Jetstream 31, G-LOVA

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Aircraft Type and Registration:	Jetstream 31, G-LOVA
No & Type of Engines:	2 Garret TPE 331-1OUR-513H turboshaft engines
Year of Manufacture:	1984
Date & Time (UTC):	30 June 1998 at 1212 hrs
Location:	London (Stansted) Airport
Type of Flight:	Public Transport
Persons on Board:	Crew - 2 - Passengers - 8
Injuries:	Crew - None - Passengers - None
Nature of Damage:	None
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	61 years
Commander's Flying Experience:	18,000 hours (of which 425 were on type)
	Last 90 days - 82 hours
	Last 28 days - 19 hours
Information Source:	AAIB Field Investigation

Circumstances

The aircraft and crew were planned to fly a non-scheduled passenger flight from London (Stansted) to Le Bourget, France. The forecast meteorological conditions for the departure were good and were accurately reflected in the ATIS broadcast at 1150 hrs which recorded: surface wind of 315°/08 kt, visibility greater than 10 km, present weather nil, cloud few at 2,400 feet, surface temperature of +16°C and QNH 1012 mb. Runway 23 was the runway in use which has an asphalt surface and an available take-off distance of 3,048 metres, the runway surface was dry.

The aircraft was fitted with a four channel Cockpit Voice Recorder (CVR) only, as allowed by the Air Navigation Order for Scale S(i) aircraft which requires either a CVR or a Flight Data Recorder.

Prior to the engine start at 12:02 hrs the aircraft was parked on the northern side of the runway, at the Business Aviation Terminal. The start was normal except that the left engine was slightly slow to accelerate. This was a known characteristic of this particular engine and was within the published limits. After receiving the ATC departure clearance the aircraft was cleared to taxi to the

Golf/Bravo holding position. During this taxi all engine parameters were normal as were the braking performance and the hydraulic indications. After a brief hold the aircraft was cleared to enter the runway for a short backtrack. The aircraft lined up on Runway 23, abeam the entrance to the rapid exit turn off at Hotel/Juliet, and was then cleared for take off at 12:12:30 hrs and passed the surface wind of 330°/12 kt.

A rolling take off was initiated using full power. All cockpit indications were normal with both the torques and RPMs at 100 % and both EGTs at approximately 610°C. The commander, in the left seat, was the handling pilot and initially he used the nosewheel steering to maintain the aircraft on the runway centreline; he later commented that minimal steering inputs were required to track the centreline accurately. At the 70 kt call he relinquished control of the nosewheel steering, placed his left hand on the control yoke and called "my stick"; these actions were subsequently verified by the first officer (FO). Analysis of the sound of the aircraft running over the runway centreline lighting at this point showed that the aircraft had achieved a ground speed of 73 kt. At approximately 80 kt a slight, low frequency vibration was noted by both pilots, however, it was of no particular significance and the commander later stated that he certainly did not consider aborting the take off. The aircraft then began to turn to the left at a rate that both pilots described as rapid. They later described the motion as being very similar to a simulated engine failure at a low speed although there was no perceived change in engine noise nor was there any cockpit indication or warning of an engine malfunction. Frequency analysis of the area microphone recording on the CVR showed no evidence of engine asymmetry.

As the aircraft yawed to the left the commander applied full right rudder and then right brake but could not contain the heading deviation. As the aircraft was about to leave the runway surface he closed both throttles and once on the grass he selected full reverse thrust on both engines: this symmetric selection of full reverse was verified by analysis of the CVR. The FO notified ATC that they were aborting the take off as the aircraft left the runway. As the aircraft slowed the commander reverted to use of the nosewheel steering and brought the aircraft to a halt on a heading roughly parallel to the runway heading and about 50 yards displaced from the runway edge.

The parking brake was applied and the commander commenced the emergency shutdown checks whilst the FO went back into the cabin to organise the passenger evacuation. However, just before the FO left his seat he reported smoke from the engine intake of the right engine. Another aircraft, who had seen the incident, reported to ATC that there was smoke from the left side of the aircraft. The commander shutdown both engines using the feather levers; these levers shut both the low pressure and high pressure fuel cocks, feather the propellers, shut the hydraulic cocks and inhibit the engine starting circuits. As the engines were winding down the commander saw flames in the intake of the right engine, he fired both right engine fire extinguishers and told the FO to get the passengers evacuated quickly. The passengers vacated the aircraft through the main door (left rear) without injury. Once the emergency shut down checks had been completed the crew also left the aircraft. The airfield fire services arrived on site promptly.

Runway marks

A clear set of tyre marks was present on the runway, beginning with a faint pair of nose tyre tracks which diverged to the left from the centre line. Some 50 m further on, marks from both the left and right main wheel tyres were apparent, as well as both nose tyres. The marks from the nose and right mainwheel tyres then became darker and more pronounced, with the right mainwheel track showing signs of anti-skid function. The initially curving track of the aircraft straightened briefly in this area, albeit still heading some 10° to the left of runway heading, before resuming its curved track to the left and departing the runway paved surface at angle of about 15° to left of runway heading. Once onto the grass, the aircraft continued briefly before starting to recover heading, coming finally to rest some 145 m from the point where it left the runway. The nose tyre marks remained separated throughout.

It was evident from the marks on the runway that the excursion was caused by a progressive uncommanded nosewheel steering offset to the left. (Had the nosewheel been castering freely, as it should have been at that stage, then no side forces would have been developed by the nose tyres, and no marks left by them on the tarmac). The correlation between the darkest and most clearly distinct nose tyre marks and the heavy right mainwheel marks, together with the brief straightening of the aircraft's track, is evidence that the pilot's efforts to correct the swing had some effect initially, the darker marks being the result of the developing *conflict* between the nose tyres (attempting to turn the aircraft left) and the right wheel braking and rudder (attempting to turn the aircraft right). The fact that the aircraft then started to curve to the left again, despite right wheel braking beyond the limit of the anti-skid threshold, suggested that the nosewheel steering angle had increased progressively throughout the event; however, it was apparent, from the separation between the nose tyres tracks, that the steering angle never became extreme.

Examination of the aircraft

There was no evidence of sooting or heat damage in the vicinity of either engine intake, or within either cowl. It is likely, therefore, that the brief indications of fire immediately after the incident were associated with a back-flow of gases through the engines, after shutdown, due to the wind.

Routine function checks of the brake system showed no abnormality, and the investigation into the cause of the runway excursion was concentrated on the nosewheel steering system.

Description of nosewheel steering system

The nose gear steering system is hydraulically actuated via a conventional linear actuator located on the nose gear housing, which pivots the nosewheels about the oelo axis in the conventional manner. The pilot's steering inputs are made using a tiller wheel located on the cockpit left-side control panel. These movements are transferred, via a chain and sprocket closed-loop system, to the input shaft of the steering control valve assembly.

The control valve assembly is mounted in the roof of the nosewheel bay, directly above the nose gear strut, on the steering pivot axis. It comprises a conventional hydraulic *spool* type control valve, which incorporates a mechanical linkage which *sums* the pilot's input and the steering-angle negative feedback signals, the latter derived mechanically from the top of the nose gear via a torque link which accommodates the changing orientation of the gear during retraction. The output from the summing link positions the control valve spool, which is of the conventional *bobbin* type. Although conventional so far as its principles of operation are concerned, the mechanical arrangement of the summing linkage is unusual.

The *summing* linkage senses relative rotational movements of the input and feedback elements, about the vertical axis. The mechanism, which is shown schematically in the diagrams at Figures 1a to 1d, comprises:-

1. An input shaft, at the top of the unit, driven by a chain sprocket-wheel connected to the pilot's control tiller.

2. A steering angle feedback shaft, at the bottom of the unit. The lower end of this shaft connects via the torque link (not shown in the diagram) to the top end of the nose gear strut, and rotates with the nose gear as the steering angle changes.
3. A yoke assembly, integral with the lower end of the input shaft, fitted with roller wheels at each end.
4. A *rocker* (also known as the *differential*), interposed between the *input* and *feedback* elements of the linkage. This is pivoted at its lower end on a cross pin, mounted on the upper end of the feedback shaft.

The outer rim of the rocker has cut-outs on opposite sides which accommodate the rollers of the yoke. One of these cut-outs is a close fit on its roller; the other is larger, providing a clearance between the sides of the cut-out and its associated roller. The lower part of the rocker has a large circumferential groove around its periphery. One end of the control valve input lever engages this groove, as shown in the diagram, such that *tilting* movement of the rocker on its cross-shaft moves the lever, and positions the control valve spool. The valve spool itself is lightly spring-centred to the null position. In addition, a pair of spring cartridges, each comprising a spring loaded plunger with pointed ends in contact with the underside of the rocker, provides a centering action which returns the rocker to the neutral position. These spring cartridges work in compression only, and therefore each cartridge controls the return to centre from one direction only. The extended length of each cartridge is governed by screw-stops, which must be adjusted accurately to give a specified (minimal) clearance between the spring plunger tips and the underside of the rocker, with the rocker in the centred (null) position.

In operation, the pilot's steering inputs turn the input shaft via the sprocket wheel, causing the yoke at its lower end to rotate and the roller to contact the side of the smaller cut-out in the rocker. Because the rocker is not free to rotate, the action of the roller pushing against the side of the cut-out causes the rocker to tilt about the cross-shaft. This tilting movement produces a corresponding movement of the lever engaged in the groove at the bottom of the rocker, which positions the valve spool to direct fluid to the appropriate side of the steering actuator. As the steering actuator responds and the nose leg turns, there is a corresponding follow-up rotation of the feedback shaft. Because the cross-shaft, upon which the rocker is pivoted, is mounted on the feedback shaft, the follow-up rotation of the feedback shaft produces a circumferential movement of the rocker cut-out relative to the roller on the input yoke; this reduces the tilt of the rocker. The angular differential displacement between *demanded* and *achieved* steering angles is thus converted into a corresponding linear displacement of the valve spool.

The maximum differential movement between the *input* and *feedback* elements of the mechanism is limited by the clearance between the larger cut-out in the rocker and the corresponding roller wheel on the input yoke. The circumferential groove on the rocker is wider around the *rear* half of its circumference, allowing the maximum differential (rocker to tilt within the limits of the larger cut-out) to be achieved without displacing the steering valve, whenever the nosewheels are turned beyond the normal steering range, eg during towing operations.

Investigation of the nosewheel steering system

The system displayed no visual evidence of damage, disconnections, or abnormality, and there was no slackness or stiffness in the closed loop system connecting the pilot's steering tiller to the control valve. However, significant wear was apparent in the bushes of the torque link which formed part of the feedback mechanism. The hydraulic system was pressurised, and the nosewheel steering system extensively exercised in an effort to replicate the malfunction, without any abnormal behaviour becoming apparent. Manual manipulation of the worn feedback linkage also failed to induce any response from the system. The steering actuator and control valve were therefore removed and taken to the manufacturer's facility where they were subject to detailed investigation under the AAIB supervision.

When removing the valve from the aircraft, some 3° of rotational slack was evident in the shear pin at the coupling which connected the lower end of the feedback torque link to the top of the nose leg.

An additional 3° of rotational slack was measured at the manufacturer's facility, due to wear in the various bushes of the torque link itself, giving a total of 6° of rotational slack in the feedback linkage connecting the top of the nose leg to the *bottom* of the control valve assembly.

Strip examination of the steering actuator revealed severe deterioration of the piston seals, but the unit was otherwise serviceable and nothing was found which could have caused the uncommanded actuator movement. The piston seals were of an early, fibrous, type.

Preparatory inspection of the control valve assembly revealed minor contamination of the *pressure* and *drain* filters with very small particles of what appeared to be rubber, and fibres; this contamination was judged acceptable for a unit removed from an in-service aircraft. The two filters in the pressure feed lines to the actuator were heavily contaminated with similar material, consistent with the degradation (described earlier) of the steering actuator piston seals. However, the filters had clearly been effective in preventing debris from reaching the valve cavity, and it was considered unlikely that contamination had caused the uncommanded actuator movements.

Function testing of the control valve operation on a hydraulic test bench showed that with the pilot's input disconnected, ie free, there was (correctly) no flow of fluid from the ports supplying the actuator. Manual manipulation of the sprocket wheel on the *input* side of the unit produced a normal response to steering demands to the right, with a flow being set up through the appropriate actuator feed ports; this steering demand cancelled correctly, evidenced by a cessation of fluid flow, when the sprocket wheel was released. When a manual steering demand to the left was applied at the sprocket wheel, the valve directed fluid to the correct port to supply the actuator. However, when the input was removed by releasing the sprocket wheel, the flow rate reduced substantially but did not stop completely, and a residual fluid flow continued to issue from the *steer left* actuator port. These actions were repeated a number of times, with similar results, and it was apparent that the control valve was failing to return cleanly to the null position after being displaced in the *steer left* direction. Further investigation showed that it was possible to re-centre the spool by manipulating the input manually. The torque at the input sprocket required to achieve a pressure of 1,500 psi at the valve output was measured and found to be 18 lbf in when the input was moved in a *turn to starboard* direction, and 5 lbf in when rotated in a *turn to port* direction; this compared with the test specification figure of 12 to 29 lbf in. Further experimentation showed that the malfunction was apparent to a greater extent when the unit was pressurised: with pressure removed, the valve spool was less prone to *stick*. A small dead band region was subsequently identified in the mechanical input to the valve, close to the null position on the *steer left* side.

The control valve assembly was dismantled, and evidence of wear was found at the pointed tips of the rocker return spring plungers, and at the corresponding contact areas on the underside of the rocker. This wear was more pronounced on the spring cartridge which returned to the rocker to the null position from a *steer left* direction, the resulting excess clearances preventing the rocker from centralising consistently following a displacement in the *steer left* sense. The affected areas were not lubricated, and fretting and wear products were clearly visible.

Examination of valve spool showed that it moved freely within its normal range of linear movement, but became very stiff when it was moved beyond its normal range due to a small accumulation of very fine sludge in the *dead* spaces of the valve cavity. No mechanical damage was apparent on either the spool itself or the bore of the cavity, and, after washing to clear any deposits, the spool moved freely through the length of the bore.

Cause of the uncommanded steering movement

The worn rocker return spring plunger would have created conditions in which the rocker could have retained a residual *steer left* offset following an initial displacement in the *steer left* direction. It was shown during testing that such small offsets of the rocker could overcome the very light centering spring of the valve spool, resulting in a small valve offset and associated fluid flow to the steering actuator. It would appear that a residual offset set in for some reason during the take off, and that this offset was effectively masked by the slack in the feedback linkage. As a consequence, the normal corrective action of the feedback mechanism was inhibited resulting in a progressive displacement of the nosewheels.

Whilst it was possible to induce a residual offset of the valve quite easily on the test rig, the condition did not manifest itself during the extensive testing carried out on the aircraft prior to removal of the valve; this despite inputs being made which were designed expressly to induce such a condition. It is not surprising, therefore that nothing abnormal was noted by the crew when they taxied out, or during the initial stages of the take off when the steering system was being actively used. It is likely, therefore, that some factor other than the pilot's control inputs triggered the fault condition in this instance.

It was apparent, both from the initial position of the nose tyre marks on the runway and from the CVR recording, that the aircraft was accurately tracking the centreline and that the nose wheels were *thumping* the runway centreline lights as it did so. Because of the twin nosewheel configuration, this would have generated a succession of torsional shock loads, about the steering axis, which would have been fed back up through the nose leg and into the steering feedback linkage. During the initial stages of the take off, the tiller was being actively used by the pilot to hold the aircraft straight and so the fault condition would have been unlikely to arise. However, after tiller release, the nose leg would have reverted to castering mode, and it is probable that the shock loads fed back to the control valve via the feedback link were sufficient to displace the valve spool slightly, into the *dead* band just to the left side of neutral, whilst remaining within the regime of slackness present in the feedback system. This is the most probable explanation for the progressive uncommanded *steer left* movement at the actuator. When the steering tiller was operated subsequently, these inputs would have swamped any residual offset, and thereafter the steering system was likely to have responded normally, as reported by the crew in this case.

Safety actions

Although the nose gear was a *lifed* component, the steering control valve assembly was an *on condition* item. It is mounted separately from both the nose gear and the steering actuator, and is physically awkward to remove; consequently, many of these items are likely be high time units. It was difficult to see any justification for making the steering control valve an *on-condition* item, since it is impossible to assess its condition without removal of the unit and inspection of internal components for wear and defects. Certainly, the design of the rocker return springs is such that the tips of the plungers, and the mating surfaces on the underside of the rocker, will be subject both to wear and fretting erosion over time.

Upon conclusion of the examination and testing of the valve from G-LOVA, very shortly after the accident, both the manufacturer of the aircraft and the valve manufacturer accepted that it was not appropriate for the control valve to have no fixed life. The risk of other in-service aircraft suffering a similar uncommanded excursion of the nose steering system, due to a combination of valve wear and slack in the feedback links, was also accepted and airworthiness measures were set in train both to address the immediate safety issues, and to revise the inspection period applicable to the nosewheel steering control valve. As a result of these actions, the following service bulletins were issued:

1. *Alert Mandatory Service Bulletin N° 32-A-JA980840* (original issue date 28 October 1998) introduced measures to inspect in situ for wear in the feedback and input linkages, with appropriate rectification actions.
2. *Service Bulletin N° 32-JA98084* (original issue date 28 October 1998) introduced a one time requirement for removal of the steering control valve and return to an approved agency for overhaul, and subsequent overhaul at 10,000 hrs intervals.

These service bulletins have been subject to subsequent review and amendment in light of ongoing experience, and revisions incorporated into to the maintenance schedule and appropriate manuals to bring these into line with the Service Bulletin requirements.

Although the worn actuator piston seals did not play any causal role in this incident, an existing Service Bulletin (32-JA900942) implementing revised piston seals has now been mandated in light of this investigation.