INCIDENT

Aircraft Type and Registration:	Jetstream 3202, G-BYRA	
No & Type of Engines:	2 Garrett TPE331 turboprop engines	
Year of Manufacture:	1989	
Date & Time (UTC):	10 January 2004 at 1930 hrs	
Location:	Near Farnborough, Hampshire	
Type of Flight:	Public Transport (Passenger)	
Persons on Board:	Crew - 3	Passengers - 17
Injuries:	Crew - None	Passengers - N/A
Nature of Damage:	Mechanical failure of the right engine propeller reduction gearbox	
Commander's Licence:	Airline Transport Pilot's Licence	
Commander's Age:	64 years	
Commander's Flying Experience:	30,000 hours (of which 2,000 were on type) Last 90 days - 97 hours Last 28 days - 50 hours	
Information Source:	AAIB Field Investigation	

Synopsis

The incident occurred during a charter flight from Southampton Airport to Manchester Airport. The aircraft was passing FL120 in the climb when there was a loud bang from the area of the right engine. High levels of vibration did not permit reading of the engine instruments and control of the aircraft was difficult due to unexpectedly strong tendencies to yaw and roll. The right engine was identified as not producing power and an emergency checklist shutdown carried out. After the right propeller feathered a single-engine diversion to Farnborough was safely accomplished.

History of the flight

The aircraft was carrying out a charter flight to take a private party of 17 passengers from Manchester Airport to Southampton Airport. The party was then to return to Manchester that evening on the same aircraft.

In order to undertake the charter the aircraft was positioned that morning from Leeds Bradford Airport by a flight crew of two pilots. The aircraft was not fitted with an autopilot (AP) but it had a serviceable yaw damper; the only unserviceable item was the left engine Single Red Line Computer (SRLC). The company procedure was for the co-pilot to carry out the pre-flight inspection whilst the aircraft commander completed the internal cabin and cockpit checks.

Having completed their preparations, the aircraft departed Leeds Bradford and, following an uneventful flight, arrived at Manchester. The flight crew met the cabin attendant who was to accompany them for the next two sectors on which the passengers were to be carried and, following a briefing, crew and passengers boarded the aircraft. Departure from Manchester was normal and an uneventful transit to Southampton was made at FL170 in good weather arriving at 1241 hrs.

Whilst the passengers attended their function, the crew rested at the airport. Prior to the scheduled departure time of 1845 hrs, they prepared the aircraft for the return flight to Manchester. The crew adopted the same procedure as before with the co-pilot carrying out the pre-flight inspection, which included checking the engine oil levels. The passengers were delayed arriving at the aircraft but as soon as they were boarded, the aircraft's engines were started. Both engines started normally and the aircraft was taxied for Runway 20. With the cabin secure and all checks completed, the aircraft departed Southampton at 1905 hrs.

The takeoff was carried out with the commander as the pilot flying (PF) and the co-pilot as the pilot non-flying (PNF). The PNF set the propeller RPM levers to 100% and the PF then set the engine torque to 100% on both engines. The right engine achieved 100% slightly before the left but both were matched at 100% torque. The aircraft accelerated normally with the PNF calling the airspeeds in accordance with normal company procedures. The commander followed the Standard Instrument Departure (SID) which required a climb to 2,000 feet with a right turn onto a track of 360º climbing to 4,000 feet. Landing gear and flaps were retracted and power and propeller RPM set for the climb. During the climb the aircraft passed through a layer of stratus cloud but no airframe icing was encountered; the engine anti icing system had been selected on prior to departure. The behaviour of the aircraft, including the rate of climb, all appeared normal. Radar control of the aircraft was passed from Solent Radar to the London Terminal Control Centre (LTCC) and the aircraft cleared to the requested cruising level of FL160 as they proceeded under their own navigation direct to NORRY (a virtual waypoint near Pangbourne) In the darkness, there was no clearly defined horizon or external references such as ground illumination or stars, and so the aircraft was being flown by sole reference to the flight instruments.

Immediately before the incident, the PF had both his hands on the control column and his feet on the floor. As the aircraft passed FL120, there was a loud bang from the area of the right engine.

Simultaneously, the red Central Annunciator Panel (CAP) warning light illuminated and the aircraft decelerated, yawing and rolling rapidly to the right. Some passengers saw a shower of sparks from the right engine, swept aft by the slipstream. The PF immediately placed both feet on the rudder pedals and attempted to oppose the yaw and roll to the right with large amounts of opposite rudder and aileron. The bang had been accompanied by a severe high frequency vibration which made reading the engine instruments very difficult, and confirmation of the right engine problem was not possible at that stage. With the IAS decaying rapidly, and the aircraft still yawing and rolling, in order to maintain control the PF reduced both engine power levers to idle and lowered the aircraft's nose to ensure a safe airspeed was maintained. The PNF was instructed to transmit a MAYDAY distress on the operating frequency informing them of the situation and to ask for radar vectors to the nearest airfield; this was acknowledged by London Control, who passed a heading of 080° to vector the aircraft towards London Heathrow Airport.

With the aircraft under control, but with the vibration still present, the pilot advanced each power lever individually to identify the vibrating powerplant and shortly after the failure the right engine OIL caption, right generator failure and bus tie lights illuminated. Having positively identified the right engine as the failed engine, the PF had his diagnosis confirmed by the PNF. The PNF completed the memory items of the "ENGINE FAILURE OR IN FLIGHT SHUTDOWN" emergency drill with the PF confirming the correct selection of operating controls prior to them being moved. Having placed the right power lever to idle and the left propeller RPM lever to 100%, the PNF turned and pulled the right engine propeller feathering lever and heard the distinct sound of the propeller feathering. He then visually confirmed that the propeller had stopped, and that the engine fuel cocks for the right engine had closed. The PF considered that this activity led to a loss of some 2,000 feet altitude before the aircraft levelled off. The aircraft was re-trimmed for the asymmetric condition using rudder and aileron trim.

The secondary checklist items were commenced with the PF monitoring the PNF actions. LTCC offered Farnborough Airport as a closer diversion which was accepted with a request from the PF to be vectored for an 8 mile final approach.

The cabin attendant who had been serving a light meal at the time of the engine failure moved to the flight deck. She was aware of the high level of activity being undertaken by the two pilots, and was careful to choose an appropriate moment to talk to the PNF. She was asked to brief the passengers of their intended diversion to Farnborough and she informed the flight crew that there had been some misty vapour and a smell of burning at the forward part of the cabin. All the passengers had their seat belts fastened at the time of the incident and although understandably alarmed by the incident, they were calm. The cabin attendant informed the passengers of the situation and secured the cabin for landing.

The PNF tried to complete the emergency drills but had to respond to ATC messages and make a written note of the Farnborough weather. He then extracted the Farnborough Approach charts from the Aerad book and set the ILS frequency and course bar for Runway 24 for both pilots. The approach minima were checked and the PF briefed for the approach. The PNF then completed the emergency checklist followed by the descent and approach checks. During this time the aircraft heading increased by some 90º, which, when noticed by the crew, was corrected although the PF was having difficulty in holding the heading. Air traffic control of the aircraft was transferred to Farnborough Approach, who requested which direction of turn the pilot would prefer. Left turns were requested, towards the live engine, which took the aircraft onto the ILS localiser. An accurate ILS approach was then flown, during which the landing gear and two stages of flap were lowered. The PF maintained a higher than normal approach speed at 150 kt, some 20 kt faster than the 130 kt required for the weight, and he first saw the runway lights at a height of about 400 feet. After touch down a lower than normal amount of reverse thrust was used on the live engine together with moderate wheel braking to bring the aircraft to a stop. The aircraft was then taxied to the allocated parking stand, attended by the airfield Rescue and Fire Fighting Service (RFFS), where the crew and passengers disembarked.

Weather

The synoptic situation at 1900 hrs showed a warm sector covering southern England with a light or moderate south-westerly flow over the initial part of the route from Southampton to Manchester. The surface weather was overcast with mist and some outbreaks of drizzle from extensive, low-altitude stratus cloud. The METAR's for Southampton and Farnborough airports covering the departure and landing were as follows:

Southampton: EGHI 101850Z 24007KT 5000 –RADZ SCT003 BKN004 11/09 Q1010=
Farnborough: EGLF 101920Z 22012KT 8000 DZ OVC005 11/11 Q1008=

Powerplant details

The engine involved was a Garrett TPE 331-12UHR-703H, built in 1989 as a model TPE331-12UAR-705H but modified and redesignated as a –12UHR-703H in July 1998. It was rated at 1,100 shaft horsepower (SHP) for takeoff, with a continuous rating of 1,050 SHP. The engine had been owned by the engine manufacturer from new, and had been used as a loan unit throughout its life.

At the time of the incident the engine had accumulated a total of 10,154 hours from new. It was installed on the right wing of G-BYRA on 25 November 2003, having accumulated 10,046 total hours. Previously, in December 2000, the engine had been removed from a sister aircraft of the operator's fleet and returned to the manufacturer's overhaul facility in Germany for inspection following a birdstrike. Between completion of the birdstrike inspection in January 2001 and its installation on G-BYRA in November 2003, it is understood to have remained in storage at the manufacturer's overhaul facility in Germany.

The engine's last overhaul was in April 2000, some 525 hours prior to the incident, at which time the reduction gearbox high-speed pinion, bull gear, and the sun gear forward bearing were replaced with new components. The engine logbook contained no entries of significance to the investigation. The records showed that the engine had been subject to spectrographic oil sample analyses (SOAP checks) at the intervals specified by the manufacturer to provide warning of impending gear failures. The SOAP trends showed no anomalies.

The engine was driving a Dowty Rotol variable pitch propeller.

Examination of right powerplant in situ

Oil was visible externally on the upper surface of the wing in the vicinity of the engine, and ground staff at Farnborough reported that oil could be seen dripping from the engine cowlings immediately after the aircraft had landed.

The propeller blades were fully feathered, but the propeller itself could not be turned beyond a very small amount, comparable to the backlash which would normally be expected in the splined coupling and second-stage reduction gears. It was apparent that the gearbox was effectively locked by some form of internal obstruction.

The engine cowls were intact but a large number of the cowl fasteners had loosened off, or were missing. Removal of the cowlings revealed widespread damage to ancillary components mounted on the engine, consistent with exposure to severe vibration. A detailed description of this damage is at Appendix A.

The engine/gearbox and propeller were removed from the wing in preparation for detailed strip examination, with no further damage being noted. In particular, the rubber engine mount blocks exhibited no signs of damage.

In summary, examination of the powerplant in situ suggested that a major failure of the input stage to the reduction gearbox had occurred, resulting in a severe vibration which lasted for a period sufficient to cause widespread secondary damage including disruption of fuel, oil, and electrical systems.

Engine and gearbox configuration

The Honeywell (Garrett) TPE 331 series powerplants comprise a range of single-shaft turbine engines which drive the propeller via an integral reduction gearbox, the casing of which also incorporates the engine intake duct. The gas generator comprises a two stage centrifugal compressor supplying air to a reverse (forward) flow annular combustor, which surrounds the three-stage axial turbine section. The combustion gasses are turned back through 180º at the inlet to the turbine section, and after passing through the turbine, discharge rearward into a conventional exhaust duct. The engine can be installed either erect (with the intake below the engine axis) or inverted (intake above). On the Jetstream, the engine is mounted inverted.

The –12 engine, as installed on G-BYRA, was introduced in 1988 as a development of the –11, providing an increased power margin for hot and high conditions. Although there are significant variations in the detailed design of components across the full range of the TPE 331 format, the –11 and 12 variants are, for all practical purposes, identical.

Figure 1 is a cut-away view of the TPE 331 series engine and gearbox of the type installed in G-BYRA. The 41,750 RPM rotational speed of the gas generator is reduced to 1,591 RPM at the propeller in two stages. The first stage reduction is achieved via a simple pair of straight-cut gears, comprising a high-speed (input) pinion mounted on the engine shaft driving a large bull gear. The second (epicyclic) stage reduction comprises a sun gear, formed integrally with the forward face of the bull gear, driving a set of planet gears which in turn drive the propeller shaft directly via a splined coupling to the planet gear carrier.

Figure 2 shows a schematic sectional view through the reduction gearbox. The input pinion (coloured dark blue) and bull gear (coloured red) are supported within a split aluminium housing within the gear casing known as the diaphragm; the two halves are manufactured as a matched set. The epicyclic second stage occupies the front half of the gear case cavity, formed by the nose casing. The ring gear of the epicyclic stage is anchored to the forward face of the diaphragm.

Negative torque sensing

Because the power absorbed by a windmilling powerplant could potentially result in very high drag being developed, and attendant aircraft control problems, a negative torque sensing (NTS) system is provided which automatically adjusts the propeller pitch to minimise drag in the event of power loss. It should be noted that the NTS system is a drag reduction system not a drag elimination system; it cannot drive the propeller into the feathered position. Feathering per se is achieved solely under the control of the pilot, by pulling the feathering handle to manually open the feathering valve. Until the propeller is feathered and as long as the propeller rotates, there will be some windmilling drag.

To accommodate the NTS system, the attachment of the epicyclic ring gear to the diaphragm incorporates a sloppy link, which permits a very small amount of rotational movement of the ring gear to occur in either direction, before coming up against a hard stop and reacting any torque being developed by the gear. The slight movement of the ring gear (within the sloppy link regime) arising from a negative torque condition moves a linkage which causes the NTS dump valve to close, creating an accompanying rise in NTS oil pressure. The increasing NTS pressure acts on an internal portion of the feather valve, opening a bleed path in the oil circuit to the propeller dome, and coarsening off the blade pitch toward the feather position. When a stage is reached where the propeller is no longer back-driving the engine and a positive torque is sensed by the torque sensing system, the change in torque produces an opposite movement of the ring gear within the sloppy link regime, causing the bleed path to close and allowing oil back into the propeller to reduce blade pitch. Thereafter, whilst the engine remains unable to drive the propeller normally, the torque tends to cycle between positive and negative as the NTS system endeavours to maintain the propeller in a minimum drag condition.

Detailed examination of the engine

Bulk teardown inspection

The engine was strip examined under the direction of the AAIB investigator at the manufacturer's plant in the USA.

Preliminary external inspection revealed evidence of additional external damage, over and above that detailed at Appendix A, consistent with heavy vibration comprising:

1. Deformation of the bearing plate on the accessory case which supports the hydraulic pump take-off shaft.
2. Partial loosening of the feathering valve housing at its attachment to the engine case.

Removal of the nose casing, with the propeller shaft in-situ, revealed that the epicyclic reduction stage was intact. The sun, planet, and ring gears displayed no overt signs of significant damage or deterioration, and the mechanism which provided the mechanical signal to the NTS system was undamaged. The crushed remains of a threaded bolt shank were found inside the nose casing together with a quantity of metallic shards, and numerous internal casing screws were also loose or missing.

When the diaphragm plate was split from the rear section of the gear case, it was evident that a major failure of the first stage gears had occurred, see Figure 3. The debris thus exposed included: broken pieces of gear tooth; crushed remains of various bolts and studs; fragments of the subsidiary housing which enclosed the input gears; and a large quantity of general debris.

A large segment of the bull gear rim, comprising approximately one third of the gear's circumference, had separated and burst out through the side of the subsidiary housing and had become jammed hard up against the starter generator shaft, fracturing and crushing the hollow shaft, see Figure 4.

Although debris restricted movement of the remaining part of the bull gear, a small range of movement was possible: sufficient to show that it was able to turn freely in its bearings.

Amongst the debris which fell clear during disassembly of the diaphragm were:

- A third, much smaller, fragment of bull gear rim encompassing four gear teeth.
- A small segment of the bull gear web, from a region adjoining the juncture of the fractures associated with the large and small rim segments.
- Pieces of shattered subsidiary housing, from where the large bull gear segment had broken through.
- Numerous miscellaneous fragments comprising broken and/or crushed remains of components originating from the input stage gear casing.

The subsidiary housing was removed from the diaphragm, allowing removal of the remaining part of the bull gear and the input (high speed) pinion. The input pinion was intact but all of the teeth had been stripped, leaving just the remains of the tooth roots, see Figure 5. The drive shaft had sheared from the pinion at the reduced section, which effectively formed a weak point shear neck.

Gear fracture details

Close inspection of the fractured pieces of bull gear revealed clear indications of fatigue consistent with propagation from an origin region in the web at approximately 60% radius. Figure 6 shows the fractured bull gear, with the principal separated fragments held in position to illustrate the fracture paths and position of the origin region, from which two primary crack fronts propagated, labelled 'A' and 'B' respectively.

The shorter of the two primary cracks ('A' in Figure 6) propagated radially outwards for a short distance until it met the thicker section of the rim, where it turned and ran circumferentially for a short distance before reverting back to a radial direction and intercepting the free edge of the wheel at the root of a tooth. The much larger primary crack ('B') propagated radially inwards initially, in opposition to crack 'A', then turned briefly in a circumferential direction (also away from crack 'A') before turning back inward again to follow an oblique path towards the centre of the wheel. As it approached the blend radius marking the transition from the web into the hub, the crack was deflected again and thereafter it followed an oblique path back outwards towards the rim of the wheel, where it intercepted the free edge at the root of a tooth. During the course of its progress, numerous secondary cracks branched off crack 'B' to form a network of fractures in the adjoining web. The consequence of this multiplicity of cracks was the separation and detachment of:

1. The large rim segment comprising approximately ⅓ of the wheel circumference, with vestigial web attached.
2. The small rim segment comprising four teeth.
3. Numerous fragments of the inner web from within the region of secondary cracking, identified in Figure 6, of which four pieces in total were eventually recovered and positively identified. (Figure 6 shows only the largest of the recovered pieces.)

Significant heat discolouration was evident in the region of secondary cracking around the hub blend radius, consistent with large-scale cyclic deformations of the material in these areas at a late stage in the fracture process, prior to rim separation.

Tooth condition

The condition of the teeth on the main section of the fractured bull gear varied progressively from completely stripped at 'X' in Figure 7 (adjacent to the large segment) through to a substantially undamaged state at 'Y' (adjacent to the small separated rim segment). This pattern of damage, together with the completely stripped condition of the high-speed pinion, was consistent with the main segment of the fractured bull gear attempting to re-mesh with the high-speed pinion following separation of the rim segments.

Metallurgical examination of the failed gear wheel

The fractured bull gear was subjected to detailed metallurgical examination at the manufacturer's materials laboratory. This confirmed the provisional assessment of crack propagation made during the teardown, and established that the fracture origins were on the aft face of the web approximately 3.7 inches from the rotational axis.

The failure characteristics were broadly comparable to those seen previously by the manufacturer during post-failure investigations of fractured bull gears from TPE 331 –11 and –12 series engines, extending over many years.

History of gearbox failures on TPE 331 series reduction gears

The –12 series bull gear is reportedly the most highly loaded of any gear in the Honeywell series of propulsion engines, and the bull gear itself and/or its associated components have suffered a number of failures since the type's introduction into service in 1983. Some of these failures resulted in the ejection of uncontained debris, either from the gear case directly or via the air intake duct. Of the latter, a number resulted in ejected debris being struck by the propeller and forcibly projected against the fuselage side, in one instance resulting in penetration into the cabin. The manufacturer identified imperfect tooth contact as being a significant causal, or contributory, factor in a majority of these failures, giving rise to:

- Load pulses in the bull gear which excited a resonance mode leading ultimately to the initiation of a fatigue crack in the web of the bull gear, and consequent separation of segments of rim.
- Initiation of fatigue cracks in the roots of the teeth, which propagated into the rim and web of the bull gear, resulting in separation of rim segments.

Factors previously identified as contributing, or potentially contributing, to contact pattern degradation included:

- Changes to manufacturing methods, which had tended to produce an involute profile with inadequate tip and/or root relief, leading to increased tooth loading (on an already very highly loaded gear).
- Distortion, over time, of the housings in the diaphragm plate which supports the bull gear and high-speed pinion bearings, resulting in displacement of the centres of rotation of the support bearings by as much as 0.006" from their correct positions; giving rise to associated tooth misalignment and increased wear.
- Re-dressing of gear teeth profiles during overhaul.
- Installation of gears in unmatched sets.

Remedial measures taken to date

In an effort to address the problem of bull gear system failures, the manufacturer implemented a number of remedial measures, with variable success, which are summarised together with their outcomes below.

Service Bulletin TPE331-A72-2011

A design change to the bull gear was introduced in 1997 via Service Bulletin (SB) TPE331-A72-2011, which comprised:

1. The introduction of a Metco spray coating on the web adjacent to the rim, intended to increase the damping inherent in the gear itself thereby reducing the potential for damaging amplitudes to occur within the various flexural modes of the gear.
2. Shot peening of the tooth roots, to locally increase resistance to fatigue initiation in those areas.

Testing of this revised design showed that it potentially cured the resonance and related fatigue initiation problems within the bull gear, but the manner in which the revised gear was introduced into service threw up a range of new, but related, failures affecting the high-speed pinion. Specifically:

- Production of the revised bull gear included reworks of the original pattern gear (P/N 3102585). Re-working of the gear teeth, a consequence of which tended to be a further reduction in the amount of involute tip/root relief.
- Mixing of existing (used) high speed pinions with reworked/new-manufacture revised pattern bull gears occurred, with consequent deleterious implications for tooth contact pattern.

The outcome was that whilst the revised bull gear was successful in reducing the incidence of resonance-induced failures and rim separations specifically, the (unhardened) splines on the high speed torque shaft, which transmitted torque from the engine to the high speed pinion, started to wear. As a consequence of this wear, high cycle fatigue cracks initiated in the non working splines which in turn led ultimately to failures of the high speed torque shaft.

Compared with bull gears which had been reworked from the original pattern to incorporate the changed design, those gears manufactured as new components to the revised design (allocated P/N 3108197) appeared relatively immune to these problems.

The issue of diaphragm distortion, and attendant alignment problems, remained unaddressed.

Service Bulletin TPE331-A72-2062

SB TPE331-A72-2062 was introduced in 1999 removing the Metco coating, on the assumption that in-service failures would return to a pattern similar to that associated with the original design of bull gear. The shot peen element of the revised design was retained, however.

The situation did indeed revert partially to the original failure pattern: all of the previously identified initiating factors were present including gears with re-worked teeth; gears installed on a mix and match basis; and diaphragm distortion. Moreover, without the damping provided by the Metco coating, resonance-induced failures returned, including some rim separations. Mostly the failures affected re-worked gears, but some new gears also failed; these were all associated with heavily deformed diaphragms, which the manufacturer estimated caused potential increases of up to 40% in the dynamic loading of the gear teeth.

The shot peening of the teeth, which had been retained from Service Bulletin TPE331-A72-2011, appeared to be effective in reducing crack initiations in the tooth roots; instead, failures were tending to originate in the web.

Diaphragm inspection & matched-pair gears

Revised interim measures were introduced in 2001 pending a complete redesign of the bull gear. These measures comprised:

1. Inspection of the diaphragm bearing housing positions to detect and reject housings which had suffered displacement beyond acceptable limits.
2. Introduction of matched-pair gear sets, incorporating:
    - Shot-peened tooth roots.
    - Improved tip relief.
    - Reduction in life to 3,500 hours (previously on condition).

Introduction of SOAP checks at 100 hr intervals

Because sub-optimal tooth contact patterns had been established as a factor contributing to the failures, and such tooth contacts invariably result in abnormal tooth wear, the manufacturer considered that monitoring the rate of accumulation of tooth wear-product in the lubricating oil could provide prior warning of impending failure. Accordingly, a requirement was introduced for regular spectrographic analysis of oil samples taken when the oil filter was changed. The interval between filter changes (and hence SOAP checks) was specified at 200 hrs when the requirement was first introduced in 1999, later reduced to 100 hr intervals in October 2001.

Re-designed gear sets

A permanent solution to the problem was sought through a total re-design of the high-speed pinion and the bull gear. The revised gear sets, which incorporate a helical tooth form, thicker web, thicker rim, and improved cooling, was implemented by SB TPE331-A72-2114 in August 2004.

Recorded data

Data sources

The aircraft was fitted with a 30 minute Fairchild A100A Cockpit Voice Recorder (CVR) and a 25 hour, 5 parameter Honeywell UFDR Flight Data Recorder (FDR). The CVR had been left running after the incident so did not yield any useful information. The FDR recorded altitude, normal acceleration, indicated air speed, heading and the VHF transmission key.

Other sources of recorded information included radar data, weather data and ATC recordings from five ATC centres including Southampton and Farnborough.

The radar provided track data from a point shortly before the failure event until shortly before touch down. The altitudes recorded were consistent with the FDR record, and provided a common reference allowing UTC time stamping of the FDR record. The radar track was also found to correlate well with the FDR heading and speed parameters. The weather data correlated approximately with the difference between radar-recorded ground speed and FDR-recorded indicated airspeed.

The quality of ATC data varied by source with some of the 60 second stamped periods taking 64 seconds to replay. The ATC data was correlated with the radar and FDR data by matching the VHF transmission key FDR parameter with the ATC recorded transmissions.

Interpretation of the data

At 1910 hrs UTC the aircraft started climbing out of Southampton Airport in a southerly direction before turning onto a northerly heading and starting its climb towards FL70 in accordance with ATC directions. This climb profile was maintained in accordance with ATC instructions through various ATC hand overs.

At 1920 hrs the aircraft was at FL120 climbing for FL140 and still heading north when the normal acceleration trace 'spiked' down to 0.28g and became very noisy, accompanied by a heading change to the right. These events, which were consistent with the sudden loss of thrust which was caused by the No 2 engine gearbox failure, were accompanied by a reduction in altitude of approximately 130 feet, followed by a brief recovery; then a reducing altitude once more. Thereafter, the 'noise' in the normal acceleration parameter remained for approximately two minutes before abruptly disappearing. During that time the right hand turn continued accompanied by reducing altitude. The turn continued for approximately one minute after the 'noise' in the normal acceleration trace ceased; after that the flight path was consistent with ATC instructions to descend and divert to Farnborough. During the period between the failure event and the aircraft reverting to follow ATC instructions for the descent into Farnborough, the aircraft had turned through approximately 180º from its heading at the time of the event.

An audio analysis was undertaken of those parts of the ATC tapes containing transmissions from the aircraft, in order to check for anomalies before, during or after the vibration period. However, the analysis was hampered by the variable quality of the recordings and the fact that the aircraft signal would have undergone a number of processes before finally being recorded. The ATC tape captured a configuration alert when the aircraft lined up with the Farnborough runway centre line but nothing further of significance was found.

Analysis

The gearbox failure

In light of the extensive prior history of bull gear failures and the program of implemented and planned activity by the manufacturer to address the issue, the focus of the technical investigation was directed primarily towards:

1. Establishing whether this failure exhibited features which suggested that new and previously unidentified causal factors might have come into play.
2. Studying the implications of the gear failure so far as they affected aircraft handling, and in particular the crew's ability to retain full control of the aircraft and subsequently to execute a safe landing.

The widespread damage within the gearbox was such that it was not possible to determine in every detail the sequence of failure, but it was clear that most of the damage was secondary and that it had been sustained as a direct consequence of a fatigue failure of the bull gear, which resulted in the release of large segments of the gear rim into the gear housing and adjacent rotating components. Detailed visual and metallurgical examination of the failed bull gear showed that its mode of failure fell within the ambit of the modes identified in previously studied instances of bull gear failure. There was little doubt too that the underlying causal factors associated with these previous failures would have been applicable to G-BYRA, such as uneven tooth wear causing increased tooth loading and the excitation of resonance modes leading to fatigue failure from origins in the web of the gear. Whilst the full range of contributory factors in this case could not be identified, due to secondary damage, these would have been likely to fall within the range of factors identified previously, and summarised earlier in this report.

Whilst the failure of the bull gear undoubtedly fell within the known pattern of crack propagation and rim separation, the consequences of the failure in this case was not typical insofar as it set in train a sequence of events which compounded significantly the problems faced by the crew in their efforts to deal with the resulting emergency. The following technical analysis will therefore focus primarily on the implications of the failure for the continued safety of the flight.

Flight safety implications

Whilst in the case of G-BYRA no debris was ejected through the gear case or from the engine intake, and consequently there was no direct risk to the occupants arising from potential penetrations of the fuselage by debris, the engine was subjected to extreme levels of vibration as a consequence of the gear failure which, indirectly, did hazard the aircraft. Specifically:

1. The level of vibration was such as to fracture, or compromise the integrity of, both fuel and oil supply lines together with proximate electrical systems, creating a potential fire hazard.
2. Substantial numbers of stiff-nuts and studs on the gear case itself, and on associated components mounted on the forward end of the engine casing, were vibrated off or otherwise compromised in a manner which suggested that, had the vibration persisted and the damage accumulated, it could have threatened the structural integrity of the gear case; with an attendant potential for the nose housing, and propeller, to separate from the aircraft.
3. The heavy vibration associated with the failure rendered critical flight deck instruments unreadable, adding to the difficulties faced by the flight crew in retaining control of the aircraft.

It is clear, therefore, that the vibration which followed as a direct consequence of the bull gear failure was an important factor in terms of flight safety, and both its cause and its effects require further analysis to determine its significance in terms of the continued safety of the flight.

Source of the vibration

If the bull gear had continued to rotate post-failure, whether driven from the engine or back-driven from the propeller, then the resulting rotational imbalance would have generated a high-frequency forced vibration of the whole engine installation, capable potentially of causing both the observed secondary damage and the vibration of the instrument panel on the flight deck. No other potential source of the vibration could be identified but for such a condition to have occurred, it would have required the bull gear to remain clear of obstruction.

Based on a visual assessment alone, it was not possible to determine with confidence whether the separated rim segment, which had burst through the side of the subsidiary housing and become jammed against the starter generator connecting shaft, would have obstructed the remaining part of the bull gear and thus prevented its rotation in the post-failure period.

In order to resolve this issue a simple 3-D CAD model was constructed of the detached rim segment, together with the remains of the fractured gear and relevant parts of the adjacent gearbox casing. After setting up the model to match the observed position of the jammed rim segment, (see Figure 8), it was evident that the combination of its radial position, and tilted orientation relative to the surviving part of the gear, was such that it would not have interfered. Consequently, it would have been possible for post failure rotation of the bull gear to have taken place, and thus for it to have been the source of the severe vibration, provided the drive line from the engine, or alternatively from the propeller shaft, had remained intact following gear fracture.

Based on the distribution of secondary damage within the gearbox, it is very unlikely that the engine would have been capable of driving the fractured bull gear. The stripped condition of the high-speed pinion is consistent with its forced re-engagement with the disrupted rim of the bull gear in the instant following separation of the detached section of the rim. This process is likely to have been virtually instantaneous – due to the rapid acceleration of the gas generator shaft in the interval between the shaft becoming unloaded, as the pinion disengaged momentarily from the fractured bull gear, before attempting to re-engage again as it came into contact with the far side of the missing section of rim. Indeed, the distribution of tooth damage on the bull gear indicates that all of the pinion's teeth were effectively wiped off within about half a revolution of the bull gear, and there is little doubt that the pinion coupling sheared at some point during this sequence. From that stage onwards the engine would have been disconnected from the gearbox input and, assuming that the fuel delivery side of the system was still operable, it would have accelerated rapidly until constrained by the overspeed governor. Continued operation of the engine, however, would not have been possible because of collateral damage from the gear failure, which disrupted the drive to the fuel control unit thus rendering the gas producer inoperative. In summary, therefore, it is evident that any post-fracture rotation of the bull gear, and the attendant vibration, must have been the result of it being back-driven by the propeller.

The FDR data provides further evidence in support of the contention that the severe vibration was associated with continued rotation of the propeller. Examination of the normal acceleration trace showed the onset of an apparently high frequency vibration, manifesting as noise on the data trace, at a point when other recorded parameters showed changes consistent with the gear-failure event. Because of the poor frequency response of the recording system, the true frequency and amplitude of this vibration could not be established and so it was not possible to educe its source from the frequency content of the recorded signal. However, not only does the vibration begin coincident with the gear failure but it also ends approximately two minutes later at about the time, based on the crew's testimony, when the propeller was feathered. Assuming that the noise on the FDR signal is indeed a reflection of the very heavy level of high-frequency vibration evidenced by the engine damage and the crew's account of unreadable flight deck instruments, then it was undoubtedly significant. Also, it appears to correlate with the period between gear failure and the propeller eventually being feathered – suggesting strongly that the vibration was associated with a windmilling right propeller. Furthermore, the mere fact of its detection by the aircraft's normal 'g' transducer (which is mounted in the fuselage and not sensitive to high-frequency vibrations) implies that the level of vibration at its source, significantly remote from the transducer, must have been severe indeed.

Normally, the NTS system will modulate blade pitch to minimise the drag caused by a windmilling propeller, but in this case the effective disconnection of the bull gear from the input pinion would have compromised the system's ability to function as intended and as flight tested. The drive train to the propeller governor arguably remained intact during the period that the propeller apparently continued to rotate post gear failure, and during this period it potentially would have had the capability to modulate propeller pitch in an effort to hold the selected propeller RPM. However, the governor's oil supply would potentially have been compromised at an early stage, because of the early failure of the input pinion from which the engine oil lubricating pump is driven, and the attendant cessation of a pumped supply of oil to the oil gallery feeding the governor. Whilst the behaviour of both the NTS and propeller governing systems under these abnormal conditions cannot be predicted with any degree of confidence, it is evident from the FDR traces and from the crew testimony that sufficient propeller pitch was maintained to cause the propeller to back-drive the broken bull gear, causing the severe vibration reported by the crew. It is also possible that, until the feathering valve was operated manually by the crew and the propeller actually achieved a feathered state, the compromised propeller pitch control system may have caused abnormal blade-pitch variations to occur, with attendant yawing moments being imposed on the aircraft.

Summary of findings arising out of the technical investigation

The failure of the bull gear system occurred as a result of a fatigue failure initiating in the web of the bull gear, which propagated on two fronts leading ultimately to the separation of a large segment of outer web and rim comprising approximately one-third of the gear's circumference. In terms of both its overall characteristics and underlying causal factors, the failure fell within the ambit of previous failures which have been studied in detail by the manufacturer and addressed by a series of remedial measures, culminating in a total redesign of the bull gear and related components, implemented under SB TPE331-A72-2114 in August 2004.

Following the gearbox failure and associated disconnection of the engine input, the fractured bull gear was back-driven at speed by the windmilling propeller for approximately two minutes before the crew was able to identify the source of the problem and feather the No 2 propeller. During this period, the resulting rotational imbalance caused a severe vibration which resulted in extensive and potentially hazardous secondary damage to oil, fuel, and electrical components mounted on the engine, and to the gearbox casing. The vibration also: rendered the flight deck instruments unreadable, seriously compromising the crew's ability to identify which powerplant was affected and frustrated their efforts to deal with the emergency. Any oscillations in propeller pitch which may have occurred during this period, due to abnormal operation of the NTS and/or propeller governor systems, could have given rise to oscillatory yawing moments producing an associated dutch-roll like motion of the kind reported by the crew. This would not only have added to their control problems, but also made it more difficult for them to identify promptly which powerplant was malfunctioning.

Handling of the emergency

At the time of the gearbox failure, the aircraft was in the climb on a heading 360º, with the yaw damper engaged. The loss of power from the right engine would have caused the aircraft to yaw to the right with an associated roll to the right. The yaw damper will disengage when the rate of roll exceeds 7º sec or at bank angles greater than 45º; consequently it is not likely to have made any significant contribution to the crew's efforts to retain control of the aircraft.

Illumination of the oil pressure, generator fail and bus tie warning lights was indicative of the engine having stopped and not just run down to idle yet the pilot experienced great difficulty, not only in correcting the departures, but also in preventing himself from over-controlling as if the aircraft yaw to the right was not constant but varying as if power was fluctuating. For reasons discussed earlier in the technical analysis, the yawing and rolling oscillations are likely to have been caused by fluctuations in blade pitch on the right propeller associated with either the governor's attempts to control the RPM on the disconnected and windmilling propeller, or erratic intervention of the NTS system. This is not a condition which would normally accompany a loss of thrust engine failure and it would have presented significant handling difficulties, both directly and indirectly by masking the underlying problem, thus compromising the crew's ability to take appropriate corrective action.

With no external horizon, all flight was by sole reference to instruments, which were being shaken by the severe vibration. It was not possible to read the engine instruments and in order to try and stabilise the aircraft the pilot brought back to the idle position the two engine power levers. His plan was to accept a loss of altitude whilst maintaining a safe IAS in order to maintain control of the aircraft and give him and the PNF time to properly analyse the situation. However, whilst this was an entirely appropriate action in the circumstances, and one that would have reduced the steady-state component of the thrust asymmetry, it would not have eliminated any yawing oscillations associated with blade-pitch oscillations of the right propeller. As the instruments were still not readable, but being aware that some form of engine problem was present, the PF advanced each engine power lever in turn and, on finding a positive power increase on the left and none on the right, confirmed the right engine was malfunctioning. The shut down and feathering drills were then accomplished using the abnormal checklist, and once the right propeller was feathered the vibration ceased and the pilot was able to continue the flight using the left engine with the flight controls trimmed for the asymmetric condition. By the time that this process was complete and the crew were in a position to begin their recovery to Farnborough, some three minutes after the initial failure event, the aircraft had gently turned through 180º; this was probably due to a break-down in instrument scan, due to the concentration required to maintain wings level and to maintain the desired IAS attitude.

The increase in the approach speed of 20 kt was to ensure that in the event of a go-around and any re-emergence of handling difficulties, an increased safety margin above V_{MCA} was available. The increase still permitted a safe landing to be made in the landing distance available.

Conclusion

This serious incident was the result of a major failure of the propeller gearbox which led to the aircraft yawing and rolling to the right and left. The crew were unable easily to identify the nature of the problem but with some difficulty they maintained control of the aircraft. Through a process of elimination, the crew correctly identified the right powerplant as the source of the problem. When the engine was shut down and the propeller feathered, the aircraft's handling qualities were restored to normal single-engine flight.

Safety action

The technical analysis has shown that the gear failure on G-BYRA fitted a pattern of failure already identified by the manufacturer as a result of its investigations of previous gear failures. The factors contributing to the failure on G-BYRA also fell within the ambit of factors identified previously as having contributed to these earlier failures, which have themselves been the subject of a range of remedial measures already implemented by the engine manufacturer. The culmination of these actions by the engine manufacturer, comprising the introduction in August 2004 (via SB TPE331-A72-2114) of a completely redesigned bull gear assembly, renders moot any recommendations arising out of this investigation which might otherwise have been made.

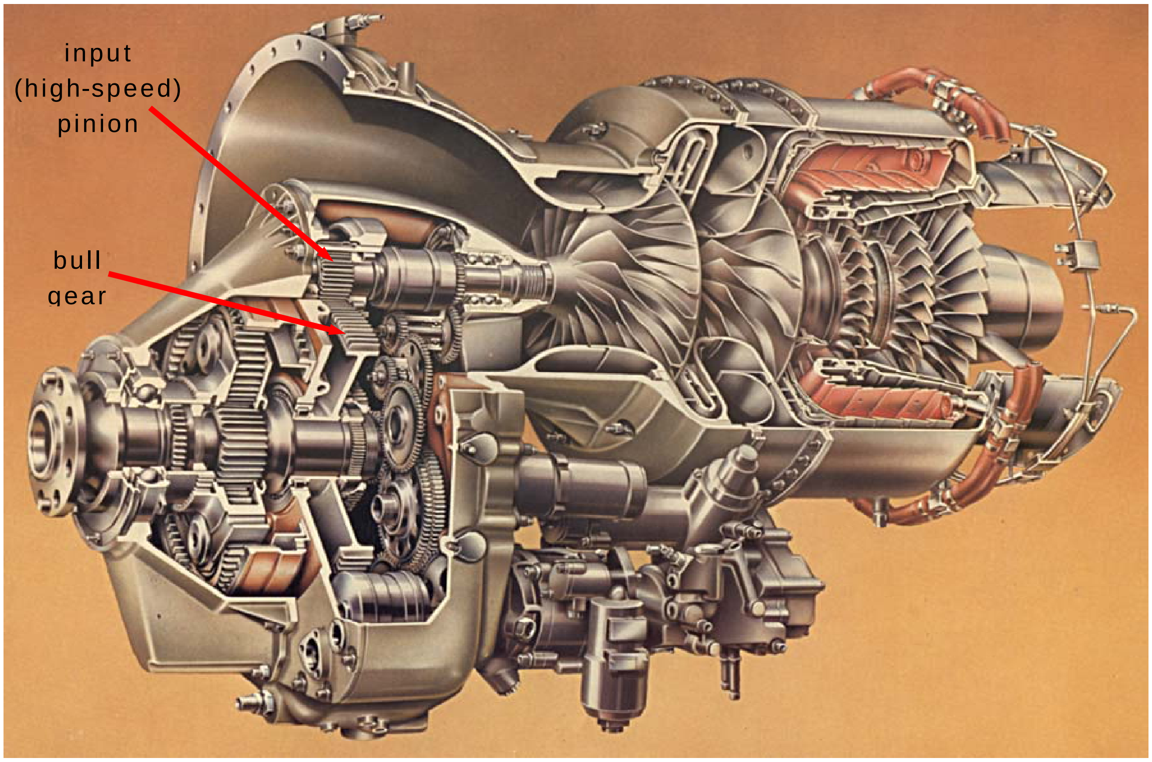

Figure 1:
Configuration of TPE 331 engine as installed on the Jetstream

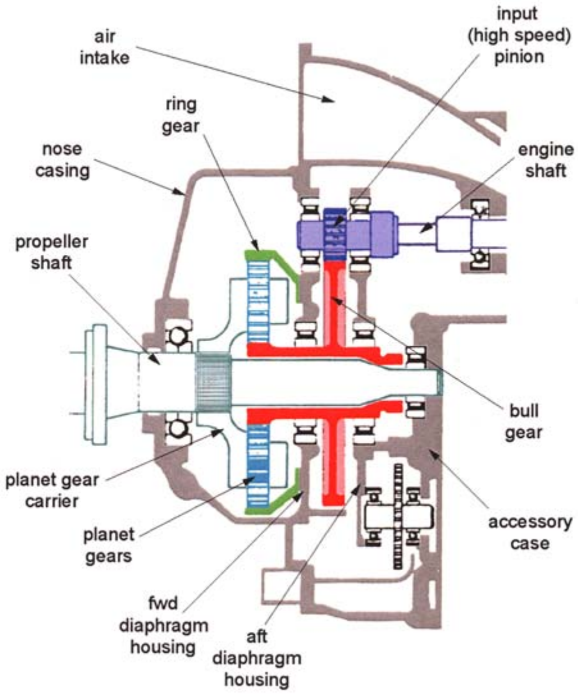

Figure 2:
Sectional view through gearbox (schematic)

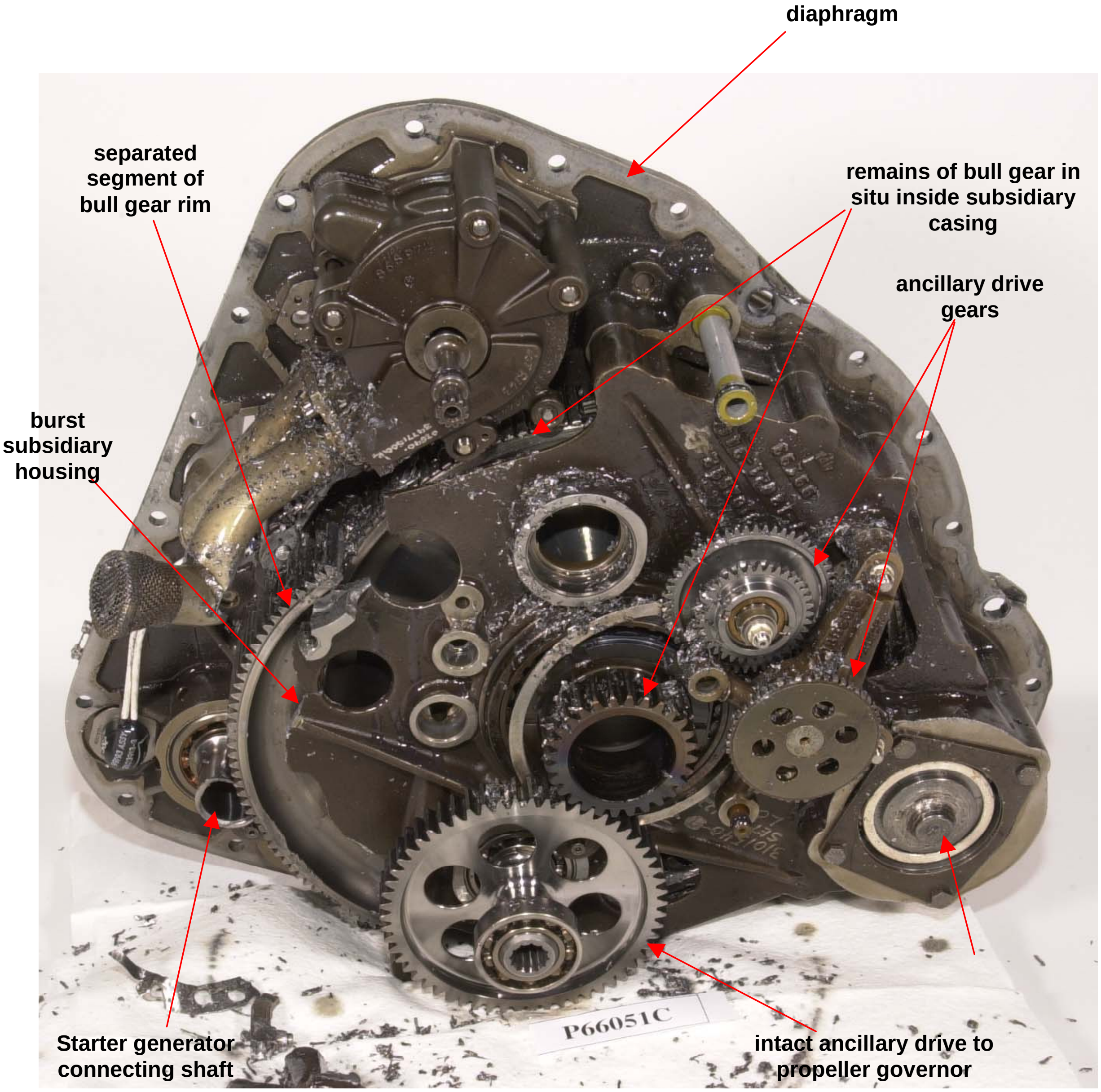

Figure 3:
View onto aft face of diaphragm, with damaged components in situ

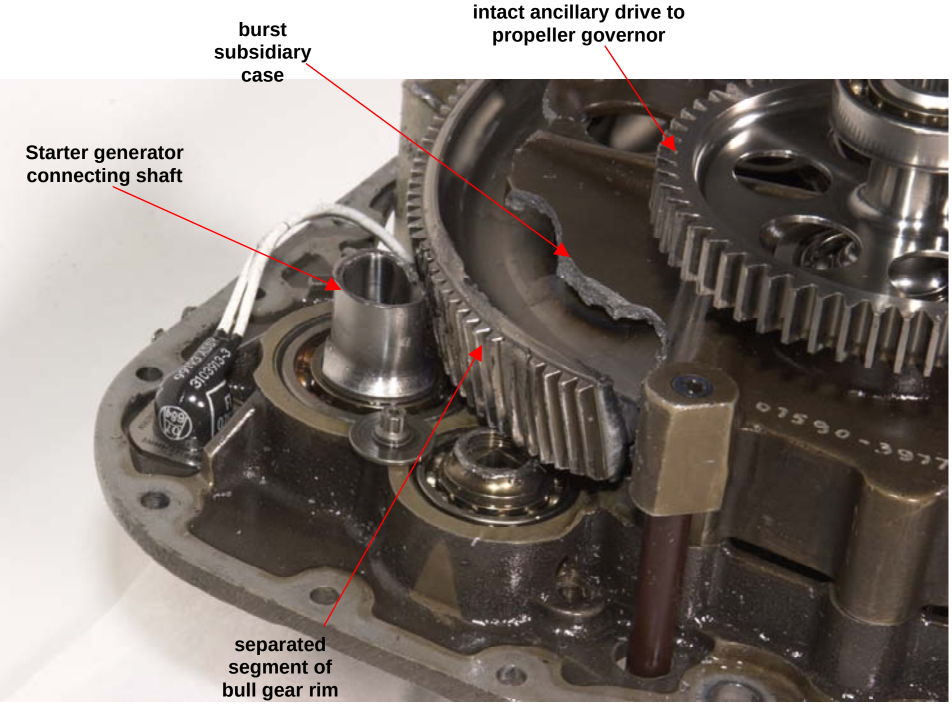

Figure 4:
Detail of separated segment of bull bear

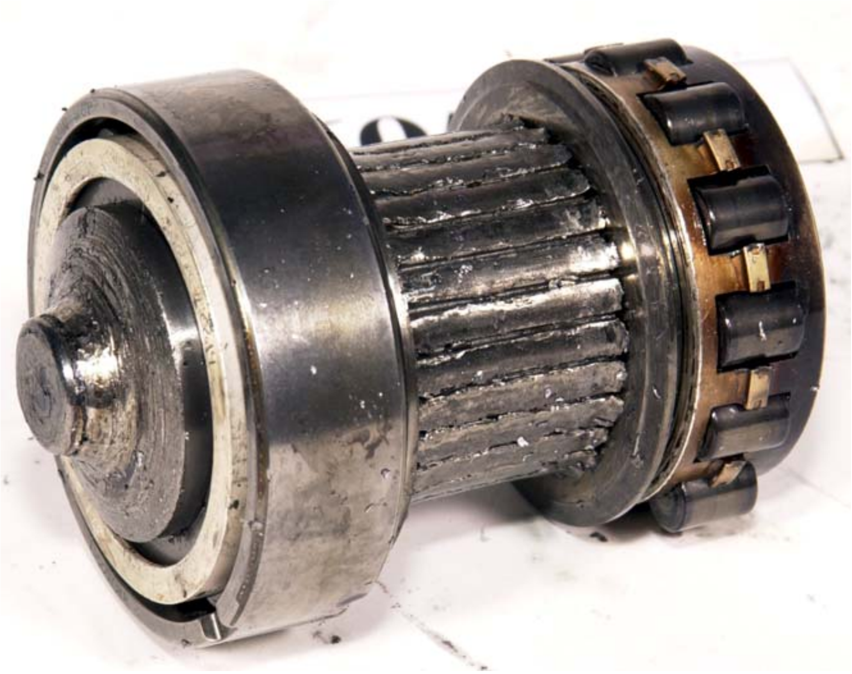

Figure 5
Input (high speed) pinion, showing sheared drive neck

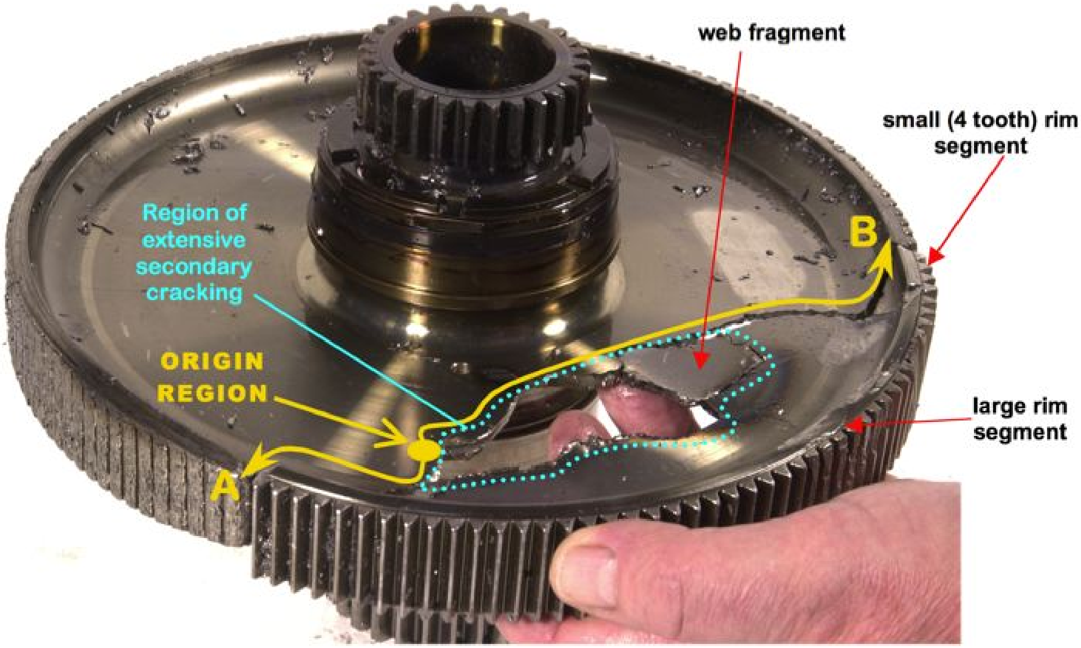

Figure 6
Fractured bull gear, showing principal fracture paths

Figure 7
Pattern of post-fracture tooth damage

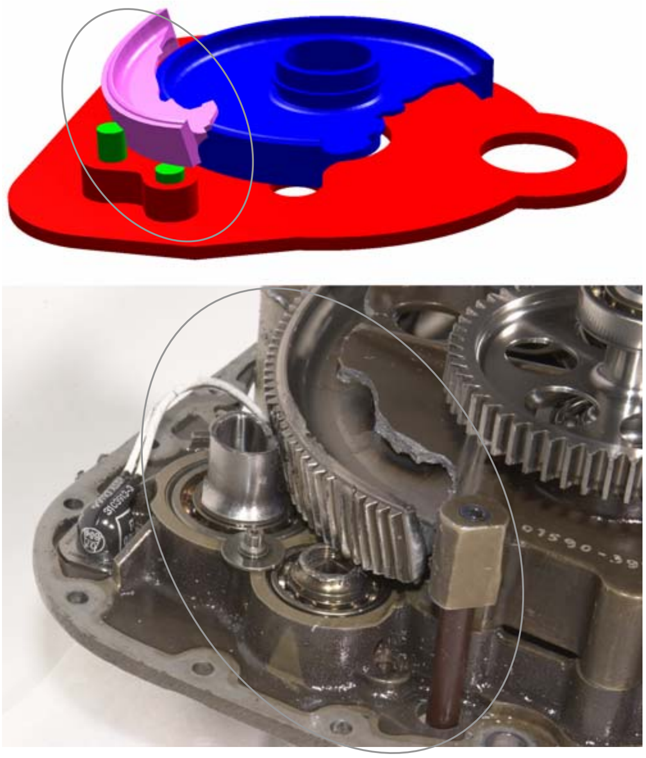

Figure 8:
CAD model showing relative positions of separated rim segment and remains of bull gear

DETAILED DESCRIPTION OF ENGINE DAMAGE

1. Fracture and break-up of the mounting brackets supporting the igniter control box, leaving the box loose and supported only its connecting cables.
2. Fracture of the air-bleed pipe supplying the intake de-icer, at a point adjacent to the off-take boss on the compressor case, together with cracking of the boss itself.
3. Loosening and separation of a 'B nut' securing a main lubrication pipe to a 'T' connector on the right side of the engine, just below the fractured air-bleed pipe.
4. Fracture of the main fuel feed pipe adjacent to its connection to the fuel flow transducer.
5. Loosening of the fuel flow transducer body in its mounting clamp, and partial migration of the unit out of the clamp.
6. Numerous loose and missing stiff-nuts, studs, and bolts securing the gearbox nose-cone to the diaphragm plate, and the diaphragm plate to the main gear case.
7. Several fractured studs and missing nuts on the fuel control housing, primarily at a flanged joint between the inner and outer ends of the housing immediately aft the unit's fixture to the accessories case, resulting in springing of the affected joint and partial expulsion of the associated O ring seal.
8. Deformation of the firewall ring-seal diaphragm at the jet pipe connection, consistent with violent oscillation of the entire powerplant on its rubber mounts.
9. Fracture of studs attaching the fuel-cooled oil cooler to the gearbox case.
10. Fracture of the shear neck coupling to the starter generator, and deformation of the associated transfer shaft bearing-retainer in the accessory case.

The engine oil tank was empty. Significant quantities of metallic shards were present in the oil filter housing, but its impending bypass tell-tale button was in its normal (flush) position.

There was no evidence of fire or elevated temperatures anywhere within the engine nacelle.

A visual inspection of the turbine via the jet pipe revealed that the pair of studs securing the turbine rear bearing cover had fractured, and the cover plate was missing. The turbine itself appeared to be intact but slight metal spatter was visible on the final-stage guide vanes. Manual rotation of the turbine was possible, and produced comparable rotation of the compressor confirming that the main shaft was intact between the compressor and the turbine sections; however, substantial roughness was apparent in the bearings. Examination of the compressor face, via the inlet duct, showed that the first stage impeller was intact but there was evidence of severe tip rubbing which, together with the roughness of rotation, was indicative of front bearing failure. With the exception of the missing rear bearing cover, there was no evidence of separation or non-containment of the engine core.