National Transportation Safety Board
Office of Research and Engineering
Washington, D.C. 20594
April 1, 2011

Airplane Performance Study Addendum

Specialist's Report Addendum
Timothy Burtch

A. ACCIDENT

Location: Lubbock, TX
Date: January 27, 2009
Time: 1037 GMT (437 CDT)
Airplane: ATR-42-320, N902FX
NTSB Accident Number: CEN09MA142

B. INFORMATION

On November 18 and 19, 2010, the Investigator-in-Charge, the Operations Group Chairman, and the Performance Group Chairman visited the facilities of ATR in Toulouse, France, to review the investigative data for the Lubbock, TX, accident. During the visit, new preliminary performance information was provided by ATR to the Performance Group Chairman. The performance data contained in this addendum discuss the new performance data and largely concern the last 30 seconds of the flight which were not addressed in detail in the Airplane Performance Study.

The Toulouse airplane performance discussions included a question that was asked of ATR in August of 2010 after an uncommanded right roll was identified in the flight data recorder (FDR) data. The data show that, around 10:36:20 when the airplane was between 150 and 200 ft above ground level (agl) and seconds from impact, the airplane started banking right to approximately 35 degrees. As a result of their work to answer the roll question, ATR introduced two new possibilities in the area of airplane performance:

1. The flaps returned to a symmetric configuration (approximately 4.5 degrees) about the time the airplane emerged from the 500 ft overcast ceiling at 1036:00.

2. A gust was encountered at approximately 1036:20 during the final seconds of the approach. ATR's simulation analysis determined that a gust of 15 knots for three seconds could account for the uncommanded, 35 degree, right roll recorded on the FDR.

The final results of ATR's analysis were provided to the NTSB on February 10, 2011, in an attachment titled "ATR 42-3210 – MSN175 – Simulations: Last seconds of Flight 8284" (ATR document #DO/TD-3829/10) and dated 1/12/11.

1. Flaps Returned to Symmetric Configuration

As noted in the Airplane Performance Study, at 1035:48, approximately 39 seconds before impact, the captain assumed control of the airplane. About 1036:00, the airplane emerged from the overcast cloud ceiling and was over two dots high and to the right of the instrument landing system (ILS) glideslope and localizer. The captain input an estimated 36 pounds of column force, 112 pounds of pedal force, and 29 pounds of wheel force in an apparent attempt to reposition the airplane on the approach to the runway. At this time, the FDR captured a movement in the flap sensor position (which is an average flap position) from about 3.5 degrees to 4.5 degrees.

According to ATR and based on airplane performance, simulation results, and FDR data, the left flaps retracted from an actual position of 8-10 degrees to approximately 4.5 degrees. The right flaps, on the other hand, extended to approximately 4.5 degrees. At this point, all four flaps were symmetrically extended to 4.5 degrees, and the captain's control input to counteract the flap asymmetry was no longer required. See the configuration change reflected in the shift in control wheel position around 1036:00 noted in Figure 1.

The repositioning of flaps to a symmetric configuration is consistent with both the FDR data and the NTSB's aerodynamic coefficient data extraction. (A detailed discussion of the lift coefficient extraction will follow in a later section, "A Wing Stall as the Source of Roll".)

Time histories of the FDR wheel position, average flap position, and the resulting vertical and lateral accelerations are shown in Figure 1. Additional information regarding the flap system is provided in the Airworthiness Group Factual Report Addendum 2.

2. A Gust Encounter Six Seconds Before Impact

In addition to the new flap position information, the possibility of a gust encounter during the final seconds of Empire 8284's approach was introduced by ATR during the NTSB's November 18-19, 2010 visit to Toulouse. At 1036:20, the FDR data indicate that the accident airplane began rolling right at approximately 14 degrees/second without input from the pilot. See Figure 2.

ATR's analysis of the roll event indicates that a lateral gust of approximately 15 knots for three seconds could account for the uncommanded, 35 degree, right roll. (Wind conditions observed 16 minutes after the accident were 020 degrees at 13 knots, gusting to 18 knots. This represents a change of 5 knots.) ATR reported that a match between their simulation and the recorded FDR data could be achieved with a gust of this magnitude just prior to the recorded roll-off. This is documented in the "Third scenario" of ATR document DO/TD-3829/10.

Without the ATR-42 airplane simulation models to directly validate ATR's gust assumption, the NTSB considered the possibility of a wind gust by other means. The NTSB assessed the winds in the accident by estimating both the airplane's sideslip angle and the winds that were actually present during the flight's approach into Lubbock based on FDR data. The estimates used accelerometer, airspeed, and angle-of-attack (AOA) data recorded on the FDR.

Figure 3 shows the estimated sideslip angle based on the lateral acceleration and rudder deflection recorded on the FDR. Sideslip angle does induce airplane roll, and the calculated sideslip does fluctuate ±2° around a mean of about -2° in the seconds before the 35 degree roll upset. However, the small sideslip angles are consistent with the small rudder input that the captain was carrying during most of the approach, likely due to the quartering tailwind. See the rudder deflection in Figure 2. The large 8° to 10° change in sideslip at 10:36:01 corresponds to the 112 lb pedal force input made by the captain and, as previously discussed, is about the time the flaps returned to a symmetric configuration.

Figure 3 also includes the wind speed and wind direction calculated for the final seconds of Empire flight 8284. Figure 4 is a table of the recorded Automated Surface Observing System (ASOS) one minute wind data around the time of the accident. Each one minute report in the table represents the average wind over the previous two minutes using a five second sampling period (i.e., 24 samples in two minutes). The average winds are recorded 10 meters above the ground or 32.8 ft agl. The ASOS report closest to the accident is for 1036:00 and was a 13 kt average wind with a peak wind of 15 kt (and is highlighted in yellow). This is very close to the NTSB estimate of 15 kt from 021° shown in Figure 3 at 1036:00. It should also be noted that "a gust" requires a fluctuation of at least 10 kt to be reported at all by the airport. There were no gust reports around the time of the accident. ATR assumed a 15 kt gust lasting three seconds in their analysis.

While the precise effect of rudder pedal, sideslip, and wind gusts on the ATR-42 lateral / directional dynamics would require ATR-42 simulation model data, the 35 degree right bank shown in Figure 2 does not appear to be the result of a wind gust. The NTSB considered two other potential sources for the uncommanded roll: a <u>second flap asymmetry</u> and a <u>wing stall</u>.

Second Flap Asymmetry as Source of Roll

The possibility that a second flap asymmetry caused the roll at 1036:20 was considered. A right rolling tendency would result if the flaps returned to the asymmetric configuration recorded earlier in the approach[1]. However, no shift in flap position was recorded on the FDR subsequent to the movement at 1036:00. Figure 1 shows the recorded flap position and the airplane bank angle. No significant movement of the flap can be seen around the time of the uncommanded roll.

[1] The first flap asymmetry occurred at the top of the approach at 1034:25.

A Wing Stall as the Source of Roll

As can be seen in Figure 5, the amount of load factor that results for a given change in angle-of-attack (which is proportional to lift) appears to be diminished when a comparison is made between the load factor peak around 1036:00 (from an elevator input that peaked at 10:35:59) and the load factor peak around 1036:20 (from an elevator input that peaked just beyond 10:36:18). This reduction can be the result of a wing that is approaching a stalled condition and, because of the separated air flow, is no longer able to effectively generate lift. ATR also identified an asymmetric loss of lift as a potential source of the uncommanded roll during the accident flight.

A measure of the wing's ability to generate lift is the gradient of load factor with angle-of-attack, or $\Delta nz/\Delta\alpha$: the greater the gradient, the more effective the wing is operating. At stall, the wing is no longer able to generate additional lift and the gradient goes to zero. In this case, for the 1036:00 elevator input, the load factor increased by about 0.8 g's with a 7 degree increase in angle-of-attack or $\Delta nz/\Delta\alpha = 0.1$ g/degrees (1035:57 ≤ t ≤ 1035:60). For the 1036:18 elevator input, $\Delta nz/\Delta\alpha$ is 0.25g/3.5 degrees or 0.07 g/degrees (1036:19 ≤ t ≤ 1036:20). While other factors can affect the gradient (like elevator input), the 30% reduction prompted a closer look at the possibility of a wing stall in the final seconds of Empire flight 8284's approach.

The stall protection system on the ATR-42 includes both a stall warning (aural cricket + stick shaker) and a stick pusher. ATR has indicated that the stick pusher was installed on the ATR-42 to avoid a deep stall condition in a non-iced condition which may be unrecoverable. The stick pusher is considered "stall" on the ATR-42 when the ice protection system (IPS) is turned off. The stick shaker angle-of-attack activation angle (or trigger angle) is lowered when the IPS is selected in order to provide the necessary 7% stall speed margin required for certification. The stick pusher trigger angle does not change when IPS is selected. [2]

"Stall" is defined differently depending upon whether or not the IPS has been selected. With the IPS off, stick pusher is considered the point of stall, and there should exist a 7% speed margin between stick shaker speed and stick pusher speed. With the IPS turned on, the speed at which the first indication of stall occurs (as defined by CFR 25.201) is considered stall, or Vs_{min}[3]. With the IPS on, there should exist a 7% speed margin between stick shaker and Vs_{min}. The AOA at Vs_{min} is approximately the AOA at C_{Lmax}. ATR wind tunnel data show an AOA of about 8.4

---

[2] Unlike the ATR-42, the ATR-72 stick pusher trigger angle is lowered with the IPS selected and does play an active role in stall protection in ice as well. The ATR-72 stick pusher is disabled below 500 ft agl while the ATR-42's is not.

[3] AC 25-7, "Flight Test Guide for Certification of Transport Category Airplanes", describes in detail one method of determining Vs_{min} using a 1.1Vs entry rate slope from numerous stall tests of varying entry rates.

degrees at C_{Lmax}. See Figure 6 for a pictorial of the ATR-42 stall margin thresholds. Figure 7 summarizes the stall "trigger" AOA's with and without ice protection.[4]

The stick shaker and aural cricket activated five times during the accident approach into Lubbock according to the CVR transcript[5]: 1035:30, 1035:32, 1036:00, 1036:19, and 1036:20. However, the first two and last two warnings were sufficiently close enough together that only three stall warning times were considered: 1035:30, 1036:00, and 1036:19. The first activation occurred near the top of the approach while the first officer was the flying pilot, and it disconnected the autopilot. The second at 1036:00 occurred when the airplane was close to the reported ceiling and the captain input an estimated 36 pounds of column force, 112 pounds of pedal force, and 29 pounds of wheel force in an apparent attempt to reposition the airplane. The final stall warning at 1036:19 had the associated reduction in $\Delta nz/\Delta\alpha$ and the possible wing stall. See Figures 10 and 11.

The lift coefficient for the accident approach was extracted using primarily the FDR accelerometer, angular rates, and angle-of-attack data to look for the presence of a stall. In addition, airplane geometry, mass properties, and engine thrust were required and were either obtained from ATR or estimated. Figure 8 shows the NTSB's estimated lift coefficient based on FDR data (green). Figure 8 also includes ATR's estimated lift coefficient for flight 8284 including the effect of the captain's full roll spoiler input beyond stick shaker at 7.8 degrees angle-of-attack (red). Finally, Figure 8 has wind tunnel lift coefficient data for the ATR-42 with "cruise ice"[6] shapes with and without full roll spoiler (blue and orange, respectively).

Figure 8 shows the lift coefficient extraction for the accident and lift coefficient data from the original ice certification program. However, every ice encounter produces unique accretions. It is therefore not possible to draw conclusions about the actual ice accretion on Empire 8284 beyond stating that the NTSB's extracted lift data looks similar to ATR's "cruise ice" lift data for angles-of-attacks slightly greater than stick shaker. Small variances in the height and location of the ice accretion can have large effects in the stall region of the lift curve.

The Federal Aviation Administration's Office of Aviation Research published the effects of such variances for a NACA 230 series airfoil (vs. the NACA 430 series on the ATR-42) in its final report, "Effects of Large-Droplet Ice Accretion on Airfoil and Wing Aerodynamics and Control" (DOT/FAA/AR-00/14). Figure 9 contains excerpts from the report which show that the linear portion of the lift curve does not vary greatly with ice shape; however, the maximum lift

---

[4] "Local" AOA shown in Figure 7 is the same as "vane" AOA. The Crew Alerting Computer on the ATR-42 uses both the left and right vane AOA's, one on each side of the forward fuselage, to compute an average AOA for triggering the stall warning system: $AOA_{stall\ warning} = (AOA_{LH} + AOA_{RH})/2$. However, only AOA_{LH} is recorded on the FDR and plotted here.

[5] The CVR transcript reports stall warning to the closest second.

[6] "Cruise ice" for the ATR-42 consists of inter-cycle ice on the airplane's protected surfaces and 3" ice shapes on the unprotected portions.

coefficient and, as a result, stall, is highly dependent on the ice shape and its location on the wing.

The NTSB lift extraction highlights the fact that Empire flight 8284 had very little stall margin remaining as the captain started increasing torque to over 95% and the elevator started increasing to over 10 degrees airplane-nose-up at approximately 1036:18 and 1036:21, respectively (see Figures 10 and 11). Stick shaker AOA had already been exceeded. Without roll input from the pilot, the airplane began to roll right at 1036:20 about the same time it reached an AOA of 8.6 degrees. In response, the pilot started inputting maximum left-wing-down (LWD) control wheel around 1036:21 and reached 60 degrees of wheel about a second later. Rudder deflection reached approximately 22 degree airplane-nose-left (ANL) at the same time. At 1036:23, two seconds after the captain's LWD wheel input, the airplane reached a 35-degree right-wing-down (RWD) bank angle. There was approximately a one second delay in the airplane's bank angle response to the captain's LWD command. The airplane was at an altitude of about 114 ft above the ground at 1036:23.

Based on the NTSB's lift coefficient extraction, the gradient of load factor with angle-of-attack, $\Delta nz/\Delta\alpha$, and the airplane's response to the captain's inputs, it is likely that the airplane stalled at approximately 1036:20, just prior to reaching 8 degrees angle-of-attack. The uncommanded roll at 1036:20 is consistent with an accelerated stall. The captain's aileron input at 1036:21 likely exacerbated the RWD roll, and the airplane reached a maximum 35° RWD bank before the right roll was arrested and the airplane began rolling left.

3. Stall Margin for Final Stall Warning

The provisions of CFR 25.207, Stall Warning, (c) state that "the stall warning must begin at a speed exceeding the stalling speed (i.e., the speed at which the airplane stalls or the minimum speed demonstrated, whichever is applicable under the provisions of § 25.201(d)) by seven percent or at any lesser margin if the stall warning has enough clarity, duration, distinctiveness, or similar properties."

The third stall warning on Empire flight 8284 occurred at 1036:19 at a recorded airspeed between 125.7 and 124.3 knots indicated airspeed (KIAS). The stall occurred about a second later at about 124.5 KIAS and 1.12g. Correcting the accident stall speed for an equivalent 1g airspeed, flight 8284 would have stalled at a lower speed, Vs_{1g}, around 117 KIAS. This results in about a 7% speed margin. However, while the regulation requires a 7% stall margin, the FAA definition of stall speed mentioned in footnote 3 is Vs_{min} and is slightly lower than the Vs_{1g} stall speed calculated here.

The provisions of CFR 201, Stall Demonstration, (d) state that the "occurrence of stall is defined as follows:

(1) The airplane may be considered stalled when, at an angle-of-attack measurably greater than that for maximum lift, the inherent flight characteristics give a clear and distinctive indication to the pilot that the airplane is stalled. Typical indications of a stall, occurring individually or in combination, are -
   (i) A nose-down pitch that cannot be readily arrested;
   (ii) A roll that cannot be readily arrested; or
   (iii) If clear enough, a loss of control effectiveness, an abrupt change in control force or motion, or a distinctive shaking of the pilot's controls."

The captain exceeded stick shaker and the airplane was operating with ice. However, there were no natural cues for the flight crew to indentify an impending stall before Empire flight 8284 rolled off at 1036:20. Despite full opposite control wheel and over 20 degrees of rudder control input, the airplane continued to roll.

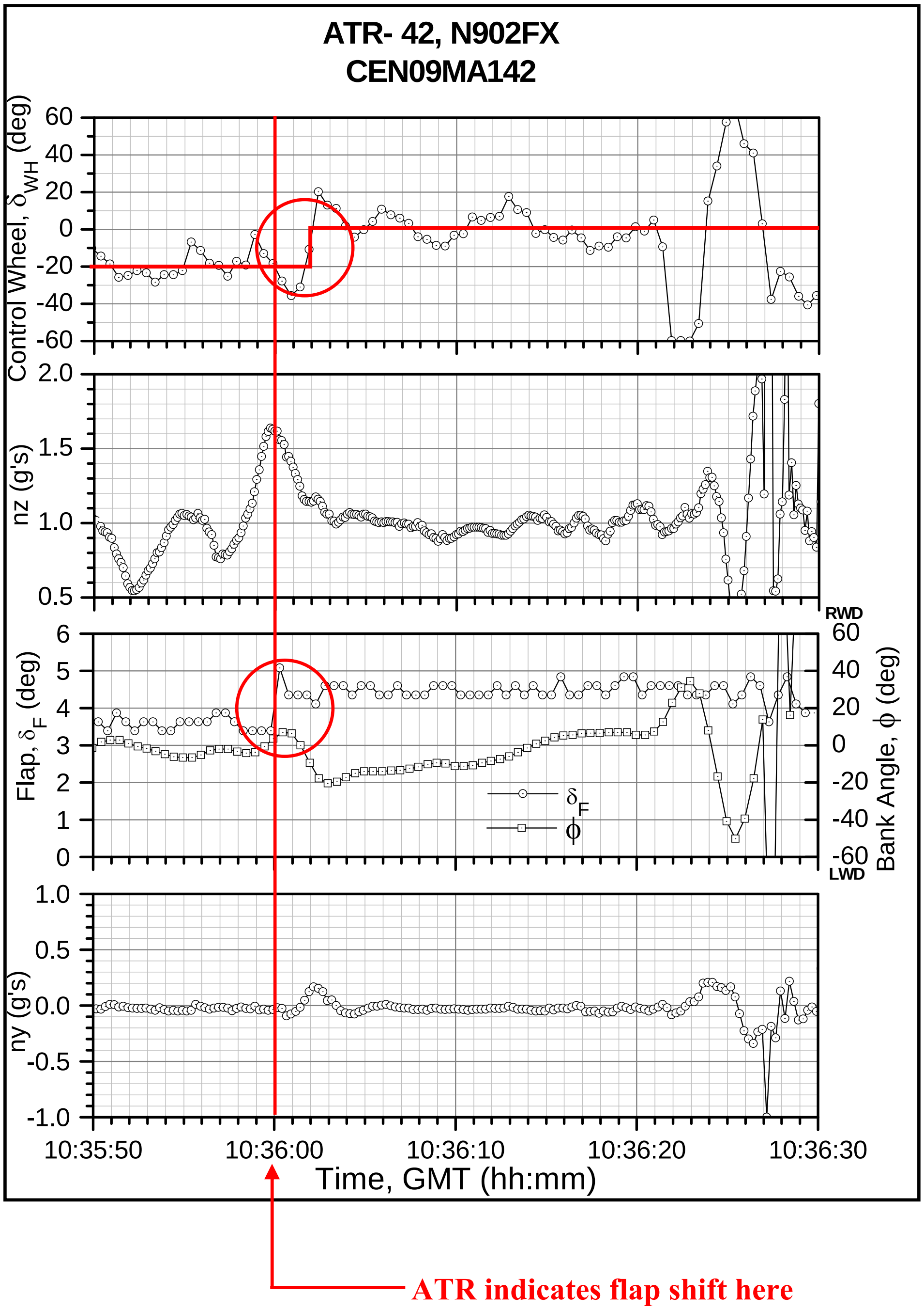

Figure 1. Flap Shift at 10:36:00, About the Same Time as Pilot Input

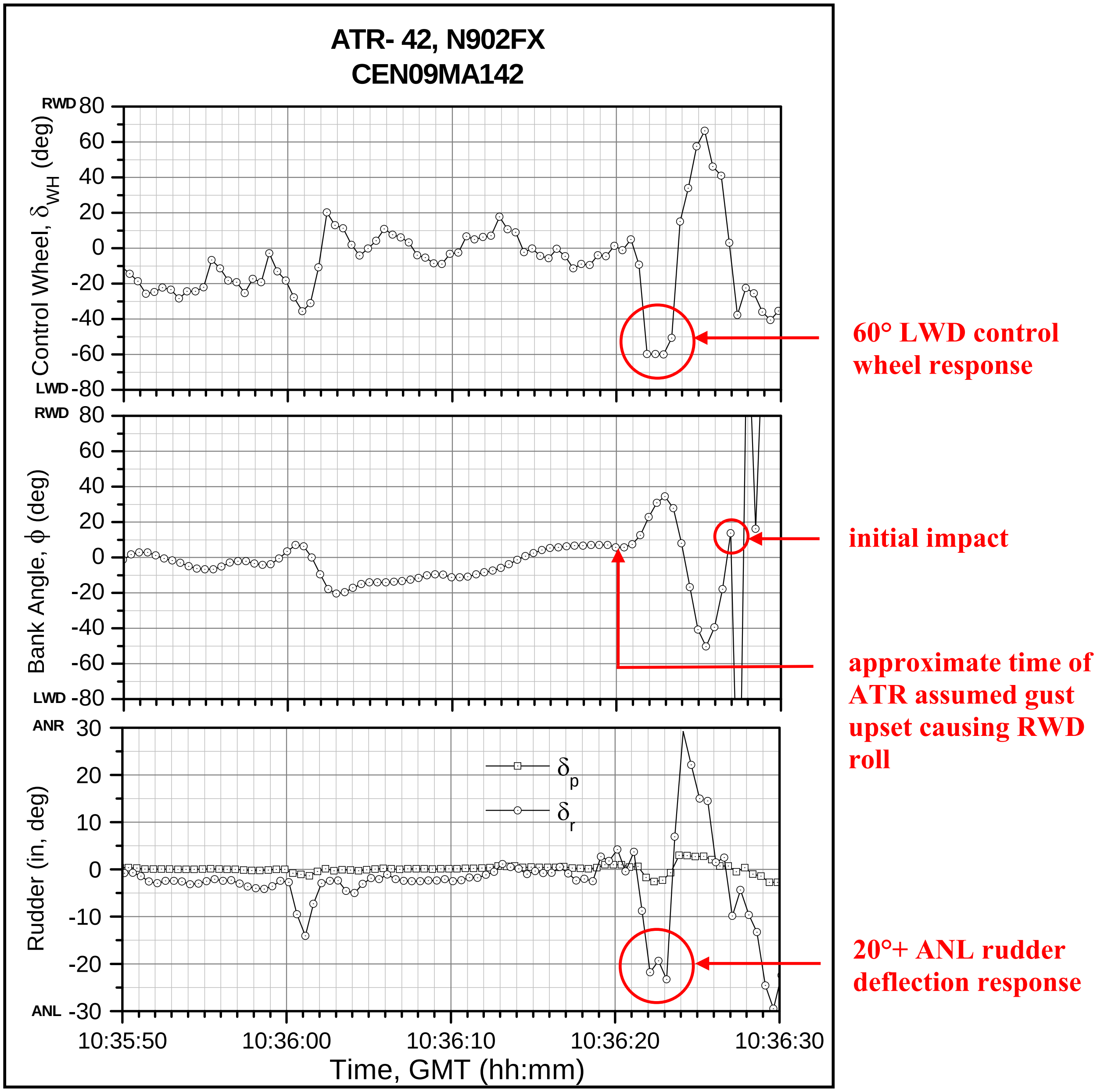

Figure 2. ATR Assumed Gust Upset at 1036:21 and the Recorded Pilot Response

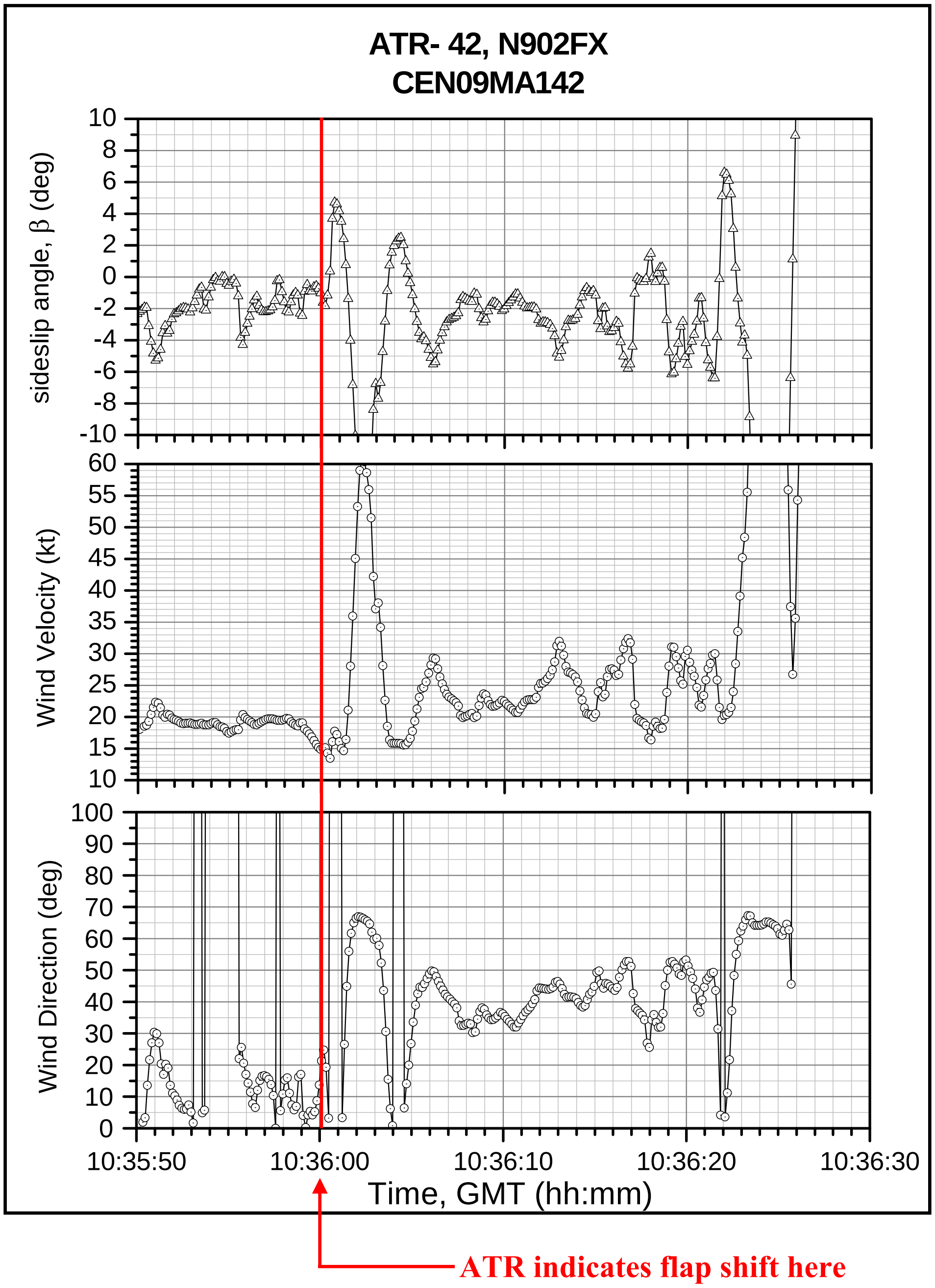

Figure 3. Sideslip and Wind Estimated from FDR Accelerometer Measurements

Time (GMT)	Avg Direction	Avg Speed	Peak Direction	Peak Speed
1030	012°	14 KT	009°	17 KT
1031	015°	13 KT	021°	15 KT
1032	018°	13 KT	019°	16 KT
1033	021°	13 KT	019°	16 KT
1034	020°	12 KT	021°	16 KT
1035	018°	12 KT	022°	17 KT
1036	019°	13 KT	017°	15 KT
1037	016°	12 KT	012°	14 KT
1038	014°	11 KT	022°	14 KT
1039	012°	12 KT	005°	18 KT
1040	009°	14 KT	010°	18 KT

Figure 4. ASOS One Minute Wind Data Around the Time of the Accident

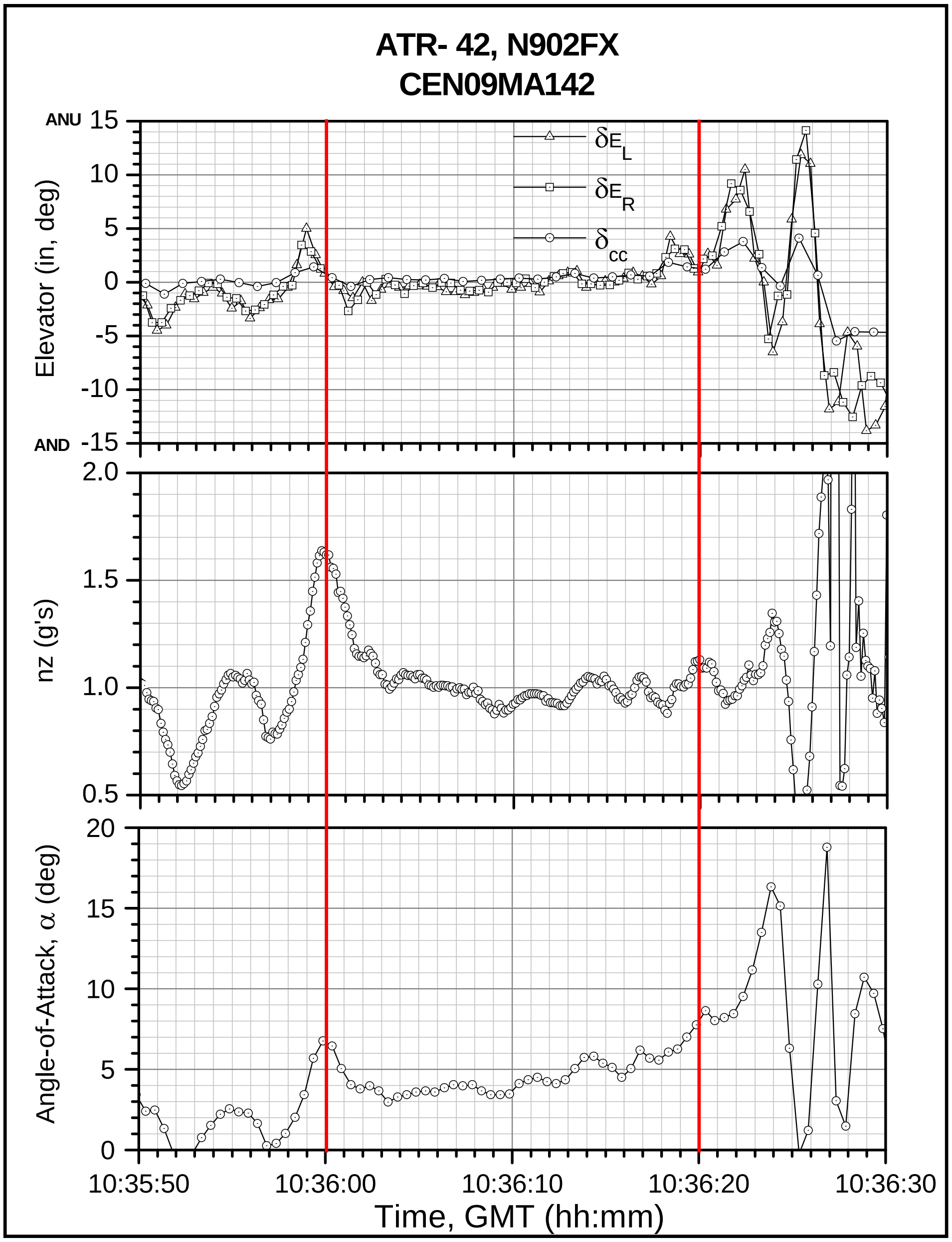

Figure 5. Vertical Load Factor with AOA

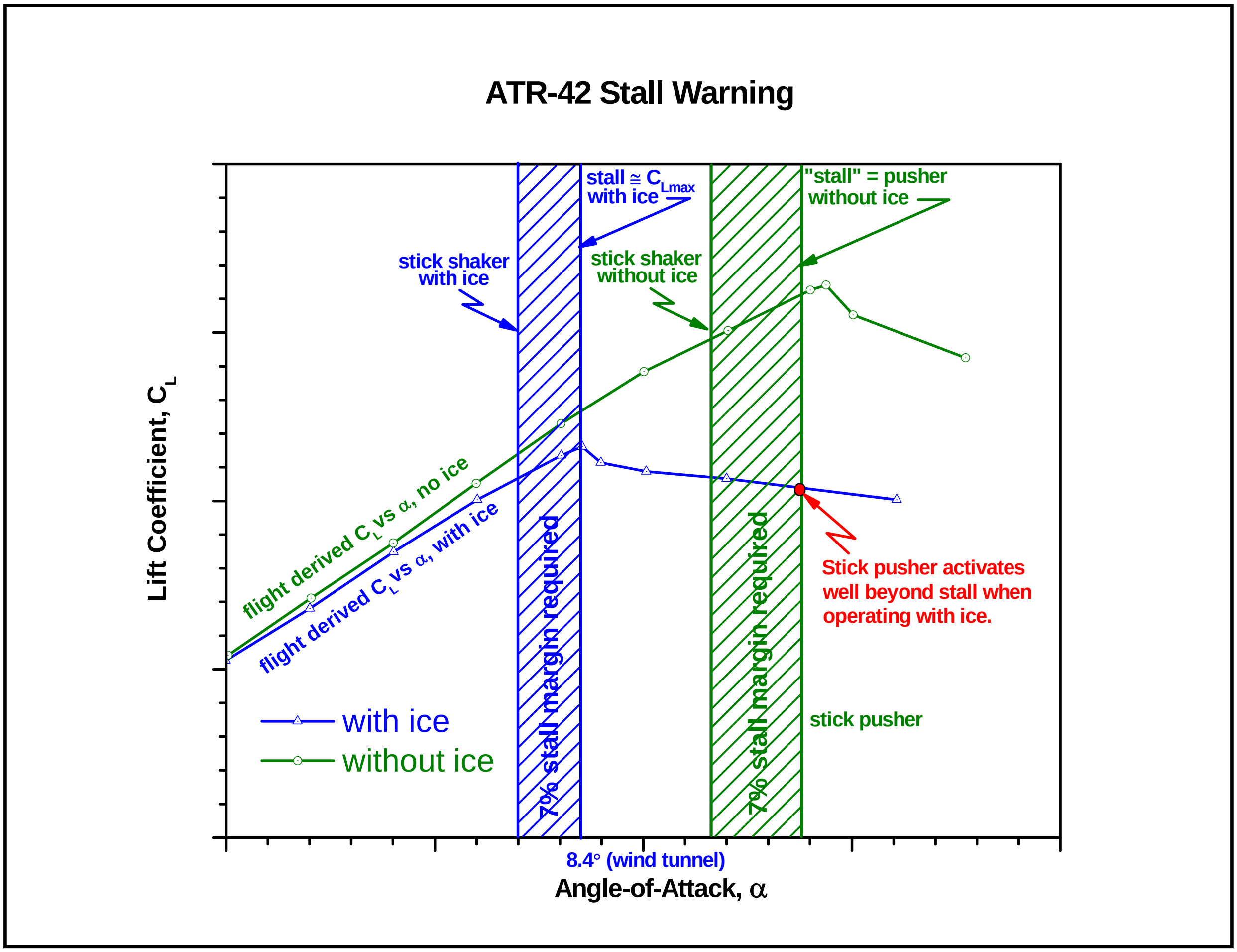

Figure 6. ATR-42 Stall Margin Thresholds, With and Without IPS

stick shaker, normal (deg)	stick shaker, ice (deg)	stick pusher (deg)	stick pusher, ice (deg)	Clmax, normal (wind tun.)	Clmax, ice (wind tun.)	
18.1	11	18.0°-21.55°	18.0°-21.55°	22.5	13.2	(vane)
11.6	7.0	11.5° - 13.8°	11.5° - 13.8°	14.4	8.4	(reference)

Figure 7. Stick Shaker and Stall Warning AOA Activation Schedule with Zero Flap Handle Position

Note: An attempt has been made to use "reference" angle-of-attack consistently throughout this addendum. However, it is "local", or "vane", angle-of-attack that is actually recorded on the FDR (as noted in footnote 4), and a calibration provided by ATR has been applied to obtain reference angles.

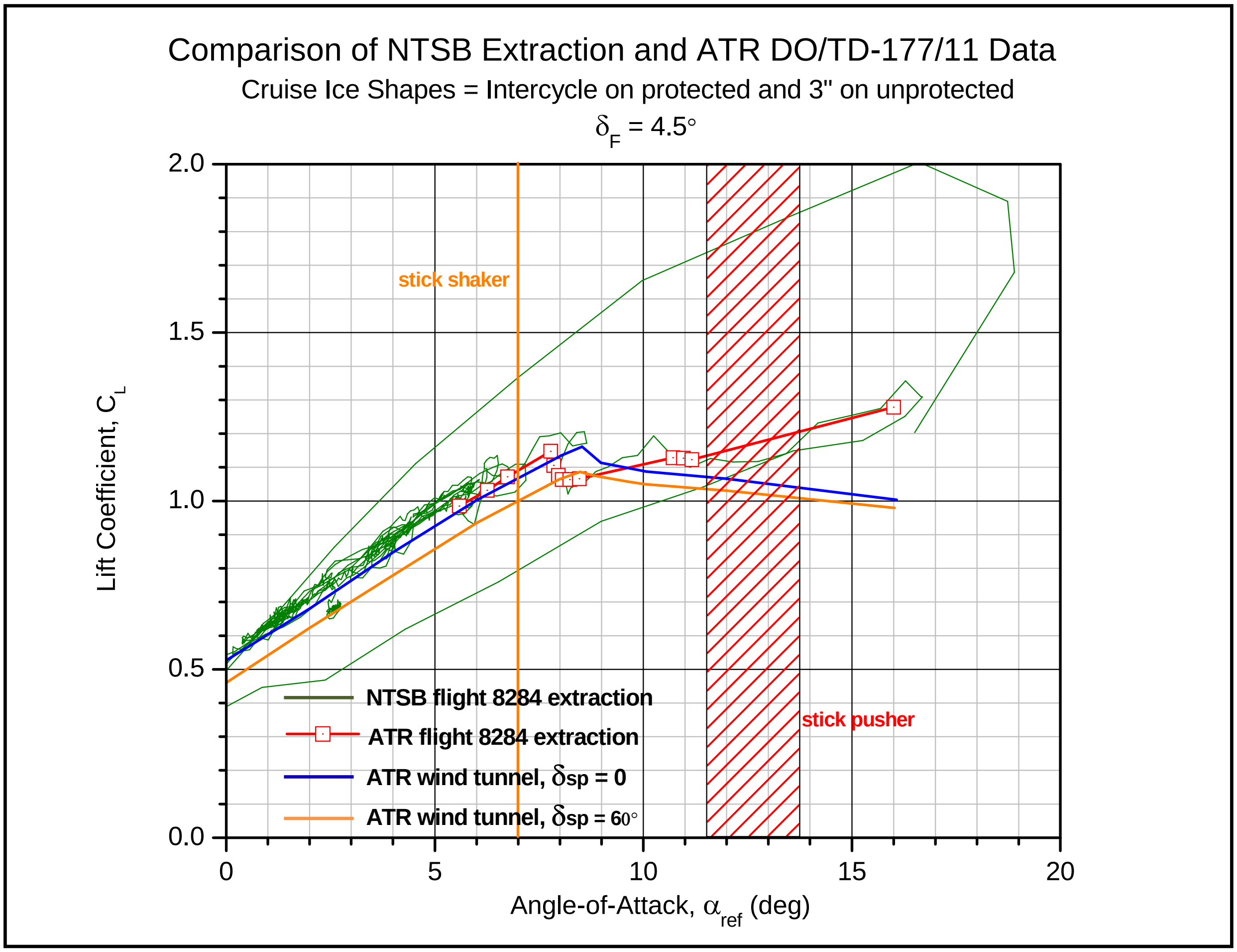

Figure 8. Comparison of NTSB and ATR Extracted Lift Coefficient for Empire flight 8284

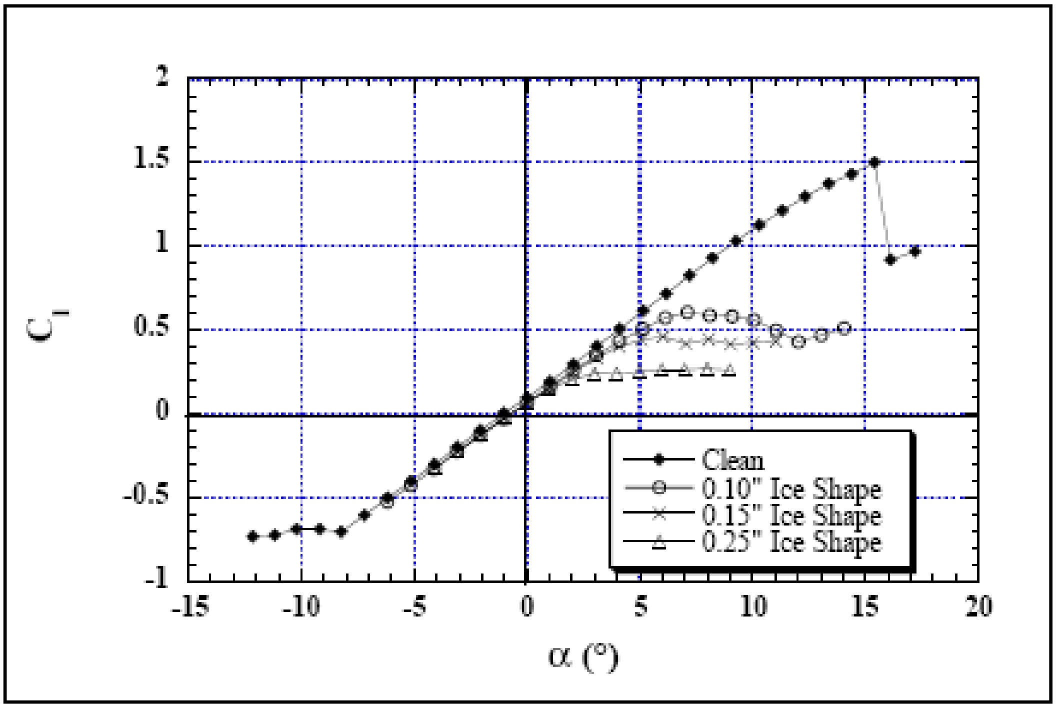

Figure 9(a). Effect of Simulated Ice Shapes on Lift Coefficient for NACA 230 Series Airfoil

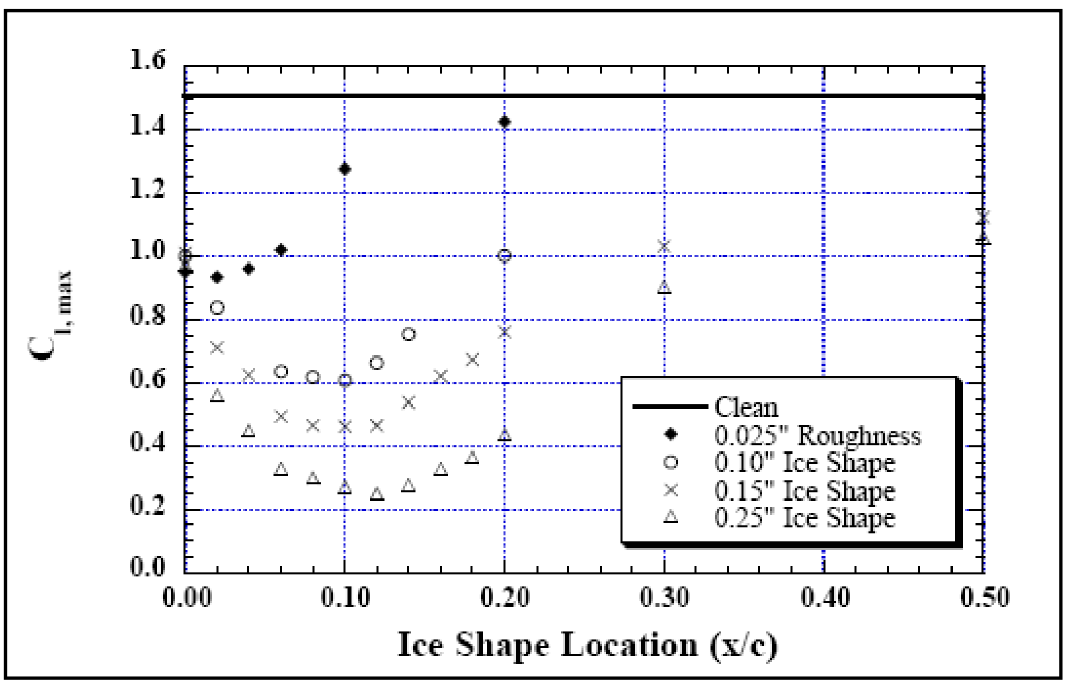

Figure 9(b). Effect of Simulated Ice Shapes on C_{Lmax} for NACA 230 Series Airfoil

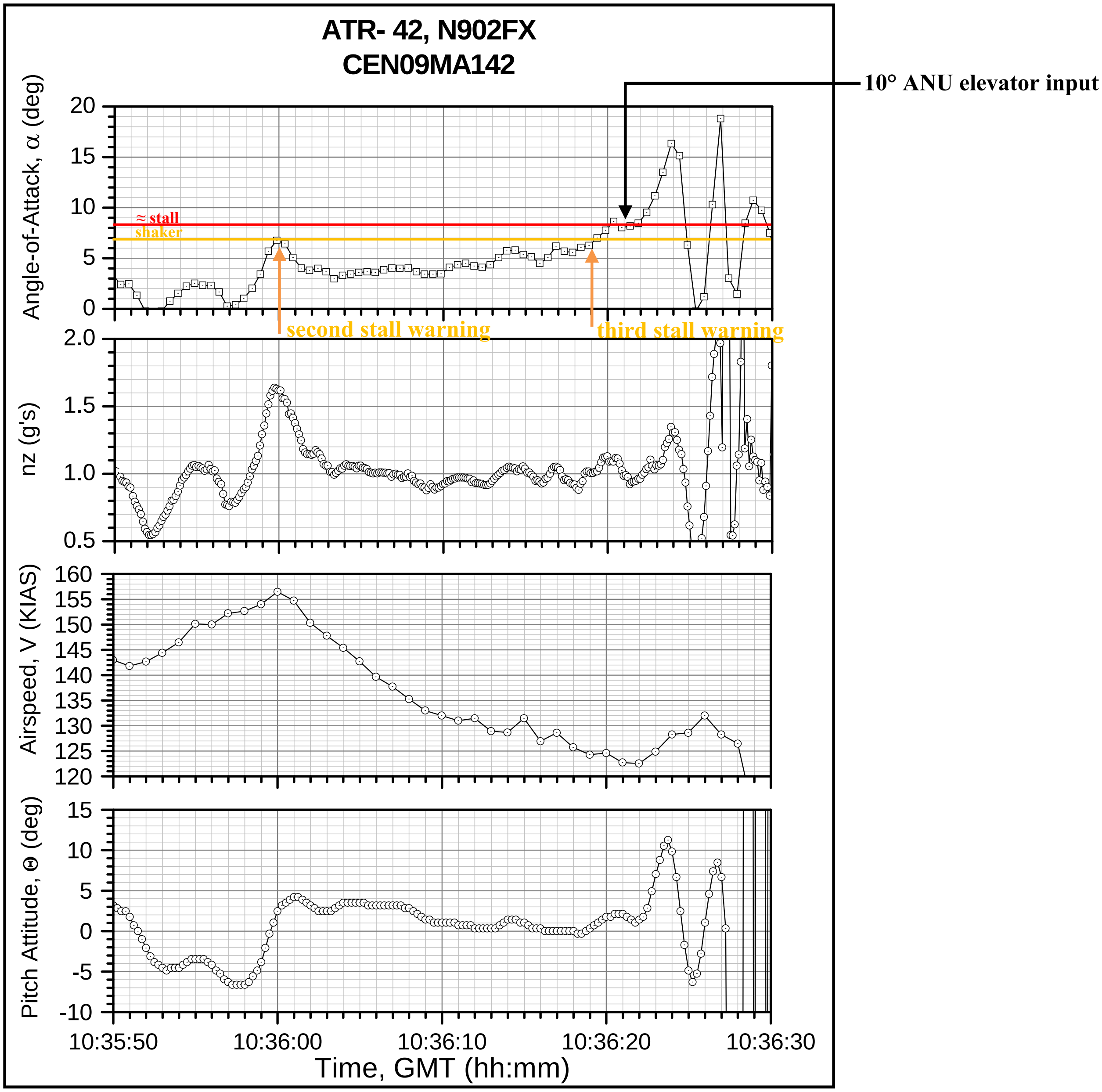

Figure 10. Final Stall Warning at 10:36:19

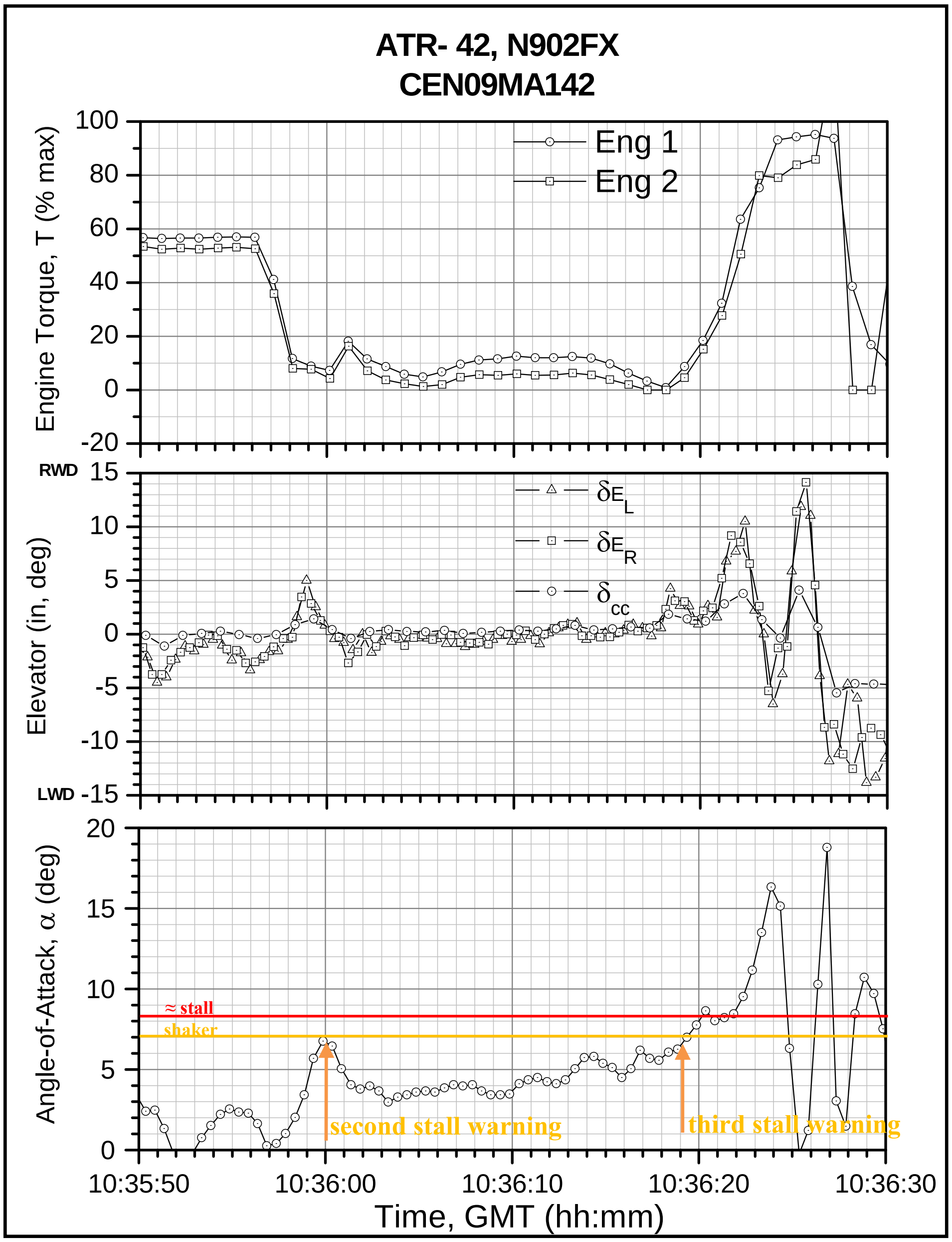

Figure 11. Final Stall Warning at 10:36:19