Computer-Related Incidents with Commercial Aircraft

Lufthansa A320, incorrectly-wired sidestick, Frankfurt am Main, March 2001

20 March 2001

Synopsis On takeoff from FRA, the A320 encountered turbulence which tipped the left wing down. The captain, who was the pilot flying, corrected with right stick, whereupon the aircraft banked even further left. The left wingtip was said to have come within two meters of hitting the ground. The first officer saw what was going on, cut out the captain's stick inputs (there is a "takeover" button), and took over control. The aircraft landed again at FRA, after the crew checked out the first officer's control at altitude.

The incident was due to the miswiring of the captain's control stick during maintenance. Left stick normally commands left bank; right stick right bank. In this case, left stick commanded right bank and right stick left bank. The captain's control inputs to the turbulence-induced left bank thus made the left bank steeper, rather than correcting it.

Why did maintenance make such a mistake? Because they misread the document trail showing them how the wiring was to be connected on this particular aircraft. When they returned the aircraft to the flight line from maintenance, they tested the controls from the copilot's side, but not from the captain's side, although they had rewired his sidestick to the flight control computers. And the flight crew did not detect the anomaly during pre-flight check of the controls.

Reversing the control connections happens every so often to conventional aircraft, in particular to general aviation aircraft. Some pilots cope; some pilots don't. Best to make sure you know about it *before* takeoff. When I reclaimed my Piper Archer after maintenance, I always checked to make sure the control surfaces moved in the right direction. People thought that this kind of thing could not happen to fly-by-wire aircraft. Surprise: it can and did.

I wrote about this incident in the Risks Forum, in articles A320 Incident in Risks 21.48, before the Final Report had been published, and A320 Incident in Risks 23.24, afterwards. As I said in my Risks 23.24 note, the explanation still leaves me puzzled. I still do not understand why the two ELAC flight control computers did not receive contradictory bank inputs from the captain's sidestick control (only one plug, to one ELAC, was rewired) and thus report an anomaly at preflight check or before.

A320 Incident

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Tim van Beveren reported in *Flight International*, 22-28 May 2001, on a 20
Mar 2001 incident to a Lufthansa Airbus A320 on takeoff from Frankfurt.
This incident was reported at greater length and detail in *Air Safety
Week*, 4 Jun 2001, by David Evans and Tim van Beveren.
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The captain was Pilot Flying (PF). there was some degree of turbulence during takeoff, shortly after rotation, which resulted in the left wing moving down. The captain applied correction (right lateral roll control) but the wing dipped further left, reaching 21 degrees bank, and the wingtip is reported to have come within half a meter of the ground, and according to computer modelling of the digital flight data recorder the airplane "came within a few seconds of striking the ground".

The First Officer, the pilot not flying (PNF), realising there could be a control problem, switched "priority" to his sidestick controller and recovered the aircraft. The aircraft was flown up to 12,000ft on autopilot, the crew confirmed the problem, that the CAP's sidestick was controlling for roll in the reverse sense (normally, putting the sidestick to the left commands left roll; to the right commands right roll. Control-reversal here means that CAP's sidestick gave right roll on a left movement and left roll on a right movement).

The aircraft had just come out of maintenance. Maintenance is a known risk -- James Reason, an authority on human factors in aviation safety and Professor of Psychology at the University of Manchester, amongst others, has detailed how significant problems may arise through maintenance of complex systems.

It has happened many times that aircraft have come out of maintenance with control systems reversed in one or more of the three axes (roll, pitch, yaw). This has been the cause of a number of accidents with general aviation aircraft, but my informal requests for information turned up no recent accidents to commercial aircraft due to this cause. Evans and van Beveren report that "reversed controls are deemed impossible on transport-category aircraft" and that Boeing claims that the B737 aircraft cannot be reverse-connected without it being discovered before flight, normally through mandatory post-maintenance checks, but at the latest by the pilot's preflight check, as the controls could not be moved.

At Lufthansa's code-sharing partner, United Air Lines, certified inspectors must be stationed both inside and outside the cockpit to conduct a functional check after the flight control system has been worked on; a flight test is also required before the aircraft is returned to service after this kind of repair. It is believed that either of these measures would have caught the control-reversal problem, and so general maintenance procedures at Lufthansa Technik will be subject to detailed inquiry.

There have been a number of reports as to what fault caused the lateral control reversal, including the two sources above. However, I have found none of the explanations so far satisfactory, as they raise further puzzles that they do not solve.

The following architectural description of the A320 primary flight control system (PFCS) is drawn from Cary R. Spitzer, Digital Avionics Systems, Second Edition, McGraw-Hill 1993. The A320 sidestick controller generates input to five of the seven flight control computers which form part of the primary flight control system (PFCS). These five are the two Elevator Aileron Computers (ELACs) and the three Spoiler Elevator Computers (SECs). Each wing has two outboard ailerons, and five inboard spoilers (overwing surfaces which can be raised). Lateral (roll) control proceeds via four of the five spoilers and the two ailerons. Each of the two ELACS and three SECs control some combination of these 12 control surfaces. There is a significant amount of control redundancy.

Initial reports said that Lufthansa Technik personnel had been repairing one of the two ELACs, and had found a damaged pin on a connector. They had replaced the connector and this had apparently caused the control reversal. This explanation made no sense to me as it stood, because
(a) the connectors are standardised. Replacing one with another should give exactly the same connections as were there before;
(b) if one ELAC was receiving reversed signals, and the other was not, and the three SECs were not, then
  (i) the PFCS architecture would detect a discrepancy on the channels, and
  (ii) on each side, one aileron would operate counter to the other, but all spoilers would operate correctly-sensed, and it is hard to see how this could lead to the extreme control discrepancy reportedly experienced by the PF.

The Aviation Safety Week report on June 4 suggested that "Repair work involving complete rewiring "upstream" of the connector pins was conducted over several work shifts". The ELAC connector with the damaged pin has 140 pins and is one of four such for the ELAC, for a total of 560 pins.

It seems to me that to get control reversal without the phenomena in (b) above, there must have been a reversed signal downstream of the sidestick but upstream of where the sidestick movement is multiplexed into the five input signals to the five PFCS computers which receive them. I do not yet have, nor have I heard, a coherent suggestion as to how that could occur.

There has been considerable discussion of and speculation concerning: maintenance procedures at Lufthansa Technik, which has one of the very highest reputations for maintenance quality; wiring, wiring conventions and connectors in the A320 series; why the pilots did not discover the discrepancy during the usual preflight control checks (the A320 displays control surface displacement on the cockpit display, the ECAM, when the sidestick is intentionally moved and the airplane is on the ground, as during a preflight control system check). I think it is fair to say that few hard facts have emerged yet concerning any of these, and I find it hard to make any useful inferences about what actually went on from the publicly available information.

What emerges most clearly so far from this incident is that the simple physical complexity of the control system has confused some. Amongst other things, explanations have been proposed by presumably technically competent people that do not fit the control system architecture. It is hard to see how that phenomenon could have occurred with the simpler architectures of mechanical control systems. On the other hand, the PNF was able to take over normal control of the aircraft with one button push (the "control priority" takeover on the sidestick), which could also not happen with the simpler mechanical architectures.

We have very little information so far on the incident. It is certain that the puzzles will be solved further along the investigative line, and very likely that the results of the investigation will be highly significant for the care and feeding of fly-by-wire architectures.

Re: A320 Incident (Ladkin, RISKS-21.48, June 2001)

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In RISKS-21.48, 21 June 2001, I reported on an incident to a Lufthansa A320. The A320 is a "fly-by-wire" aircraft, in that primary control is effected through computers and electrics rather than mechanical means.

The captain's (CAP) sidestick controller was miswired during maintenance so that a "bank right" command initiated a "bank left" control signal and vice versa. This was discovered on take-off, when the captain corrected a left wing dip due to turbulent air flow with right sidestick movement ("bank right") and the aircraft's left wing dipped further, reportedly coming within two meters of touching the ground. The copilot took priority control (a feature of the electronic control architecture) and recovered the aircraft. The crew flew up a few thousand feet altitude, familiarised themselves with the problem as best they could, and returned to land the aircraft.

It turned out that two wires connecting the CAP's sidestick to one Elevator and Aileron Computer (ELAC), of which there are two, had been reverse-connected during maintenance, and the fault had been discovered neither by post-maintenance check, nor by post-maintenance cross-check, nor by the flight crew's pre-take-off control system check.

I had suggested in my Risks 21.48 note that I was puzzled by the partial reports of the incident then available. The final report was published as report 5X004-0/01 in April 2003 by the German Federal Bureau of Aircraft Accidents Investigation (german acronym BFU) and is available in English at http://www.bfu-web.de/berichte/01_5x004efr.pdf Thanks to John Sampson for bringing it to my attention.

Salient facts are as follows. During previous flights, one of the two ELACs failed. Maintenance found a defect in the X-TALK-BUS between ELAC Nos 1 and 2, found to be "caused by a bent connection pin (Pin 6K) in the plug segment AE of the socket for the ELAC no. 1." The attempt to replace just the pin failed and it was decided to replace the plug segment AE. There was no suitable spare plug AE for this series of airplane in stock, and the AE segments they had were not compatible with the remaining installed segments so it was decided to replace all four plug segments AA, AB, AD, AE with a compatible set. This meant that "in a confined space approx. 420 assigned connector pins had to be reconnected."

The method chosen was "ONE TO ONE", whereby "the wires were disconnected one after the other from the old plug and immediately connected to the new one."
The mechanics used the wrong wiring diagram.

How could this be? Well, an airplane and its equipment are identified by serial number (SN). The manufacturer knows what equipment was installed at build. Subsequently, the manufacturer issues Service Bulletins (SB) for modifications to installed equipment, and these SBs have different grades of urgency. Some are only "recommended", for example. So the installed equipment is identified by SN, and further by the log of which SBs have been accomplished. The applicable wiring diagram on p2 of the Airplane Wiring Manual (AWM) contained a designation that said it was applicable to airplanes with an "effectivity range" of 013-018 and those with effectivity 001-012 on which SB 27-1030 had been accomplished. P4 of the AWM was applicable to those airplanes with effectivity range 001 to 034 on which SB27-1030 and SB27-1084 had been accomplished. SB27-1084 had been accomplished, but not SB27-1030, and the aircraft had effectivity 017. Hence p2 was applicable, but the mechanics thought p4 was applicable as SB27-1084 had been accomplished.

Each numbered wire consists of a twisted red-blue pair. In segment AE, the "Monitor Channel" is connected by pair 0603. The Control Channel is connected by pair 0597. P2 specifies that these wires must be cross-connected (blue to red, red to blue) between the sidestick and ELAC

plug. P4 specifies that these wires must be connected straight through (red to red, blue to blue).

Furthermore, in the Aircraft Wiring List (AWL), the twisted pairs are always assigned in the order red, then blue, in the alphanumeric sequence of plug segment coordinates, except for these two wires. Wire 0603 is assigned blue then red to the pins 3C/3D, and wire 0597 blue then red to 15J/15K. Why? The manufacturer wanted to effect a uniform wiring for all its FBW airplanes, and from a certain type series on, the A320 wiring was planned to be identical to that of the A330 and A340. An interchange of colors was accepted for a certain transition period, and this aircraft belonged to the transition series.

The BFU report points out that, had only the AE segment been exchanged, only the Monitor Channel would have been falsely connected, and with high probability an error message would have appeared on the cockpit aircraft monitoring display (ECAM). It doesn't say at which point this message would have appeared - at check, at cross-check (both performed only with the right sidestick), or at pre-take-off check (about which I speculate that maybe only the right side stick operation checked again - see last paragraph).

The process of reconnecting 400-odd wires was a "major action on the control system", and the manufacturer Airbus requires in AMM 20-52-10 that a continuity check be performed on each individual wire, followed by an operational or functional test of the related function. This action was orally cancelled by maintenance supervisors upon inquiry by the mechanics, the reason being that the functional test to be performed after maintenance would reveal wiring errors. Well, it didn't.

It was also required to perform a functional check and a control system check independently of each other. Well, they were performed simultaneously, and the check person "had not been informed sufficiently about the previous work flow", in particular that the reconnected wires had not been measured as required.

Further, the control system test and functional test were performed only from the right sidestick, not from both, and a visual comparison check of the control surfaces was not performed. The report points out that the manufacturer's instruction in AMM-27-93-00-710-050 is ambiguous. It talks about how to perform the test with "the side stick". There are two. The mechanics told the investigators that it did not matter which sidestick was used to perform the tests, since "as both ELACs were connected to each other[,] possible faults of the one or the other ELAC would surely be indicated. This statement indicates lacking system knowledge of the mechanics."

The cross-check staff member also used the same system documents to conduct his cross-check that were used by the staff member who conducted the first check. Regulations require a second set of documents to be used, to assure independence, which was thereby lost.

The BFU points out that reconnecting all 400* wires of the ELAC plug "was connected to a high risk of errors." It also says that "a complicated and complex documentation system which thus is difficult to handle increases the risk of mistakes. The 173 procedural instructions valid for the area concerned contain many cross references making handling considerably more difficult. It was very time-consuming to find out which procedural instructions were relevant to the tasks to be performed."

The BFU also points out that quality assurance and monitoring, including checks of the maintenance organisation by the LBA (the german regulator) were inadequate.

After starting the engines, the AFTER START CHECKLIST for flight crew apparently only contained the instruction that the lateral flight controls were to be checked for full deflection, but not for the correct direction of deflection.

The report illustrates the "causal chain" through the "Swiss Cheese Model" of James Reason. The "holes" that "line up" and allow the accident to happen are:

1. "Quality assurance: insufficient support of the work flow, misinterpretation of regulations";
2. "Documentation: complex, difficult-to-handle working documents; accomplished works was [sic] misdocumented";
3. "Mistakes: inverted connection of 2 pairs of wires on ELAC plugs";
4. "Test procedures: use of incorrect documentation wrongly accomplished tests; severity of action was not kept in mind";
5. "Flight Operation: Checklist are [sic] insufficient; aileron deflection were [sic] not checked for correct deflection" leading to "Occurrence: "Serious Incident" Aircraft reacts inverted to the input of the left sidestick at the time of the take off".

These factors correspond roughly to the statement of causes and contributing factors.

In my RISKS-21.48 note, I recounted my puzzlement engendered by the partial accounts then available, on the basis

(a) hat the plugs were standardised, and that
(b) a mistaken wire-up on ELAC 1 would have caused command signals in the reverse sense to those detected by ELAC 2 and the three Spoiler Elevator Computers (SEC), and I felt this should have been detected by the aircraft monitoring systems.

Concerning (a), the report makes clear that the plug wiring was by no means standardised. The airplane belonged to a "transitional series" in which two wiring pairs were to be cross-connected, and the mechanics thought they should be connected straight-through, thanks to confusion over the appropriate wiring diagram.

Concerning (b), the control signal discrepancy - ELAC 1 sensing a "bank left" command and and ELAC 2 and the three SECs sensing "bank right" - was not detected by the aircraft monitoring systems and displayed on the ECAM during test because the left sidestick was not tested. However, had CAP checked sidestick deflection during pre-take-off check, this discrepancy would surely have been triggered. Had only the first officer checked the lateral controls, the discrepancy would not have shown. The report says that "according to statements of the crew, this check was accomplished pursuant to the valid procedures." I wonder whether the "valid procedures" require both pilots to perform pre-take-off flight control checks?

So the report leaves me still puzzled. If the CAP's sidestick had been moved in the direction of lateral control at any time before takeoff, then the two ELACs would have received contradictory sensor information, and ELAC No. 1 would have received sensor information contradicting that received by the three SECs. I also suppose that both pilots should to perform pre-take-off control checks, since sidestick operation is independent. So we are either to suppose that a standard comparison across multiple channels is not performed by the control system architecture, or else that CAP did not perform a control check before departure and

therefore either the pre-take-off checklist procedures omit an important requirement not noted by the BFU, or that the crew lied about performing the check according to procedures. It would have been more satisfactory had the report sorted these possibilities out.