NATIONAL TRANSPORTATION SAFETY BOARD
Office of Aviation Safety
Washington, D.C. 20594

August 19, 2003

Human Performance

Study Report of Human Performance Ground Test Data
Airbus A300-600 Ground Test

1. ACCIDENT

Operator: American Airlines (flight 587)
Location: Belle Harbor, New York
Date: November 12, 2001
Time: 0916 eastern standard time[1]
Aircraft: Airbus A300-600, N14053
NTSB Number: DCA02MA001

2. HUMAN PERFORMANCE GROUP

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[1] Unless otherwise indicated, all times are Eastern Standard Time, based on a 24-hour clock.

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3. INTRODUCTION

On November 12, 2001, about 0916 eastern standard time, American Airlines flight 587, an Airbus A300-600, was destroyed when it crashed into a residential area of Belle Harbor, New York, shortly after takeoff from the John F. Kennedy International Airport (JFK), Jamaica, New York. Two pilots, 7 flight attendants, 251 passengers, and 5 persons on the ground were fatally injured. Visual meteorological conditions prevailed and an instrument flight rules flight plan had been filed for the flight destined for Santo Domingo, Dominican Republic. The scheduled passenger flight was conducted under Title 14 Code of Federal Regulations (CFR) Part 121.

This report addresses Human Performance issues related to the interaction between a subject and the flight controls on an A300-600 during dynamic activities. All of the activities discussed in this report were performed on the ground. These issues focus on the dynamic force requirements and inputs on each of the three flight control axes through the analysis of the ground test data.

3.1. Background

Much research has been performed on aircraft control forces and their effect on pilot performance during various phases of flight. Controllability is an issue at both high and low force levels. At high force levels, there is a ceiling effect where additional force production is not possible.[2,3] Similarly, variability in force production, referring to the inconsistency of force application when trying to reach a target force level, has been found to increase as the force level increases.[4] At low force levels one study reported increased force variability,[5] which would have interesting consequences for aircraft with light force requirements or for fly-by-wire aircraft. For example, increased force variability may result in inaccurate control movements, making precise inputs on the control system difficult. McDaniel[6] indicated pilots might have a tendency to over-control an aircraft that requires only light control forces. Hewson et al.[7] demonstrated that pilots were least accurate in landing performance on a flight simulator when they were exerting 90% of their maximum force. A trend toward decreased performance was also noted when pilots were at 25% of maximum force levels although differences in force variability were not found between the low and high force levels. The authors concluded that pilots may have been applying the same forces during the low force

[2] Carlton MJ, Robertson RN, Calton LG, et al. Response timing variability: coherence of kinematic and EMG parameters. J Mot Behav 1985; 17:301-19.

[3] Newell KM, Calton LG. Force variability in isometric responses. J Exp Psychol Hum Percept Perf 1988; 14:37-44.

[4] Jenkins WO. The discrimination and reproduction of motor adjustments with various types of aircraft controls. Am J Psychol 1947; 60:397-406.

[5] Sherwood DE, Schmidt RA. The relationship between force and force variability in minimal and near-maximal static and dynamic contractions. J Mot Behav 1980; 12:75-89.

[6] Daniel JW. Strength capabilities for operating aircraft controls. In Aghazedeh F, ed. Advances in industrial ergonomics and safety VI. Washington, DC: Taylor and Francis, 1994; 705-12.

[7] Hewson DJ, McNair PJ, Marshall RN. The effect of aircraft control forces on pilot performance during instrument landings in a flight simulator. Aviat Space Environ Med 2001; 72:617-23.

landing as during the normal force landing and thus, were over-controlling the aircraft. They recommended that designers strike a balance between large and small control forces so that aircraft are controllable during all types of maneuvers.

Performance in force production directly relates to the handling qualities of a vehicle. In addition to force production and accuracy, much work has been conducted to better understand the ergonomic differences between a statically, or quasi-statically,[8] applied force on a control and one that is applied dynamically. Of course, once a control is in motion, its inertia helps it to stay in motion and thus, less force is required to continue the motion. Whereas for a quasi-static motion, the control is moving so slowly that the force required to continue its motion is similar throughout (except if there is a breakout force required to move a control past its neutral position).

Rate saturation of control surfaces can also affect the handling characteristics of a vehicle.[9] Control rate limiting is discussed in the literature when evaluating aircraft pilot coupling issues. Pilot induced oscillation (PIO) categories have been established based on the linearity of the system, where a linear system is a Type I PIO and a system with rate dependencies is labeled as a Type II PIO. A Type III PIO may have more complex and extensive non-linear attributes. Understanding when and how rate dependencies may be encountered on an aircraft is critical in fully comprehending the coupling between pilot and aircraft.

3.2. Purpose

The purpose of the test for the Human Performance Group was to record flight crew input forces applied at the captain or 1st officer's position under dynamic conditions to rudder pedals, control wheel and column, and the corresponding flight control surface positions. These measurements were used as a comparison to the static force versus deflection curves provided in the A300-600 maintenance manual to better understand the interaction between the pilots and the aircraft during dynamic activities.

4. METHODS

4.1. Ground Test Activities

On September 10, 2002 the Human Performance Group convened at the Airbus Facility in Toulouse, France to participate in the ground test. The Human Performance Group, the Systems Group and the Recorders Group were all present to conduct a variety of tests and measurements on an A300-600 provided by Airbus. All activities were performed on the ground. (See Figure 1) Flight tests were not conducted with these activities. The Aircraft Instrumentation Division of the Naval Air Warfare Center in Patuxent River, Maryland was contracted to supply the data system to monitor, record, and process the

[8] For this report, quasi-static refers to the condition where an object is moved but it is moved so slowly that the inertia of the object does not help it to stay in motion.

[9] Aviation Safety and Pilot Control-Understanding and Preventing Unfavorable Pilot-Vehicle Interactions, Committee on the Effects of Aircraft-Pilot Coupling on Flight Safety, Aeronautics and Space Engineering Board, National Research Council, Washington, DC 1997.

series of ground tests. (See Figure 2 for a picture from the test aircraft showing the data processing equipment.)

Figure 1: The A300-600 tested during the ground test activities.

Figure 2: A photograph of the data processing equipment provided by the Aircraft Instrumentation Division of the Naval Air Warfare Center in Patuxent River, Maryland.

4.2. Test Method

The Human Performance Group conducted a variety of tests addressing the pedal, wheel, and column motion only, and also combined motions of pedal and wheel. Four airspeeds were examined: 165, 190, 240 and 325 knots. As this was a ground test, airspeed was altered by an electrical manipulation of the pitot system, which caused the flight controls and control surfaces to act as though the airplane was operating at the designated airspeeds. These four airspeeds represent different amounts of rudder pedal limiting and also different amounts of control column force. For the 165 knot condition, the pedal travel is at its maximum and therefore, this condition can be considered the baseline condition. As the airspeed increases, the pedal travel decreases.

For the wheel and column flight control axes, tests were performed both with two hands moving the controls and with only one hand moving the controls. Tests were also conducted where the subjects were instructed to move the wheel and pedal controls to 100% of the available range and also to only 50% of the available range. Feedback was not provided to the subjects concerning the control displacement.[10] The rates of control movement were approximately 0.25 Hz (or one cycle every four seconds), 0.5 Hz, and 1 Hz. These rates were chosen to bracket the input rates seen on the accident aircraft.

Subjects were placed in the cockpit of the A300-600 and asked to perform a variety of tasks involving use of the rudder pedals, control wheel, and control column. Each subject performed a total of 108 exercises or tests. For each exercise, the subject moved the controls at the assigned rate for approximately four cycles. Auditory cues were provided to the subjects to indicate the rate at which to move each of the flight controls. Each condition was repeated once before moving onto the next flight control axis. Table 1 and Table 2 are the matrices detailing each of the tests. Subjects first moved the pedal only with the conditions of airspeed and frequency randomized. The next exercises were the two-handed[11] wheel exercises,[12] followed by the two-handed column exercises. Again, the conditions of airspeed and frequency were randomized. The next two exercises were the one-handed wheel, at the 1.0 Hz frequency, and the one-handed column, also at the 1.0 Hz frequency. After these tests were completed, exercises were performed using both the pedal and wheel simultaneously. The first exercise was a two-handed exercise moving both the pedal and wheel to the full travel, with airspeed and frequency randomized. Subjects were then asked to perform this exercise at the 0.25 Hz and 1.0 Hz frequency only while moving the controls to half of their full displacement. Finally, subjects attempted to recreate the flight control motions from the 587 accident flight, without feedback, using both two-hands on the controls and only one-hand on the controls at the 240 knot airspeed.

Table 1: A matrix detailing the single axis tests conducted by the Human Performance Group with the aircraft powered by three hydraulic power carts and ground electrical power.

	Flight Control Axes								
			Two-Handed				One-Handed		
Airspeed (knots)	Pedal		Wheel		Column		Wheel	Column
	Frequency (Hz)		Frequency (Hz)		Frequency (Hz)		Frequency (Hz)	Frequency (Hz)
165	0.5	1.0	0.5	-	0.5	1.0	1.0	1.0
190	0.5	1.0	0.5	-	0.5	1.0	1.0	1.0
240	0.5	1.0	-	1.0	0.5	1.0	1.0	1.0
325	0.5	1.0	-	1.0	0.5	1.0	1.0	1.0

[10] Beyond proprioceptive feedback.
[11] Both hands were on the control wheel.
[12] The characteristics of the wheel do not change as airspeed changes and therefore, a more limited set of tests was performed for the wheel only condition. In addition, for the wheel only condition, each test was performed only once, whereas the test was repeated for all of the other conditions.

Table 2: A matrix detailing the tests with both wheel and pedal conducted by the Human Performance Group with the aircraft powered by three hydraulic power carts and ground electrical power.

	Flight Control Axes – Wheel and Pedal Simultaneously						
	Two-Handed						One-Handed
Airspeed (knots)	Full Displacement (100%)			Half Displacement (50%)		Mimic 587 Flight	Mimic 587 Flight
	Frequency (Hz)			Frequency (Hz)		Frequency (Hz)	Frequency (Hz)
165	0.25	0.5	1.0	0.25	1.0	-	-
190	0.25	0.5	1.0	0.25	1.0	-	-
240	0.25	0.5	1.0	0.25	1.0	Accident[13]	Accident
325	0.25	0.5	1.0	0.25	1.0	-	-

Three subjects participated in the Human Performance Group ground tests. These subjects were familiar with the A300-600 and were type rated on the aircraft. Two of the subjects were test pilots.

For all of the tests listed in Table 1 and Table 2 above, the test aircraft was powered with three hydraulic power carts and ground electrical power. During these activities and during the February 2002 activities in Tulsa, OK,[14] subjects experienced an increased force in the wheel when the wheel was moved at the 1.0 Hz frequency. In order to be certain that these increased forces in the wheel were a result of aircraft design rather than inadequate power from the hydraulic carts, an additional 15 tests were performed with the aircraft tethered outdoors and with various ranges of engine power applied. These tests are shown in Table 3 below. (Only subjects 1 and 3 participated in this portion of the testing.) Both the wheel and pedal were moved simultaneously for the engine tests.

4.3. Instrumentation

The Aircraft Instrumentation Division from Patuxent River, Maryland provided two pieces of instrumentation to directly support the Human Performance Group testing. The first piece was an instrumented A300 pilot's control wheel. The wheel was instrumented with strain gauges to measure the longitudinal force (control column force) and lateral force (control wheel force). (See Figure 3) The second was a bending beam transducer assembly, which was installed on the rudder pedals to measure force. See the Instrumentation System Report for further details.[15]

[13] The label 'Accident' indicates that subjects attempted to move the controls at the rate of the accident flight and in the same order.
[14] Refer to the Human Performance Group Addendum 1 in the docket.
[15] TAP01-05-533, Instrumentation System For Airbus A300, MSN 701 NTSB Ground Test, available on the NTSB Public Docket System.

Table 3: A matrix detailing the tests conducted by the Human Performance Group with the aircraft powered by the engines.

Subject	Engine Power	Airspeed (knots)	Frequency (Hz)
3	65% N2	165	0.5
			1.0
		240	Accident
	80% N2	165	0.5
			1.0
		240	Accident
	95% N2	165	0.5
			1.0
		240	Accident
	94% N1	240	Accident
1	95% N2	165	0.5
			1.0
		240	Accident
	95% N1	165	0.5
		240	Accident

Figure 3: The instrumented control wheel.

4.4. Measurements

A variety of data was collected during the Human Performance Group ground tests. The parameters most essential to the Human Performance Group were the time history of the forces applied to the flight controls: rudder pedal force, control wheel force,[16] and control

[16] Although the control wheel motion is angular, the instrumentation provided by Aircraft Instrumentation Division from Patuxent River, Maryland calibrated the strain in the wheel to force. Control wheel torque

column force. Also essential were the deflection of the flight controls and the deflection of the corresponding flight control surfaces over time. A variety of other parameters were collected but were not included for this study.

4.5. Airbus Force Versus Deflection Characteristics for the A300-600

To adequately compare the results of the ground test data to the Airbus defined static force feel system[17] of the A300-600, the characteristics of the aircraft are defined in Table 4.

Table 4: A table of the force versus deflection limits for the roll and yaw axis, as defined by Airbus.

	Airspeed (knots)			
Limits	**165**	**190**	**240**	**325**
Rudder Limit (deg)	±30	±23	±11	±4.6
Pedal Limit (deg)	±21	±16.7	±8.9	±4.4
Pedal Force (lbf)	66.1	54.1	35.3	25.6
Aileron Down Limit (deg)	19	19	19	19
Aileron Up Limit (deg)	23	23	23	23
Wheel Limit (deg)	±78	±78	±78	±78
Wheel Force (lbf)	11.2	11.2	11.2	11.2

The steady-state load felt at the control column is proportional to actuator extension. The actuator extension is dependent on the Mach number. The values for 0 mm of actuator extension for elevator nose down and nose up are 15 deg and 30 deg, respectively. The column nose down and nose up limits at 0 mm extension are 25.5 deg and 30.5 deg, respectively. The corresponding column nose down force and nose up force are 33.7 lbf and 67.41 lbf, respectively.

5. RESULTS

Time histories of the flight control motions for the tested airspeeds are graphed in Attachments I, II, and III for subjects 1, 2, and 3, respectively.[18] Only the two handed conditions were graphed. A comparison between the static force feel system, the dynamic forces applied to the pedal, the rudder surface displacement, and the pedal surface displacement are shown in Attachment IV. In addition, Attachment IV shows the comparison between the static force feel system, the control wheel displacement and the control wheel force. For Attachment IV, the data shown represents the first subject only.

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was then calculated based on the radius of the wheel. In addition, Airbus reports the control wheel force versus deflection in their A300-600 Aircraft Maintenance Manual.

[17] Defined in the Airbus A300-600 Aircraft Maintenance Manual.

[18] In the attachments, the input frequencies 0.25 Hz, 0.5 Hz, and 1.0 Hz are sometimes labeled slow, medium, and fast for comparison purposes. These labels are not intended to reflect a pilot's perception of the control input rate as all three rates might be considered relatively rapid for many transport flying applications.

5.1. Pedal and Wheel Forces and Displacements

Table 5 and Table 6 provide an overall summary of the results from the wheel and pedal exercises. These tables show the average peak force for three cycles applied both to the pedal and wheel. Table 5 details the condition where the controls are moved to full travel or 100%, while Table 6 details the condition where subjects were asked to displace the controls to half of full travel or 50%. For both the 100% condition and the 50% condition, only the 240 knots airspeed is shown.

Table 5: A comparison of the average peak force applied to the pedal and wheel when displaced to full travel at 240 knots. The standard deviation is shown in parentheses.

	Pedal Force (lbf)			Wheel Force (lbf)		
Rate (Hz)	Subject 1	Subject 2	Subject 3	Subject 1	Subject 2	Subject 3
0.25	61.1 (9.4)	137.4 (22.3)	78.4 (14.0)	28.2 (2.5)	33.6 (2.7)	44.5 (20.8)
0.5	130.2 (34.3)	113.7 (7.7)	116.0 (21.7)	93.5 (15.8)	80.8 (18.9)	62.5 (22.1)
1.0	138.3 (14.5)	125.6 (10.1)	99.3 (20.0)	129.4 (29.8)	112.1 (12.6)	77.4 (26.3)

Table 6: A comparison of the average peak force applied to the pedal and wheel when displaced to 50% of full travel at 240 knots. The standard deviation is shown in parentheses.

	Pedal Force (lbf)			Wheel Force (lbf)		
Rate (Hz)	Subject 1	Subject 2	Subject 3	Subject 1	Subject 2	Subject 3
0.25	32.8 (1.5)	30.2 (6.4)	32.6 (3.6)	16.7 (3.0)	20.3 (3.2)	19.0 (2.3)
-	-	-	-	-	-	-
1.0	34.4 (7.7)	65.8 (19.7)	39.6 (5.6)	52.6 (20.8)	60.2 (19.6)	31.8 (8.7)

Since the 0.25 Hz frequency gave subjects the most opportunity for controlled input, the average peak force values for this input frequency were summarized for each of the four airspeeds in Table 7. Figure 4 shows these peak forces as compared to the Airbus A300-600 static-force feel design.

Table 7: A comparison of the average peak force applied to the pedal and wheel for each of the four airspeeds at the 0.25 Hz frequency (100% of full motion). The standard deviation is shown in parentheses.

Airspeed	Pedal Force (lbf)			Wheel Force (lbf)		
(knots)	Subject 1	Subject 2	Subject 3	Subject 1	Subject 2	Subject 3
165	74.7 (7.2)	68.8 (4.8)	75.2 (21.3)	35.3 (6.5)	32.6 (5.0)	52.2 (14.8)
190	62.2 (6.5)	76.6 (11.4)	58.8 (4.8)	33.0 (3.6)	38.0 (4.7)	31.3 (3.3)
240	61.1 (9.4)	137.4 (22.3)	78.4 (14.0)	28.2 (2.5)	33.6 (2.7)	44.5 (20.8)
325	72.2 (25.0)	115.7 (17.9)	90.9 (22.3)	30.2 (3.7)	30.9 (4.5)	36.3 (8.7)
Average	**67.6 (14.6)**	**99.6 (23.4)**	**75.8 (19.8)**	**31.7 (4.9)**	**33.8 (4.8)**	**41.1 (15.1)**

Figure 4: A comparison of the average peak force applied to the pedal for each of the four airspeeds at the 0.25 Hz frequency (100% of full motion). The force requirements based on the A300-600 design are also plotted for reference.

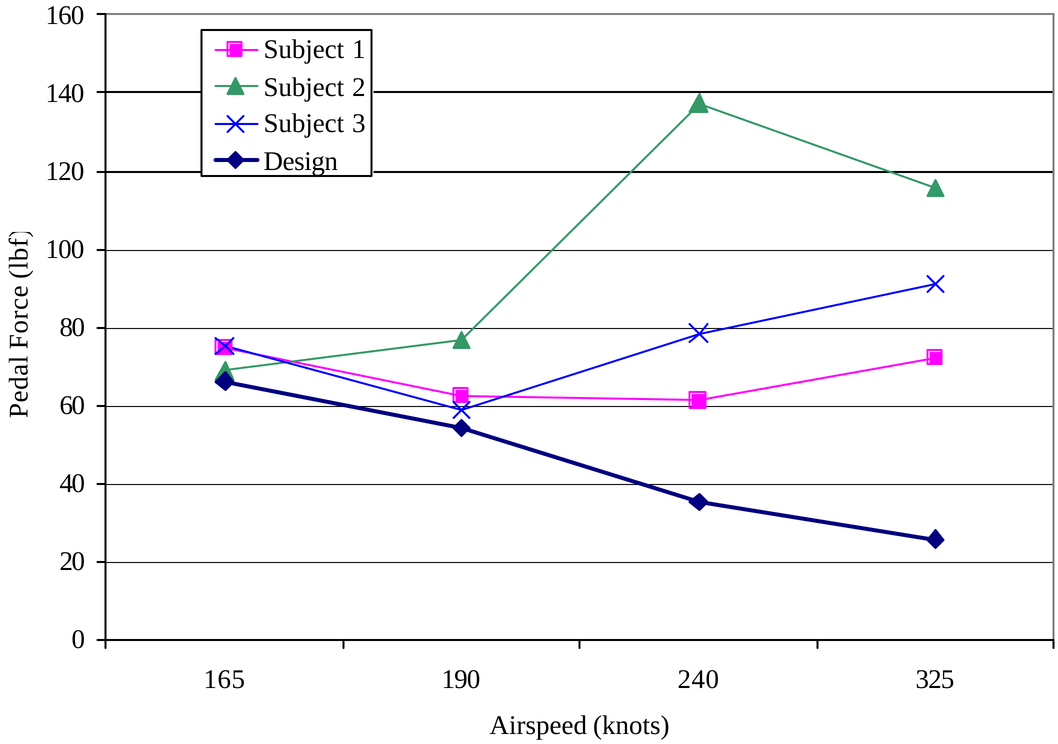


Table 8: A comparison of the amount of rudder pedal travel and applied pedal force used to reach full rudder travel for the 0.25 Hz frequency condition (100% of full motion).

	Subject 1			Subject 2			Subject 3		
Airspeed (knots)	Pedal (deg)	Rudder (deg)	Force (lbf)	Pedal (deg)	Rudder (deg)	Force (lbf)	Pedal (deg)	Rudder (deg)	Force (lbf)
165	20.2	30.3	82.5	18.4	30.3	56.9	20.5	30.3	58.6
190	14.6	22.8	68.2	13.4	22.8	54.5	13.1	22.7	43.3
240	7.4	9.8	41.4	7.2	10.0	48.1	7.6	10.1	54.6
325	3.6	3.6	42.5	3.3	3.6	33.8	4.6	3.6	66.5

*All values were taken from input of right pedal.

The amount of pedal travel and pedal force used to reach full rudder surface travel is shown in Attachment I through III and is also summarized in Table 8. Full rudder travel here is defined as the first time the rudder surface reaches the plateau point seen in the attachments. Therefore, the pedal travel and pedal force are not the maximum values but rather the values required to first reach full surface travel. In Table 8, the values were taken from the 100% condition when both the wheel and pedal were exercised at the 0.25 Hz frequency. The faster frequency conditions showed a greater tendency for system compliance, which in this case is referring to the increase in pedal travel without an equivalent increase in rudder surface travel. Even at the 0.25 Hz condition at 325 knots, this pattern was seen in the results for subject 3 who showed more than 1 degree greater pedal travel than the other two subjects displayed.

5.2. Compliance in the Rudder System

The amount of compliance in the rudder system[19] can be quantified by subtracting the maximum pedal travel in the 0.25 Hz frequency from the maximum pedal travel in the 1.0 Hz frequency, since higher forces were applied during the faster frequency conditions.[20] The higher forces should therefore result in greater pedal displacement and greater amounts of compliance than the lower forces. Again looking at the exercise where both pedal and wheel were moved simultaneously to 100% of full travel, the maximum displacement of the right pedal during the 0.25 Hz and 1.0 Hz frequency inputs was taken at each airspeed. The values were then averaged for each subject and the results are shown in Table 9.

Table 9: The amount of rudder system compliance determined based on the average maximum pedal displacement for a right pedal input applied during the 1.0 Hz frequency and the 0.25 Hz frequency input. The standard deviation for the three subjects is shown in parentheses.

	Averaged Values for Three Subjects		
	Maximum Pedal Displacement (deg)		Compliance (deg)
Airspeed (knots)	0.25 Hz	1.0 Hz	
165	20.2 (1.3)	17.1 (2.7)	-3.1
190	15.2 (0.5)	16.9 (1.5)	1.7
240	9.5 (0.7)	11.6 (0.5)	2.1
325	6.0 (1.2)	7.6 (1.1)	1.6

5.3. Control Surface Rate Saturation

Rate saturation can be seen in many of the 0.5 Hz and 1.0 Hz frequency conditions graphed in Attachments I through III and even in a few of the 0.25 Hz frequency conditions.[21] Saturation was seen when the surface rate changed from a smooth wave to a square wave. Similarly, when examining the surface position, rate saturation resulted in a constant change in surface position over time. Rate saturation occurred during the transition between full wheel input in one direction to full wheel input in the other direction or for the same scenario with pedal input. Figure 5 and Figure 6 show the rate limiting which occurred in the rudder and aileron systems at the 0.5 Hz and 0.25 Hz frequencies, respectively. As the input frequency increased, rate limiting became more pronounced.

[19] Compliance in the rudder system may result from several factors but predominately the compliance is the result of 'elastic cable stretch'.

[20] Only the maximum displacements were examined, rather than looking at amounts of compliance throughout the entire period, to indicate the maximum compliance possible in these test scenarios.

[21] Hess, RA, Time delay effects on systems subject to manual control, Journal of Guidance, Control and Dynamics, 1984, 7(4):416-421.

Figure 5: A pedal graph from Attachment 1 showing the 0.5 Hz frequency condition at 240 knots for subject 1. The vertical red lines highlight the rate limiting occurring in the rudder system.

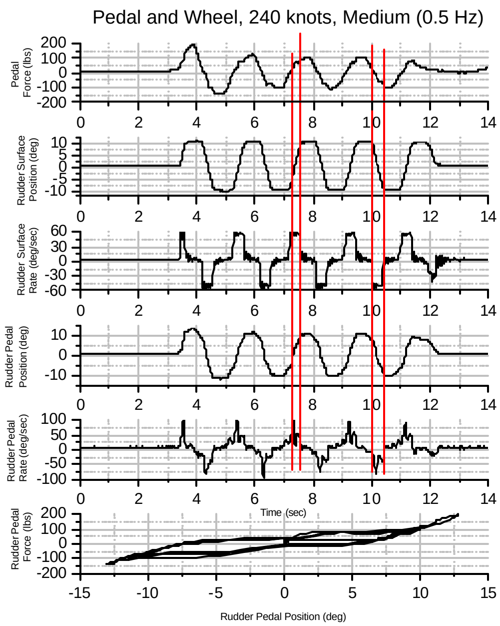


Figure 6: A wheel graph from Attachment 1 showing the 0.25 Hz frequency condition at 240 knots for subject 1. The vertical red lines highlight the minor rate limiting occurring in the aileron system.

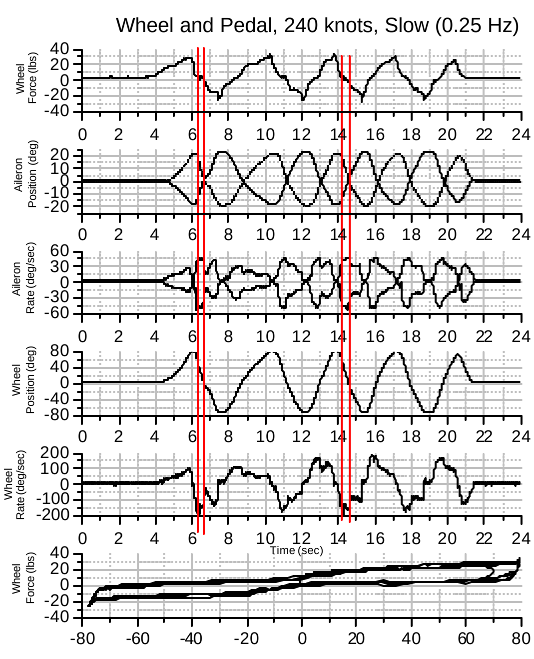
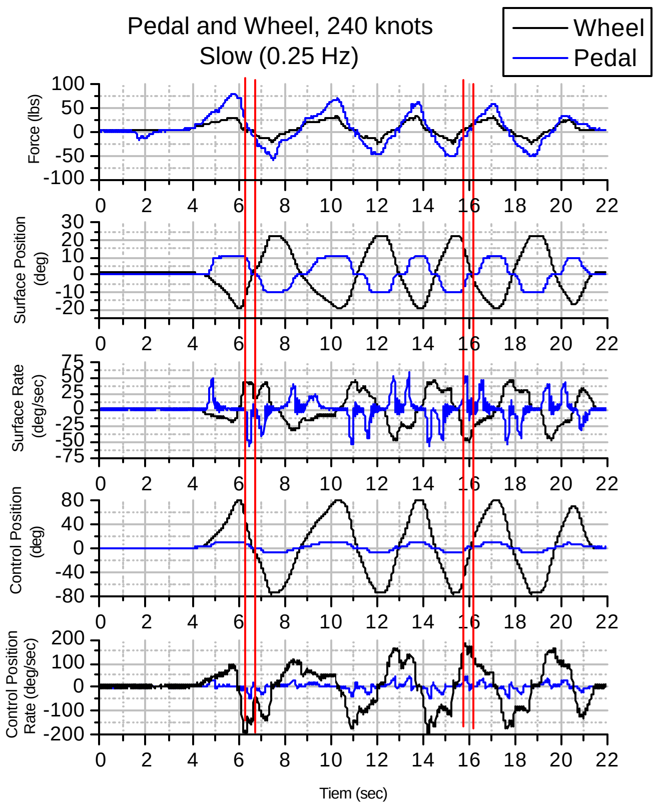


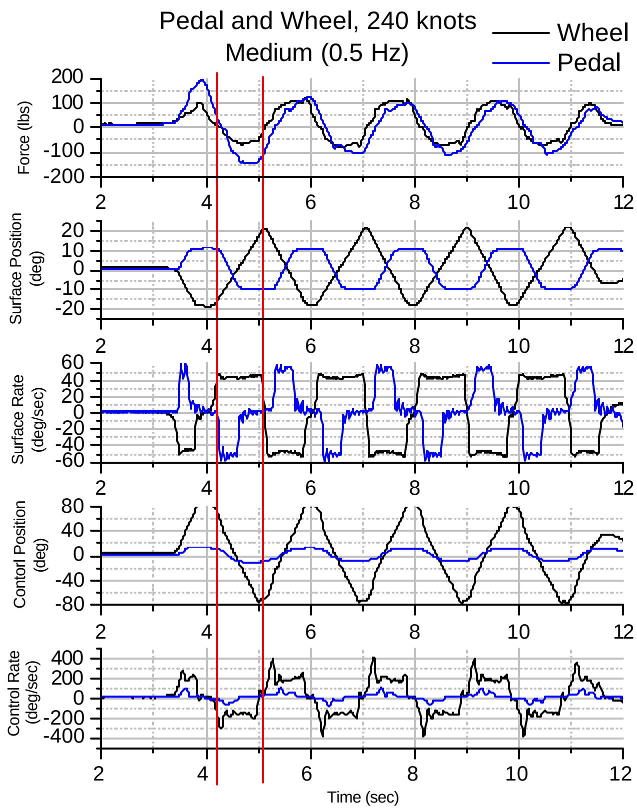
Figure 7 shows an overlay of the wheel and pedal time histories for the 240 knots, 0.25 Hz frequency condition. In the graph, the periods of minor aileron rate limiting are denoted with the vertical red lines. This time period also corresponds to the higher rudder surface rate of deflection indicating a change in direction. Variations in force are not seen for the wheel or pedal during this period.

Figure 7: An overlay of the time histories for the pedal and wheel during the 240 knots, 0.25 Hz frequency condition. (Subject 1) The left aileron deflection and rate are shown in these plots.



For the 0.5 Hz frequency under the same conditions, the wheel rate saturation lasted for a longer time period. Interestingly, during this period the rudder surface was also saturated but when looking at the surface deflection for the rudder and aileron, the rudder reached full deflection prior to the aileron reaching full deflection. Similarly, the rudder surface was at full deflection for a longer time period than the aileron since the direction of the deflection reversed once the aileron reached the stop. (See Figure 8)

Figure 8: An overlay of the time histories for the pedal and wheel during the 240 knots, 0.5 Hz frequency condition. (Subject 1) The left aileron deflection and rate are shown in these plots.



5.4. Comparison of Engine Run Tests to Hydraulic Cart Tests

Time histories of the flight control motions for the engine run conditions are graphed in Attachment V for many of the conditions tested. Attachment V also contains two graphs comparing the engine run test to the hydraulic cart test for the 165 knot condition, subject 1, at the 0.5 Hz frequency.

6. DISCUSSION

6.1. Pedal and Wheel Forces and Displacements

It is interesting to compare the 50% versus 100% of full motion for the wheel and pedal. For the 0.25 Hz frequency, both the wheel deflection and the aileron deflection reached 100% and 50% of full travel for each respective condition.[22] At the 1.0 Hz frequency, the rate of aileron deflection was not rapid enough for the aileron to reach full travel despite full travel of the wheel but the 50% condition still showed half of full displacement on the wheel and aileron. For the pedal, the same pattern was not seen. Even though the force applied by subject 3 to the pedal was half of the applied force for the 100% travel

[22] Subject 1 displaced the wheel slightly more than 39 degrees or half of full displacement and therefore, aileron deflection was also slightly greater than half of full displacement.

case at the 0.25 Hz input frequency, the resulting displacement of the rudder surface was still full travel.[23] Similar results were seen for subject 2. Yet for subject 1, despite similar levels of force application during the 50% condition, rudder surface deflection was less than full travel. This result appears to be related to the rate of pedal input. Subject 1 did not show as many rate variations during the 0.25 Hz condition as the other two subjects did.

Pilots do not typically make control inputs when flying based on percentages of full travel but instead rely on the observed motion of the aircraft resulting from their inputs. As a result, during a first input the pilot must wait for the plane reaction, which means from a control theory perspective, the first input is open-loop and its magnitude is based on prior experience and knowledge. In the ground test, the pedal force applied during the 50% condition was half the pedal force applied at the 100% condition but the resultant rudder surface motion was still full travel, whereas for the wheel, the reduced force resulted in reduced aileron deflection.

The slowest frequency tested in the Human Performance ground test was the 0.25 Hz condition, which represents the best-case scenario for controllability in the Human Performance test matrix. For each subject, the pedal forces applied at each of the three higher airspeeds (190, 240 and 325 knots) were either similar to the forces applied at the baseline airspeed of 165 knots or were greater than the baseline force. (See Table 7 and Figure 4.) A similar result was seen for the applied wheel forces.

Interestingly, according to the design of the A300-600, the amount of force required to achieve full pedal travel decreases as the airspeed increases while the force to maximum travel on the wheel is independent of airspeed. (See Table 4.) So, the results of the ground test indicated that the applied pedal forces at airspeeds above 165 knots were greater than required by the system to reach full travel. For the control wheel, on the other hand, the applied forces in the ground test were consistent with the design of this control system. These results are similar to those found by Hewson et al.[7] In that research, the authors felt that pilots were applying the same forces during the low force landing as during the normal force landing. Similarly, these results indicate that the three subjects applied similar or higher pedal force values over all airspeeds despite a decrease in the force required to achieve maximum pedal travel. As Hewson et al. suggested, this may be an indication of the potential for over control.

In addition, according to the quasi-static force-feel system for the rudder, a pedal force of 66.1 lbf is necessary to reach full travel at 165 knots. The average value for all three subjects was almost always above this value and in fact, the lowest average peak force was applied during the 240 knots condition for subject 1 (61.1 lbf). Similarly for the control wheel, the quasi-static force-feel system indicates a maximum force of 11.2 lbf while the forces applied during the ground test were typically between 30 and 40 lbf. For the column or pitch system, differences in elevator surface deflection or column deflection were not large comparing over airspeed. Force applied to the column varied

[23] At 250 knots, a quasi-static pilot force of only about 32 lbf is necessary to move the rudder surface to full travel.

between –125 lbf and 200 lbf and the column position varied between ±12 deg for the 0.5 Hz frequency input at all tested airspeeds. Elevator deflection varied between approximately –15 deg and 29 deg for all airspeeds.

When only looking at the force required to first obtain maximum rudder surface deflection[24] in Table 8, there appeared to be a decrease in the force required to reach full rudder surface travel as airspeed increased for subjects 1 and 2 but not for subject 3. Even so, the applied forces were generally higher than those defined by the quasi-static force feel system in Table 4.

6.2. Compliance in the Rudder System

The amount of rudder system compliance calculated by subtracting the 0.25 Hz frequency inputs from the 1.0 Hz frequency inputs ranged between 7.9% and 10.3% of the full pedal travel at 165 knots. Interestingly, the maximum pedal displacement at the 165 knot condition during the 1.0 Hz frequency input was always less than the maximum pedal displacement during the 0.25 Hz frequency input. This may result because it was difficult to displace the rudder pedal to full travel at high rates of motion whereas when the pedal was moved at a slower rate, full travel was achieved.

6.3. Control Surface Rate Saturation

Rate saturation may affect the handling characteristics of an aircraft and has been associated with pilot induced oscillations.[9] Moving the controls at the rates in the ground test resulted in some amounts of rate saturation in the control surfaces. The rudder surface appeared to saturate somewhere between the 0.25 Hz input frequency and the 0.5 Hz input frequency for the 240 knot condition since rate limiting was not seen at the 0.25 Hz frequency but was observed at the 0.5 Hz frequency. Rudder pedal rates at the 0.25 Hz frequency ranged between 0-45 deg/sec while for the 0.5 Hz frequency the pedal rates ranged between 0-100 deg/sec. For the 1.0 Hz frequency, pedal rates peaked at approximately 150 deg/sec.

The ailerons appeared to also saturate somewhere between the 0.25 and the 0.5 Hz range. Wheel rates were about 100-200 deg/sec for the 0.25 Hz frequency whereas they were between 200-400 deg/sec for the 0.5 Hz frequency. Wheel rates for the 1.0 Hz frequency were between 200-600 deg/sec.

For the elevator system, rate saturation was seen at the lowest airspeed during the 0.5 Hz frequency input.[25] The saturation was similar for each of the tested airspeeds. Column rate varied between –100 deg/sec and 150 deg/sec at 165 knots but decreased to approximately ±100 deg/sec at 325 knots. Elevator rates were consistently limited to 40 deg/sec.

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[24] Ideally, at the 0.25 Hz frequency, the rate of pedal input is slow enough such that the rudder surface can reach full travel without significant lag and prior to large amounts of compliance in the system.
[25] The column was not exercised at the 0.25 Hz input frequency.

6.4. Comparison of Engine Run Tests to Hydraulic Cart Tests

Similar results were seen between the engine run tests at the level of 95% N1 and the tests run with the hydraulic carts. This result is consistent with the comments made by the subjects during the engine run tests. Therefore, the feel of the control systems using the hydraulic carts can be assumed to represent the feel of the control systems with high engine power running the aircraft.