Air Accident Investigation Unit Ireland

SYNOPTIC REPORT

Serious Incident
Piper PA 32, G-OCTI
Lorrha, Co. Tipperary
24 December 2014

An Roinn Iompair
Turasóireachta agus Spóirt
Department of Transport,
Tourism and Sport

Foreword

This safety investigation is exclusively of a technical nature and the Final Report reflects the determination of the AAIU regarding the circumstances of this occurrence and its probable cause(s).

In accordance with the provisions of Annex 13[1] to the Convention on International Civil Aviation, Regulation (EU) No 996/2010[2] and Statutory Instrument No. 460 of 2009[3], safety investigations are in no case concerned with apportioning blame or liability. They are independent of, separate from and without prejudice to any judicial or administrative proceedings to apportion blame or liability. The sole objective of this safety investigation and Final Report is the prevention of accidents and incidents.

Accordingly, it is inappropriate that AAIU Reports should be used to assign fault or blame or determine liability, since neither the safety investigation nor the reporting process has been undertaken for that purpose.

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[1] **Annex 13**: International Civil Aviation Organization, Annex 13 to the Convention on International Civil Aviation, Air Accident and Incident Investigation.
[2] **Regulation (EU) No 996/2010** of the European Parliament and of the Council of 20 October 2010 on the investigation and prevention of accidents and incidents in civil aviation.
[3] **Statutory Instrument (SI) No. 460 of 2009**: Air Navigation (Notification and Investigation of Accidents, Serious Incidents and Incidents) Regulations 2009.

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In accordance with Annex 13 to the Convention on International Civil Aviation, Regulation (EU) No 996/2010 and the provisions of SI 460 of 2009, the Chief Inspector of Air Accidents, on 24 December 2014, appointed Mr John Owens as the Investigator-in-Charge to carry out an Investigation into this Serious Incident and prepare a Report.

Aircraft Type and Registration:	Piper Aircraft Inc. PA 32, G-OCTI
Number and Type of Engines:	1 x Lycoming O-540-E4C5CE4B5
Aircraft Serial Number:	32-288
Year of Manufacture:	1966
Date / Time (UTC[4]):	24 December 2014 @ 14.10 hrs
Location:	Lorrha, County Tipperary, Ireland
Type of Operation:	General Aviation
Persons on Board:	Pilot - 1 Passengers - 3
Injuries:	Pilot - Nil Passengers - Nil
Nature of Damage:	Minor to aircraft, substantial to engine
Commander's Licence:	Private Pilot Licence (PPL) Aeroplanes (A) issued by the Civil Aviation Authority (CAA) of the United Kingdom (UK)
Commander's Details:	Male, aged 39 years
Commander's Flying Experience:	268 hours, of which 41 were on type
Notification Source:	Shannon Air Traffic Control (ATC)
Information Source:	AAIU Report Form submitted by the Pilot AAIU Field Investigation

[4] **UTC**: Co-ordinated Universal Time (The same as local time on the day of the accident). All times in this report are UTC.

SYNOPSIS

The single-engined aircraft was on a private flight from the Isle of Wight (UK) to Galway Airport (EICM), with one Pilot, three passengers and a pet dog on board. While over the south midlands of Ireland, the aircraft developed engine vibration followed by a loss of engine power and smoke in the aircraft cabin. The Pilot, who was also an experienced glider pilot, shut down the engine and performed a forced landing into an agricultural field in County Tipperary. There was no fire and except for minor damage to the engine cowling, the aircraft was undamaged. None of the occupants were injured. The cause of the engine power loss was due to the detachment of the number five cylinder, which the Investigation established was as a result of the fatigue failure of several of its retention studs.

1. FACTUAL INFORMATION

1.1 History of Flight

The aircraft departed from Bembridge Airfield (EGHJ) in the Isle of Wight, for a flight to EICM, with four persons and a pet dog on board. A planned landing was performed en route at Haverfordwest (EGFE), UK, to refuel. The Pilot confirmed to the Investigation that the engine operated normally on this leg of the journey and that no unusual vibrations were observed. He said that following refuelling he checked the engine oil level, which was found to be normal. The aircraft departed EGFE at approximately 12.20 hrs for EICM.

According to the Pilot's report, at approximately 14.00 hrs, a vibration developed from the engine area, following which there was a drop in engine power. The Pilot reported that he applied carburettor heat[5], switched on the fuel pump and selected a different fuel tank, but that these selections made no difference to the vibration. He said that a more significant drop in power then occurred, which was followed by "*a gush of oil smoke in the cabin*". This was cleared by opening the storm window (a small hinged panel in the forward portside cockpit window). The Pilot stated that he then began to think about his landing options. A short time later, a loud bang was heard and the Pilot said that he thought he saw "*an object firing through the top of the cowling*". This was followed by more "*oil smoke*" and another bang and a loss of power, but that the engine was still running. However, the Pilot considered that the engine was not providing any benefit at that point and deemed it to be a "*potential risk*", so he shut it down. A glide approach to a large agricultural field in Lorrha, Co. Tipperary was performed, where the aircraft was landed without further incident (**Photo No. 1**).

Except for minor damage to the engine cowling caused by the engine failure, the aircraft was undamaged and there was no fire. There were no injuries and all occupants were able to disembark the aircraft normally.

[5] **Carburettor heat:** A system used to prevent carburettor icing, a known cause of engine rough-running.

Photo No. 1: Final resting position of G-OCTI (post event date in daylight conditions)

1.2 Personnel Information

The Pilot held a PPL with an SEP (Land)[6] rating and a Class 2 Medical Certificate, both of which were issued by the UK CAA and were valid at the time of the event. He had a total flying experience of 268 hours on powered aircraft, of which 41 were on type. He informed the Investigation that he also had approximately 1,000 hours flying experience on gliders.

1.3 Meteorological Information

Met Éireann, the Irish meteorological service, was asked to provide details on the weather conditions prevailing in the area on the day of the occurrence. They stated that the meteorological conditions were as follows: A fresh, unstable north-westerly airflow covered the entire country. The air mass was cool and clear with generally excellent visibility and a high cloud ceiling. Wind 290^{o} 30 kts (at 2,000 ft), 270^{o} 10-15 kts (on ground), with potential for gusts of 25 kts, clouds FEW/SCT[7] 2,500 ft - 3,000 ft, surface temperature 6^{o} Centigrade (C), Mean Sea Level Pressure 1021 hPa[8] and visibility 25-30+ km.

1.4 Aircraft Information

The aircraft, a Piper Aircraft PA 32-260 'Cherokee', is a six-seat, low wing, all-metal monoplane, fitted with a non-retractable tricycle undercarriage. It has a maximum take-off weight of 1,542 kgs (3,400 lbs) and was manufactured in 1966.

[6] **SEP (Land):** Single Engine Piston landplanes.
[7] **SCT:** Scattered.
[8] **hPa:** Hectopascal – A unit of pressure.

The Airworthiness Review Certificate (ARC) for the aircraft was certified by a UK CAA approved Continuing Airworthiness Management Organisation (CAMO) on 16 October 2014 and was valid until 15 October 2015.

The last scheduled maintenance check was an Annual Inspection which was performed by the same organisation, which also holds CAA European Aviation Safety Agency (EASA) Part 145[9] approval as a Maintenance/Repair Organisation (MRO). The aircraft was released from this check on 16 October 2014. The total aircraft operating hours on this date was 5,828.

1.5 Engine Details

1.5.1 General

The engine fitted to the aircraft was a six-cylinder, horizontally opposed unit manufactured by Lycoming (model number O-540-E4C5CE4B5, serial number RL-14541-40). The engine cylinders are numbered as follows: one, three and five on the right hand side when viewed from the cockpit, with number five being the most aft, and two, four and six on the left hand side, with number six being the most aft (**Figure No. 1**). The engine was fitted with a variable pitch, two-bladed aluminium alloy propeller.

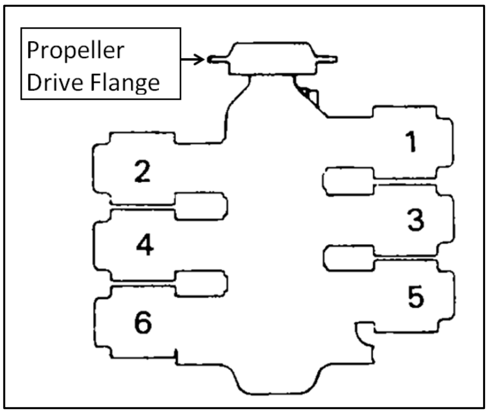

Figure No. 1: Cylinder numbering system (viewed from the top)

The engine is comprised of two crankcase halves with three cylinders fitted to each half. Each cylinder is retained by eight nuts, which are tightened onto studs in the crankcase halves. Four of the studs have a larger thread diameter than the other four studs. Two of the larger diameter studs at each cylinder are classified by the Engine Manufacturer as "*thru-studs*", in that they pass through both crankcase halves and are used to secure the two crankcase halves together in addition to securing two opposing cylinders. The remaining six studs at each cylinder are shorter and do not pass through both crankcase halves, but are screwed into threaded holes in each crankcase half.

The last entry made in the '*Time Run Since New or Complete Overhaul*' section of the engine log book was 1,035 hours. This was entered on 22 September 2014, at the commencement of the Annual Inspection.

[9] **EASA Part 145:** To obtain European regulatory authority approval, an aircraft Maintenance/Repair Organisation, must be in compliance with the standards contained in EASA Part 145.

1.5.2 Engine Maintenance

It is recorded in the engine log book (engine log book number two) that the engine was rebuilt (overhauled) on 23 June 1987. However, this log book was only in use from 29 May 2010 and therefore did not contain details of this engine overhaul or the certification documentation for the work. The current Owner of the aircraft did not have the first engine log book (engine log book number one) and efforts to locate it were unsuccessful. The Owner contacted all previous owners, who advised that the engine was not overhauled when the aircraft was under their ownership.

Engine maintenance records indicate that the numbers three, five and six cylinders were replaced on 24 September 2010 at 804 engine hours due to corrosion at the exhaust flanges. The MRO's work sheet for the task contained the following handwritten entry: "*Base nuts torqued IAW* [in accordance with] *MM* [Maintenance Manual]". The MRO subsequently advised the Investigation that the Manual that is actually used is the Overhaul Manual. Records also indicate that the number one cylinder was replaced on 29 September 2011 at 919 engine hours by the same MRO, due to a crack in the exhaust port. The MRO's work sheet for this task contained the following handwritten entry: "*Base nuts torqued to 35 flbs*[10] *& 50 flbs*". There is no record in the engine log book of any major engine work carried out since the replacement of the number one cylinder. The MRO where the cylinders were replaced is not the same organisation that carried out the Annual Inspection and ARC review.

The work pack for the last Annual Inspection, completed on 16 October 2014, indicates that detailed engine ground runs were carried out as part of the Inspection, during which checks of the engine oil pressure and temperature, cylinder head temperature, and exhaust gas temperature were performed. No anomalies were noted in relation to these checks. A cylinder compression test was performed with no adverse findings noted. An inspection of the '*Powerplant Installation*' is also recorded in the work pack. Such an inspection would not normally include a torque check of the cylinder retention nuts.

1.5.3 Engine Overhaul and Repair Requirements

The Engine Manufacturer's Service Instruction No. 1009AW on the '*Recommended Time Between Overhaul* [TBO] *Periods*' for its engines (dated 24 February 2014) specifies that the recommended TBO, for the engine type fitted to G-OCTI is 2,000 hours. This Service Instruction also includes a note stating that due to concerns regarding "*engine deterioration in the form of corrosion*" and other adverse consequences of engines not being operated for extended periods of time that "[…] *all engines that do not accumulate the hourly period of TBO specified in this publication are recommended to be overhauled in the twelfth year*". This note was included in previous revisions of the publication.

Section '*GR No. 24 - Light Aircraft Piston Engine Overhaul Periods*' of the UK CAA's publication CAP 747 '*Mandatory Requirements for Airworthiness*' permits engines that are installed in aircraft not being used for the purposes of Public Transport or Aerial Work (i.e. used for Private Flights only) to continue in service beyond the Manufacturer's recommended calendar time. This is subject to certain conditions and the accomplishment of mandatory bulletins, modifications and inspections.

[10] **Flbs:** As written on the work sheet, meaning foot pounds (ft. lbs.). A foot pound is a unit of torque, also written as lb. ft.

The engine log book records that a "*GR No. 24 Extension to TBO*" inspection was carried out during the last Annual Inspection to assess the condition of the engine for continued operation beyond the Manufacturer's recommended limits. The inspection criteria are described in '*Appendix 3 to GR No. 24'*. There are no prescribed inspections relating to the cylinder retention studs.

Section 6 '*Cylinders, Pistons and Valve Train*' of the Manufacturer's engine Overhaul Manual for the engine type fitted to G-OCTI states that to "*assure proper assembly of the crankcase halves and to eliminate the possibility of subsequent loosening of cylinder base nuts, a definite and specific sequence of tightening all crankcase and cylinder base nuts must be followed*".

Part II of the Engine Manufacturer's Service Instruction No. 1029D (dated 15 August 1986) describes the "*Tightening procedure for cylinder replacement (assembled engines)*". The procedure includes a note stating "[…] *both ends of free-thru studs* [the type fitted to G-OCTI's engine] *must be tightened simultaneously. At any time one or more cylinders are replaced, it is necessary to retorque the thru-studs on the cylinder on the opposite side of the engine".*

Both the Overhaul Manual and Service Instruction No. 1029D contain the correct torque sequence to be followed. The correct torque figures for the cylinder retention nuts are contained in the Overhaul Manual and in Service Instruction No. 1029D. These are 300 in.lb.[11] (25 ft.lb.) for the smaller diameter nuts (3/8 inch) and 600 in.lb. (50 ft. lb.) for the larger diameter nuts (1/2 inch).

1.5.4 Engine Damage

The engine was examined by the Investigation shortly after the forced landing. It was found that the number five cylinder had completely detached from the crankcase (**Photo No. 2**).

Photo No. 2: Engine damage

[11] **In.lb:** Inch-pound – A unit of torque (ft.lb/12).

The number five piston was broken into three pieces and the number five connecting rod was detached from the crankshaft big end (rod) journal. The crankcase was found to be severely damaged above and below the number five cylinder mounting pad, with large sections having been broken off.

1.5.5 Engine Disassembly and Examination

1.5.5.1 General

The aircraft Owner wished to arrange for the engine to be replaced as soon as possible and contracted a Part 145-approved engine overhaul agency based in the UK to supply a replacement engine, utilising, if possible, some components from the failed engine. To facilitate the Owner, the damaged engine was shipped to this overhaul agency, where it was dismantled in the presence of an AAIU Engineering Inspector.

Prior to disassembly, it was noted that there was surface corrosion and paint flaking in evidence at several locations on the engine.

1.5.5.2 Cylinder Retention Nut Torque Check

To assist with determining the cause of the detachment to the number five cylinder, a torque (tightness) check was performed on the nuts securing the remaining engine cylinders prior to engine disassembly. The check was carried out by marking the position of the cylinder retention nuts. Then, the normal tightening torque was applied in the tightening direction to each nut. If the nuts rotated, it would indicate that they were not currently at their correct torque values. The torque check revealed that almost all of the nuts retaining the number one and the number three cylinders (on the same side as the detached cylinder) moved, indicating that they were currently below the specified torque value. Almost none of the nuts retaining the number two and the number four cylinders moved, suggesting that they were torqued to at least the correct values. The nuts securing the number six cylinder, which is the opposing cylinder to the one that detached (number five), were particularly loose, including one which was only hand-tight.

1.5.5.3 Engine Examination

Examination of the engine identified that the detached cylinder suffered significant damage to its skirt (the lower cylinder wall, where it extends into the crankcase). Witness marks on the ends of the fractured skirt were found to have an outward orientation, consistent with the fracture being caused by being hit from the inside in an outward direction.

A circumferential indentation was found on the face of the broken piston, which appeared to have been caused by impact with a sharp, curved edge. The number five connecting rod was bent and the small end section was found to have broken away from the number five piston pin.

No evidence of fretting[12] was found on either the cylinder mounting faces or the crankcase mounting pads. In addition, no evidence of fretting was found on the crankcase main bearing housing mating faces. Fretting in these areas could result from the cylinder retention nuts being under-torqued.

1.6 Metallurgical Analysis

The detached number five cylinder, the engine crankcase and the failed cylinder retention studs were sent to a specialist facility for detailed metallurgical examination and analysis. Four of the failed studs were still in place in the crankcase (#1, #2, #4 and #6), two were still attached to the cylinder (#7 and #8) and the remaining two (#3 and #5) had completely separated (**Photo No. 3**).

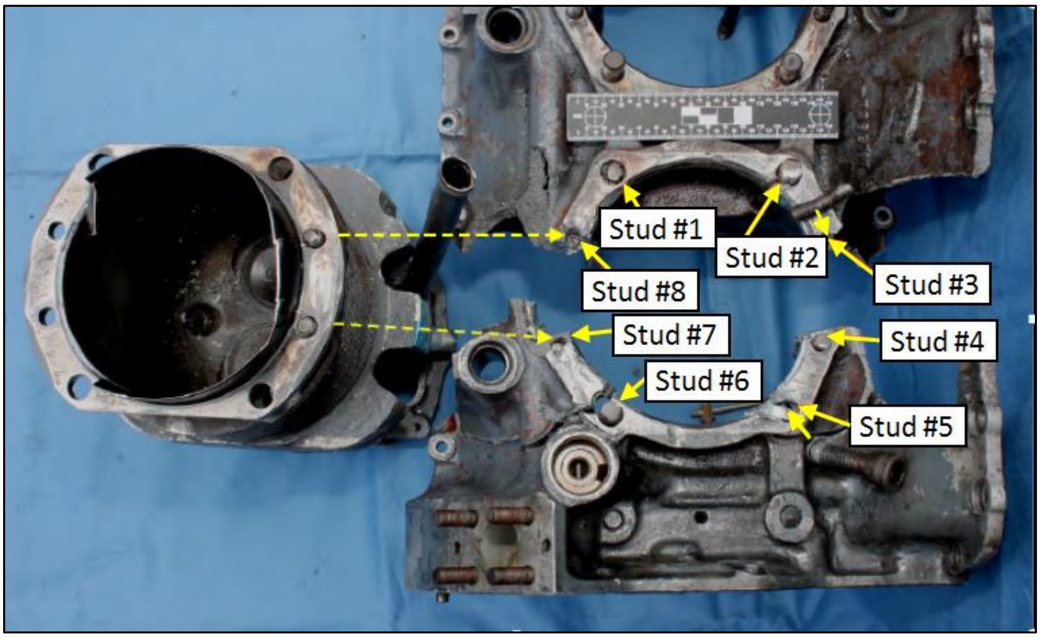

Photo No. 3: Components sent for metallurgical analysis with stud numbers identified

Regarding the damage to the cylinder skirt, fatigue[13] arrest marks[14] were visible on the fracture surface. Ratchet marks[15] were also present along the edge of the fracture surface, on the outer diameter of the cylinder. The metallurgical examination report stated that "*there was no evidence of pre-existing material defects at the crack initiation sites"* and that it was considered that this fracture was *"consequential to the bolt* [stud] *failures*".

[12] **Fretting:** A wear process that occurs at the contact area between two materials under load and subject to minute relative motion due to vibration or some other force.

[13] **Fatigue:** The progressive, localised, and permanent structural change that occurs in a material subjected to repeated or fluctuating strains at nominal stresses that have maximum values less than (and often much less than) the static yield strength of the material. Fatigue may culminate into cracks and cause fracture after a sufficient number of fluctuations.

[14] **Arrest Marks:** Progression marks on a fatigue fracture.

[15] **Ratchet Marks**: Ratchet marks are a feature that can be observed on fatigue fracture surfaces. These marks are formed when multiple cracks, originating at different points, join together, creating steps on the fracture surface.

The crankcase half had fractured into at least six pieces. Metallurgical analysis found that the crankcase fracture surfaces were "*visually consistent with failure by instantaneous overloading*" and that "*it was considered most likely that this was caused by unrestrained movement of the number five piston, after the cylinder had departed the engine*".

The damaged studs are shown in **Photo No. 4** below. Studs #1, #2, #3, #4 and #6 had fractured (studs #1 and #2 are thru-studs). Studs #5, #7 and #8 had not fractured, but coils of aluminium were found to be present in the thread roots. Metallurgical analysis deemed the coils of aluminium to be "*clean and fresh looking with no significant evidence of heat exposure*", indicating that studs #5, #7 and #8 had been forcibly stripped from the crankcase when the cylinder became detached.

Photo No. 4: Damaged studs

Visual examination identified that the cadmium plating[16] was absent from large areas on all of the studs. This was confirmed by Energy Dispersive X-Ray[17] (EDX) analysis of the flanks of the threads, adjacent to the fracture surfaces. A dusting of red rust was observed on the thread flanks, but it was noted that there was *"no evidence of corrosion pitting*".

It should be noted that following the event, the aircraft was stored in the open and exposed to the elements for a period of weeks before the engine was removed. The engine cowlings remained fitted during this time.

[16] **Cadmium Plating:** This protects steel from corrosion in a sacrificial manner, in that the plating corrodes in preference to the steel. Over a long service life, the complete plating thickness may be consumed by corrosion, leaving the underlying steel exposed.

[17] **Energy Dispersive X-Ray:** An analytical technique used for the elemental analysis or chemical characterisation of a sample.

The Metallurgist was asked by the Investigation if he considered it possible if the deterioration of the cadmium plating resulted in a loss of fastener torque. He stated that this was unlikely. He also advised that there was no "*significant build-up of paint on the mating surfaces of either the cylinder flange or the crankcase*". Excessive paint has been identified as a potential cause of loss of fastener torque and hence stud failure in other cases (**Section 1.8** refers).

The studs were found to meet the specified hardness requirements, with the exception of stud #3. However, the difference was deemed to be small and was "*not considered to be significant to its failure*". Chemical analysis was also performed on the studs. Metallurgical analysis found that the compositions of the studs met the Engine Manufacturer's specifications. However, minor discrepancies, which were also deemed to be insignificant, were found with studs #3 and #6 (Details of these discrepancies are included in **Appendix A).**

The conclusions of the metallurgical examination were as follows:

> *Considering all five fractured studs in combination, the general direction of fatigue crack growth was from the inside of the cylinder towards the outside. This was consistent with cyclic pressurisation loads, resulting from strokes of the piston.*
>
> *It was considered most likely that some of them had undergone final separation before the others. However, it was not possible to determine the order in which they had finally separated.*
>
> *The Pilot reported that there were no abnormal engine vibrations before the incident flight. It could therefore be assumed that the cyclic stresses, which resulted in the fatigue failures of the studs, had arisen from normal engine operation.*
>
> *The fatigue fractures on studs #1, 2, 3, 4 and 6 did not initiate from corrosion pitting or any other pre-existing material defects. Having discounted abnormal loading conditions and material defects or deficiencies, the most likely root cause of the stud failures was insufficient torque. This could have been due either to insufficient torque being applied to the nuts on assembly or to the nuts backing off in service.*
>
> *The cadmium plating was damaged and missing from large areas on all of the fractured studs. Cadmium plating protects steel from corrosion in a sacrificial manner. That is, the plating corrodes in preference to the steel. Over a long service lifetime, the full plating thickness may be consumed by corrosion, leaving the underlying steel exposed. This had occurred on the threads of several of the failed studs. There was a dusting of red rust on the flanks of these threads but no evidence of corrosion pitting. It is generally accepted that any form of corrosion will accelerate the initiation of fatigue cracking. This was considered to be a contributory factor to the subject stud failures, even though insufficient assembly torque was the most likely root cause.*

The metallurgical examination did not find any evidence of stud failure relating to an over-torque condition. See **Appendix A** for further details regarding the metallurgical analysis.

1.7 Bolted Joints

Regarding bolted joints, the following is an extract from Volume 11 of the ASM - '*Failures of Mechanical Fasteners'*:

> *In the theory of joint design, the ideal application can be represented as a situation in which there is a rigid structure and a flexible or elastic fastener* [such as a bolt/stud]. *The bolt then behaves like a spring.*
>
> *When the bolt is preloaded* [tightened/torqued] *or when the spring is stretched, a stress is induced in the bolt (and a clamping force in the structure) before any working load is encountered. As the working load is applied, the preloaded bolt does not encounter an additional load until the working load equals the preload in the bolt. At this point, the force between members is zero. As more load is applied, the bolt must stretch. Only beyond this point will any cyclic working load be transmitted to the bolt.*

It is further explained that in an actual application, the fastener will experience some increases in load before the working load equals the preload, due to the elasticity of the structural members (in this case, the engine cylinder and crankcase).

1.8 Special Airworthiness Information Bulletin

A Special Airworthiness Information Bulletin produced by the FAA[18], entitled '*Reciprocating Engines – Cylinder Mounting Studs*' (Reference No. NE-14-13, dated 24 March 2014) relates to failures of engine thru-studs, and/or cylinder mounting studs on engines manufactured by Lycoming. This Bulletin was also made available by EASA on the Safety Information Bulletin section of their website. The Bulletin notes that an Aviation Authority from another country reported that a cylinder had separated from a crankcase following the failure of its retaining studs. This resulted in damage to the surrounding crankcase and a failed connecting rod. Of the eight studs that secured the cylinder to the crankcase prior to failure, four were lost with the released sections of the crankcase and cylinder.

It was stated that "*laboratory analysis determined that one of the four remaining studs had a high cycle fatigue fracture. The fracture started from a single point corresponding to a corrosion pit in a thread root. Evidence of cadmium plating remained on the coarse threaded section of the stud, but there was no evidence of the cadmium plating where the corrosion pit developed*".

The Aviation Authority to whom the FAA referred to in its Bulletin issued the following Safety Recommendation:

> *It is recommended that Lycoming introduce additional maintenance requirements to ensure that the cadmium plating on the cylinder mounting studs, fitted to Lycoming engines, is not permitted to degrade to a level where corrosion of the base stud material can result in failure of the stud.*

[18] **FAA:** Federal Aviation Administration of the United States of America.

The Bulletin outlines that, when contacted by the FAA, Lycoming maintained that the instructions in its Overhaul Manual were adequate. Lycoming also advised that potential causes of stud failure include:

- *Improper torque at cylinder installation*
- *Corrosion pitting*
- *Improper torque due to excessive paint on the cylinder flange (all Lycoming cylinders are painted, the problem is caused by excessive paint on the cylinder flange mounting surface to the crankcase and/or the hold down nut area, prior to installation)*
- *Fretting on the crankcase main bearing mating surfaces*

The Bulletin also states that the FAA reviewed the National Transportation Safety Board's (NTSB) database for cylinder stud failures occurring between January 2000 and June 2013. The review identified that the fatigue failures of the studs were caused predominately by "*insufficient preload and/or improper installation*". Corrosion pitting was not mentioned as a cause of failure by the Board. The Bulletin outlines that 11 engine shops in the USA "*were asked about their experience with cylinder studs and the Lycoming Overhaul Manual. They all agreed that the instructions in the Lycoming Overhaul Manual are adequate. Some engine shops reported seeing some stud failures, but they did not indicate that corrosion pitting was a problem*".

1.9 Additional Information from Engine Manufacturer

The Engine Manufacturer advised that they were unaware of any cases of correctly torqued cylinder retention nuts backing off (working their way loose) in service.

Regarding the deterioration of the cadmium plating observed during metallurgical examination, the Manufacturer stated that the wearing away of the cadmium plating on the exposed portion of the threaded fasteners can be expected over a long service life. The Manufacturer also considered it unlikely that the deterioration of the cadmium plating would result in a loss of fastener torque.

2. ANALYSIS

2.1 Forced Landing

While en route from EGFE to EICM, the Pilot reported that engine vibration developed, followed by a loss of engine power and the presence of smoke in the cockpit. The smoke was quickly cleared; however, the extent of the engine problem resulted in the Pilot shutting down the engine. Consequently, the Pilot, who was experienced on gliders, performed a forced landing into a large agricultural field. The forced landing was successful in that there were no injuries and except for minor damage to the engine cowling due to the engine failure, the aircraft was undamaged.

2.2 Engine Overhaul Criteria

Engine log book number two (the only log book available to the Investigation) records that the engine had completed 1,035 hours since last overhaul. The Engine Manufacturer's Service Instruction on the '*Recommended Time Between Overhaul Periods*' (No. 1009AW) specifies that the recommended TBO for the engine type fitted to G-OCTI is 2,000 hours. Therefore, the engine was within the recommended TBO in terms of hours of operation.

The Service Instruction also states that engines that do not accumulate the TBO specified "*are recommended to be overhauled in the twelfth year*". This recommendation was included in previous revisions of the Service Instruction. It is recorded in the engine log book that the date of the last overhaul was 23 June 1987. This overhaul date is supported by Information the aircraft Owner obtained from previous owners. The engine had therefore been in operation for over 27 years since overhaul.

The aircraft is UK-registered and as such, comes under the authority of the UK CAA. Section GR No. 24 of the CAA's CAP 747 publication, permits the continued operation of light aircraft piston engines, subject to certain conditions, which include the accomplishment of mandatory bulletins, modifications and inspections. A further condition is that the aircraft, to which the engine is fitted, shall only be used for Private Flights. The engine log book records that a "*GR No. 24 Extension to TBO*" inspection, to assess the condition of the engine for continued operation was carried out during the last Annual Inspection. A review of all mandatory requirements is normally completed during ARC renewals. There are no prescribed inspections relating to the cylinder retention studs. The aircraft was operating on a valid ARC, was privately owned and was operating on a Private Flight.

2.3 Engine Failure

The circumferential indentation present on the fractured piston face appears to have been caused by impact with a sharp, curved edge. This mark spans the fractured piston. There is no such edge on the inside of the cylinder and therefore the mark could not have been caused while the piston was operating inside the cylinder. The only such edge is on the cylinder skirt. Witness marks on the fractured skirt have an outward orientation consistent with the fracture being caused by being hit from the inside out. Furthermore, metallurgical analysis did not detect any pre-existing material defects on the skirt and it was stated in the associated report that the fracture was "*consequential to the bolt* [stud] *fractures*". It is therefore concluded that the piston was intact when it struck the cylinder skirt. For the intact piston to strike the skirt, the cylinder must have moved out from the crankcase and the piston must have no longer been inside the cylinder. The evidence of stripping of the threads in the crankcase by the studs would suggest that the crankcase was still intact at that time. Metallurgical analysis of the fractured crankcase supports this conclusion, in that the fracture surfaces were found to be "*visually consistent with failure by instantaneous overloading*".

Based on a review of the engine damage and the metallurgical analysis carried out, the most likely failure sequence is as follows: The fatigue failure of five of the cylinder retention studs and the forcible stripping of the crankcase threads on the remaining three studs resulted in the number five cylinder moving outwards. This allowed the piston to make contact with the cylinder skirt, fracturing the piston and skirt and pushing the cylinder even further out. Thereafter, the flailing con rod made contact with and fractured the engine crankcase.

2.4 Cylinder Retention Stud Failure

2.4.1 Introduction

Detailed examination of the fractured cylinder retention studs at a specialist metallurgical facility identified that they failed due to fatigue.

For a fatigue failure of a threaded fastener such as a cylinder retention stud to occur, the stud would have to be subjected to fluctuating stresses. If a cylinder retention nut was at the correct torque value as specified by the Manufacturer, the stud would be correctly pre-loaded and the fluctuating stresses sustained would be minimal. However, if the torque was lower than that specified, the pre-load on the stud would be proportionally reduced, resulting in the stud being subjected to greater than normal fluctuating stresses, thereby increasing the likelihood of a fatigue failure.

The torque check carried out on the cylinder retention nuts during G-OCTI's engine disassembly revealed that most of the nuts securing the number one and the number three cylinders (on the same side as the detached number five cylinder) were below the Manufacturer's specified torque. The nuts securing the number six cylinder were found to be particularly loose. Almost all of the nuts securing the number two and the number four cylinders were deemed to be at least at the correct torque values.

2.4.2 Causes documented in the FAA's Special Airworthiness Information Bulletin

The FAA's Special Airworthiness Information Bulletin, NE-14-13, described a previous event involving a Lycoming engine, whereby a cylinder retention stud failed due to fatigue and states that the fracture "*started from a single point corresponding to a corrosion pit in a thread root". The Bulletin notes that "there was no evidence of the cadmium plating where the corrosion pit developed".*

In addition to corrosion, the FAA's Bulletin highlights several other causes of stud failure which include:

- *Improper torque due to excessive paint on the cylinder flange, the mounting surface to the crankcase and/or the hold down nut area, prior to installation*
- *Fretting on the crankcase main bearing mating surfaces*
- *Improper torque at cylinder installation*

2.4.2.1 Loss of Cadmium Plating leading to Corrosion

The Bulletin discusses a recommendation that had been issued to the FAA to request that the Engine Manufacturer introduce additional maintenance requirements to "e*nsure that the cadmium plating on the cylinder mounting studs, fitted to Lycoming engines, is not permitted to degrade to a level where corrosion of the base stud material can result in failure of the stud*."

The Bulletin notes that the engine manufacturer advised the FAA that the existing instructions were deemed to be adequate.

In the case of G-OCTI's engine, the cadmium plating was found to be damaged and missing from large areas on all of the fractured studs. Cadmium plating is a sacrificial coating which will deteriorate over time and the Engine Manufacturer considered the deterioration to be normal. The Metallurgist and the Engine Manufacturer considered it unlikely that the deterioration of the cadmium plating had an adverse effect on the fastener torque.

It was noted during metallurgical analysis that there was a "*dusting of red rust"* on the flanks of the threads of the cylinder retention studs. However, no corrosion pitting was observed and it was specifically stated in the metallurgical examination report that the failure of the studs "*did not initiate from corrosion pitting or any other pre-existing material defects"*. Notwithstanding this, the report noted that any form of corrosion would accelerate the initiation of fatigue cracking and therefore stated that the corrosion was "*a contributory factor to the subject stud failures, even though insufficient assembly torque was the most likely root cause".*

The possibility was considered that the corrosion on the studs may have been as result of the aircraft remaining in storage in the open before the engine was removed for disassembly. However, the engine cowlings remained fitted during this period and such storage conditions would not be unusual for General Aviation aircraft. It is therefore likely that the extended period of time that the engine was in service since it was last overhauled contributed to the corrosion observed.

2.4.2.2 Excessive Paint of the Cylinder Mating Surfaces

Inspection during engine disassembly revealed no evidence of excessive paint on the cylinder flange, on the crankcase cylinder mounting surface or on the hold down nut area surfaces. Therefore, improper torque due to excessive paint was deemed not to be a factor in the failure of the studs.

2.4.2.3 Fretting

Fretting on the mating faces at the cylinder to crankcase interfaces and at the crankcase main bearing mating faces would be an indication of relative movement, which could result from the cylinder retention nuts, including those fitted to the thru-studs, being under-torqued. In the case of the engine from G-OCTI, there was no evidence of fretting on the cylinder mounting faces nor was there any evidence of fretting on the crankcase main bearing faces.

The possibility was considered that due to the lack of evidence of fretting, the under-torque observed during engine disassembly may have been solely as a result of the severe distress the engine suffered following the detachment of the number five cylinder. As stated above, the retention nuts securing the number six cylinder were found to be particularly loose and two of these were fitted to thru-studs which are also used to secure the number five cylinder. It is therefore possible that the detachment of the number five cylinder adversely affected the torque of the nuts securing the number six cylinder. However, the finding of the metallurgical analysis that the number five cylinder retention studs failed due to fatigue as a result of a loss of torque, indicates that the nuts securing the number five cylinder were in an under-torque condition for a considerable period of time.

The under-torque condition of the cylinder retention studs, although not causing fretting at the cylinder mounting faces and the crankcase main bearing faces, could have resulted in the studs being subjected to increased cyclical loading, leading to the fatigue failure of the studs securing the number five cylinder. This conclusion is consistent with the FAA's review of the NTSB's database for cylinder stud failures, which identified that the failures were due to fatigue that was caused predominately by "*insufficient preload* [due to insufficient torque] *and/or improper installation*".

2.4.2.4 Improper Torque at Cylinder Installation

Engine maintenance records indicate that the number three, five and six cylinders were replaced on 24 September 2010 at 804 engine hours and that the number one cylinder was replaced on 29 September 2011 at 919 engine hours.

The procedures to be followed for tightening the cylinder retention nuts when replacing cylinders on assembled engines are described in Part II of the Manufacturer's Service Instruction No. 1029D, which states that *"both ends of free-thru studs* [as fitted to G-OCTI's engine] *must be tightened simultaneously. At any time one or more cylinders are replaced, it is necessary to retorque the thru-studs on the cylinder on the opposite side of the engine".* Related to this, the Overhaul Manual warns that to "*eliminate the possibility of subsequent loosening of cylinder base nuts"* the correct tightening sequence must be followed.

The work sheet for the replacements of cylinders number three, five and six records that the cylinder retention nuts were torqued in accordance with the "*MM*" (Maintenance Manual). The MRO subsequently advised the Investigation that the manual actually used is the Overhaul Manual. It is possible therefore that the work sheet entry was a typographical error, and the actual intention was to refer to the Overhaul Manual. Furthermore, the Investigation notes that an incorrect torque value of 35 ft.lb. instead of the correct value of 25 ft.lb. is quoted on the work sheet for the replacement of the number one cylinder. The possibility was considered that this over-torque value could also have been used when the number five cylinder was installed. However, metallurgical analysis did not find any evidence of stud failure due to over-torque. Therefore, it is possible that this work sheet entry may also have been a typographical error.

Metallurgical examination identified that the cylinder retention studs failed due to fatigue as a result of insufficient preload caused by the retention nuts being in an under-torque condition. The under-torque condition of the retention nuts securing the engine cylinders that had been replaced, the results of the metallurgical analysis, the paperwork anomalies identified, and the fact that the Engine Manufacturer advised the Investigation that they were unaware of any cases of correctly torqued nuts backing off in service, suggests that an installation error cannot be ruled out. However, the torque check carried out during engine disassembly also found that not all of the retention nuts securing the number two and the number four cylinders were at the correct torque value and there is no record of these cylinders being replaced in the engine log book available to the Investigation.

2.4.3 Failure Summary

The Investigation examined a number of potential causes for the retention nut under-torque observed during engine disassembly, and the likely similar under-torque condition of the nuts that secured the number five cylinder. However, a definitive cause could not be established and therefore no Safety Recommendation is made.

3. CONCLUSIONS

(a) Findings

1. The aircraft was operating on a valid ARC.

2. The number five engine cylinder detached in flight, resulting in a loss of engine power which necessitated a forced landing.

3. The cylinder detached due to the fatigue failure of several of the cylinder retention studs.

4. The cadmium plating was damaged and missing from large areas on all of the fractured studs.

5. Corrosion in the form of a dusting of red rust was found on the flanks of the threads of the studs. However, the stud failures did not initiate from corrosion pitting or any other pre-existing material defects.

6. Metallurgical analysis identified that the fatigue failure of the studs was caused either by insufficient torque being applied to the retention nuts during assembly or by the nuts backing off in service.

7. The number one cylinder had been replaced on 29 September 2011. The number three, five and six cylinders had been replaced on 24 September 2010 by the same MRO. The engine operated for over 200 hours since the replacement of the number five cylinder.

8. The torque check carried out by the Investigation during engine disassembly found that almost all of the nuts retaining number one and three cylinders (on the same side as the detached cylinder) were below the specified torque value. The nuts securing the number six cylinder, which is the opposing cylinder to the number five cylinder (the detached cylinder), were found to be particularly loose.

9. The Engine Manufacturer advised that they are unaware of any cases of correctly torqued nuts backing off in service.

10. An Annual Inspection was completed on the aircraft on 16 October 2014. A check of the cylinder retention torques does not normally form part of an Annual Inspection.

11. Records indicate that the engine had operated for approximately 1,035 hours since last overhaul. The recommended TBO for the engine type based on operating hours is 2,000 hours.

12. The Engine Manufacturer recommends that the engine type fitted is overhauled in the twelfth year, if it does not reach the recommended TBO based on hours of operation.

13. The CAA permits engines that are installed in aircraft being used for Private Flights only, to continue in service beyond the Manufacturer's recommended calendar time, subject to certain conditions and inspection requirements.

14. Engine log book records and information obtained from the Owner indicate that the engine was last overhauled in 1987. The engine had therefore been in operation for over 27 years since overhaul.

(b) Probable Cause

Detachment of the number five engine cylinder due to the fatigue failure of a number of the cylinder retention studs.

(c) Contributory Factors

1. Insufficient pre-load on the cylinder retention studs.

2. The presence of corrosion on the studs as a consequence of the loss of the cadmium plating.

4. SAFETY RECOMMENDATIONS

The Investigation does not sustain any safety recommendations.

Appendix A

Metallurgical Analysis Details

Hardness Testing

Metallurgical analysis identified that the studs met the Engine Manufacturer's hardness specifications, with the exception of stud #3. The hardness for this stud was found to be 47HR30N[19], compared to a specified minimum of 48.6HR30N. Metallurgical Analysis concluded that such a small difference was not considered significant to its failure.

Chemical Analysis

Stud #3 showed an aluminium content of 1.38%, which is not included in any of the alloy specifications quoted by the Engine Manufacturer. This stud showed extensive post-fracture damage, which included abrasion of its threads. It was most likely that aluminium from the crankcase had been trapped within the abraded threads and could not be removed, prior to analysis. Therefore, this was not considered to be significant to the cause of its failure.

The manganese content of stud #6 was 0.71%, which was slightly below the specified minimum of 0.75%. However, such a small difference was not considered to significant to its failure.

Fracture Analysis

Metallurgical Analysis found that the fracture surfaces of studs #1, #2, #4 and #6 were similar in appearance and characteristics. The following description applies to each of these studs. The fracture surface was macroscopically flat and was perpendicular to the major axis of the stud. Macroscopic fatigue arrest marks were visible on this surface. When examined at high magnification in a Scanning Electron Microscope (SEM), it showed an "*array of parallel microcracks, typical of fatigue crack growth in hardened and tempered low alloy steels* [stud material]". Analysis indicated that the fatigue failure had initiated around one half of the stud circumference and had progressed across its diameter. "*Ratchet*" marks at the edge of the fracture surface indicated that the fatigue fracture had initiated from multiple sites and merged to form a single, major crack front. It was stated that "*there was no evidence of pitting corrosion or other pre-existing material defects at the initiation sites*".

The metallurgical report noted that "*on the opposite side of the fracture surface, there was a small area, which was inclined on a 45^o shear plane. When examined at high magnification in the SEM, this region showed a dimpled appearance, typical of ductile separation, due to instantaneous overloading. These characteristics were consistent with final separation of the stud, when the remaining uncracked ligament became overloaded by the advancing fatigue crack. The large area of fatigue growth, compared with the small area of final separation was consistent with a low magnitude of cyclic stress, repeated for a large number of stress cycles. These stress cycles most likely correspond to strokes of the piston*".

[19] **HR30N:** A Rockwell Hardness Sensitivity Coefficient.

The metallurgical report continues as follows: "*The fracture surface of stud #3 differed slightly from the remainder of the fractured studs. In this case, fatigue arrest markings indicated that the failure had occurred by the coalescence of at least four major crack fronts, each of which had initiated in thread roots. This stud had become liberated from the crankcase, after the detachment of the cylinder. It had consequently suffered significant post fracture damage, which had obscured the fracture initiation sites. However, secondary fatigue cracks were present in the roots of other threads. There was no evidence of corrosion pitting or other pre-existing material defects at their initiation sites*".

- END -

In accordance with Annex 13 to the Convention on International Civil Aviation, Regulation (EU) No 996/2010, and Statutory Instrument No. 460 of 2009, Air Navigation (Notification and Investigation of Accidents, Serious Incidents and Incidents) Regulation, 2009, the sole purpose of this investigation is to prevent aviation accidents and serious incidents. It is not the purpose of any such investigation and the associated investigation report to apportion blame or liability.

A safety recommendation shall in no case create a presumption of blame or liability for an occurrence.

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