

ACCIDENT

Aircraft Type and Registration:	DHC-8-402 Dash 8 Q400, G-JEDU
No & Type of Engines:	2 Pratt & Whitney Canada PW150A turboprop engines
Year of Manufacture:	2004 (Serial no: 4089)
Date & Time (UTC):	10 November 2017 at 1330 hrs
Location:	Belfast International Airport
Type of Flight:	Commercial Air Transport (Passenger)
Persons on Board:	Crew - 4 Passengers - 53
Injuries:	Crew - None Passengers - 2 (Minor)
Nature of Damage:	Forward underside of the nose, front pressure bulkhead, nose landing gear and landing gear doors damaged
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	47
Commander's Flying Experience:	9,112 hours (of which 8,734 were on type) Last 90 days - 208 hours Last 28 days - 40 hours
Information Source:	AAIB Field Investigation

Synopsis

The aircraft was carrying out the third sector of a four-sector day from Belfast City Airport to Inverness Airport. After takeoff, the landing gear was selected UP. Cockpit indications indicated that the main landing gear (MLG) retracted normally but the nose landing gear (NLG) did not. The crew carried out the actions in the relevant abnormal checklists and were unable to lower the NLG. After burning off fuel, the aircraft was diverted to Belfast International Airport where it landed with the NLG retracted. The crew initiated an emergency evacuation.

It was determined that a damaged electrical harness on one of the nose landing gear proximity sensors caused an erroneous signal, which resulted in the forward NLG doors starting to close while the NLG was still in transit to the UP position. The nose landing gear tyres contacted the forward doors, causing the NLG to rotate off-centre. Although the NLG subsequently retracted, the forward doors remained open and the tyres became jammed in the NLG bay. This prevented the nose landing gear from extending when subsequently commanded.

The damage to the harness resulted from a cyclically-driven fatigue failure mechanism, which occurred because the harness had been secured with a non-flexible cable tie which restricted it from flexing during normal nose landing gear operation.

The aircraft manufacturer has taken action to clarify nose landing gear proximity sensor harness routing and attachment instructions in the Aircraft Maintenance Manual, and has published inspection requirements. Following the accident, the operator carried out an inspection of the nose landing gear proximity sensor harness routing on its Dash 8 Q400 fleet and undertook rectification of any anomalies noted. The aircraft and landing gear manufacturers are also working to identify a more flexible harness design; this activity had been initiated before the accident to G-JEDU.

History of the flight

The crew reported for duty at Belfast City Airport at 0550 hrs to carry out a four-sector day flying to London City Airport and Inverness Airport. The first two sectors to London City and returning to Belfast City were flown without incident and with all the aircraft equipment and systems operating normally. Following a normal turnaround and flight preparation, the aircraft was refuelled and the passengers boarded. The weather was good with a surface wind of 260° at 12 kt, CAVOK with an OAT of +8°C and a dew point of +4°C. The aircraft was started and taxied for Runway 22, from which it departed at 1118 hrs.

Shortly after takeoff, the landing gear selector lever was selected to the UP position. On the Landing Gear Control and Indication Panel (LGCIP), which is shown in Figure 6, the crew observed that the landing gear green lights extinguished, the three red lights and the amber landing gear door lights as well as the amber light in the landing gear selector lever all illuminated. After a short time, all three red lights extinguished, the left and right DOOR lights extinguished but the nose door light and the light in the landing gear selector lever remained illuminated. The crew kept the airspeed below the 185 kt landing gear limit speed and climbed to 4,000 feet, routing to waypoint Magee to take up the hold whilst they assessed the problem. The aircraft entered the hold at 1132 hrs and the total fuel onboard was 2,800 kg.

Whilst in the hold, the crew initially actioned the 'LANDING GEAR FAIL TO RETRACT' abnormal checklist followed by the 'LANDING GEAR FAIL TO INDICATE LOCKED DOWN' abnormal checklist. The MLG lowered and indicated locked down, but the NLG showed the unsafe indication with the amber nose door light still illuminated. The landing gear inoperative (LDG GEAR INOP) caption also illuminated on the Caution and Warning Annunciator Panel. They actioned the 'ALTERNATE LANDING GEAR EXTENSION' abnormal checklist and made several attempts to operate the nose landing gear alternate release handle but the indications remained the same.

They reviewed the 'EMERGENCY LANDING – ONE OR BOTH ENGINES OPERATING' abnormal checklist and decided to divert to Belfast International Airport. At this stage, the crew did not know if the NLG was up or down. The crew sought advice from their company and this confirmed their decision to go to Belfast International Airport. They reviewed the fuel and decided to leave the hold with 1,100 kg which would minimise the fuel onboard at touchdown but ensure sufficient fuel to carry out a go-around if required.

The Senior Cabin Crew Member (SCCM) was called to the flight deck and the situation explained to her along with a NITS¹ briefing which included the procedure for an emergency evacuation, should it be required. Passengers seated adjacent to the propellers were moved to other seats away from the possible arc of any debris in case the propellers should contact the runway. Following this, the commander briefed the passengers on the problem and his intentions using the PA system.

The cabin crew played the pre-recorded passenger emergency briefing and then walked through the cabin ensuring the passengers were all aware of what was required and that their restraint harnesses were secure. The passengers at the rear of the aircraft were warned of a possible increased drop to the ground from the rear doors due to the nose-down attitude if the NLG was not lowered.

At Belfast International Airport, Runway 25 was in use, the surface wind was 250° at 12 kt, visibility more than 10 km, clouds few at 1,800 feet and scattered at 2,900 feet, temperature +12°C, dew point +3°C, and the QNH 1020 hPa. The crew briefed for a radar vectored ILS approach for Runway 25 with full landing flap and an approach speed of 110 kt. They also reviewed the emergency landing actions and reminded themselves where the CVR/FDR circuit breakers were located in order to ensure they were pulled after landing.

The aircraft left the hold at 1320 hrs with 1,100 kg of fuel as planned and commenced the approach. All the normal checks were carried out and at about 4 nm, ATC informed them that the nose landing gear had not extended. The approach was continued as briefed and at 200 ft, the co-pilot gave the 'BRACE' command over the PA and all the passengers were seen to adopt this position.

The aircraft touched down at 1332 hrs on the main wheels and the nose was held off as the speed decayed and gently lowered onto the runway. As the aircraft came to a stop, both engines were shut down and when stopped, the commander ordered the evacuation.

The cabin crew responded and described the passengers as being calm. The forward left door and the rear left and right doors were opened. The forward left door, which has built-in stairs, lay flatter than normal as it could not achieve its full downward travel. This made exiting the aircraft more difficult, but no one fell whilst using it. At the rear, some passengers were reluctant to jump given the door sill height but some of the passengers who had left the aircraft returned and assisted them from below.

Smoke and a smell of burning entered the flight deck and so the flight deck door was opened which allowed it to clear. The flight crew used the 'ON GROUND EMERGENCIES' checklist on the rear of the QRH to ensure they had completed all the required actions before leaving the flight deck and checking there was nobody on the aircraft.

They then vacated the aircraft. The passengers had been gathered together by the Fire Service and were transported to the terminal on buses provided.

Footnote

¹ The standard briefing content of; Nature, Intentions, Timings and Special instructions (NITS).

Airfield information

The aircraft had departed from Belfast City Airport which has a single runway orientated 04/22, 1,829 m long and 45 m wide with an asphalt surface. Belfast International Airport has two runways. The main runway is orientated 07/25 and is 2,780 m long and 45 m wide. There is a 'cross' runway orientated 17/35 which is 1,891 m long and 45 m wide. Both runways have an asphalt surface.

Accident site and aircraft examination

Photographs taken as the aircraft landed showed that the nose landing gear was retracted and the forward NLG doors were open. The aircraft touched down on its main landing gear in the Runway 25 touchdown zone, and slightly to the right of the centreline.

Two thin parallel ground marks, corresponding to contact by the lower edges of the forward NLG doors, commenced abeam the point where the Taxiway B centreline joined Runway 25. Thereafter, a single broader ground mark indicated that the lower forward fuselage had contacted the runway surface.

The aircraft had come to rest with its nose on the ground approximately 1,973 m from the Runway 25 threshold (172 m before the intersection with Runway 17/35) and 15 m to the right of the centreline (Figure 1). The left NLG wheel was visible protruding from the NLG bay, but it was not possible to verify from initial examination whether the NLG was unlocked.

The aircraft had suffered abrasion damage to skin panels and structure on the lower surface of the forward fuselage and the VHF antenna. The NLG forward doors had also separated from the fuselage.



Figure 1

G-JEDU on Runway 25 at Belfast International Airport

Examination of the cockpit showed that the landing gear selector lever was in the DOWN position, the overhead MLG release door was opened and the handle was stowed. The guard on the L/G DOWN SELECT INHIBIT switch was lifted and the toggle switch was in the INHIBIT position. The landing gear alternate extension door on the cockpit floor was open. It was evident that the nose landing gear alternate release handle had been pulled. The cable had not retracted into its spool and approximately 12 cm of cable was exposed lying on the cockpit floor (Figure 2). The lock release button was in the UP position.

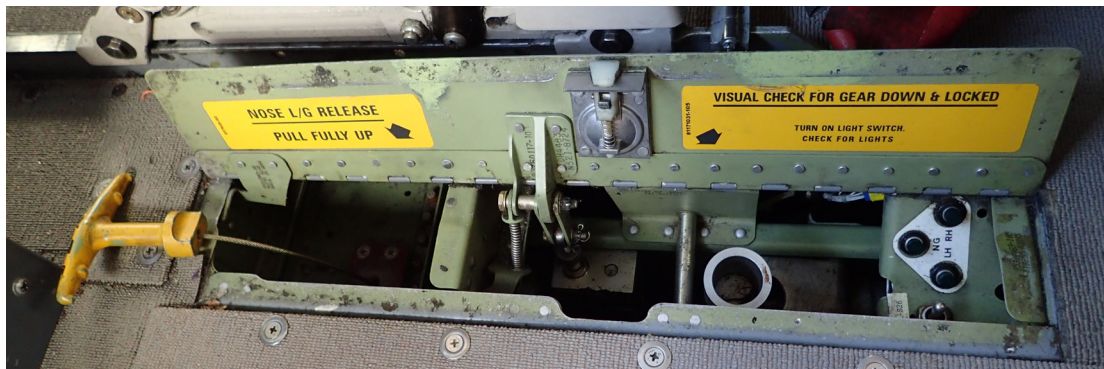


Figure 2

Position of nose landing gear alternate release handle following the accident

The aircraft nose was raised using airbags until a jack could be positioned on the forward jacking point. The NLG remained in the retracted position when the aircraft was lifted. It was evident that the NLG was not correctly centred, instead the wheels were turned to the right. The upper outside surface of the right tyre appeared to be jammed against the wall of the NLG bay (Figure 3).



Figure 3

View looking up and forward, showing nose landing gear retracted and off-centre

The nose landing gear alternate release cable remained jammed despite attempts to pull it using substantial force, however the uplock could be heard releasing when the cable was pulled. A crowbar was used to rotate and centre the NLG, releasing the right tyre from the jammed position; once the gear was centred, it extended under gravity and locked down. Coincident with this the nose landing gear alternate release cable in the cockpit was heard to retract onto its spool.

Examination of the NLG identified evidence of blue paint on the outboard shoulders of both tyres, indicating that each tyre had come into contact with the outer painted surface of the respective forward NLG doors (Figure 4).



Tow spigot

Blue paint

Figure 4

Blue paint on the tyre shoulder of left nose landing gear wheel

Both forward NLG doors exhibited extensive abrasion damage. The rubber seal and metal retaining strip from the lower edge of the forward right door were recovered from the runway. The seal had worn through as a result of ground contact and the attached remnants of the outer door skin showed evidence of tyre contact (Figure 5a). Additionally, the bottom edge of the seal-retaining strip exhibited mechanical damage in one location where a curled lip of metal had peeled upwards (Figure 5b). The location of this damage was approximately in line with the position of the tow spigot on the NLG.

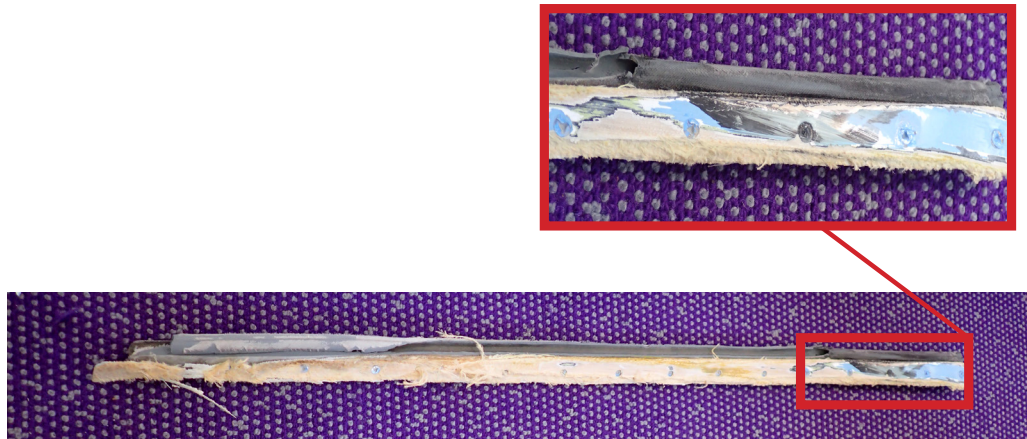


Figure 5(a)

Outer surface lower edge of forward right NLG door, showing abrasion damage to rubber seal and tyre contact marks



Figure 5(b)

Inner surface lower edge of forward right NLG door, showing mechanical damage to metal seal-retaining strip

Damage to the aircraft

The aircraft was substantially damaged by deformation and abrasion due to runway contact. This resulted in structural damage to the lower front pressure bulkhead and fuselage skin². The forward NLG doors suffered substantial abrasion damage and were partially detached from the fuselage. The aft NLG doors were in the closed position with portions of the exterior surfaces abraded and worn down to the honeycomb. The nose landing gear trunnion assembly was also damaged.

Footnote

² The damage was to stringers and frames between frame X-69.40 and X-124.00 and between stringers 30S and 30P.

Previous incidents on G-JEDU

During a go-around at Birmingham International Airport on 1 November 2017, G-JEDU's landing gear failed to retract when selected. The flight crew observed three red landing gear unsafe lights and one amber NLG door light on the LGCIP. The remainder of the go-around was flown with the gear-down and a second approach resulted in a normal landing.

Subsequent inspection identified damage to the lower edge of the forward right NLG door and the door seal. In consultation with the aircraft manufacturer, the operator's contracted maintenance organisation carried out system checks and troubleshooting which included performing a bypass check of NLG door actuator, an inductance check of the proximity sensors, and checks of the NLG centring system. The defect was not replicated during the ensuing gear swings; it was not recorded how many gear swings were performed. The forward right NLG door and the NLG door actuator were replaced and the aircraft was returned to service.

Recorded information

Flight data recorder

The aircraft was fitted with a Honeywell solid-state flight data recorder which recorded over 25 hours of flight data and contained data for 21 sectors, including the accident flight. A review of this data showed that NLG retraction time was typically 5.25 seconds. However, on two occasions on 9 November 2017, and on the accident flight, the NLG retraction time was 9.25 seconds and for one flight, on 7 November 2017, 17.25 seconds. Due to the sample rates of the parameters used to calculate the NLG retraction time these times could be in error by ± 2 seconds.

Quick access recorder

An analysis of quick access recorder data conducted by the operator also indicated that G-JEDU experienced slower than normal NLG retractions (12 seconds) during two sectors on 9 November 2017 and on one sector on 7 November 2017 (20 seconds). Additionally, slower than normal NLG retractions (12 seconds) were noted for the flight on 1 November 2017 where the landing gear failed to retract, and on the previous sector the same day (prior to the beginning of the flight recorder data).

Landing gear system description

General

The landing gear system on the Dash 8 Q400 is electrically controlled, hydraulically operated and mechanically locked. The landing gear is operated by a selector lever in the cockpit. Landing gear and landing gear door position is shown by nine advisory lights on the LGCIP and an amber light in the selector lever (Figure 6). An amber gear door advisory light will illuminate when the related door is open. A green landing gear safe advisory light is illuminated when the respective gear is down and locked. Red landing gear unsafe advisory lights are illuminated when the gear is neither uplocked nor downlocked.

When the gear is up-and-locked, and all landing gear doors have closed, all lights on the LGCIP are extinguished. The amber light in the landing gear selector lever will be illuminated when the actual position of any gear does not match the position of the lever.

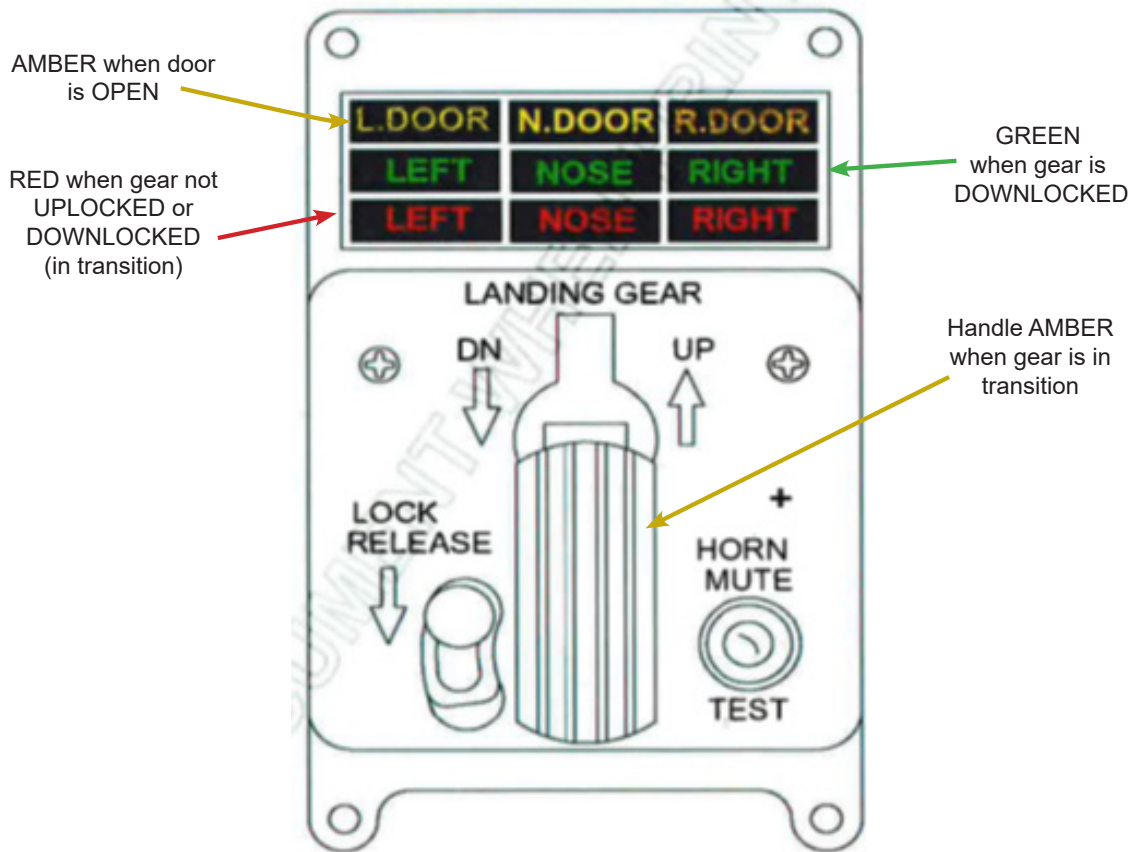


Figure 6

Dash 8 Q400 landing gear control and indication panel

Landing gear proximity sensors

A Proximity Sensing Electronic Unit (PSEU) provides landing gear control, sequencing and status indication. It monitors discrete inputs from the landing gear system, such as the extend and retract commands from the landing gear selector lever and the position of the landing gear components based on readings from 20 landing gear proximity sensors. It uses logic based on this information to generate discrete outputs which govern the landing gear operation.

The proximity sensors are hermitically-sealed devices that contain an inductor. When a ferrous metal target moves into position near the sensor face the inductance³ of the sensor increases to a value where the PSEU detects a NEAR target condition. When the target

Footnote

³ Inductance is a property of an electric circuit by which an electromotive force (voltage) is induced by a change of current, either in the same circuit or in a neighbouring circuit. It is an effect caused by the magnetic field of a current-carrying conductor acting upon the conductor. Inductance is the ratio of the induced voltage to the rate of change of the inducing current. The unit of inductance is the henry (H).

moves away from the sensor the inductance decreases to a value where the PSEU detects a FAR target condition. The PSEU uses the NEAR and FAR sensor condition to determine the position of the landing gears and gear doors and the aircraft weight-on-wheels status.

Nose landing gear proximity sensors

There are eight proximity sensors on the nose landing gear. These include a 'nosewheel centred' sensor (NWCENT), a 'nose gear doors closed' sensor (NGDRCL) and a pair of sensors giving primary and alternate indication for each of the following functions: 'nose gear weight-off-wheels' (NGWOFW1 and NGWOFW2), 'nose gear down' (NGDN1 and NGDN2) and 'nose gear locked' (NGLK1 and NGLK2).

The NGWOFW sensors indicate when the nose landing gear is on the ground (FAR) or in the air (NEAR). The NGDRCL sensor is NEAR when the forward NLG doors are closed and the NWCENT sensor is NEAR when the nosewheel is centred.

The NGDN1 and NGDN2 sensors are in the NEAR state only when the NLG is fully extended down; they will transition to FAR early in the nose landing gear retraction sequence and remain FAR until the gear is fully extended again.

The NGLK1 and NGLK2 sensors are in the NEAR state when the NLG is either fully down and locked or fully up-and-locked and are in the FAR state when the NLG is transitioning between these positions.

Nose landing gear retraction sequence

Logic Equation 2⁴ governs the operation of the retract selector valve. Logic Equation 3⁴ monitors the NGLK and NGDN sensors and governs the nose landing gear door sequence valve, which controls the function of the NLG doors. When landing gear retraction is commanded the PSEU senses that the landing selector lever is in the UP position. For the retraction operation to commence the PSEU must also sense a NGWOFW and NWCENT signal and that the landing gear inhibit switch is not inhibited. When these conditions are met, the nose landing gear door sequence valve is energised. In parallel, the retract selector valve is 'shuttled' to the 'retract' state and ports system hydraulic pressure to the retract side of the landing gear hydraulic system. The NLG doors open, and the NLG unlocks and begins to retract (NGDN1 and 2 and NGLK1 and 2 transition from NEAR to FAR).

Once the nose landing gear is in the up-and-locked position (NGLK1 or NGLK2 NEAR), the PSEU deactivates the output to the NLG door sequence valve which is de-energised to close the forward NLG doors. The PSEU deactivates the retract output three seconds after the NGDRCL reads NEAR.

The aft NLG doors are mechanically linked to the NLG and open/close with the gear. The retraction sequence normally takes between five and seven seconds, from first door open to last door closed. If the NWCENT signal is lost at any point, the retraction sequence will

Footnote

⁴ de-Havilland Dash 8, Series 400 'Interface control document for the proximity sensor system', Revision AB, dated 13 January 2016.

stop within three seconds and if the gear is not in uplock when the retraction sequence is stopped, the gear will extend.

NGLK sensor inductance faults

The PSEU stores current faults in the 'Present Faults' page and fault history for 31 flight legs. There are three types of proximity sensor fault: proximity sensor 'short', proximity sensor 'open', and proximity sensor 'unreasonable'. An open or short circuit can occur in the sensor or the associated sensor wiring and the PSEU will flag the sensor as OPEN or SHORT respectively if the measured circuit resistance is outside of predetermined limits. The PSEU will use the non-faulted sensor and set the faulted sensor to a FAR state.

Sensor 'reasonableness' is evaluated by the PSEU for each of five operating modes: 'air' mode (weight-off-wheels), 'ground' mode (weight-on-wheels), 'gear down and locked', 'gear in transit' and 'gear up and locked'. If a proximity sensor does not match the expected state for the current operating mode (ie if the sensor target is in the wrong NEAR or FAR position) then a reasonableness fault (UNRSNABL NEAR or UNRSNABL FAR) is reported and logged in the Present Faults page. For an NGLK sensor, such a fault would be logged if it was not in the expected state during the 'gear in transit' for a period of 3.5 ± 2 seconds.

For the NGLK sensors, inductance values in the range 8.055 to 9.9 millihenries (mH) correspond to the NEAR state and those in the range 7.1 to 7.73 mH correspond to the FAR state. If the measured inductance is outside the NEAR/FAR operating range (ie below 7.1 mH or above 9.9 mH) for between 0.5 and 1.5 seconds, a fault is logged in the Present Faults page of the PSEU and the default state sensor state (FAR) is reported/used. If the measured inductance drops below the fault threshold within 1.5 seconds, the sensor state will revert back to the live-monitored state. A fault will be logged in the fault history with no associated faults in Present Faults. If the fault condition persists for more than 1.5 seconds, the reported fault is latched and will continue to be logged in Present Faults. The sensor state will be latched in the default (FAR) state and live measurement of inductance and resistance is stopped.

Following a power-on reset or cold start, the latch associated with the sensor fault and sensor status will be removed and live measurement of sensor and resistance is resumed. The sensor will be re-evaluated for correctness/validity and depending on the outcome of this evaluation the fault will either return to being logged in Present Faults or will be logged in the PSEU fault history with no associated faults logged in Present Faults.

Landing gear alternate extension system

A cable-actuated alternate extension system can be used to extend the landing gear if the No 2 Hydraulic system or the PSEU are not serviceable, or if the normal extension system fails to lock the landing gear in the down position. To use the alternate extension system, the landing gear inhibit switch is switched from NORMAL to INHIBIT to isolate power from the landing gear door solenoid sequence valves and the landing gear selector valve.

Pulling the landing gear alternate release handle, which is accessed through the landing gear alternate release door in the ceiling of the flight deck, opens the MLG aft doors and

releases the MLG uplocks. The MLG freefalls in to the down position and a hydraulic hand pump can be used to fully extend the MLG if necessary.

A nose landing gear alternate release handle in the flight deck floor is pulled to release the NLG. The first stage of the pull unlocks the NLG forward doors; as the handle is pulled further, a spring-loaded kicker arm rotates until it contacts the pivot tube on the drag strut, which in turn rotates to release the NLG uplock. The NLG then freefalls to the fully extended position. Springs on the NLG drag strut move the lock links into the down and locked position.

Tests and research

Download of PSEU fault history

Following the accident, a review of the PSEU Present Faults showed a NWCENT UNRSNABL FAR fault. The fault history for the accident flight (present leg) also showed a number of faults including one NWCENT UNRSNABL FAR, nine NWCENT PROX SENS OPEN, one NGDRCL UNRSNABL FAR and nine PSEU CHAN A FAIL CHAN INOP faults.

It was determined that the 'unreasonable' faults were associated with the off-centre position of the NLG and the forward doors which remained open, while the NLG was up-and-locked. The NWCENT PROX SENS OPEN and PSEU CHAN A FAIL CHAN INOP faults were logged in 'weight-on-wheels' mode and considered to have resulted from the abrasion damage suffered by the centring sensor when the NLG contacted the ground during the landing.

There were no faults associated with the NGLK sensors for the accident flight.

Numerous faults were logged for flight leg 30, which corresponded to the slow retraction incident on 1 November 2017. These included UNRSNABL FAR faults for NGLK1 and 2 in 'gear down and locked' mode and UNRSNABL NEAR FAULTS for NGLK1 and 2 and NGDN1 and 2 in 'gear in transit' mode.

On-aircraft testing - general

Following the accident, a temporary repair was performed on G-JEDU and it was flown on a gear-down ferry flight to the operator's main base, where testing of the landing gear extension/retraction system was conducted under the supervision of the AAIB. Representatives from the operator, the aircraft and landing gear manufacturers, Transport Canada and the Transportation Safety Board (TSB) of Canada were in attendance.

Based on the observations from the aircraft examination, a test programme was devised by the aircraft and landing gear manufacturers to test all components which had the potential to influence the NLG extension/retraction sequence. In preparation for the testing, the nosewheel centring sensor, which had been damaged in the accident, was replaced, the NLG doors which had been replaced after the accident were removed to avoid potential interference between the NLG and the NLG doors and the aircraft was jacked.

As well as dimensional and rigging checks, multiple landing gear extension/retractions were performed while the indications on the LGCIP and the PSEU display were monitored.

During the first set of ten gear swings the first two retractions happened smoothly, but on the third attempt the forward NLG doors closed while the gear was in transit and the NLG stalled mid-retraction. The doors remained closed and the NLG then extended very slowly as hydraulic pressure dissipated from the system. When the NLG was almost completely down, but before it had reached the downlock position, the forward NLG doors opened⁵ and the retraction recommenced swiftly and completed successfully. This behaviour was observed three times during the first set of ten gear retractions. In addition, during one retraction the forward NLG doors began to close and then almost immediately reopened and the NLG momentarily stalled, but the gear proceeded to complete the retraction.

Further landing gear swings were performed and a number of stalled NLG retractions were observed. The PSEU display indications for the NGLK1 and 2 sensors were monitored in real time and it was noted that the NGLK1 and 2 sensor indications appeared to correctly reflect the position of the NLG when in the NEAR state (ie when the NLG was either downlocked or uplocked). However, on those occasions when the NLG stalled mid-retraction, shortly after transitioning from the NEAR to FAR state, the displayed NGLK1 inductance value briefly spiked to a value within the NEAR inductance range before once again going back FAR. While the exact value varied each time, it was observed to be high enough to register a NEAR signal in the PSEU but remained below the 9.1 mH limit, at which the PSEU would fault the sensor. The PSEU therefore considered these inductance spikes to represent a valid NEAR signal and stopped the NLG retraction sequence.

Each time the retraction stalled, the NLG was observed to descend slowly until almost fully extended after which the retraction swing would recommence and successfully complete. Monitoring of the PSEU display indicated that retraction would recommence as both the NGDN1 and 2 sensors transitioned from the FAR to the NEAR state, but before either of the NGLK sensors had achieved the NEAR state indicating downlock.

The PSEU was replaced with a new unit and several gear swings were carried out. The NLG continued to stall mid-retraction at intermittent intervals. The PSEU was therefore eliminated as a potential cause and the original unit was reinstalled.

On-aircraft examination of NGLK1 harness

The NGLK1 harness was unclipped from its routing and progressively flexed along its length, while monitoring the NGLK1 inductance indication on the PSEU display. Inductance spikes were observed when the harness was manipulated at a position approximately 15 cm from the sensor, indicating the possibility of mechanical damage within the electrical harness. The NGLK1 sensor and harness were removed for further examination and replaced. A further 40 gear retractions were conducted with no anomalies noted.

During removal of the NGLK1 harness from the aircraft it was noted that there appeared to be little slack in the harness and there was a tight bend where it entered the airframe connector (Figure 7).

Footnote

⁵ Although the forward NLG doors had been removed for testing, the door mechanism operated such that the doors would have opened if they had been attached.



Tight bend radius

Figure 7

NGLK1 harness termination at airframe connector

Computed tomography examination

A subsequent computed tomography (CT) scan of the NGLK1 sensor and harness assembly identified that one of the two conductors in the harness was fractured at a location approximately 15 cm above the sensor. In addition, a number of sites which indicated the initiation of possible similar damage were identified.

Proximity sensor harness additional information

The proximity sensor harnesses are made from a M27500⁶ standard cable, comprising a twisted pair of 22-gauge conductors, and these are cut to length for each individual sensor application. Each conductor wire is made from 19 strands of silver-coated copper, covered in a thin layer of insulation (teal-coloured) and a thicker layer of white fluoropolymer insulation. One of the conductors has a blue stripe on the white insulation; this denotes it as the 'drive' wire. The other conductor is the 'sense' wire.

Footnote

⁶ M27500 is an aerospace-standard specification, formerly known as MIL-DTL-27500.

The twisted pair are shielded by two layers of woven metal braiding, an inner layer five-strand metal shield and an outer six-strand layer. This assembly is encased in an outer white fluoropolymer 'jacket' and a corrugated black conduit.

NGLK sensor harness routing

The NGLK sensors are mounted on the aft face of the NLG drag strut and their associated harnesses run vertically up the drag strut, secured by p-clips at two locations (Figure 8). Above p-clip 2, flexible rubber lacing holds both harnesses together. The harnesses then route horizontally aft along the top of the NLG bay, where they are secured to a bracket by a third p-clip, before terminating at their respective airframe connectors on the front pressure bulkhead.

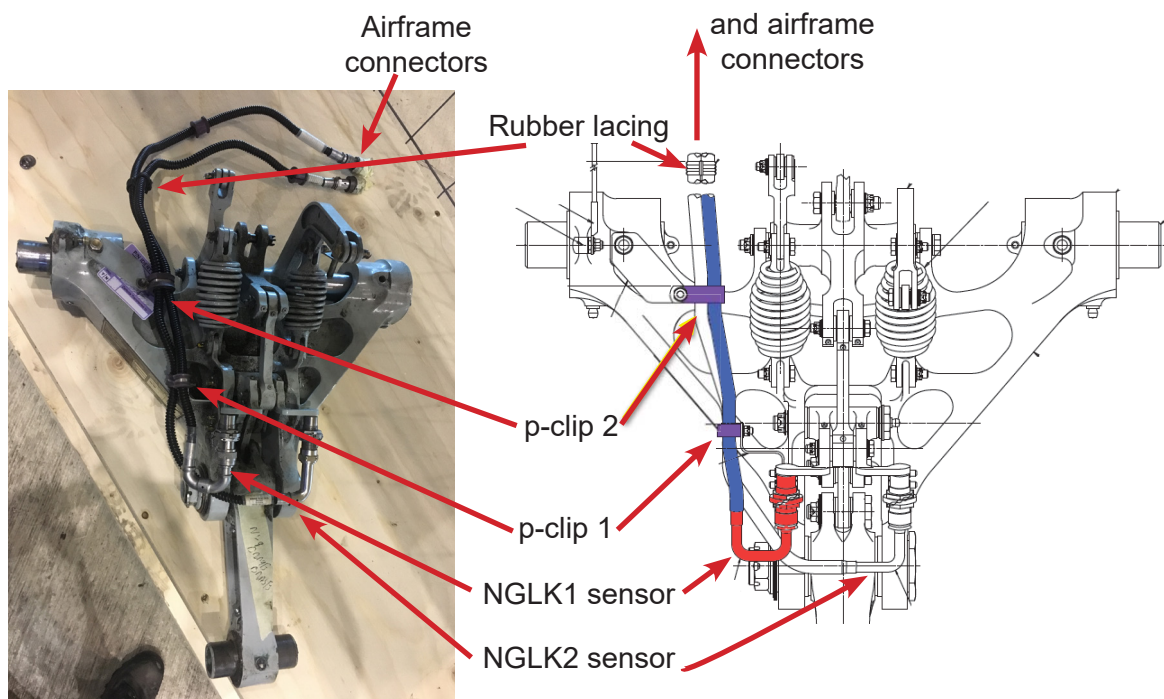


Figure 8

NGLK1 and NGLK2 harness routing on drag strut

Laboratory examination

The NGLK1 harness was subjected to a detailed forensic disassembly and strip examination by the University of Southampton's nC² engineering consultancy. Additional CT scanning of the NGLK1 harness was carried out by the university's MuVis facility.

NGLK1 harness

Visual examination of the harness revealed a distinct bend above the p-clip 2 location. The harness did not lie flat but exhibited a permanent deformation. A kink in the black corrugated conduit was evident at the joint with the airframe connector (Figure 9).

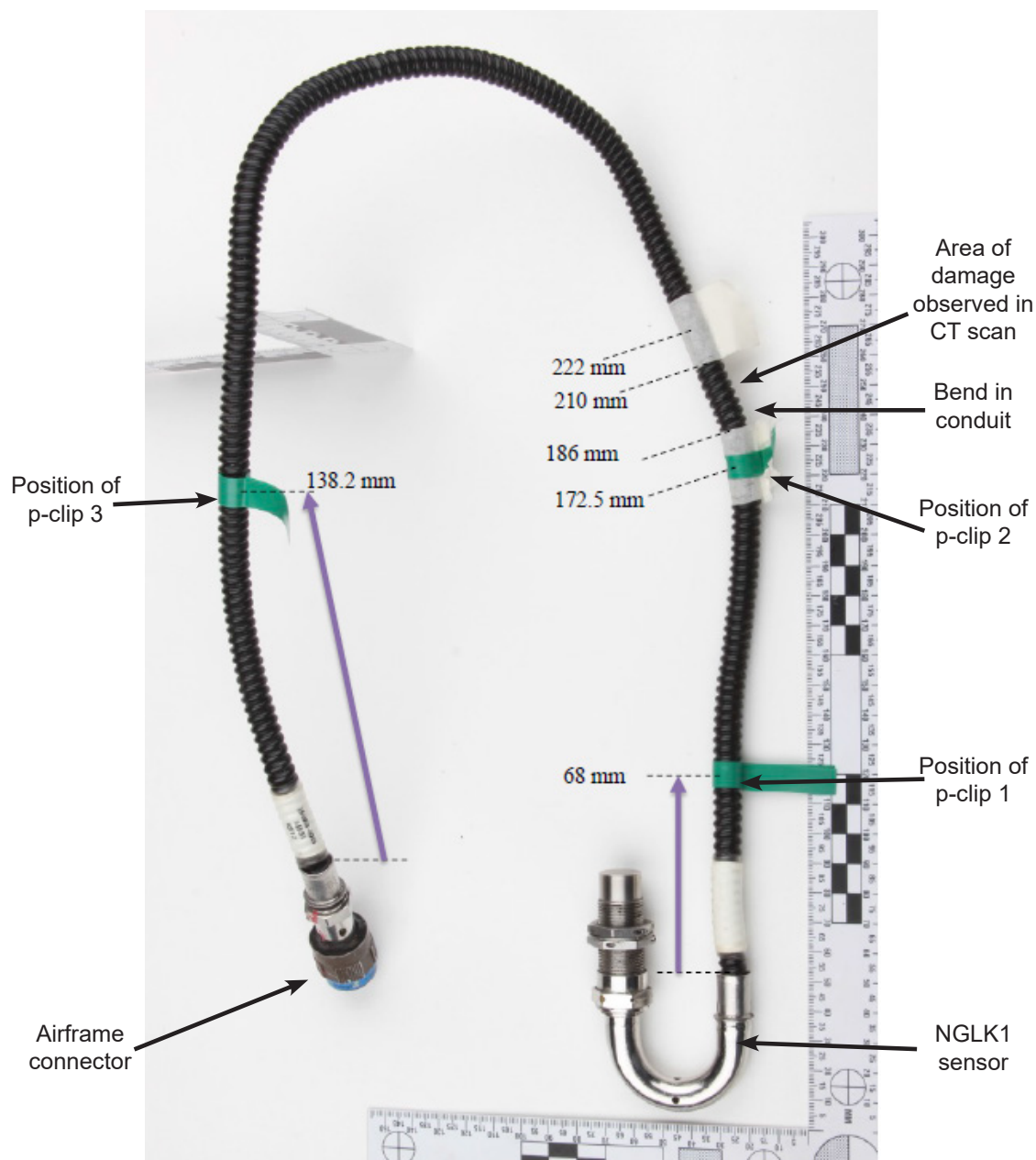


Figure 9

NGLK1 harness. Note: p-clip positions marked with green tape, and the area of damage identified on the initial CT scan was marked with white tape

When the corrugated conduit was removed to expose the cable, a split in the white polymer jacket was apparent (Figure 10), coincident with the concave side of the ‘permanent set’⁷ bend highlighted in Figure 9. The jacket also exhibited permanent set suggesting it had been held at a tight angle. There was evidence of buckling on the white jacket, either side of the split which was indicative of compressive loading. Broken strands of woven metal

Footnote

⁷ Permanent set refers to the permanent change in shape, or plastic deformation, of a material that occurs when the load to which it is subjected causes the elastic limit of the material to be exceeded. The material does not return to its original shape when the load is removed.

braiding were visible protruding through the split and the line of fractures was consistent with the point of maximum compression of the bend. Scratch marks were noted on the inner surface of the corrugated conduit, indicating that the exposed strands had made contact in this area and that the cable was moving relative to the conduit.

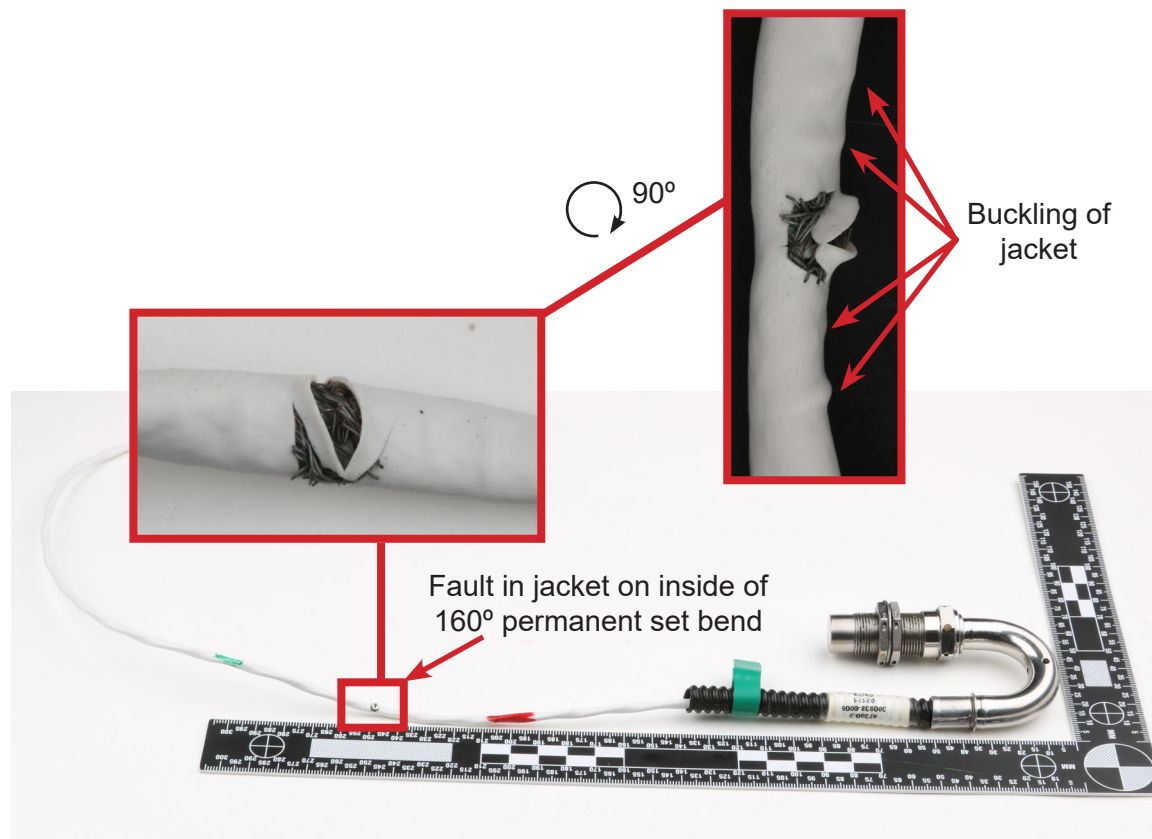


Figure 10

NGLK1 harness partially disassembled showing split in polymer jacket

A 100 mm section of cable was cut from the harness for additional examination, CT scanning and disassembly. The CT scan showed that one of the central multi-stranded conductors (white with blue stripe) had completely fractured at one location including through the two layers of insulation (Figure 11). It also exhibited multiple transverse fractures on individual wire strands either side of the bulk fracture, resulting in numerous short strand lengths. It was apparent that an electrical path could still have existed across the bulk fracture, bridged by short lengths of wire strands. The second wire (white) also displayed many transverse fractures on individual wire strands, predominantly on the concave side of the cable but was still contained within its insulation and was capable of making an electrical circuit.

Examination in a scanning electron microscope (SEM) showed that the fracture surfaces of the broken strands from both layers of metal braiding were corroded but the overall shape was flat and not consistent with ductile overload failure. Under higher magnifications features consistent with fatigue striations were observed between the areas of corrosion. It was not possible to measure striation spacing with any confidence on the failed strands

from the outer six-strand layer, however on the inner five-strand layer, striation spacing was approximately 0.3 m, suggesting that over 330 cycles would have been required to fail one strand.

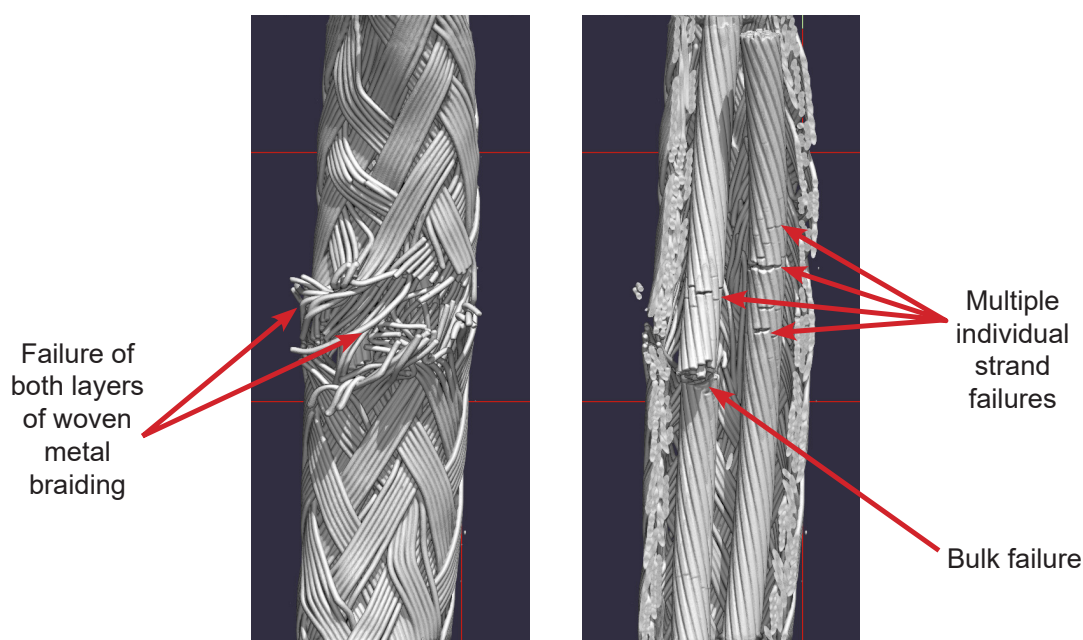


Figure 11

CT images of the concave side of the wire, orientation sensor down.

Left image shows deformation and damage to the metal braiding (with polymer jacket 'virtually' removed).

Right image shows the damage to both conductor (with polymer jacket, both layers of metal braiding and wire insulation 'virtually' removed)

The fracture surfaces of the failed wire strands from both conductors were flat and displayed evidence of fretting damage but were too corroded to find striations. However, the features that were present, including the general flat shape, indications of crack arrest and ratchet marks, were consistent with a cyclically-driven fatigue propagation failure mechanism initiating at sites of fretting damage.

Examination of NGLK2 harness

Based on the results of the NGLK1 examination and the common routing shared by both harnesses, forensic disassembly and strip examination of the NGLK2 harness was also performed. Upon removing the harness cable from the black conduit a visible fault, similar to that observed on the NGLK1 harness, was evident in the white jacketing just above the position of p-clip 2. The fault included a large transverse split in the white polymer jacket at the centre of the concave side of a permanent set bend in the cable, approximately 305 mm from the end of the sensor. The jacketing also displayed permanent set, suggesting it had been held at a tight angle. Both layers of protective woven metal braiding had failed and broken strands were exiting the split in the jacket. The fracture surfaces of the broken strands were flat, indicative of a fatigue failure mechanism. There were signs of localised corrosion on the outer six-stranded layer.

Beneath both layers of woven metal braiding, the two insulated conductors were found to be intact and displayed no macro evidence of failure, however they were not examined in the SEM.

ATP Testing of NGLK1 sensor

The NGLK1 sensor removed from G-JEDU was subjected to the standard Acceptance Test Procedures at the manufacturer's facility and no faults were found.

NGLK1 comparative testing by landing gear manufacturer

The landing gear manufacturer undertook testing on an example NLGLK1 sensor/harness assembly to simulate various fault conditions in the harness wiring while monitoring the reported sensor state, inductance and resistance. The testing confirmed that an intermittent open circuit in either the drive or the sense wire could cause an inductance increase and a momentary sensor state change from FAR to NEAR without isolating an inductance-based (FAR/NEAR) or resistance-based (OPEN/SHORT) fault. The intermittent open circuit was simulated by manually disconnecting and reconnecting the wire rapidly at an approximate 0.5 second interval.

A review of the nose landing gear control laws and logic determined that a state change on the NGLK1 sensor from FAR to NEAR without a fault being isolated, could cause unexpected premature closing of the forward NLG doors, before the NLG was fully retracted.

The landing gear manufacturer advised that filters are used in the system to provide fault tolerance to limited intermittent conditions (resistance) while still allowing sensitivity at the mechanical NEAR/FAR trip points (inductance). As a result, some intermittent failure conditions resulting from rapid changes in resistance might not be detectable prior to associated changes in inductance.

Extension/retraction videos

The aircraft manufacturer installed some video cameras in the NLG bay of a production Dash 8 Q400 and filmed the movement of the NGLK harnesses during landing gear extension and retraction. Analysis of the video footage showed that the drag strut, and hence p-clip 2 and the portions of both NGLK harness attached to the drag strut, rotate through approximately 90° during landing gear retraction and back during extension. A substantial amount of slack is evident in the harnesses between p-clip 2 and 3, and this portion flexes to a large radius as the nose landing gear is cycled through its positions. The movement includes a sudden jolt as the gear comes out of downlock and as it uplocks, due to the over-centre mechanism.

NGLK harness routing on G-JEDU

Further to the findings of the forensic examination, a retrospective review of photographs of the NGLK1 and NGLK2 harness routing on G-JEDU identified that both harnesses had been secured to neighbouring harnesses mounted on the sidewall of the NLG bay using a non-flexible cable tie (Figure 12).

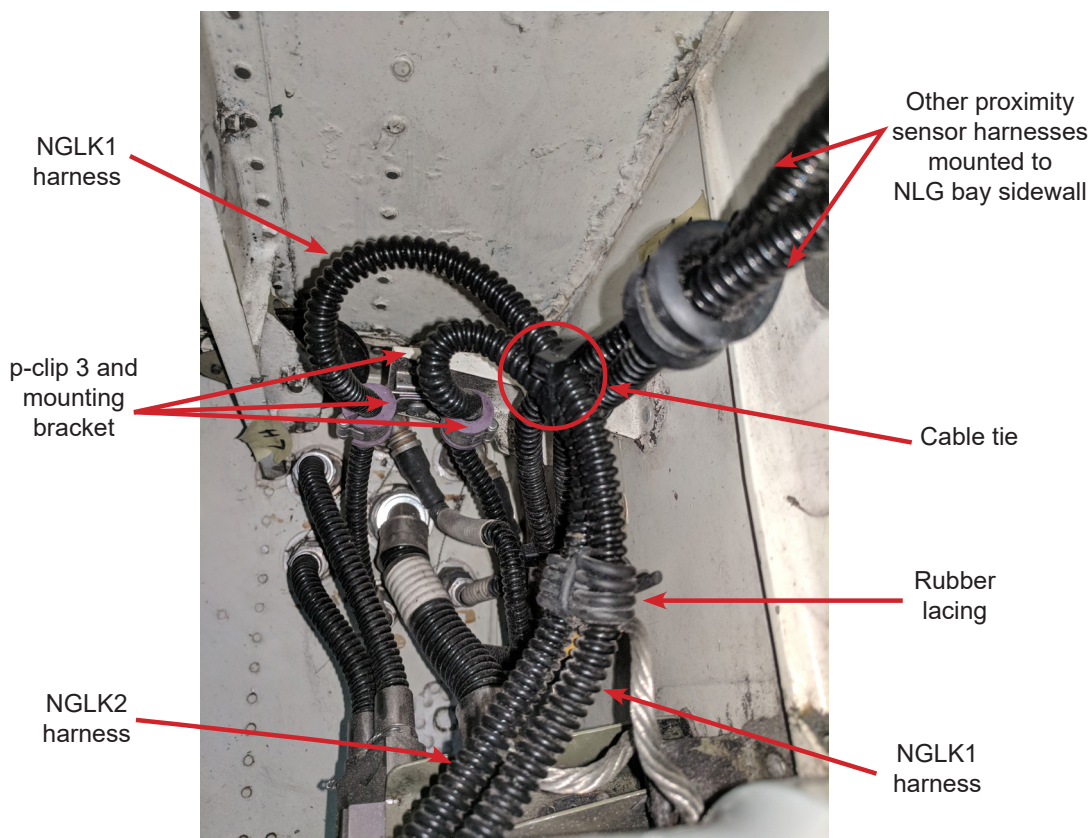


Figure 12

NGLK1 and 2 harness routing on G-JEDU, showing cable tie

Previous problems with NGLK harnesses

In the early 2000s, the aircraft manufacturer received reports of several Dash 8 Q400 operators removing large numbers of NGLK1 and 2 harness assemblies due to broken wires. Investigation at the time identified that the failures had resulted from excess stress developed at the second pclip on the drag strut, where the harness was being kinked, as the NLG rotated towards the up-and-locked position. Reported failures occurred between 3,900 and 5,000 flight cycles.

In 2003, the aircraft manufacturer introduced a modification⁸ to revise the attachment method for the NGLK1 and 2 harnesses on the NLG drag strut by replacing the existing attachment bracket on the back of the drag strut. The new installation, introduced as a production change from aircraft serial number (S/N) 4088 onwards, relocated the NGLK1 and 2 harness attachment points approximately 1 cm inboard and 2 cm down from the original position, thus removing the extreme bend between p-clip 2 and 3 and allowing them to bend in a large natural radius. The S/N for G-JEDU is 4089 and it would have had this change embodied during production.

Footnote

⁸ ISQ3200004 'NLG Drag Strut – revised attachment installation of the NLG #1 and #2 down lock harness', first issued 12 Mar 2003, and subsequent revisions – currently at Rev F 19 Jan 2006.

The aircraft manufacturer advised that the landing gear proximity sensor harnesses are not tracked items and operators that experience problems tend to discard and replace the harnesses. From the data it did have available, the aircraft manufacturer conducted a history search for events relating to NGLK sensors between 2011 and 2018. It identified seven incidents where the NLG interfered with the forward doors during retraction, two of which were the events which occurred on G-JEDU on 1 and 10 November 2017. In all but one of the events the NGLK sensor harnesses were found to be at fault. In the remaining event, multiple components were replaced but the description of the event and the damage to the NLG forward doors were very similar to that experienced on G-JEDU.

NGLK harness installation - general

A review of the NLG installation drawings and associated Aircraft Maintenance Manual (AMM) tasks relating to the nose landing proximity sensors revealed several inconsistencies regarding the routing and installation requirements for the NGLK sensors. In one instance, an AMM illustration incorrectly showed the NGLK sensor harnesses crossing over each other on the back of the drag strut between p-clip 1 and 2.

As a result of these observations the aircraft manufacturer undertook the following actions:

- In October 2018, issued a Service Letter to inform Dash 8 Q400 operators of the correct routing of the nose landing gear lock (NGLK) sensor harnesses. The Service Letter emphasises that correct routing and retention, using rubber lacing, ensures no interference with surrounding harnesses and structure while maintaining freedom of movement during the retraction and extension. It refers to in-service occurrences where the sensor harnesses have been secured to neighbouring harnesses using cable ties, which have resulted restricted movement and subsequent damage to the harness conduit and the internal sensor wire, which can contribute to poor sensor operation. It includes photographs of correct versus incorrect installation.
- In November 2018, issued Service Bulletin 84-32-157 '*Landing gear – Nose landing gear – Drag strut – Special inspection and rectification – electrical harness re-routing*' to inspect the NGLK sensors for correct routing and signs of wear, abrasion or fretting.
- In January 2019, updated the following AMM tasks: 32-21-11-400-801 '*Installation of the NLG electrical harnesses*', 32-21-06-400-801 '*Installation of the NLG drag strut*' and 32-21-06-000-801 '*Removal of the NLG drag strut*'. Amendments included clarifying the harness routing on the back of the drag strut, instructions for the location of the rubber lacing, addition of cautions indicating that the harnesses should not be retained or restricted at locations other than the specified p-clips and correcting a routing installation illustration.

G-JEDU aircraft maintenance history

Prior to the accident G-JEDU had accumulated 25,477 flight hours and 29,405 flight cycles. The most recent maintenance check had been a C-check in October 2017, but no work was done on the nose landing gear.

In October 2015, a nose landing gear 'Electrical Connector Care' maintenance work package was performed on G-JEDU. This included disconnecting all the NLG sensor harness electrical connectors at the bulkhead, cleaning and drying them, examination for and removal of corrosion, application of corrosion inhibitor and application of heat-shrink tubing to the connectors. No findings were reported on G-JEDU.

On 9 April 2016, a newly overhauled drag strut assembly was fitted to G-JEDU, at which point the aircraft had accumulated 22,286 flight hours and 25,991 flight cycles. New NGLK1 and NGLK2 sensor/harness assemblies had been fitted to the drag strut at overhaul.

In September 2016, the operator raised an internal Technical Order for removal of the heatshrink tubing on the NGLK1 and NGLK2 electrical connectors on all its Dash 8 Q400 aircraft, due to a concern that the heat-shrink tubing, previously-applied during the connector care programme, may be covering a drain hole on the electrical connectors and trapping water in the harness conduit and causing corrosion. The Technical Order noted that upon removal of the heat-shrink tubing, water might be seen to drip from the harness conduit. This task was accomplished on G-JEDU on 13 September 2016; no water was observed to drip from the harness conduit.

A review of defects between April 2016 and November 2017 did not identify any other defects or entries relating to the NGLK1 sensor or harness.

Failure Mode and Effects Criticality Analysis

The Failure Mode and Effects Criticality Analysis (FMECA) for the Dash 8 Q400 proximity sensing system, conducted as part of the aircraft certification process, identified seven potential failure modes for the NGLK sensors, all of which had a severity classification of 'minor'. These included electrical faults (internal open or short circuit), mechanical faults and inductance drift of the sensors. For each of these faults the documented 'system effect' indicated that the PSEU would identify that the sensor was faulted and refer to the remaining valid sensor, such that the nose landing gear would safely extend or retract. The FMECA did not identify any failure modes relating to erroneous intermittent change of state of the NGLK sensors which did not meet the threshold for the sensor to be flagged as faulted.

Following this accident, the landing gear manufacturer undertook to produce a revised FMECA for all landing gear proximity sensors based on the failure modes identified in this investigation. For the NGLK sensors this resulted in the new failure modes '*NGLK1/2 indicating intermittent NEAR while gear in transit*' being identified for the extension and retraction case. For the retraction case the 'effects of failure' included '*NGLK [1 or 2] indicates intermittent near, NLG SSV de-energised intermittently, NLG doors may not completely close*' with the 'end effect' being '*Potential collision between NLG and forward*

doors.’ However, this accident showed that the plausible end effect is failure of NLG to extend following a collision between the NLG and forward doors.

At the time of publication of this report, the revised failure modes had not been fully evaluated. The Functional Hazard Analysis (FHA) for the Dash 8 Q400 landing gear system categorises failure of the NLG to extend as having a severity classification of ‘major’⁹, so the severity classification of the revised failure modes will not be greater than ‘major’.

Proximity sensor harness redesign activity

The aircraft and landing gear manufacturers are aware of other instances of NGLK sensor harness failures in normal operation. During normal retraction, extension and steering operations, the NGLK harnesses are subject to dynamic movement and bending which can result in degradation and breakage of the internal wires. The landing gear manufacturer initiated a product improvement review of the proximity sensor harness with the aim of improving the performance of the landing gear system. The need for this activity was identified prior to the G-JEDU accident, but it has been informed by the findings of this investigation. This activity included a detailed review of harness failures for all proximity sensors throughout the Dash 8 Q400 aircraft, which identified harness stiffness/inflexibility, due to its construction, as a possible cause of failure.

As a result of its findings, the landing gear manufacturer initiated a redesign activity to improve the robustness of the existing harness construction. The current proximity sensor harness is comprised of a double-shielded twisted pair of wires within a convoluted conduit. A new, more robust, high-flex sensor wire, coupled with a more rigid, yet still flexible, conduit design is being explored. This aims to provide further protection for the sensor and wire from damage due to repetitive dynamic movement and external environmental conditions.

In August 2018, the landing gear manufacturer submitted a preliminary design concept to the aircraft manufacturer for review. The implementation plan and project schedule for the new harness will be developed following finalisation of the design concept, which is expected in the first half of 2019.

Operator fleet inspections

As a result of the findings of this investigation, throughout August and September 2018 the operator carried out an inspection of the NLGLK harness routing on the remainder of its Dash 8 Q400 fleet. Minor routing anomalies were noted and rectified on a number of aircraft; the most common finding was the absence of the rubber lacing. Other findings included the use of a cable tie in place of rubber lacing, incorrect p-clips and in one case, a damaged NGLK2 harness.

One of the operator’s aircraft experienced a slow landing gear retraction on the third sector after this inspection had been performed. The flight crew reported ‘*Undercarriage failed to retract for considerable time*’. The routing and security of the harnesses had been found to

Footnote

⁹ The FHA describes four levels of severity classification: minor, major, hazardous and catastrophic.

be correct, but the position of the harnesses had been disturbed to facilitate inspection. A review of flight data showed that, following the gear-up command, the landing gear came out of down lock and the retraction commenced but then stalled. The NLG dropped down under gravity and the retraction re-started and completed successfully. The operator considered that the only difference between that incident and the G-JEDU accident was the timing at which the retraction stalled; and therefore, contact between the NLG and NLG door did not occur. The operator replaced the landing gear selector valve, PSEU and both NGLK harnesses and conducted function tests before releasing the aircraft back into service. No detailed examination of the removed NGLK harnesses was undertaken.

Analysis

Operational aspects

After the landing gear retraction, the crew were aware that there was a problem with the nose landing gear. They immediately ensured that they did not exceed the gear limiting speed of 185 kt and decided to enter the hold to assess and deal with the problem. They followed the actions set out in the abnormal checklists but were unable to obtain the nose landing gear down-and-locked indication.

They decided to divert to Belfast International Airport as it had a long runway which was aligned with the surface wind of 250° at 12 kt. A fuel calculation was carried out and it was decided to minimise the fuel on landing and that the aircraft would remain in the hold until 1,100 kg of fuel remained. During the time in the hold, they followed the checklists three times to ensure nothing had been missed.

The commander agreed the plan and actions to be taken with the co-pilot and that he would fly the aircraft for the approach and landing. He briefed the SCCM and the passengers on the situation and the cabin crew prepared the passengers for the landing and played them the pre-recorded tape for an emergency landing.

The crew had a clear plan and enough fuel for a go-around and a second approach if required. The final approach was normal and at 4 nm from touchdown ATC advised them that the nose landing gear was not extended. Their plan had allowed for this and they continued their approach touching down at the normal touchdown point and gently lowering the nose onto the runway. When the aircraft came to a stop, the engines were shut down and the propellers stopped. The evacuation was carried out in an orderly manner and resulted in only two minor injuries to those onboard. The only delay was at the rear doors where passengers were concerned about the drop to the ground due to the aircraft's nose-down attitude.

The crew reported smoke and a burning smell in the flight deck after the aircraft had come to a stop. The exact source was not determined during the aircraft examination however, it was considered likely to have resulted from the abrasion of the lower fuselage structure with the runway surface, during the later stages of the landing roll.

Examination of the aircraft

Following the accident, the nose landing gear was found to be retracted but not unlocked. It was off-centre, having rotated about the shock strut axis and the right tyre was jammed against the sidewall of the NLG bay, preventing the gear from extending. Ground marks and damage to the aircraft indicated that the forward NLG doors had been open at landing.

It was determined that the flight crew had followed all relevant procedures but the way the nose landing gear was jammed meant that the landing gear alternate extension procedures would not have been effective in lowering the NLG. Due to the position of the NLG, it is believed that as the pilot continued pulling the nose gear alternate release handle, the kicker arm was able to pass the pivot tube. This theory could explain why the nose landing gear alternate release cable did not rewind onto its spool. Following the accident, considerable force was required to release and re-centre the NLG before it was free to extend under gravity.

Both NLG tyres and forward doors exhibited evidence of having contacted each other. The position and shape of the mechanical damage on the seal-retaining strip indicated that it had likely been caused by contact with the NLG tow spigot. Retraction logic prevents retraction commencing unless the nosewheel is correctly centred, so it was determined that the nose landing gear rotated off-centre after retraction commenced, most probably as a result of contacting the forward NLG doors.

A review of flight data showed that G-JEDU had experienced several slower than normal nose landing gear retractions prior to the accident on 10 November 2017. One of these was related to an incident on 1 November 2017 when the landing gear failed to retract. Subsequent inspection identified damage to the lower edge of the forward right NLG door and the door seal. Although not identified at the time, it is considered likely this damage was a result of the NLG tyres contacting the forward doors during retraction. Troubleshooting following that incident did not identify the cause, but the forward right NLG door and the NLG door actuator were replaced.

Post-accident testing

In normal landing gear operation, the NGLK1 and 2 proximity sensors are in the NEAR state when the nose landing gear is in either the unlocked or downlocked position, and in the FAR state when the gear is in transit. Post-accident testing identified a condition where an erroneous state change of the NGLK1 proximity sensor from FAR to NEAR while the gear was in transit could cause an unexpected output to the retract selector valve and the nose landing gear door sequence valve, interrupting the retraction sequence. When this occurred the forward NLG doors closed prematurely causing the gear to stall mid-retraction and the retraction would only recommence when the system logic conditions required for retraction were met.

The erroneous sensor state change was evidenced by an inductance spike on the PSEU, which although sufficient for the PSEU to detect a state change, was not high enough for the PSEU to flag the sensor as faulted.

This condition was consistently repeated during testing but occurred only intermittently and not on every retraction. There was variation in the timing at which the sensor state change occurred, its duration and the angle at which the gear stalled but it was evident during some retractions that interference between the NLG tyres and forward doors would have occurred, if the doors had been fitted. Flexing of the NGLK1 harness along its length while monitoring the displayed inductance values identified the possibility of mechanical damage in the harness, and this was subsequently confirmed by a CT scan.

Laboratory examination

Forensic examination of the NGLK1 and 2 harnesses identified that the white polymer jacketing on both cables had failed on the concave side of a permanent set bend, just above the position of the shared p-clip 2, which attaches both harness to the drag strut. In both cases the shape of the failure suggested that the cables had been forced into and held in a tight bend with small radius.

The two layers of woven metal braiding had failed at the fault location in both harnesses. The fracture surfaces of the individual failed strands were observed to be normal to their own axis suggesting a fatigue failure mechanism. Higher magnification SEM examination of the fracture surfaces on the failed braiding strands from NGLK1 revealed fatigue striations, consistent with a cyclically-driven fatigue propagation failure mechanism. Striation spacing indicated that it would have taken at least 330 loading cycles to fail a single strand of braiding. The aircraft had completed 3,414 flight cycles since the NGLK1 and 2 harnesses were installed. The multiple landing gear retractions conducted during post-accident testing would also have contributed to the loading cycles on the harnesses.

Beneath the woven metal braiding of NGLK2, both insulated conductors were found intact and did not display any macro-indications of failure.

Beneath the woven metal braiding of NGLK1, one of the multi-stranded conductors (white with blue stripe) exhibited a complete through-thickness bulk fracture, including the two layers of insulation, as well as multiple transverse fractures on individual wire strands either side of the bulk fracture. As the conductor was still largely retained within its insulation, it was apparent that an electrical path could still have existed across the bulk fracture, bridged by short lengths of wire strands. The second conductor (plain white) displayed many transverse fractures on individual wire strands, predominantly on the concave side of the bend and although the failure had not progressed to a bulk fracture, it was on the way to creating one. The fracture surfaces from the bulk fracture on the blue-striped wire, and those on individual wire strands from both conductors, displayed flat transverse fractures that were typical of fatigue that propagated away from sites of fretting. The fretting marks suggested relative movement between wire strands, which would be expected on a multi-stranded wire under cyclic loading. The presence of cyclic loading was confirmed by evidence of fatigue striations on the failed braiding strands from NGLK1. Fretting would have produced a local stress-raiser from which fatigue initiated.

NGLK harness routing on G-JEDU

A retrospective review of the harness installation on G-JEDU identified that a non-flexible cable tie had been used to secure the NGLK1 and 2 harnesses to some adjacent non-moving harnesses mounted on the sidewall of the NLG bay, between p-clip 2 and 3.

Examination of video footage taken within the NLG bay of a production aircraft demonstrated the extent to which correctly-routed NGLK1 and 2 harnesses are required to flex between the p-clip 2 and 3 positions, in order to accommodate movement of the NLG during retraction and extension. The permanent set bend just above the p-clip 2 position displayed by the NGLK1 and 2 harnesses from G-JEDU, indicated that they had been restricted from flexing. In addition, the sharp bend-radius observed at the airframe connector on the NGLK1 harness indicated that there was no slack between p-clip 3 and the connector.

It was concluded that the cable tie had the effect of creating an artificial constraint, restricting the freedom of movement of the NGLK1 and 2 harnesses between p-clip 2 and p-clip 3. This removed slack in the harnesses that would otherwise have absorbed the flex associated with normal landing gear operation. In this condition, normal operational of the landing gear would have produced the loading cycles sufficient to create a fatigue-driven failure mechanism in the harnesses.

The drag strut had been replaced on G-JEDU in April 2016 and since then there had been a number of maintenance interventions associated with the nose landing gear proximity sensors. Consequently, it was not possible to identify when or by whom the cable tie had been fitted to the NGLK1 & 2 harnesses.

As a result of the findings of this investigation, the operator undertook an inspection of its Dash 8 Q400 fleet to determine if a similar installation existed. A number of minor routing anomalies were found including the absence of rubber lacing, incorrect p-clips and a damaged NGLK2 harness. In some cases, a cable tie was found to have been used in place of rubber lacing to secure the NGLK1 and 2 harnesses to each other, although not to adjacent harnesses, as in the case G-JEDU.

While carrying out the inspection the operator identified an inconsistency between two AMM drawings regarding the harness routing; these have subsequently been amended.

Accident scenario (effect of failure)

During landing gear retraction, a NEAR signal from the NGLK sensors is the only thing that confirms when the nose landing gear is successfully retracted and unlocked. In the case of a faulty sensor, the retraction logic must rely on the remaining good sensor to ensure that the NLG doors do not stay open after the NLG is unlocked.

Based on evidence from examination of the aircraft and observations from on-aircraft testing and comparative testing to simulate an intermittent NGLK1 fault, the following scenario describes the sequence of events during the accident.

Following the command to retract the landing gear, the NGLK1 and 2 and NGDN1 and 2 sensors became FAR as the NLG came out of downlock and commenced retracting. Shortly after this, the NGLK1 sensor briefly, and erroneously, transitioned from FAR to NEAR but the resulting inductance was not sufficiently high for the PSEU to flag the sensor as faulted. Since the state change on the NGLK1 sensor from FAR to NEAR was intermittent during 'gear in transit' mode, a reasonableness fault was not reported or logged.

The PSEU sensed the erroneous NEAR status of NGLK1, but as the sensor had not been faulted, it considered this a valid indication that the gear was uplocked. The initial effect of the NGLK1 sensor going FAR to NEAR was to de-energise the nose landing gear selector valve. When this happened the forward NLG doors started to close.

If the NLG doors had closed fully before NGLK1 transitioned back to FAR the NRDCL sensor would have sent a NEAR signal to the PSEU, de-energising the retract selector valve and removing pressure from the landing gear retraction-extension hydraulic circuit, so the doors could no longer move.

When the NGLK1 signal transitioned back to FAR, the nose landing gear door selector valve would have become energised once more, putting it in a state to open the doors once the retract selector valve became energised. The NLG would have extended slowly, hydraulic fluid bleeding off through the inline restrictors, until when almost fully extended (NGDN1 and 2 became NEAR), the retract selector valve output from the PSEU once again became active, opening the NLG doors and allowing retraction to recommence.

At some point during the sequence where the NLG doors closed as the NLG was still in transit to the up position, contact was made between the doors and the NLG tyres, either during door closing, or when they began re-opening. Testing showed that the timing of this sequence of events can vary due to system tolerances and when the NGLK1 sensor transitions from far to near and then back to far. Contact with the doors caused the NLG to become off-centred, however although the NWCENT signal would have been lost at this point, a three-second delay in the logic meant that the NLG achieved the up-and-locked position.

If NLG doors had not closed fully before NGLK1 transitioned back to FAR then the NLG doors would have reopened immediately, allowing the NLG to continue retracting after only a short interruption. This is likely to have been the case in some of the slow retraction events experienced by G-JEDU prior to the accident.

Failure modes

Prior to this accident the failure mode of a sensor providing erroneous state information, but below the threshold at which it would declare itself faulted, had not previously been identified. Although the system design includes redundancy within the NGLK sensors, the nature of this failure mode meant that a single-point failure prevented extension of the nose landing gear. Due to the intermittent nature of the fault, maintenance troubleshooting after an incident may not identify the problem. Although the FMECA for the landing gear proximity sensors was revised following the accident to include this new failure mode, it has

not resulted in changes to the documented aircraft-level effects or the associated landing gear extension/retraction logic.

The landing gear manufacturer advised that filters used in the system provide fault tolerance to limited intermittent conditions while still allowing sensitivity to detect sensor state changes, but as a result, some intermittent failure conditions resulting from rapid changes in resistance may not be detectable prior to associated changes in inductance.

Subsequent incident

Another of the operator's aircraft experienced a slow landing gear retraction incident some months after the G-JEDU accident. A review of the flight data indicated that that incident was similar to the G-JEDU event in many respects, except the timing of the stalled NLG retraction was such that contact between the NLG and NLG door did not occur, and ultimately the NLG achieved successful retraction. A number of components, including both NGLK harnesses were replaced but as a detailed examination of the removed NGLK harnesses was not undertaken, it was not determined whether mechanical damage to one of the harnesses could have been a factor.

Proximity sensor harnesses failures

Although the use of an unapproved cable tie contributed to the failure of the NGLK1 sensor harness on G-JEDU, the aircraft and landing gear manufacturers are aware of other instances of NGLK sensor harness failures. During normal retraction, extension and steering operations, harnesses are subject to dynamic movement and bending which can result in degradation and breakage of the internal wires. Following a review of harness failures for all proximity sensors throughout the Dash 8 Q400, the landing gear manufacturer initiated a harness redesign to address the effects of repetitive bending and other environmental effects. The new design being explored will incorporate a more flexible sensor wire along with a more rigid conduit. Although initiated prior to the G-JEDU accident as a product improvement activity, this ongoing redesign work removes the need for any Safety Recommendations relating to harness design.

Conclusion

The investigation concluded that mechanical damage within the electrical harness of the primary 'nose gear lock' proximity sensor caused an intermittent and erroneous sensor state change during landing gear retraction. The measured inductance value associated with the sensor state change was not sufficiently high for the sensor to be flagged as faulted, and the erroneous state change was therefore considered valid. This had the effect of interrupting the NLG retraction sequence by causing the forward NLG doors to close prematurely while the NLG was still retracting, such that the tyres came into contact with the doors. When the NLG finally retracted, the tyres became jammed in the NLG bay, preventing it from extending when subsequently commanded. The flight crew followed the appropriate procedures for dealing with the incident, which led to the safe landing and evacuation.

Prior to this accident, the failure mode of an erroneous sensor state change below the threshold at which the sensor would declare itself faulted, had not previously been identified.

The investigation determined that the harness had been secured by a non-flexible cable tie, which restricted it from flexing during normal operation of the nose landing gear. This created loading cycles sufficient to create a cyclically-driven fatigue failure mechanism in the two conductor wires within the harness.

The aircraft manufacturer has taken action to clarify nose landing gear proximity harness routing and attachment instructions in relevant AMM tasks, and has published inspection requirements. The aircraft and landing gear manufacturers are working to identify a more flexible harness design.

Safety action

The following safety actions have been taken:

The aircraft manufacturer has:

- In October 2018, issued a Service Letter to inform operators of the Dash 8 Q400, of the correct routing of the nose landing gear lock (NGLK) sensor harnesses.
- In November 2018, issued Service Bulletin 84-32-157 to inspect the NGLK sensors for correct routing and signs of wear, abrasion or fretting.
- In January 2019, updated three AMM tasks in order to clarify the harness routing, provide instructions for the location of the rubber lacing, to add cautions indicating that harnesses should not be retained or restricted at locations other than the specified p-clips and to correct a routing installation illustration.

Throughout August and September 2018, the operator carried out an inspection of the nose landing gear proximity sensor harness routing on its Dash 8 Q400 fleet and undertook rectification of any anomalies noted.

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