SUBMISSION OF AMERICAN AIRLINES, INC. TO THE NATIONAL TRANSPORTATION SAFETY BOARD

ADDENDUM 1
THE EFFECT OF WAKE TURBULENCE

ACCIDENT INVOLVING AMERICAN AIRLINES FLIGHT 587
AT BELLE HARBOR, NEW YORK
NOVEMBER 12, 2001

DCA02MA001

JUNE 8, 2004

I. Introduction

The wake vortex related information in American Airlines' submission was largely based on NASA's PowerPoint presentation from the 2002 Flight 587 Public Hearing. American recently received NASA's new April 2004 report entitled, "Meteorology and Wake Vortex Influence on American Airlines FL-587 Accident." Although the new report states that the conclusions were presented at the Public Hearing, it contains significant new findings and a new conclusion.[1] Since the report provides new insight into the wake vortex related accelerations that the crew of Flight 587 experienced, American is submitting this Addendum to briefly address that new information and how it relates to the Flight 587 investigation.

II. Overview

Before the April 2004 NASA Report, the only energy assessment of JAL Flight 47's wake was that it maintained 63 to 80 percent of its strength, based on circulation velocity. The new report, however, describes the turbulence Flight 587 encountered just seconds before the accident as a "strong wake vortex" that was undergoing the onset of Crow Instability. This new information enhances the conclusion that this was not a typical or normal wake. Crow Instability develops as the wake vortex circulation decreases; ironically, circulation speed has less influence than the vortex's integrated circulatory flow on aircraft roll accelerations experienced in a wake encounter. Therefore, despite the fact that the wake still maintained 63 to 80 percent of its original strength based on circulation velocity, the onset of Crow Instability was the primary source of Flight 587's roll and pitch accelerations that were reversing from up/left to down/right approximately once a second. Since the DFDR only samples rate of pitch and roll once per second, it is unlikely that these accelerations would be recorded in a meaningful way.

Dr. Ronald Hess addresses roll and pitch rates of acceleration in his Report prepared for the Safety Board's Human Performance Group. He concluded that for Flight 587, roll and pitch rates were the dominant cues prompting the First Officer's compensatory flight control inputs. It is consistent with Dr. Hess's Report to conclude that the First Officer made the rudder input (in accordance with Airbus's "appropriate standard" for rudder use) because of higher than anticipated roll rate and the ineffectiveness of full roll control to arrest the roll.

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[1] NASA's original 2002 PowerPoint presentation, entitled "Modeling and Analysis by NASA Langley Research Center," is Appendix B to the Aircraft Performance Group's Factual Report.

III. Summary of Key NASA Report Findings

(a) Critical Wake

Synopsis: The wake encounter beginning approximately 8.5 seconds before stabilizer separation is referred to as the "critical wake."

Ambient DFDR derived wind profiles from Flight 587 and JAL Flight 47 were not consistent, which influenced where the wake vortices from JAL Flight 47 would have been relative to Flight 587. Therefore, "it is not conclusive that the first suspected wake encounter was due to the JAL 47 wake." (April 2004 NASA Report, p.14.) For that reason, this Addendum refers to the suspected second wake as the "critical wake."

According to the AVOSS Prediction Algorithm (APA), the critical "wake vortices lay on the port side of AA 587, with the aircraft trajectory being nearly parallel to the axis of the wake vortices. Hence, the APA predictions support a sustained encounter with a strong wake vortex within the region of the suspected second encounter." (April 2004 NASA Report, p. 17)

(b) Crow Instability

Synopsis: Contrary to Airbus's Submission conclusion, the JAL Flight 47 vortices were in the process of linking in a phenomenon known as "Crow Instability," which was not specifically addressed in NASA's 2002 Public Hearing presentation.

Trailing vortices from each wing of an airplane "merge into a pair of prominent counter-rotating vortices that trail along the aircraft's path." (April 2004 NASA Report, p. 4-5.) Figure 2 below from the April 2004 NASA Report illustrates this evolution, during which vortex strength diminishes with distance and time downstream of the generating airplane at a rate dependent on aircraft parameters and environmental conditions. "Linking between the vortex pair to form crude vortex rings may occur some distance behind the generating aircraft. This linking, called Crow Instability, is associated with a rapid decrease in vortex circulation." (April 2004 NASA Report, p. 5.)

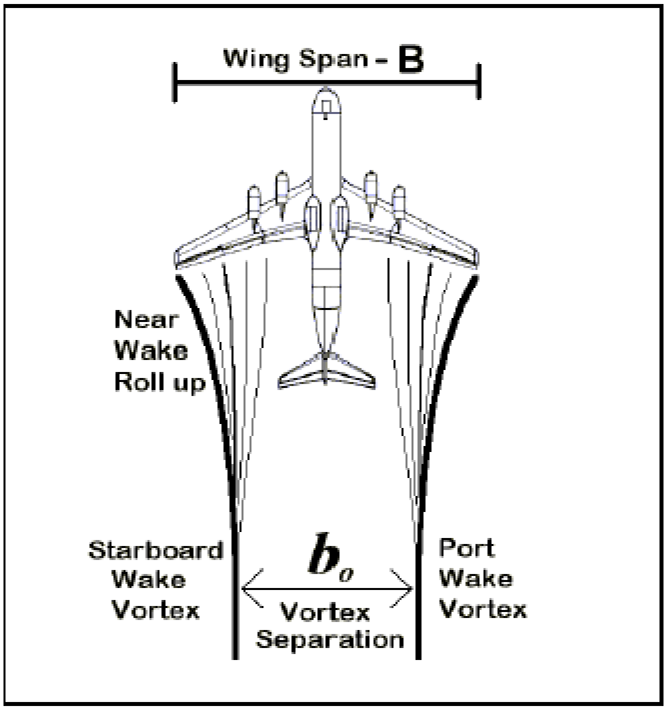

Figure 2. Aircraft wake vortices in relation to generating aircraft (viewed from below).

Slide B8 from NASA's Public Hearing presentation addresses three-dimensional instability resulting in rapid vortex decay. Similarly, Slide B11 illustrates the relationship between vortex lifespan (time to link) and turbulence intensity. Despite the association of these two factors of the vortex to Crow Instability, NASA's Public Hearing presentation did not mention the term; nor is there any reference to Crow Instability in the conclusions on Slide B50.

This lack of a specific reference apparently led Airbus to determine that there was no Crow Instability. In its submission, Airbus refers to NASA's Public Hearing presentation to support its conclusion that "there were no linking instabilities, such as Crow Instability, going on at the time," and that "it was a typical wake vortex with nothing extraordinary or unusual about it." (Airbus Submission, p. 24.) The April 2004 NASA Report, however, is a more complete analysis and demonstrates that Flight 587 encountered the critical wake during the onset of Crow Instability.

(c) Vortex Circulation

Synopsis: Vortex circulation patterns, not the velocity of circulating air within the vortex, are the primary indicator of a vortex's threat to aircraft.

Both NASA documents conclude that JAL Flight 47's wake decayed slowly with vortex circulations at 63 to 80 percent of their original energy (depending on what model was used in the analysis) when Flight 587 encountered the critical wake. Circulation speed, however, is not the critical factor to evaluate a wake vortex's threat. "The hazard resulting from a wake vortex encounter is best estimated by vortex circulation rather than peak tangential velocity. The high velocity near the vortex core is less important in contributing to aircraft roll than the integrated flowfield across the span of the encountering aircraft. The average circulation has been shown to be correlated with aircraft roll rate." (April 2004 NASA Report, p. 6.)

Despite the relatively long lifetime of the critical wake, it was diminishing. NASA uses Figure 13 below to illustrate the "perspective of the simulated wake vortex" at about the age and the approximate distance behind JAL Flight 47 to simulate the wake encountered by Flight 587. (April 2004 NASA Report, p. 19.) It shows that "Sinusoidal instabilities are beginning to show as a precursor of Crow linking. As is typical for wake vortices undergoing the onset of Crow Instability, the vortex separation is most narrow at its lowest point and greatest at its highest point. The two counter-rotating vortices will eventually link at the spots where the separation is most narrow, forming crude vortex rings." (April 2004 NASA Report, p. 19.) "Although the linking process is underway at the time and location of the apparent encounters, the simulation indicates that vortex linking does not occur until the vortices have aged an additional 21 seconds." (April 2004 NASA Report, p. 19.)

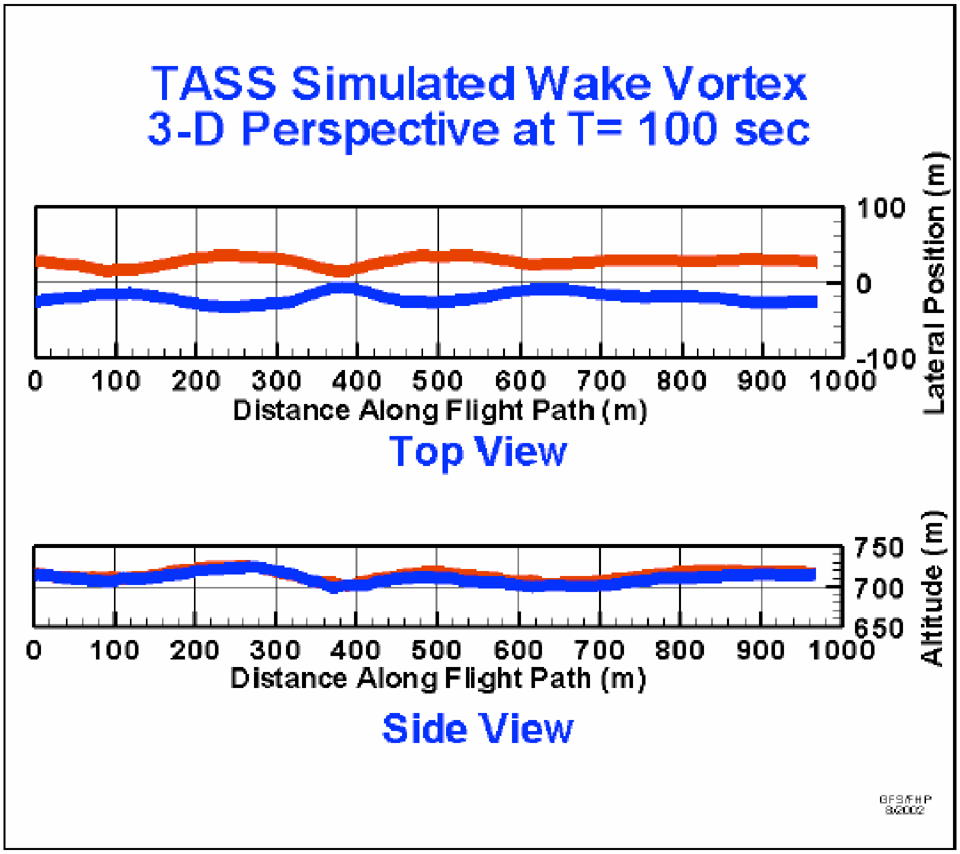

Figure 13. Three-dimensional perspective of simulated JAL 47 wake vortex at time of encounter.

NASA uses Figures 14 and 15 below to illustrate the three dimensional velocity fields varying along track, lateral, and vertical directions. "The onset of linking instability causes obvious variation in the flow field between each cross-sectional plane." (April 2004 NASA Report, p. 21.)

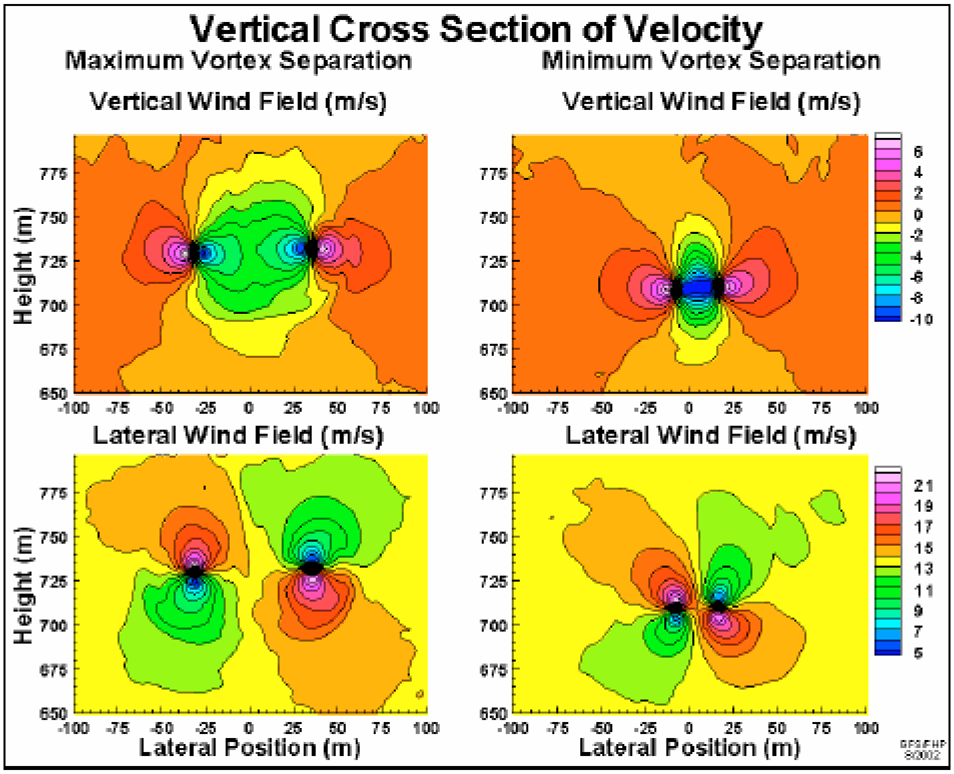

Figure 14. Simulated contour fields of velocity at time of encounter (100 seconds).

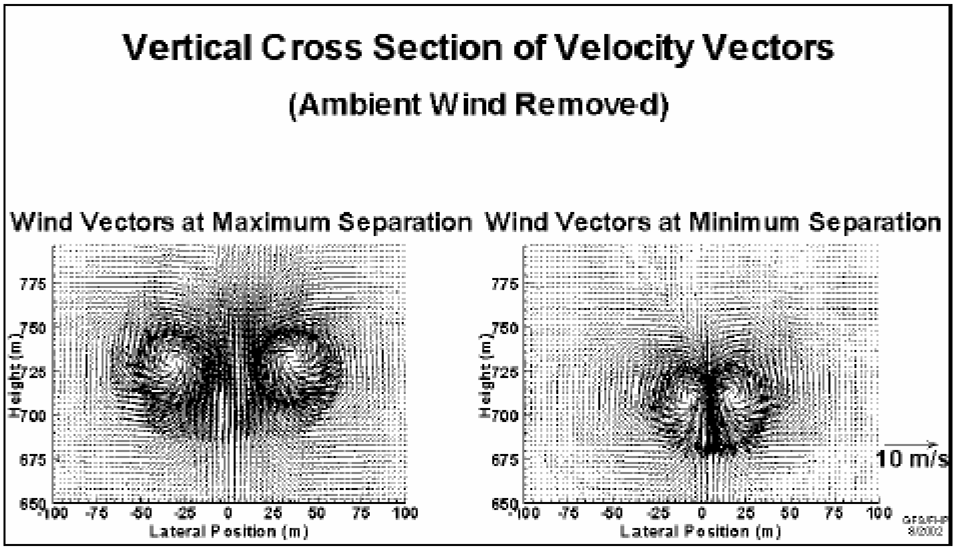

Figure 15. Same as fig 14, but for wind vector field

The NASA model, which includes sink rate of the vortex and climb rate of the generating airplane, is illustrated in Figure 18 below. It shows the resulting three dimensionality identified by the model. As NASA explains, "The growing sinusoidal oscillations from the onset of Crow Instability are correctly centered on two planes that are offset 45° from the vertical." (April 2004 NASA Report, p. 25.)

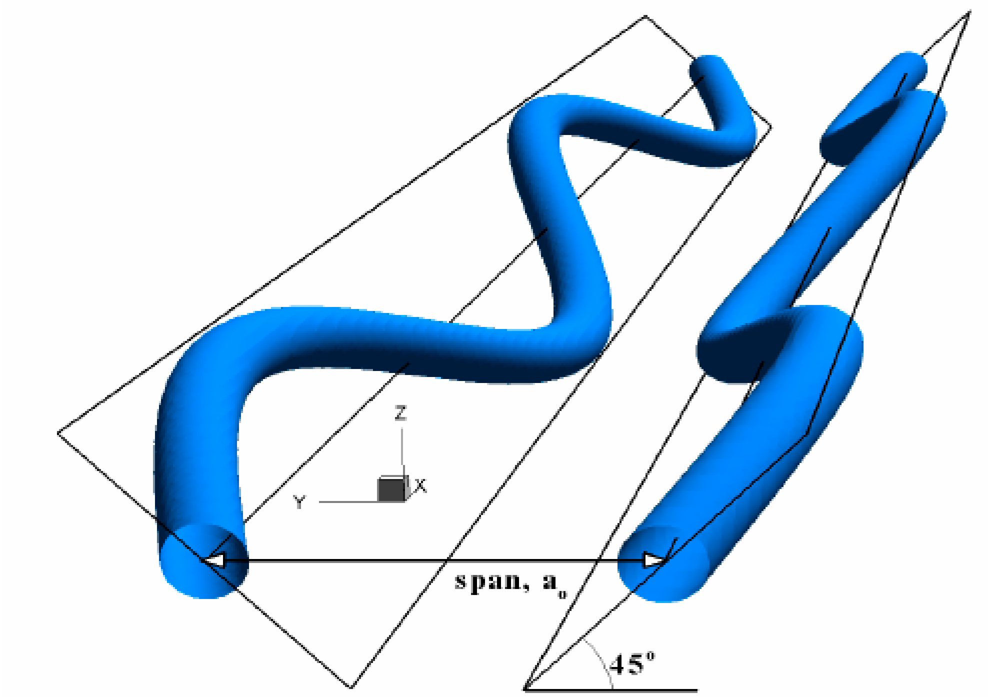

Figure 18. Three-dimensional projection of vortex pair from proposed algebraic model (with $C_1=0$).

(d) The Development of Crow Instability and its Influence on Vortex Circulation

Synopsis: Using parameters from the Flight 587 critical wake encounter, NASA modeling indicates airflow patterns oscillating from up/left to down/right at one-second intervals.

At the speed of Flight 587 at the time of the accident, the airplane "would encounter one complete oscillation every 2.1 seconds." (April 2004 NASA Report, p. 25.) "The aircraft would encounter an updraft with a crosswind to port, reversing to a downdraft with a crosswind to starboard in about *one second*. Rudder deflections out of sync with this motion might only amplify the loss of stability and control. The above model (Figure 18) should be investigated in theoretical and flight simulation studies to determine if a similar scenario may have occurred for AA 587, which experienced opposite changes in rudder inputs about every one second just before the crash." (April 2004 NASA Report, p. 25)

(e) Conclusions of NASA's PowerPoint Presentation as supplemented by the April 2004 Report

Synopsis: The most recent NASA Report adds to the Agency's original public hearing presentation a conclusion that finds Crow Instability forming.

NASA's 2002 presentation contained five conclusions, all of which are repeated in the Summary and Conclusions Section of the April 2004 NASA Report. The new report, however, adds one additional finding: "At this age the wake vortex was beginning to develop sinusoidal oscillations resulting from the onset of Crow Instability. These oscillations might also have contributed to the accident, but this needs to be investigated further in situation and flight response studies." (April 2004 NASA Report, p. 25.)

The original assessment of the critical vortex was based solely on the 63 to 80 percent residual strength calculated using various simulation methods. The new conclusion that Crow Instability had developed implies a more hazardous wake than investigators previously perceived, which was based strictly on circulation velocity.

IV. Relevance of NASA Report to the Findings of the NTSB Aircraft Performance and Human Performance Groups

(a) Aircraft Performance

Synopsis: Due to limited DFDR sampling rates of roll and pitch and the rapid oscillatory nature of Crow instability, it is not possible to use DFDR based simulation or modeling to measure the effect of the onset of Crow instability in the critical wake encounter.

Addendum 1 to the Aircraft Performance Group Report addresses simulation of expected aircraft performance with no flight control input following the wake encounter. The simulation indicated that, absent any flight control input, angle-of-bank would have gone from 24 degrees left to 34 degrees left, decreased to 24 degrees left, and increased to a maximum of 36 degrees left, with a roll rate for the first 10 degree excursion to the left of about 9.2 degrees per second. Crow Instability was not included in this simulation, which also did not consider the rate driven cues felt by Flight 587's pilots. Even if it had, the simulation would not have captured the dynamics of the onset of Crow Instability due to infrequent DFDR sampling rates.

(b) Human Performance

Synopsis: In a report prepared for the Safety Board, an independent expert in pilot induced or pilot involved oscillations (PIO) determined that the primary cues sensed by Flight 587's First Officer were roll and pitch rates. Compared to a more typical wake vortex, roll and pitch rates probably were magnified by the onset of Crow Instability, and could have prompted the First Officer's initial rudder input.

Addendum 2 to the Human Performance Group Report is a report by Dr. Ronald A. Hess entitled, "An Inquiry Into Whether A Pilot-Induced Oscillation Was a Factor in the Crash of American Airlines Flight 587." In his Report, Dr. Hess concludes that a pilot induced (or involved) oscillation (PIO) is a closed-loop phenomenon in which the pilot senses a cue about his/her aircraft's performance that prompts corrective (compensatory) flight control inputs. In what Dr. Hess refers to as "regressive behavior," a pilot uses rate of roll, pitch, or yaw as the "variable sensed and controlled." (Hess Report, p.13-14.) In the case of Flight 587, "roll rate and pitch rate become the primary cues" as sensed by the inner ear. (Hess Report, p. 14.)

Dr. Hess also refers to "ancillary factors," one of which was column inputs. He suggests that Flight 587 experienced a longitudinal PIO that was triggered by vertical accelerations from flight control inputs or "other sources of this normal load factor decrement." (Hess Report, p. 14.) The cycle of updrafts and downdrafts associated with Crow Instability could have served as the ancillary factors or environmental triggers leading to longitudinal PIO.

To calculate the roll and pitch rates referred to by Dr. Hess, one must compare angles of bank and pitch relative to time. The VMS Backdrive simulation, however, was limited in its fidelity by the sampling rate of critical acceleration data, in this case pitch and bank, which are recorded once per second by the DFDR. Since Crow Instability accelerations were reversing once per second, the resulting accelerations would not have been reflected on the DFDR, and therefore could not have been accurately simulated in the VMS Backdrive simulation.

Since the VMS Phase 1 Testing was the only effort to simulate cockpit accelerations, the human performance effect of Crow Instability has not been considered by the Human Performance Group. In the absence of any realistic way to simulate the accelerations from Crow Instability and its effect on a pilot's reaction to aircraft acceleration, the Human Performance Group's work is incomplete. The Human Performance Group should document NASA's conclusions and attempt to correlate them with Dr. Hess's finding that roll rate and pitch rate were the primary cues for Flight 587's First Officer.

Currently, the Human Performance Group Report does not address the triggering event for the initial rudder input by the First Officer. The April 2004 NASA Report's conclusion about the onset of Crow Instability makes the triggering nature of the critical wake more apparent than before, when all that was known was the vortex velocity-driven residual strength. Similarly, Dr. Hess determined that the First Officer's initial wheel and rudder pedal input was prompted by his "desire to bring the aircraft to a wing's level attitude after the initial vertical and roll accelerations in the second wake encounter." (Hess Report, p. 10.) Like the role of pitch and roll rates as cues, Crow Instability as a triggering event should be addressed in the Human Performance Group Report.

V. Analysis

The most significant finding of the April 2004 NASA Report is its conclusion that wake vortices from JAL Flight 47 were evolving into the onset of Crow Instability at about the time that Flight 587 encountered the nearly parallel axis of the critical wake. This resulted in an encounter with a "strong wake vortex," which retained 63-80% of its initial strength. In addition, and more important than the power of the wake vortex, is the fact that its circulation pattern had changed. This pattern can be correlated to increased aircraft roll rate and oscillations from upward/left to downward/right accelerations at a rate of approximately once per second. This frequency of oscillating forces could cause unrecorded roll rates due to the DFDR's low sampling rate. In short, this was not a typical wake vortex encounter. Moreover, NASA's findings are consistent with the ineffectiveness of the First Officer's initial input of full right roll control to arrest the vortex induced continued left roll. (According to the NASA Report, there is no evidence of Crow Instability during the first "suspected" wake vortex encounter.)

The oscillating accelerations induced by the onset of Crow Instability are consistent with Dr. Hess's description of a rate driven triggering event. The oscillating accelerations caused by the wake vortex are also consistent with NASA's conclusion that "rudder deflections out of sync with this motion might only amplify the loss of stability and control." (April 2004 NASA Report, p. 25.)

Once the initial rudder pedal input was made, which required only 1.2 inches of pedal movement to reach maximum displacement with 32 pounds of force (only 10 pounds above breakout), the pilot was in a closed-loop PIO/aircraft pilot coupling event, and he had only seconds to recognize and recover before the vertical stabilizer failed. Therefore, it is critical to consider the relationship between the wake vortex, the First Officer's initial rudder input, and the unique sensitivity of the A300-600 flight control system.

Even without the onset of Crow Instability, we know that full roll control was ineffective to stop the increasing left roll. We now better understand why; Crow Instability reveals the likelihood of a stronger degree of initial acceleration than is typically associated with wake turbulence and which was not recorded by the DFDR. Therefore, it is consistent with Dr. Hess's Report to conclude that the First Officer made the rudder input due to higher than anticipated roll rate and the ineffectiveness of full roll control to arrest the roll. Of course, the First Officer's actions were also consistent with Airbus's guidance, both before and since the accident: "Although a simple rule about rudder usage cannot be stated, an appropriate standard is to first use full aileron control. Then, if the aircraft is not responding, use rudder as necessary to obtain the desired airplane response." (Airbus Submission, American Flight 587, p. 34.)

Unfortunately, the unique flight control system design of the A300-600 induced adverse aircraft pilot coupling characteristics, causing the initial rudder input to evolve into cyclic rudder control applications in response to aircraft motions.

Dr. Hess found that “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.” (Hess Report, p. 11.) That conclusion is supported and illustrated by the following Human Performance Group references:

1. Attachments 9 and 10 of Addendum 1, which compare rudder design data of 20 comparable airplanes, including the A300-600 and A310;

2. Table 1 of Addendum 2, the Hess Report, which shows rudder pedal responsiveness of 15 comparable airplanes; and

3. Tables 5 and 6 of the A300-600 Ground Test Data Report, which shows average peak rudder pedal forces applied by subject pilots at a simulated airspeed of 240 knots.

The unique rudder sensitivity of the A300-600/A310 makes that series of airplanes far more susceptible to PIO/aircraft pilot coupling related rudder reversals than any comparable airplane. For that reason, it is likely that the rudder input in response to the wake vortex during the onset of Crow Instability encountered by Flight 587 would not have resulted in PIO/aircraft pilot coupling and rudder reversals in any of the other airplanes listed in items 1 and 2 above.

VI. Conclusions

1. The vertical stabilizer failed 8.5 seconds after the beginning of a wake encounter in which Crow Instability was developing.

2. The wake vortex from JAL Flight 47 did not result in a typical wake encounter; the onset of Crow Instability made the encounter atypical.

3. The onset of Crow Instability resulted in sinusoidal oscillations dramatically changing the circulation patterns within the wake, making it more of a hazard to Flight 587 than it would have been based solely on the vortices’ tangential velocities.

4. The onset of Crow Instability led to aircraft accelerations at a frequency very near the DFDR’s sampling rate of pitch and yaw, making the detection of those accelerations based on DFDR data imprecise at best.

5. Aircraft accelerations associated with Crow Instability led to high pitch and roll rates as the airplane entered the critical wake’s airflow pattern, oscillating from up/left to down/right at one-second intervals.

6. The primary cues for flight control inputs sensed by Flight 587's First Officer were roll and pitch rates, which were magnified by Crow Instability compared to the already significant wake from JAL Flight 47.

7. Crow Instability enhanced roll and pitch rates were the likely triggering events for the First Officer's initial rudder input after the aircraft did not respond to full aileron and spoiler control (which was, and is, entirely consistent with Airbus's standard for rudder use).

8. Due to the A300-600's unique flight control characteristics, the initial rudder input immediately created accelerations that led to PIO/adverse aircraft pilot coupling and structural failure of the stabilizer 6.5 seconds after the initial rudder input.