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

December 23, 2003

Human Performance

GROUP CHAIRMAN'S FACTUAL REPORT
ADDENDUM 2

REPORT BY RONALD A. HESS
"AN INQUIRY INTO WHETHER A PILOT-INDUCED OSCILLATION WAS A FACTOR IN THE CRASH OF AMERICAN AIRLINES FLIGHT 587"

A. ACCIDENT

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

B. HUMAN PERFORMANCE GROUP CHAIRMAN:

Malcolm Brenner, Ph.D.
National Resource Specialist -- Human Performance
National Transportation Safety Board

B. ACCIDENT SUMMARY

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.

C. DETAILS OF THE INVESTIGATION

At the Safety Board's request, Dr. Ronald A. Hess prepared the attached report concerning whether pilot-induced oscillations (PIO) might explain the high amplitude control inputs made by the flying pilot during the accident sequence.

Dr. Hess is Professor and Vice-Chairman of the Department of Mechanical and Aeronautical Engineering at the University of California, Davis. He holds a Ph.D. in Aerospace Engineering from the University of Cincinnati and served previously as a Research Scientist at the NASA-Ames Research Center. He served as a member of the National Research Council Committee on the Effects of Aircraft-Pilot Coupling on Air Safety (1996-97)[1] and his publications include numerous articles on aircraft stability and control issues.[2] Dr. Hess is recipient of the Mechanics and Control of Flight Award (August, 2000) of the American Institute of Aeronautics and Astronautics (AIAA).

Dr. Hess discussed PIO issues with the Human Performance Group at its meeting on February 19-21, 2003 in Washington, DC. Following the meeting, all members of the Human Performance Group agreed to his qualifications to provide an expert opinion on the possible role of PIO in the accident and the Safety Board requested Dr. Hess' to prepare the enclosed report.

Submitted By:

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Malcolm Brenner, Ph.D.
National Resource Specialist--Human Performance

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[1]The committee produced the text: *Aviation Safety and Pilot Control – Understanding and Preventing Unfavorable Pilot-Vehicle Interactions*, National Academy Press, Washington D. C., 1997.

[2] E.g. Hess, R. A. (2002). Pilot control. In *Principles and Practice of Aviation Psychology* (Eds: P. S. Tang, M. A. Vidulich), Mahwah, N.J.: Erlbaum (Chapter 8). Hess, R. A. (2002). Aircraft Dynamics and Control. In Wiley *Online Encyclopedia of Electrical and Electronics Engineering* (Ed: J.G. Webster).

An Inquiry into Whether a Pilot-Induced Oscillation was a Factor in the Crash of American Airlines Flight 587

A Report Submitted to the National Transportation Safety Board

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Executive Summary

The name *pilot-induced* oscillation (PIO) has led to an unfortunate and misleading implication, i.e., that a PIO is the fault of the pilot. Suffice to say, serious PIOs can nearly always be traced to one or more control system characteristics that are conducive to PIOs and not to poor piloting skills or aberrant pilot behavior.

This report discusses the phenomenon of pilot-induced oscillations and demonstrates that pilot control activity in the moments before loss of AA 587 is consistent with such a phenomenon. In addition, a control system characteristic possibly conducive to PIO is identified.

I. Introduction

This report is outlined as follows. Section II defines a pilot-induced oscillation (PIO) and the conditions that surround such events. Section III examines the AA 587 accident with emphasis upon PIO as a factor. Conclusions are drawn in Section IV.

II. The PIO Phenomenon

A. Definition

A pilot-induced oscillation is a phenomenon that can occur when a pilot is attempting precise control of an aircraft. As the name PIO implies, oscillations develop in the aircraft's response variables, e.g., pitch or roll attitude. A PIO is distinguished from aircraft oscillations caused by deliberate, pilot-imposed periodic control motions in that, in a PIO, the oscillatory motions are unintended. The figure below is taken from Ref. 1 and illustrates a PIO that occurred in the flight test of an Air Force C-17 transport aircraft. This event occurred in a landing approach. The C-17 is a large vehicle, and was chosen here to demonstrate that PIOs are not restricted to small, high performance aircraft such as fighters. The PIO in question is a so-called lateral-directional PIO since the variables involved (lateral control stick deflection, roll-rate, roll-attitude, etc) are each concerned with the lateral-directional motion of the aircraft [2]. The PIO, itself, is evident in the traces from about t = 25 sec to t =35 sec in this figure.

These oscillations are distinguished from the other control/response oscillations by their magnitude and regularity. As Fig. 1 indicates, the PIO was effectively eliminated by the pilot sharply reducing lateral stick inputs from t = 35 sec to t = 42.5 sec.

The oscillations apparent in Fig. 1 may appear at first glance to be little more than a transitory annoyance. However one must realize that, in the 10 sec period in which the oscillations are apparent, the pilot has effectively lost control of the aircraft. The fact that the incident occurred in a landing approach obviously made it quite dangerous. In an environment in which large dynamic pressures[1] are in evidence, a PIO can lead to structural failure. One such event occurred at White Sands NM on May 18, 1961. An Air Force F-4 fighter aircraft was attempting to set a low-altitude 3 kilometer speed record. A longitudinal PIO developed in the attempt and the aircraft disintegrated due to the extreme aerodynamic forces caused by high-dynamic pressure [3].

[1] dynamic pressure = 0.5*(air density)x(aircraft velocity)^2

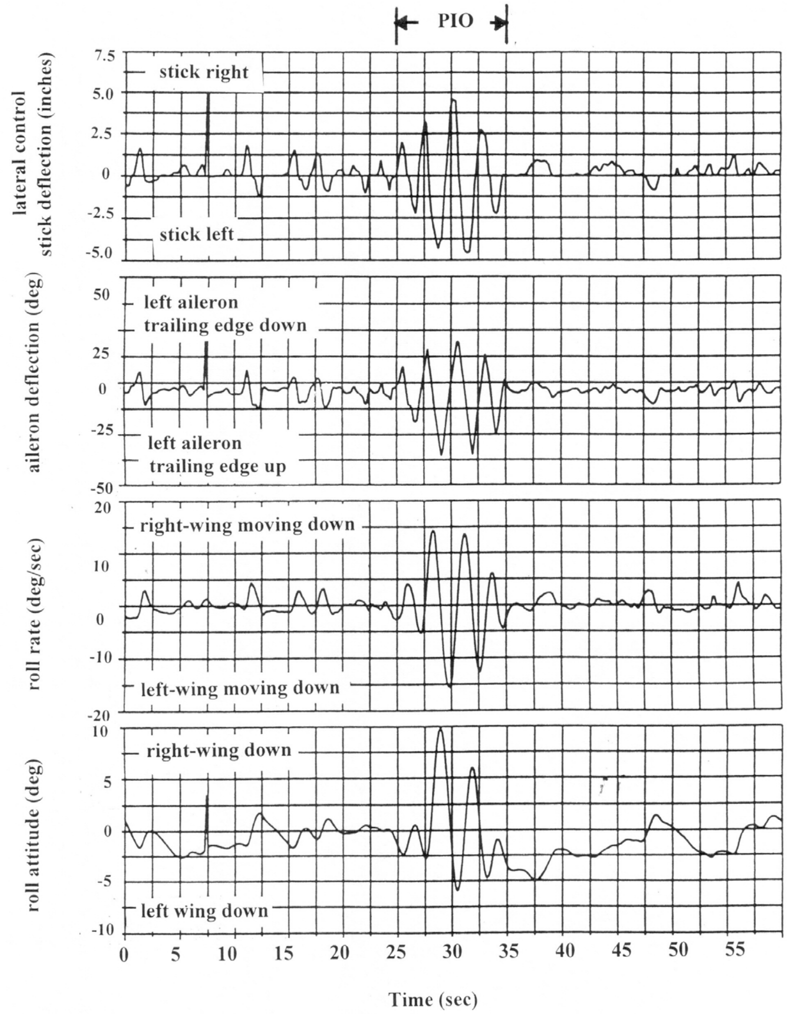

Figure 1 C-17 lateral-directional PIO

Nearly all adverse pilot/aircraft interactions, including such phenomena as PIOs, only become apparent when the pilot is involved in relatively "high-gain" closed loop tracking. Pilot "gain" is the sensitivity with which the pilot reacts to a given stimulus. If the situation is deemed urgent, the pilot is likely to react with large corrective inputs even for small stimuli. When this happens, the pilot is said to be exhibiting "high gain" behavior. More relaxed responses imply a lower pilot gain [3]. "Tracking" involves the pilot's adaptation of *compensatory* control behavior in which he/she is attempting to null some perceived system "error". Here error is not used in the more traditional sense to indicate some type of malfunction, whether human or mechanical, but in a control system sense, to indicate that the vehicle response variable of interest is not at some desired or commanded value. For example, in an instrument landing system (ILS) approach, an "error" might be defined as the aircraft being to the left or right of the localizer beam. Compensatory pilot behavior can be contrasted to "higher" levels of pilot control activity such as *pursuit* or *precognitive* behavior [3]. The latter can be exemplified by the pilot's inputting a rehearsed series of control inputs to the vehicle, with little dependence upon the perceived vehicle response. An example of precognitive behavior in automobile driving is the somewhat automatic driver response of steering out of a slide on an icy road.

B. Triggering Events

PIO incidents are almost invariably preceded by a “triggering” event [3]. A trigger is a stimulus that can cause a pilot to change his/her control behavior. Triggers have been categorized as (a) Environmental Triggers (such as those caused by turbulence encounters or task-induced stress), (b) Vehicle Triggers (such as those that involve changes in the vehicle dynamics that cause a mismatch between pilot control strategy and the aircraft dynamics), and (c) System Failures, (such as the failure of an actuator or hydraulic system).

Triggers can cause a pilot to move from non-tracking or low-gain tracking behavior to high-gain tracking behavior. For example, a sudden and large turbulence encounter can cause a pilot to actively begin high-gain, compensatory attitude tracking when previous to the encounter he/she was only monitoring aircraft trim or making low-gain corrections to vehicle attitude.

Of and by itself, a triggering event may not be a catalyst for a PIO. Typically, some flight control system property conducive to a PIO is revealed when high-gain behavior begins. A good example of this is the PIO that occurred in the Shuttle Orbiter Enterprise in October of 1977 (ALT-5). This flight involved the Enterprise being carried aloft on a Boeing 747, then released to make a landing at specific touch-down point on a concrete runway at Edwards AFB (previous landings took place on a dry lake bed). The triggering event here could be described as an Environmental Trigger associated with the stress of attempting what amounted to a spot landing. High gain pilot tracking activity then began that involved large and rapid pilot inputs in the final segment of the approach. The combination of large time delays in the flight control system coupled with the aforementioned control inputs caused the vehicle’s elevon actuators to rate saturate or rate limit.[2] This means that the actuators were moving the elevons as rapidly as their designs permit. The intrinsic time delays constituted the control system property conducive to a PIO. The rate saturation dramatically changed the vehicle dynamics by introducing even larger time delays into the control loop. A PIO in both lateral and longitudinal axes ensued. The PIO was terminated when the pilot-in-command released the control stick, i.e. completely “backed out of the loop”.

It has been hypothesized that a true PIO will involve the pilot adopting a “regressive” form of tracking behavior marked by the control of *error-rate* rather than an error itself [4], [5]. For example, if a PIO in the roll-control axis[3] has begun, the pilot will regress to control of roll-*rate* rather than roll-attitude. Once this regressive behavior has been adopted by the pilot, it is difficult for the pilot to “back out of the loop”. A sustained PIO is likely. Often at this point the pilot believes that something is wrong with the aircraft,

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[2] The terms "saturation" and "limiting" will be used interchangeably in this report.
[3] "Axis" here refers to one of the three axes normally identified in the analysis of aircraft dynamics. They are the pitch axis, the roll axis and the yaw axis.

i.e., that a failure has occurred. As far as the pilot is concerned, the aircraft is behaving strangely. Some pilots who have survived serious PIO encounters have said that they simply "no longer recognized the aircraft".

C. Control System Characteristics Conducive to PIO

A control system characteristic conducive to a PIO is *any characteristic of an aircraft or its associated systems that significantly increases the aircraft's susceptibility to PIOs.* In the two PIO examples cited in Sections II A and B, (C-17 and Shuttle Orbiter), the control system characteristics were excessive time delays in the flight control system.

The progression of a PIO can be expressed as

triggering event ⇨ **control system characteristic** ⇨ **regressive behavior** ⇨ **PIO**

that is, a triggering event exposes a control system characteristic conducive to a PIO which leads to regressive pilot behavior and a PIO.

A useful example of a control system characteristic conducive to a PIO is provided by Fig. 2. This figure, adopted from Ref. 6, portrays a subset of results from a series of flight tests conducted with a large variable stability aircraft that concentrated on the pitch axis.[4] The flight condition was landing approach. Two different vehicle configurations are shown in Fig. 2, defined respectively as "1" and "2". For Config. 1, the pitch control sensitivity was varied from approximately 0.6 to 0.25 (deg/sec^2 of aircraft pitch acceleration per lbf of column force) with 0.1 sec added time delay in the pitch-attitude control loop. For Config."2" an added control system time delay was varied from approximately 0.2 to 0 sec with a constant pitch control sensitivity of approximately 0.42 deg/sec^2/lbf. The solid symbols indicate that PIOs occurred in flight with the particular time delays and sensitivities indicated, while the open symbols indicate that no PIO occurred. The combinations of time delay and sensitivity that define the solid symbols would clearly constitute control system characteristics conducive to PIOs. The large font legend at the top of the figure is taken directly from Ref. 6 and emphasizes the role that control sensitivity can play in PIOs.

[4] A "variable stability" aircraft is one that can be made to emulate the response characteristics of different aircraft by appropriately programming the on-board flight control computers.

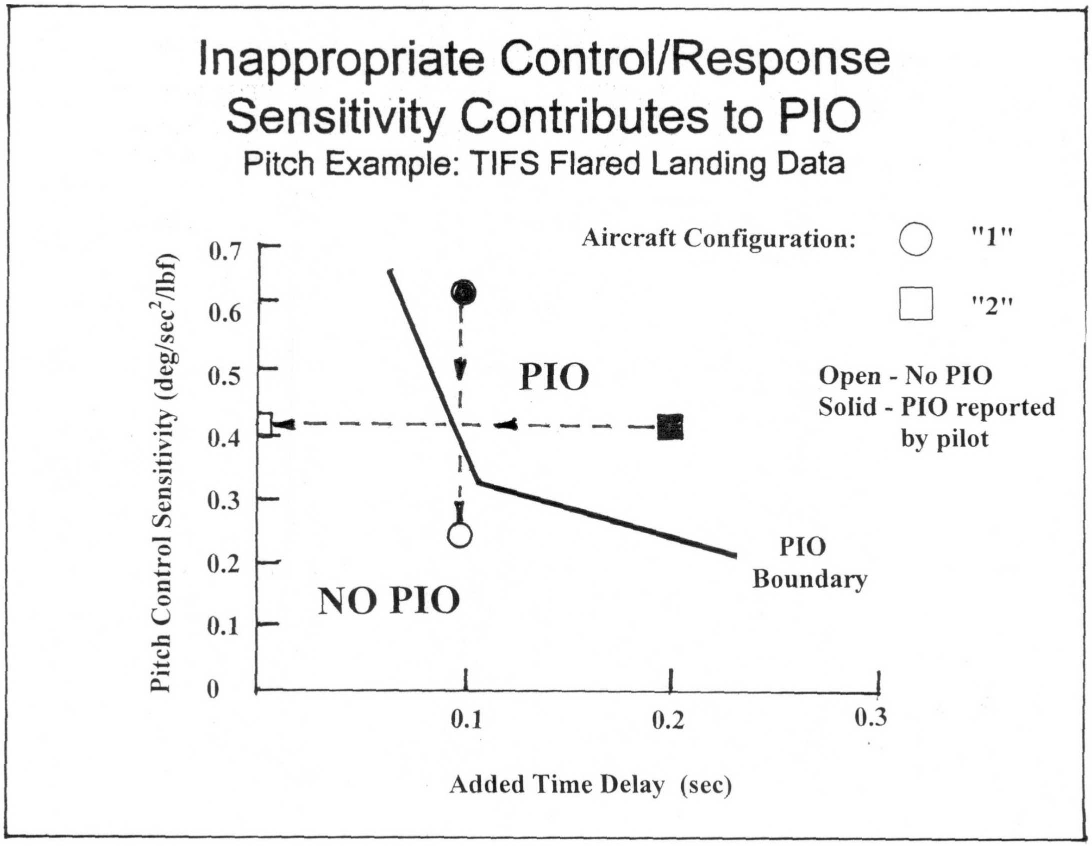

Figure 2 PIO flight test results reported in Ref. 6.

The role that control sensitivity can play in PIO susceptibility can be further exemplified by some flight simulator data reported in Ref. 7. In that study, a number of aircraft configurations were evaluated as regards their PIO susceptibility using a moving-base flight simulator. The results of one of the series of experiments is presented in Fig. 3. The task involved a fighter aircraft involved in pitch-attitude tracking task. The only vehicle parameter that was varied in this particular series of experiments was the sensitivity of the control stick. This sensitivity was denoted K_{n_z}, and represented the ratio of normal acceleration in g's to stick displacement in mm. An "optimal" K_{n_z} was first selected by the evaluation pilots based upon the value that yielded the best handling qualities rating on the Cooper-Harper pilot rating scale. Next, K_{n_z} was varied so that the ratio of K_{n_z} to the optimum value ranged from 0.2 to 10. Pilot-induced oscillation ratings (PIORs) were then assigned by the evaluation pilots. These values were assigned using the PIOR scale shown in Fig. 4. This scale goes from 1 to 6, with increasing values indicating increasing PIO susceptibility.

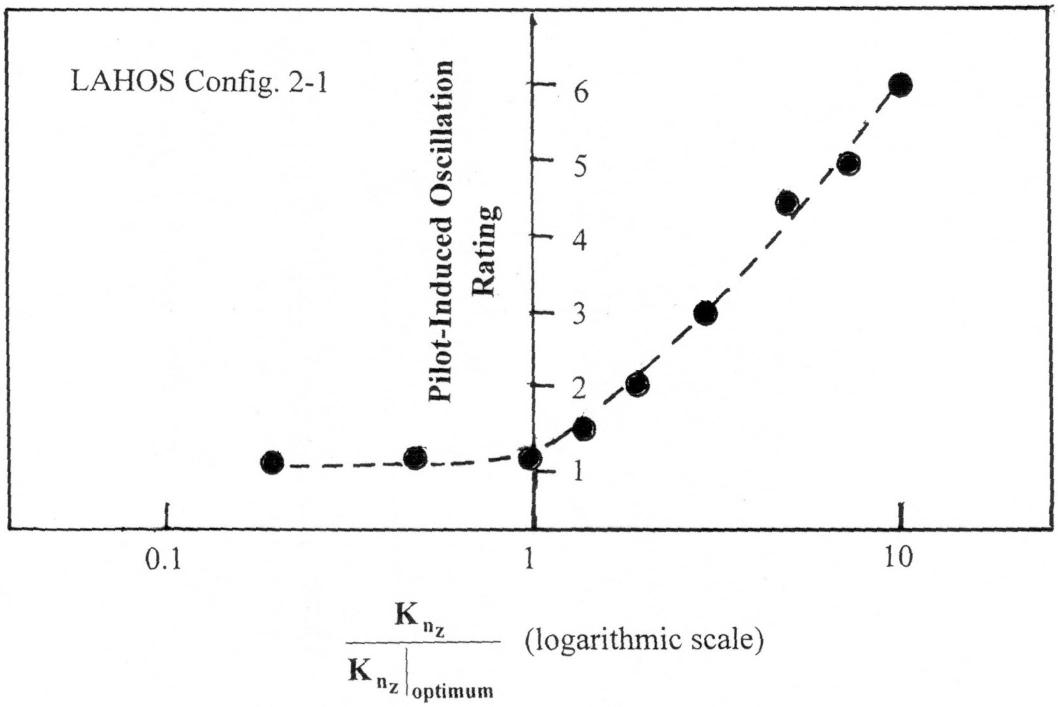

Figure 3 Effect of varying control sensitivity on the PIO susceptibility of a fighter aircraft

DESCRIPTION	NUMERICAL RATING	
NO TENDENCY FOR PILOT TO INDUCE UNDESIRABLE MOTIONS	1	$1 \le PIOR \le 2$
UNDESIRABLE MOTIONS TEND TO OCCUR WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BY PILOT TECHNIQUE	2	
UNDESIRABLE MOTIONS EASILY INDUCED WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BUT ONLY AT SACRIFICE TO TASK PERFORMANCE OR THROUGH CONSIDERABLE PILOT ATTENTION AND EFFORT	3	$2 < PIOR < 4$
OSCILLATIONS TEND TO DEVELOP WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. PILOT MUST REDUCE GAIN OR ABANDON TASK TO RECOVER	4	
DIVERGENT OSCILLATIONS TEND TO DEVELOP WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. PILOT MUST OPEN LOOP BY RELEASING OR FREEZING THE STICK	5	$PIOR \ge 4$
DISTURBANCE OR NORMAL PILOT CONTROL MAY CAUSE DIVERGENT OSCILLATION. PILOT MUST OPEN CONTROL LOOP BY RELEASING OR FREEZING THE STICK	6	

Figure 4 The Pilot-Induced Oscillation Rating Scale

Figure 3 clearly shows that by increasing the control sensitivity, alone, an aircraft with exceptional handling qualities (Cooper-Harper rating of 2.0 and PIOR of 1) can be made to be very PIO prone (PIOR of 6). The results of Fig. 3 are for a fighter aircraft. However, the authors of Ref. 7 go on to state the following:

"These and quite a number of other data available show that regularities of the effect of control sensitivity and feel system characteristics on handling qualities and PIO, being referred to their optimum value, *are the same for different piloting conditions, aircraft classes, control channels, piloting tasks, dynamic performance and manipulator feel systems."* (emphasis added)

III. Examination of the AA 587 Accident as PIO Related

A. Summary of the Events

Detailed background information describing the AA 587 accident has been provided in Ref. 8, and only pertinent details will be discussed here. The aircraft (Airbus Industrie A300-600) had just departed from JFK International Airport. During climb-out, the aircraft experienced two encounters with the wake vortices of another aircraft, a Japan Airlines (JAL) Boeing 747 that had departed JFK moments earlier. Appendix B of Ref. 8 provides detailed information about these encounters. The first wake encounter occurred at approximately 9:15:36 and has been hypothesized to be the vortex emanating from the left wing tip of the JAL 747. The pilot-flying (PF) responded with significant wheel inputs (30-40 deg of wheel rotation) but little in the way of pedal inputs. At about the time of the first encounter, AA587 was instructed to initiate a left turn. At approximately 9:15:51, an encounter with the second wake vortex occurred, this one hypothesized to be emanating from the right wing tip of the JAL 747. At this time, the aircraft was in a left bank of approximately 25 deg. The cockpit accelerations that occurred in the second encounter appear to be dominated by a vertical acceleration, i.e., nose down, and a roll acceleration to the left. As opposed to the first encounter, the second one led to large wheel and pedal inputs. Indeed, Flight Data Recorder (FDR) information indicates that both the wheel and pedal were moved repeatedly to their maximum positions.

B. Interpretation of the Events

1.) Establishing Oscillatory Behavior

An examination of the FDR time histories from Ref. 8 clearly indicates that oscillatory pilot/vehicle responses were in evidence after the second wake encounter. This is particularly true for the control inputs (wheel, column and rudder). Figure 5 is taken from Ref. 8 and shows these inputs. With the possible exception of the constant and maximum right pedal input occurring from 9:15:54 to 9:15:56, continuous oscillation of the cockpit controls are in evidence. The column inputs exhibit an approximate frequency of 0.46 Hz (2.89 rad/sec). The regularity of the wheel input is affected by the constant pedal input evident in Fig. 5. Focusing upon the wheel inputs before the constant pedal input was initiated at 9:15:54, one can approximate a frequency of oscillation of 0.54 Hz (3.43

rad/sec). Identifying a pedal frequency of oscillation is somewhat problematic because of the aforementioned 2 sec "hard-on-stop" behavior of the pilot. However, an approximate 0.5 Hz (3.142 rad/sec) frequency can be gleaned for one cycle before the aforementioned 2 sec amplitude limit. The fact that a "pure" sinusoidal frequency is absent from these time histories should not necessarily preclude describing this incident as a PIO. The necessity of having to approximate a PIO frequency in such incidents is not uncommon [3].

2.) Establishing a Triggering Event

A plausible triggering event can be established in the accident, namely, the large cockpit lateral accelerations that occurred immediately after the pilot initiated pedal inputs. Depending upon the methodology used to calculate the cockpit accelerations, Ref. 8 indicates an initial maximum lateral acceleration approaching 0.5 g's (nose right) occurring about 0.2 sec after the pedal was driven to its limit (right pedal) for the first time. This is a large acceleration for a transport aircraft of this size. It is likely that the impetus behind the large wheel and pedal inputs that produced this triggering event was the PF's desire to bring the aircraft to a wing's level attitude after the initial vertical and roll accelerations in the second wake encounter. It is likely that both wheel and pedal inputs were employed with this goal in mind. Recall that these initial accelerations were in a sense that would <u>increase</u> the 25 deg left bank that the aircraft was experiencing at the time.

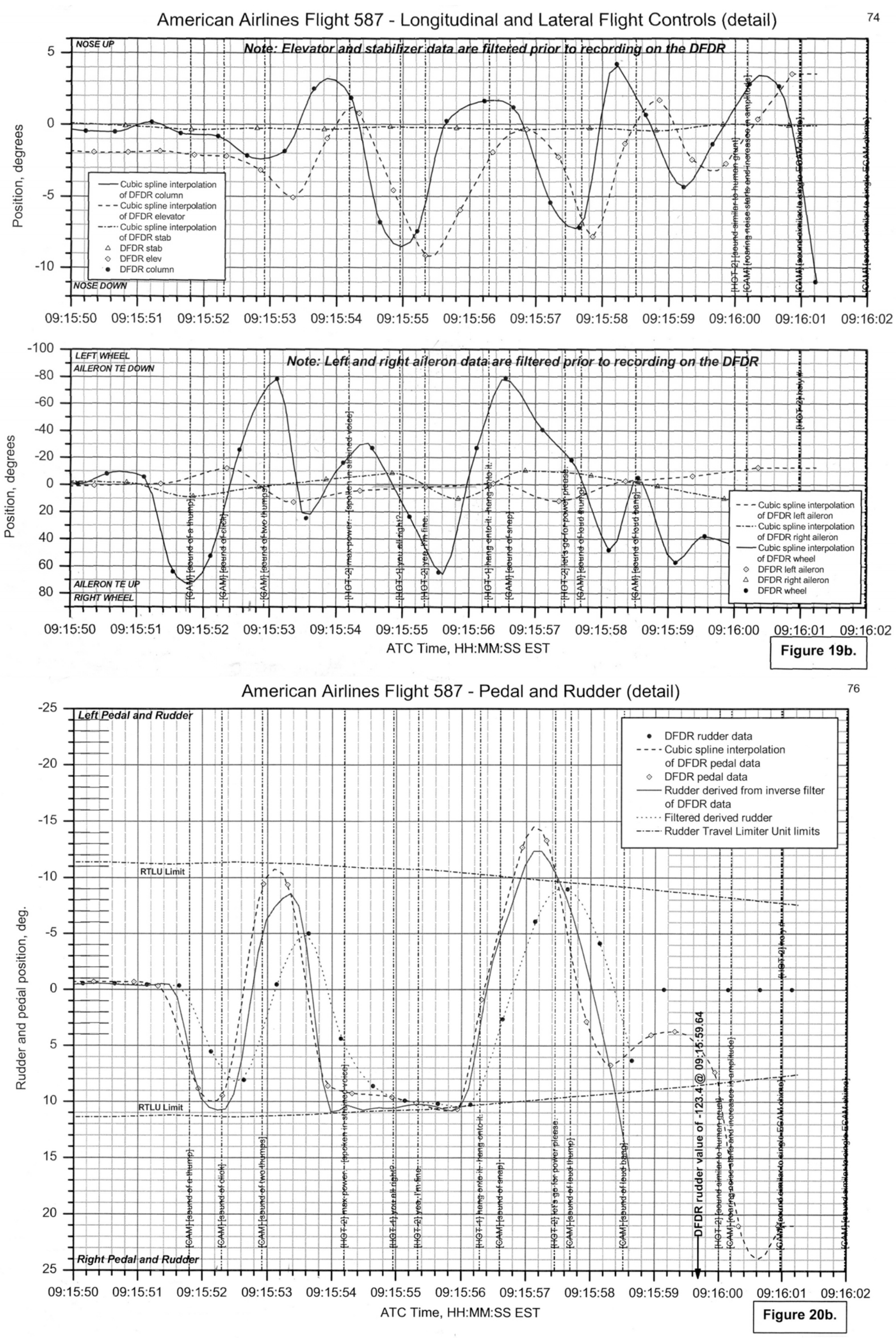

Figure 5 Control input time histories from Ref. 8

3.) Establishing a Control System Characteristic Conducive to PIO

The pedal/rudder sensitivity of the A300-600 at the airspeed at which the AA 587 accident occurred is the highest of all comparative transport aircraft. Here sensitivity can be expressed as the degrees of rudder commanded per pound of pedal force above breakout. Maximum applied force refers to the force that would move the pedal (and rudder) to the maximum travel allowed at this airspeed. The table below was provide by the NTSB and summarizes the sensitivity data.

Table 1 Comparison of Rudder Pedal Responsiveness of Various Transport Aircraft (Airspeed = 250 kts)

Aircraft	Maximum force/breakout force	Degrees of rudder per pound of force above breakout
A300-600	**1.45**	**0.93**
A300-600B2*	4.68	0.09
A300-600B4*	4.68	0.09
B747	4.21	0.197
B757	5.00	0.094
B767	4.71	0.127
B777	3.33	0.214
B717	3.25	0.289
B727	2.94	0.212
B737	3.33	0.114
DC9	3.75	0.182
MD80	4.00	0.178
MD90	3.25	0.288
DC10	6.50	0.255
MD11	6.50	0.273

*The A300-600-B2-B4 aircraft were predecessors to the A300-600 series

For another comparison, consider an aircraft of comparable size to the A300-600, namely the Boeing 767. At 250 knots, the pilot of a B767 would have to apply 80 lbf to the pedals (17 lbf breakout force) to achieve maximum displacement (3.6 inches of pedal travel and 8 deg of rudder). The pilot of an A300-600 would have to apply only 32 lbf (22 lbf breakout force) to the pedals to achieve maximum displacement (1.2 inches of pedal travel and 9.3 deg of rudder). Said another way, the A300-600 pedal/rudder sensitivity is over seven-times greater than that of the B767.

A final comparison can be made between the A300-600, and its predecessor series, the A300-600B2 and A300-600B4. As Table 1 indicates, the latter series exhibited much less pedal/rudder sensitivity, and exhibited values comparable to the B767. The A300-600 rudder/pedal sensitivity is over ten-times greater than the A300-600B2 and A300-600B4B4. An additional graphical comparison can be made showing the ratio of yaw acceleration induced per pound of pedal force above breakout for the A300-600 and A300-600-B2 and A300-600B4 series aircraft. This is shown in Fig. 6 below and is based upon a 40 lbf pedal input. The solid vertical line indicates the airspeed appropriate for the AA 587 accident. Note that at this airspeed, the A300-600 exhibits over six times the yaw acceleration per pound of pedal input of the A300-600B2 and A300-600B4 series.

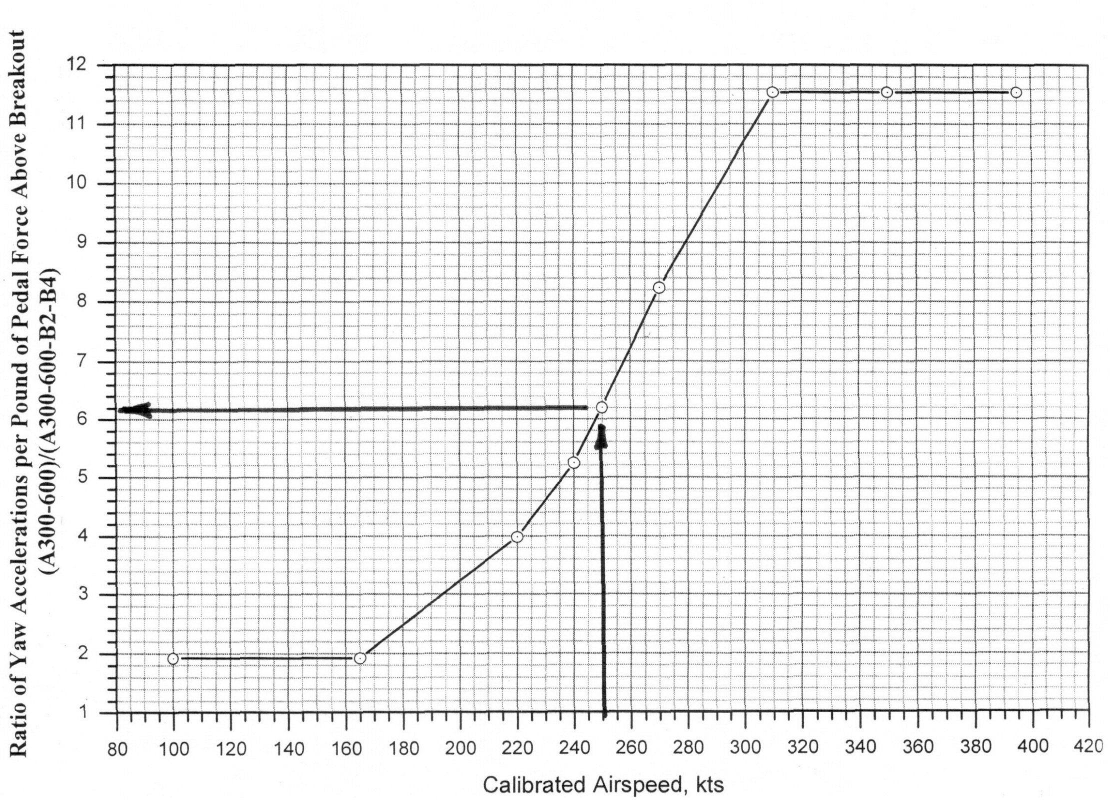

Figure 6 The ratio of yaw accelerations per pound of pedal force at 40 lbf (A300-600)/(A300-600-B2-B4)

The sensitive nature of the rudder/pedal system is a plausible candidate for a control system property conducive to a PIO and exposed by the triggering event defined in Section III.B.2. The muscles used by a pilot to move the pedals are among the most powerful in the human body, namely the *vastus lateralis*, a member of the *quadriceps* group [9]. It is estimated that a pilot can exert over 400 pounds of force to rudder pedals using these muscles [10]. The greater muscle size, however, comes at the expense of sensitivity, i.e. the ability of the human to accurately command relatively small forces. In addition, the rudder is probably the most powerful aerodynamic surface on the A300-600. It constitutes 30% of the area of the entire vertical stabilizer, itself nearly 490 ft^2 in area [11]. The rudder in the A300-600, as in any conventionally configured aircraft, can induce moments about two axes, roll and yaw. Thus, one has a very powerful aerodynamic surface with multi-axis control authority activated by one of the most powerful muscles in the human body commanding a pedal/rudder system that is considerably more sensitive than that of any comparable aircraft.

4.) Establishing Pilot Cues in the PIO

A PIO is fundamentally a closed-loop phenomenon. That is, the pilot is sensing some cue associated with the aircraft's response and is using this cue to create a corrective control input. In the so-called regressive behavior the cue being utilized by a pilot in a fully-developed PIO is the <u>time derivative</u> of the response variable normally controlled by the pilot in the axis in question. That is, if roll attitude is being controlled by a combination of wheel and pedal inputs, then in a PIO, roll *rate* becomes the variable sensed and controlled. Likewise, if pitch attitude is the variable being controlled by column inputs, then in a PIO pitch *rate* becomes the variable sensed and controlled. Thus in the PIOs that may have occurred in AA 587, roll rate and pitch rate become the primary cues. It should be noted that both of the rate cues just identified can easily be sensed by the human vestibular system, most notably the otoliths and semicircular canals of the inner ear [12], and visual cues may not be needed.

5.) Ancillary Factors

In the AA 587 accident there existed what might be termed ancillary factors, which accompanied the lateral-directional PIO and likely contributed to its severity and duration.

a.) Column Inputs

It is apparent from Fig. 5, that column inputs as well as wheel and pedal inputs were applied in the moments before the loss of the vertical stabilizer on AA 587. It is possible that such a longitudinal-axis PIO was triggered by vertical accelerations that occurred when the wing spoilers were brought into play to assist the ailerons. The spoilers on the A300-600 are employed to increase roll control power when wheel inputs exceed certain magnitudes. As opposed to aileron deflections, spoiler deflections can sharply reduce the overall lift that an aircraft is developing. This loss of lift would, in turn, induce aircraft vertical acceleration. Significant column inputs do not appear until approximately 9:15:54, some three seconds after the initiation of large wheel inputs. At approximately 9:15:54, the average normal load factor in the cockpit drops well below the 1g level to approximately 0.58 g's and remains there. This is indicated in Fig. 7, taken from Ref. 8 and annotated for emphasis. Other sources of this normal load factor decrement are, of course, possible. Among these are changes in angle of attack and sideslip. Figure 12b in Ref. 8 shows an angle of attack reduction also occurring in the same time frame.

Thus, a second triggering event, a large change in normal load factor at the cockpit, likely induced a longitudinal PIO that involved oscillatory column inputs. It may have been the spoiler deflections caused by the PF's *lateral-directional PIO* that induced these "triggering" normal accelerations. Thus pedal/rudder sensitivity remains as the control system property conducive to a PIO.

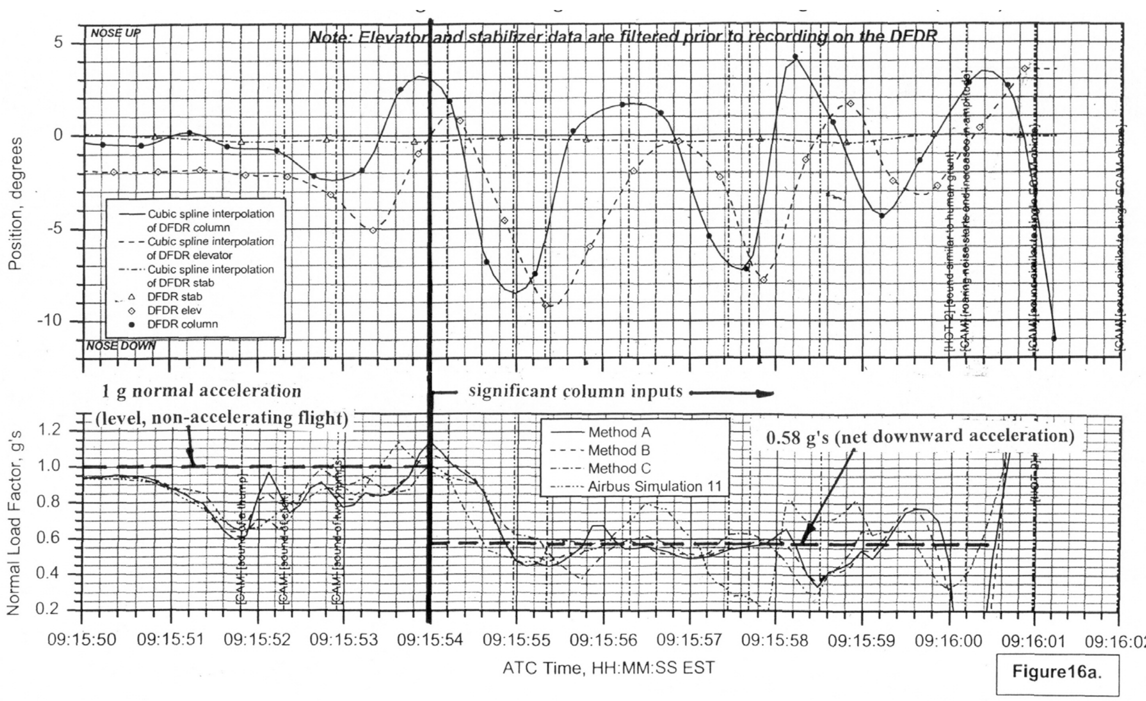

Figure 7 Comparison of column inputs and normal load factor in cockpit from Ref. 8

b.) Rate Limiting and Control Forces

Reference 13 describes a ground test performed on an A300-600 aircraft. Details are provided in the reference and only the highlights will be discussed here. In Ref. 13, a group of test subjects, all type rated on the aircraft, were asked to move the column, wheel and pedals in a sinusoidal fashion using full and partial displacement of these controls. Three frequencies were used in the test, 0.25 Hz, 0.5 Hz and 1 Hz. The full displacement experiments at 0.5 Hz are of interest here, since this motion and frequency closely approximates that of the wheel and pedal of AA 587 in the last seconds of flight. Figure 8 below typifies the results for the wheel, while Fig. 9 does the same for the pedal.

Figure 8 shows the applied wheel force, resulting aileron deflection, and aileron rate when both the wheel and pedal are oscillated at a frequency of 0.5 Hz and full wheel and pedal throw is required (pedal data is not shown). The figure clearly shows that the aileron actuator is under nearly constant rate saturation. This means the actuator is moving the aileron at the maximum rate possible, here ± 45 deg/sec. Rate saturation can adversely effect aircraft stability, e.g. [3], [5] and [14]. The reason that actuator rate saturation can be destabilizing is also shown in Fig. 8. By comparing the time that elapsed between corresponding "zero crossings" of the *force* applied to the wheel and aileron motion, an effective time delay of over 450 milliseconds can be seen for this run.

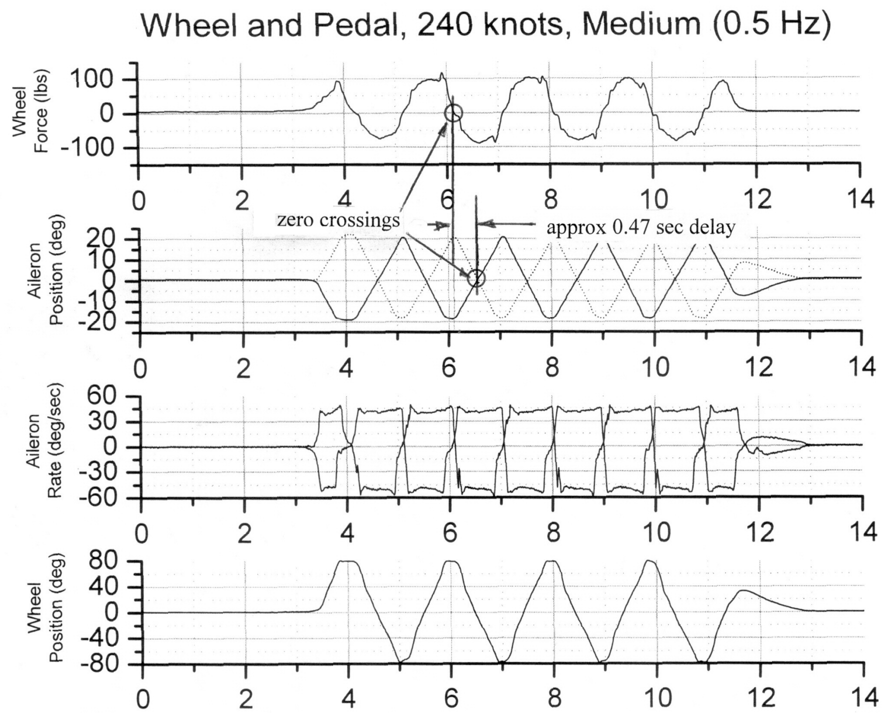

Figure 8 A300-600 ground test results for wheel from Ref. 12

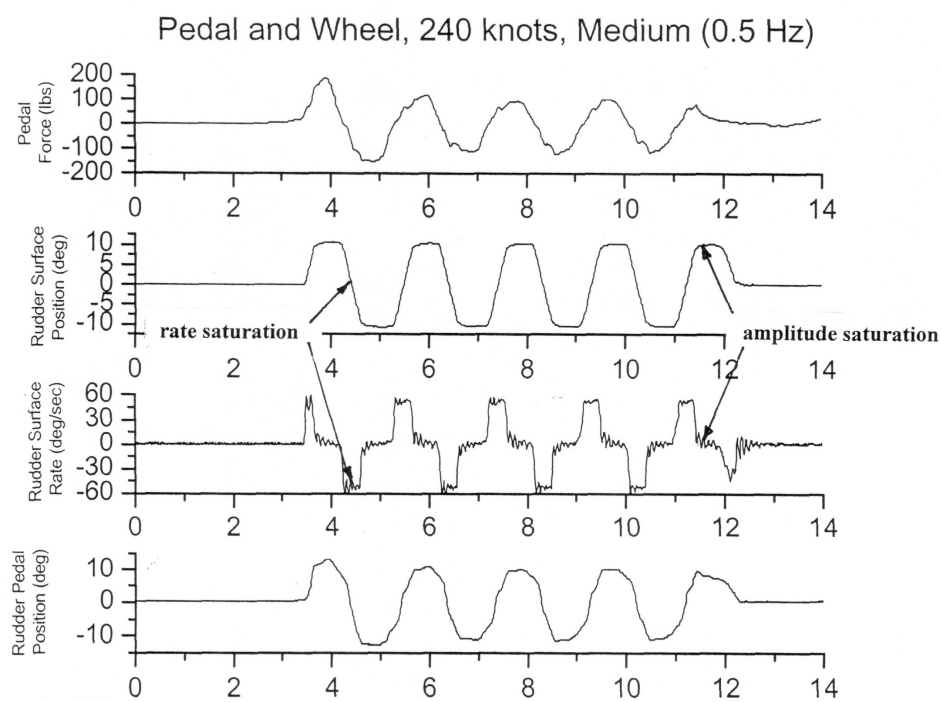

Figure 9 A300-600 ground test results for pedal from Ref. 12

Ideally, the aileron and applied wheel force would pass through their zero or null values simultaneously. This would indicate that the aileron is following wheel force inputs with no lag or time delay. In reality, of course, some lags do occur due to the dynamics of both the cockpit force/feel system and the actuator itself. However values of over 450 milliseconds would be considered very large, even for an aircraft the size of the A300-600. When the command oscillation frequency was reduced to 0.25 Hz, with the full-throw requirement was still in effect, minimal aileron actuator rate limiting was noted and the apparent time delay between wheel force inputs and aileron deflection was reduced to a much smaller value. Similar, albeit smaller, delays occurred with pedal inputs as can be gleaned from Fig. 9.

The experiments of Ref. 13 also indicated that the maximum forces that the subjects applied to the wheel and pedals in the 240 kt, 0.5 Hz, full-displacement experiments significantly exceeded those required to move the controls to their full displacement in a quasi-static condition. Again, this can be seen from Figs. 8 and 9. The maximum pedal forces also significantly exceeded those for the wheel despite the fact that the forces required for both in a quasi-static condition are nearly equal.[5] One plausible explanation for the increased forces in both cases is that the pilot valves in the actuators were hitting their travel limits during the periods that the actuators were rate saturated. Also note that the nature of the rate saturation is significantly different between Figs. 8 and 9. In Fig. 8 the aileron actuator remains in nearly constant rate saturation, but only briefly *amplitude* saturates (reaches the limits of its travel). In contrast, Fig. 9 shows the rudder actuator quickly amplitude saturating after brief periods of rate saturation. These characteristics could again be attributed to the sensitivity of the pedal/rudder system. That is, rather than the smooth, albeit rate-saturated movement of the aileron, the rudder quickly amplitude saturates and remains amplitude saturated for about 0.6 secs in each half cycle in an "on-off" type of movement.

An additional interesting characteristic can be gleaned from the experiments of Ref. 13 regarding the rapidity with which the pilot could command full rudder deflection from pedal inputs. Concentrating upon the experimental results of Fig. 9, it can be seen that the pilot can move the rudder from +10 deg to -10 deg (full opposite deflections) in approximately 0.35 - 0.4 sec. This would mean that the surface could be moved from 0 deg to ±10 deg in less that 0.2 sec. Reference 15 states the following: "*Manipulator Designs to be Avoided - Those which permit the pilot to generate large control surface deflections within about one pilot delay period (0.25 seconds, or so) <u>will promote PIO</u>*" (emphasis added).

The only significant use of pedal inputs previous to the oscillation that began at 9:15:52 occurred while taxiing to takeoff position. At approximately 9:02:06 the PF initiated a very slow "rudder check" that lasted nearly 20 sec and involved full pedal motion (which in this condition was ± 30 deg, three times the maximum displacement available at 240 kts). This is shown in Fig. 10. The pedal and rudder displacements have been highlighted in this figure. The maximum force in this quasi-static movement was probably 65 lbf .

[5] A "quasi-static" condition is one in which the pedals would be moved to maximum displacement very slowly.

With the experiments of Ref. 13 as a background, one can conclude that wheel, aileron and rudder rate limiting likely occurred in the oscillations beginning at 9:15:51. In addition, increased control forces may have been present as suggested by the experiments of Ref. 13. It should be noted that it is possible that comparable transport aircraft (with mechanical as opposed to fly-by-wire flight control systems) would exhibit similar nonlinear characteristics if experiments such as those of Ref. 13 were conducted with these aircraft. Indeed, this limiting should not be considered as the fundamental control system characteristic that led to the oscillations apparent in AA 587. Rather, the limiting evident in the A300-600 could be considered as an *effect* attributable to the large, rapid wheel and pedal deflections that were involved in the initial oscillations. The rate limiting would, however, contribute to the severity and duration of a PIO because of the added time delays that accompanied this limiting.

Finally, it should be noted that "overcontrol" by the PF might be cited as a factor in the accident. The great majority of PIOs that have been documented, however (e.g., [3]), have involved pilot control inputs that could be deemed inappropriately large for the task at hand. In such cases it is erroneous to attribute these inputs as a *cause* rather than an *effect*.

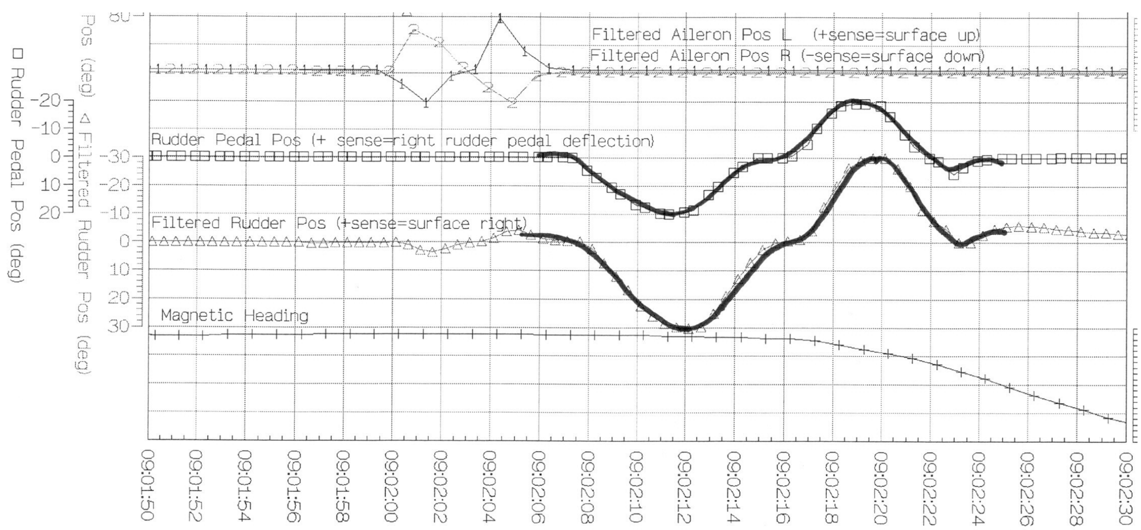

Figure 10 AA 587 preflight control checks showing slow rudder check

IV. Conclusions

This report concludes that activity consistent with a lateral-directional pilot-induced oscillation (PIO) was evident in the moments before the crash of AA 587. The lateral-directional PIO was likely accompanied by a similar oscillation in the longitudinal axis. There was a high probability of rate saturation of the aileron and rudder actuators during the oscillations. It has been demonstrated in ground tests that this saturation can create additional time delays in the flight control system and require increased wheel and pedal forces of the pilot, both of which could contribute to the severity and duration of a PIO. The sensitivity of the rudder/pedal control system of the A300-600 aircraft could constitute a control system characteristic conducive to a PIO. One necessary (but not sufficient) condition for the pedal/rudder sensitivity to serve as such as characteristic would be a demonstration that, in its absence, PIOs do not occur. One such demonstration occurred in AA 587, itself. That is, in the first wake vortex encounter, pedal inputs were minimal and sustained oscillations did not occur.

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