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An evaluation of the technical condition of the ROTAX 912S Engine based on spectrographic oil analysis

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Abstract

Flight safety, which characterizes the aviation industry, is an important element that contributes to increasing the trust of customers and passengers. The aforementioned factor closely corresponds to the reliability of aircraft and their individual components, including power units. Over one hundred years of development of aviation techniques has led aviation to the currently observed level of safety and reliability. Aviation techniques should be understood as technologies as well as local and global regulations affecting individual branches of the industry.

Guidelines No. 9 of the President of Polish Civil Authority of August 29, 2016 on the inter-repair periods of piston engines, indicate the possibility of waiving the requirements related to the performance of major repairs, and a number of conditions must be met. One of the requirements set out in the Guidelines is performing a spectrographic analysis of engine oil in order to estimate the rate of wear of individual engine parts (ULC, 2016). .

The main goal of this study was to recognize whether regular analysis of engine oil may affect the assessment of the technical condition of aircraft piston engines based on the example of ROTAX 912S, thus affecting or not influencing the maintenance intervals. The engines referred to in the research were produced in the amount of about 2,000 units. Thus, these engines gained popularity as power units for airplanes, helicopters, and gyroplanes. With the increasing number of ROTAX units introduced into service, research into the technical condition becomes more important due to their percentage share in the market.

Keywords: aircraft operation, maintenance, oil analysis, safety

1. Introduction

Nowadays, the aviation industry providing transport services with the use of aircraft is recognized as one of the safer means of transport. This statement is reflected in the statistics. As an example, mention should be made of the Bureau of Aircraft Archives, where, as reported in the years 1918-2020, the number of fatalities using air transport was about 156,000 (BAA, 2022). Comparing the above with 1.35 million victims of road transport accidents (WHO, 2022), , the discussed volume from aviation seems to be relatively small.

Several factors can be identified that influence this level of air transport safety. Two basic ones can be indicated: conducting continuous airworthiness supervision over the operated aircraft, and performing maintenance in accordance with the manufacturer's requirements, and applicable regulations, as well as taking into account all aviation supervision guidelines. Regular engine oil analysis is one of the activities that allow monitoring the technical condition of aircraft piston engines.

There is a plethora of aircraft on which reciprocating engines are mounted. These include the AERO AT-3 R100 aircraft. Airplanes with piston engines are used in aviation training centers where future flight crews are trained. Adepts going through the basic training process are not required to have all the practical skills, operational awareness or analytical skills needed to perform a flight, because they take their first steps as trainees in the initial stage of training. In such a situation, the drive unit may be operated more often in conditions that exceed the permissible parameters (over-speed, oil overheating, coolant overheating, etc.). With this in mind, it seems that under training conditions, it is appropriate to perform additional maintenance monitoring activities, such as the lubricant analysis mentioned above.

2. Purpose of the research

The aim of the research was to assess the technical condition of Rotax 912S piston engines used in aircraft of the Aviation Training Center of the Silesian University of Technology, the basis of which a spectrographic analysis of engine oil was to be conducted. An additional goal was to determine whether and to what extent the oil analysis may affect the above-mentioned assessment, which could further extend the safe operation of these engines, in accordance with the Guidelines No. 9 of the President of the Polish Civil Aviation Authority of August 29, 2016. Currently, spectographic tests of lubricants are used to determine their technical condition. Current trends indicate the possibility of using artificial intelligence for this type of process (Grimmig et al., 2021; Rahimi et al., 2022). Lubricant analysis can be used wherever there is contact between moving machine parts.

3. Research methodology

The initial step in determining trends in the mechanical wear of the moving parts of the Rotax 912S engine was to examine the content of elements in the sample of unprocessed engine oil. All results obtained from the fresh oil test are taken as reference results. The spectrographic analysis was performed taking into account the following standards:

- examining the content of the elements (ASTM, 2018);
- kinematic viscosity testing (PKN, 2021);
- acid number testing (ASTM, 2019).

Additionally, the PQ index was examined. results were sorted and are presented below. The group of elements for unused oil, the excessively high content of which in the engine oil may indicate progress in the mechanical wear of the drive unit, is presented in Table 1.

The applied oil test allows determining the level of ferromagnetic particles in the elements presented in Table 1. The level of metallic abrasive contained in the lubricant is given as the PQ index value. In a situation where the PQ index is lower than 25 pmm, the drive unit is subjected to the normal process of mechanical wear. If the content of ferromagnetic particles in the engine oil, given in mg / kg, is high and the PQ index is low, this indicates corrosion. This is due to the low magnetic properties of the rust components, which translates into low PQ readings. In a situation where there is a high level of the PQ index, and simultaneously small amounts of Fe and Ni - measured by atomic emission spectroscopy, this indicates the occurrence of increased degradation processes of the surface layers - e.g., by abrasion (Rahimi et al., 2022).

Table 1. The content of the elements indicating wear in the reference sample

Element	Symbol	Content [ppm]
Iron	Fe	<1
Aluminum	Al.	<1
Copper	Cu	<1
Lead	Pb	<1
INDEX PQ		<25

Source and study own.

Another group of elements contained in the oil are elements that are enriching additives, i.e., those whose presence improves the properties of the lubricant. One of the additives, dispersants, keeps the carbon black particles in suspension. Keeping the soot particles in a slurry reduces the negative impact of soot build-up in the oil channels and sump.

The next group of additives modifying the properties of the oil are those additives whose task is to improve the viscosity of the lubricant at operating temperatures. These additives can, in turn, be divided into viscosators and depressants. Viscosers improve the viscosity of the oil at high temperatures, allowing the formation of a permanent oil film on the working surfaces. Subsequently, depressants counteract the precipitation of paraffin from mineral oil. The content of enriching additives in the reference sample is presented in Table 2.

Table 2. The content of enriching additives in the reference sample

Element	Symbol	Content [ppm]
Calcium	Ca	2752
Zinc	Zn	2286
Phosphorus	P	1872
Sulfur	S	5290
Magnesium	Mg	27
Boron	B	72

Source and study own.

Pollution is the next group. These include airborne dust, soot, coke, ash, tribological wear products, corrosion products, coating particles, abrasive particles, etc. The results of their content in the new oil sample are presented in Table 3. The kinematic viscosity and acid number are presented in Table 4.

Table 3. The content of impurities in the reference sample

Element	Symbol	Content [ppm]
Silicon	Si	14
Potassium	K	2

Source and study own.

Table 3. Continuation. The content of impurities in the reference sample

Element	Symbol	Content [ppm]
Sodium	Na	4

Source and study own.

Table 4. Kinematic viscosity and acid number of the reference sample

Property	Value
Kinematic viscosity in 100^{0}C [cSt]	14.44
Acid number [mgKOH/g]	5.46

Source and study own.

4. Results

The research material was a semi-synthetic aviation engine oil - Aero Shell Sport Plus 4. The sampling interval was dictated by the maintenance program and was 100 hours of flight time. The sampling times were successively 200, 400, 600, 800 and 1000 flying hours, so the entire test cycle covered the engine with 1000 hours of flight time. The results are shown below. The tested content of metallic particles indicating mechanical wear and the PQ index (number of ferromagnetic particles) in the sample after 200 hours of flight do not indicate the existence of disturbing wear processes (Table 5, levels higher than the reference sample). The content of enriching additives in the sample in question (Table 6) has decreased, while the level of impurities is comparable to the reference sample (Table 7). The kinematic viscosity and the acid number of the sample were compared with the results for the reference sample and presented in Table 8. The tests showed that both of these values are lower for the used oil.

Table 5. Content of elements indicating wear, found in a sample taken after 200 hours of flight

Element	Symbol	Content [ppm] in reference sample	Content [ppm] after 200 flight hours
Iron	Fe	<1	9
Aluminum	Al.	<1	2
Copper	Cu	<1	8
Lead	Pb	<1	4
Index PQ		<25	<25

Source and study own.

Table 6. The content of enriching additives in the sample taken after 200 hours of flight

Element	Symbol	Content [ppm] in reference sample	Content [ppm] after 200 flight hours
Calcium	Ca	2752	2226
Zinc	Zn	2286	1462
Phosphorus	P	1872	1272
Sulfur	S	5290	4898
Magnesium	Mg	27	24
Boron	B	72	46

Source and study own.

Table 7. Contaminant content in a sample taken after 200 flight hours

Element	Symbol	Content [ppm] in reference sample	Content [ppm] after 200 flight hours
Silicon	Si	14	9
Potassium	K	2	1
Sodium	Na	4	5

Source and study own.

Table 8. Kinematic viscosity and acid number of the sample after 200 hours of flight

Property	Value in reference sample	Value after 200 flight hours
Kinematic viscosity in 100^{0}C [cSt]	14.44	12.15
Acid number [mgKOH/g]	5.46	4.17

The results presented below are for a sample taken after 400 hours of flight. The content of the elements characteristic for mechanical wear is presented in Table 9. Table 10 presents the content of improvers, while the content of impurities is presented in Table 11. The results of the kinematic viscosity and the acid number are shown in Table 12.

Table 9. Content of elements indicating wear, present in a sample taken after 400 hours of flight

Element	Symbol	Content [ppm] in reference sample	Content [ppm] after 400 flight hours
Iron	Fe	<1	23
Aluminum	Al.	<1	4
Copper	Cu	<1	16
Lead	Pb	<1	6
Index PQ		<25	<25

Source and study own.

Table 10. The content of enriching additives in the sample taken after 400 hours of flight

Element	Symbol	Content [ppm] in reference sample	Content [ppm] after 400 flight hours
Calcium	Ca	2752	2842
Zinc	Zn	2286	2256
Phosphorus	P	1872	1778
Sulfur	S	5290	4822
Magnesium	Mg	27	31
Boron	B	72	70

Source and study own.

Table 11. Contaminant content in a sample taken after 400 flight hours

Element	Symbol	Content [ppm] in reference sample	Content [ppm] after 400 flight hours
Silicon	Si	14	9
Potassium	K	2	2

Source and study own.

Table 11. Continuation. Contaminant content in a sample taken after 400 flight hours

Element	Symbol	Content [ppm] in reference sample	Content [ppm] after 400 flight hours
Sodium	Na	4	13

Source and study own.

Table 12. Kinematic viscosity and acid number of the sample after 400 hours of flight

Property	Value in reference sample	Value after 400 flight hours
Kinematic viscosity in 100^{0}C [cSt]	14.44	12.02
Acid number [mgKOH/g]	5.46	4.31

The results for a sample taken after 600 hours of flight time of the power unit, with the lubricant performing 100 hours of flight time, are presented below. Table 13 shows the results of the elements indicating wear. The content of enriching additives is presented in Table 14. Table 15 shows the results concerning the content of impurities in the tested sample, while Table 16 shows the values of the kinematic viscosity and the acid number. Both the PQ index and the content of metallic particles do not show aberrations that would break the trend of the results from previous samples. The content of enriching additives decreased for all the determined elements. The value of the elements defined as impurities has changed for all the elements determined. The kinematic viscosity and the acid number decreased. No signs of excessive engine wear. Lubricant consumption trend maintained.

Table 13. Content of elements indicating wear, present in a sample taken after 600 hours of flight

Element	Symbol	Content [ppm] in reference sample	Content [ppm] after 600 flight hours
Iron	Fe	<1	30
Aluminum	Al.	<1	3
Copper	Cu	<1	11
Lead	Pb	<1	2
Index PQ		<25	<25

Source and study own.

Table 14. The content of enriching additives in the sample taken after 600 hours of flight

Element	Symbol	Content [ppm] in reference sample	Content [ppm] after 600 flight hours
Calcium	Ca	2752	2694
Zinc	Zn	2286	1986
Phosphorus	P	1872	1556
Sulfur	S	5290	4898
Magnesium	Mg	27	21
Boron	B	72	86

Source and study own.

Table 15. Contaminant content in a sample taken after 600 flight hours

Element	Symbol	Content [ppm] In reference sample	Content [ppm] after 600 flight hours
Silicon	Si	14	3
Potassium	K	2	1
Sodium	Na	4	6

Table 16. Kinematic viscosity and acid number of the sample after 600 hours of flight

Property	Value in reference sample	Value after 600 flight hours
Kinematic viscosity in 100^{0}C [cSt]	14.44	12.15
Acid number [mgKOH/g]	5.46	4.17

Source and study own.

The oil sample discussed below was taken from a vessel that had completed 800 flying hours. This oil worked in the engine for 100 flying hours. The level of metallic particles, which may indicate mechanical wear, and the PQ index are presented in Table 17. Table 18 presents the results relating to the level of conditioners. The content of impurities in the sample in question is presented in Table 19. The kinematic viscosity and acid number are presented in Table 20.

For the oil collected at the discussed interval of engine flight hours, no excessive level of particles that could indicate mechanical wear was observed, and the PQ index also showed no deviations from the reference sample. The level of performance additives decreased; however, these results do not relate to the Ca content, the content of which has increased. The content of impurities slightly changed.

Table 17. Content of elements indicating wear, found in a sample taken after 800 hours of flight

Element	Symbol	Content [ppm] In reference sample	Content [ppm] after 800 flight hours
Iron	Fe	<1	18
Aluminum	Al.	<1	3
Copper	Cu	<1	12
Lead	Pb	<1	2
Index PQ		<25	<25

Source and study own.

Table 18. The content of enriching additives in the sample taken after 800 hours of flight

Element	Symbol	Content [ppm] In reference sample	Content [ppm] after 800 flight hours
Calcium	Ca	2752	3016
Zinc	Zn	2286	1976
Phosphorus	P	1872	1642
Sulfur	S	5290	3906
Magnesium	Mg	27	24
Boron	B	72	45

Source and study own.

Table 19. Contaminant content in a sample taken after 800 flight hours

Element	Symbol	Content [ppm] In reference sample	Content [ppm] after 800 flight hours
Silicon	Si	14	13
Potassium	K	2	1
Sodium	Na	4	7

Source and study own.

Table 20. Kinematic viscosity and acid number of the sample after 800 hours of flight

Property	Value in reference sample	Value after 800 flight hours
Kinematic viscosity in 100^0C [cSt]	14.44	11.24
Acid number [mgKOH/g]	5.46	3.33

Source and study own.

The lubricant for the tests after 1000 hours of flight time of the power unit was taken after 100 hours of flight. This situation was dictated by technical issues related to the aircraft maintenance schedule. The obtained results were sorted and compared with the results for the reference sample, as shown in Tables 21-24.

The content of metallic particles as well as the PQ index (Table 21) for the discussed sample does not raise suspicions of excessive engine wear. A comparison of these results to those obtained previously reveals no significant deviations. The number of enriching additives (Table 22) decreased. The content of impurities (Table 23) in the case of sodium and potassium slightly changed. The kinematic viscosity and the acid number are presented in Table 24. No results indicating the occurrence of corrosion processes were found

Table 21. Content of elements indicating wear, found in a sample taken after 1000 flight hours

Element	Symbol	Content [ppm] In reference sample	Content [ppm] after 1000 flight hours
Iron	Fe	<1	16
Aluminum	Al.	<1	3
Copper	Cu	<1	7
Lead	Pb	<1	3
Index PQ		<25	<25

Source and study own.

Table 22. The content of enriching additives in the sample taken after 1000 flight hours

Element	Symbol	Content [ppm] In reference sample	Content [ppm] after 1000 flight hours
Calcium	Ca	2752	2464
Zinc	Zn	2286	1954
Phosphorus	P	1872	1486
Sulfur	S	5290	4270
Magnesium	Mg	27	26
Boron	B	72	57

Source and study own.

Table 23. Contaminant content in a sample taken after 1000 flight hours

Element	Symbol	Content [ppm] In reference sample	Content [ppm] after 1000 flight hours
Silicon	Si	14	7
Potassium	K	2	1
Sodium	Na	4	5

Source and study own.

Table 24. Kinematic viscosity and acid number of the sample after 1000 hours of flight

Property	Value in reference sample	Value after 1000 flight hours
Kinematic viscosity in 100^{0}C [cSt]	14.44	11.64
Acid number [mgKOH/g]	5.46	4.91

Source and study own.

5. Summary

The conducted tests allowed us to obtain the results of the AeroShell Sport Plus 4 engine oil analysis. These results indicate the correct course of the operation of the ROTAX 912S power unit, from which samples were taken for testing. The collected data does not indicate any tendency to excessive mechanical wear of the engine. The enriching additives contained in the discussed type of engine oil did not show any disturbing changes in the content in the oil change intervals (100 flight hours). It should also be noted that the kinematic viscosity value, with each oil change interval, fell below the values specific for the 10W-40 oil. This indicates that it is not possible to extend the service interval for this type of oil used in ROTAX 912S engines.

Systematic, periodic lubricant changes, carried out in accordance with the operating instructions, allow for obtaining optimal conditions for pairing the drive unit. At the same time, as shown by the above test results, the used oil should not be used any longer at the time of replacement due to a decrease in kinematic viscosity. The planned and implemented engine oil spectrographic analysis program could potentially support the activities of the continuing airworthiness management organization in terms of monitoring trends in engine wear. Such analyses will not replace other diagnostic methods, nor will they exclude technical services provided by aviation equipment manufacturers; however, they may complement them, providing an extended picture of the technical condition of the engine.

When summarizing the collected results of engine oil spectroscopy, the following conclusions can be drawn:

- oil analysis potentially allows for extending the life of the drive unit and reducing the failure rate by monitoring operational wear using data from the spectrographic analysis of the lubricant;
- oil testing is a relatively simple method of obtaining engine health data. Such tests are definitely an economically justified alternative to the disassembly of the mechanical parts of the engine and subjecting them to other - direct tests aimed at verifying its condition;
- the aforementioned methodology allows for identifying the root causes of potential failures (soot, fuel, dust, mechanical abrasion, etc.).

Declaration of interest

The authors declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article

References

1. American Society for Testing and Materials. (2019). *Standard Test Metod for Acid Number of Petroleum Products by Potentiometric Titration.* (ASTM D664-18E2).
2. American Society for Testing and Materials. (2018). *Standard Test Method for Multielement Determination of Used and Unused Lubrication Oils by Inductively Coupled Plasma Atomic Emission Spectometry (ICP-AES)* (ASTM D5185-18).
3. Bureau of Aircraft Accidents Archives. (2022, 15 stycznia). *Death rate per year*. https://www.baaa-acro.com/statistics/death-rate-per-year
4. Grimmig, R., Lindner, S., Gillemot, P., Winkler, M., Witzleben, S. (2021). Analyses of used engine oils via atomic spectroscopy – Influence of sample pre-treatment and machine learning for engine type classification and lifetime assessment. *Talanta Volume 232*. https://doi.org/10.1016/j.talanta.2021.122431
5. Polski Komitet Normalizacyjny. (2021). *Przetwory naftowe – ciecze przezroczyste i nieprzezroczyste – oznaczanie lepkości kinematycznej i obliczanie lepkości dynamicznej*. (PN-EN ISO 3104:2021-03).
6. Rahimi, M., Pourramezan, M-R., Rohani, A. (2022). Modeling and classifying the in operando effects of wear and metal contaminations of lubricating oil on diesel engine: A machine learning approach. *Expert Systems with Applications Volume 203*. https://doi.org/10.1016/j.eswa.2022.117494
7. World Health Organization. (2022, 15 stycznia). *Road traffic injuries*. https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries
8. Wytyczne Nr 9 Prezesa Urzędu Lotnictwa Cywilnego z dnia 29 sierpnia 2016 r. w sprawie okresów międzyremontowych silników tłokowych (2016) (Polska). https://www.ulc.gov.pl/_download/ltt/ciagla_zdolnosc/wytyczne-nr-9-Prezesa-ULC.pdf