ACCIDENT

Aircraft Type and Registration:	Cessna 525A Citation CJ2+, N380CR
No & Type of Engines:	2 Williams FJ44-3A-24 turbofan engines
Year of Manufacture:	2010 (Serial no: 525A0465)
Date & Time (UTC):	31 December 2013 at 1100 hrs
Location:	5.7 nm north-west of Coventry, Warwickshire
Type of Flight:	Private
Persons on Board:	Crew - 1 Passengers - 1
Injuries:	Crew - None Passengers - None
Nature of Damage:	Structural damage to left and right wings, broken HF antenna, dent to fin leading edge
Commander's Licence:	FAA Private Pilot's Licence
Commander's Age:	69 years
Commander's Flying Experience:	3,900 hours (of which 600 were on type) Last 90 days - 16 hours Last 28 days - 5 hours
Information Source:	AAIB Field Investigation

Synopsis

As the aircraft approached its cruising altitude of FL430, the pilot was not monitoring the indicated airspeed and the aircraft stalled, departing from controlled flight in a series of five 360° rolls to the right. The pilot briefly regained control before the aircraft stalled again and in the following recovery, the aircraft's wings were damaged in overload. The pilot made a successful landing and examination of the aircraft's recorded data revealed that the angle of attack (AOA) sensing system had 'stuck' in flight and the aircraft's stall warning system did not operate prior to the stall onset. Two Safety Recommendations are made, relating to the continued airworthiness of the AOA sensing system.

History of the flight

The aircraft was kept in a heated hangar at Leeds Bradford Airport. On the day of the accident the owner planned to fly, with one passenger, from Leeds Bradford Airport to Palma de Majorca, Spain. He occupied the left cockpit seat and the passenger sat towards the middle of the cabin on the right side, wearing a three-point harness. Three small dogs were in the cabin, unrestrained, on and around the passenger's lap. Before flight the owner had conducted a pre-flight inspection, noting no defects. The pitot and static heat were selected ON before departure and the takeoff and initial climb were without incident. The aircraft followed a southerly track, climbing continuously towards the planned cruising level of FL430.

The pilot later reported one brief icing encounter, which he described as a "flash" of frost across an unheated area of the windscreen. The engine anti-ice had been selected ON earlier in the climb and the pilot then selected the wing and tail de-ice ON as a precaution, although no ice was seen on the wing at any time. The engine, wing and tail ice protection systems were selected OFF later in the climb.

The climb was conducted with the autopilot engaged in vertical speed (VS) mode with a selected rate of climb of 2,000 ft/min and the thrust levers, for the FADEC-controlled engines, in the Maximum Continuous Thrust (MCT) detent. As the aircraft climbed, the selected rate was reduced in 500 ft/min decrements and, passing FL 410, the aircraft was climbing at 1,000 ft/min. At this point (1057:38 hrs) recorded aircraft data shows that the indicated airspeed reduced below 150 kt. The indicated airspeed continued to decrease, reducing below 140 kt, 46 seconds later. The pilot noted that the indicated airspeed was lower than he had expected, with the green 'donut' marker on the speed tape (indicating V_{REF})[1] being slightly faster than his actual airspeed. He therefore reduced the rate of climb to 500 ft/min. The recorded data suggests that this occurred around 1059:17 hrs, when the indicated airspeed was 128 kt. Based on his experience, the pilot considered that the selection of a vertical speed of 500 ft/min should have managed the aircraft's energy sufficiently to achieve FL430 without incident. However, recorded data shows that over the next 50 seconds, the speed gradually reduced by a further 10 kt.

At some point between FL420 and FL430 the pilot noted the upper wind, displayed on the primary flight display (PFD), and decided to check the forecast winds chart that he had saved on his tablet-style portable electronic device (PED). He therefore looked down to the PED, located on the unoccupied right cockpit seat for what he believed to be a second or two. The pilot later recalled being "head down" looking at the PED when, without warning, he heard a 'click' and the aircraft pitched severely nose-down and rolled to the right. He thought that the stick shaker may have activated once as the aircraft pitched down; data shows that this occurred at 1100:08 hrs.

The pilot then recalled a violent and very confusing rolling departure from controlled flight. The aircraft almost immediately entered high cirrus cloud, obscuring the horizon. The pilot was unable to interpret the PFD attitude indicator, which he described as presenting information that he could not recall having seen before. He did not recall exactly how long this persisted but he did recall checking both the left and right PFD displays, which were similar in appearance.

The pilot made several attempts to recover the aircraft, although he could not later recall what control inputs he made. He recalled selecting idle thrust and achieving almost level flight at one point but, he had not increased thrust and the aircraft slowed rapidly and again departed from controlled flight. During the period that the aircraft was out of control it descended into clearer air between cloud layers, with a visible external horizon allowing the pilot to regain control.

Footnote

1 V_{REF} is defined as 1.3 x stall speed.

The pilot re-established communications with ATC who instructed him to maintain FL280. He believed that he had re-engaged the autopilot, but when he released the yoke the aircraft immediately adopted a nose-up attitude and climbed approximately 2,000 ft before he regained control. He then noted that the pitch trim was in the fully nose-up position and the autopilot had not engaged.

Having set an appropriate trim position and now in a stable flight regime, the pilot confirmed that his passenger was uninjured. He noted damage to the upper surface of the left wing and his passenger reported similar damage to the right wing.

Given the damage to the aircraft, the pilot did not want to exceed 1,000 ft/min during descent and therefore he estimated that it would take 25 to 30 minutes to land. This placed Leeds Bradford Airport within the available options and, as he had only recently left that airport, was certain of the weather and was familiar with the airport, he considered this the best option with the lowest risk. He informed ATC of his decision and the remainder of the flight was without further incident. The pilot stated that the aircraft handling appeared unchanged by the damage it had sustained.

The pilot, passenger and the dogs were uninjured.

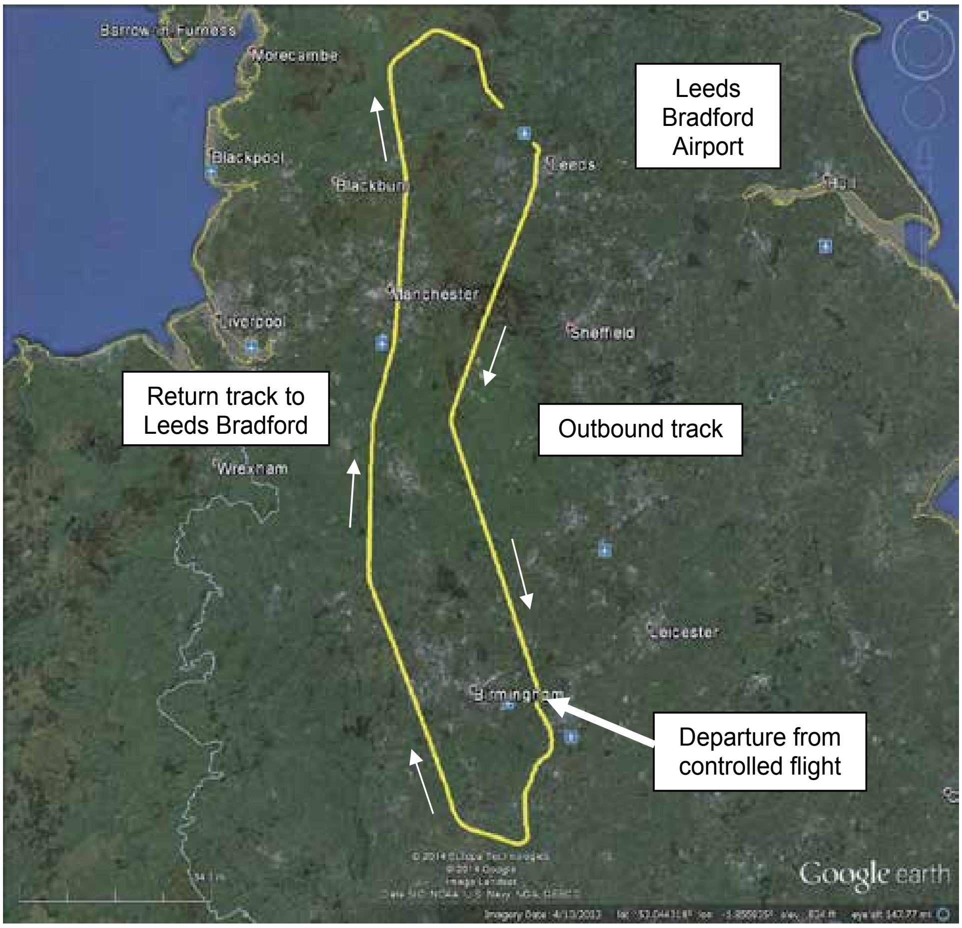

Figure 1
N380CR track

Aircraft examination

Inspection after the accident flight showed that the aircraft's wings were damaged in a manner consistent with overload in positive symmetrical bending. Five ribs in the outboard wingbox of the left and right wings were damaged by buckling in a manner similar to that shown in Figure 2, and the bonded joints between the ribs and the upper and lower wing skins had failed in overload. The upper and lower outboard wing skins of both wings were permanently deformed with a significant loss of aerofoil shape. Despite the disruption to the wing structure, which on this aircraft type forms an integral fuel tank, no fuel had leaked from the wings and the wing skins remained firmly attached to the front and rear spars. The upper wing skins above the main wheel wells, at the inboard end of the wing close to the fuselage, were also found buckled due to overload. The damage was consistent with symmetrical 'pullout' manoeuvre loads between +3.6g ('limit' load) and +5.4g ('ultimate' load).

Figure 2

Right wing internal damage at WS255.25, at approximately mid-span of the aileron

Both ailerons showed evidence of skin wrinkling along the trailing edge on their upper and lower surfaces.

The aircraft's HF (high-frequency band) antenna had broken at its connection to the top of the vertical fin and the antenna's spring tension unit was missing. The antenna had remained attached at its forward mounting on the upper fuselage skin, and flailing of the antenna during flight had caused a dent on the left side of the fin leading edge, close to the fin root rib.

A review of the weight and balance calculations for the flight showed that the CG and aircraft weight were within flight manual limits at all stages of the flight.

Weather

The UK Met Office provided an aftercast of the weather conditions likely to have been encountered during the accident flight. It reported that there was occasional stratus cloud at 600 ft agl with tops at 1,000 ft, leading to broken cumulus and stratocumulus between 2,000 ft and 8,000 ft with alto-cumulus and alto-stratus above these heights. The freezing level was at about 4,300 ft.

Above this it was likely that there was no cloud up to about FL290, above which cirrus was likely. The absolute cloud tops were probably in the region of FL350. Data above those levels was sparse but the profile showed no significant wind shear at any level. There were no rapid or unusual changes in temperature relative to the normal ISA lapse rate but there was a slight rise, from -57°C to -55°C, between FL400 and FL430.

Recorded information

A number of data sources were available to the investigation, including ground-based radar and data stored in on-board avionics components. The aircraft was not fitted with a flight data or cockpit voice recorder, nor was it required under airworthiness regulations.

The aircraft was, however, fitted with a system known as AReS (Aircraft Recording System) by the aircraft manufacturer. This was fitted as a system diagnostic and troubleshooting tool but in this instance was also available for accident investigation purposes. The system installed on N380CR recorded 6 channels of ARINC 429 data, sourced from various avionics components of the Rockwell Collins Pro Line 21 Avionics System.

Review of the AReS data confirmed that the accident flight had been recorded along with eight preceding flights, with over 3,000 parameters available. As this data recorder was fitted by the aircraft manufacturer voluntarily, it was not subject to the rigours of flight data recorders fitted to aircraft by regulation, which have a minimum parameter list. A large number of useful parameters for this investigation were therefore not available[2].

A key parameter for this investigation that was recorded was 'normalised' angle of attack (AOA)[3]. This parameter was sourced from the AOA computer and converted into a digital signal by the Pro Line 21 avionics. If the AOA signal was detected as invalid, the Pro Line 21 system would 'freeze' the normalised AOA at the last known value but would also provide an 'invalidity' marker of when this had occurred. The aircraft AOA system is described in further detail in the 'Aircraft description' section of this report.

In addition to the AReS data, the Enhanced Ground Proximity Warning System (EGPWS) recorded a number of events, which were also downloaded.

Footnote

2 This included AOA validity, AOA heater status, roll rate, control column and rudder pedal positions, control surface positions, stick shaker and pitch trim parameters.

3 Normalised AOA is the ratio of actual angle of attack to stalling angle of attack.

Previous flights of N380CR

Flights, dating back to 4 October 2013, had been retained in the AReS system and were analysed to review aircraft operations during the climb and the corresponding AOA activity. On 7 December 2013, four flights prior to the accident flight, the aircraft flew from Palma de Majorca, Spain, to Leeds Bradford Airport. At the top of the climb, the recorded normalised AOA remained static for approximately 90 seconds despite changes in pitch attitude. The recorded static air temperature (SAT) at the time was -61°C although not the minimum of -66°C which occurred just over 20 minutes later.

Analysis of the recorded normalised AOA data confirmed that the Pro Line 21 system had declared this data as 'valid' throughout the entire flight. No other static AOA activity was noted during any recorded flight, apart from the accident flight and that on 7 December. A summary of the minimum SAT encountered during each of the flights is shown in Table 1:

Date of flight	Minimum static air temperature	Maximum altitude
4 October 2013	-58°C	FL430
25 October 2013	-61°C	FL430
5 November 2013	-58°C	FL430
29 November 2013	-64°C	FL430
7 December 2013	-66°C	FL430
17 December 2013	-43°C	FL280
17 December 2013	-23°C	FL200
17 December 2013	-50°C	FL320
31 December 2013 (accident flight)	-57°C	FL420

Table 1

Summary of minimum static air temperature encountered by N380CR during nine flights recorded on the AReS system

Accident flight

Analysis of the recorded normalised AOA data during the accident flight again confirmed that the data was always deemed 'valid' by the aircraft system.

Climb to FL420

Figure 3 shows that at 1044:02 hrs, the recorded AReS data shows the normalised AOA remaining static as the aircraft climbed through FL197 at a SAT of -22°C. Despite recovering intermittently, as the aircraft climbed and the SAT reduced, periods of static normalised AOA were recorded.

At 1053:43 hrs while climbing through FL356, the indicated airspeed stabilised at 180 kt as the vertical speed reduced from approximately 1,750 ft/min to 1,400 ft/min. This airspeed was maintained for a minute after which it began to reduce. At 1056:41 hrs, the vertical speed reduced further to 1,000 ft/min as the aircraft climbed through FL395 at an indicated airspeed of 158 kt.

At 1059:17 hrs, at FL420 and 128 kt, a further reduction in the vertical speed to 500 ft/min was recorded but this did not stop the decay in airspeed. Nine seconds later, a 'step' change in the normalised AOA was recorded, from 0.46 to 0.61 units, where it remained for the next 45 seconds, despite a reducing airspeed and increasing pitch attitude. This step change (and others noted above FL300) were considered by the aircraft manufacturer to be characteristic of the AOA vane momentarily breaking loose from its static position. At 1100:01 hrs, the indicated airspeed reduced to below 120 kt with a recorded normalised AOA of 0.61 units and pitch attitude of 10.8° pitch-up.

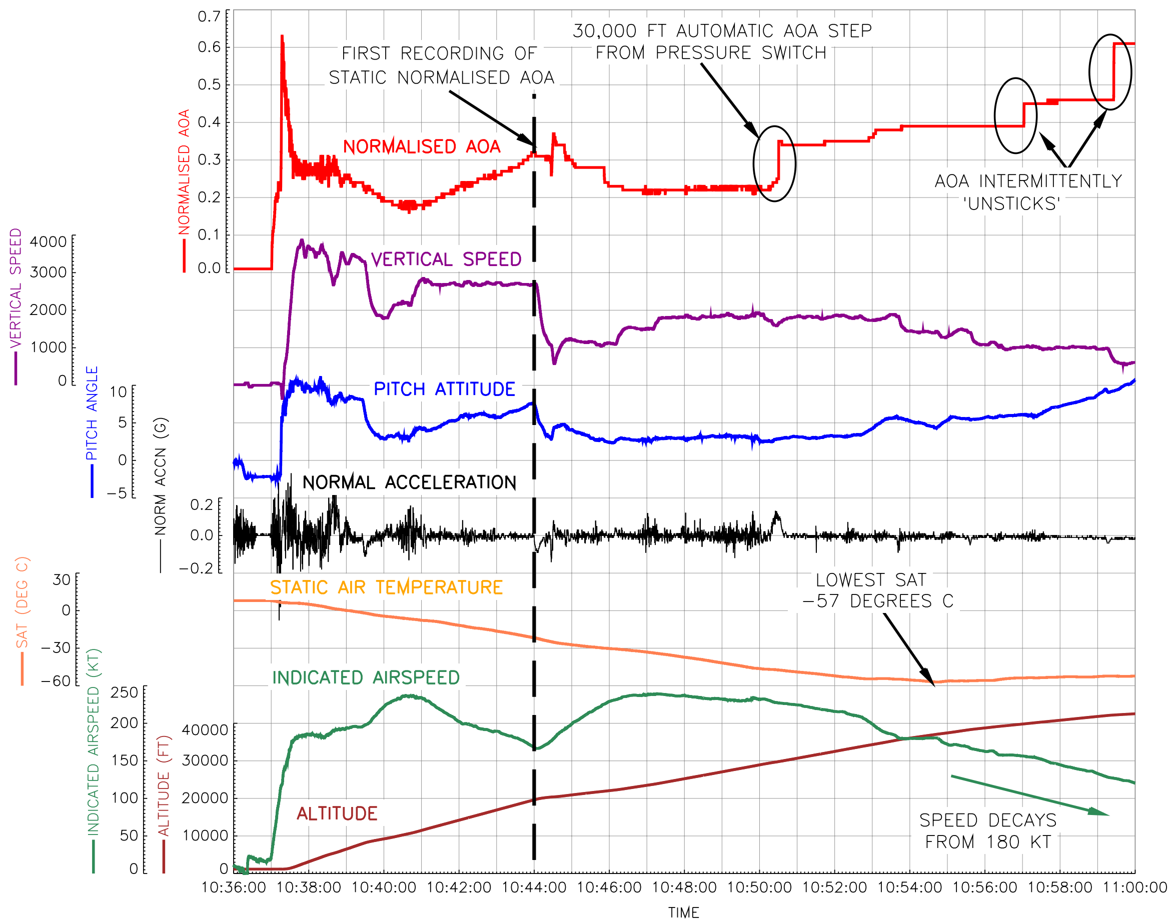

Figure 3

N380CR AReS data during climb

Departure from controlled flight

At 1100:08 hrs, while climbing through FL426 with a pitch attitude of 11.5°, the aircraft rolled right to 57° over a period of four seconds (Figure 4). No buffet vibration could be identified prior to this from the recorded accelerations. This roll attitude should have triggered the PFD 'declutter'[4] mode and an EGPWS bank angle warning[5]. During this time, the aircraft pitched down to -9°, the autopilot disengaged[6], the aircraft reached an indicated airspeed of 116.7 kt but the recorded normalised AOA remained at 0.61 units prior to reducing to 0.27 units.

The aircraft then rolled back to the left during which the normalised AOA increased to above the threshold required to activate the stick shaker (0.87) for approximately 0.5 seconds before again sticking at a value of 0.78. Control column and rudder pedal positions were not recorded, so it was not possible to establish the control inputs being made by the pilot.

After rolling to the left to -66°, the aircraft rolled back to the right and between 1100:12 hrs and 1100:35 hrs completed five 360° rolls to the right. The derived roll rates[7] increased progressively from 111°/sec to 120, 152, 153 and finally to 181°/sec. During this, the EGPWS download confirmed a further 12 bank angle warnings and the aircraft oscillated in pitch and slowly pitched down to a minimum of -68°, before then pitching up to -3.6° with a normal acceleration of a 3.25g[8]. The outcome of this was not to arrest the descent but to reduce the airspeed significantly.

Engine power was reduced to IDLE at 1100:34 hrs and remained there for the next 72 seconds. During the fourth complete roll, the recorded normalised AOA became unstuck and increased to 1.0 for six seconds. No further static AOA behaviour was noted for the remainder of the recording.

After the 3.25g pull-out, the aircraft pitched down again and appeared to turn through a further 360° roll to the right while pitching down almost vertically to a minimum pitch attitude of -89.7°. The Attitude Heading Computer (AHC) manufacturer indicated that at such pitch attitude, the roll and heading values "are not well defined".

Pitch attitude then increased, and there followed two oscillatory pitching manoeuvres over the next minute and a half (Figure 5). During the first of these, the aircraft rolled to 115° right, the indicated airspeed reached its maximum of 295 kt (Mach 0.77) and an overspeed warning was recorded.

Footnote

4 'Declutter' mode is defined in the Aircraft Description section.
5 When the EGPWS senses a bank angle in excess of ±50 degrees, an audio callout of 'BANK ANGLE' is triggered.
6 The autopilot will automatically disengage if the roll attitude exceeds 45º.
7 Roll rate was not recorded by the AReS system.
8 AReS records normal acceleration with the acceleration due to gravity removed. As such, when stationary on the ground, normal acceleration is recorded as 0g instead of 1g. Normal acceleration figures quoted in this report are the recorded value plus 1.

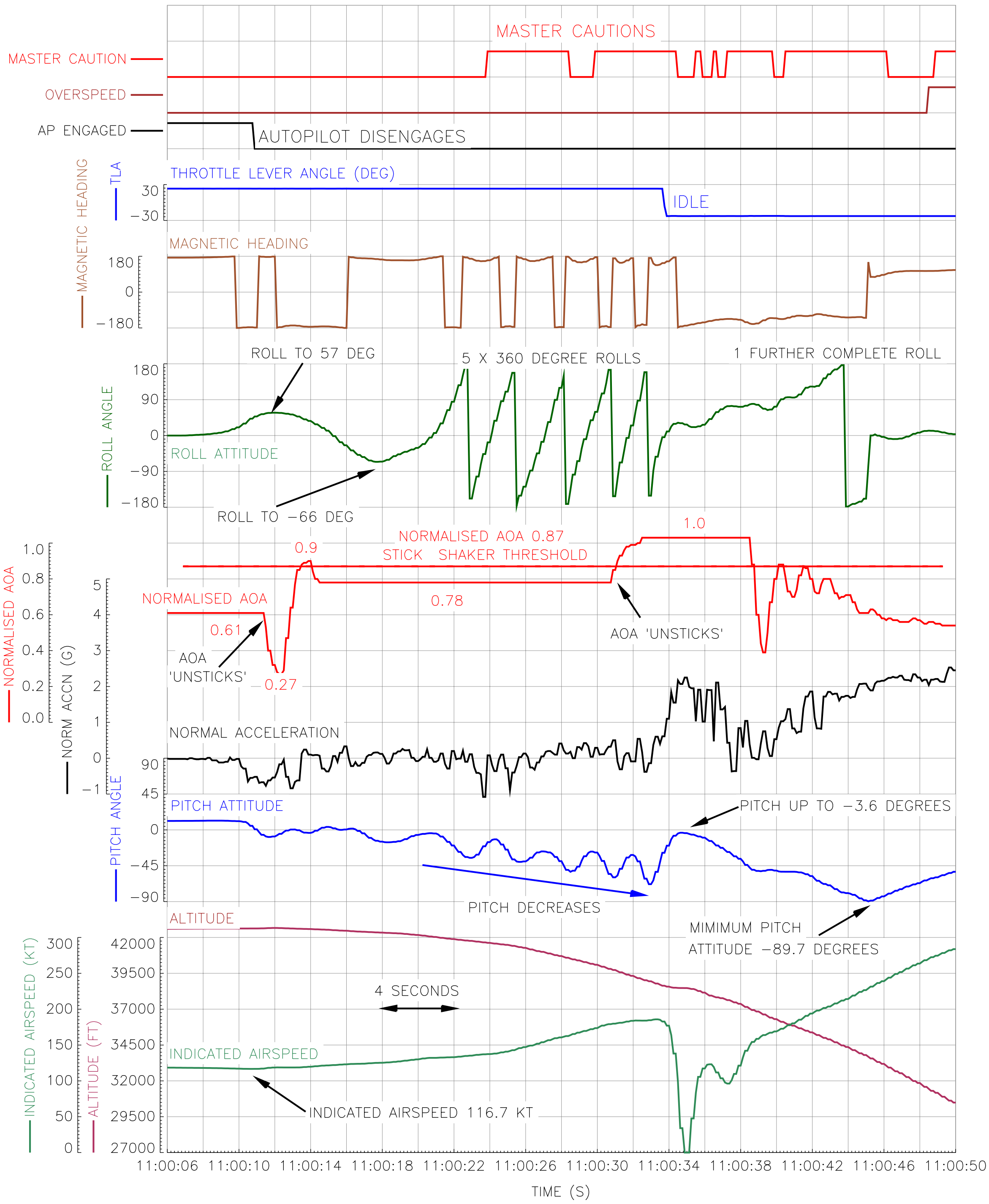

Figure 4

AReS parameters during loss of control

At 1100:58 hrs, as the pitch attitude increased, the descent was arrested at FL270, which also corresponded with the peak normal acceleration of 4.48g. The descent of 15,662 ft over 46 seconds equated to a vertical speed of approximately 20,000 ft/min. Ten seconds prior to reaching the maximum pitch attitude of 70° during this pitching manoeuvre, the normalised

AOA increased to above 0.87 (peaking at 1.0) and remained there for the next 33 seconds. The minimum indicated airspeed as the aircraft began to pitch down again was 44 kt.

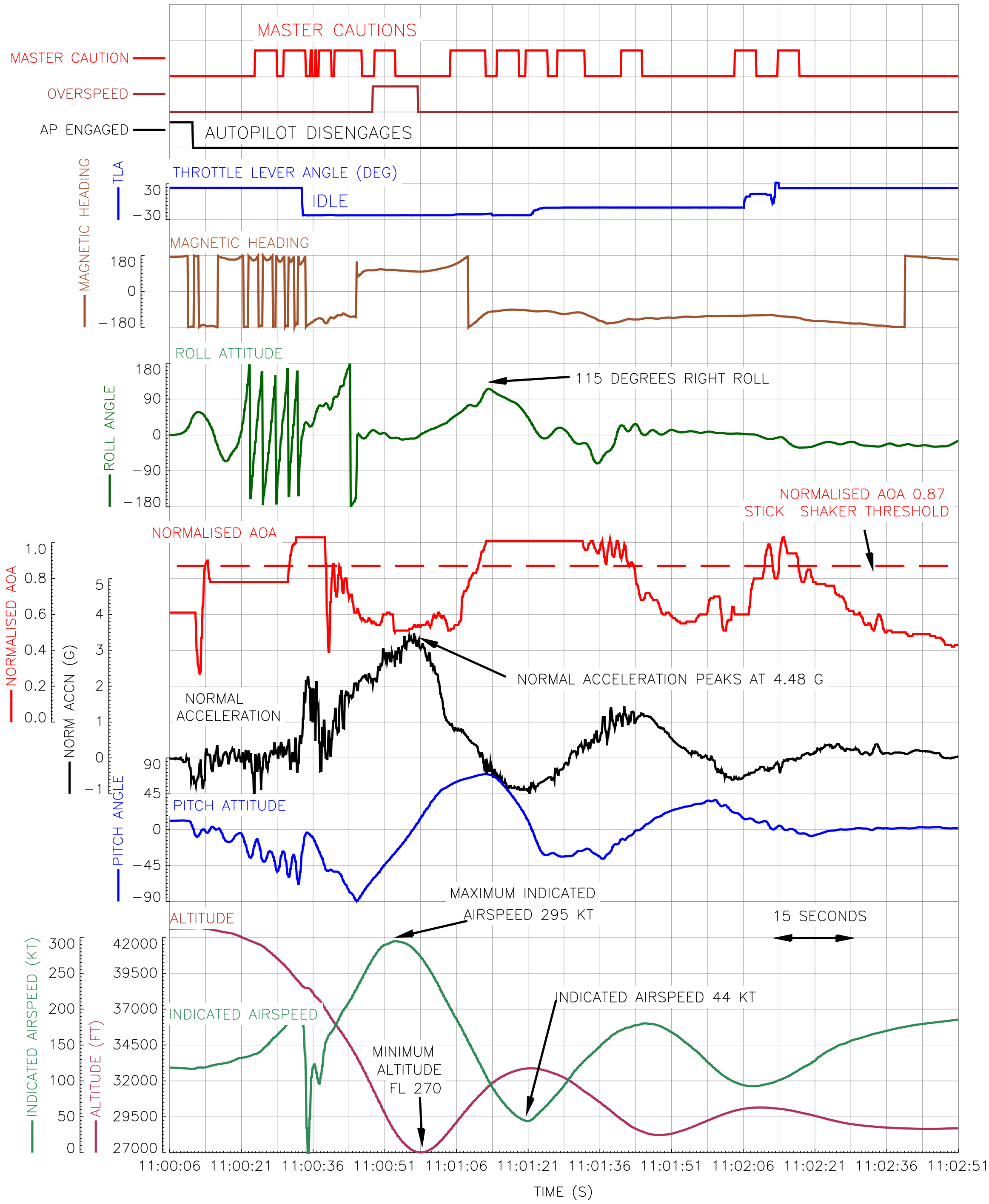

Figure 5

AReS data showing recovery

At the top of the second pitching manoeuvre, the normalised AOA again exceeded 0.87 for two separate periods of two seconds and four seconds, with a minimum recorded indicated airspeed of 93 kt.

At 1103:10 hrs, the pitch, roll and heading parameters stabilised, airspeed increased through 200 kt whilst the aircraft maintained FL300. Vertical speed for the next minute and a half varied between 2,400 ft/min to -2,300 ft/min but eventually stabilised. The autopilot was then re-engaged and the aircraft returned to Leeds Bradford Airport.

Aircraft description - general

The Citation CJ2+ is a low-wing monoplane business jet, with retractable tricycle landing gear and a T-tail. The cabin is pressurised and N380CR was equipped with seating for six passengers and two pilots. The aircraft is powered by two turbofan engines mounted on pylons attached to the rear fuselage.

The aircraft is certificated to FAR 23 in the Normal Category and the maximum indicated operating Mach number (M_{MO}), between 29,124 ft and the maximum operating altitude of 45,000ft, is 0.737. The maximum takeoff weight is 12,500 lbs and the maximum positive load factor, or 'limit load' with the flaps retracted, is +3.6g. The limit load is the load level that the aircraft's structure must be capable of sustaining without permanent deformation or damage occurring. The prescribed minimum factor of safety in FAR 23 for limit loads is 1.5[9], meaning that the 'ultimate' positive load factor on the aircraft is at least +5.4g. When the structure is subjected to load levels above the limit load but lower than the ultimate load, the structure must withstand the additional load but may permanently deform whilst doing so.

The Citation CJ2+, in common with many other twin turbofan business jets that are certified in the FAR 23 and EASA CS-23 categories, is equipped with a single AOA vane. Larger jet aircraft certified in the FAR 25 and EASA CS-25 '*Large Aeroplane*' categories are typically equipped with two or three AOA vanes, providing a degree of redundancy, and monitoring, in the AOA sensing system.

N380CR

Prior to the accident flight on 31 December 2013, N380CR had accumulated 312.2 flying hours since its manufacture in June 2010. The last scheduled maintenance inspection was completed on 17 September 2013 and no maintenance had been performed on the aircraft's AOA system since manufacture, in accordance with the aircraft's approved maintenance programme.

Aircraft attitude display

The aircraft was fitted with a Rockwell Collins Pro Line 21 Avionics System which features a fully integrated flight instrument, autopilot, communication, and navigation system. Part of this fit is the Attitude Heading Reference System (AHRS), including two separate Attitude Heading Computers (AHCs) which sense the aircraft attitude, heading, and three-axis rate of angular accelerations. This information is then displayed to the pilot on the Primary Flight Display (PFD).

Footnote

[9] FAR 23.303 '*Factor of Safety*'.

The Pro Line 21 Manual describes the PFD attitude display as:

> *'The attitude ball is the traditional blue sky and brown earth depiction separated by a white horizon line. A V-shaped single cue aircraft symbol is in the center of the attitude ball.'*

The PFD attitude also includes a 'declutter' mode which is activated when an aircraft enters an unusual attitude:

> *'When pitch angle is greater than 30 degrees nose up or 20 degrees nose down, or roll angle exceeds 65 degrees, the warning chevrons show on the pitch tape. Non-essential information is removed from the PFD to emphasize the unusual attitude condition. The display returns to normal when pitch angle is ±25 degrees nose up or 15 degrees nose down, or roll angle is ±60 degrees.*
>
> *NOTE*
> *Non-essential information refers to any information on the PFD that is not airspeed, altitude, attitude, vertical speed, engine data, compass, YD[10] disengage, AP[11] engage/disengage, TRIM fail, and mistrim annunciations.'*

Figure 6 shows both a PFD nominal attitude display and the declutter mode encountered when at a roll attitude in excess of 60°.

Figure 6

Nominal PFD (left) and PFD declutter mode
after roll attitude greater than 60 degrees (right)
Picture courtesy of Rockwell Collins

Footnote

10 Yaw damper.
11 Autopilot.

Figure 7 shows the declutter mode at 65° pitch-up, which also features a large warning chevron pointing to the direction of the horizon:

Figure 7

PFD declutter mode at a pitch attitude of +65°

Picture courtesy of Rockwell Collins

Angle-of-attack (AOA) system

The aircraft's AOA system is shown diagrammatically in Figure 8. The system is electrically powered and consists of the following primary components:

- A single AOA airflow sensing vane mounted on the right side of the forward fuselage (Safe Flight Instrument Corporation model C-12717-1)
- Inputs from flap position and landing gear squat switches
- An analogue AOA gauge mounted in the upper left corner of the instrument panel
- An AOA 'indexer light' mounted above the glareshield, to the left of the windshield centre post
- A high-altitude ST035 barometric pressure switch
- An AOA normalisation module
- Outputs to the PFD and stick shaker unit

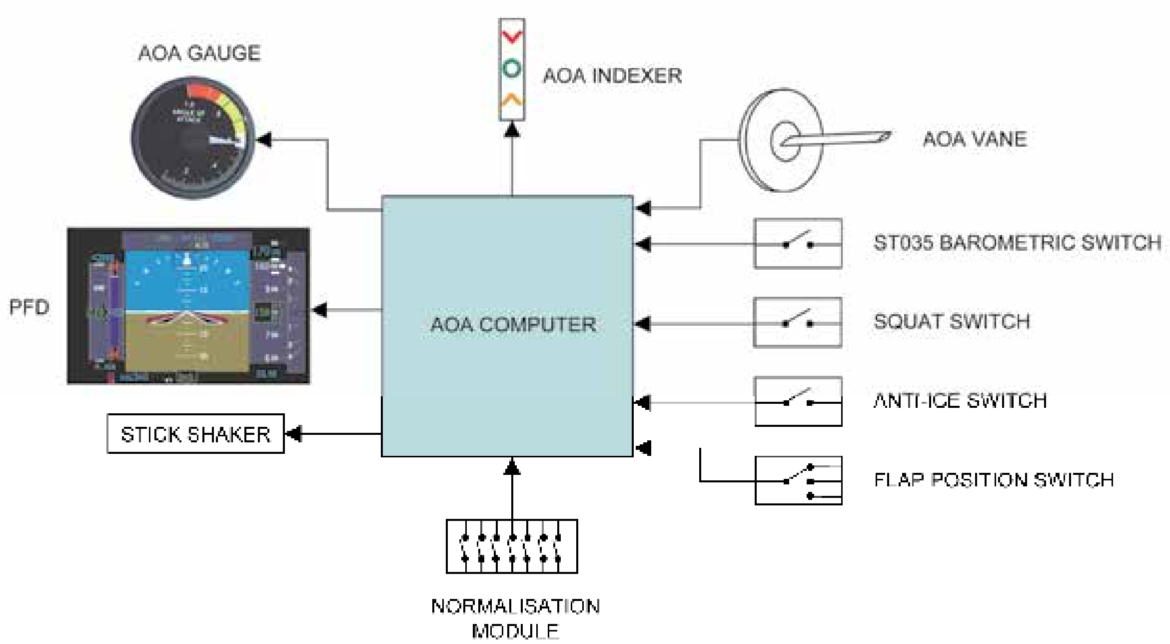

Figure 8

AOA system block diagram

The AOA vane's position is derived by a rotary transducer within the AOA vane case, and is sent to the AOA computer, which converts the AOA vane position into an analogue DC voltage, equivalent to a 'normalised[12]' value of AOA ranging between 0.0 and 1.0. A value of 0.6 AOA equates to V_{REF}, 1.3 times the stalling speed for any flap setting or weight. The stick shaker activates at a value of 0.87 or 0.88 AOA, depending on the pressure altitude[13], and a full stall occurs at 1.0 AOA.

The computed value of AOA is displayed on the analogue AOA gauge on the instrument panel and on the glareshield indexer light, which displays a green circle or 'donut' when the AOA value is 0.6. The indexer lights are only active when the landing gear is down and locked. If the airspeed is below V_{REF} the indexer light displays a downward pointing red chevron and if it is above V_{REF}, an upward pointing yellow chevron is displayed.

The AOA computer also provides a signal to the PFD such that a small green circle ('donut'), corresponding to V_{REF}, is displayed on the airspeed tape. This circle is displayed regardless of the landing gear position.

The AOA vane is electrically heated for operation in icing conditions, although no separate AOA vane case heater is fitted. AOA vane heating is turned on when the pitot-static heating switch on the anti-ice/de-ice switch panel is selected ON. If the vane heater has been detected as failed, the annunciator panel AOA HTR FAIL warning is illuminated.

Footnote

12 Normalised AOA is the ratio of actual angle-of-attack to stalling angle-of-attack.

13 A reduced stick shaker onset point of 0.87 AOA is used above a pressure altitude of 30,000 ft, as sensed by the ST035 high-altitude barometric pressure switch.

A configurable AOA 'normalisation' module is connected to the AOA computer. This unit consists of seven 'dip' switches, each of which may be set to ON or OFF, to allow calibration of the AOA system during production flight testing. Inspection of the aircraft's production flight test report showed that the normalisation unit's dip switch settings at the time of the accident were the same as those set following the production flight tests.

Output to Pro Line 21 system

The AOA computer provides two signals to the Pro Line 21 system; an analogue DC voltage representing normalised AOA and an 'AOA validity' discrete[14]. These signals are acquired by the Data Concentrator Units (DCUs) which convert them into a digital signal. This digital signal is then transmitted to other avionics components fitted to the aircraft on an ARINC 429 databus.

The 'AOA valid' discrete and the analogue signal are monitored for validity by the DCU. If the AOA signal is detected as invalid, a warning flag will appear on the PFD and the data on the databus will be fixed at the last valid value. The ARINC 429 Sign/Status Matrix (SSM)[15] will be set to a condition other than Normal Operation so it is possible to ascertain whether data which appears static on the databus is due to a declared failure or from a static AOA position.

Low-speed alerting and stall warning system

The manufacturer's operating manual describes the stall warning system as:

> *'Stall Warning*
>
> *Stall warning includes one stall strip on the inboard leading edge of each wing and a stick shaker that the angle-of-attack system operates. Stall strips (Figure 15-2) create turbulent airflow at high angles of attack, which causes a buffet to warn of approaching stall conditions.'*

The aircraft therefore has a combination of aerodynamic and electro-mechanical warnings.

The Pro Line 21 Operator's Guide describes the PFD in more detail. Low-speed alerting is provided by various elements on the PFD speed tape. A red Impending Stall Speed (ISS) bar (Figure 9) is positioned at the speed equivalent to 1.1 V_s[16]. This is calculated by the avionics system using airspeed, AOA and normal acceleration.

If the aircraft speed trend is slower than ISS by 2 or more knots for more than 5 seconds, or the indicated airspeed is slower than ISS by 2 or more knots, then a visual warning occurs with the line changing to a wider blue and red checkerboard pattern. The airspeed readout flashes red for 5 seconds, then shows steady red when the current airspeed is less than or equal to the ISS.

Footnote

[14] A discrete signal is one which conveys one of two states such as on or off, open or closed.
[15] ARINC 429 uses the SSM to indicate one of four health states of the data; Failure Warning, No Computed Data, Functional Test or Normal Operation.
[16] V_s is the stall speed for the aircraft configuration.

Figure 9

PFD showing ISS with an aircraft speed of 120 kt, normalised AOA of 0.9

Should the system detect an invalid AOA then the 'low speed range marker' replaces the ISS. This consists of a yellow bar covering the 72 to 97 kt speed range.

Autopilot vertical modes

The following vertical modes are available for selection by the pilot:

- Pitch
- Flight Level Change (FLC)
- Vertical Navigation (VNAV)
- Altitude (ALT)
- Vertical Speed (VS)

VS mode

The Pro Line 21 Operator's Guide states:

> *'Vertical Speed mode generates commands to capture and track the Vertical Speed reference shown on the PFD.'*

There is no reference in any supplied manual to the risks of operating in VS mode with insufficient energy to achieve the selected vertical speed.

Flight Level Change mode

The Pro Line 21 operator's guide states:

> *'Pressing the flight level change (FLC) button selects and deselects a speed command for climbs or descents.'*

The Collins Pro Line 21 Manual describes the PFD AOA display as follows:

> *'The Reference Approach Speed (RAS) cue is a small green circle that shows at the bottom right of the airspeed tape to indicate the calculated RAS.*
>
> *• RAS is variable and is automatically calculated using 1.3 VS. Airspeed, AOA, and normal acceleration are also used to calculate RAS'*

Based on the calculations supplied by the Pro Line 21 manufacturer and recorded AReS data, just prior to the loss of control, with the normalised AOA static at 0.61, at 117 kt, the calculated ISS would have been 100 kt, with the 'green donut' at 122 kt. For a normalised AOA of 0.87, the onset of the stall warning, the ISS would have been 122 kt and the green donut at 141 kt.

Tests and research

Pitot-static system

The aircraft's pitot-static system was tested for leaks and calibration in accordance with the AMM and, apart from a minor 30 ft discrepancy in the standby altimeter at one test point, all measurements were within the required tolerances. The actuation values for the aircraft's stick shaker system were tested by rotating the AOA vane with a calibrated test fixture and measuring the AOA values when the stick shaker operated, in accordance with the test procedure listed in the AMM. The stick shaker operated as required at a value of 0.88 AOA at a test pressure altitude of 5,000 ft and also operated correctly at 0.87 AOA when the test pressure altitude was increased to 30,000 ft. This showed that the ST035 pressure switch was operating correctly.

AOA system

The AOA vane's heater was functionally tested by following the ground test procedure provided in the AMM and was determined to function correctly. The AOA vane unit was

CT-scanned[17] prior to disassembly to record its internal condition. The CT scans showed that an internal PTFE (polytetrafluoroethylene – a synthetic fluoropolymer) seal was laterally displaced and was not concentric with the vane spindle assembly or the AOA vane case, Figures 10 and 11. When viewed from the side, a gap was visible between the PTFE seal flange and the vane spindle assembly, which is not intended by the design, as the PTFE seal is required to prevent moisture and foreign objects from entering the AOA vane case from outside the unit.

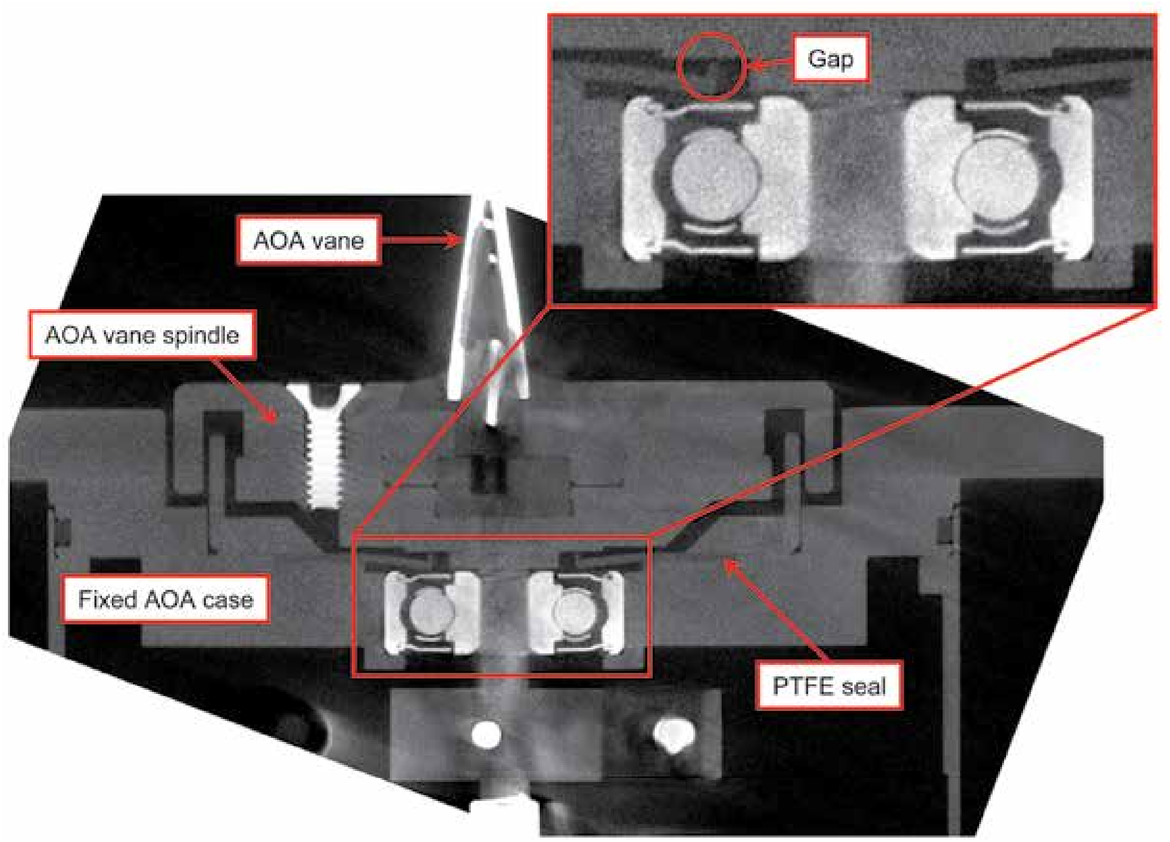

Figure 10

Gap between AOA seal and vane spindle

AOA vane unit and AOA computer were taken to the manufacturer for detailed testing and inspection. When subjected to the factory acceptance test procedure, the AOA computer passed all the tests with no failures and was deemed to be serviceable. The AOA vane unit was initially leak checked to assess the sealing capability of the PTFE seal. This procedure is followed for new production and repaired units, but is not conducted when units are received for overhaul. The AOA vane unit was attached to a sealed box, using the mounting flange screws and sealing gasket as it would be installed in the aircraft. The box was then pressurised to 10.1 psi and the leak rate through the unit was measured using a calibrated mass flow instrument. The measured leak rate was 1,338 cm^3/min, which is approximately

Footnote

[17] Computed Tomography is an X-ray scanning technique in which X-ray images are computer-processed to produce individual 'slice' images through an object.

2.6 times the factory acceptance limit value of 500 cm³/min. Application of a soap bubble solution showed that the leaking air was escaping past the internal PTFE seal and through the annulus formed between the AOA vane spindle and the AOA case.

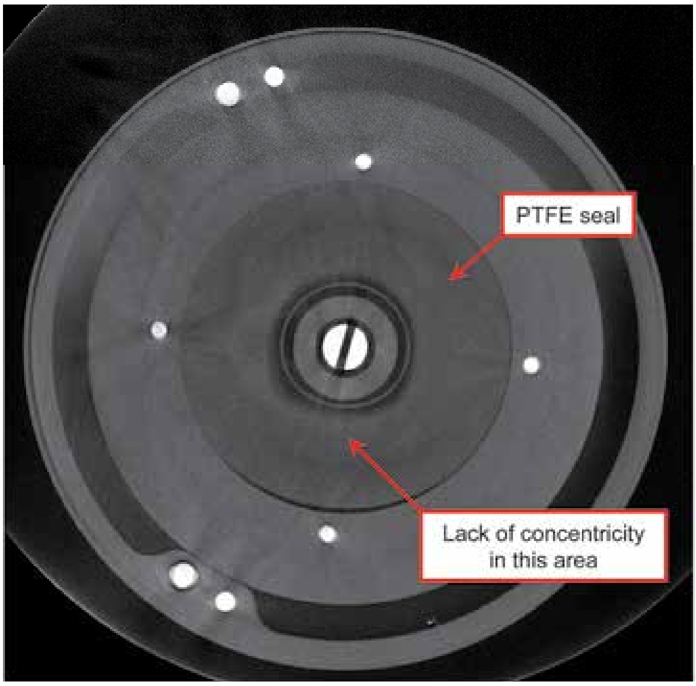

Figure 11
Lack of concentricity of AOA seal

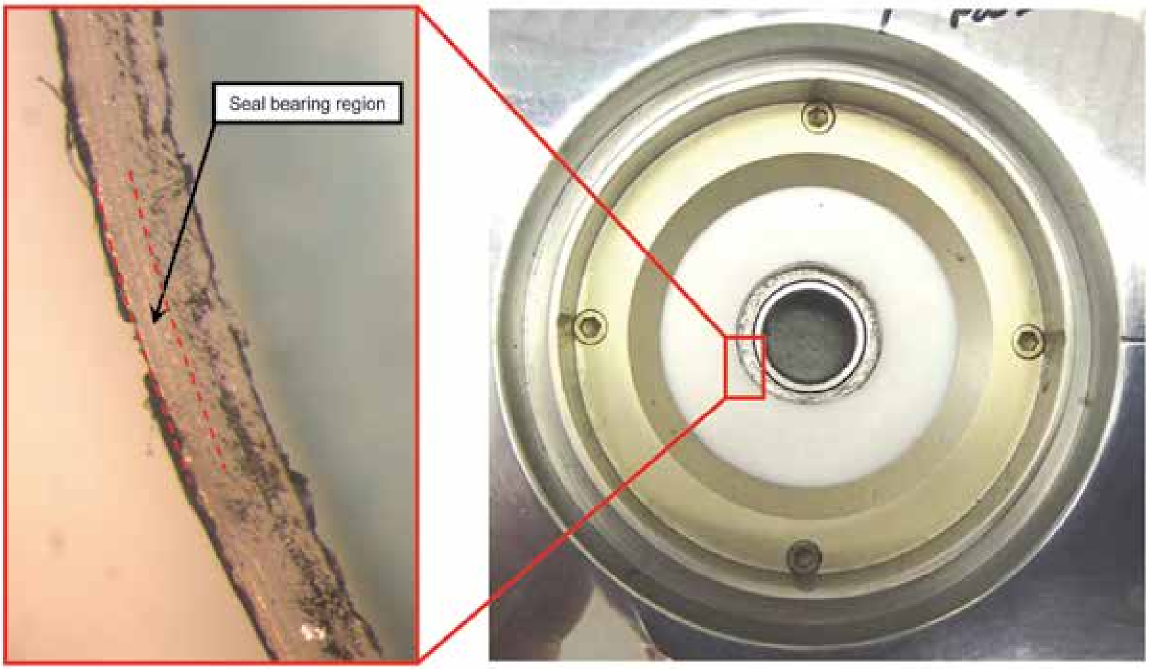

Figure 12
AOA seal condition showing circumferential wear marks on the bearing region

The AOA vane unit was functionally tested using the procedures set out in the factory acceptance test procedure. The unit passed all the tests and the accuracy and linearity of the angular position of the vane spindle was well within allowable tolerances. The AOA vane unit was then carefully disassembled and each component inspected; apart from the lack of concentricity of the PTFE seal, as previously seen in the CT scans, there were no discrepancies. The PTFE seal had been firmly clamped within the vane case by a clamping plate and four cap screws, indicating that this lack of concentricity had occurred when the unit was assembled.

The sealing flange of the PTFE seal exhibited surface wear marks around the complete circumference of the flange, indicating that at some point following manufacture, the entirety of the seal's flange had been in sliding contact with the AOA vane spindle. It was therefore determined that the PFTE seal flange had moved to its deflected position at some point during the unit's service life on N380CR.

Aircraft operation

Suggested climb profile

The manufacturer's Operating Manual page 18-5 describes the climb as:

> *'Climb*
>
> *Ensure gear and flaps are up, set power as needed and select autopilot (if desired). Monitor pressurization and fuel. Climb at approximately 200 kt until nearing 30,000 feet, then use a slower speed. Complete appropriate checks (refer to the AFM).'*

Chapter 20, on page four of the Manual provides a table to allow calculation of cruise climb performance. To climb from sea level to 43,000 ft at a takeoff weight of 12,250 lb and an average of ISA-5°C requires:

Time (Minutes)	20.25
Distance (Nm)	100.5
Fuel (lbs)	449.3
Vetical speed (ft/min)	638.5

Table 2

Cruise climb table

The manual also provides a cruise climb speed table that recommends maintaining an indicated airspeed of 230 kt to 20,000 ft, then reducing gradually to 181 kt at 35,000 ft, 160 kt at 40,000 ft and 142 kt at 45,000 ft.

Stalling speed table

The manufacturer's Airplane Flight Manual (AFM) includes a table of stalling speeds. The manufacturer informed the AAIB that this table is only applicable within the certified takeoff and landing altitudes of the aircraft, plus a margin of 1,500 ft, which for this aircraft is a maximum altitude of 15,500 ft. It is therefore not applicable for use at high altitudes.

Low-speed buffet

The cruise-climb performance section of the aircraft Operating Manual directs the pilot to check the buffet onset table in the AFM to ensure sufficient manoeuvre margin exists for the planned flight.

The AFM provides a method for calculating the available buffet margin for various weights and altitudes. Applying the aircraft's estimated weight of 11,758 lb and an altitude of 42,500 ft shows that, using a 1.3g margin, the low-speed buffet would be encountered at M 0.52 and an indicated airspeed of 140 kt. The accident aircraft was effectively in wings-level flight with 1g recorded just before the loss of control and in this condition the buffet speed is reported as M 0.45 (120 kt) – very close to the actual recorded speed of the accident aircraft just before it departed from controlled flight.

Certification requirements - stalling

FAR 23.201(e) states that the stall characteristics should be such that:

> *'… during the entry into and the recovery from stalls performed at or above 25,000 feet, it must be possible to prevent more than 25 degrees of roll or yaw by the normal use of controls'*

Regarding stall warning FAR23.207(c)[18] requires that:

> *' … the stall warning must begin at a speed exceeding the stalling speed by a margin of not less than 5 knots and must continue until the stall occurs'*

The manufacturer provided data from certification flight tests, including one conducted at 43,267 ft, and at a similar weight to the accident aircraft, to show that the aircraft met these requirements. In this high altitude test, the stick shaker activated at an indicated airspeed of approximately 116 kt and the minimum airspeed was 109 kt. Buffet was encountered at approximately 115 kt followed by left roll with the maximum roll attitude encountered during the recovery of approximately 10º which was quickly corrected by control inputs.

Footnote

[18] http://www.ecfr.gov/cgi-bin/text-idx?SID=04108958b44cc3c6236ce36f096951c3&node=14:1.0.1.3.10&rgn=div5#14:1.0.1.3.10.2.65.41

Pilot training

The pilot held a FAA Private Pilot Licence issued on the basis of his UK PPL. He completed initial type rating training for the Citation CJ series at a major training provider in Witchita, in 2006 and had returned to this provider for annual recurrent simulator and ground school training.

In addition he had completed a 'jet upset' course on an L-39 aircraft in Albuquerque, New Mexico in 2006. This comprised ground school and two flight sorties of 0.6 hours each.

The Training organisation's textbook states that the PFD attitude display features include:

> *'Large red chevrons point towards the horizon line when pitch attitudes approach 30° up or down…*
>
> *The PFD declutters (removes unnecessary information) automatically if pitch exceeds 30° nose up, 20° nose down, or 65° of bank. Only attitude, heading, airspeed and altitude are displayed in declutter mode. As pitch and/or bank is reduced all normal displays return.'*

Climb technique

The pilot later stated that he had started to use Vertical Speed mode during the climb after he found that N380CR "hunted in pitch" when climbing in Flight Level Change mode.

Analysis

Operational aspects and aircraft examination

The investigation determined that the pilot was trained and licensed in accordance with the relevant regulations. He was experienced and in current flying practice. When the aircraft departed from controlled flight, it was subjected to normal accelerations beyond its design limit, which was reflected in the damage sustained by the airframe. The aircraft had been maintained in accordance with the approved maintenance schedule and the only technical anomaly identified was in the AOA sensing system.

Use of the autopilot

The pilot had previously noticed his aircraft "hunting" in pitch in FLC mode and had therefore decided to operate in VS mode during the climb. Whilst the use of VS mode in the climb is not prohibited by the AFM, it exposed the aircraft to the risk of entering a low-energy state during the climb. Without greater systems knowledge the pilot was unaware of the additional risks involved in the use of VS mode. Therefore he was unable to make an informed decision regarding this autoflight mode.

The autopilot will, in this mode, prioritise maintaining vertical speed over airspeed and pilot vigilance and intervention is required to avoid a low-speed condition. As the aircraft was operating at the edge of its climb performance envelope there was insufficient thrust to follow the selected climb profile. Over a period of 50 seconds up to the departure from controlled flight, the airspeed steadily decayed, by 10 kt.

As the pilot approached FL430 he was distracted by looking at a portable electronic device. The upper winds information provided on the device was pertinent to the flight but was not as important at this point as the flightpath and energy information available on the PFD. Therefore he did not recognise the alerting features of low energy flight, specifically an unusually nose-high attitude, and unusually low, and decreasing, airspeed. The pilot's ability to recognise the low airspeed was also partially compromised by the static normalised AOA. The relationship between the red ISS and green V_{REF} 'donut' marker is complex. However, the green 'donut' would have been almost co-incidental with the aircraft's speed and the red ISS bar 19 kt below the speed indication on the tape. If the pilot had looked at this area of the display, the relationship between the red ISS, green 'donut' and indicated airspeed would have looked relatively normal and therefore unlikely to attract his attention, although the indicated airspeed would have been unusually low. At this point the pilot was not observing the PFD, the roll forces overcame the autopilot's control authority and the aircraft rolled to beyond 45°, disengaging the autopilot.

Stall warning system performance

The AReS recorded data shows that the AOA vane was sticking on the accident flight and also on a previous flight on 7 December 2013, in which the sticking AOA occurred at or close to the top of the climb to cruising altitude, where the ambient air temperature was very low. On the accident flight, this appeared to occur at a higher static air temperature and lower altitude but, in both cases, any moisture within the AOA vane case would readily form into ice, restricting the rotation of the AOA vane.

CT-scanning images of the AOA vane showed that an internal PTFE seal was displaced and was not sealing correctly against the vane spindle, and leak testing of the unit confirmed the lack of sealing capability of the PTFE seal. Witness marks on the PTFE seal's flange showed that, at some point since the AOA vane unit was manufactured, the seal had been in full circumferential sliding contact with the vane spindle. It must, therefore, have moved position at some point during its service life in N380CR.

The presence of a gap between the PTFE seal and the internal volume of the AOA vane case provided a path for moisture to enter the vane case, when the aircraft is parked and unpressurised. There was, however, no visible evidence of water staining or corrosion on the internal components of the AOA case when those parts were examined but it is likely that only a small amount of moisture would be required to create an intermittent AOA 'sticking' mechanism. The sticking of the AOA position represented a subtle, dormant failure that was not readily apparent to the pilot as it did not generate a warning annunciation.

The stall warning system was reliant on a single AOA vane to provide data to both the indicating system on the PFD and the stick shaker, which should have activated at least 5 kt before the stall. The sticking of the AOA vane, probably by freezing, removed the safety feature that was designed specifically to be a barrier to this type of event.

This aircraft type relies on a single AOA vane to provide stall warning, and failure of the internal PTFE seal may render the AOA vane unserviceable. As shown in this report, the AOA data recorded on the AReS system installed in the Citation CJ2+ is capable of detecting a 'sticking' (static) AOA vane during flight operations. Therefore, in the absence of any maintenance instruction that would result in this abnormal condition being detected in service, the following Safety Recommendations are made:

Safety Recommendation 2014-041

It is recommended that the Federal Aviation Administration requires the Cessna Aircraft Company, as the Type Certificate holder for the Citation CJ2+ aircraft, to conduct a survey of recorded flight data from Safe Flight Instrument Corporation model C-12717-1 angle-of-attack vane units, to determine the frequency of 'sticking' (static) angle-of-attack data.

Safety Recommendation 2014-042

It is recommended that the Federal Aviation Administration requires the Cessna Aircraft Company, as the Type Certificate holder for the Citation CJ2+ aircraft, to use the results of their survey (Safety Recommendation 2014-041) of recorded flight data from Safe Flight Instrument Corporation model C-12717-1 angle-of-attack vane units to amend the safety assessment of the aircraft's stall warning system.

Loss of control

From the analysis, the loss of control in this accident was caused by four factors:

- The pilot chose to operate in an autopilot flight mode that allowed the aircraft to decelerate to the stall.
- The pilot was distracted by a PED at a critical phase of flight and did not recognise the low airspeed, excessive pitch attitude or unusual roll angle.
- Whilst approaching a stall, the aircraft began to roll to the right. This was not corrected and the roll continued to 57° to the right in four seconds, causing the autopilot to disconnect.
- The safety feature provided by the stall warning system failed without alerting the pilot, due to the angle of attack probe freezing at 0.61 AOA.

Without recorded data showing control inputs, or the ability to model or simulate post-stall aircraft behaviour, it cannot be determined why the aircraft initially rolled right before departing from controlled flight.

After the initial roll to the right, the pilot was not presented with the correct ISS indication on his PFD, valid normalised AOA on the AOA gauge or the operation of the stick shaker. Other classic indications of an impending stall would have been present, including buffet and a display of low airspeed. The confusion encountered after autopilot disconnection, uncommanded roll and distraction from his PED is likely to have compromised any immediate recovery by reducing angle of attack.

As the aircraft departed from controlled flight into the sequence of right rolls, the display system reverted to the 'declutter' mode, with which the pilot was not familiar. A number of EGPWS 'BANK ANGLE' audio warnings were triggered and the AOA vane only moved during the fourth complete roll, which should have led to a stick-shaker activation for six seconds. The high roll rate, its effect on the attitude display and the prevailing IMC conditions resulted in a prolonged upset that was only recovered once the pilot had a visual external horizon. This recovery may, in part, have been due to the additional upset training the pilot received in 2006.

Conclusion

The pilot operated the aircraft in an autopilot mode which left it vulnerable to a stall and did not monitor the reducing airspeed as the aircraft reached its cruising altitude. The 'sticking' of the stall warning system removed the safety feature specifically designed to protect against this.