BAe ATP, G-MANG, 18 March 1998 at 0934 hrs

AAIB Bulletin No: 4/99 Ref: EW/C98/3/4 Category: 1.1

Aircraft Type and Registration:	BAe ATP, G-MANG
No & Type of Engines:	2 Pratt and Whitney Canada PW-126 turboprop engines
Year of Manufacture:	1989
Date & Time (UTC):	18 March 1998 at 0934 hrs
Location:	Manchester Airport
Type of Flight:	Scheduled Public Transport
Persons on Board:	Crew - 4 - Passengers - 58
Injuries:	Crew - None - Passengers - 1 Serious
Nature of Damage:	Nose landing gear attachment structure torn from fuselage and leg collapsed rearwards
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	60 years
Commander's Flying Experience:	Approximately 17,000 hours (of which 85 were on type)
	Last 90 days - 85 hours
	Last 28 days - 58 hours
Information Source:	AAIB Field Investigation

History of flight

The aircraft was operating a scheduled service from Southampton to Manchester. The same crew and aircraft had earlier operated the Manchester to Southampton service. Until the landing rollout at Manchester, both flights had been uneventful and aircraft behaviour had been normal.

Shortly before touchdown on Runway 24, the surface wind was given as 300° at 13 kt. The co-pilot was handling and after using left rudder to reduce drift during the flare he executed a gentle touchdown on the main wheels. After touchdown he lowered the nosewheels on to the runway, selected reverse thrust on both engines, and announced to the commander "you have control". (There is no nosewheel steering tiller on the co-pilot's side of the ATP flight deck and the steering system is not connected to the rudder pedals. Consequently the left seat pilot always taxies the aircraft).

Initially the rollout continued normally with little if any requirement for nosewheel steering inputs or wheelbraking. However, about nine seconds after the commander took control, a vibration started which rapidly grew in intensity. The vibration, which lasted about 15 seconds, was so severe that items on the flight deck became airborne and the lids of some overhead lockers in the cabin, particularly those nearer the nose, burst open and some contents were ejected. Thinking that a nose landing gear tyre had burst, the commander tried to steer towards the nearest runway exit, intending to park the aircraft on the taxiway. However, before he could do so, he lost nosewheel steering authority and a few seconds later the nose leg collapsed. Both pilots were immediately aware that the leg had collapsed as the aircraft came to a halt on the runway with the forward fuselage resting on the nosewheel tyres. ATC staff in the visual control room had seen the aircraft come to a stop with the nose landing gear collapsed and the appropriate emergency services were despatched without a request from the flight crew.

Evacuation

As the aircraft came to a halt the forward cabin attendant spoke to the pilots by interphone to ask if there was a problem but they were pre-occupied with immediate action drills and she decided to wait for an answer. She listened to their actions and after the commander said "condition levers off, abandon the aircraft" she specifically asked whether to evacuate the aircraft using the slides. The commander replied that she should evacuate the aircraft using all available exits on both sides and he told her that the nosewheel had collapsed. The cabin attendant was not aware of a subsequent brief discussion between the pilots about the wisdom of using the rear slides in view of the aircraft's nose-down attitude. The commander decided that the priority was to get people out as soon as possible and that the rear slides should be used. The pilots were about to action the evacuation checklist when the forward cabin crew member spoke again by interphone to report that the forward door slide would not inflate. She was instructed to use all other available doors including the overwing exits. At about this time the fire crews were making their way towards the aircraft and the commander spoke to the passengers on the cabin address system instructing them to abandon the aircraft because the nosewheel had collapsed but that there was no fire risk.

There was no panic in the cabin. The forward cabin attendant made an announcement instructing the passengers to leave but several were seen fetching their belongings from the lockers. At this stage an off-duty pilot from the airline issued instructions to passengers to evacuate without their belongings and he removed one of the overwing exits. The other overwing exit was removed by a passenger.

A video taken by the fire service showed that more people evacuated from the overwing exits than from the rear exits. The rear slides were steep but they reached the ground. The rear cabin attendant and a fireman assisted people using the rear slides. One person was seriously injured when he jumped off the leading edge of the wing instead of sliding off the trailing edge and fractured both heel bones. Three other passengers were treated in situ for minor cuts and bruises.

Evacuation checklist

The order and content of the evacuation checklist were discussed with the aircraft manufacturer who agreed to make changes to the checklist to reflect the requirement to ensure that the propellers have stopped rotating before passengers evacuate. The manufacturer also agreed to add wing flaps to the checklist so that the flaps are lowered, if time permits, thereby assisting passengers to slide off the wing trailing edge. The appropriate revisions to the checklist are currently with the CAA awaiting approval.

Flight recorders

The aircraft was fitted with a Fairchild A100, 30 minute recycling Cockpit Voice Recorder (CVR) and a 25 hour Plessey PV1584 Digital Flight Data Recorder (DFDR) which were both replayed after the accident. The information recorded on the DFDR showed a normal approach with an indicated airspeed at touchdown of 97 kt. The pitch attitude at touchdown was 3.4° and this started to decrease as the nosewheels lowered onto the runway. Three seconds after mainwheel touchdown the data recorded became corrupted. The last sampled pitch attitude was 0.3°. No data was recovered during the subsequent landing roll. From the CVR, a loud vibration became audible around ten seconds after touchdown, this continued until the aircraft came to a stop 34 seconds after touchdown. Six seconds before the aircraft stopped the landing gear unsafe warning was audible on the recording.

The corruption of the data during the landing roll is due to tape speed fluctuations within the DFDR. This is not an uncommon problem on this type of recorder; there have been several cases where the data has been difficult to retrieve in high vibration or high 'g' loading situations. The loss of the data and the contact of the nosewheels with the runway seemingly occurred simultaneously. This suggests that there was some unusual vibration being transmitted through the airframe to the DFDR. There was no loss of data on the previous flight.

Nosewheel oscillation (shimmy)

Torsional oscillation of a nosewheel is effectively a feature which can occur on virtually any design employing a castoring system of mounting. It can manifest itself as a low-amplitude oscillation which the crew of an aircraft would sense as a vibration. In such cases, if judged worthy of comment, maintenance staff would check such things as tyre pressures or look for abnormal wear in bushes and bearings, all of which can have an influence on the susceptibility of any given installation to such an instability. Whilst, at the design stage, attempts are made to minimise any tendency towards torsional vibratory modes, in practice with steerable nose landing gears, some form of damping is required to suppress these modes. Called 'shimmy' damping, it is normal for aircraft with hydraulically-steered nosewheels to use this system to also provide damping against torsional oscillation.

Although such oscillations are commonly referred-to as 'shimmy', designers tend to reserve this term for the more potentially damaging modes in which the frequency of the forced oscillation approaches the natural frequency of the landing gear and mounting structure. In this mode, the vibration can become progressively more violent, usually varying with speed, until the forces required to react the oscillation become intolerable and some part of the system will break. Often, it is the torque link connecting the oleo to the barrel through which steering of the wheels is accomplished but, as it appears in this case, the aircraft structure itself can be compromised.

Description of the nose landing gear steering system

The nosewheels on ATP aircraft can be steered from the left crew position only using a tiller mounted on the left side console. Rotary movement of the tiller is transmitted by a shaft down into the nose landing gear bay where a quadrant on the end of the shaft transfers the motion to two short cables which run aft-and-across the roof of the bay via a pair of idler pulleys to a second quadrant. This latter quadrant transmits rotary motion (via a scissor linkage to accommodate gear retraction movement) to a shaft running down the back of the NLG leg to the steering control valve (Figure 1). The steering control valve ports hydraulic pressure, in response to pilot inputs, to either side of two steering jacks which move the wheels in the appropriate direction. During the design of the leg, it was a basic assumption that fluid would always be present in the steering jacks and steering control valves, even in the event of main hydraulic pressure failure, to provide shimmy damping through a restrictor as fluid circulated between the two jacks in response to forced oscillatory inputs from the wheels. If fluid was not present, hydraulic damping would also not be effective. To prevent fluid from bleeding away from the steering circuit, a compensator was fitted in the steering control valve return line to maintain a minimum 250 psi pressure in the circuit between the steering shut off valve and the compensator (Figure 3).

Pressure in the aircraft's single hydraulic system is not required for cruise flight and as a consequence the original design de-pressurises the system when the landing gear is Up and locked. Upon gear DOWN selection, the system is pressurised and pressure is ported to the extension/retraction system. As the NLG enters its downlock, a microswitch is closed to both inform the crew of this fact and to prepare the steering system for operation. Assuming the pilot has selected steering with the cockpit switch before the steering system is pressurised, a further microswitch mounted on the nose leg and operated by torque link movement (Figure 2), requires to be opened before the steering selector valve solenoid opens to port fluid into the system making normal steering available to the Captain. This 'weight-on-wheels' switch assembly utilises a standard microswitch body to which is added a purpose-made spring loaded plunger assembly and application-specific wiring loom (Figure 4). In this form it is allocated manufacturer's part number 201278-214 or 201049-246 (latest modification standard), depending on which of the two different lengths of nose oleo legs available on the ATP is applicable.

Description of the 'weight-on wheels' microswitch

The plunger, which bears down on the switch contacts as the oleo extends into the AIR mode, also has a second spring which provides overtravel protection of the plunger. Referring to Figure 4, it can be seen that initial movement of the plunger assembly causes the primary and secondary plungers to move together against the main spring compression. As the switch contacts are made, further downward movement of the main plunger causes the secondary plunger spring to compress, preventing damage to the switch assembly. The secondary plunger, which is made of mild steel, is retained within the main plunger by inserting it through the spring retainer and a brass washer, following which a 'head' is spin-formed on the end of the secondary plunger in a manner analogous to forming a rivet tail. Consideration of the mechanism thus formed will show that, if the spin-formed head was to fail, the secondary spring force will project the secondary plunger downwards against the switch contacts even though the main plunger is in the fully extended position, ie the switch will remain in the AIR condition even though the nose oleo is physically in the GROUND state. Hydraulic pressure will not be ported into the steering system.

The switch and plunger assembly, although not classed as an hermetically sealed unit, has several features intended to keep moisture from entering both the switch and plunger mechanisms. In particular the main plunger has ice-scraping and 'O'-ring seals where it enters the body of the assembly. The whole unit is assembled using potting and brazing techniques such that it can only be disassembled destructively. There is therefore no overhaul or inspection method available other than to measure contact resistance and verify correct operation and, prior to this accident, the assembly was classified as 'on-condition'.

On-site examination

The aircraft had come to rest with the NLG leg folded backwards underneath the fuselage, which was resting on the still-inflated nosewheel tyres. It was immediately apparent that this had occurred because the nose gear pintle mounting structure had torn out of the nose gear bay (Figure 1), pivoting the leg around the downlock mechanism. Examination of the runway marks showed that the nosewheel tyres had left a 'chevron' pattern over a length of some 250 metres before the collapse occurred (Figure 5). These marks were typical of that caused by torsional oscillation of the nose leg, with alternate excursions in excess of 30° to left and right. As the marks commenced, the aircraft diverged from the centreline to the right but it was returning to the left as the collapse occurred and thus remained on the paved surface. The propellers had not apparently touched the ground as there was no tip damage. Clearance was, however, minimal.

Metallurgical examination of the failed pintle mounting structure did not reveal any evidence of pre-existing damage and concluded that the failure of the various structural elements occurred due to pure overload with no direct indications of load cycling. No abnormalities were found in respect of excessive bearing or bush clearances, either on the NLG itself or the attachment structure. Tyre pressures were very similar and within the required limits. The NLG was remarkably little damaged and it was decided that it should be despatched to the manufacturer for testing in their nosewheel steering test rig, together with the other components of the steering system.

During examination of the aircraft itself, the two steering cables, transmitting rotary motion of the steering tiller to a quadrant located above the leg, had been found broken. These were removed and examined under a microscope which revealed that both cables were badly worn in the fractured area, one close to the final quadrant and the other associated with the pulleys located roughly in the middle of the cable run. This discovery led to an hypothesis that one or both cables had fractured prior-to or during the accident landing roll and may have precipitated the shimmy. It also led to the issue of BAe Alert Service Bulletin ATP-A32-90 requiring fleet-wide inspection of the cables.

Subsequent examination

At Messier-Dowty's facility, a survey confirmed that the NLG steering could be tested with replacement of a few crushed hydraulic pipes and re-attachment of the steering shut-off valve, which had become dislodged by the accident. The subsequent test revealed no significant anomalies but the test of the steering compensator showed that its leak rate was out-of-limits by a considerable margin. It should be noted that the above work did not involve testing the integrity of the air/ground microswitch mounted on the bottom of the oleo cylinder and actuated by compression or extension of the torque links. The significance of this will be discussed later.

Discussions were held with Messier-Dowty about the possible effects of steering cable breakage on torsional stability of the NLG, during which they advised that their original analysis had not taken this case into account. They embarked on an exercise to review the calculations but the subsequent analysis did not conclude a significant degradation of shimmy stability would result from steering cable failure.

Whilst the analysis progressed, Messier-Dowty carried out further strip and inspection of the NLG. It was during the course of this that it was discovered that the NLG steering air/ground sense microswitch Dowty P/No 201049-246 had apparently failed in the AIR sense. Failure in this manner would mean that no main hydraulic system pressure would be available to the steering system, even if the nosewheels were on the ground. The switch was despatched to the manfacturer's facility where x-ray photographs and a strip-inspection in the presence of AAIB, Messier-Dowty and British Aerospace confirmed that a fault condition was present. In essence, moisture contamination had led to serious local corrosion of the actuator secondary plunger (Figure 4) eventually causing failure of the spin-formed attachment such that secondary spring force, intended to accommodate the overtravel protection of the plunger, instead was pressing the plunger down onto the switch contacts.

The manufacturer was able to determine that the switch had been manufactured in 1993, and further interrogation of the technical records showed that it had been fitted to the accident NLG when it was last overhauled in January 1996. The NLG had been released to the operator in February/March 1996 and was fitted to G-MANG shortly afterwards. Since that time it had accumulated 2,995 landings in-service until the date of the accident.

Detailed examination of the switch and plunger assembly showed that the most probable cause of the moisture contamination was a damaged 'O' ring seal intended to prevent such ingress (Figure 5). This had probably been damaged during assembly of the plunger. Analysis of contaminant deposits within the plunger casing did not suggest that anything other than water had entered the assembly by this route.

The NLG strip inspection report from the manufacturer indicates that no other anomalies were found.

Previous occurrences of nosewheel oscillation.

As discussed earlier in this Bulletin, nosewheel oscillation can be experienced by the crew as anything from a relatively minor vibration to a rapidly divergent, and increasingly violent, oscillation which can damage the structure. Interrogation of the CAA's Mandatory Occurrence Report database showed several instances of severe vibration, two of which also involved reports of partial or full loss of nosewheel steering. The first of these was to an ATP operated by another UK operator which had 13 reports for 'nosewheel shimmy' and two for 'severe vibration' occurring over a period of about 7 months. The latter of these, dated 11 June 1997, resulted in a loss of steering to the right. Extensive troubleshooting failed to reveal a definite reason for the failure of the steering system, although it was postulated that a loss of supply pressure coupled with a leaking compensator was consistent with the sequence of events.

On 10 September 1997, another ATP operated by the same airline as G-MANG suffered severe vibration during the landing roll which started at 60 to 70 kt and "steadily worsened" although there was no reported damage to the nose landing gear or its structure. The pilot found that he had lost steering control and the aircraft had to be towed from the runway. A steering cable was found broken due to "excessive wear resulting from either long service or high tension". The operator's maintenance schedule was amended to include an 1,800 hour repeat detailed visual inspection of the cables but it appears that no analysis of the nosewheel oscillation phenomenon was carried out.

BAe drew attention to another nosewheel oscillation incident which, although it appeared on the CAA database, had not initially been recognised as such since the event was listed as 'Landing gear failed to extend'. On 15 May 1992, during a manufacturer's production flight test, an ATP suffered a major loss of hydraulic fluid which resulted in the crew having to use the emergency system to lower the landing gear. Although the aircraft landed safely, it experienced a violent nosewheel oscillation at about 50 kt which left identical marks on the runway to those observed during this investigation but did not result in structural damage. It appears that the subsequent investigation centred on the reason for the hydraulic fluid loss (a displaced 'O' ring seal in the right MLG retraction actuator damper) and that, as with the September 1997 incident described above, the significance of the nosewheel oscillation was overlooked.

Discussion

As previously stated, shimmy-damping on the ATP aircraft is achieved by hydraulic fluid circulating through restrictors to both sides of the steering motor. To ensure that fluid is available to perform this function, a compensator is incorporated in the circuit which should ensure that a minimum of 250 psi is maintained in the return line from the steering valve in the event of failure of the hydraulic supply. However some time ago, pre-dating this accident, it was recognised that this pressure could also bleed away through internal leakage in other components and Messier-Dowty drew-up a modification in 1996 to fit a non-return valve (NRV) to the steering valve pressure supply to prevent this. Compliance was 'Recommended-at next overhaul'. G-MANG did not have this modification which has not, until now, been covered by a BAe Service Bulletin to allow operators to opt for embodiment at other times. *However, as this AAIB Bulletin is being prepared, this modification is being withdrawn due to in-service problems (see 'Subsequent Airworthiness Actions' below).*

There now seems little doubt that shimmy in the strict sense of the word was responsible for the failure of the NLG mounting structure of G-MANG. There is some evidence (failure of the DFDR) that vibration was present early in the landing roll even though it was not reported by the crew but, as the aircraft slowed, the conditions for divergent shimmy approached and were met as the damping system hydraulic fluid became depleted. The pre-existing worn condition of the NLG steering cables would appear to be a feature which was exploited by the accident sequence rather than as a cause of the shimmy. The most likely cause was the failure of the air/ground microswitch to pressurise the steering system upon landing coupled with the leaking compensator was unable to maintain the minimum pressure and hence fluid in the damping circuit. It would appear that the crew's impression that they had steering control during most of the landing roll was probably incorrect: the failed microswitch would have completely disabled the system and, although it is impossible to say exactly when it failed, it most likely occurred upon nosewheel compression during the accident landing. That is the time at which tensile loads are experienced by the spin-formed end of the actuator plunger which resulted in it pulling through the bush and washer.

Subsequent airworthiness actions

There are several possible reasons why the steering system might not be pressurised by full system pressure upon landing or take off ranging from component failures, such as occurred here, to inadvertent crew de-selection. It is clearly unacceptable that such a relatively benign, and predictable, system failure can result in structural failure of the nose landing gear or its mounting structure.

The first action to be taken by British Aerospace was to issue Alert Service Bulletin (ASB) No. ATP-A32-90 calling-up an inspection of the NLG steering cables. Although classified as OPTIONAL, the ASB was HIGHLY RECOMMENDED by British Aerospace Regional Aircraft.

Following inspection of several ATP aircraft it was then found that, on certain aircraft, there was evidence of the NLG steering cables being misaligned with their quadrants and idler pulleys which was leading to abnormal wear. A design review found that this could occur effectively randomly on any aircraft due to variables such as build tolerances etc. A revised ASB, No ATP-32-91, was issued, this time with MANDATORY compliance, to repeatedly-inspect the cables and the pulleys for signs of wear and also introduced a life limitation on the steering cables.

During the course of the investigation of NLG steering cable wear, an anomaly came to light regarding the material specification of not only these cables, but potentially all cables used in aircraft made by this manufacturer. When it was first evolved from the HS748 aircraft, the ATP designers specified stainless steel control cables to overcome a corrosion problem on the former type, which used carbon steel. However, it soon became apparent that stainless steel forfeited fatigue life to gain this corrosion resistance and the decision was taken by BAe to return to carbon steel. The cable manufacturers were given a revised specification and a Service Bulletin, No ATP-27-27, dated 4 April 1990, was issued to enable operators to embody the change. Compliance was 'desirable' and it was suggested that it be embodied at the earliest opportunity. It was intended that all new cables supplied would be of the carbon steel type and, in time, the stainless steel cables would be phased-out of service.

However, the investigation of the steering cable wear problem showed that a number of cables ostensibly to post-modification 27-27 standard were actually found to be made of stainless steel, as had also been discovered during examination of a failed flap cable in July 1998. Investigation showed that the original MIL specification for cables had been superseded by a revised specification which required the user to specify composition A (carbon steel) or B (stainless steel). It appeared that BAe were unaware of the MIL specification change and, in the absence of instructions to adopt a particular material option, the supplier had unilaterally opted for composition B. BAe have since categorically informed their suppliers of the requirement to manufacture the cables from carbon steel but do not consider it necessary to campaign for removal of in-service stainless steel cables. Only carbon steel items will henceforth be supplied and in-service stainless steel cables should be phased-out on an attrition basis.

The above measures, as already stated, are not considered fundamental to the causes of the destructive shimmy experienced by G-MANG. The causal factors which were, are being addressed by Mandatory Service Bulletin (MSB) action notified to operators by an All Operators Message Dated 16 September 1998:-

1) All in-service NLG weight-on-wheels microswitches were to be replaced by 15 December 1998. Replacements are to be lifed at four years calendar time. If operators can show that the in-service units have achieved less than four years time, then replacement may be deferred until the stipulated four years is reached (MSB ATP-A-32-93).

2) The steering compensator was to receive a specially-devised on-aircraft serviceability check. This check specifies the acceptable leak rate for the unit to remain in-service for up to three months and an unacceptable rate above which the compensator must be replaced before further flight. The check was to be accomplished before 15 October 1998 and to be repeated every 4,000 landings (MSB ATP-A-32-94).

3) The Messier-Dowty and Dowty Hydraulics Service Bulletins covering fitment of the Non-Return Valve (NRV) to the Steering Control Valve (described above) were revised to allow operators the ability to achieve compliance by removing the Control Valve from the leg for embodiment of the modification. A mandatory BAe Service Bulletin, ATP-A-32-78, was raised to cover these vendor SB's. However, at the time of preparation of this AAIB Bulletin, an unforeseen problem has been encountered during towing on aircraft already modified to this standard and, as a

result, the MSB has been withdrawn and affected aircraft will be de-modified, pending resolution of the problem.

4) The existing BAe Service Bulletin, ATP-29-14, which covers "inhibition of the Hydraulic Pump off-load system" was re-issued as HIGHLY RECOMMENDED compliance. This should ensure that hydraulic system pressure is maintained throughout the flight. The reasoning behind this move is that, in cases where component internal leakage occurs upstream of the steering motor, fluid pressure in this unit will not bleed away to zero in-flight but instead remain 'topped-up' by the same leakage path.

5) Messier-Dowty are investigating whether a suitable hermetically-sealed microswitch with a fully stainless steel body can be used in place of the existing NLG weight-on-wheels microswitch assembly. This is to attempt to obviate the lifing requirement introduced by 1) above.

Escape slide performance

Reports of actions taken in respect of securing the forward escape slide during recovery of the aircraft prior to arrival of the AAIB team were conflicting. It was initially reported that the undeployed slide had been discharged either inadvertently or deliberately during recovery whilst still attached to the aircraft. Video evidence from the emergency services, however, shows pictures of the slide in both the undeployed and inflated condition remote from the aircraft. It is understood that it was originally found on the aircraft with its inflation lanyard pulled tight but insufficiently so to cause discharge of the inflation bottle. It must then have been removed from the aircraft in the undischarged state and subsequently discharged as a safety measure by pulling on the lanyard. It was noted that the manual inflation rip-cord did not appear to have been pulled.

With this type of escape slide, it is the weight and momentum of the inflation bottle, dropping under gravity, which discharges the bottle by pulling on the inflation lanyard attached between the girt bar and the operating head. On an ATP aircraft with a collapsed NLG, the drop-distance of the slide and bottle is insufficient to allow this to happen before hitting the ground. Studies by the manufacturer have indicated that shortening the lanyard will still not guarantee deployment in this attitude due to insufficient kinetic energy of the assembly. However, it would certainly appear that, had the cabin attendant pulled on the manual inflation rip-cord, the slide would have deployed.