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Jabiru Engine Reliability

Analysis Report

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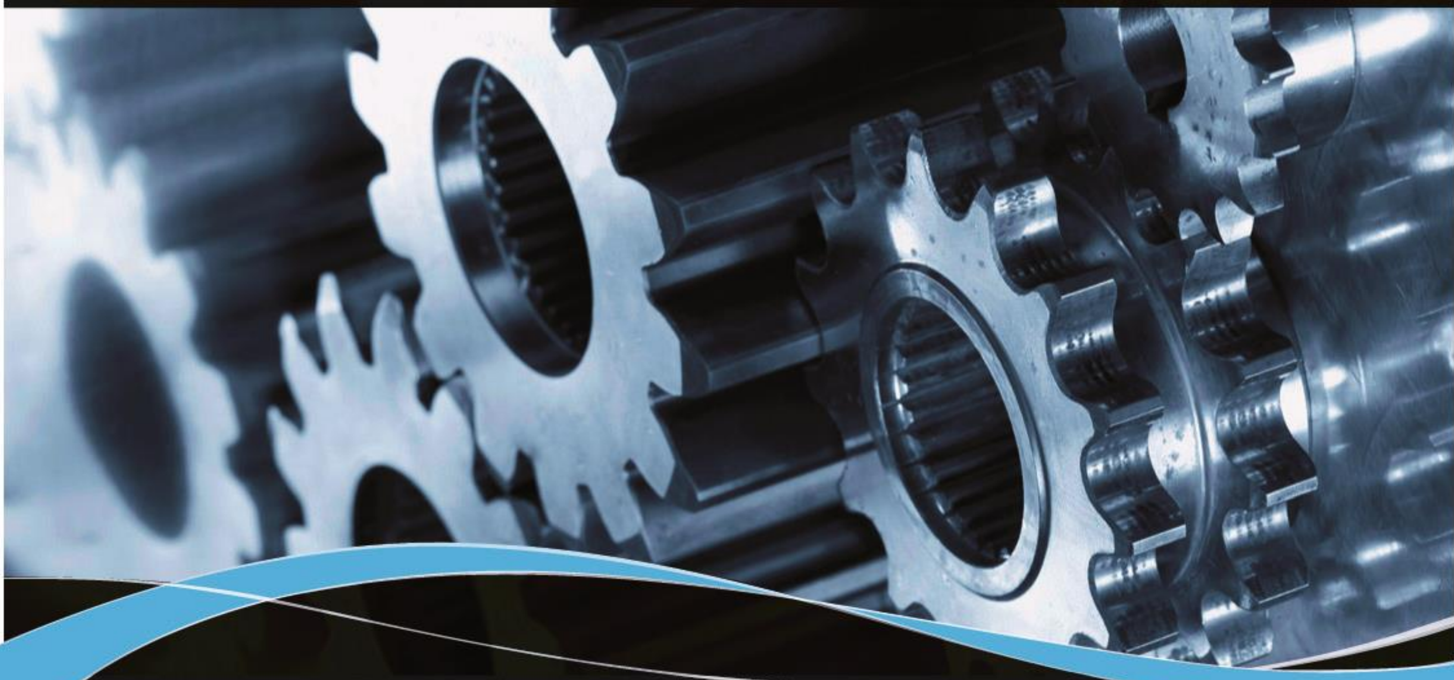
CIVIL AVIATION SAFETY AUTHORITY



safe skies for all

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A. Introduction

This report reflects the results of the investigation and analysis conducted by CASA, in conjunction with Alan Kerr, Principal Engineer, the Aeronautical Design Service (on behalf of Jabiru Aircraft Pty Ltd**)**, with a view to determining the causes of the loss-of-power events involving certain Jabiru-manufactured engines, and to identify actions that might be taken to address those problems.

On the basis of previous and ongoing consideration of the matter, involving CASA and Jabiru, it was agreed that an example engine with 956hrs of operation be disassembled, to establish the condition and associated durability of a Jabiru engine that met certain criteria for configuration, operation and maintenance. Conceptually, the premise of this exercise was that, if CASA could be satisfied that the durability and reliability of a particular configuration of engine could be established, then a potential path to relaxing or lifting the operational limitations to which all Jabiru-powered aircraft are currently subject might be achieved.

On 13th August 2015, CASA staff attended the disassembly of the example engine at the Jabiru facility in Bundaberg. This example engine presented in a condition that was considered satisfactory in relation to airworthiness and the defects noted in the disassembly process would be considered normal for an engine with 956hrs of operation completed.

The disassembly activity established a data point and a basis of substantiation in support of the durability of the engine in the identified configuration. However, this activity did not address the issue of reliability and as such, CASA found itself in a position from which further consideration would need to be given as to how acceptable reliability could be demonstrated in order to allow the relaxation of the operating limitations.

B. Discussion

The terms reliability and durability have on occasion been used interchangeably in discussions regarding the concerns surrounding the Jabiru engine. This has caused some confusion and blurred somewhat a clearer focus on the original reported issue of poor reliability.

In mechanical engineering terms, durability refers to the ability of a machine or component of a mechanical system to operate for a given amount of time with an expected level of resistance to wear under predetermined conditions. The acceptable measure of durability of an aircraft engine is usually reflected as a Time Between Overhaul (TBO) and is a number usually defined by the manufacturer of the expected useful life of the engine under normal operating conditions. The Jabiru engine has a TBO for the “Top End” of 1,000hrs and for complete overhaul at 2,000hrs.

Reliability however is the ability for a machine or component of a mechanical system to operate consistently or repeatedly without failure within the expected durability timeframe. In the aviation context, reliability is typically measured in one of two ways:

> ***Mean Time Between Failure*** where the total time in service for the entire population is plotted against the total number of failures. This is typically used for individual components or accessories (e.g. an exhaust valve or Fuel Pump) and is quoted as a figure in hours (e.g. 53,250hrs MTBF)

Failure Rate/In Flight Shut Down rate (IFSD) where the number of failures is plotted against the total time in service for the entire population. This is typically quoted on a per 1,000hrs basis e.g. 0.03/1000hrs relates to one engine IFSD per 33,000hrs of operation

Hence, the acceptable and measureable reliability of a product is the ability of the product to repeatedly function to its design requirements to a pre-determined IFSD rate based on existing industry performance or an agreed rate where the rate can be generally described as "As Low As Reasonably Practicable" (ALARP)

On this basis, the inspection of a single engine is not a representation or confirmation of acceptable reliability. A certain number of engine failures can be anticipated in an imperfect world and while not desired, such failures may be considered acceptable when the rate is lower than an authoritatively settled figure.

1) Issues regarding the measurement of reliability of the Jabiru engine

The design standards do not require an acceptable level of *reliability* for aircraft or aircraft engines. This is simply due to the fact that reliability is dependent on many factors outside of the aircraft design, such as environmental conditions, maintenance, operator experience, etc. Hence reliability can only be measured once operational experience is attained and even then, the measures need to be carefully understood to assure that an appropriate interpretation of what has been measured is identified.

However, when the Jabiru failures are broken down into primary apparent causes, it is clear that engine through bolts and valve train failures are important concerns in relation to the reliability and subsequent airworthiness of the Jabiru engine. The ATSB report AR-2013-107 (Attachment 1) provides a good breakdown of the pertinent data. Figure 9 on page 18 of that report clearly shows that, if these two primary failures can be controlled, the reliability of the Jabiru engine would be satisfactory as other failure modes do not show a trend of failure.

2) Through bolt failures

A through bolt failure does not cause an instant engine power loss. The failure of a through bolt reduces the clamping forces that restrain a cylinder to the engine cases and redistribute the load between the three remaining bolts (for a through bolt, this would be on two cylinders as each bolt restrains the cylinders on opposite sides of the cases). With time, the combustion pressure will fatigue the remaining bolts and mating surfaces with an eventual tightening of the bore clearances (as the cylinder bore is able to move off centre) causing a binding of the piston in the bore with subsequent and gradual increase in rough running, leading to catastrophic failure if ignored.

A leading indicator of an impending through bolt failure would be oil leaks around the base of the cylinder as the bolt forces reduce (as the fatigue progress prior to complete failure). Such leaks should be investigated prior to further flight to ascertain the integrity of the through bolt.

A pull test on the propeller prior to first flight of the day *may* provide an indication of a tight engine, however this is very subjective and depends on the experience of the pilot to recognise small changes when performing a pull test.

Lastly, and the most obvious would be identifying a broken through bolt by visual inspection from pilot reports of rough running or via a reduced inspection interval.

3) Valve train failures

Valve train failures can be caused by many factors, however the complete power loss of an engine is typically through a valve stuck open and impacting the piston on the next stroke. This impact causes significant damage to the valve (typically by stem bending) and subsequent strokes cause damage to the piston, leading to severe vibration and significant power loss. A similar but slightly different failure mode is where the valve head becomes overheated and literally drops off into the cylinder, causing a similar failure effect to that described for the stuck valve. An alternative to this is where the retaining system (collets or washer) fail allowing the entire valve to drop into the cylinder with catastrophic consequences for the engine.

Partially stuck valves that do not impact the piston typically lead to rough running, as would a spring failure in a double spring configuration. The new configuration of Jabiru piston has recesses machined into the crown (or head) that provide some relief if a valve were to stick, the recess allows enough clearance to not cause an impact and subsequent power loss although the stuck valve may still lead to rough running. The recessed head does not of course alleviate any failure due to a dropped valve or valve head.

4) Maintenance considerations

The Jabiru engine has been designed to be lightweight for light sport applications and also to be easy and efficient to maintain. From the data provided, however, it appears that the engine is very reliant on a fastidious maintenance regime and is intolerant of variation to the schedule provided by the manufacturer.

In the case of valve train failures, Jabiru have issued a comprehensive Service Letter (JSL014-2), This was originally issued in December 2014. The Letter covers valve train maintenance practices. Jabiru run maintenance courses on these practices and we understand they have received consistent feedback from students that they did not realise the level of complexity of the maintenance Jabiru cylinder heads and the associated valve train require.

5) When is a Jabiru engine not a Jabiru engine?

CASA Instrument 102/15 applies to "*an aircraft powered by an engine manufactured by Jabiru*". The term is defined in the instrument as follows:

***manufactured by Jabiru**, in relation to an engine, includes an engine that is wholly or partly manufactured by a person under licence from, or under a contract with, Jabiru.*

It is understood that "aftermarket" parts are available for experimental aircraft, and certain Jabiru engines may have been modified in ways that involve the installation of non-Jabiru manufactured parts. All of these modifications have the potential to contribute to the reliability of the engine, in both a positive and negative manner.

Per the requirements for LSA, the aircraft/engine must not be modified without the manufacturer's approval. We recognise that no such requirement applies to experimental category aircraft, and some of the complexities this situation may involve.

In keeping with the points made in the context of the discussion of reliability above, CASA recognises that a true and complete picture of reliability can only be achieved on the basis of a consideration of known configurations. In this instance, the decision to impose operational limitations was taken as a *precautionary* measure, without the benefit of complete, comprehensive and determinative data. It was the safety risks inherent in the situation that necessarily governed CASA's decision-making, rather than the degree to which the manufacturer could or could not control some of the variables involved.

C. Recommendations

The Appendix to this report provides a summary of the suggested operational limitations for some Jabiru manufactured engines based on the data assessed. A significant outcome of the analysis is that the current limitations would not apply to the majority of the fleet where it can be demonstrated that the engines involved have had sufficient and acceptable levels of reliable operation since the original limitations were set.

The following is a detailed breakdown of the limitations and associated conditions and provides justification for each of the key points.

1) When operational Limitations should apply:

Generation 2 engines, manufactured with flat faced hydraulic valve lifters, engaged in, or have engaged in flying school operations with 3/8" through bolts and studs above 500hrs (engine time) of operation.

Justification: Through bolt failures have not been experienced on generation 1 or generation 3 engines (solid lifter and roller follower hydraulic lifters respectively). Of the 23 failures that have been confirmed, 19 are known to be Generation 2 engines in flight training operations with the remaining 3 failures unable to be positively attributed to a known operation (i.e. not enough information from the data to ascertain whether flight training or not).

The current Jabiru requirement per Service Bulletin JSB031 requires replacement of 3/8" through bolts in flight schools at 500hrs. To date, there have been no reported failures of any through bolts since 1st April 2015 (bearing in mind the limitations have been in place during this time). Replacement of the through bolts with the existing 3/8" configuration would be an impediment to flight schools, hence upgrading to the 7/16" configuration, while a significant modification due to the machining of the engine cases, will provide relief from the limitations and the confidence of a proven and reliable configuration.

Jabiru manufactured engines modified using non-Jabiru manufactured parts

Justification: The design characteristics of the Jabiru engine discussed in (5) above indicate that the engine design and subsequent reliability of performance is potentially volatile with regard to any change in design. This provides an undesirable outcome in the experimental category due to modifications being made that are unable to consider the implications of the changes as part of the entire system. One example identified during the analysis was the use of Solid Lifters that had been manufactured by an individual, with the components sold to an engine owner who installed the items as direct replacements in place of hydraulic lifters. In this example, the wider effects of this change with regard to oil distribution, resonance and applied forces within the valve train cannot be understood without detailed design data or significant reverse engineering.

Regardless of who the engine manufacturer is, such modifications should not be considered within the dataset of reliability as the original manufacturer has no control over such changes. While this limitation is appropriate in the context of the Jabiru, caution must be given to the perception of a commercial advantage being given to Jabiru, hence this issue should be considered in the broader sense that includes all manufacturers (i.e. this is not a Jabiru problem) and also in the context of the experimental category.

2) <u>Where operational Limitations DO NOT apply:</u>

Generation 1 and generation 3 engine configurations.

Justification: Through bolt failures have not been experienced on generation 1 or generation 3 engines. The vibratory characteristics of the Generation 1 engines has been shown to exhibit a distinct difference in the natural frequency to the hydraulic lifter crankcase which had unfortunate characteristics relative to the engine excitation frequency, causing the crankcase to vibrate and fret.

Additionally, Jabiru have shown that the 3/8" through bolt is more susceptible to thermal loading than the 7/16" for the same temperature increase. This has been attributed to the 3/8" through bolt having a higher spring rate than the 7/16" through bolt. (refer reference 6, Jabiru report AVDALSR109-1).

The valve train failures that have been experienced are not configuration specific. The roller cam configuration of the Generation 3 engine does provide for a smoother transition of the required forces to move the valve train, however this has not shown to be significant in addressing the primary causes of the failures experienced.

The failures experienced can generally be attributed to the maintenance practices, not necessarily poor quality of maintenance but as discussed above, any deviation from the current Jabiru recommendations does appear to introduce conditions that can rapidly deteriorate the engine health to the point of failure. Hence, the current maintenance schedule (in particular 25hr oil changes) and the maintenance requirements for cylinder head inspections/maintenance per Service Letter JSL014 can be expected to provide for an acceptable level of reliable operation if they are adhered to with some vigilance.

In consideration of the Generation 3 configuration, the tear down of engine 22B303 following 956hrs of operation did not reveal any concerns regarding the integrity or durability of the component parts, providing some confidence that when maintained appropriately, the engine design has the capability of achieving the forecast top end overhaul of 1,000hrs.

Generation 2 engines with 7/16" through bolts and studs (any operational type).

Justification: For the reasons discussed above, the 7/16 through bolts have proven to be durable as no known failures have occurred in any configuration at this time. This through bolt configuration coupled with the recommended maintenance practices can expect acceptable levels of reliability. The upgrade to this configuration requires significant rework of the engine cases, but once upgraded, unrestricted operation should be considered acceptable.

Generation 2 engines with 3/8" through bolts that have not conducted any flying school operations.1

Justification: As discussed for Generation 1 and Generation 3 engines, Jabiru have shown that the 3/8" through bolt is more susceptible to thermal loading than the 7/16" for the same temperature increase. This has been attributed to the 3/8" through bolt having a higher spring rate than the 7/16" though bolt. (refer Attachment 6, Jabiru report AVDALSR109-1). The flying profile of the flying schools exacerbates this condition with the high frequency temperature changes throughout the flying day due to multiple power changes, training flights, touch-and-go, etc.

Secondary to this, the above discussion regarding the ability to identify an impending failure or even to reasonably manage an engine that has experienced a failure shows that there is no immediate or catastrophic mode of failure. Raising awareness to the symptoms of through bolt failure should be considered a sufficient mitigation strategy for recreational operators (i.e. not flying schools) that elect to not upgrade their engines to the 7/16 configuration. It must be remembered that an upgrade requires significant work as the engine cases must be removed and reworked using specialised machine tools. It is reasonable based on the data available that CASA allows participants in this sector to make an informed decision as to whether they choose to invest in an upgrade or accept the need for a higher degree of vigilance with regard to being mindful of the deficiencies of the 3/8" configuration.

3) <u>General requirements:</u>

Mandatory requirements as a condition of normal operations:

All recommendations above are conditional on the recommended maintenance practices being performed. An assessment of a selection of maintenance records for 5 aircraft revealed generally poor practices and quality in the records. Two of the aircraft (inadvertently maintained by the same organisation) did display a high degree of compliance with the Jabiru requirements and these aircraft have not experienced any difficulties in service.

As a result of a review of the recommended maintenance practices issued by Jabiru, the Appendix to this report highlights the critical areas. While compliance with these practices should be performed without requiring restatement in a legislative instrument, there is a clear need for participants in this sector to be aware that the Jabiru engine maintenance schedule must be followed to the letter (i.e. within +/- 3hrs) otherwise poor reliability should be anticipated.

The critical practices listed in the Appendix are not intended to trivialise any other maintenance requirement set by the manufactures schedule. All maintenance is to be performed to the schedule as a condition of unlimited operations.

D. Appendix – Summary of recommendations

1) Definitions of configuration:

	Manufactured s/n range (4cyl)	Manufactured s/n range (6cyl)	Description
Generation 1	22A0001 through 22A2067	33A0001 through 33A0960	Manufactured with solid valve lifters
Generation 2	22A2068 through 22A3595	33A0961 through 33A2539	Manufactured with flat faced hydraulic valve lifters
Generation 3	22A3596 and above	33A2540 and above	Manufactured with roller hydraulic valve lifters

2) Where operational Limitations apply:

1. ***Generation 2*** engines, engaged in, or have engaged in flying school operations with 3/8” through bolts and studs above 500hrs (engine time) of operation.
2. Jabiru manufactured engines modified using non-Jabiru manufactured parts.*

* *This would apply to a CAMit hybrid engine but not a CAMit designed and manufactured engine. Also applies to experimental modifications (solid lifters in hydraulic cases) and water cooled heads.*

3) Where operational Limitations DO NOT apply:

1. ***Generation 1*** and ***generation 3*** engine configurations.
2. ***Generation 2*** engines with 7/16” through bolts and studs (any operational type).
3. ***Generation 2*** engines with 3/8” through bolts that have not conducted any flying school operations.

4) Mandatory requirements as a condition of normal operations:

1. All through bolts and studs, regardless of configuration are to be replaced prior to 1,000hrs of operation.
2. The Jabiru maintenance schedule is to be performed as per the manufacturers schedule. Of specific note within the current requirements of the Jabiru ***JEM0002-6 Maintenance Manual*** are:
    a. Oil and filter change (every 25hrs – Table 13 item 37)
    b. Compression or leak down check (every 50hrs – Table 13 item 18)
    c. Intake and exhaust systems Inspection (every 25hrs – Table 13 item 14)
    d. Permanent and temporary storage requirements (Paragraph 7.2)
    e. “Pulling Through” the Engine as part of the pre-flight inspection (first flight of the day as described in the Pilot’s Operating Handbook)
    f. Engine tuning per the current maintenance manual requirements (JSL002 configuration must not be used).

Note: *This list is not intended to trivialise any other maintenance requirement set by the manufactures schedule. All maintenance is to be performed to the schedule as a condition of unlimited operations.*

3. Significant Jabiru Service Bulletin's (SB's) and Service Letters (SL's) must be complied with to the latest revision. Specifically:
    a. JSL014 – Cylinder Head Inspections
    b. JSL031 – Through bolt replacement and upgrade
    c. JSL008 - Valve Spring Washer Adverse Wear.
4. The correct fuel and oil must be used at all times. Refer JSL007 – Alcohol lead compression ratio fuel guidance.
5. Engine hours must be used at all times (Hobbs time) not air time hours. Refer JSL010 – Service Time Intervals.
6. Correct and complete maintenance certifications must be made by appropriate personnel for all the above requirements.

5) Supplemental recommendations (not required for operational limitations)

1. CHT & EGT monitoring equipment is recommended for engine health monitoring.
2. Recessed pistons to assist in the avoidance of total power loss in the event of a valve stuck fully open.
3. Specific Engine maintenance training as provided by Jabiru.

E. Attachments

1) ATSB Report AR-2013-107 - Engine failures and malfunctions in light aeroplanes

2) CASA 102/15 - Conditions and direction concerning certain aircraft fitted with engines manufactured by Jabiru Aircraft Pty Ltd

3) Report No. 141118-1-70 – Justification – Relaxation CASA limitations (Alan Kerr) – CASA Ref: D16/173796

4) Report No. 141118-1-30 – Teardown inspection report 22B303 (Alan Kerr) CASA Ref: D15/619101

5) Through bolt strain gauge tests - AVDALSR109-1 – CASA Ref: D15/738192