ACCIDENT

Aircraft Type and Registration:	Robinson R22 Beta, G-CHZN
No & Type of Engines:	1 Lycoming O-320-B2C piston engine
Year of Manufacture:	1988 (Serial no: 884)
Date & Time (UTC):	6 January 2012 at 1126 hrs
Location:	Ely, Cambridgeshire
Type of Flight:	Private
Persons on Board:	Crew - 1 Passengers - None
Injuries:	Crew - 1 (Fatal) Passengers - N/A
Nature of Damage:	Aircraft destroyed
Commander's Licence:	Private Pilot's Licence (Helicopters)
Commander's Age:	50 years
Commander's Flying Experience:	59 hours (of which 59 were on type) – Helicopters 4,960 hours – Aeroplanes Last 90 days - 18 hours Last 28 days - 12 hours
Information Source:	AAIB Field Investigation

Synopsis

The Robinson R22 helicopter was flying from Manston to Fenland. Near Ely, witnesses on the ground saw it pitch and roll rapidly, the two main rotor blades separated from the rotor head and the aircraft fell to the ground. The pilot was fatally injured.

The accident was caused by main rotor divergence resulting in mast bumping, the rotor blades striking the airframe and rotor blade separation. The report includes Safety Recommendations, to the EASA and the FAA, that refer to the certification requirements for future light helicopters, to reduce the risk of 'loss of main rotor control' accidents.

History of the flight

Background information

The pilot of G-CHZN was an experienced fixed-wing pilot with 4,960 hours of flying experience. He held an ATPL(A), and was a Flight Instructor (FI(A)) and examiner. His PPL(H) was issued on 14 December 2011 and he had flown six flights in the Robinson R22 between that date and the date of the accident. The pilot planned to build his helicopter flying hours to gain a CPL(H) and FI(H) and, prior to the accident flight, he had a total time of 58 hours flying helicopters, all of which were in the R22.

The accident flight

G–CHZN departed from Manston Airport at 0958 hrs for a flight to Fenland Airfield. It climbed to 2,000 feet amsl, passed Whitstable and crossed the Thames estuary tracking towards Southend Airport. Information on the route flown by the helicopter is shown in Figures 1 and 2. When north of the estuary, it descended to approximately 1,500 feet amsl and remained predominantly between 1,200 and 1500 ft amsl for the remainder of the flight. The helicopter continued north towards Earls Colne airfield and, after passing overhead, turned towards Cambridge. At 1056 hrs, the pilot contacted Cambridge Airport and asked to pass overhead, en route to Fenland. The controller instructed him to report when he was 5 nm from the airport.

The helicopter remained on track for Cambridge Airport until 1105 hrs when it was approximately 12 nm to the south-east, near the town of Haverhill. At this point the pilot turned 30° to the right onto a track of approximately 345°T, which took him towards Newmarket. At 1111 hrs, he reported to the controller that he was "5 MILES TO RUN" and confirmed that he was routing directly towards the overhead of Cambridge Airport. The controller gave the pilot an SSR code and, when he had identified G-CHZN on his radar, informed the pilot that he was

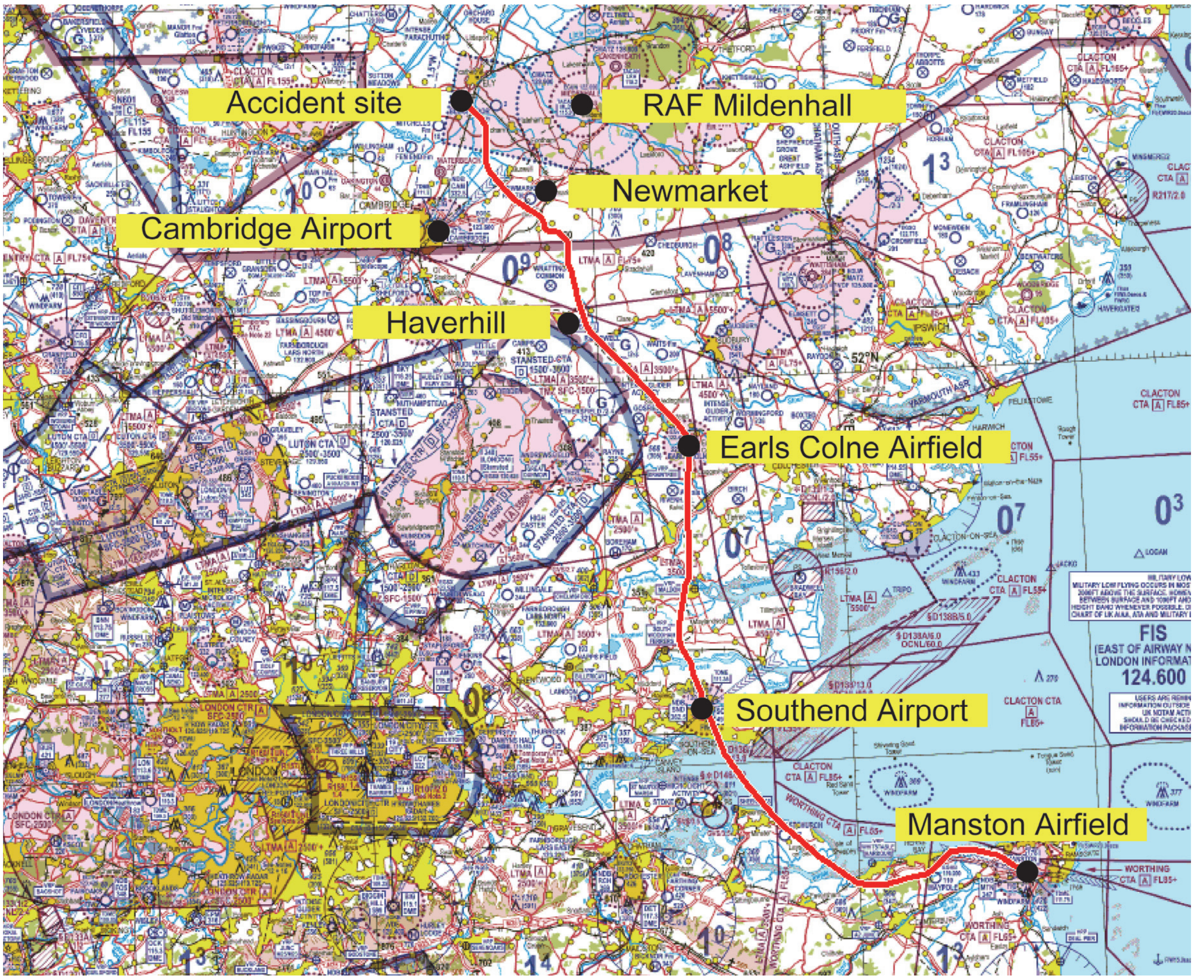

Figure 1

Track derived from GPS unit and radar data

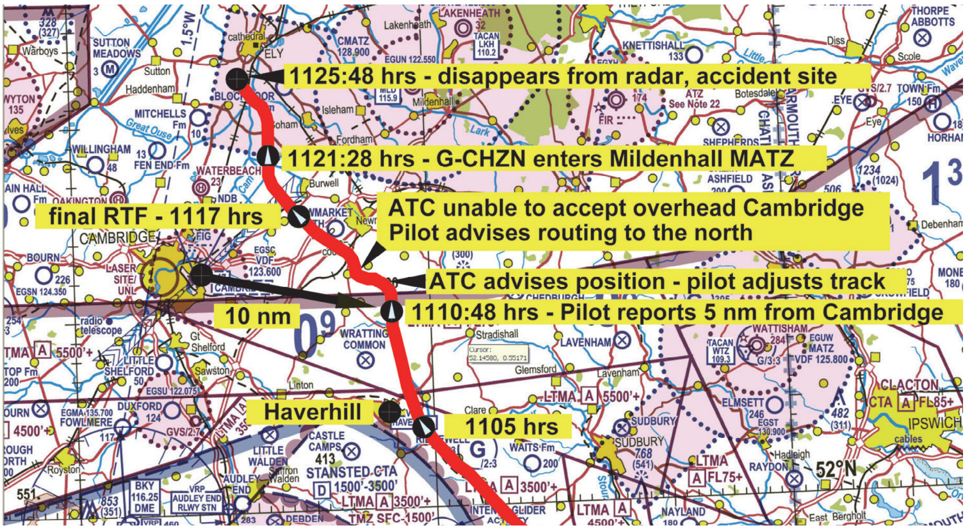

Figure 2

Information relating to the final 20 minutes of flight

10 miles east of Cambridge tracking north. The pilot replied: "AFFIRM, JUST TURNING LEFT". The controller transmitted that he thought the pilot had been lost and the pilot apologised.

At 1114 hrs, the controller told the pilot of G-CHZN that he would be unable to clear him through the overhead of the airport because of traffic in the circuit. The pilot acknowledged the information and turned towards Fenland. At 1118 hrs, the pilot reported his altitude as "ONE THOUSAND FOUR HUNDRED FEET, QNH 1026", which was the last radio transmission received from the helicopter.

At 1121 hrs, G-CHZN was on a northerly track when it entered the western stub of the Mildenhall Military Aerodrome Traffic Zone (MATZ). The helicopter was at 1,350 ft amsl and the MATZ stub extended from 1,033 ft to 3,033 ft amsl. At 1123 hrs, approximately 3 nm south of the town of Ely, the pilot turned left towards Fenland and, at 1125:48 hrs, G-CHZN disappeared from radar. Wreckage of the helicopter was found in a field 2 miles south-west of Ely.

Witness information

Two witnesses were standing approximately 600 m southwest of the accident site. One witness observed the helicopter fly over his farm at what he estimated to be 1,500 ft agl on a heading of approximately 300°(M). While he was watching, he thought the helicopter had started to perform some aerobatics because it suddenly began to roll left. The other witness also saw the helicopter roll to the left, and both heard a "pop as if it was a paper bag you banged in your hands". Both witnesses also saw objects separate from the helicopter. The helicopter then fell inverted to the ground without rotating about any axis. One of the witnesses thought that the helicopter engine sounded louder than most helicopters but was confident that the engine note was constant until the point when the helicopter rolled. The other witness thought that the helicopter pitched up before it rolled to the left.

A third witness was standing approximately 200 m southwest of the accident site. He heard a "backfire" or a "pop", which made him look around. He saw a puff of smoke and a few sparks and he thought the body of the helicopter remained intact. He did not see it roll and he was not aware of any rotor blades detaching from the helicopter.

Recorded information

Recorded information was available from radars at Stansted Airport, Debden and Cambridge Airport, a GPS[1] unit from the helicopter, and ground based radio telephony (RTF) recorders. Information from the GPS is shown in Figure 3.

Radar and GPS information

The radars at Stansted Airport, Debden and Cambridge Airport are located approximately 29 nm, 23 nm and 11 nm to the south of the accident site and recorded the helicopter's position at a nominal rate of once every four, six and five seconds respectively. The helicopter's transponder was transmitting Mode A information only as the Mode C function was inoperative, thus no altitude record was available from the radar recordings. The final radar positions were between 15 m and 220 m of where the helicopter's fuselage impacted the ground, with the last recorded position at 1125:48 hrs.

The GPS unit, which was normally attached to the top of the instrument panel in G-CHZN, was found 50 m away from the main wreckage. Although damaged, a track log of the flight was recovered containing aircraft GPS-derived position, track, altitude and groundspeed recorded at a nominal rate of once every thirty seconds. The GPS track log commenced at 0958 hrs as the helicopter departed Manston Airport and ended at 1125:20 hrs. The final GPS position was 875 m to the south-east of where the helicopter's fuselage impacted

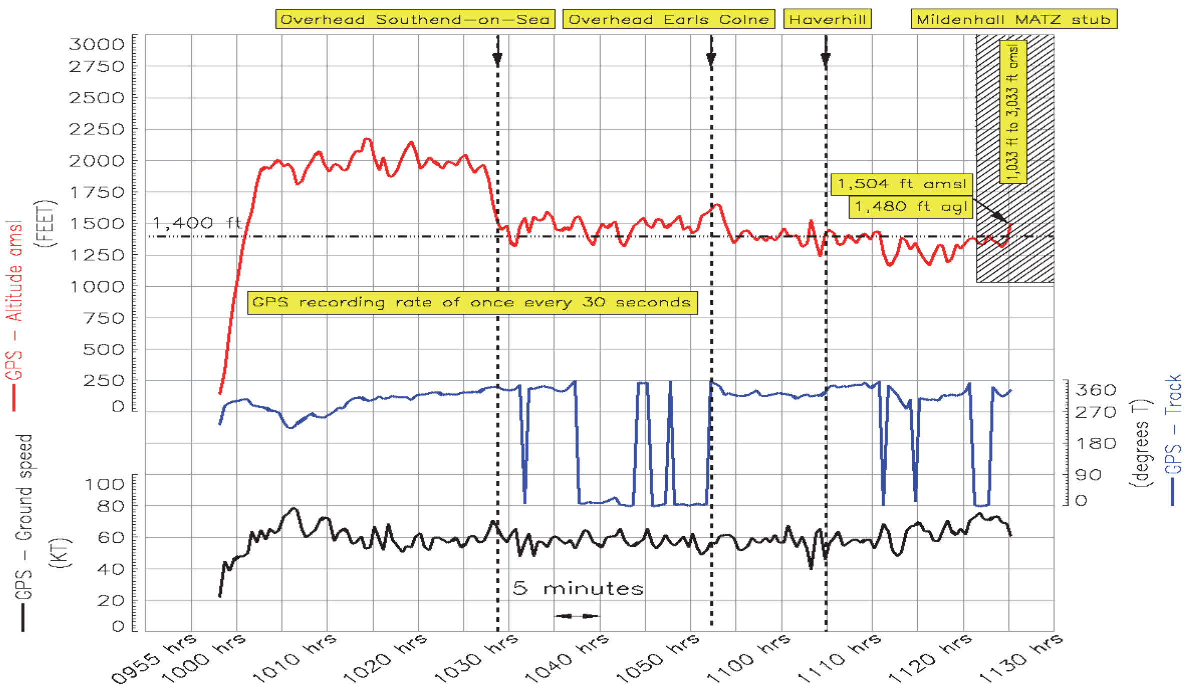

Figure 3

G-CHZN – GPS-derived information

Footnote

[1] Honeywell-manufactured Skymap IIIC.

the ground. There was a close correlation between the radar and GPS information.

Navigation using this GPS unit may be performed by programming a route, using the DIRECT TO[2] function, displaying the map, or a permutation of all three functions. Routes are stored within the memory of the GPS but no route had been programmed between Manston Airport and Fenland Airfield. It could not be determined whether the DIRECT TO function was being used or the map was being displayed as these settings were lost when the unit became disconnected from its electrical supply during the accident. Had the map been selected, the Mildenhall MATZ would have been displayed. The unit can provide an aural warning when entering airspace such as a MATZ but this function was selected OFF.

At 1125:20 hrs, the final GPS point was recorded with the helicopter at an altitude of 1,504 ft (approximately 1,480 ft agl) and on a track of 333°. The three radar tracks, which continued beyond the final recording of the GPS, indicated that the helicopter continued on a track of approximately 330° until it disappeared from radar at 1125:48 hrs. Due to the nominal accuracy of the radar and the low recording rate of the GPS unit, it could not be determined whether the helicopter made any sudden manoeuvres during this, or any other period of the flight.

Radio Telephony (RTF) information

RTF records were available from Manston, Southend and Cambridge Airports. The final series of transmissions were compared with those made earlier in the flight to determine if there were any inconsistencies or abnormalities in the background sounds that might have been generated by the helicopter's rotor system or engine. No inconsistencies or abnormalities were found.

The pilot did not refer to any problem with the helicopter's controls or engine during any of the radio transmissions.

Mobile phone information

It was established from mobile phone records that the pilot neither made nor received a phone call or electronic message during the flight.

Information about other aircraft or birds in the vicinity

Radar records from shortly before the accident were analysed to determine if G-CHZN might have encountered wake turbulence[3] from a nearby aircraft or if the pilot might have been required to alter the helicopter's flight path suddenly to avoid another aircraft, or birds.

When G-CHZN was last recorded by radar at 1125:48 hrs, the nearest aircraft was a Cessna 182 orbiting 2.5 nm ahead of it. The Cessna 182 was at an altitude of 2,600 ft, approximately 1,100 ft above the last recorded altitude of G-CHZN. In the three minutes before the accident, there was no record of any aircraft having flown within 1.7 nm of the accident site at an altitude of less than 10,000 ft. The fact that there was no radar record of any other aircraft in the immediate vicinity of G-CHZN did not exclude the possibility that birds were present.

Footnote

[2] A route may consist of a series of legs interspersed with waypoints, whilst the DIRECT TO function consists of just one flight leg. When the DIRECT TO function is in use, the GPS will display a track line for the pilot to follow. At any time, a new position on the map may be selected using the front-mounted joystick and a new track selected using the DIRECT TO option.

Footnote

[3] Both fixed- and rotary-wing aircraft generate vortices at the wing (or rotor) tips as a consequence of producing lift. The strongest vortices are generated by heavy aircraft flying slowly, and these pose the greatest risk to light aircraft (light is categorised as aircraft weighing less than 17,000 kg). In the most severe case, a complete loss of control may occur.

It is highly unlikely that G-CHZN encountered wake turbulence or that the pilot manoeuvred suddenly to avoid a conflicting aircraft. The possibility that the pilot manoeuvred suddenly to avoid birds could not be discounted.

Aviation pathology

The pilot received fatal injuries when the aircraft struck the ground. Post-mortem examination revealed that he had an undiagnosed medical condition which had the potential to cause intermittent symptoms such as palpitations, anxiety, tremor, headache and nausea, although there was no evidence that he had previously experienced these symptoms. The possibility that he experienced an acute episode of the symptoms in-flight could not be excluded entirely but was considered unlikely.

The pilot had a laceration on the palm of his right hand, which suggested that he was grasping something, most likely the cyclic control, at the time the aircraft struck the ground. This indicated that he was still conscious at the time.

Toxicological tests revealed no evidence of alcohol but no tests were carried out for drugs or carbon monoxide. However, examination of the exhaust manifold in the area of the cabin air heating shroud did not reveal any cracks that would permit a carbon monoxide leak.

Weather - Met Office report

The Met Office produced an assessment of the weather conditions that existed in the area at the time of the accident. A warm front was pushing into the west of the UK under a ridge of high pressure. The weather in the area of the accident was good, with visibility of 30 km or more and little cloud below 25,000 ft. The light, westerly wind did not appear to have been strong enough to generate low level turbulence. Mountain waves[4] were visible on the satellite picture over the southern Pennines and there was a very small possibility that their influence extended as far south-east as Cambridgeshire leading to areas of light turbulence. It was unlikely, however, that there would have been moderate turbulence at such a distance from the mountains.

Data from the Larkhill radiosonde[5], launched at 1000 hrs on 6 January 2012, suggested that the temperature in the area of the accident at 1,500 feet amsl was approximately 5°C and the dewpoint was approximately 0°C. Figure 4 shows that moderate or serious carburettor icing is possible at any engine power with this combination of temperature and dewpoint.

Aircraft description

The Robinson R22 Beta is a two-seat light helicopter powered by a four-cylinder carburetted Lycoming O-320-B2C piston engine (Figure 5). It has a standard mechanical collective and cyclic control system with no hydraulic assistance. The main rotor gearbox is driven by the engine via a sheave[6] and belt system and the main rotor consists of two all-metal main rotor blades connected to the main rotor hub by coning bolts at coning hinges[7]. The main rotor hub is mounted to the main rotor shaft with a teeter hinge located above the coning hinges (Figure 6) and blade pitch is

Footnote

[4] A mountain wave is a powerful air mass immediately downstream of a transverse mountain range, rotating about a horizontal axis. There can be a succession of such waves.

[5] Instrumentation for the measurement of atmospheric data, usually temperature, pressure and humidity, carried aloft by balloon.

[6] A sheave is a wheel with a groove for a belt to run on.

[7] The coning hinges are also referred to as flapping hinges. Flapping and coning both refer to motion of the blades about their hinge. 'Flapping' refers to the up and down motion of a single blade about its hinge during one rotation of the main rotor hub. Coning is the upward motion imparted to both blades by the combination of lift and the centrifugal reaction to rotation. The coning angle is the angle between the longitudinal axis of the rotor blade (assuming no blade bending) and the plane described by the path of the rotor tip (the rotor disc plane of rotation).

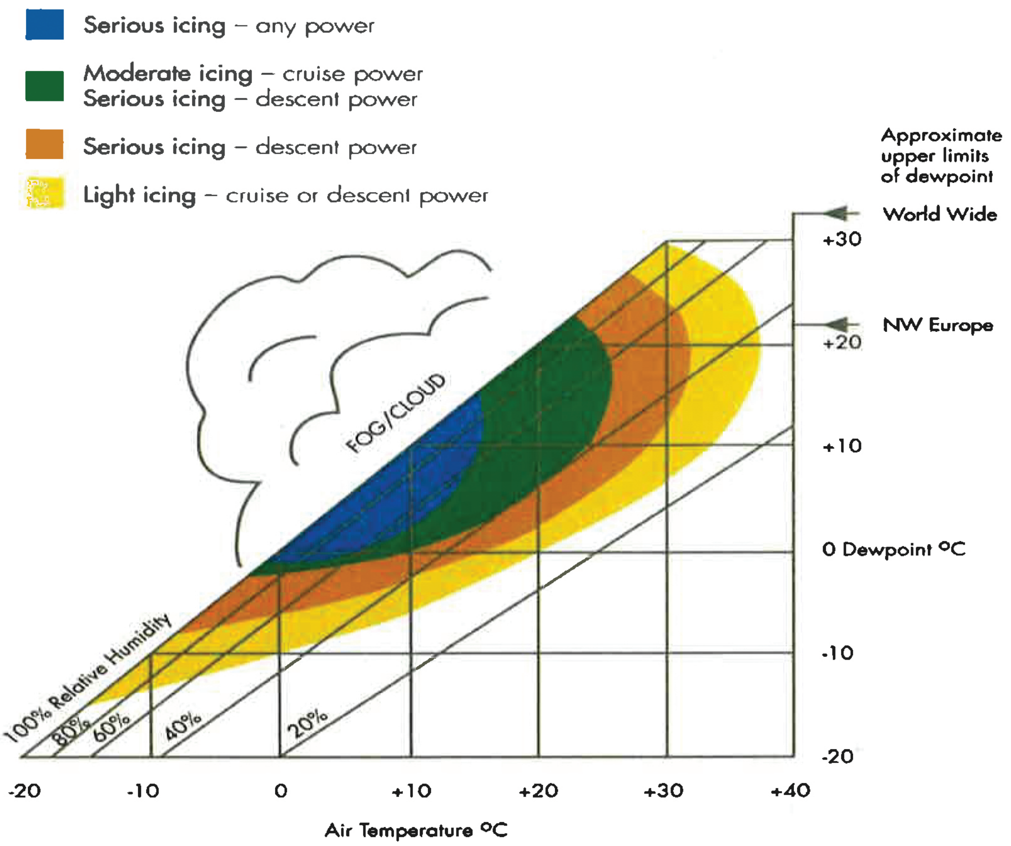

Figure 4

Carburettor Icing Chart

Extract from: CAA Safety Sense Leaflet 14
Piston Engine Icing

Figure 5

Accident aircraft - G-CHZN

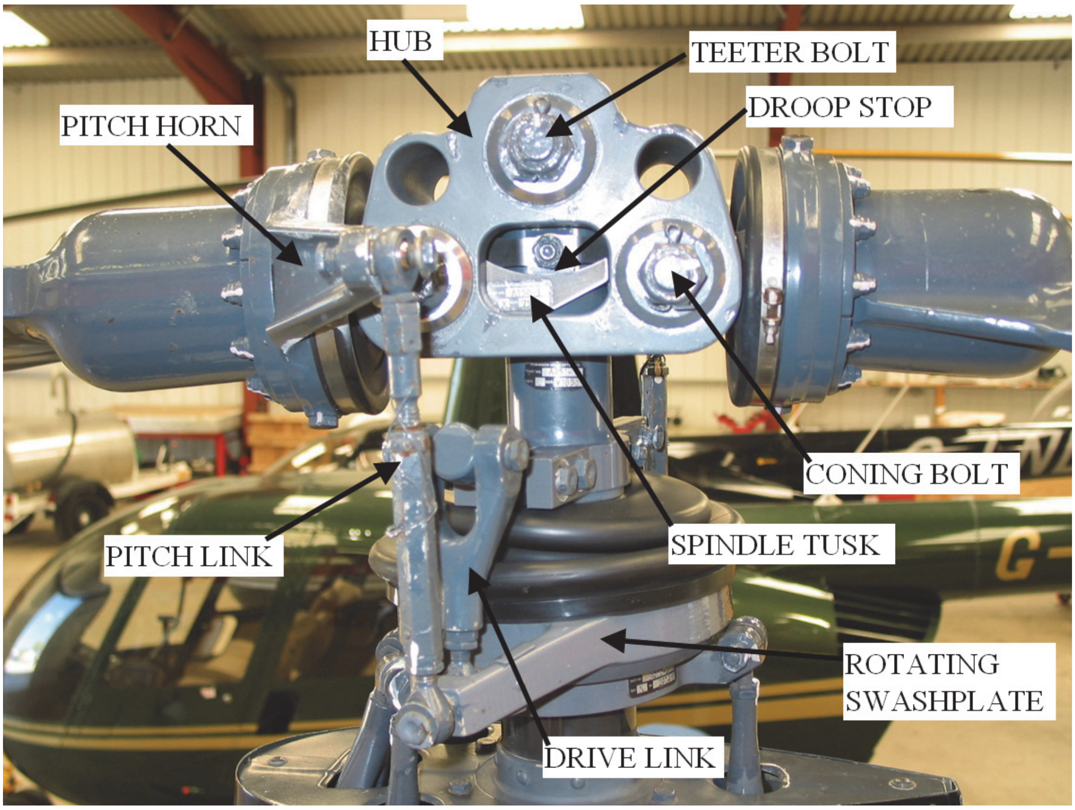

Figure 6

Robinson R22 Main Rotor Hub and Assembly

controlled by pitch links which connect the pitch horns to the rotating swashplate. The rotating swashplate is moved by the fixed swashplate, which is connected via push-pull tubes to the cyclic and collective controls in the cockpit.

The maximum authorised weight (MAW) of the R22 is 1,370 lb and G-CHZN's weight at the time of the accident was estimated at 1,206 lb (164 lb below the MAW).

Aircraft maintenance history

G-CHZN was manufactured in 1988 and had accumulated 6,407 hours on the airframe and 1,595 hours on the engine at the time of the accident. The aircraft's last maintenance check was a 50-hour check that was completed on 6 December 2011 (28 flying hours prior to the accident). No defects were found during this check apart from an inoperative landing light and inoperative navigation light. The previous check was a 100-hour check, completed on 20 October 2011, which did not involve any significant rectification work apart from replacement of the engine rocker cover gaskets. The aircraft's last annual maintenance check was on 16 May 2011 which included replacement of the drive belts. There was no record of the pitch control links having been disturbed in the year prior to the accident. The last known disturbance of the rotor system was when the main rotor blades were removed in April 2010 to replace the spindle bearings. The airframe's last overhaul was in September 2006, at 4,812 hours.

Accident site and initial wreckage examination

The main wreckage was found lying inverted in a field 2 miles south-west of Ely with its main rotor shaft buried in the ground (Figure 7). The lack of ground marks surrounding the wreckage indicated that the helicopter had struck the ground in an inverted attitude with very little horizontal speed. The main rotor (MR) blades were missing and one blade was found 315 m south-east of the main wreckage, in a hedge with its root embedded in the ground and its tip in the air (this will be referred to as MR blade No 1). The other MR blade was found 450 m east of the main wreckage lying flat in a field (this will be referred to as MR blade No 2). Both blades had separated from the main rotor hub at the coning hinge. Scattered along the length of a 500 m wreckage trail (Figure 8) orientated to the south-east of the main wreckage were multiple pieces of broken 'perspex' transparency and items from the cockpit. The left door, a small part of the right door and parts from the front left skid were located about 220 m from the main wreckage.

One tail rotor blade had separated near its root and was not found – the other tail rotor blade was still attached and intact but slightly bent. There was no evidence of the main rotor having struck the tail boom (tail boom separation following main rotor contact has been a characteristic of a number of R22 inflight structural failures). The vertical and horizontal tail assembly had detached and was resting on the ground 2 m aft of the tail rotor. All other significant parts of the helicopter were accounted for except for the pitch link from MR blade No 1 and its connecting bolts, and the heads of both coning bolts, which could not be located despite a detailed search in the fields.

Figure 7

Main wreckage

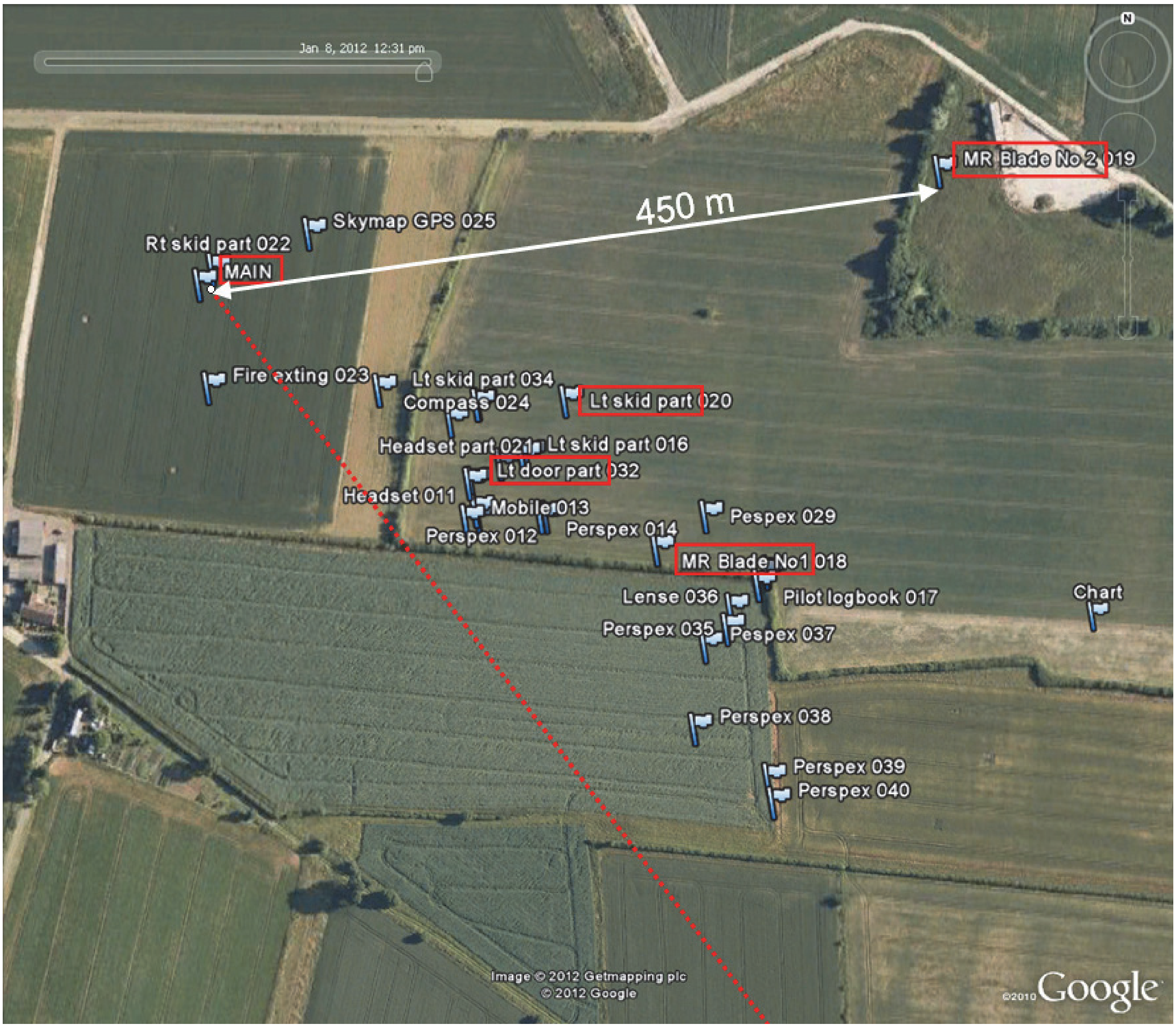

Figure 8

Wreckage plot overlaid with probable final track (dashed red line)
(*image copyright Google Earth ™ mapping service/Getmapping plc*)

Detailed wreckage examination

Airframe

The airframe was significantly disrupted from the inverted impact. Both fuel tanks had ruptured and there was no remaining fuel, although a small fuel sample was recovered from the filter bowl and it had the appearance and odour of 100LL AVGAS and was free of water. The left door, which had separated in flight, had its latch in the closed and locked position and its hinge pins were in place. The left door's structure had failed in overload around the hinges and the top rear quarter of the window frame had been sliced off. The right door was found to have separated from its hinge attachment when the helicopter struck the ground – its latch was in the closed and unlocked position. A small section of the upper rear corner of the right door window frame had been cut and had separated in flight. The left skid had failed in flight at the front, consistent with it having been struck by a solid object such as a main rotor blade. The damage to the tail boom, and separation of the vertical and horizontal tail assembly, was consistent with the ground impact loads.

The pilot had been seated in the right seat and his shoulder and lap harness were found to be secure. The left seat flying controls had been disconnected and were found stowed beneath the left seat. The bulb filaments from the warning and caution lights were examined for indications of 'stretch' which can indicate that a bulb was hot and therefore 'on' at impact, but no significant indications of stretch were found. The 'clutch light' caution bulb was too badly damaged to assess. The magneto switch was found set to the left magneto but the key was bent so it could have moved in the impact. The clutch switch was engaged and guarded and both the battery and alternator switches were ON. The governor switch was OFF but this is a small unguarded switch at the end of the collective and could have been easily knocked. The vertical speed indicator was pegged at its maximum indicated rate of descent, 2,200 ft/min, and the altimeter pressure setting was 1025 hPa. The carburettor temperature gauge had suffered internal damage and could not be tested. The carburettor hot air selector was found extended by 2 cm – full hot air extension was 6.5 cm.

Flight controls

A detailed examination of the flight controls revealed numerous overload failures of push-pull control tubes but all were consistent with impact forces. There were no flight control disconnects and no evidence of a control restriction.

Main rotor blades

MR blade No 1 was bent downwards in a curve (Figure 9) and its lower skin was crinkled along the full span while the upper skin was crinkled from mid-span outwards. The blade also had a slight aft bend near the tip. The leading edge of the blade was undamaged, but it had a few black and red smears. At about 2.36 m span there was light scuffing on the leading edge which could have been caused by contact with the left skid. At

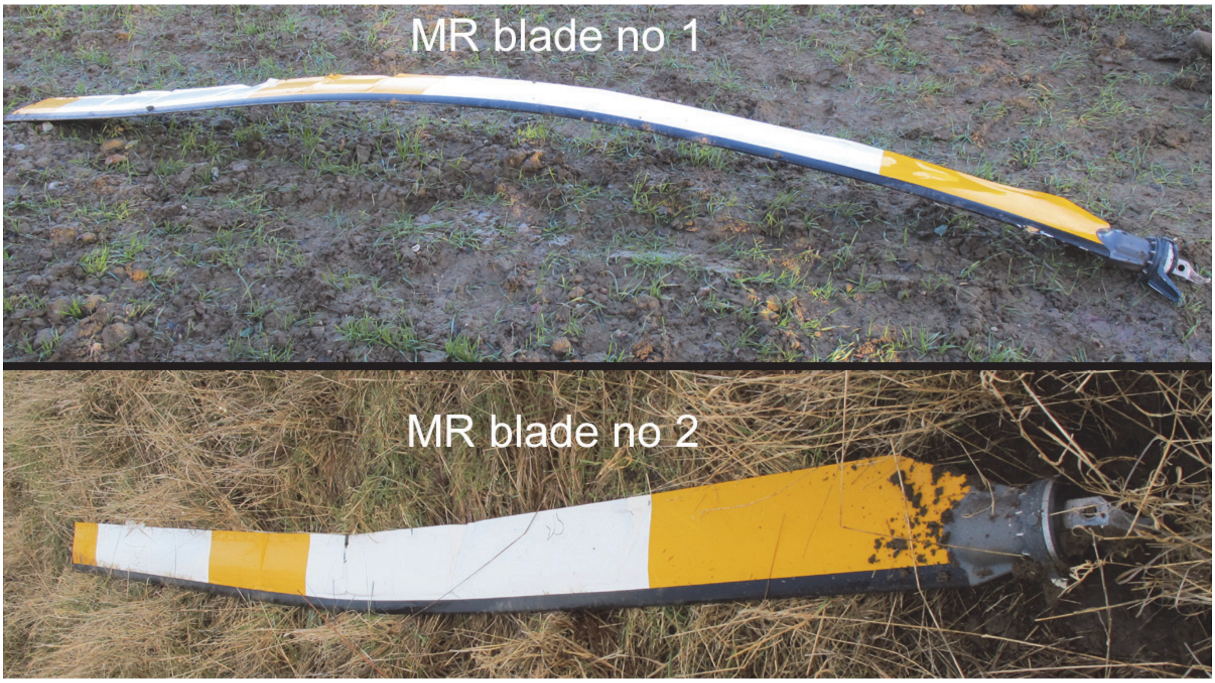

Figure 9

Main rotor blades No 1 and No 2 as recovered from the accident site the blade's root the spindle tusk was bent 'aft' by about 10° (aft meaning opposite to the direction of rotation). The pitch horn was intact, but slightly bent, and there were witness marks at the edges of the hole that had secured the missing pitch link bolt – this indicated that a force was applied to the bolt before it separated. The spindle bearings were free to rotate with no 'ratchety' feel.

MR blade No 2 was bent aft at about mid-span and had a crinkled upper and lower skin (Figure 9). There was no leading edge or tip damage, but there were a few red and white smears on the leading edge. The spindle tusk was bent aft by about 40°. The pitch horn had failed near the blade root and metallurgical examination of the fracture surface revealed that this was an overload failure. The separated pitch horn was still attached to the pitch link which was still attached to the rotating swashplate. The spindle bearings were free to rotate with no 'ratchety' feel.

Main rotor hub assembly

The main rotor hub was damaged as a result of the in-flight main rotor blade separations (Figure 10). The No 1 coning bolt had failed and was bent aft and the aft lug was also bent outwards. Metallurgical examination of the coning bolt fracture surface revealed that it had failed in overload with no evidence of fatigue. This evidence indicated that MR blade No 1 had separated following a radial and aft loading at the coning bolt that was in excess of design loads. MR blade No 2 had separated in a similar manner, failing the No 2 coning bolt in overload, and tearing the aft lug rearwards (Figure 10 – right image) – metallurgical examination of the hub fracture surfaces did not reveal any evidence of fatigue.

Both elastomeric teeter stops (Figure 10) were damaged and had split in the middle. This occurs when the blades flap downwards to an extreme angle and strike the mast and is known as 'mast bumping'. Witness marks on

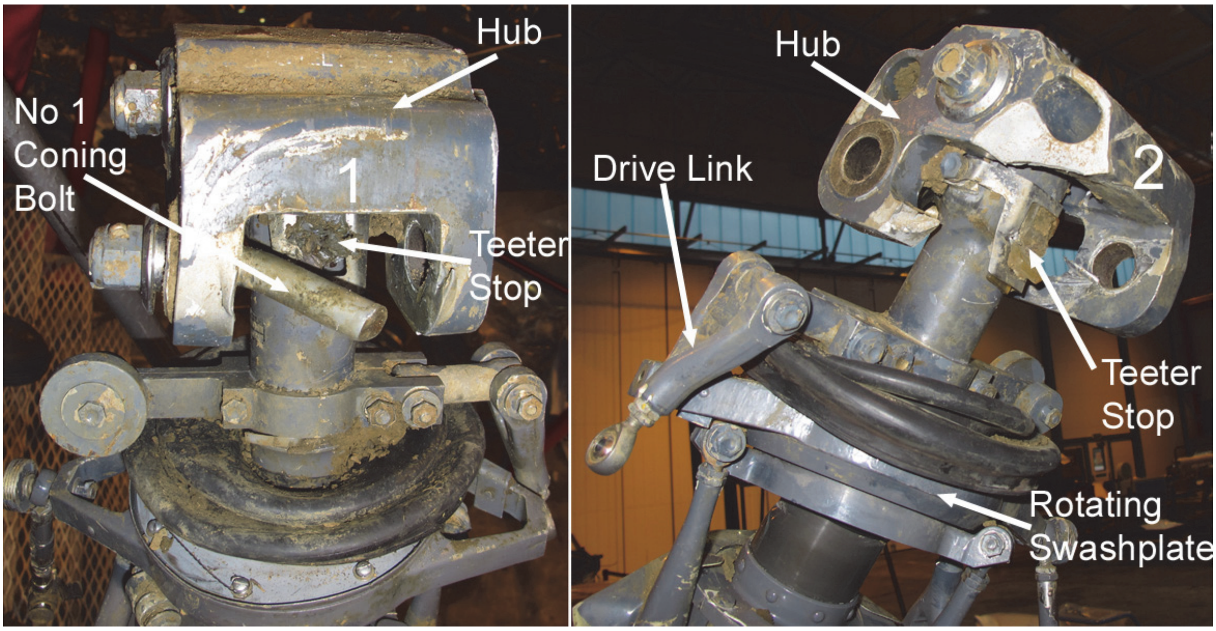

Figure 10

Main rotor head as recovered from accident site, showing damaged teeter stops and drive link disconnected from rotating swashplate the hub above the coning bolts also revealed that the blades had flapped upwards to an extreme angle and had struck the hub.

The No 1 pitch link had separated and the bolts at both the swashplate end and pitch horn end were missing. The pitch link bolt at the swashplate end secures the drive link to the swashplate through an eye end, so when this bolt separated the drive link detached from the swashplate as shown in Figure 10 (the drive link attaches on the inside of the swashplate, shown in Figure 6). Witness marks in the eye end of the drive link indicated that the bolt had been forced sideways and this lined up with a witness mark on the inside of the swashplate attachment hole. Such witness marks would not have been made if the nut had simply come off the bolt, or had broken, but the marks indicated that a high force was applied and therefore probably failed the bolt in overload. Similar witness marks at the pitch horn end of the pitch link indicated that this bolt probably also failed in overload, resulting in the separation of the No 1 pitch link. The No 2 pitch link was found still secured at both ends but had separated from the blade where the pitch horn had failed (Figure 11).

Rotary drive components

The main rotor gearbox and tail rotor gearbox were free to rotate. An inspection of the main rotor gearbox ring gear did not reveal any damage and there was no overheat indication on the 'telatemp' (thermal indicator) sticker. There was also no evidence of rotor brake overheat, indicating that the rotor brake was off. There were overload failures in the tail rotor shaft but no disconnects. The upper and lower sheaves were free to rotate and the 'sprag' clutch internal to the upper sheave was functioning. One drive belt had a clean cut through it but was otherwise undamaged indicating that it was probably cut during the impact. The other drive belt was undamaged, but had separated from the sheave as a result of overload failure of the clutch actuator. Although the clutch actuator had failed, it was found extended to a normal in-flight position.

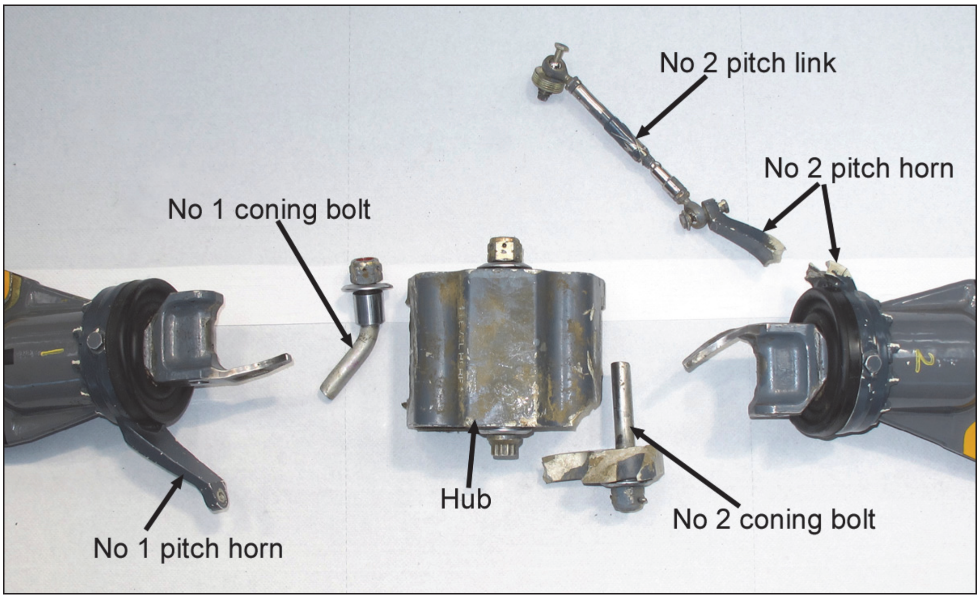

Figure 11

Main rotor blade roots, coning bolts, hub and No 2 pitch link
(No 1 coning bolt removed from hub, No 2 pitch link disconnected from rotating swashplate.
No 1 pitch link and coning bolt heads were not found)

Powerplant

There was an impact imprint on the upper sheave from five teeth on the engine's starter ring gear (Figure 12) which probably occurred when the helicopter struck the ground inverted, causing the engine to strike the sheave. If the engine had been running at impact then multiple scores on the upper sheave would have been expected, therefore the engine was probably not rotating at impact. Fuel flow from the fuel tanks to the engine is by a gravity-feed system with no fuel pump, therefore the helicopter's inverted attitude prior to impact could have interrupted the fuel flow and caused engine stoppage prior to impact. To determine if engine stoppage had been an initiating event to the accident a strip examination was carried out.

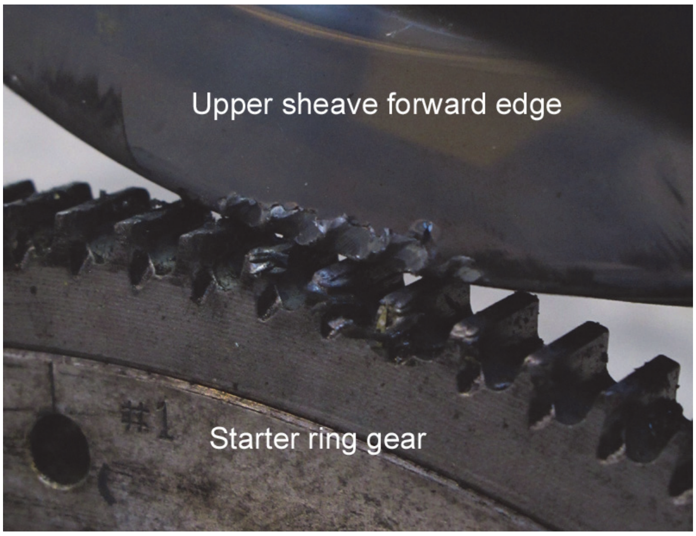

Figure 12

Impact imprint on upper sheave from starter ring gear

The engine had sustained damage to its upper surface in the impact and all the valve pushrods were bent. Once the pushrods were removed the engine could be rotated by hand but there was external impact damage to the No 4 cylinder wall which prevented full stroke of the No 4 piston. The No 4 cylinder was removed revealing an undamaged piston, which showed that the engine was not rotating when this impact damage occurred. With the No 4 cylinder removed the engine was free to rotate. The engine teardown did not reveal any mechanical faults, excessive wear or evidence of overheat, the spark plugs were in good condition and the valves actuated normally. The right magneto had broken off in the impact but when tested it produced a good steady spark from 105 rpm and up (minimum specification 150 rpm). The left magneto was loose but it had also suffered impact damage – it produced a good steady spark from 120 rpm and up.

The carburettor was removed from the engine and bench tested. There was a small leak from the inlet nut measured at about 0.5 l/hr but when the nut was tightened the leak stopped. It is possible that the inlet hose had been knocked in the impact loosening the nut, but if the leak had been present in flight it would have had minimal impact on engine performance because a typical cruise fuel flow rate is 8 US gal/hr (30.4 l/hr). All tests and measurements of the carburettor were within specification except for some wear on the body and mixture lever which would have resulted in a slightly over-rich setting with the lever in the 'full rich' position. However, this wear would have existed prior to the accident flight and no engine performance problems had been reported.

There were no disconnections in the throttle, mixture or carburettor heat control linkages. The carburettor heat selector moves a guillotine in the air box which slides between a cold air intake and a hot air intake. The guillotine was found positioned such that 73% of the area of the cold air inlet was open and 31% of the area the hot air intake was open (that is, more cold air than hot air was selected).

The electronic engine governor and motor, which adjusts the throttle to maintain the rotor rpm within the 'green band' limits, were removed for testing. The electronic governor casing had been slightly distorted by impact forces and the governor failed the 'acceptance procedure' bench test. An internal examination revealed that this was caused by a faulty input/output IC4 chip. When the chip was removed and replaced with a new one the governor passed all the specification tests. Examination of the IC4 chip revealed that the chip package material had become disbonded and several of the internal fine bond wires had broken. However, there was no discolouration of the die or melting of the bond wires, which would have been an indication of an electronic fault. Consultation with an electronics expert revealed that the package disbond was more likely to have been caused by impact loads than as a result of an electronic fault, but this could not be proven. The governor motor which actuates the throttle was also tested and found to operate normally within specification.

Causes of main rotor divergence

The evidence from the damage to the main rotor hub and to the teeter stops revealed that the main rotor blades had flapped to extreme up and down angles prior to separation. This extreme flapping is known as 'main rotor divergence' as the disk of the main rotor diverges from its normal plane of rotation. There are a number of factors that are known to cause main rotor divergence in helicopters with teetering two-bladed rotors such as the R22; they are 'Low-g manoeuvre', 'Low rotor rpm', 'Turbulence' and 'Large abrupt control inputs', and these are described as follows:

'Low-g manoeuvre'

A low-g manoeuvre results from pushing the cyclic forwards which causes the rotor disk to unload and generate less than 1g, making the pilot feel light in the seat. In a helicopter such as the R22, with a teetering rotor head, pitch and roll moments are generated by tilting the rotor thrust vector relative to the helicopter's CG. In a low-g manoeuvre this rotor thrust is reduced which reduces the pilot's ability to roll and pitch the helicopter. However, the tail rotor continues to produce thrust and will generate a right roll.[8] During this roll the rotor disk tilt angle lags behind the airframe roll rate, which reduces the flapping margin between the blades and mast on the left side of the helicopter. If a pilot then applies left cyclic to correct for the right roll this will have little effect on the roll rate but it will cause the rotor blades to flap down further on the left side of the helicopter, further reducing the flapping margin and possibly leading to mast contact ('mast bumping'), airframe contact and mast separation. The Robinson R22 Pilot's Operating Handbook (POH) states that the best way to avoid mast bumping is to avoid abrupt cyclic pushovers during forward flight and that if the pilot encounters a feeling of weightlessness, to bring the cyclic aft to regain main rotor thrust before applying lateral cyclic control.

'Low rotor rpm'

The flapping angle of a blade is determined by a combination of forces, principally the weight of the blade, the aerodynamic forces (lift and drag) and the centrifugal reaction to rotation. In normal flight the lift of a blade significantly exceeds its weight (each blade is lifting half the weight of the helicopter) but the centrifugal reaction prevents the lift from causing the blade to flap up to the hub stops. Two things can happen if the rotor rpm drops: both blades can flap up excessively as the centrifugal reaction reduces and the low rpm can result in rotor stall, with the retreating blade

Foonote

[8] The main rotor rotates counter-clockwise as viewed from above which creates a torque effect that tries to rotate the aircraft clockwise. This is countered by the tail rotor which produces a thrust to the right which creates a balancing counter-clockwise moment. When the aircraft is pitched nose down in a low-g manoeuvre, this tail rotor thrust acting above the CG causes the aircraft to roll right.

stalling first causing it to flap down excessively[9]. The end result is main rotor divergence which can lead to the blades striking the mast and/or parts of the airframe.

Low rotor rpm can be caused by an engine failure, or loss of engine power, if it is followed by a delay in the pilot lowering the collective to maintain rotor rpm. Low rotor rpm and blade stall can also be caused by the pilot pulling up excessively on the collective, which causes the main rotor blades to pitch up excessively ('over-pitching') and results in the drag on the blades exceeding the engine power available. This is more likely to occur at high weight and high altitude where the rotor blades are already operating at high pitch angles.

Turbulence

Flying in turbulence can lead to the rotor experiencing large vertical gusts of wind. A large gust downwards through the rotor disc can lead to unloading of the rotor, which could result in low-g, and a large gust upwards would load the rotor and increase the blade angle of attack. These situations can be exacerbated if the pilot over-controls the helicopter in the turbulence, because over-controlling can result in excessive blade flapping and main rotor divergence (see next paragraph). The R22 POH states that 'Flying in high winds or turbulence should be avoided' but that if it is encountered the airspeed should be reduced to between 60 and 70 KIAS.

Large abrupt control inputs

A very large and abrupt control input in either pitch or roll could cause the rotor hub to teeter excessively about the teeter bolt and result in the blades striking the mast and/or airframe. There is no force feedback in the control system, other than a bungee in the pitch axis, so only light forces are required to apply full cyclic deflection in pitch or roll. As previously discussed, a large abrupt upwards collective deflection could also cause blade stall. Full abrupt cyclic control deflections have never been flight tested on the R22 because of the risk to flight safety but simulator studies confirm that mast bumping and blade stall could occur. A study by the US National Transportation Safety Board (NTSB) (discussed later) stated that:

> *'Large, abrupt control inputs can lead directly to mast bumping or induce blade stall, which, in turn, can lead to mast bumping.'*

Based on an analysis of an R22 accident in Richmond, California, a study by Bell Helicopters and a study by the Georgia Institute of Technology, the NTSB concluded that:

> *'the low inertia main rotor blade can diverge from normal rotation to strike the body of the helicopter in just a few revolutions of the blade. This would take less than 0.5 seconds when the blade is operating at a normal rate of 530 rpm. Thus, unless the instructor is actually holding the cyclic handle and preventing a large, abrupt input, there is insufficient time for the instructor to react once a student makes such an input.'*

Aircraft manufacturer's explanations of the evidence

The aircraft manufacturer's accident investigators were consulted during the investigation and the rotor head components and main rotor blade roots from G-CHZN were taken to the aircraft manufacturer for examination. They commented that main rotor blade separation at the coning bolt was unusual but that they had seen it before. They did not consider the evidence

Footnote

[9] In the low rpm case, it is the retreating blade that will stall first with the helicopter in forward flight because it has a lower airspeed than the advancing blade and therefore is at a higher angle of attack to maintain the same lift as the advancing blade.

to be indicative of an overspeed situation as rotor overspeed usually results in 'brinelling' of the spindle bearings creating a 'ratchety' feel when rotated, which was not the case in G-CHZN. They stated that the coning bolts probably failed as a result of aerodynamic loads being applied to rotor blades that had pitched up or down to 90°. Failure of the pitch links would allow the blades to pitch to any angle, and the coning bolts are not designed to withstand the drag loads on a blade that had pitched to 90°, the upper or lower surface being presented flat to the airstream like a paddle. The aft bending (opposite the direction of rotation) of the coning bolts and hub lugs supports this theory.

To explain the failure of the No 1 pitch link, the manufacturer set up a rig of an R22 main rotor head assembly (Figure 13), with the elastomeric teeter stops removed to simulate the geometric situation following mast bumping where the stops have been split and the blade root is striking the mast. Normally the pitch link is aligned vertically, perpendicular to the plane of rotation, and experiences pure tensile and compressive loads, but at extreme teetering angles the pitch link tilts aft. This allows bending loads to be applied to the pitch link and retaining bolts. The aerodynamic forces during rotor blade divergence could be sufficient to pitch the rotor blade further nose down than in Figure 13, which would force the pitch link down and fail the lower attachment bolt in a downwards and forward direction. This was consistent with the witness marks found in the swashplate attachment hole and the eye end of the drive link.

Failure and separation of the No 1 pitch link lower attachment bolt would have resulted in a loss of drive to the rotating swashplate, because the same bolt secures the drive link. This would cause the rotor to 'overtake' the swashplate which would have caused a nose down pitching moment of blade No 2 as the No 2 pitch link lower attachment bolt lagged behind the upper bolt. It is possible that separation of MR blade No 2 followed this sequence and that it was blade separation that caused the pitch horn to fail.

The physical evidence could, therefore, be explained by main rotor divergence and subsequent mast bumping but there was insufficient evidence to determine the cause of the main rotor divergence. The aircraft manufacturer considered that low rpm was more likely than low-g because the forces on the mast in the low-g situation are more likely to fracture the mast and shaft causing the head to separate, which did not occur in G-CHZN. The manufacturer also considered that low rpm would be required to cause a blade to flap up sufficiently to cause the No 1 pitch link to separate in the manner described.

Figure 13

R22 rotor head with elastomeric teeter stops removed to simulate the static geometry when mast bumping occurs. The MR blade on the left has been pitched to the maximum nose-down position that could be attained with hand force – the pitch link is no longer 'over-centre'

The manufacturer agreed that more evidence is required to fully understand the causes of accidents involving main rotor divergence, and is investigating the feasibility of installing a small lightweight (non crash-protected) flight data recorder on the R22, R44 and R66. The technology already exists to create a small light-weight recorder that includes solid-state 3-axis gyros, 3-axis accelerometers, GPS and an altitude pressure sensor, but one of the challenges is to develop a lightweight and non-invasive means of measuring control positions.

The manufacturer also plans to carry out research on carburettor icing using an environmental chamber and to test the effects of installing a heated throttle butterfly in the carburettor.

Safety information - Robinson R22 Pilot's Operating Handbook

Section 10 of the R22 POH contains Safety Notices that warn pilots about the handling characteristics explained in the previous paragraphs. The Safety Notices are reproduced in full in Appendices A to F but certain sections are discussed below.

Safety Notice SN–10, *Fatal Accidents Caused by Low RPM Rotor Stall* states:

> *'A primary cause of fatal accidents in light helicopters is failure to maintain rotor RPM. No matter what causes the low rotor RPM, the pilots must first roll on throttle and lower the collective simultaneously to recover RPM <u>before</u> investigating the problem.'*

Safety Notice SN-11, *Low-g Pushovers – Extremely Dangerous,* states:

> *'Pushing the cyclic forward following a pull up or rapid climb, or even from level flight, produces a low-g (weightless) flight condition. If the helicopter is still pitching forward when the pilot applies aft cyclic to reload the rotor, the rotor 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 a powerful right rolling moment on the fuselage. With no lift from the rotor, there is no lateral control to stop rapid right roll and mast bumping can occur. Severe in-flight mast bumping usually results in main rotor shaft separation and/or rotor blade contact with the fuselage.'*

Safety Notice SN-24, *Low RPM Rotor Stall Can Be Fatal,* states:

> *'As the RPM of the rotor gets lower, the angle of attack of the rotor blades must be higher to generate the lift required to support the weight of the helicopter. As with the aeroplane wing, the blade aerofoil will stall at a critical angle, resulting in a sudden loss of lift and a large increase in drag. The increased drag on the blade acts like a huge rotor brake, causing the rotor RPM to rapidly decrease, further increasing the rotor stall.'*

In a fixed-wing aircraft, a pilot's reaction to a stall warning horn would be to reduce the angle of attack of the wing by moving the control column forward and to add power. Safety Notice SN-29, *Airplane Pilots High Risk When Flying Helicopters,* states:

> *'In a helicopter, application of forward stick when the pilot hears a horn (low RPM) would drive the RPM even lower and could result in rotor stall, especially if he also "adds power" (up collective). In less than one second the pilot could stall his rotor, causing the helicopter to fall out of the sky.'*

In order to descend, for example to avoid a bird or other aircraft, a fixed-wing pilot would push the control column forward whereas a helicopter pilot should lower the collective lever with very little movement of the cyclic control. Safety Notice SN-29 states:

> *'A rapid forward movement of the helicopter cyclic stick under these conditions would result in a low "g" condition which would cause mast bumping, resulting in separation of the rotor shaft or one blade striking the fuselage.'*

Carburettor icing typically causes a loss of rpm or manifold pressure. Safety Notice SN–31, *Governor Can Mask Carb Ice*, states:

> *'The governor will automatically adjust throttle to maintain constant RPM which will also result in constant manifold pressure.'*

The flying training organisation that prepared the pilot to gain his PPL(H) reported that he had shown a good understanding of the issues discussed in this section of the report. In addition, it commented that he was cautious, had "completely and utterly the right attitude" and was not overconfident. The operator from which the pilot hired G-CHZN also commented that the pilot understood these issues.

Special regulatory requirements for R22 operation

Special Federal Aviation Regulation (SFAR) Number 73

In March 1995 the FAA introduced SFAR 73, as an Emergency Rule, which gives special requirements for pilots in the USA wishing to fly the R22 helicopter[10]. The requirements were introduced to ensure that pilots flying the helicopter were aware of, and trained to respect, the handling characteristics previously explained in this report. The rule was due to expire on 31 December 1997 but was extended twice and in June 2009 was made permanent.

SFAR 73 required (and continues to require) awareness training to be undertaken to cover energy management, mast bumping, low rotor rpm (blade stall), low-g hazards and rotor rpm decay. In addition, no person could act as PIC of an R22 helicopter unless that person had already obtained at least 200 hours flying helicopters, at least 50 hours of which were gained in the R22. Alternatively, a pilot required at least 10 hours of dual instruction in the R22 before being cleared to fly as PIC. Every 12 months, a pilot must undergo a check flight, which must include training in advanced autorotation, engine rotor rpm control without the use of the governor, low rotor rpm recognition and recovery, and the effects of low-g manoeuvres and proper recovery procedures.

The CAA informed UK owners/operators of the R22, in *Letter to Owners/Operators (LTO) 1485,* that the awareness training specified by SFAR 73 was adequately covered by the existing CAA-recognised flight crew training syllabus. In addition:

Footnote

[10] SFAR No 73 also applies to the Robinson R44 helicopter, a larger four-seat version of the R22 employing the same rotor head system.

'Provided that they have accumulated at least 200 flight hours on helicopters, at least 50 hours of which are on the specific type (R22 or R44) being flown, UK licensed helicopter pilots are deemed to have completed the awareness training.'

The European Aviation Safety Agency (EASA) does not issue helicopter class ratings and, before flying the R22 as PIC, a pilot must undergo a type rating course (or the PPL(H) course leading to a type rating) and the rating must be renewed every 12 months. However, the theoretical elements that are mandated in SFAR 73 are not present in the PPL syllabus. EASA Safety Information Bulletin 2009–35 recommended that SFAR 73 training be implemented for Robinson helicopter training in EU states. In response, EASA proposes to incorporate awareness training in the PPL(H) syllabus by amending the Annex, *Acceptable Means of Compliance and Guidance Material to Part–FCL,*[11] to ED Decision 2011/016/R[12].

FAA Airworthiness Directive (AD) 95–26–04

In 1995, FAA Airworthiness Directive (AD) 95–26–04 was issued to prevent main rotor stall or mast bumping leading to loss of control of R22 helicopters. Limitations were added to the POH, which were to be observed unless the pilot had logged 200 or more flight hours in helicopters, at least 50 which were gained in the R22, and had completed the awareness training specified in SFAR 73. The limitations were:

'(1) Flight when surface winds exceed 25 kt, including gusts, is prohibited.

(2) Flight when surface wind gust speeds exceed 15 kt is prohibited.

(3) Continued flight in moderate, severe, or extreme turbulence is prohibited.'

NTSB study of Robinson R22 main rotor loss of control accidents, 1996

In April 1996 the US NTSB published '*Special Investigation Report – Robinson Helicopter Company R22 Loss of Main Rotor Control Accidents*' (NTSB/SIR-96/03) which examined a number of R22 'loss of main rotor control accidents'[13] and made recommendations intended to prevent recurrence. The study determined that, between 1981 and 1994, the rate for R22 fatal accidents involving loss of main rotor control or loss of control for unknown reasons (LOC[14]) was 1.509 per 100,000 flight hours, three times higher than for the next highest helicopter.

The study was also prompted, in part, by an R22 accident in 1992[15] which involved an in-flight breakup that resulted in the tail boom and the mast assembly (with blades attached) separating from the airframe. In this accident, involving an instructor and student pilot, spectral analysis of an audiotape that was onboard revealed that the rotor rpm was normal and did not decay before the breakup. Examination of the wreckage did not reveal any evidence of a pre-impact control

Footnote

[11] Acceptable Means of Compliance and Guidance Material to Commission Regulation (EU) No 1178/2011 of 3 November 2011 laying down technical requirements and administrative procedures related to civil aviation aircrew pursuant to Regulation (EC) No 216/2008 of the European Parliament and of the Council.

[12] Decision Number 2011/016/R of the Executive Director of the European Aviation Safety Agency dated 15 December 2011.

Footnote

[13] The study uses the term 'loss of main rotor control' which is essentially the same as 'main rotor divergence'.

[14] The NTSB defined LOC as '*involved an in flight: loss of main rotor control; structural failure of the main rotor blade that did not involve pre-existing fatigue of rotor blade materials; or, loss of aircraft control or collision with terrain for unknown reasons, in the absence of structural failure, encounter with instrument meteorological conditions, or pilot impairment due to drugs or alcohol.*'

[15] Accident to Robinson R22 (registration N83858) on 29 June 1992 near Richmond, California, USA.

system or airframe failure that might have initiated the breakup. The NTSB could not find evidence of a specific event that caused or allowed the main rotor blades to diverge from their normal flightpath plane and strike the airframe - there was no loss of rotor rpm and the circumstances did not support a deliberate low-g manoeuvre. This accident remains unexplained.

Between 1981 and the publication of their study in 1996 the NTSB investigated or researched 31 R22 and three R44 accidents involving in-flight loss of main rotor control and contact of the main rotor blades with the tail boom or fuselage.

The NTSB also conducted a detailed examination of six of its most recent (at the time) R22 accidents involving loss of main rotor control and determined that most of the damage occurred after the main rotor blades began to diverge from their normal plane of rotation. The NTSB was aware of only two cases in which an R22 exhibited signs of significant mast bumping and was able to land. The report stated that:

> *'once over-teetering and mast bumping occurs, structural failure of the main rotor mast or shaft is highly likely and would be quickly followed by overload of the pitch control system of the blade. The available wreckage from all six accidents is consistent with this scenario.'*

The report details a number of R22 technical reviews and studies that were carried out by the US Federal Aviation Administration (FAA) in the 1980s and 1990s. These resulted in the new pilot training requirements (SFAR 73), and aircraft modifications (an electronic governor and an increased 'low rpm' warning threshold) primarily to address the issue of accidents caused by loss of rotor rpm. Other than the training requirements, there were no changes made to address the issue of low-g or large abrupt control inputs which are the other possible causes of main rotor divergence.

The first two safety recommendations (A-96-9 and A-96-10) in the NTSB's report concerned pilot training requirements and they were accepted and implemented by the FAA. The third recommendation (A-96-11) concerned certification requirements and followed from a paragraph in the body of the report which stated:

> *'The Safety Board believes that the FAA should require helicopter manufacturers to provide data on the response of helicopters to large, abrupt cyclic inputs as a part of the certification process and require operational limitations or other measures for those helicopters that are more responsive, such as the R22.'*

The safety recommendation to the FAA (A-96-11) stated:

> *'Require helicopter manufacturers to provide data on the response of helicopters to flight control inputs to be used as part of the certification process, and require operational limitations or other measures for those helicopters that are highly responsive.'*

Recommendations A-96-12 and A-96-14 asked the FAA and NASA respectively to develop a:

> *'simulator model of lightweight helicopters, using flight tests and whirl tower tests as needed to validate the model, to create a national resource tool for the study of flight control systems and main rotor blade dynamics.'*

Responses to recommendations in the NTSB study

The FAA's response to recommendation A-96-11 was to amend Advisory Circular (AC) 27.661, which concerns 'Rotor Blade Clearance'. The relevant procedure stated that testing for blade clearance compliance should be conducted:

> *'in all areas of the envelope during all operational manoeuvres expected throughout the life of the aircraft'*

and should include a blade flapping survey to determine flapping angles/margins, blade bending, and blade clearance from the entire airframe, and it should determine what margins exist at low rpm.

The AC did not define a flight envelope or define what:

> *'all operational manoeuvres expected '*

were and neither did it define what clearance margins would be acceptable. It did not specifically require that data be gathered on the response to large, abrupt cyclic inputs as originally intended by the NTSB study. Nevertheless, the NTSB closed this recommendation in March 2000 and recorded '*Acceptable Action*'.

In response to recommendations A-96-12 and A-96-14, NASA awarded a contract to Advanced Rotorcraft Technology Inc., to conduct a one-year study of '*Rotor Dynamics Analysis of Light Helicopters*'. The study involved the development of a simulator model closely based on the R22 and included an analysis of the blade response following gust inputs. The study did not identify any inherent dynamic problems for a two-bladed rotor with a teetering hub and offset flapping hinge; however, it stated that the results could not be validated because appropriate flight and wind tunnel test data was not available, particularly at high angles of attack and sideslip. The investigation into the response following large abrupt control inputs was limited. The study made a number of recommendations for further work, including gathering experimental data and modelling the elastic properties of rotor blades, which could affect the blade-to-airframe clearance in extreme manoeuvring. After reviewing the study, the NTSB closed the safety recommendation and stated that:

> *'Although R22 helicopters are not accident free, the operating envelope and more stringent weather/training requirements imposed by the FAA appear to have greatly reduced instances of loss of main rotor control for R22s. The Safety Board is persuaded that the results of the NASA study indicate that there is no justification for flight or wind tunnel testing at this time.'*

R22 main rotor loss of control accidents since the NTSB study

The 1996 NTSB study stated that following the FAA's implementation of new operational, experience and training requirements for R22 pilots (SFAR 73 and AD 95-26-04):

> *'There have been no in-flight rotor/fuselage contacts of the R22 in the United States in the past year since the changes were implemented. Although the Safety Board cannot conclude that the operational changes will eliminate all in-flight rotor strikes, the absence of such accidents since these actions were implemented suggests that they have been effective.'*

However, since the NTSB study was published in 1996, there have been at least 16 fatal R22 accidents involving loss of main rotor control, including G-CHZN

(Appendices G & H) – 10 in the USA and 6 elsewhere. Out of the 10 accidents in the USA, one is still under investigation, and three were concluded to have been caused by '*Main rotor divergence for undetermined reason*.' Out of the 16, three were attributed to possible turbulence, five to possible low rpm, and one to low-g. Two of the accidents involved separation of a single main rotor blade at the coning bolt and one accident, in addition to G-CHZN, involved separation of both main rotor blades at the coning bolts (Appendices G & H): In this accident (N7779M, near Del Valle, Texas, 27/6/2011) a pitch link was found to have separated due to failure of the bolts at both ends (Figure G2 in Appendix G).

Light helicopter stability and control requirements

The certification requirements for light helicopters are contained in EASA Certification Specification CS-27 and in the USA equivalent, FAA Aviation Regulation (FAR) Part 27. The regulations require that the rotorcraft '*must be safely controllable and manoeuvrable*' during various flight conditions. Flight controls may not exhibit excessive breakout force or friction, but there are no restrictions on how light the control forces can be. In terms of static longitudinal stability a rearward movement of the control must result in a reduction in airspeed and a forward movement must result in an increase. However, there are no stability-related stick force requirements for light helicopters, unlike for light fixed-wing aircraft where there is a requirement to demonstrate that the stick force varies with speed (CS-23 and FAR-23). For light fixed-wing aircraft there are requirements to demonstrate that any short-period oscillation is heavily damped and any long-period oscillation must not be so unstable as to cause unacceptable pilot workload; there are no equivalent dynamic stability requirements for light helicopters.

In November 2005 NASA published a report on '*The Implications of Handling Qualities in Civil Helicopter Accidents Involving Hover and Low Speed Flight*'[16], co-authored by the Deputy Director of the National Rotorcraft Technology Center at NASA. The study considered hover, hover-taxi and low speed accidents, which occurred mainly on helicopters that had no stability augmentation. Out of 547 accidents analysed, 126 (or 23%) '*could be attributed to loss of control by the pilot which was caused or aggravated by inadequate or deficient handling qualities*.' The report stated that the FAA:

> *'imposes standards for handling qualities as defined in the Federal Aviation Regulation (FAR) Part 27; however, these require only minimal standards. Military helicopters must meet the requirements of ADS-33D-PRF which are more stringent than those of the old MIL-H-8501.'*

The report concluded that:

> *'From the accidents reviewed, and the other statistics on civil helicopter accidents attributed to loss of control, it is puzzling why poor handling qualities have not been pinpointed as causes or factors in the accidents. Improvements in handling qualities were not even recommended, within the scope of this research, as a means or investment in safety to reduce the frequency of such accidents.*
>
> *It can be inferred that a significant reduction in accidents, injuries, and property damage*

Footnote

[16] '*The Implications of Handling Qualities in Civil Helicopter Accidents Involving Hover and Low Speed Flight*' (TM-2005-213473) by Daniel Dugan, Deputy Director of the National Rotorcraft Technology Center at NASA Ames, and Cdr Kevin Delamer, Navy Liaison Officer at the same centre.

> *could be achieved by the integration of stability augmentation systems into the control systems of the lower priced helicopters.'*

The report goes on to recommend that:

> *'The feasibility of designing or incorporating a low cost, lightweight stability augmentation system should be explored by the helicopter manufacturers. Today's technology may provide the means to accomplish a goal of significantly improving the handling qualities of their helicopters. Where a hydraulic system is not practical for inclusion in the design, the technology exists to provide the secondary or automatic flight control system functions with small electrical actuators.'*

Additional information - Stability augmentation systems for light helicopters

In November 2009 Cobham PLC obtained a supplemental type certificate (STC) for the installation of a stability augmentation system called HeliSAS on the larger Robinson R44 helicopter. This system is an 'attitude command'/'attitude hold' augmentation system and includes force feedback. It can maintain the helicopter in a cruise attitude or in a hover with the pilot's hands free of the cyclic. Pilot-applied cyclic force is required to manoeuvre the helicopter away from the trim condition and releasing the cyclic will result in the helicopter automatically returning to the trim condition. The system was tested by the aircraft manufacturer, by a NASA test pilot and by a test pilot from the National Test Pilot School in 2005, and '*very favourable*' comments were received (ref NASA report TM-2005-213473). The system tested weighed 5.5 kg and had a projected cost in 2005 of $30,000 (ref NASA report TM-2005-213473).

The HeliSAS system is not currently available for purchase on the R44 and has not been designed for the R22, but it is an available modification for the Bell 206, Bell 407 and Eurocopter AS350.

Additional information - Pilot reaction times following a loss of power in single-engine helicopters

A significant factor in R22 accidents involving loss of engine power is the short time period a pilot has to lower the collective lever and enter autorotation before the rotor enters an unrecoverable stalled condition. The time available for a pilot to respond to a loss of power is primarily a function of rotor design and the inertia in the rotor system. The R22 rotor blades have relatively low inertia compared to larger helicopters. The certification requirements in CS 27.143(d) and FAR 27.143(d) state that, after complete engine failure, a single-engine rotorcraft must be controllable with a corrective action time delay following power failure of at least:

> *'(i) For the cruise condition, one second, or normal pilot reaction time (whichever is greater); and*
>
> *(ii) For any other condition, normal pilot reaction time.'*

'Normal pilot reaction time' is not defined in the regulations but according to the CAA a figure of 0.3 seconds is typically used. Therefore, a minimum of 1 second reaction time is required in cruise and only 0.3 seconds in any other flight condition.

During manufacturer flight testing of the R22 in 1982, the collective lever was lowered approximately 1.6 seconds after a 'power chop' during the cruise, and one second during the climb, to demonstrate that the helicopter met the certification requirements. Time delays beyond these would have risked stalling the rotor.

EASA has initiated rulemaking task RMT.0246 (MDM.050) entitled '*Pilot Intervention Time Following Power Failure in Single-Engine Helicopters*', and has requested tenders for carrying out a regulatory impact assessment to investigate the effects of changing the requirements for pilot reaction time. The terms of reference question whether the existing rules and certification practices are representative of normal pilot response in such situations. Research previously undertaken by the CAA (CAA Paper 99001) had identified, through simulation, mean values up to 4.1 seconds, with up to 5.7 seconds if the 90th percentile pilot was considered.

Analysis

Accident site and wreckage examination

The evidence from the accident site revealed that the helicopter had suffered an in-flight breakup. Both MR blades had leading edge paint transfer marks consistent with having struck parts of the airframe, shattering the cockpit 'perspex' transparency, severing the left door and part of the right door. One of the MR blades (probably MR blade No 1) had severed the left front skid. For the MR blades to do this damage the main rotor had to diverge from its normal plane of rotation and strike the mast (mast bumping) and there was clear evidence on the mast and hub that this had occurred. Both MR blades had then separated from the hub, failing both coning bolts in overload – these failures must have occurred in very rapid succession because the main rotor gearbox had not separated from the airframe (a failure mode that would have been observed if a single MR blade had remained attached for any time because of the out-of-balance forces that would have existed). There was no evidence of fatigue, corrosion or material defects in the rotor head components analysed – all failure modes were overload. The coning bolts most likely failed as a result of the blades pitching to an extreme up or down angle with the resulting drag loads on the blades exceeding the design loads of the bolts and failing the hub lugs in an aft (opposite the direction of rotation) manner. The evidence was not consistent with a rotor overspeed.

The No 1 pitch link and retaining bolts were not found but the witness marks inside the bolt attachment holes indicated that a very high bending force had been applied to both bolts – these witness marks would not have been produced if the nuts had come off the bolts. The aircraft manufacturer considered that the bolts could have failed as a result of extreme nose-down pitching of the No 1 MR blade coupled with high upwards flapping. It is very unusual for both ends in a pitch link to fail but another example is shown in Figure G2, Appendix G. With its pitch link separated, the No 1 MR blade was free to pitch to any angle and, if the rotor blade stalled, the resulting aerodynamic moment would probably have pitched it down. Once the upper surface of the blade was presented flat to the airstream, the blade would have overloaded the coning bolt and separated. The No 2 MR blade probably separated almost immediately, failing the pitch horn.

The wreckage examination did not reveal any evidence of a disconnected flight control or restriction and there was no evidence that a failure in any of the rotary drive components precipitated the main rotor divergence. The powerplant examination did not reveal any faults that might have caused a loss of power and fuel records indicated that there was sufficient fuel onboard at the time of the accident.

The possibility of carburettor ice having formed inside the carburettor causing a loss of power or engine stoppage could not be ruled out. The carburettor hot air selector was extended by 2 cm which resulted in some hot air, but mostly cold air, entering the air box. The atmospheric conditions at the time were conducive to carburettor icing and, although the engine was probably operating at cruise power, the engine is de-rated such that the throttle butterfly is only partially open even at cruise power settings, which makes carburettor icing more likely.

In summary, the physical evidence clearly pointed to main rotor divergence, also known as a 'loss of main rotor control', as being the cause of the rotor head failures, airframe failures and main rotor blade separation.

Causes of main rotor divergence

There are several factors that can cause main rotor divergence: low-g flight, low rpm, turbulence and large abrupt control inputs. The meteorological conditions at the time were not conducive to turbulence caused by wind or mountain wave activity so it is unlikely that turbulence was a factor in the accident. Further, radar evidence allowed the investigation to discount the presence of wake turbulence from a nearby aircraft as a factor.

Low-g pushover

A low-g pushover was a possible cause of the main rotor divergence. The rotor struck the left door and left front skid, which are typical features of low-g accidents because the pilot's natural response to a rapid right roll (induced in a low-g situation) is to apply full left cyclic which, when the rotor is unloaded, can cause the rotor disk to tilt to an extreme left angle and strike the airframe. A possible reason for the pilot to perform a low-g pushover would have been to initiate a rapid descent by pushing forward on the cyclic, perhaps because he realised he had entered the Mildenhall MATZ and wanted to descend below it, or perhaps because he wanted to avoid a bird, or birds, by descending. Alternatively, the pilot might have pushed forward on the cyclic to level the helicopter having pulled up to avoid a bird, or birds, or to correct for an unexpected pitch-up during a period of inattention or distraction. Although moving the cyclic forward is an inappropriate technique in a helicopter in these circumstances, the pilot's experience was primarily in fixed-wing aircraft in which moving the control column forward rapidly would have been appropriate. Application of the incorrect technique in circumstances such as these is known to be hazardous and Safety Notices within the R22 POH warn pilots of the possible consequences.

Some features of low-g accidents were absent in this case. In many R22 accidents associated with low-g, the mast separated just below the rotor head, which did not occur with G-CHZN. However, it is not certain whether mast separation will always occur and it may be dependent on the severity of the entry to low-g or the actual reduction in g that is achieved. Another feature missing from the low-g scenario was that a low-g pushover results in a rapid roll to the right, whereas witnesses reported seeing a rapid roll to the left.

Low rotor rpm

Low rotor rpm and subsequent rotor stall can cause main rotor divergence. Low rotor rpm is caused either by a loss of engine power followed by the pilot reacting too slowly to lower the collective, or by the pilot raising the collective too much and over-pitching the blades. G-CHZN was in the cruise at relatively low altitude, and at least 164 lb below its maximum weight, which are conditions that would not require a particularly high blade pitch angle. Nevertheless, a loss of rotor rpm due to over-pitching might have occurred had the pilot made a large upward input on the collective, perhaps to climb over a bird, or birds. The aircraft manufacturer believed that excessive upward flapping of the blades would be required to fail the No 1 pitch link in the manner observed, and that this would not occur at high rpm because the centrifugal reaction to rotation would limit the flapping angle.

A loss of rotor rpm due to a loss of power is a possible factor in this accident, although no evidence of an engine fault was found. There was evidence that the engine had stopped prior to impact but this was likely to have occurred in any case due to an interruption in fuel flow as a result of the helicopter's inverted attitude prior to impact. The atmospheric conditions were conducive to carburettor icing, which might have caused a reduction in power. The electronic governor on the R22 can mask the onset of carburettor icing because, as the ice builds and the power reduces, the governor automatically increases the throttle to compensate. This prevents the drop in manifold air pressure that would normally alert the pilot to the problem. Once the throttle has been fully opened, and if ice is still building, power and rotor RPM will reduce quickly. If the pilot does not respond by lowering the collective within about 1.5 seconds the rotor can enter an unrecoverable condition and the engine can stop.

In a number of R22 accidents that have been attributed to low rotor rpm there was evidence that the tail boom had been struck by the main rotor, with the retreating blade stalling first, causing it to drop and strike the tail boom. This did not happen with G-CHZN but cyclic control inputs made by the pilot at the time of the rotor stall may have an effect on whether or not the tail boom is struck.

Large abrupt cyclic inputs

According to the NTSB study '*Large, abrupt control inputs can lead directly to mast bumping or induce blade stall, which, in turn, can lead to mast bumping*.' This, and other, studies imply that large cyclic inputs in any direction could cause mast bumping. Full cyclic control deflections at cruise speed have not been demonstrated in flight due to the '*significant risk to flight safety*' but simulator modelling provides some evidence to support the theory. A large abrupt sideways cyclic input, if maintained, would generate a rapid roll that would invert the helicopter very quickly, according to the manufacturer. This might explain the rapid roll observed by witnesses but it is difficult to explain what would have caused the pilot to do this, unless it was inadvertent and possibly due to a distraction. In a fixed-wing aircraft it is more difficult to apply full control deflection at increasing speed because the control forces increase with deflection. This is not the case in a light helicopter like the R22 without a stability augmentation system and only very light forces are required to obtain full deflection. The helicopter manufacturer explained that light cyclic control forces are required for controllability in the hover because in some cases large and rapid control deflections are required.

It is possible that a combination of low rpm, an abrupt control input and low-g caused the main rotor divergence in G-CHZN. If carburettor ice caused a loss of rotor rpm this would have triggered the low rpm audio warning, and this warning sounds like the stall warning in some light fixed-wing aircraft. The response of a fixed-wing pilot to a stall warning is often to push forward on the controls to un-stall the wing. This would be an inappropriate response from the pilot in these circumstances, but understandable given that the vast majority of his flying was in fixed-wing aircraft. The loss of rotor rpm could explain why the pitch link failed in the way that was observed. The forward deflection of the cyclic, leading to a low-g flight condition, could explain the rapid roll but only if the witnesses were mistaken and the roll was, in fact, to the right.

Incapacitation

The investigation considered the possibility that the pilot became incapacitated and that this was the initiating event that led to the main rotor divergence. This possibility was considered unlikely because post-mortem examination indicated that the pilot was probably conscious at impact and it is unlikely that the pilot suffered an acute episode of symptoms associated with his undiagnosed medical condition.

Safety action and Safety Recommendations

R22 accidents involving main rotor divergence were analysed in depth by the NTSB in 1996. They concluded that:

> *'the FAA should require helicopter manufacturers to provide data on the response of helicopters to large, abrupt cyclic inputs as a part of the certification process.'*

This recommendation was implemented in part by changes to AC-27.661 which required manufacturers to carry out a blade flapping survey. However, the AC did not define what the control deflections should be or what the rate of input should be. It specified that margins should be determined but it did not specify what the margins should be. The NTSB closed their recommendation (A-96-11) with an 'Acceptable' response, but this was influenced by the reduction in R22 'main rotor loss of control' accidents that had occurred in the mid 1990s. The NTSB attributed this to the increased training and experience requirements imposed by the FAA. However, since the 1996 NTSB study there have been at least a further 16 fatal R22 accidents involving loss of main rotor control.

Reaction time

Some of these accidents were probably caused by a loss of rotor rpm following a loss of power without the pilot lowering the collective quickly enough. In the R22 the pilot must react to a loss of power by lowering the collective in less than about 1.5 seconds in the cruise, or 1 second in the climb, to prevent rotor stall. EASA has therefore initiated a Regulatory Impact Assessment to study the effect of increasing the required reaction times.

Handling qualities

Another probable factor in continuing fatal accidents involving R22 'main rotor loss of control' relates to the handling qualities. Only light control forces are required to apply full cyclic deflection in the R22, making it easy inadvertently to enter a low-g situation or to make an abrupt and rapid control input leading to rotor stall and mast bumping. In contrast to fixed-wing aircraft, there are no certification requirements for stick forces for light civilian helicopters and the certification requirements in FAR-27 (FAA), and now CS-27 (EASA), have changed little in several decades and are less stringent than the equivalent military requirements. The NASA Ames study (TM-2005-213473) recommended that manufacturers should explore the feasibility of designing a low-cost, lightweight stability augmentation system, which would also provide benefits for the reduction of low-speed and hovering helicopter accidents. A stability augmentation system would provide some control force feedback thereby making large abrupt cyclic inputs less likely, as well as recovering the aircraft to a safe attitude should the pilot release the cyclic control. There may be other design solutions which would reduce the likelihood of 'loss of main rotor control' accidents.

Therefore the certification requirements for future helicopter designs should be updated and improved to reduce the risk of 'loss of control' and 'loss of main rotor control' accidents. It is desirable that the EASA and FAA co-operate in this task and therefore the following two Safety Recommendations are made:

Safety Recommendation 2012-038

The European Aviation Safety Agency should amend the requirements in Certification Specification Part 27 to reduce the risk of 'loss of main rotor control' accidents in future light helicopter designs.

Safety Recommendation 2012-039

The Federal Aviation Administration should amend the requirements in Federal Aviation Regulation Part 27 to reduce the risk of 'loss of main rotor control' accidents in future light helicopter designs.

Conclusions

This accident to G-CHZN was caused by main rotor divergence which resulted in mast bumping, the rotor blades striking the airframe and rotor blade separation. The main rotor divergence was probably caused by a loss of rotor rpm (not followed by rapid lowering of the collective lever), a low-g pushover, a large abrupt control input - or a combination thereof. A loss of rotor rpm could have been caused by a build-up of carburettor ice which was not recognised and removed by applying sufficient carburettor heat. A low-g pushover or a large abrupt control input could have been generated for a number of reasons, and the light control forces in the R22 make it relatively easy to enter such conditions.

Fatal accidents involving the R22 continue to occur due to main rotor divergence, the causes of which are rarely determined conclusively because the pilot's control inputs leading up to the divergence are rarely known. If the helicopter manufacturer succeeds in developing a lightweight flight data recorder for the R22 that includes recordings of control positions, it is likely that there will be new insights into the causes of main rotor divergence.

Work is being carried out to investigate changing the certification requirements to allow a longer pilot reaction time to a loss of rpm, because the probability of a fatal outcome following a loss of power in a light helicopter is high. This report has recommended that the regulators amend the certification requirements to reduce the risk of 'loss of main rotor control' accidents in future light helicopters.

Appendix A

Safety Notice SN-10

Issued: Oct 82 Rev: Feb 89; Jun 94

FATAL ACCIDENTS CAUSED BY LOW RPM ROTOR STALL

A primary cause of fatal accidents in light helicopters is failure to maintain rotor RPM. To avoid this, every pilot must have his reflexes conditioned so he will instantly add throttle and lower collective to maintain RPM in any emergency.

The R22 and R44 have demonstrated excellent crashworthiness as long as the pilot flies the aircraft all the way to the ground and executes a flare at the bottom to reduce his airspeed and rate of descend. Even when going down into rough terrain, trees, wires or water, he must force himself to lower the collective to maintain RPM until just before impact. The ship may roll over and be severely damaged, but the occupants have an excellent chance of walking away from it without injury.

Power available from the engine is directly proportional to RPM. If the RPM drops 10%, there is 10% less power. With less power, the helicopter will start to settle, and if the collective is raised to stop it from settling, the RPM will be pulled down even lower, causing the ship to settle even faster. If the pilot not only fails to lower collective, but instead pulls up on the collective to keep the ship from going down, the rotor will stall almost immediately. When it stalls, the blades will either “blow back” and cut off the tail cone or it will just stop flying, allowing the helicopter to fall at an extreme rate. In either case, the resulting crash is likely to be fatal.

No matter what causes the low rotor RPM, the pilot must first roll on throttle and lower the collective simultaneously to recover RPM before investigating the problem. It must be a conditioned reflex. In forward flight, applying aft cyclic to bleed off airspeed will also help recover lost RPM.

Appendix B

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Safety Notice SN-11

Issued: Oct 82 Rev: Nov 00

LOW-G PUSHOVERS - EXTREMELY DANGEROUS

Pushing the cyclic forward following a pull-up or rapid climb, or even from level flight, produces a low-G (weightless) flight condition. If the helicopter is still pitching forward when the pilot applies aft cyclic to reload the rotor, the rotor 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 a powerful right rolling moment on the fuselage. With no lift from the rotor, there is no lateral control to stop the rapid right roll and mast bumping can occur. Severe in-flight mast bumping usually results in main rotor shaft separation and/or rotor blade contact with the fuselage.

The rotor must be reloaded before lateral cyclic can stop the right roll. To reload the rotor, apply an immediate gentle aft cyclic, but avoid any large aft cyclic inputs. (The low-G which occurs during a rapid autorotation entry is not a problem because lowering collective reduces both rotor lift and rotor torque at the same time.)

Never attempt to demonstrate or experiment with low-G maneuvers, regardless of your skill or experience level. Even highly experienced test pilots have been killed investigating the low-G flight condition. Always use great care to avoid any maneuver which could result in a low-G condition. Low-G mast bumping accidents are almost always fatal.

NEVER PERFORM A LOW-G PUSHOVER!!

Appendix C

ROBINSON
HELICOPTER COMPANY

Safety Notice SN-24

Issued: Sep 86 Rev: Jun 94

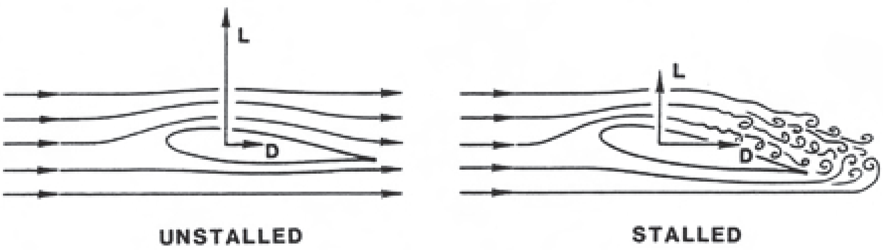
LOW RPM ROTOR STALL CAN BE FATAL

Rotor stall due to low RPM causes a very high percentage of helicopter accidents, both fatal and non-fatal. Frequently misunderstood, rotor stall is not to be confused with retreating tip stall which occurs only at high forward speeds when stall occurs over a small portion of the retreating blade tip. Retreating tip stall causes vibration and control problems, but the rotor is still very capable of providing sufficient lift to support the weight of the helicopter.

Rotor stall, on the other hand, can occur at any airspeed and when it does, the rotor stops producing the lift required to support the helicopter and the aircraft literally falls out of the sky. Fortunately, rotor stall accidents most often occur close to the ground during takeoff or landing and the helicopter falls only four or five feet. The helicopter is wrecked but the occupants survive. However, rotor stall also occurs at higher altitudes and when it happens at heights above 40 or 50 feet AGL it is most likely to be fatal.

Rotor stall is very similar to the stall of an airplane wing at low airspeeds. As the airspeed of an airplane gets lower, the nose-up angle, or angle-of-attack, of the wing must be higher for the wing to produce the lift required to support the weight of the airplane. At a critical angle (about 15 degrees), the airflow over the wing will separate and stall, causing a sudden loss of lift and a very large increase in drag. The airplane pilot recovers by lowering the nose of the airplane to reduce the wing angle-of-attack below stall and adds power to recover the lost airspeed.

The same thing happens during rotor stall with a helicopter except it occurs due to low rotor RPM instead of low airspeed. As the RPM of the rotor gets lower, the angle-of-attack of the rotor blades must be higher to generate the lift required to support the weight of the helicopter. Even if the collective is not raised by the pilot to provide the higher blade angle, the helicopter will start to descend until the



Wing or rotor blade unstalled and stalled.

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Appendix C cont

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Safety Notice SN-24 (continued)

upward movement of air to the rotor provides the necessary increase in blade angle-of-attack. As with the airplane wing, the blade airfoil will stall at a critical angle, resulting in a sudden loss of lift and a large increase in drag. The increased drag on the blades acts like a huge rotor brake causing the rotor RPM to rapidly decrease, further increasing the rotor stall. As the helicopter begins to fall, the upward rushing air continues to increase the angle-of-attack on the slowly rotating blades, making recovery virtually impossible, even with full down collective.

When the rotor stalls, it does not do so symmetrically because any forward airspeed of the helicopter will produce a higher airflow on the advancing blade than on the retreating blade. This causes the retreating blade to stall first, allowing it to dive as it goes aft while the advancing blade is still climbing as it goes forward. The resulting low aft blade and high forward blade become a rapid aft tilting of the rotor disc sometimes referred to as "rotor blow-back". Also, as the helicopter begins to fall, the upward flow of air under the tail surfaces tends to pitch the aircraft nose-down. These two effects, combined with aft cyclic by the pilot attempting to keep the nose from dropping, will frequently allow the rotor blades to blow back and chop off the tailboom as the stalled helicopter falls. Due to the magnitude of the forces involved and the flexibility of rotor blades, rotor teeter stops will not prevent the boom chop. The resulting boom chop, however, is academic, as the aircraft and its occupants are already doomed by the stalled rotor before the chop occurs.

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Appendix D

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Safety Notice SN-25

Issued: Dec 86 Rev: Nov 99

CARBURETOR ICE

Carburetor ice can cause engine stoppage and is most likely to occur when there is high humidity or visible moisture and air temperature is below 70°F (21°C). When these conditions exist, the following precautions must be taken:

During Takeoff - Unlike airplanes, which take off at wide open throttle, helicopters take off using only power as required, making them vulnerable to carb ice, especially when engine and induction system are still cold. Use full carb heat (it is filtered) during engine warm-up to preheat induction system and then apply carb heat as required during hover and takeoff to keep CAT gage out of yellow arc.

During Climb or Cruise - Apply carb heat as required to keep CAT gage out of yellow arc.

During Descent or Autorotation -

R22 - Below 18 inches manifold pressure, ignore CAT gage and apply full carb heat.

R44 - Apply carb heat as required to keep CAT gage out of yellow arc and full carb heat when there is visible moisture.

Appendix E

Safety Notice SN-29

Issued: Mar 93 Rev: Jun 94

AIRPLANE PILOTS HIGH RISK WHEN FLYING HELICOPTERS

There have been a number of fatal accidents involving experienced pilots who have many hours in airplanes but with only limited experience flying helicopters.

The ingrained reactions of an experienced airplane pilot can be deadly when flying a helicopter. The airplane pilot may fly the helicopter well when doing normal maneuvers under ordinary conditions when there is time to think about the proper control response. But when required to react suddenly under unexpected circumstances, he may revert to his airplane reactions and commit a fatal error. Under those conditions, his hands and feet move purely by reaction without conscious thought. Those reactions may well be based on his greater experience, ie. the reactions developed flying airplanes.

For example, in an airplane his reaction to a warning horn (stall) would be to immediately go forward with the stick and add power. In a helicopter, application of forward stick when the pilot hears a horn (low RPM) would drive the RPM even lower and could result in rotor stall, especially if he also "adds power" (up collective). In less than one second the pilot could stall his rotor, causing the helicopter to fall out of the sky.

Another example is the reaction necessary to make the aircraft go down. If the helicopter pilot must suddenly descend to avoid a bird or another aircraft, he rapidly lowers the collective with very little movement of the cyclic stick. In the same situation, the airplane pilot would push the stick forward to dive. A rapid forward movement of the helicopter cyclic stick under these conditions would result in a low "G" condition which could cause mast bumping, resulting in separation of the rotor shaft or one blade striking the fuselage. A similar situation exists when terminating a climb after a pull-up. The airplane pilot does it with forward stick. The helicopter pilot must use his collective or a very gradual, gentle application of forward cyclic.

To stay alive in the helicopter, the experienced airplane pilot must devote considerable time and effort to developing safe helicopter reactions. The helicopter reactions must be stronger and take precedence over the pilot's airplane reactions because everything happens faster in a helicopter. The pilot does not have time to realize he made the wrong move, think about it, and then correct it. It's too late; the rotor has already stalled or a blade has already struck the airframe and there is no chance of recovery. To develop safe helicopter reactions, the airplane pilot must practice each procedure over and over again with a competent instructor until his hands and feet will always make the right move without requiring conscious thought. AND, ABOVE ALL, HE MUST NEVER ABRUPTLY PUSH THE CYCLIC STICK FORWARD.

Also see Safety Notices SN-11 and SN-24.

Appendix F

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Safety Notice SN-31

Issued: Dec 96

GOVERNOR CAN MASK CARB ICE

With throttle governor on, carb ice will not become apparent as a loss of either RPM or manifold pressure. The governor will automatically adjust throttle to maintain constant RPM which will also result in constant manifold pressure. When in doubt, apply carb heat as required to keep CAT out of yellow arc during hover, climb, or cruise, and apply full carb heat when manifold pressure is below 18 inches.

Also remember, if carb heat assist is used it will reduce carb heat when you lift off to a hover and the control may require readjustment in flight.

Appendix G

R22 'main rotor loss of control accidents' since 1996 NTSB study

Since the NTSB study was published in 1996 there have been at least 16 fatal R22 accidents involving loss of main rotor control (including G-CHZN) – 10 in the USA and 6 elsewhere in the UK, France, Canada and New Zealand (Appendix H for full list). These were identified using primarily the NTSB's accident database which included some but not all fatal R22 accidents outside the USA. These accidents all involved main rotor divergence and those accidents with evidence of an engine problem or which were associated with a loss of rpm at high altitude were excluded from the list. Out of the 10 accidents in the USA, one is still under investigation, and three were concluded to have been caused by '*Main rotor divergence for undetermined reason*'. Out of the 16, three were attributed to possible turbulence, five to possible low rpm, and one to low-g. Two of the accidents involved separation of a single main rotor blade at the coning bolt, and one accident, in addition to G-CHZN, involved separation of both main rotor blades at the coning bolt. These are discussed below.

On 17 January 2003 an R22 (registration ZK-HUL) suffered an in-flight breakup after departing from Masterton Aerodrome in New Zealand. The pilot had 157 hours on helicopters including 10.5 hours on the R22. Shortly after takeoff at about 400 feet, witnesses heard a loud noise and saw pieces flying off the helicopter and then it fell straight to the ground. One main rotor blade had detached from the hub and had '*fractured the hub trailing edge side mounting bolt hole area in overload*.' This detached blade was found to have entered the cabin at an extreme, almost vertical angle, slicing off the left half of the canopy as well as the left door. An instructor had commented that this particular helicopter had a tendency for the collective pitch to increase when flown hands off with insufficient collective friction applied. The report stated that the pilot may have removed his hand from the collective in order to adjust the cyclic control trim with insufficient collective friction applied. The investigation concluded that the initiating factor was unlikely to have been an engine failure and that:

> *'the accident sequence was consistent with over-pitching of the main rotor, resulting in loss of control and the striking of the airframe by one main rotor blade.'*

On 20 February 2004 an R22 (registration C-FILW) suffered an in-flight breakup at Kumealon Inlet, British Columbia, Canada. The pilot had approximately 1,200 hours on the R22. There were no witnesses to the accident but one main rotor blade was found 150 m from the main wreckage site and it had separated following overload failure of the coning bolt. There was evidence of mast bumping but there were no obvious blade strikes to the airframe. The engine and its accessories demonstrated signatures of power/rotation at impact. Turbulence had been reported in the area and the investigation report concluded that:

> *'The helicopter encountered turbulent air that unloaded the main-rotor system resulting in damage that led to the helicopter becoming uncontrollable. Subsequent forces overloaded and broke one of the main rotor blade attachment bolts, and the blade separated.'*

On 27 June 2011 an R22 (registration N7779M) suffered an in-flight breakup near Del Valle, Texas, USA. This accident is still under investigation but the NTSB provided the following information. The pilot had logged 220 flight hours, all of which were on the R22. Witnesses reported seeing it flying just above the trees and as it crossed the Colorado River they heard a loud 'pop' or 'bang' and saw something fall off the helicopter into the river. Both main rotor blades were found to have separated at the coning bolt and were located 265 m and 297 m respectively from the main wreckage. Both bolts were determined to have failed in overload and a corner of the hub had also failed, similar to the hub on G-CHZN (Figure G1). There was also clear evidence of mast bumping. One pitch link had failed at the upper thread and the other pitch link had separated following failure of both attachment bolts (Figure G2).

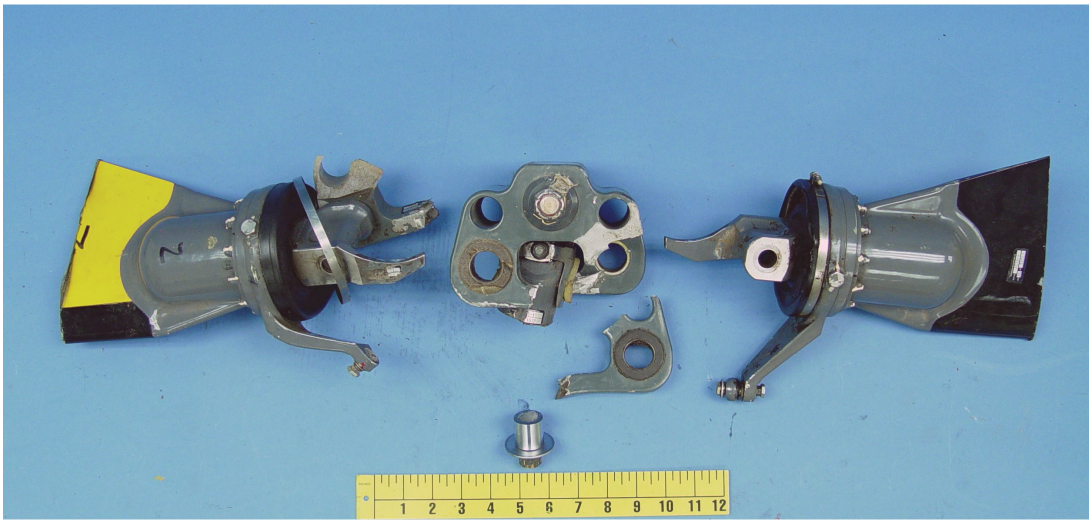

Figure G1

Rotor head components recovered from R22 accident (N7779M) near Del Valle, Texas – blade roots have been cut for examination

Figure G2

Separated pitch link from R22 accident (N7779M) near Del Valle, Texas – bolts at both ends have failed

Appendix H

R22 'Loss of Main Rotor Control' Fatal Accidents since 1996 NTSB study

The following list excludes accidents with clear evidence of an engine failure or low rpm caused by high altitude. The list was established using primarily data from the NTSB database which captures some but not all non-US fatal R22 accidents.

6/1/2012, G-CHZN, Cambridgeshire, UK
Both main rotor blades separated in flight at the coning bolt. Left skid and left door separated in flight. Main rotor divergence for undetermined reason.

27/6/2011, N7779M, Del Valle, TX, USA
Both main rotor blades separated in flight at the coning bolt. Still under investigation.

09/12/2010, G-CBVL, France
Main rotor struck left door and left skid in flight. Possible turbulence. Still under investigation.

2/6/2010, N522SA, Spokane, WA, USA
Student pilot on a solo flight. Helicopter 'fell' to ground and tail boom separated. Witnesses observed 'V-shaped' main rotor. Possible low rotor rpm. Still under investigation.

20/9/2009, N956SH, Forest Grove, OR, USA
An instructor and a pilot training to become an instructor were seen to be performing autorotations. Main rotor blades were bent upwards and teeter stops split. Tail boom intact. Low rpm bulb filament stretched. Attributed to low rotor rpm.

31/1/2009, N4160A, Fillmore, CA, USA
Main rotor severed tail boom in flight. Both main rotor blades bent up. '*There was no evidence found that would explain the main rotor disc's divergence from the normal plane of rotation and its subsequent contact with the tail boom.*'

13/3/2008, N2215R, Wilmington, NC, USA
Both main rotor blades coned up. Evidence of in-flight tail boom strike. Attributed to low rotor rpm.

27/11/2004, N4029Q, Arlington, WA, USA
Both doors separated in flight. Some evidence of tail boom contact. Door pins not installed. '*The initiating event that produced the main rotor divergence could not be determined.*'

29/08/2004, N871CL, Northport, NY, USA

Main rotor shaft separated and both pitch links failed. No tail boom damage. Possible low-g to avoid a kite.

20/02/2004, C-FILW, British Columbia, Canada

In-flight breakup. One main rotor blade separated in flight at the coning bolt. Possible turbulence.

17/01/2003, ZK-HUL, Masterton, New Zealand

In-flight breakup shortly after takeoff. One main rotor blade detached from the hub. Attributed to inadvertent over-pitching of the main rotor.

13/07/2002, G-VFSI, Warwickshire, UK

Tail boom separated. Mast bumping. Possible inadvertent control input by passenger.

16/05/2001, C-FHRL, British Columbia, Canada

Flight instructor and student onboard. Tail boom separated and mast bent. Main rotor seen stationary and coned up. Attributed to low rotor rpm due to possible carburettor icing.

18/08/2000, N8313Z, Watsonville, CA, USA

Student pilot. Main rotor shaft separated. Damage to left door and left skid. '*The initiating event that produced the main rotor divergence could not be determined.*'

26/2/1998, N8457J, Littlerock, CA, USA

Main rotor shaft separated. Attributed to mountain wave turbulence.

19/10/1996, N512HH, Halsey, OR, USA

Main rotor blades separated (both bent or broken upward). Tail boom separated. Overload failure of one pitch link. No hub to mast contact. Low rpm and oil bulb filaments stretched. Attributed to low rotor rpm.