.21				
17	0.92	2.03	0.53	15.48	3.07	12.36	10.18	7.88	0.67	0.53	1.28	1.52	15.48	0.13	2.95	4.32
17	0.57	0.50	0.47	2.19	1.00	7.31	0.13	0.50	0.22	0.25	0.30	1.03				
18	0.21	2.24	1.09	1.15	6.18	8.86	0.39	1.31	2.79	1.68	0.42	1.34	8.86	0.09	1.70	2.46
18	0.14	0.59	0.13	0.09	2.08	7.97	0.12	0.14	0.14	0.75	0.22	0.78				

Max	3.13	5.37	9.52	15.48	49.18	38.19	11.80	22.38	19.37	23.28	4.43	11.20
Min	0.01	0.08	0.08	0.09	0.08	0.01	0.10	0.14	0.02	0.13	0.04	0.07
Average	0.57	1.10	2.03	3.39	7.77	9.75	1.54	4.40	1.74	3.55	0.91	1.37
Stdev	0.66	1.14	2.34	3.79	11.16	10.19	2.64	5.09	3.28	4.45	1.05	1.90

Note: These peak values of cross spectra for frequencies greater than 0.2 Hz have been multiplied by 100. The shaded area is the center of the test matrix where M, B, and X are constant (90 lbs, 26.5 lbs, and 2.5 inches, respectively).

Table 9. Estimated Coefficients for Response Surface Equation for Peak Values of Cross Spectra

b1	b2	b3	b4	b5	b6	b7	b8	b9	b10
10.98996	-0.03575	-0.05935	-4.11895	-0.00028	0.003131	-0.0123	0.000207	0.002066	0.611491

For example, the equation was used to populate the test matrix as shown in Table 10. The results are, in general, consistent with the pilot ratings. The shorter travels generally have both higher pilot ratings (undesirable) and larger tendencies toward PIOs (undesirable). However, the smaller breakout forces sometimes had lower pilot ratings but slightly larger indicated tendencies toward PIOs.

Table 10. Predicted Peak Values of Cross Spectra

		Force at Max Travel, lbs																								
		30.0					47.1					90.0					132.9					150.0				
		Breakout Force, lbs					Breakout Force, lbs					Breakout Force, lbs					Breakout Force, lbs					Breakout Force, lbs				
		3.0	9.7	26.5	43.3	50.0	3.0	9.7	26.5	43.3	50.0	3.0	9.7	26.5	43.3	50.0	3.0	9.7	26.5	43.3	50.0	3.0	9.7	26.5	43.3	50.0
Max Travel, inches	1.00													5.11												
	1.43							4.66		5.31								4.94		4.78						
	2.50			2.70								3.35		2.07		3.08								2.94		
	3.57							2.44		2.21								3.30		2.26						
	4.00													1.79												

Contour plots of constant peak power spectra values (PIO tendencies) are shown in Figures 22 through 25 for the same combinations of pedal feel characteristics as those in Figures 15 through 19 for the pilot ratings. A comparison of the two sets of figures indicates that the indicated PIO tendencies are generally consistent with the pilot ratings. This consistency is examined in more detail in the next section.

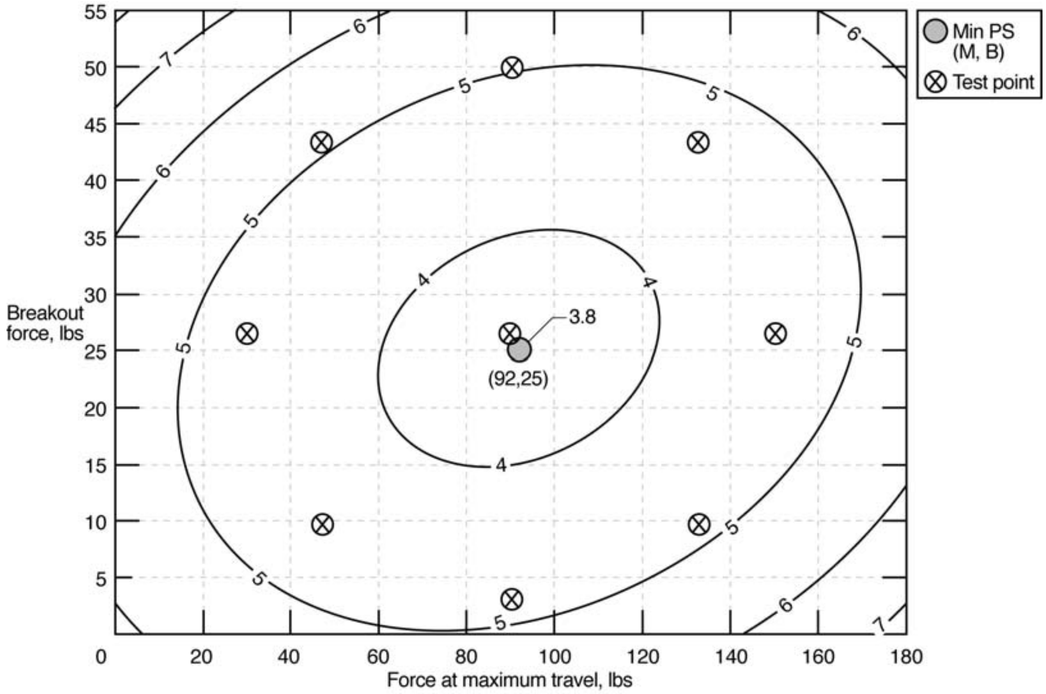


Figure 22. Contours of Peak Values of Cross Spectra for a Maximum Travel of 1.5 inches.

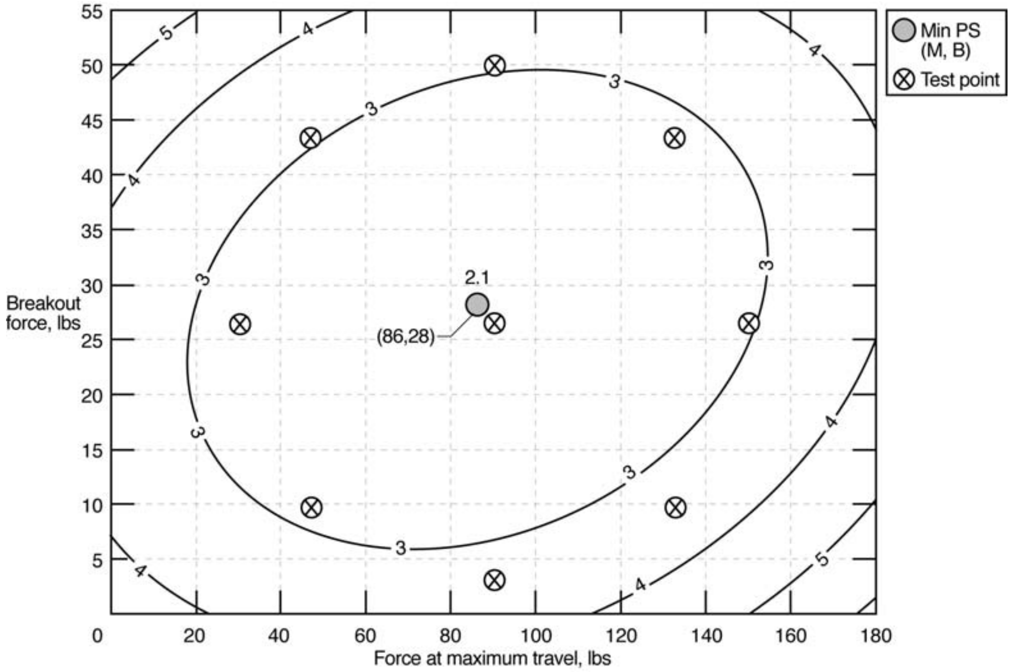


Figure 23. Contours of Peak Values of Cross Spectra for a Maximum Travel of 2.5 inches.

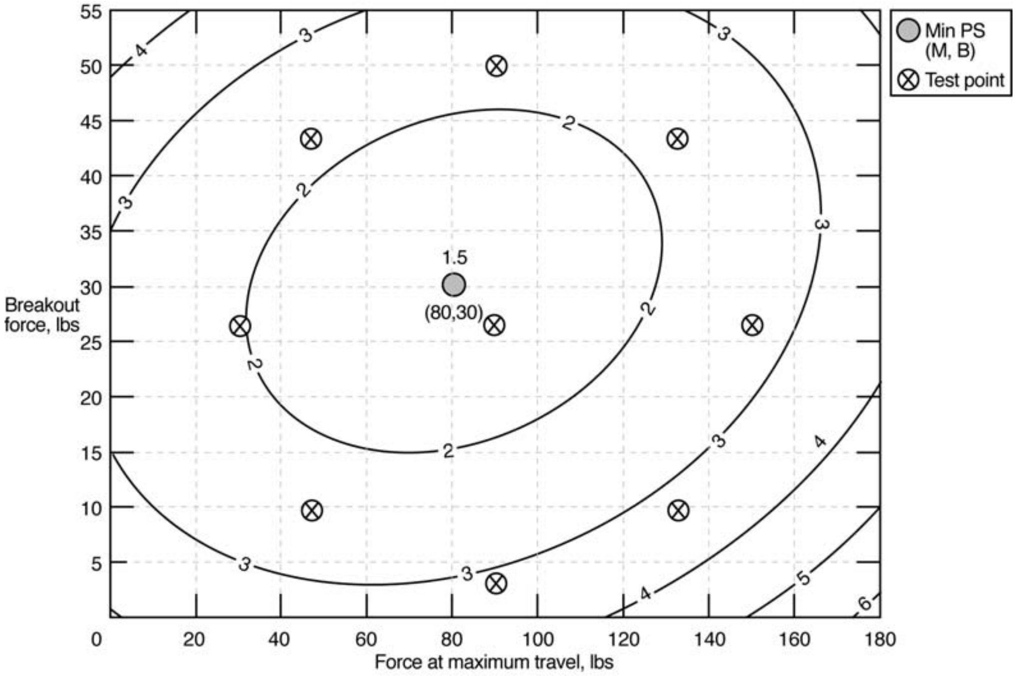


Figure 24. Contours of Peak Values of Cross Spectra for a Maximum Travel of 3.5 inches.

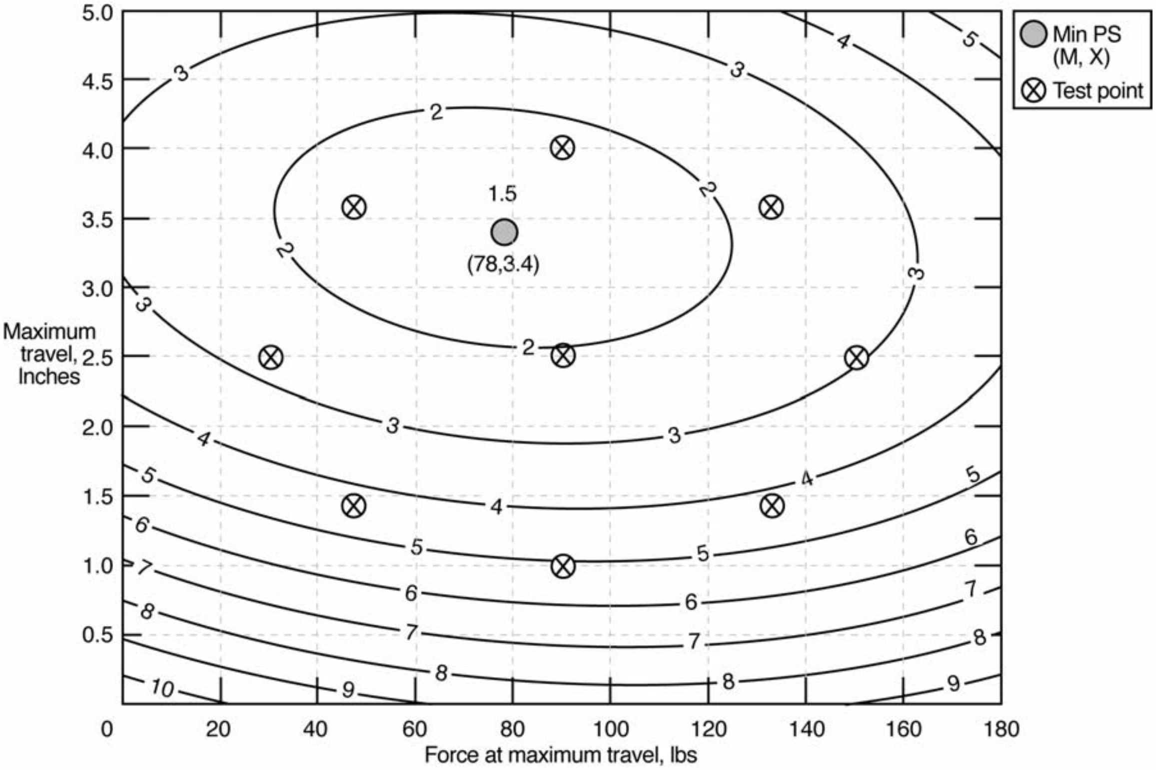


Figure 25. Contours of Peak Values of Cross Spectra for a Breakout Force of 26.5 lbs.

Sensitivity Analysis: The response surface (EQ. 1 and 2) can be used to determine the sensitivity to changes in M, B, and X about an initial combination or design point. To illustrate this capability, the initial combination was set to 90, 26.5, and 2.5, which is the center of the test matrix. However, any other initial combination could have been selected.

The sensitivity of PR and PS to changes in the force at maximum travel, M, is shown in Figure 26. Although the minimums in the two curves occur at different values of M due to the flatness of curves near the minimum, the shape and trends of the two curves are similar. The same observations are made for the sensitivity curves for B and X shown in Figures 27 and 28, respectively. Thus, it appears that the quantitative peak power spectra data are consistent with the qualitative pilot rating data.

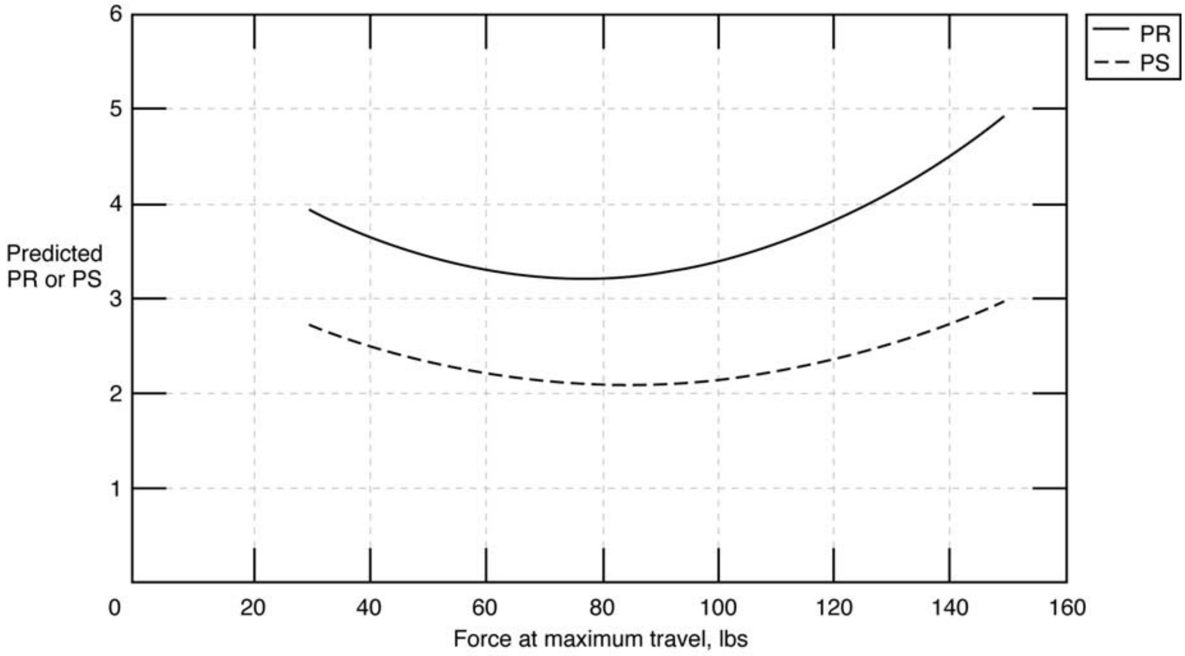


Figure 26. Sensitivity of pilot ratings and peak power spectra values to changes in the force at maximum travel. Breakout force = 26.5 lbs and maximum travel = 2.5 inches.

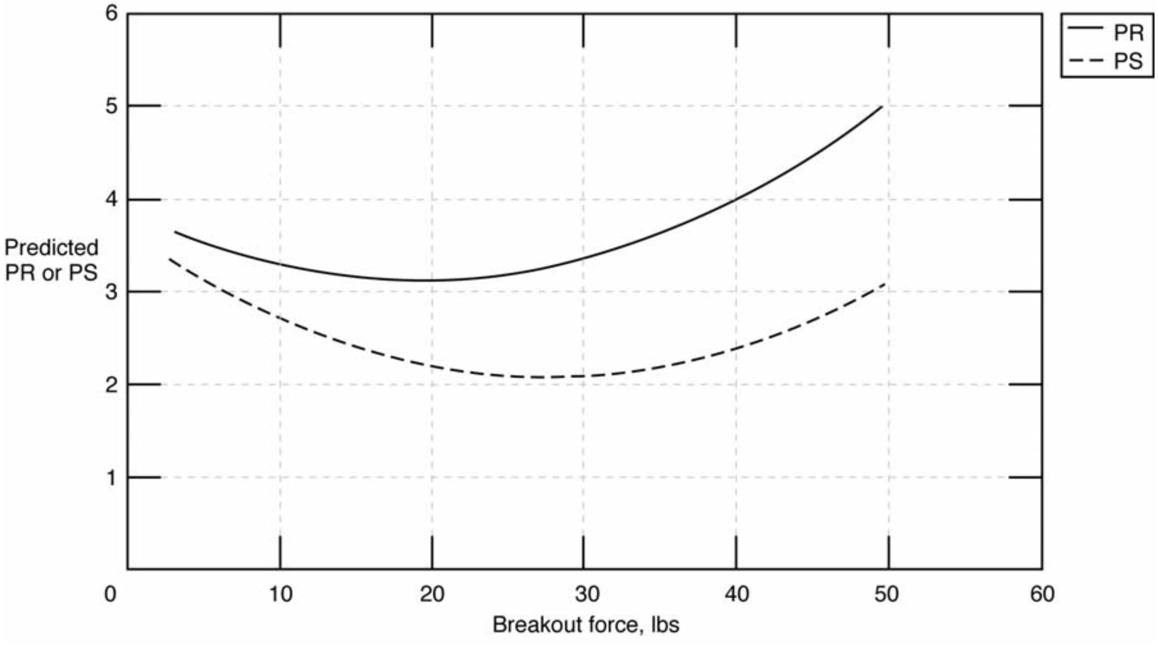


Figure 27. Sensitivity of pilot ratings and peak power spectra values to changes in the break out force. Force at maximum travel = 90 lbs and maximum travel = 2.5 inches.

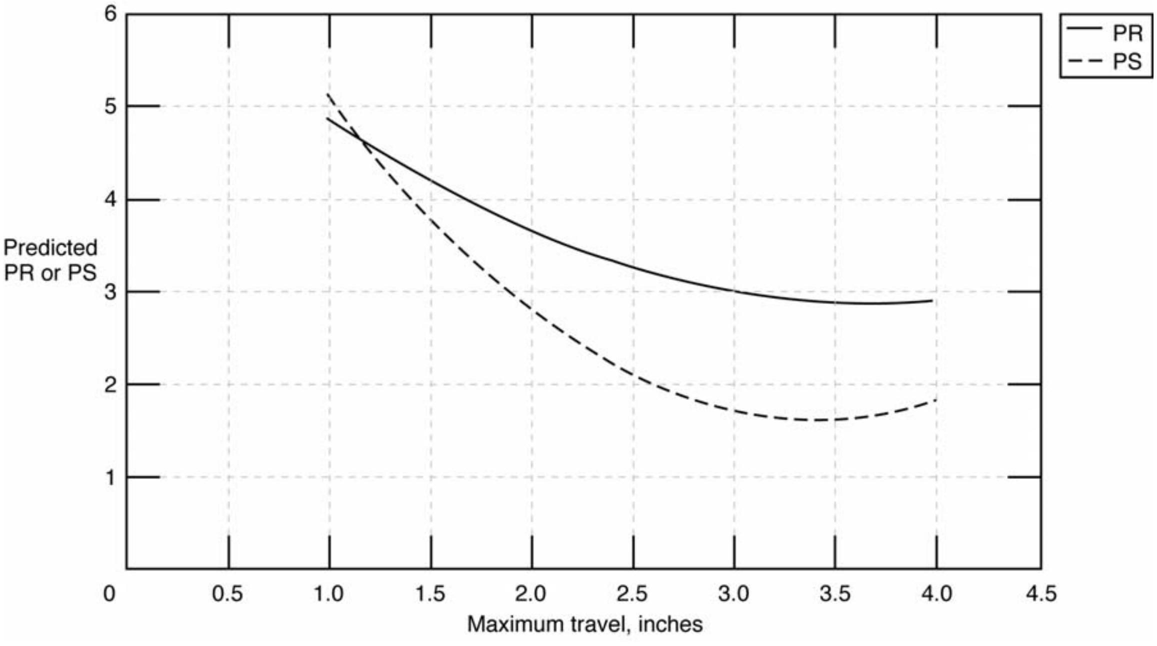


Figure 28. Sensitivity of pilot ratings and peak power spectra values to changes in the maximum travel. Force at maximum travel = 90 lbs and breakout force = 26.5 lbs.

SUMMARY AND RECOMMENDATIONS

The rudder pedal static force feel characteristics of a medium-size commercial transport have been studied on a fixed-base simulator using active airline pilots as test subjects. The pilots assessed the handling qualities for an artificial research maneuver using the C-H rating scale. Pilot inputs and airplane responses were measured and analyzed. The following summarizes the results of this study:

1. A test matrix based on a central composite design was effectively used to evaluate the effects of rudder pedal force breakout, maximum force, and maximum pedal deflection for an artificial research maneuver.
2. A response surface equation was developed to predict the C-H pilot ratings for different combinations of three static rudder pedal force/feel characteristics. This equation is useful for constructing pilot rating contour plots, predicting combinations of pedal characteristics for minimum pilot ratings, and determining sensitivity to changes about a given combination of static rudder pedal force/feel characteristics.
3. An analysis of the cross power spectra of the pilot input and airplane response demonstrated a correlation of the peak values of the cross power spectra with PIOs. A response surface equation was developed to predict the peak values of the cross power spectra. This equation is also useful for constructing contour plots of the peak values, predicting combinations of pedal characteristics for minimum peak values, and determining the sensitivity to changes about a given combination of static rudder pedal force/feel characteristics. The predictions of the pilot ratings and cross power spectra are generally consistent with each other. That is, they show similar trends for the same combinations of pedal force/feel characteristics.
4. Although the airline pilots who participated in this study had limited experience in the use of the C-H rating scale, the central-composite-design/response-surface-equation methodology converged on a consistent average answer for about six pilots. This convergence was in spite of large variations in the individual pilot ratings and the peak values of the cross power spectra.
5. An experimental stereo sound system designed to provide lateral directional cues in the fixed-base simulator was ineffective.
6. It is recommended that future research determine the effects of: (a) simulator motion cues; (b) the research maneuver used; (c) the choice of the nominal pedal force/feel combination; (d) wheel force/feel characteristics; (e) column force/feel characteristics; and (f) the transient directional response to rudder inputs.

REFERENCES

1. Anon., “Part 25 – Airworthiness Standards: Transport Category Airplanes,” Department of Transportation, Federal Aviation Administration, 2002.
2. Chalk, C.R., Neal, T. P., Harris, T. M., and Pritchard, F. C., “Background Information and User Guide for MIL-F_8785B (ASG), ‘Military Specification—Flying Qualities of Piloted Airplanes,’” AFFDL-TR_69_72, Air Force Flight Dynamics Lab, Wright-Patterson AFB, OH, August 1969.
3. Anon “In-Flight Separation of Vertical Stabilizer American Airlines Flight 587 Airbus Industrie A300-605R, N14053 Belle Harbor, New York November 12, 2001,” Aircraft Accident Report NTSB/AAR-04/04 National Transportation Safety Board, Washington, D.C.
4. Lee, B. “Criteria to Select Directional Control Sensitivity,” AIAA Paper 2005-6033, August 2005.
5. Lee, B.; Rodchenko, V.; Zaichik, L.; and Yashin, Yu, “Effect of Pedal Feel System Characteristics on Aircraft HQ,” AIAA Paper 2005-6034, August 2005.
6. Hess, Ronald A. “Certification and Design Issues for Rudder Control Systems in Transport Aircraft,” Journal of Guidance, Control, and Dynamics Vol. 29, No. 5, September-October, 2006.
7. Montgomery, Douglas C. “Design and Analysis of Experiments,” Fifth Edition 2001 John Wiley & Son, Inc; ISBN 0-471-31649-0; QA279.M66200
8. Cooper, George E. and Harper, Robert P.: “The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities,” NASA TN D-5153; April 1969.

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14. ABSTRACT

A piloted simulation study was conducted in a fixed-base research simulator to assess the directional handling qualities for various rudder pedal feel characteristics for commercial transport airplanes. Effects of static pedal force at maximum pedal travel, breakout force, and maximum pedal travel on handling qualities were studied. An artificial maneuver with a severe lateral wind shear and requiring runway tracking at an altitude of 50 feet in a crosswind was used to fully exercise the rudder pedals. Twelve active airline pilots voluntarily participated in the study and flew approximately 500 maneuvers. Pilots rated the maneuver performance with various rudder pedal feel characteristics using the Cooper-Harper rating scale. The test matrix had 15 unique combinations of the 3 static pedal feel characteristics. This analysis found that the peak values of the cross power spectra of the pedal force and heading angle could be used to quantify the tendency toward directional pilot induced oscillations (PIO). Subjective data (Cooper-Harper pilot ratings) were consistent with the objective data (peak values of the cross power spectra).

15. SUBJECT TERMS

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