Embraer EMB-145EU, G-EMBN

AAIB Bulletin No: 11/2001	**Ref: EW/C2000/11/01**	**Category: 1.1**
Aircraft Type and Registration:	Embraer EMB-145EU, G-EMBN	
No & Type of Engines:	2 Allison AE3007/A1/1 turbofan engines	
Year of Manufacture:	2000	
Date & Time (UTC):	7 November 2000 at 1207 hrs	
Location:	Belfast International Airport	
Type of Flight:	Public Transport	
Persons on Board:	Crew - 4	Passengers - 26
Injuries:	Crew - None	Passengers - None
Nature of Damage:	None	
Commander's Licence:	Airline Transport Pilot's Licence	
Commander's Age:	34 years	
Commander's Flying Experience:	5,700 hours (of which 1,100 were on type)	
	Last 90 days - 110 hours	
	Last 28 days - 78 hours	
Information Source:	AAIB Field Investigation	

History of the flight

The aircraft was operating a scheduled passenger service to Manchester International Airport. The flight deck crew comprised a recently appointed Training Captain operating in the left seat, who was conducting the 20th sector of a line training programme with a first officer. The first officer had recently joined the E145 fleet, having previously flown a twin engined turboprop type with the same operator.

Shortly after becoming airborne, the aircraft was subjected to full nose up stabilizer trim. The crew were immediately aware of the aircraft being excessively out of trim and both pilots applied significant nose down control column inputs in order to control the aircraft's pitch attitude. The crew found themselves in a very stressful situation and were not immediately aware of what had caused the pitch control problem, consequently, their subsequent recollection of events was incomplete.

The aircraft's two solid state recorders were replayed satisfactorily. Both the 25 hour data recorder and the two hour voice recorder retained a record of the entire incident flight, including the take-off phase. The following description of the events has therefore been compiled from crew statements and data recovered from the Digital Flight Data Recorder and the Cockpit Voice Recorder. Quoted heights above ground level (agl) are taken from the recording of the radio altimeter, other altitudes below transition (6,000 feet) have been corrected for the applicable QNH.

The crew had reported for duty at Manchester at 0545 hrs on the day of the incident in order to operate a planned four sector working day, on flights between Manchester and Belfast. The first two sectors of the day were completed uneventfully on another aircraft in the fleet. There was then an aircraft change to operate G-EMBN. The first officer acted as handling pilot for the first and third sectors and was to be the handling pilot for the fourth and final sector of the day.

The aircraft taxied for departure from Runway 07 at Belfast at 1155 hrs. The surface wind at the time was from 020° at 12 kt, with gusts to 18 kt, visibility in excess of 10 km in rain, with scattered cloud base 2,500 feet and overcast at 2,800 feet, temperature +8°C, QNH 990 mb. Windshear conditions were being advised on the airport's ATIS. The take-off was therefore to be conducted with a crosswind from the left. The aircraft configuration for the take-off was Flap 9°, ALT-TO power setting (86% N1), engine anti-ice selected ON, take-off weight 16,313 kg (maximum allowable 19,990 kg), take-off cg of 26.1% mac (mid-cg), take-off trim setting -7° (nose up), rotation speed (VR) 125 kt, take-off safety speed (V2) 129 kt. The take-off roll was commenced from the intersection of Runways 07 and 19 at 1207 hrs.

On the E145 aircraft, during a normal take-off and climb, the pitch control forces are such that nose down trim is required to be applied very soon after take-off in order to maintain the target pitch attitude for the initial climb with low residual pitch control force.

Because of the crosswind conditions, the first officer applied an aileron correction of 10° to the right as the aircraft accelerated through a speed of 43 kt during the initial part of the take-off roll. However, this application was not in the correct sense for the prevailing crosswind conditions. The commander advised the first officer about this, using the phrase 'put it the other way', as the aircraft accelerated between 80 kts and decision speed (V1). The first officer then centralised the aileron input.

The first officer rotated the aircraft in response to the 'Rotate' call from the commander at the correct speed. After initial rotation and lift off, as the aircraft climbed through 38 feet agl with an airspeed of 147 kt, the pitch trim started to move in a nose-up direction. The landing gear retraction was initiated by the commander in response to a request from the first officer. Over the next seven seconds the trim setting changed to the full nose-up position of -10° in two consecutive movements, during which the first officer was recorded as saying '.... wrong way'. The aircraft's pitch attitude, which had been 14° nose up at the start of this movement, had changed to 19.4° nose up and was still increasing by the end of it. Over the same period, control column position changed from neutral to in excess of 70% of forward travel from neutral.

As the commander's attention returned from the landing gear up selection to the EFIS Primary Flight Display (PFD), he noted that the aircraft was a few degrees above the normal pitch target of 14° nose up. He immediately prompted the first officer about the pitch attitude. The pitch trim remained at full nose up as the aircraft accelerated to a peak of 160 kt. As it climbed above 400 feet agl, the pitch attitude continued to increase through 21.8° nose up.

At that time an occurrence of a master caution on the FDR and a single chime on the CVR was recorded. Systems examination indicated that this was due to the fact that engine anti-ice had previously been selected to 'ON' for take-off but that icing conditions were not currently being detected. The caution message was inhibited by design during the take-off phase to avoid crew distraction.

The first officer required greater than usual push force on the control column in his attempt to maintain the correct target pitch attitude and the control column was well forward. He commented on this fact to the commander, who promptly took control of the aircraft. There were no EICAS Pitch Trim warnings generated during the event.

By 580 feet agl the control column position was recorded as being full forward, airspeed had peaked at 160 kt and was starting to reduce; pitch attitude had increased to 22.7° nose up. At that point a small nose-down pitch trim movement was recorded, which reduced the setting to -9.5°. The pitch trim position then remained constant at that value for the next one minute and 40 seconds.

Soon after taking over control, the commander ordered that the pitch trim cut out system on the console be operated as he assessed that the aircraft had suffered a nose up pitch trim runaway. This action, which was in accordance with the appropriate QRH procedure was intended to isolate the pitch stabilizer trim electrical operation in both normal and backup modes. With no manual pitch trim system available, no alleviation of the push load on the control columns was available and the relatively high forces had to be controlled by sustained manual input.

By 1,400 feet agl, the pitch attitude had reached a maximum of 25.7° nose up and airspeed had reduced through 151 kt. On operation of the pitch trim cutout switches, a master warning was recorded on the FDR together with 3 chimes recorded on the CVR. The master warning was cancelled by the crew 14 seconds later, during which time the commander confirmed that the pitch trim was cutout and reaffirmed that he had control as the aircraft's pitch attitude began to reduce.

At this stage, the aircraft had entered a long period (phugoid) pitch oscillation, maintaining the Flap 9° take-off configuration and ALT-TO power.

With both control columns fully forward, the commander then assessed that the aircraft may have suffered an elevator jammed in the nose up (rotation) position. He therefore ordered that the Elevator Disconnect switch be operated. This had the effect of splitting the elevator system such that the left elevator was being controlled by the left control column and the right elevator by the right control column. As the aircraft was climbing through 3,300 feet the elevator disconnect lever was operated.

At this time, three altitude alert tones were audible on the CVR because the aircraft had climbed in excess of 300 feet above its cleared altitude of 3,000 feet. ATC requested confirmation that the aircraft was maintaining 3,000 feet to which the first officer replied 'standby'. The commander then issued a 'Mayday' call to ATC advising of the pitch control problem and the aircraft continued to climb despite the best efforts of both pilots to apply full forward control columns to reduce the pitch attitude.

Airspeed again started to increase as a disparity in the recorded values from the two control column positions confirmed that they had been disconnected. As airspeed increased through 155 kt, pitch attitude, which had lowered to a minimum of 12.7° nose up, again began to increase. Two further

complete cycles of this phugoid behaviour were recorded as the aircraft climbed through 8,000 feet, two minutes after take-off. The airspeed varied between 137 kt and 164 kt as the pitch attitude varied between 10° and 24° nose up during this period. The effect of the long period oscillation was to make the crew uncertain as to whether their control inputs were actually having any effect on the aircraft's pitch attitude.

The commander recalled his attempts to trim the aircraft by re-engagement of the Backup Trim system. Passing 8,000 feet a further nose-down change in pitch trim was recorded, moving to -7°. This occurred as pitch attitude was reducing and airspeed was starting to increase at the start of another phugoid cycle. The right hand control column position was recorded as moving towards neutral from its previous full forward position as pitch attitude continued to reduce. The left-hand control column remained essentially full forward. Pitch attitude stopped decreasing at 2° nose up and, as the aircraft began to pitch up again, the right control column was moved to its full forward position.

With no further changes in pitch trim position, a further series of four and a half phugoid cycles began, this time with higher peak airspeed values (170 kt to 207kt) but lower pitch attitude excursions (18° nose up to 1.3° nose down). At the end of the third cycle, engine power was reduced to 80% N1 and the excursions in pitch attitude were observed to decrease. Two further step reductions in engine power (to 68% N1 then 60% N1) further reduced the amplitude of the pitch attitude and airspeed variations. The aircraft reached a maximum altitude for the flight of 17,000 feet at that time. During the final half cycle, the flaps (which had remained at 9° since departure) were inadvertently extended to 18° before being immediately retracted. Upon flap retraction the pitch and airspeed fluctuations ceased altogether and the aircraft began to descend. The relevant parameters recorded during the period of pitch instability are shown in figure 1*(JPG 201kb).*

As the aircraft descended airspeed increased and remained between 240 kt and 205 kt. Pitch attitude varied 2° either side of level and there was no evidence of the previous fluctuations recurring. The commander assessed that the weather conditions at Liverpool or Manchester would present a more favourable prospect for landing in an out-of-trim condition, so radar vectors were requested for the remainder of the flight. The aircraft leveled off at 7,000 feet and it could be observed from the recording of the control column positions that the first officer was maintaining full forward deflection whilst the commander's column was more central. To compensate for the slight roll-left moment induced by the difference in the elevator positions, a small bias of roll-right control wheel in the order of 1.5° was maintained for the remainder of the flight. As the aircraft leveled off, the pitch trim setting, which had remained constant during the descent, was adjusted to a more nose-down setting of -5.3° over a period of eight seconds. Airspeed during this trim change was approximately 210 kt.

The aircraft was flown at this altitude without further trim changes for a period of 30 minutes. During this time the crew were in discussion with their operations management personnel by radio. After some discussion and consideration of the problem, the commander elected to continue the flight to land at Manchester and the aircraft was given the appropriate radar vectoring. The commander briefed the cabin crew on the decision and instructed them to prepare for an emergency landing at Manchester. He also addressed the passengers, appraising them of the situation throughout.

The weather for the landing at Manchester was a surface wind from 350° at 10 kt, visibility more than 10 km, few cloud base 1,200 feet, scattered cloud base 2,200 feet, broken cloud base 4,500

feet, temperature +9°C, QNH 981 mb. The aircraft landed uneventfully on Runway 06L at 1300 hrs, using Flap 22°, landing weight 15,323 kg, using Vref 122 kt.

After landing, the aircraft vacated the runway without assistance and taxied to a stand where the passengers were deplaned normally.

The commander noted that as the airspeed was being reduced for the approach, the amount of push force being applied by the first officer was reduced. He also noted that at lower speeds, the aircraft handling appeared 'sloppy' in pitch.

Description of the pitch control system

The Embraer 135/145 series of aircraft use an identical electric pitch trim system driving actuators which move the entire stabilizer through angles of +10° (nose-up trim) and -4° (nose-down trim). The elevators are manually operated via spring tabs and cables connected to the control columns. The cable runs are duplicated such that the left elevator is connected to the Captain's control column and the right to the First Officer's. The two columns are connected together below the cockpit but can be separated by the crew by pulling a disconnect handle on the centre console. Once this has been done, each crew member has independent control of one surface to cater for the case of a jammed elevator but reconnection can only be done as a maintenance action on the ground.

The pitch trim is likewise duplicated into Main and Backup systems, either of which can be used to trim the aircraft in pitch. Twin electric motors driving two screw jacks via a combining gearbox move the tailplane according to demand such that the selected motor backdrives the other (inactive) motor. Both motors incorporate a current-limiting device and a clutch to prevent excessive electrical or mechanical loads being experienced by them. The motors/gearbox/jacks assembly is a single item known as Horizontal Stabiliser Actuator (HSA).

As the name implies the Main system is normally used to trim the aircraft via the conventional switches on each pilot's control yoke. As per normal practice, these switches are duplicated on each yoke such that the handling pilot has to move both switches together (the commander with his left thumb on the left yoke or the first officer with his right thumb on the right yoke) to achieve a trim command in the appropriate sense: this is to prevent a trim runaway in case of a short-circuit in one of the switches. As an additional safeguard against a full uncommanded trim movement, a timer in the system interrupts a trim selection after 3 seconds so that large trim movements require the pilots to release and select again after this period of time. On other types of aircraft fitted with conventional 'spectacle'-type control yokes the trim switches are mounted vertically such that a nose-down command requires a push with the thumb in an upward sense and a pull downwards for a nose-up sense. The Embraer 135/145 aircraft employ a 'ramshorn' design of control yoke which means that, for the switch to fall naturally to the pilot's thumb with his hand on the yoke, it is mounted at an angle of about 45° to the horizontal. The instinctive 'push for nose-down and pull for nose-up' motion is, however, the same.

Also mounted on each yoke is a 'Quick Disconnect' button. When pressed by either pilot, this button disconnects the autopilot and deactivates both trim systems. When the button is released, normal trimming is restored. In addition to the pilot commands, the Main system is used for automatic trimming by the autopilot and also by the speedbrakes, which command a small nose-down trim change when speedbrakes are deployed.

The Backup trim system is effectively a duplicate of the Main system but does not receive either of the two automatic signals mentioned above. Pilot commands are input via a single switch on the centre console, although like the yoke switches it is actually two switches which must be operated together. Unlike the yoke switches, however, it is of a 'rocker' type mounted longitudinally such that a nose-down command requires a press on its forward end and vice-versa. Just forward and either side of the backup trim switch on the console are two guarded Cut-out switches for the Main (left) and Backup (right) trim systems. Activation of one or both of these switches electrically isolates the appropriate trim systems.

Both Main and Backup trim commands are received by an avionics box in the rear of the aircraft known as the Horizontal Stabiliser Control Unit (HSCU). This contains separate channels for both systems and sends the appropriate electrical signals to the HSA motors. The HSCU also receives data from the Air Data Computer in order to modify the trim rate according to airspeed and also checks that the trim position prior to take-off is within the prescribed take-off range, otherwise an audio warning is generated.

Pitch trim fault indication

The Engine Indicating and Crew Alerting System (EICAS) fitted to G-EMBN was designed to display either 'PITCH TRIM 1 INOP or PITCH TRIM 2 INOP red warning messages on its screen if any of the following fault conditions were detected in the Main or Backup channels respectively:-

HSA main motor short circuit
HSA main motor jammed
Channel disconnected
HSCU channel internal failure

Appearance of this caption on the EICAS would be accompanied by the associated aural and visual Master Warnings.

In addition, the aircraft was equipped with a Central Maintenance Computer (CMC). This is normally downloaded by maintenance staff after every flight and contains a list of defects detected by the computer in various aircraft systems. Two messages relating to the pitch trim system may be displayed:-

(1) HOR STAB ACTUATOR FAULT which is triggered by the following conditions:

Motor jam in the main and/or backup motors
One of the channels is disconnected by pressing the Quick Disconnect Button
One of the channels is disconnected using the respective cut-out push-button
A motor short is detected in the main or backup channels

(Note: aircraft employing later CMC software than G-EMBN did not give fault indications for the last three conditions).

(2) HOR STAB CONTROL UNIT FAULT, which is triggered by the following conditions:

Power supply failure or control/monitor disagree
Resolver/commutation fault

Drive enable relay fault
Motor overspeed or clock frequency

Examination of the aircraft

The aircraft was examined in the operator's hangar at Manchester International Airport, having been left in the condition in which it had landed and otherwise shut-down normally. The external graduations of tailplane trim position on the fin indicated that the trim was at 6°. On the flight deck, the elevator disconnect handle was found to be deployed and the Backup Trim cut-out switch was operated. The Main trim cut-out switch was engaged and, upon applying power, the EICAS displayed the PITCH TRIM 2 INOP caption and the trim position indicator also showed 6°.

There were fourteen HOR STAB ACTUATOR FAULT messages displayed on the CMC. Unfortunately, the CMC does not allocate a sector number to each occurrence, but the messages appeared to have occurred over the last six sectors. Since, as noted above, the software version of the CMC fitted to the subject aircraft recorded this message every time the autopilot/trim quick disconnect button was used by the crew, maintenance crews were disregarding these messages as effectively spurious.

With electrical power re-applied to the aircraft, the Main pitch trim system was exercised many times and confirmed that its operation was normal in every respect from both the Captain's and First Officer's yoke switches (the autopilot and spoiler automatic trim functions were not checked). After resetting the Backup cut-out switch, this procedure was repeated for the Backup system using the console rocker switch and, again, everything appeared normal.

Advice was then sought from the manufacturer, who supplied a comprehensive list of actions, largely based on Maintenance Manual rigging, cable tension and serviceability checks but also including wiring continuity checks on the pitch trim system: no abnormalities were found. The list ended with a recommendation to remove the HSA, the HSCU and both Main and Backup trim switches and return them to the manufacturer for testing. In addition, it was recommended that modified Main and Backup trim switches be fitted in accordance with Service Bulletins 145-27-0071 and -0073 respectively. Although the operator is in the process of following this latter recommendation, it was felt that information from the DFDR/CVR (not analysed at the time the list was compiled) strongly suggested that there was no reason to suspect defects in the other components, so the HSA and the HSCU were not changed. Following a test flight, the aircraft was returned to service and there have been no reports of any other similar incidents on this aircraft.

Previous pitch trim incident

Prior to the incident flight, the commander had been aware of another in-flight incident related to incorrect pitch trim operation, although the full details of the occurrence had not been widely promulgated by the operator at that time. During the previous week, another UK registered aircraft, G-RJXD, belonging to a different operator had experienced a temporary failure to trim after take-off. In that event, the aircraft had become airborne but the crew then found that no movement of the Pitch Trim was possible, using either control column mounted switches or the Backup system. The crew involved therefore made a safe diversion and landing at another UK airport.

Examination of the components from G-RJXD found that the Horizontal Stab Actuator was reaching its limiting operating current due to the loading on the Horizontal Stabiliser at airspeeds encountered during the initial acceleration phase after take-off (around 200 kts). This phenomenon

was also noted on two other aircraft belonging to overseas operators during events in December 2000.

Analysis of crew action during G-EMBN event

The nature of the incident experienced on G-EMBN was totally different in character to other recorded incidents, in that the stabiliser trim had moved into the full nose up position immediately after take-off. Also, it had done so in two consecutive movements (see inset window in Figure 1). Study of the trim system and its various protections did not reveal any plausible mechanism by which the stabiliser trim would move uncommanded in such a fashion and then leave no evidence of faults or failures.

By design, the trim motor could run for a maximum period of 3 seconds before having power removed by the timer in the HSCU. The amount of trim that could be applied during this 3 second period varied with the airspeed of the aircraft, such that at low speeds such as those during the initial climb, the trim rate was between 0.7 and 0.8 degrees per second, so the maximum change of trim was limited to 2.1 to 2.4 degrees before cutoff by the timer.

In this event, the total trim change was 3 degrees nose up. Considering that this amount of movement occurred during two distinct and consecutive periods, the only possible explanation is that the input was made manually, in two stages, by the handling pilot. Given that the operation of the control column mounted trim switch is in the correct natural sense (albeit inclined inboard from the fore and aft axis of the aircraft), it is therefore likely that this inadvertent nose up input was simply due to a momentary lapse of concentration.

After the event, having listened to the CVR recording of the incident, both pilots agreed that the first officer's reference to '...wrong way...' at the time of the pitch trim input, was in fact in reference to the incorrect aileron input that had occurred during the early stages of the take-off roll. This is therefore indicative that the handling pilot's attention was focussed on an immediately prior event, and not directly at the task in hand, which was to correctly trim the aircraft for the climb.

The incorrect stabilizer trim setting was not detected by the commander as he did not make reference to the EICAS trim display (located in the lower right corner of the upper EICAS screen), which would have correctly indicated the actual position of the stabiliser trim as being full nose up. However, the commander did consider that there had been a Pitch Trim Runaway/Elevator Jam and requested the QRH procedures for these events after he had taken over the handling of the aircraft.

The long period oscillatory nature of the aircraft's pitch attitude and airspeed served to make the pilots unsure as to whether or not their control inputs were having any appreciable effect upon control of the aircraft. In response to the full nose down position of the control columns, when the aircraft pitched down and the airspeed was increasing, they believed the situation to be under control. However, during the other half of the phugoid cycle, the aircraft pitched up and the airspeed reduced, despite the opposing control inputs. Because of the stressful situation in which the pilots found themselves, this long period oscillatory behaviour was not immediately apparent. The commander experimented with the Backup Pitch Trim system in attempts to restore its operation. Some two minutes after the initial nose up trim input, the commander was successful in reducing the stabilizer trim setting back to 7° nose up (the initial take-off setting). However, because of the confusion over the pitch control oscillation, further nose down trim inputs were not made until much later in the flight. Had the nose down trim inputs continued, using the Backup

system, then the aircraft could have been returned to an in trim condition, thus alleviating the control forces for the remainder of the flight.

Pitch trim system reliability

During the course of this investigation, a survey was carried out to establish the in-service experience of reliability of the Pitch Trim system amongst the three UK operators of the type. It was established that a total of over 32 occurrences of Pitch Trim operating anomalies had been noted in aircraft Technical Logs of the UK fleet during the period between September 1997 and November 2000. Some of these had occurred prior to a change in modification standard to the pilots' trim switches, but a significant proportion continued to occur after the switch modification had been incorporated. The nature of the problems encountered - intermittent operation, with no 'hard' faults being apparent after landing or after circuit breaker reset - indicated that the phenomenon may have been electrically related to the operation of the HSCU.

Action by the manufacturer

As a result of a total of six recorded events, the manufacturer issued an Operational Bulletin, number 145-012/00, which provided advice to crews about how to handle any temporary loss of Pitch Trim command after take-off. Additionally, the manufacturer issued a Service Bulletin, number 145-27-A077 in January 2001, which introduced a maximum speed for aircraft retrimming after take-off, to ensure that crews had trimmed the aircraft in the nose down sense prior to accelerating above 160 kts.

In addition, as a result of the in depth examination of the reliability of the Pitch Trim system during these investigations, the manufacturer has undertaken to define a series of Pitch Trim System modifications which may include a 'Pitch Trim Running' indication to the flight crew, aural and visual trim switch failure indications and an increase in stabilizer actuator load capability as well as other possible changes.

From 27 to 29 March 2001 Embraer also held a Conference in Paris for all of the European Operators which included a presentation by Embraer on the Pitch Trim System and discussions on the reported occurrences of a temporary loss of pitch trim command during the take-off/initial climb phases. The causes identified for the events were high loads on the HSA induced by large elevator commands following delayed pitch trimming of the aircraft after take off, leading to an exceedence of the maximum actuator operational force (actuator in stall condition). Operators were also told that pitch trim delays after take off could be caused by system malfunctions (problems in the switches) or by incorrect operation.