Aircraft Type and Registration:	Robinson R44 Raven I, G-OUEL
No & Type of Engines:	1 Textron Lycoming O-540-F1B5 piston engine
Year of Manufacture:	2002
Date & Time (UTC):	30 July 2003 at 1004 hrs
Location:	Carlenrig, Teviothead, near Hawick, Scotland
Type of Flight:	Private
Persons on Board:	Crew - 1 Passengers - None
Injuries:	Crew - 1 (Fatal) Passengers - N/A
Nature of Damage:	Helicopter destroyed
Commander's Licence:	Private Pilot's Licence
Commander's Age:	41 years
Commander's Flying Experience:	96 hours - (of which 20 were on type) Last 90 days - 6 hours Last 28 days - 4 hours
Information Source:	AAIB Field Investigation

Synopsis

The helicopter departed on a VFR flight from a private site near Hawick in Scotland to route to Barton Airfield in Manchester. Initially it flew southwards at 1,500 feet amsl but as it approached hills, whose tops were reportedly covered by an area of low cloud, it turned away from the planned route and probably entered cloud. As the turn continued the helicopter accelerated, entered a rapid descent and the main rotor blades struck the tailboom. Most of the tailboom detached, the rotors virtually stopped and the helicopter impacted the ground at the bottom of a valley, fatally injuring the pilot.

A number of military aircraft were operating in the area at the time of the accident but none of these could have influenced the safe progress of the flight. No signs of pre-accident malfunction of the helicopter were found, but full determination of its pre-impact serviceability was prevented by extensive post-crash fire damage. The available evidence indicated that the accident followed a main rotor blade strike on the tailboom, probably caused by excessively low rotor RPM. The control loss and low rotor RPM may have resulted from spatial disorientation and mishandling of the controls but the possibility that aircraft malfunction had contributed to the accident could not be eliminated.

History of the flight

On Sunday 27 July 2003 the pilot, accompanied by an instructor, carried out a short local flight in G-OUEL from Wycombe Air Park (Booker) and the next day he flew solo from Wycombe to a private site 3 nm north-east of Hawick, Scotland, to visit friends. He planned to return to Wycombe, via Barton Airfield, on the outskirts of Manchester, two days later. He told a friend that he had 'an enjoyable flight to Hawick' and that his only problem was preventing the helicopter 'wobbling' when he attempted to fold his map.

On Tuesday 29 July, when the weather improved in the evening, the pilot carried out three short flights in the Hawick local area. The first was to refuel from a trailer bowser located at a farm strip at Midlem. The second was his return flight back to the private site. The third flight was 'a gentle 12 minute sight-seeing trip, with no steep turns or abrupt manoeuvres', carrying three friends around the local area. The pilot subsequently spent a quiet social evening with his friends before retiring to bed at about 2200 hrs.

On Wednesday morning, the day he had planned to return to Wycombe, the weather was poor with low cloud and drizzle. The pilot rose at about 0630 hrs and watched the weather report on the television. He decided to take a western route via Carlisle once the weather improved and eventually departed the site at 0956 hrs. (Note: times quoted in this report are UTC/GMT, one hour different from UK Summer Time.)

The helicopter was fitted with a Global Positioning System (GPS) navigation system that recorded the time, position, groundspeed, track and GPS altitude every 30 seconds during the flight. The GPS recorded data was downloaded at the AAIB and converted to heights above mean sea level (amsl) and Ordnance Survey Grid; the last part of the route is shown at Figure 1.

The recorded data showed that G-OUEL passed down the western edge of Hawick and followed the general line of the A7 road at a ground speed of between 107 kt and 116 kt until it reached Teviothead (8 nm south-west of Hawick) around 6 minutes after takeoff. The average GPS altitude up to this point was approximately 1,500 feet (approximately 1,000 feet agl).

GPS altitude can be subject to substantial error but the recorded values suggested that for much of the flight, where the aircraft had apparently been flown approximately level, the GPS altitude had been accurate to within ±100 feet. The possible error in the recorded altitude could have increased somewhat when the aircraft was in a banked turn, as a result of antenna shielding effects, but it was judged unlikely that there would have been a major increase. The GPS used was designed to provide highly accurate groundspeed and track and it is likely that the errors in horizontal position would have been less than the altitude errors. The timings and routing were confirmed by a small number of witnesses who had either heard or seen the helicopter.

The GPS data showed that approximately 1 nm south of Teviothead, where the A7 road turns south, the aircraft's ground speed reduced to 98 kt. Over the next 30 seconds the aircraft climbed from around 1,500 feet to 2,400 feet; an average rate of climb of 1,800 feet per minute. In this time it turned right through 32° and the ground speed reduced to 50 kt. Over the next 30 seconds the GPS altitude increased approximately 200 feet to about 2,600 feet, the right turn continued through a further 83° and the ground speed increased to 86 kt. At the final data point, timed at 1004 hrs, the GPS altitude had decreased about 150 feet to approximately 2,450 feet, the right turn had continued through a further 130° and the ground speed had increased to 120 kt. No further data points were recorded.

Recorded radar data showed one possible contact for G-OUEL, timed at 1004 hrs and located close to the accident site, but no further contacts showing its flight path. The absence of radar returns was consistent with local terrain masking the helicopter at its relatively low level. There were no eye witnesses to the final minutes of the helicopter's flight and no witnesses saw the accident take place. Several people however, heard the helicopter. Witnesses, at a farm 1,200 metres north-east of the accident site, clearly heard the engine sound from G-OUEL as it passed low overhead. One of these witnesses heard the continuous sound of the engine suddenly stop with a bang, which she likened to a rifle shot. A person, driving south along the A7 road, saw smoke and flames rising from the accident site some distance away, but they did not see the events immediately before and thought it was a bonfire.

The wreckage of the helicopter was discovered later in the day by a local farmer. The helicopter had been destroyed and the pilot had received fatal injuries.

Other air traffic

Witnesses

A number of witnesses saw or heard helicopters and jet aircraft in the area on the day of the accident. Two witnesses, a farmer and his son, were in the cab of their tractor 2,500 metres north-east of the accident site. The son reported seeing a fast-jet fly low along Carlenrig Ridge, a ridge forming the northwest side of the valley above the accident site. He described it descending into the valley near Teviothead and following the A7 towards Hawick. The time was estimated by both to be around 1000 hrs. Shortly after this the farmer noticed light grey smoke rising vertically from the approximate area of the accident site. An estimated forty five minutes later (1045 hrs) they saw a second fast-jet fly the same route. This was followed, some ten minutes later, by a Chinook helicopter. The farmer's son could not identify the type of fast-jet aircraft and neither he nor his father could be certain of the time of their observations.

Military activity

The Ministry of Defence (MoD) provided information on the military flying activity taking place in the vicinity of the accident site for the relevant time. Planned training flights had either re-routed or abandoned low flying that day due to low cloud. Radar data, recorded from Scottish Radar at Prestwick, showed the progress of a Chinook helicopter along the A7 road 10 minutes after G-OUEL. The Chinook was transiting from Lossiemouth, near Inverness, to a military training area 20 nm south of Hawick. Twice during the flight the helicopter had been forced to climb due to low cloud. It had descended to low level in VMC north of Hawick and reached a position approaching Teviothead along the line of the A7; the same routing taken by G-OUEL. Due to low cloud to the south, towards Langholm, the helicopter commander elected to route further to the west and therefore passed north of the accident site along the adjacent valley. He did not see the accident site or smoke rising from the wreckage.

Two fast-jets were booked into the Low Flying Area (LFA) encompassing the accident site. While tracking north-bound along the A7 they were forced by bad weather to abandon their low level flight in the vicinity of Hawick. Their approved time of entry into the LFA was 1030 hrs and, although the exact time at which they passed the accident site could not be determined, the aircraft had to negotiate bad weather and were delayed on their intended flight plan. They did not enter the low flying area until after 1030 hrs.

The radar recorded only one primary radar return in the vicinity of the accident site, at 1004 hrs. This was probably G-OUEL as it reached the highest point of its climb.

Weather

Aftercast

An aftercast obtained from the Meteorological Office showed the synoptic situation at 0600 hrs on the day of the accident as an area of low pressure centred just east of Middlesborough, with an occluded front lying over the English-Scottish borders. This low and the occlusion moved slowly east during the morning as high pressure began to build from the west, producing a light, rather moist, north-easterly air flow over the area. The weather was outbreaks of rain and drizzle at times with hill fog over much of the high ground. The surface visibility was 20 to 30 km deteriorating to between 2,000 metres and 8 km in rain and drizzle and 100 metres or less in hill fog. Mean sea level pressure was 1013 mb at 0700 hrs rising to 1015 mb by 1100 hrs.

Cloud was generally scattered or broken stratus with a base of 1,800 to 2,500 feet and broken strato-cumulus cloud with a base of 3,500 to 6,000 feet often deteriorating to broken or overcast stratus with a base of 1,200 to 1,800 feet. The wind was light from the north-east, between 5 kt at the surface to 15 kt at 2,000 feet altitude.

During the morning there was a great deal of layer cloud over the English/Scottish borders below 10,000 feet amsl. Much of the layer cloud was drifting in from the North Sea in the light north-easterly winds. The lower layers were patchy but at times extensive, causing transitory hill fog as areas of cloud followed by gaps moved across the area.

Actual conditions observed at 0950 hrs at Carlisle Airport, approximately 24 nm south of the accident site, gave a variable surface wind averaging 360º/05 kt, visibility greater than 10 km, broken cloud at 1,500 feet, ambient temperature of 19ºC with a dewpoint of 16ºC and a QNH of 1014 mb.

In-flight observation

The commander of the Chinook helicopter provided a report on the conditions encountered as he transited the route flown by the pilot of G-OUEL. He reported that, having crossed the high ground to the south-east of Edinburgh, the low cloud began to break up, providing a large circular clear area some 15 nm in diameter centred approximately 30 nm south-east of Edinburgh. The ground below and ahead was clearly visible and he was able to carry out a descent in good Visual Meteorological Conditions (VMC). Approximately 4 nm south of Hawick, flying at 500 feet agl and heading 220°M, he could see the cloud covering the hill tops of the high ground to the south. Although the Teviot valley south of Teviothead was, in his opinion, just about passable, there was better weather to the west and he elected to route over Eskdalemuir Forest.

The visibility was approximately 10 km below the base of the cloud, which he estimated was at about 1,600 feet amsl. The wind at this altitude, as computed by the aircraft's navigation system, was north-easterly at less than 10 kt. No turbulence or showers were encountered and the crew did not see or detect any other aircraft activity in the area of the crash site.

Witness observations

The farmer, working with his son north-east of the accident site, stated that the weather that morning had included patches of drizzle coming down from the direction of Eskdalemuir Forest, to the west of his position. Comb Hill (see Figure 1) was visible from time to time, with its top in cloud. There was no wind and the light grey smoke he saw in the area of the accident site rose vertically before spreading out and taking on a gentle south-westerly drift.

Medical and pathological information

A post-mortem examination found that the pilot had died of multiple injuries. No evidence of any pre-existing disease was found and a toxicological investigation revealed no evidence of any condition which may have caused or contributed to the accident.

Pilot's flying experience

The pilots flying log-book and licence were not recovered. The hours quoted below are therefore estimated from other available information.

The pilot carried out training for his Private Pilot's Licence/Helicopter (PPL/H) on the Enstrom helicopter, which included instrument flying appreciation. He completed the requirements and was issued with his JAR PPL/H on 24 September 2002. He amassed 76 hours on the Enstrom before carrying out a type conversion onto the R44. His R44 rating was issued on 17 January 2003. At the time of the accident he was estimated to have flown 20 hours on the R44.

Aircraft description

General

The Robinson R44, manufactured in the USA, is a single-engined helicopter of conventional layout (Figure 2) with a maximum gross weight of 2,400 lb. At the time of the accident the manufacturer had constructed approximately 1,500 R44s, in three versions, over a 10 year period. The primary fuselage structure is constructed of welded steel tubing covered with a riveted aluminium skin and is fitted with a skid landing gear. The tailcone is a monocoque aluminium structure. There are two front and two rear seats; the pilot normally occupies the front right seat. The GPS receiver fitted to G-OUEL incorporated a moving map display; it was mounted on the central frame of the forward transparency. V_{NE} (the never exceed indicated airspeed) at G-OUEL's weight and altitude at the time of the accident was 130 kt (100 kt when operating at power above Maximum Continuous.)

Powerplant and transmission

The aircraft is powered by a 6-cylinder petrol piston engine with a maximum take-off power rating of 225 shp for the R44 Raven I (de-rated from the basic engine capability of 260 shp). Fuel supply for this model is via a carburettor. A pulley sheave carried on the horizontal engine output shaft drives 4 vee-belts which transmit power to an upper sheave when the belts are tensioned. Tensioning is effected by an electric screwjack clutch actuator which, when activated, raises the upper sheave and automatically sets and maintains the required tension. An over-running clutch within the upper sheave transmits power forward to a main rotor (MR) gearbox and aft to a tail rotor (TR) driveshaft and allows the rotors to continue to turn in the event of an engine stoppage. The MR gearbox contains a spiral-bevel gear set that drives a vertical MR shaft.

Rotors

The main rotor has two all-metal blades, each of which is attached to a MR hub by a coning pivot hinge (Figure 3). The hub is mounted to the top of the MR shaft by a horizontal teeter pivot hinge located above the coning hinges. The design places the main rotor centre of mass close to the teeter hinge point under normal operating conditions to minimise vibration and improve rotor stability. The provision of coning hinges permits a lighter blade design by reducing flapping bending moments near the blade roots. Teetering travel is limited by contact of the blade spindles with elastomeric stops on the rotor shaft. Pitch-change bearings for each blade operate in an oil bath contained in a blade root housing that is sealed by a neoprene boot; nominal blade pitch angles are 2-3° with the collective fully down and 14.5-16.5° with the collective fully raised. No blade drag hinges are provided.

The MR diameter is 33 feet and the MR blade tip speed is 705 feet/second at the normal maximum rotational speed of 102% (408 RPM). Rotation is anti-clockwise viewed from above. Each blade is fitted with a tip weight, around 3.5 feet long, carried within the outer portion of the stainless steel leading edge spar. Substantial tensile loads generated in the blades by centrifugal forces limit the bending and torsional deformation of the blades in normal operation. As with all conventional helicopters, this centrifugal rigidity is essential for the correct operation of the rotor.

The TR driveshaft, running in the tailboom, transmits power to a TR gearbox containing a spiral-bevel gear set that drives a horizontal TR shaft. The TR has two all-metal blades carried on a hub which is attached to the TR shaft by a teeter hinge.

Control

The MR is controlled by varying the blade pitch angles (Figure 4) by means of a pilot-operated collective lever and cyclic stick, each connected to the MR blades by mechanical rod and bellcrank linkages. Three hydraulic servo jacks, powered by a hydraulic pump driven by the MR gearbox, provide boost to reduce control forces. Directional control is by yaw pedals, connected to the TR blades by mechanical rod and bellcrank linkages, which vary the collective pitch of the TR blades.

The engine power output required to maintain rotor RPM varies with flight control inputs and aircraft manoeuvres. Coarse adjustment of power output as a function of collective lever position is provided by a correlator mechanism acting on the engine carburettor throttle. The throttle is connected to a twistgrip on the collective lever but is normally controlled in flight by an electronic governor that acts to maintain rotor RPM. The governor moves the whole throttle system, including the twistgrip, but a clutch in the linkage between the governor and the system allows the pilot to over-ride governor activity by means of the twistgrip. The R44 Pilot's Operating Handbook (POH) specified that flight with the governor selected off is prohibited, except in the case of in-flight malfunction of the system or for emergency procedures training.

The rotor speed limitation, power on, published in the POH was 101-102%. Low rotor RPM warnings, in the form of an amber caution light and a horn, activate when rotor RPM decreases to 97% or below. The MR and its control system is designed so that with the collective lever fully lowered, aerodynamic forces on the MR blades in the resultant auto-rotative descent maintain normal rotor RPM without engine power input. A manoeuvre that increases the load factor above 1g, such as a flare or a banked turn, causes a change in relative airflow that increases the auto-rotative forces on the MR blades and thus increases the rotor RPM. Normal RPM can be maintained by increasing the collective setting while the load factor is above 1g. Similar effects in powered flight cause a reduction in the engine power required while the load factor is above 1g.

The operating sense of the throttle twistgrip requires the left hand to be rotated away from the pilot (ie clockwise, viewed from the front) in order to manually open the throttle. This is the conventional sense for a helicopter throttle as it enables the wrist to naturally rotate the throttle open as the left arm is raised to increase the collective setting, when operating the throttle manually. However, the operating sense is opposite to that of a motorcycle throttle. Several instructor pilots reported that pilots, and in particular motorcyclists, operating this type of helicopter throttle control commonly did not find the direction of manual twistgrip rotation required in response to a rotor RPM excursion to be instinctive. It was also reported that there was a common tendency for pilots under stress to apply a fixed grip to the twistgrip and inadvertently preventing the governor from maintaining the RPM within the governed range.

In order to prevent or eliminate ice build-up in the engine induction system, warmed air can be diverted to the intake by a pilot-operated carburettor hot air control that operates in conjunction with a hot air assist system correlated with the collective lever setting. Excessive induction system heating results in unnecessary power loss. The aim is to adjust the amount of hot air such that the induction system temperature, as indicated on a cockpit gauge, is maintained above the level at which ice can form. It is intended that the necessary manual control setting is made immediately after takeoff and that the amount of hot air is then varied automatically by the assist system as the collective lever setting, and thereby the engine power output, is changed. It was reported that the correlation tends not to be exact and that further manual adjustments are commonly necessary to maintain the required temperature.

Aircraft history

G-OUEL (Serial Number 1235) had been imported new to the UK in 2002 and subsequently operated by the same company until the time of the accident. Records indicated that it had been maintained in accordance with Maintenance Schedule CAA/LAMS/H/1999, Issue 1, Amendment 1, and did not suggest that there had been any significant problems with the aircraft that could have been relevant to the accident. The last maintenance check, a 50 Hour Inspection, had been carried out on 24 June 2003, at which point the airframe and engine had each accumulated 247 flight hours since new.

Accident site

The wreckage of the helicopter was located in hilly countryside around 1 nm south-west of Teviothead. The main wreckage was at Ordnance Survey position NT395039, 666 feet amsl, in a steep-sided valley orientated north-east to south-west. The valley had a relatively flat base around 150 metres wide containing a small river and numerous drainage channels. The ground was generally moderately firm and covered with tall grass and areas of high, dense bracken. The valley was between hills that, in the vicinity of the accident site, rose to 1,181 feet amsl on the south-east side (around 0.5 nm south of the main wreckage site) and to 958 feet amsl on the north-west side. The terrain 1.9 nm south of the site rose to 1,683 feet.

Examination of the site showed that components of G-OUEL had been spread over a trail around 400 metres long and 100 metres wide that ran north, diagonally down the south-east face of the valley and across the valley floor. The southern end of the trail was at about 800 feet amsl. It was possible that some of the lighter items could have been repositioned by the wind prior to the site examination but the evidence indicated that this had not generally occurred.

The items in the southern part of the trail largely consisted of multiple white paint flakes, in a trail around 200 metres long, together with a number of pages from a Pooley's Flight Guide, both of which had clearly originated from the helicopter. The Pooley's pages were A5 sized loose-leaf paper sheets, normally held in a ring binder. A number of pages from the guide were found distributed over a 100 metre wide area of the trail. They were generally undamaged, with no signs of having been pulled or torn out of a binder, but most had been spattered with a red oily fluid. It was found that they constituted 52 consecutive pages from near the front of the guide and included two bands of consecutive pages with particularly heavy fluid contamination.

A manufacturer's component dataplate, identified as part of the anti-collision beacon mounted on the top of the aft part of the tailboom, was found 90 metres along the trail. Portions of 'danger' and aircraft registration lettering decals from the tailboom were found a little further along the trail.

These were followed, at 250-320 metres, by a MR blade fragment and a number of large and small pieces of the tailboom, together forming the whole tailboom with the exception of its forward 2 feet, with the tail rotor and its gearbox attached. These items were followed by a part of the aircraft compass and a headset. Between 300 and 400 metres along the trail were several portions of the TR driveshaft and TR control rod from the tailboom. None of the above items had been fire damaged.

The main wreckage, essentially consisting of the helicopter with most of both MR blades but absent most of the tailboom, was located 380 metres along the trail, embedded deeply into the ground. Ground marks and wreckage examination showed that it had impacted the ground with high vertical speed and very low horizontal speed while rolled onto its right side. There were no appreciable ground marks from the MR blades, apart from where the outer portion of one blade (designated Blade A) had become impaled in the ground. This was apparently the result of motion along the longitudinal axis of the blade, without significant rotation.

The main wreckage had been subjected to extensive fire damage, with most of the composite and aluminium components destroyed, except for some on the right side that had been embedded into the ground. The MR had remained outside the fire area and the GPS receiver had been thrown clear and was virtually undamaged. A 1:250,000 scale and a 1:500,000 scale aviation map with a track line from the departure point to Carlisle drawn on it were found at the site. Fire damage to vegetation alongside a drainage channel adjacent to the main wreckage was consistent with a substantial quantity of fuel having flowed from the wreckage into the channel and burnt.

Examination indicated that all parts of the aircraft were present in the trail, with the exception of the tip portion of MR Blade A. It could not be located by extensive searching and digging but was subsequently recovered by members of the public, apparently from an area of bracken around 200 metres west of the main wreckage. The blade fragment located with the tailboom parts originated from the fracture area. The remains of all four cabin doors were identified in the wreckage, in each case with the door handle in the closed and locked position and generally with the two latch pins protruding, although some latch pins had fractured. The position of the doors was consistent with their having been closed, with the exception of the forward right door, which was found lying under the forward fuselage. The evidence suggested that this door had opened and over-rotated around 180° before the fuselage had struck the ground.

Following on-site examination, the wreckage was taken to the AAIB Headquarters at Farnborough for detailed inspection.

Detailed wreckage examination

It was clear from markings and damage characteristics that the tailboom had sustained three strikes from MR blades on its left side (Figure 5). One of these strikes, around mid-way along the tailboom, had been particularly heavy. The strikes had separated the boom into 7 major parts and a large number of smaller fragments. Severe localised flattening damage to the TR driveshaft and the TR control rod in the area of the heavy tailboom strike was also indicative of a MR blade strike.

Both MR blades had suffered surface gouging, consistent with contact with the tailboom, in a region between around 2.3-4.3 feet from the tip for Blade A and 4.9-7.4 feet from the tip for Blade B (Figure 4). Neither blade had sustained appreciable leading edge damage from the ground impact. The inner portion of Blade A had buckled, consistent with its end-on ground impact. The fracture of the blade, 3.5 feet from its tip, was at the inboard end of the tip weight fitted within the blade spar. The blade had a pronounced, smooth forward bend in the plane of the blade outboard of the fracture and this, together with the spar fracture surface characteristics, indicated that the fracture had resulted from in-plane bending overload. The evidence, in conjunction with that from the markings on the blade and on the tailboom and from the distribution of the detached parts, was fully consistent with the fracture having resulted from overload caused by inertial effects when the blade struck the tailboom. Blade B was intact; it exhibited marked upward bending deformation along its length.

Markings showed that the pitch change horn of each MR blade had contacted the MR hub while the blades had been coned upwards around 21° and the blade pitch angle had been around 27° leading edge up. Both elastomeric teeter stops had been impacted by the blade spindles and virtually severed. The main rotor shaft beneath the stops had a small imprint from the spindle on each side but was otherwise undeformed.

The TR blades were undamaged, with no signs of rotation at ground impact. Light scoring and minor deformation of the tailboom and slight paint scraping on the left side of both TR blades showed that both blades had made light rotating contact with the boom over a few revolutions.

Flight control and engine control systems were examined as far as possible but extensive destruction of the main fuselage prevented a full assessment. Parts of the flight control runs and most parts of the servo actuators had been destroyed by fire damage, but most control run pivots remained, with no signs of disconnection. The throttle linkage remained intact. The belt drive clutch actuator had suffered major damage but it appeared unlikely that the screwjack setting would have changed from that at ground impact; comparison with another R44 with similar flight time to G-OUEL indicated that the setting was consistent with the drive having been engaged.

Engine strip examination at the manufacturer's UK agent found no signs of mechanical failure prior to ground impact. However, most of the accessories had been destroyed by fire and no evidence as to the pre-impact state of the carburettor or magnetos was available. Analysis of a sample of fuel from the bowser used to refuel G-OUEL before its departure on the accident flight found that it generally conformed to the specification requirements for aviation gasoline. It marginally exceeded the requirement on an existant gum test but was within limits on a repeat and both results were within the repeatability of the test method. The results were consistent with the effects of sample ageing before testing and were not considered relevant to the operation of the engine.

The evidence suggested that neither the engine nor the rotor system transmission had been rotating at appreciable speed at ground impact. However, there were signs that both had been rotating at the time that significant disruption in the engine bay and in the transmission bay behind the MR gearbox had occurred. Heavy local machining of the engine oil cooler by the engine starter ring indicated engine rotation. Transmission rotation was indicated by the wrapping of a steel reinforcing wire from a MR gearbox cooling air hose around the MR gearbox input shaft. The wire remained intact and snagged on the shaft and the evidence indicated that the shaft had stopped after having made around 15 turns from the point at which it had first picked up the wire. These effects were consistent with a MR blade strike having caused deformation of the rear part of the fuselage or with a blade strike or excessive vibration having disrupted the engine and/or MR gearbox mounts. The rotational speed of the engine or transmission at the time could not be determined but the evidence suggested that both had made only a limited number of turns before stopping.

Previous research and analysis

FAA Technical Panel

The R44 configuration and MR design was similar to the Robinson R22 two-seat helicopter. Both types had suffered a number of cases of MR blade strike on the fuselage or tailboom in flight. On 19 July 1994 the Federal Aviation Administration (FAA) chartered a Technical Panel (TP) to research solutions that would reduce the potential for fatal accidents involving in-flight main rotor contact with the airframe (referred to as rotor/airframe contact accidents) of R22 and R44 helicopters. The need for the review arose from 34 fatal rotor/airframe contact accidents, 31 of which involved the R22 and three the R44. The seven member panel, in conjunction with the manufacturer and other expert bodies, conducted a comprehensive study that particularly addressed the design and behaviour of the main rotor system.

The TP convened on 8 August 1994 and, following a review of the accidents, recommended initial action on 30 December 1994. These recommendations addressed the provision to pilots of information on the conditions leading to fatal accidents, prohibiting flight in turbulence and developing pilot training requirements and the legislation to support them.

A revision of the Basic Helicopter Handbook to cover fatal accident causal factors was initiated in February 1995. After completing the initial study the TP continued its research to support FAA action. From the Executive Summary dated 30 April 1996, the flight testing of a fully instrumented R44 undertaken in July 1995 and a computer based simulation programme produced no evidence of rotor instability. Some of the earlier recommendations were refined and a recommendation was made by the TP to mandate the fitting and use of a rotor speed governor on all R22s; it was already required for continuous use on the R44 helicopter.

The TP concluded that:

> *"Accident investigators had not definitively determined the primary causal factors of any of the 34 reported R22 and R44 rotor/airframe contact accidents. Based upon the results of the research and study by the TP, the actions recommended by the TP will reduce the potential for rotor/airframe contact by eliminating some of the conditions that have accompanied those accidents and will help prevent excursions beyond the limit of the flight envelope. Those actions have mandated increased minimums in flight experience and training for those helicopters, reduced the operating flight envelopes, and will reduce pilot workload in the aircraft. Beyond the recommendations put forth in this report, the TP proposed no further action on the part of the FAA."*

Flight Testing

The flight testing mentioned above was carried out by the manufacturer with participation by the FAA. It investigated MR blade flapping angles, rotor RPM decay and helicopter pitch and roll rates resulting from a variety of manoeuvres and initial flight conditions, such as cyclic pushovers and sudden power reduction.

The manufacturer's report on the testing stated that R44 rotor head clearances allow the MR hub to teeter up to 15.1°; the teeter stops make initial contact at 7.4° and compress at larger angles. The clearances also allow for upward blade coning of around 16°; droop stop contact occurs at 1.2° downward coning. Blade contact with the tailboom would occur at a downward flapping angle (teeter angle minus upward coning angle) of approximately 15°.

The maximum aft flapping angle during the flight tests was 7.2°, given by a teeter angle of 8.2° with a 1° upward coning angle, producing a blade/tailboom clearance of 26 inch. The greatest aft teeter angles occurred with a forward helicopter centre of gravity. This condition also produced higher right roll rates during pushover manoeuvres, up to 41°/second. A high roll rate manoeuvre, where the bank angle was reversed from 45° left to 45° right at 117 kt with maximum continuous power applied, produced a maximum right roll rate of 62°/second. The lowest rotor RPM experienced was 80%, in a test where the engine power was chopped in level cruise at 105 kt and the collective was maintained at its original setting for 1.1 seconds after the chop and then fully lowered in a further 0.9 seconds.

The report concluded that the R44 met or exceeded the FAA requirements for rotor blade clearance and for rotor RPM decay associated with specified time delays in reducing the collective after sudden power loss. It concluded that the rotor system would not stall, exceed teeter limits or contact the airframe when the helicopter was flown within its approved limitations.

Main rotor-airframe strike

Information from the POH, from discussions with the aircraft manufacturer and from research findings indicated that, for a helicopter with a teetering MR, an in-flight MR blade strike on the fuselage or tailboom could result from either a MR stall or a reduced load factor condition. The factors involved are as follows:

Main rotor stall

The lift and drag forces generated by airflow over each section of the MR blades are a function of the relative speed of the airflow over the section and its angle of attack (AOA), the angle between the blade chord and the airflow (Figure 4). Increased lift and drag forces are generated by increasing AOA, up to a critical aerodynamic stall angle (around 15° for the R44), beyond which the airflow separates from the upper surface of the section. This results in a sudden reduction in lift and large increase in drag on the section.

An increased AOA is required in order to maintain the lift if MR RPM reduces. The AOA is also increased by an increase in the sink rate of the section (the descent rate of the section relative to the airflow). In the event of part of a blade reaching the stall angle, the drag increase tends to reduce the MR RPM and the loss of lift tends to increase the sink rate. Reduced centrifugal loading on the blades due to decreased RPM also allows increased torsional deformation of the blades, tending to increase blade pitch angle and thus the blade AOA. The combined resultant increase in the AOA tends to rapidly deepen the stall and extend it over a greater portion of the blade, thereby further increasing the torsional drag on the MR. For a piston-engined helicopter such as the R44, where the engine is mechanically connected directly to the rotors, a reduction in MR RPM causes a corresponding reduction in engine RPM. The maximum output power of the engine decreases in direct proportion to the reduction in its RPM. The increase in drag and reduction in the power available can cause the power required to drive the rotors to rapidly exceed the maximum output power of the engine. In this case continuing RPM reduction results.

The process of RPM reduction in a blade stall condition is very rapid and can only be reversed by immediate lowering of the collective lever, thereby reducing the pitch angle of the blades and thus their AOA. For the R44 the RPM reduction is reportedly irreversible below about 72%, ie full lowering of the collective lever will not prevent continuing rapid RPM reduction.

The speed of the airflow over a blade section is the resultant of its speed due to rotation and its speed due to motion of the helicopter. Thus, in forward flight the retreating blade (on the left side of the aircraft) experiences a lower airspeed than the advancing blade (on the right), with the speed difference increasing as the aircraft's forward speed increases. This causes the retreating blade to descend, thereby increasing its angle of attack, and the advancing blade to rise, thereby reducing its angle of attack. The effect results in equalisation of the lift on each side of the MR disc and in rotor blow-back (or 'flap-back'), where the rotor disc tilts back.

In the event of excessive blade AOA in forward flight, the retreating blade can stall first and thus cause asymmetric MR stall. The loss of lift associated with the stall causes the aircraft to sink and the resultant upward relative airflow on the tail surfaces pitches the fuselage nose down. With a teetering rotor, the combined effects of excessive MR blow-back and fuselage nose down pitching, possibly accentuated by aft cyclic control input made by the pilot to counteract the nose-down pitching, can cause the MR blades to strike the fuselage or tailboom, generally on the left side. As MR RPM reduces below normal, the likelihood of a strike is increased because of the greater out-of-plane bending excursions of the blades that can result from the loss of MR stiffness associated with the reduced centrifugal loading.

Information was obtained on an overseas R44 accident in 2004. The accident reportedly probably resulted from MR/fuselage contact due to low rotor RPM, possibly following engine power loss due to induction system icing. Evidence provided by a video recording being made by one of the helicopter's occupants at the time of the accident showed that extremely violent airframe vibration immediately preceded the MR/fuselage contact. It appeared that this was due to severe MR imbalance associated with excessive flapping excursions of the MR blades at low RPM.

A reduction in the engine power delivered to the rotors would cause the rotor RPM to decrease until corrective action were taken; it is intended that in the event of power loss the pilot should rapidly lower the collective lever fully, enter auto-rotation and carry out an engine-off landing. Practising this procedure forms a substantial part of pilot training. An excessively low MR RPM condition can quickly result from insufficiently rapid full lowering of the collective lever.

Possible causes of power loss include engine mechanical failure, engine induction system icing or malfunction of governor, ignition, fuel supply or transmission systems. Insufficient power could also result from mishandling of the throttle or governor; movement of the throttle by the governor can be inadvertently over-ridden by the pilot. In the absence of power loss, low RPM can also be caused by MR over-pitching, where the collective lever demand is maintained at a level at which the power required to drive the rotors exceeds the maximum power output of the engine.

The R44 POH notes that in conditions where low rotor RPM can occur, the effects can be accentuated by high density-altitude, aggressive manoeuvring, high forward airspeed or atmospheric turbulence.

Reduced load factor

For a helicopter with a teetering MR, such as the R44, the fuselage is effectively hung beneath the MR disc. The orientation of the fuselage relative to the disc is determined by acceleration forces on the mass of the fuselage (its weight, in 1g flight) and by aerodynamic forces on the fuselage. Reduction in the load factor below 1g, due to manoeuvring, reduces the stabilising force due to gravity.

A substantial reduction in load factor, as would be caused by an abrupt forward movement of the cyclic stick in forward flight (pushover), can result in excessive flapping of the MR disc relative to the fuselage. In the event of the pilot applying substantial aft cyclic control to reload the MR while the helicopter is pitching forward, the MR disc may tilt aft relative to the fuselage before it is reloaded. The main rotor torque reaction will then combine with tail rotor thrust to produce powerful right rolling and right yawing moments on the fuselage. With reduced MR lift there is less lateral control available to stop the right roll, which is likely to prompt a substantial left cyclic control input by the pilot. In this situation the MR blades can flap far enough for the blade spindles to forcibly contact the teetering stops on the MR mast. Such mast bumping can be vigorous enough to deform the mast (mast pinching). Severe pinching can fracture the mast and separate the MR from the aircraft. MR blade contact with the fuselage and/or tailboom can also result. The effect of a pushover type cyclic stick movement can be accentuated in conditions of high forward airspeed, turbulence or excessive sideslip. The R44 POH advises:

> *"To avoid these conditions, pilots are strongly urged to follow these recommendations:*
>
> 1) *Maintain cruise airspeed greater than 60 KIAS and less than 0.9 V_{NE} [117 kt in G-OUEL's case].*
> 2) *Use maximum "power on" RPM at all times during powered flight.*
> 3) *Avoid sideslip during flight. Maintain in-trim flight at all times.*
> 4) *Avoid large, rapid forward cyclic inputs in forward flight, and abrupt control inputs in turbulence."*

Discussion

It was apparent from wreckage markings and distribution that G-OUEL's tailboom had suffered several strikes by the MR blades and that most the tailboom had detached in-flight as a result and subsequent ground impact was inevitable. The absence of ground marks from the MR blades together with the lack of appreciable ground impact damage to the blade leading edges indicated that the rotor had stopped, or very nearly so, by the time the helicopter reached the ground. The ground impact, made with substantial vertical speed, was non-survivable. Extensive destruction of the helicopter in the ground fire meant that insufficient evidence was available for all details of the in-flight break-up sequence to be positively determined.

Witness markings on the MR hub were not consistent with the effects of ground impact and showed that both MR blades had suffered gross upward coning in flight. This was supported by the marked upward bending of Blade B, which had suffered little ground impact damage. Such severe coning could only have occurred in a situation of gross MR underspeed and consequent large reduction in the centrifugal loading on the blades. In such a condition substantial vertical excursions of the MR blades ('blade sailing') are likely; the severe coning therefore probably occurred close to the time of the MR blade/tailboom strike. Additionally, it appeared that the in-plane bending of Blade A, that had probably resulted from a tailboom strike, was unlikely to have occurred with the high tensile loads in the blades that would have been present at normal rotor RPM. This feature thus also signified that MR RPM had been relatively low at the time of the strike.

The excessive coning caused rupture of the elastomeric boot that sealed the pitch change bearing for each blade. It appeared likely that oil released from the bearings had caused the red staining on the Flight Guide pages released from the helicopter and therefore that the pages had been released close to the time of the MR blade/tailboom strike. The position at which the pages were found was also consistent with their having been released close to the time of the strike and then drifted in the prevailing light north-easterly wind. This was also the case for the trail of paint flakes, likely to have been generated by the break-up of the tailboom. The tailboom parts would have experienced more ballistic throw and less drift than the pages and the paint flakes, having a lower drag to weight ratio. Overall the wreckage trail characteristics indicated that G-OUEL had been tracking approximately north at the time of the MR blade strike.

The reasons for the release of the Flight Guide pages could not be determined. The position of the forward right cabin door in the wreckage indicated that it had opened before ground impact and this was supported by the release of two items of cabin equipment along the trail. The pages could have been sucked out when the door opened; the lack of damage to the pages indicated that they had probably been carried loose from the ring binder. The door latching mechanism was simple, with a design that appeared likely to provide positive latching of the doors in normal circumstances, and no evidence was found to indicate that R44 cabin doors had any tendency to come open. The reason for the door coming open could not be positively established but it appeared that it could have been due to deformation of the fuselage by abnormal loads. It was possible that such loads could have resulted from excessive aerodynamic loads imposed by violent manoeuvring associated with the MR blade/tailboom strike, or from the direct effects of a strike on the fuselage, or from excessive vibration. The evidence from another accident indicated that severely low rotor RPM could result in extremely violent vibration because of MR imbalance caused by excessive excursions of the blades.

Background evidence indicated that there were two possible reasons for the MR blade/tailboom strike. Some mast bumping had occurred on G-OUEL, but it appeared that this could have been associated with excessive blade coning. The absence of gross mast bumping indicated that a reduced load factor condition had probably not been responsible. However, as described above, there was evidence of severe MR underspeed and it was likely that this condition had led to the strike.

In such a case, the stalled rotor would continue to rapidly loose RPM, down to an insignificant level, following the strike and the aircraft's subsequent trajectory would effectively be ballistic, under the influence of gravity and aerodynamic drag. Thus the lack of appreciable horizontal speed when the main wreckage struck the ground indicated that the horizontal speed at the time of the strike had been relatively low. The lateral dispersion of the items in the wreckage trail was quite low, even allowing for the gentle prevailing wind, suggesting that aircraft had been no more than a few hundred feet above the ground when they had separated from the aircraft. It was therefore judged, although not positively established, that the aircraft's altitude when the strike occurred had probably been in the order of 900-1,200 feet amsl.

There were several possible reasons for a significant rotor underspeed, as described earlier. Although no signs of aircraft malfunction prior to the MR blade strike were found, the severe ground-fire destruction prevented the pre-accident serviceability of the engine or it accessories, the fuel supply system or the transmission system from being positively established. There were signs of engine and transmission rotation at the time when disruption had occurred, probably due to the MR blade strikes or to rotor imbalance. No definitive indication of the rotation speed at this point were available, but the evidence of only limited rotation following the disruption suggested that it had been low. Little evidence was available in relation to other possible causes of power loss, such as inadvertent over-riding of the governor by the pilot or engine induction system icing. The flight conditions were probably conducive to induction system icing and some reports suggested that the 'hot air assist' system, even if correctly set at takeoff, would not necessarily maintain the system free of icing without further adjustment en route. Thus the possibility of a loss of power, from a variety of causes, could not be dismissed.

In the event of significant rotor RPM reduction, due to a loss of power or an excessive collective pitch demand, it is intended for the low rotor RPM warnings (97%) to prompt a rapid lowering of the collective lever to restore normal RPM. It was clear that in some situations the rate of RPM reduction could be rapid and even a relatively short delay would result in a severe rotor underspeed; however, the ground fire damage prevented the serviceability of G-OUEL's low rotor RPM warning system from being verified.

A detailed assessment of the operational factors that could have led to a low rotor RPM situation was made. G-OUEL's pilot knew the A7 road between Hawick and Carlisle well and following the road in good weather would have been a simple task. His initial transit had been stable at approximately 110 kt groundspeed and 1,500 feet amsl and appeared to have been uneventful.

However, whilst the weather at his departure point had improved during the morning, low cloud was still in the vicinity of the high ground further south on his intended track to Carlisle. When the Chinook approached Teviothead some 10 minutes after G-OUEL, low cloud beyond this point caused the experienced RAF helicopter pilot, with his navigator, to decide not to continue south down the A7 but to route to the west of the high ground. At low level, the presence of low cloud on the route was only apparent on approaching Teviothead.

The right turn initiated by G-OUEL just south of Teviothead indicated that G-OUEL's pilot had also decided to divert from the original routing and to either land, turn back or route further west. The turn took G-OUEL along the spur of a hill that rose fairly steeply to 1,180 feet amsl and the aircraft climbed at a high rate to around 2,400 feet amsl, with the groundspeed reducing to 50 kt. Given the reported stratus cloud, with a base estimated by the Chinook pilot as around 1,600 feet amsl, it appeared likely that G-OUEL would have entered either the side or the base of the cloud during the climb. Such an entry into cloud could have been inadvertent, possibly coinciding with a distraction such as studying or refolding a map, or could have been made because of concern about terrain clearance.

Radar returns from G-OUEL, except for one approximating to the accident site position, were not recorded because of the relatively low level of the flight, and thus information on the helicopter's progress was not available. However, the GPS record suggested that between the end of the climb and the last GPS data point the aircraft accelerated to around 120 kt, without major height variation, while continuing the right turn through a further 240° onto a south-easterly track. It was likely that either the MR strike or the ground impact caused disconnection of the GPS antenna and the end of data recording. Thus a high rate manoeuvre, such as a descending, tightening right turn, would have to have occurred following the last GPS data point in order for the aircraft, less than 30 seconds later, to be on a northerly track some 1,200-1,500 feet lower when the MR strike occurred. The available evidence suggested possible scenarios for the final flight path, as follows:

Spatial disorientation

In cloud, it would have been necessary for the pilot to fly by sole reference to the flight instruments. The R44 is responsive to control inputs but, like all helicopters, is inherently unstable. Although G-OUEL's pilot had received basic instrument flying familiarisation training, his experience level made it unlikely that he would have been in a position to accurately control the aircraft in IMC. With the absence of outside visual references, physical sensations can produce compelling perceptions of the aircraft's attitude and manoeuvres that differ markedly from those indicated by the flight instruments and spatial disorientation can occur. This tends to be more likely when recent and/or total instrument flying experience is low and in a high stress situation, such as unintended entry into IMC by a relatively inexperienced pilot.

In the event of unintended IMC entry it would be appropriate to maintain a moderate airspeed while attempting to regain VMC or, having done so, while manoeuvring to remain clear of cloud. Given this, G-OUEL's acceleration to 120 kt (ie close to V_{NE}) following the climb, suggested that it was not fully under control at this point. The characteristics of the flight path described above, particularly the high airspeed and the rapid descent that followed, were consistent with the effects of spatial disorientation. It was thus possible that the accident had resulted from loss of control due to spatial disorientation following unintended entry into IMC.

Attempt to regain VMC

With the layers of stratus cloud that were apparently present, it is possible that the pilot climbed through the lower cloud and emerged between cloud layers with a limited, poorly defined horizon. The line feature formed by the river running through the valley could have been visible to the pilot, possibly intermittently, on the right side of the helicopter. This could have led him to conduct a relatively high speed, turning descent using minimum collect pitch in order to attempt to regain VMC. Such a manoeuvre was consistent with the fairly rapid altitude loss between the last recorded data point and the rotor strike, as described above. During the descent it was possible that the helicopter entered an area of denser cloud and the pilot lost sight of the river.

Low rotor RPM

In either of the above scenarios it would be expected that large cyclic and/or collective control inputs would be made at some point in an attempt to arrest the descent and possibly to reduce airspeed. An excessive, sustained collective demand could cause 'over-pitching', whereby the power required to drive the rotors exceeds the power available from the engine, and a consequent rapid reduction in rotor RPM. It was also possible that low RPM could result from over-riding of the governor action by the throttle twistgrip. One possible scenario would be manual closure of the throttle in an attempt to contain a substantial rotor overspeed resulting from a vigorous flare and/or turn with the collective lowered. A subsequent increase in the collective setting without first operating the twistgrip to open the throttle and allow the governor to act could lead rapidly to the low rotor RPM situation that precipitated the rotor strike. Both MR blades were at a high pitch angle at the time when they left evidence of excessive upward coning, but some disruption of the pitch change mechanism had occurred and there was no evidence as to the pitch angle immediately prior to this low RPM situation. Overall, there was insufficient evidence to determine why the low rotor RPM situation had occurred.

Conclusions

It was likely that the helicopter had entered IMC during a turn away from an area of low cloud on its planned route. Shortly afterwards control had been lost and the aircraft descended rapidly, possibly as the result of spatial disorientation. An excessively low rotor RPM had probably resulted and led to contact of the main rotor blades with the tailboom, causing most of it to detach, stoppage of the rotors and non-survivable ground impact. Rapid reduction in rotor RPM to a hazardous level can result from small delays in applying appropriate control inputs. The control loss and low rotor RPM may have resulted from mishandling of the controls but the possibility that aircraft malfunction had contributed to the accident could not be eliminated.

Safety Recommendations

Section 4 of the R44 Pilots Operating Handbook 'Normal Procedures' and Section 10 'Safety Tips' provide information on the rotor blade stall hazard created by low rotor RPM. However, the danger of rotor blade stall resulting from the application of rapid and excessive collective pitch is not covered. The following Safety Recommendation is therefore made:

Safety Recommendation 2005-021

It is recommended that the Robinson Helicopter Company consider including in the R44 and R22 Pilot's Operating Handbooks, a specific warning highlighting the possibility of a rapid and excessive collective pitch demand causing a hazardous loss of rotor RPM, together with guidance on the appropriate handling of the collective lever.

Following a considerable number of previous R22 and R44 accidents resulting from main rotor blade/fuselage strikes, concern has been expressed not only over the adequacy of rotor blade to fuselage clearance but also the maximum time delay that can safely be tolerated in reducing the collective pitch after a sudden power loss. Although the FAA Technical Panel assessments had concluded that FAA requirements in these regards were met or exceeded, it was clear that rotor RPM decay in the event of sudden power loss could be rapid. It was noted that a delay of as little as two seconds in selecting the collective lever fully down after activation of the low RPM caution on the R44 could result in an appreciable reduction in rotor RPM to a level that was not significantly above the RPM at which any further decrease was irreversible. The behaviour of the R22's rotor system is apparently similar. Federal Aviation Regulation (FAR) Part 27.143 concerning pilot reaction times states that:

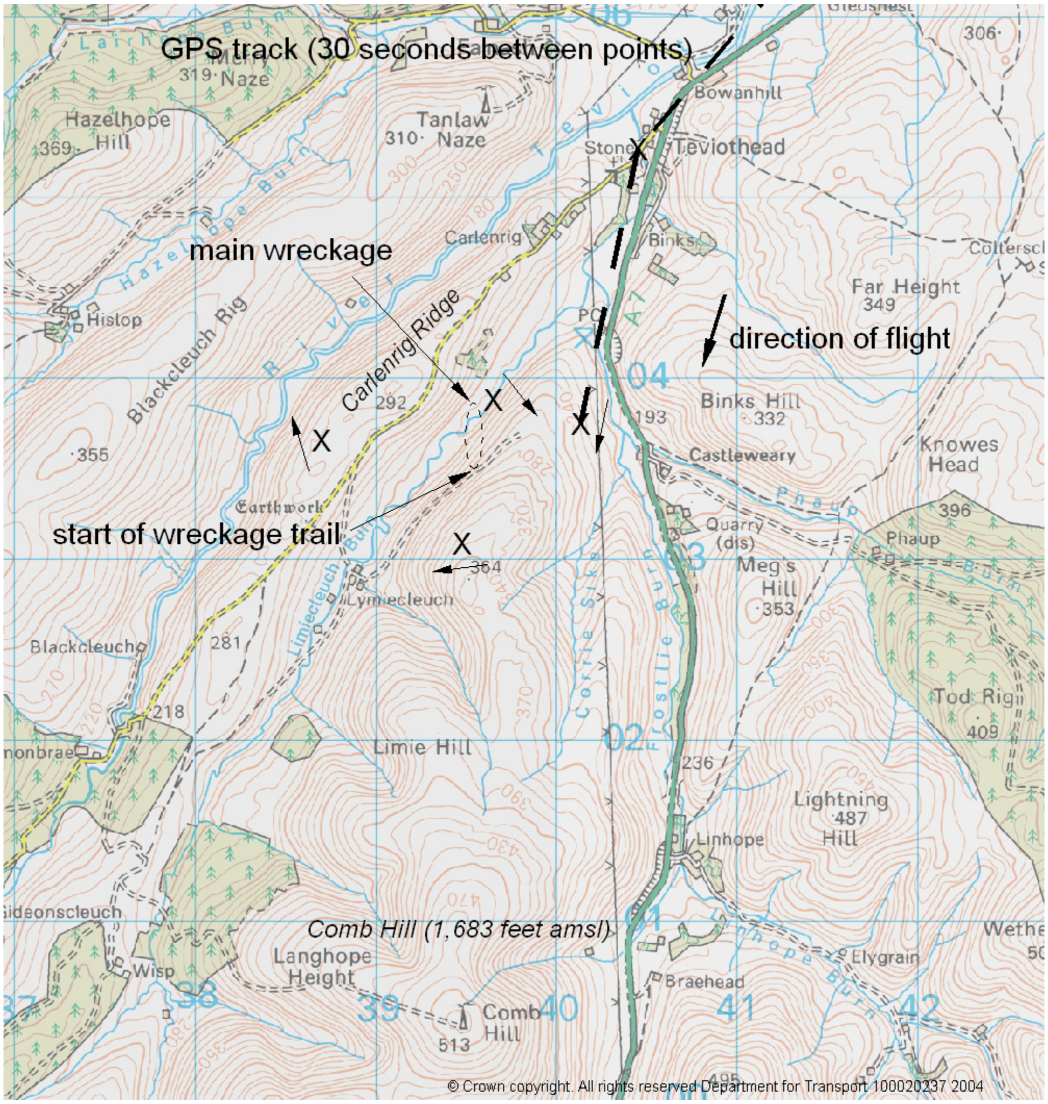
> *'No corrective action time delay for any condition following power failure may be less than - For the cruise condition, one second, or normal pilot reaction time (whichever is greater); and for any other condition normal pilot reaction time.*

It is therefore questionable that pilots, particularly of relatively low experience, should be expected to consistently and reliably react within, what appears to be, an unrealistic timescale.

The following Safety Recommendation is therefore made:

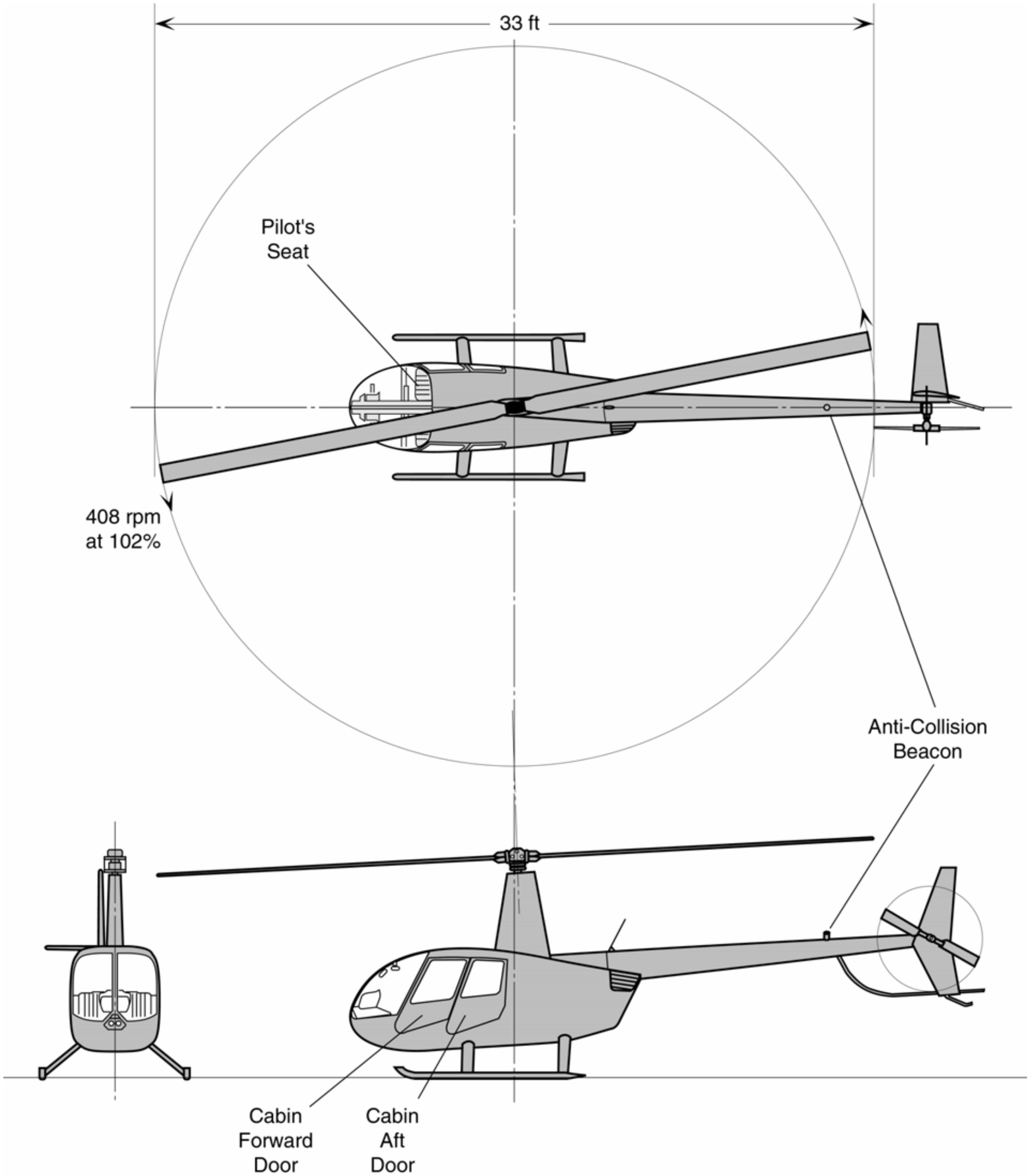
Safety Recommendation 2005-022

It is recommended that the Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA) reassess the 'corrective action time delay' in reducing the collective control after sudden power loss on a single-engined helicopter, with the aim of ensuring, as far as possible, that the minimum reaction time required is realistically within the capability of an average qualified pilot.



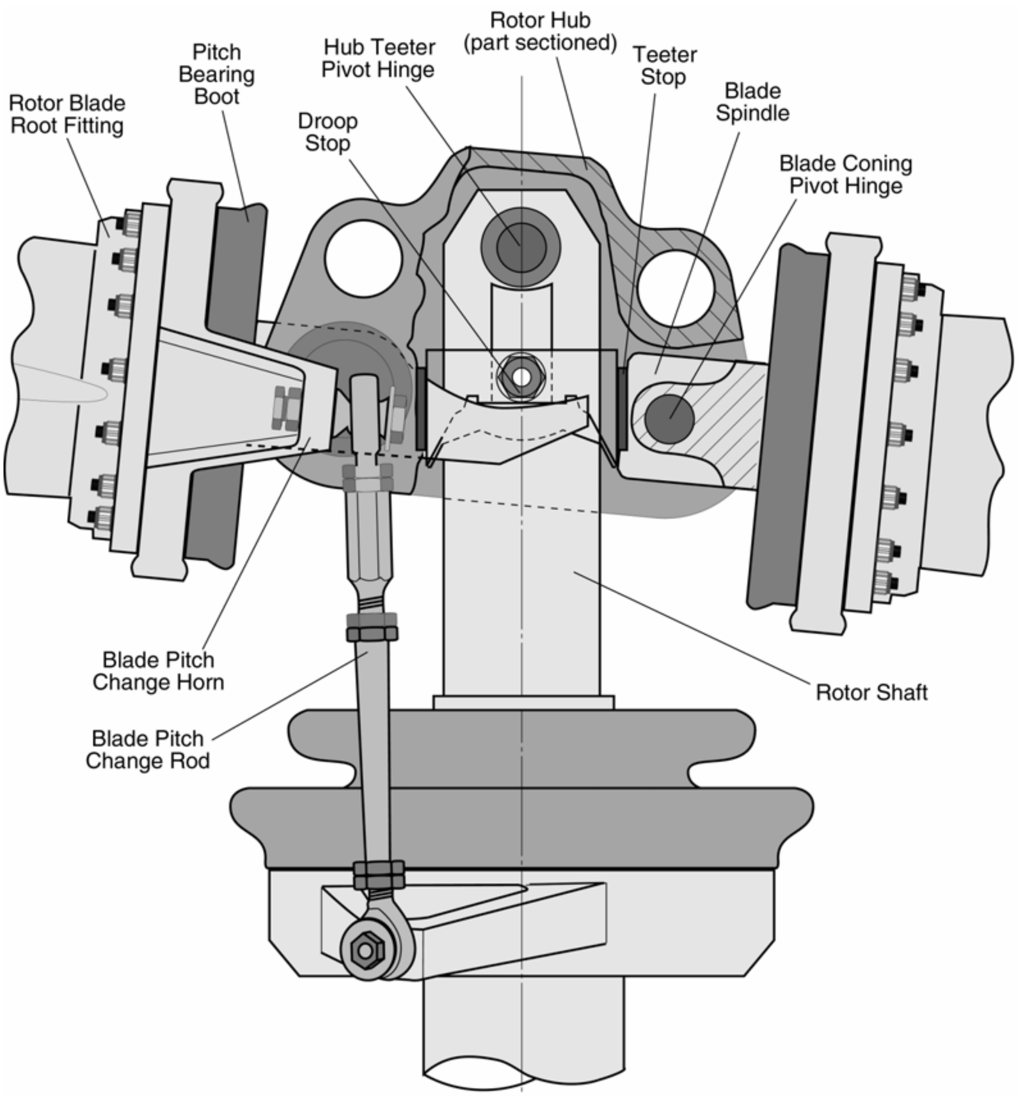
Final GPS track of G-OUEL and wreckage site location

Figure 1



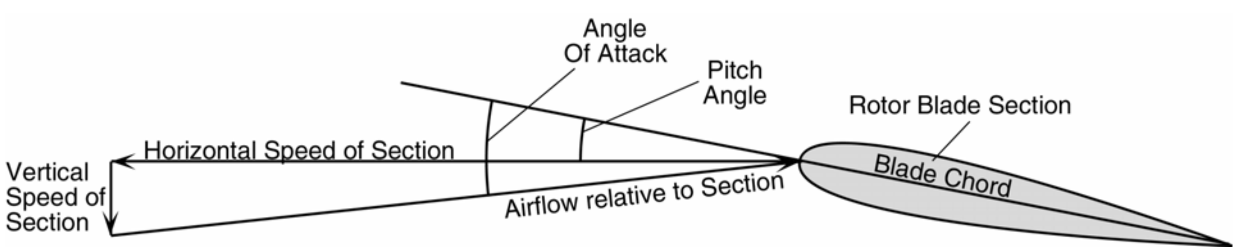
Robinson R44 - General arrangement

Figure 2



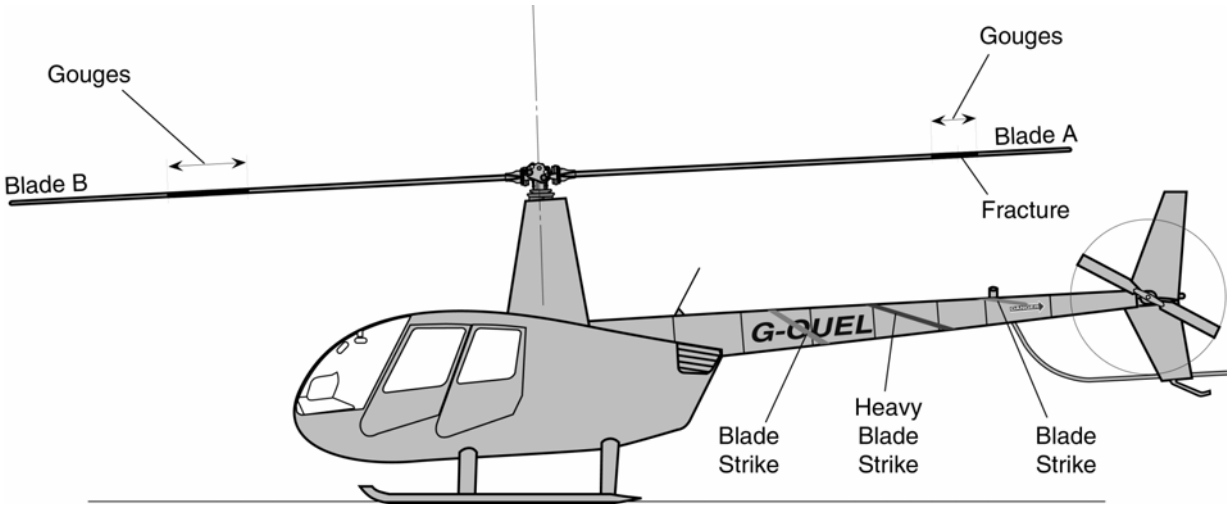
Robinson R44 Main Rotor Head

Figure 3



Rotor Blade Angles

Figure 4



G-OUEL - Main rotor blade and tailboom marks

Figure 5

Schematic of possible main rotor blade strikes on tailboom

Figure 6