ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0010.2801

ANALYSIS OF INFLUENCE OF LEGAL REQUIREMENTS ON THE DESIGN OF ELECTRONIC IGNITION SYSTEM FOR AVIATION PISTON ENGINE

Jacek Czarnigowski, Piotr Jakliński

Lublin University of Technology
Department of Thermodynamics
Fluid Mechanics and Aviation Propulsion Systems
Nadbystrzycka 36, 20-618 Lublin, Poland
tel.:+ 48 81 5384745, fax: + 48 81 5384749
e-mail: j.czarnigowski@pollub.pl, p.jaklinski@pollub.pl

Tomasz Zyska

Lublin University of Technology
Institute of Electronics and Information Technology
Nadbystrzycka 38A, 20-618 Lublin, Poland
tel.:+ 48 81 53 84 309, fax: + 48 81 53 84 312
e-mail: t.zyska@pollub.pl

Jakub Klimkiewicz

Lublin University of Technology
Department of Thermodynamics
Fluid Mechanics and Aviation Propulsion Systems
Nadbystrzycka 36, 20-618 Lublin, Poland
tel.:+ 48 81 5384745, fax: + 48 81 5384749
e-mail: j.klimkiewicz@pollub.pl

Abstract

The article is a review of European aviation regulations with respect to their impact on the design of a new electronic ignition system for aircraft engines. The analysis covers the EASA decision on certification specifications as well as recommended means of compliance and related standards on testing and designing electronic subassemblies and their programming. The analysis focuses on the following aspects: design requirements (system configuration), functional requirements (principles of operation), safety (fault tolerance), material requirements (with regard to corrosion and fire resistance of electronic components) and scope of tests for particular component.

The analysis is illustrated by a case of a research and development project to design and implement an ignition system for a piston engine. The engine with its new ignition system was to be offered commercially as a product of a Polish aircraft engine manufacturer.

The article is a review of European aviation regulations with respect to their impact on the design of a new electronic ignition system for aircraft engines. The analysis covers the EASA decision on certification specifications and their programming. It is illustrated by a case of a particular engine re-engineering project

Keywords: *transport, road transport, simulation, combustion engines, air pollution, environmental protection*

1. Introduction

Civil aviation technology advances towards reducing the environmental impact of aircraft operation, which includes cutting down fuel consumption. At the same time, the focus stays on maximizing reliability and safety [1, 2]. Although the same directions are being observed in other branches of industry, aviation is special as being subject to exceptionally strict and detailed international regulations and standardization. These refer to all aspects and to any procedure of aircraft system design and production, as well as to air traffic services, crew training, and crew certification. Enormous effort is taken to assure safety – the aviation's fundamental objective [3]. Accident statistics prove that the procedures work: air transport is leading in passenger safety. Equipment failures during operation are rare and account for only about one third of accidents [4]. However, the necessity to comply with numerous procedures naturally increases time and cost of implementing innovations.

The article is a review of European aviation regulations with respect to their impact on the design of a new electronic ignition system for aircraft engines. The analysis covers the EASA decision on certification specifications [5] as well as recommended means of compliance and related standards on testing and designing electronic subassemblies and their programming. It is illustrated by a case of a particular engine re-engineering project.

2. Project Overview

The object of modernization was the ASz-62IR-16 engine (Fig. 1). This unit is a product of a Polish company supplying it to customers in Eastern Europe, South America, and Canada, with good prospect to enter the Chinese market. The engine is used in small and medium-sized cargo (Antonov AN-2) and agricultural (M18 Dromader) aircrafts. The engine is an air-cooled, four-stroke gasoline unit of 9 cylinders in radial setup, mechanically charged by a radial compressor powered by an engine crankshaft. Total engine cubic capacity is 29.87 dm^3, and the compression ratio is 6.4:1. The maximum take-off power is 1000 HP at 2200 rpm. The maximum fuel consumption is 300 kg/h.

Fig. 1. ASz-62IR-16E Engine on test stand. Front view

The original design was created in nineteen-forties, and its last modernization took place in nineteen-eighties. It can be fuelled with Avgas 100LL (version ASz-62IR-16D) or with ES95 car engine gasoline (version ASz-62IR-16E). A successful conversion from a carburettor to electronic fuel injection [13-15] implied that the original magneto ignition system was to be replaced with an electronically controlled device. Precise electronic control was also required to facilitate changes of fuel-type related settings.

The aim of the re-engineering project was to upgrade the existing design of the engine by equipping it with a complete electronic ignition system (hardware and software). This project was supported by National Centre of Research and Development, Poland, as a part of EPOCA *Device*

for power supplying and controlling on-board and ground equipment, project number INNOLOT/I/1/NCBR/2013. The authors gratefully acknowledge the support.

The project's leader, sponsor and the main beneficiary was WSK PZL-Kalisz S.A. – a Polish company with 50 years' experience in aircraft engine production and servicing, currently the world's only provider of piston engines of power over 700 HP. Their tasks covered design and provision of subassemblies and conducting certification tests. As WSK PZL-Kalisz S.A. do not employ specialists in electronic fuelling systems, they subcontracted related tasks to a team of scientists and engineers from Lublin University of Technology, experienced in design and implementation of automotive systems. Their responsibility was to design the electronic ignition system, to develop control algorithms (including identification and verification tests), and to provide support during certification tests.

3. Brief Overview of Aviation Regulations and Standards

The basis for practically all aviation rules worldwide is the Convention on International Civil Aviation, often referred to as Chicago Convention [3]. Its Article 31 requires that "Every aircraft engaged in international navigation shall be provided with a certificate of airworthiness issued or rendered valid by the State in which it is registered". The states are thus obliged to issue their own laws and regulations to conform to the Convention (e.g. [9]). However, the national laws fully conform to the Convention.

Article 31 mentioned above implies that no aircraft is allowed to fly without some form of official consent. Standardization of particular requirements the aircrafts must conform to is the task of national authorities, such as EASA in the European Union, Federal Aviation Authority (FAA) in the US, or Civil Aviation Safety Authority (CASA) in Australia; most countries' regulations are derived directly from the regulations established by FAA and EASA. In general, the regulations are convergent, and even classification and numbering of particular guidelines are the same. The project described in the article was conducted under EASA procedures, so the authors are going to refer only to European regulations.

Each aircraft, and separately its engines and propellers, must comply with requirements described in the regulations (in the considered case – the Commission of the European Community regulations that are practically the same as their US counterparts), namely:

- Commission Regulation (EC) No. 216/2008 of the European Parliament and of the Council of 20 February 2008 on common rules in the field of civil aviation and establishing a European Aviation Safety Agency, and repealing Council Directive 91/670/EEC, Regulation (EC) No 1592/2002 and Directive 2004/36/EC, 2008 OJ L 79/1 [10],
- Commission Regulation (EC) No. 1702/2003 of 24 September 2003 laying down implementing rules for the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organizations, 2003 OJ L 243/6 [11],
- Commission Regulation (EC) No. 2042/2003 of 20 November 2003 on the continuing airworthiness of aircraft and aeronautical products, parts and appliances, and on the approval of organizations and personnel involved in these tasks, 2003 OJ L 315/1 [12].

The approval of the design of the aircraft, engines and propellers is signified by the issue of a Type Certificate. Regulation (EC) 1702/2003 does not directly specify detailed technical requirements the certified element is to comply to; instead, it regulates the basic rules of the certification process. Acceptable means of compliance and guidance for the certification are referred to in the Annex, Part 21, section 21A.16A: "The Agency shall issue (…) airworthiness codes as standard means to show compliance of products, parts and appliances with the essential requirements of Annex I to the basic Regulation". In the case of the aircraft engine and the considered project, these codes take are the following Certification Specifications (CS) and Acceptable Means of Compliance (ACM):

- CS-Definitions, introduced by the Decision No. 2007/016/R of the Executive Director of the European Aviation Safety Agency of 7 December 2007 on definitions and abbreviations used in certification specifications for products, parts and appliances,
- CS-E together with its AMC, introduced by the Decision No. 2003/009/RM of the Executive Director of the European Aviation Safety Agency of 24 October 2003 on certification specifications, including airworthiness codes and acceptable means of compliance, for engines [5].

CS-E lists the requirements the engine must meet to be eligible for certification, whereas its AMC refines these requirements and proposes how one can prove that these requirements are met. AMC base on experience and provide the potential user with tools and procedures that were previously accepted by the certification agency (EASA). They are not obligatory, but using them may speed up the certification process.

The engine being the object of modernization was to be equipped with an electronic control system – in this case, the CS-E refers to another set of guidelines, introduced by the Decision No. 2007/019/R of the Executive Director of the European Aviation Safety Agency of 19 December 2007 on general acceptable means of compliance for airworthiness of products, parts and appliances: AMC 20-1 – acceptable means of compliance in the case of certification of propulsion systems equipped with electronic control systems, and AMC 20-3 – these for certification of engines with electronic engine control systems. The AMC accompanying CS-E refer to further documents – three standards on design, provision, and testing of aircraft electronic systems by the Radio Technical Commission for Aeronautics (RTCA):

- DO-160E Environmental Conditions and Test Procedures for Airborne Equipment [6] that defines a series of minimum standard environmental test conditions and test procedures to determine the performance characteristics of airborne equipment in conditions that may be encountered in airborne operation of the equipment, like low temperatures, fire, magnetic effects, or dust,
- DO-178B Software Considerations in Airborne Systems and Equipment Certification [7] on design methods and requirements towards testing the software used in aircrafts,
- DO-254 Design *Assurance Guidance for Airborne Electronic Hardware* [8].

As AMC, these standards describe recommended ways of proving conformance to the requirements; however, according to the author's experience, in the certification process, EASA treats them as obligatory.

4. Influence of aviation regulations on electronic ignition system

In the chapters to follow, the authors describe how the standardization and regulation affected the design of electronic ignition system, starting form system structure and functionality, through demands for material properties up to tests.

4.1. Project brief

The project brief was determined, firstly, on the basis of functional requirements (in short: use motor fuels, provide reliable start-up, reduce vibrations), and secondly, by operating quality and safety regulations. Considering functional requirements of the latter, the CS-E 50 *Engine Control System* states that "(a) Engine Control System Operation. … (1) Enables selected values of relevant control parameters to be maintained and the Engine kept within the approved operating limits over changing atmospheric conditions in the declared flight envelope… (3) Allows modulation of Engine power or thrust with adequate sensitivity and accuracy over the declared range of Engine operating conditions, and (4) Does not create unacceptable thrust or power oscillations" [5].

This means that the system must assure correct operation within the completely declared flight envelope. It implies that power is to be precisely controllable and no operations instability is allowed. Therefore, the system must be equipped with sensors to identify changes of parameters within the engine's entire operating range with respect to not only speed and load, but also thermal state and characteristics of the environment.

The first step was thus to determine what parameters need to be measured to provide sufficient input. In the course of investigations, the project team decided to measure crankshaft position, manifold air pressure, and to detect knocking. This decision, seriously narrowing down input for the control system, was the effect of a trade-off between precision information on engine state and reliability of the system.

Importance of system reliability assurance is emphasized by the following clauses of CS-E 50 *Engine Control System*: "(c) Engine Control System Failures. The Engine Control System must be designed and constructed so that: … (2) In the Full-up Configuration, the system is essentially single Fault tolerant for electrical and electronic Failures with respect to LOTC/LOPC events. (3) Single Failures of Engine Control System components do not result in a Hazardous Engine Effect" [5].

Reducing the number of components leads to reducing probability of failure, but decisions in this respect cannot compromise functionality and safety at single fault. Reliability is often increased by redundancy, and according to CS-E 240 *Ignition*, the ignition system must be duplicated: "All spark-ignition Engines shall comply with the following: (a) The Engine shall be equipped either with:-(1) A dual ignition system having entirely independent magnetic and electrical circuits, including spark plugs, or, (2) An ignition system which will function with at least equivalent reliability" [5].

To meet the above requirements, the project team provided a system with two spark plugs per cylinder, and two independent spark generation systems. It is worth mentioning that elements of the duplicated systems had to be carefully separated: not only the spark plugs and coils, but also the control systems. Fig. 2 presents a schematic view of the ignition system.

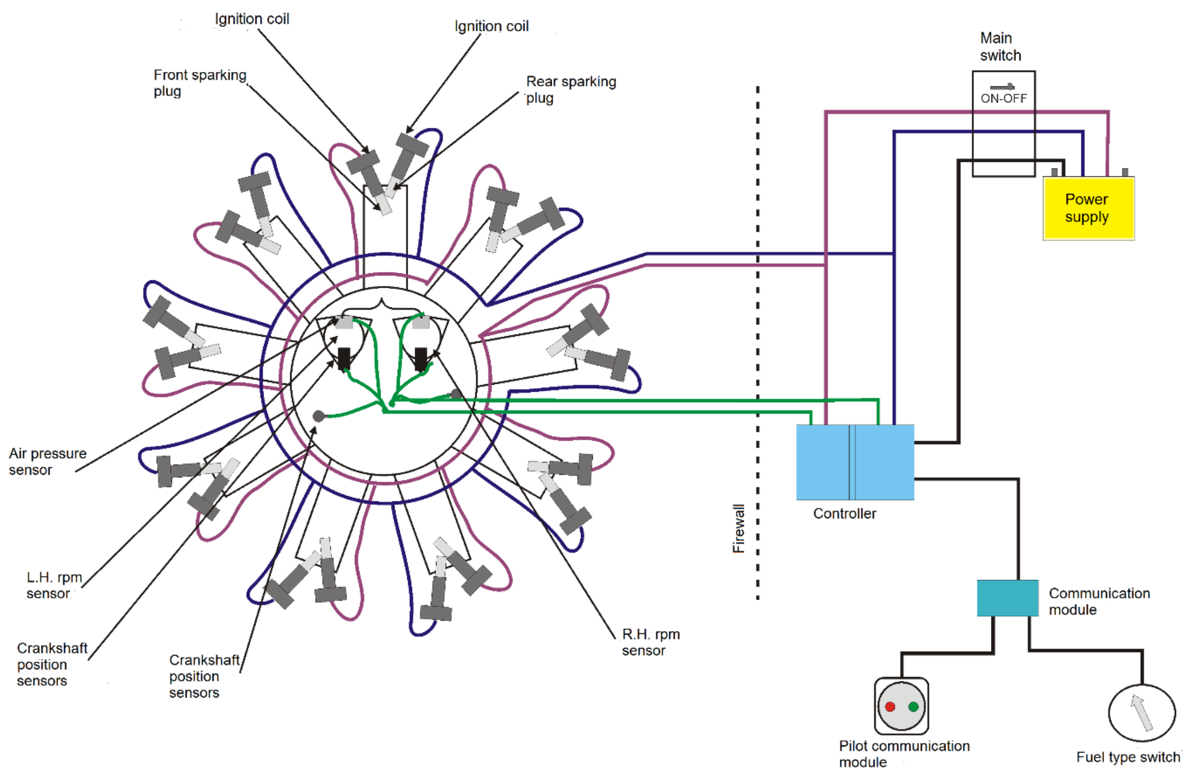

Fig. 2. Electronic ignition system

Thus, the design consists of two independent ignition systems, so each cylinder is served by two spark plugs. Each system is equipped with its individual ignition coils mounted on the cylinder head and connected to the spark plugs. Coils are connected to their electronic control systems, and these rely on their individual sets of sensors of crankshaft position, air pressure and knocking. Control units of both systems communicate with the pilot module to inform the pilot on their current condition. They are also connected with the fuel type switch. The ignition systems have also individual power supply. This design conforms to the requirements quoted previously.

Another condition to be met while designing any module of the ignition system is safety at fault. Apart from the previously quoted CS-E 50 c), there are more requirements given in CS-E 50 b): "(b) Control Transitions. It must be demonstrated that, when a Fault or Failure results in a change from one Control Mode to another, or from one channel to another, or from the Primary System to the Back-up System, the change occurs so that: (1) The Engine does not exceed any of its operating limitations, (2) The Engine does not surge, stall, flame -out or experience unacceptable thrust or power changes or oscillations, or other unacceptable characteristics, …" [5].

This indirectly implies redundancy of each system or introducing backup systems able to take over for a faulty system. Duplication of ignition systems partly fulfilled these requirements. However, it was necessary to improve safety at single fault of the systems. Two steps were taken to achieve this: one consisted in designing duplicated controllers inside each control unit, and the other – enabling information exchange between control units with regard to input from the sensors. This idea is presented in Fig. 3.

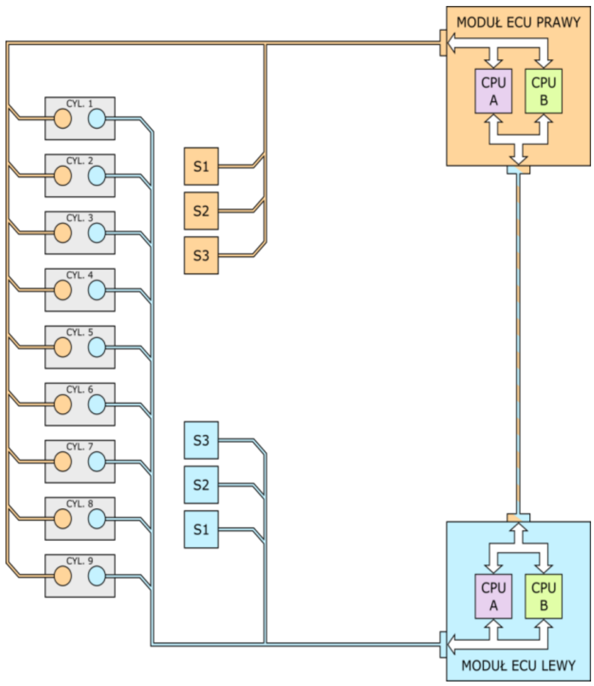

Fig. 3. Setup of control units of the ignition system

Using two controllers within each particular control units means that failure of one of the controllers has no effect on operation of the unit. Measurement of sensor signals, calculations of ignition advance, dwell angle, and execution of coils control is provided by both controllers. If one of them fails, the effect of the system's operation stays unchanged. Information exchange was intended to protect the system against sensor failure, as well as to diagnose sensors. Thus, each control unit takes input from its own set of sensors and compares it with input that independently reaches the other unit. If there is no input from a particular sensor, or if it is unreliable, the control unit either switches to input from the properly operating sensor – from its own set of sensors or transmitted by the twin unit.

4.2 Materials and detail design

As for the materials to be used for components of the engine and equipment, basic requirements are provided by CS-E 70 *Materials*: "(a) The suitability and durability of materials used in the Engine must be established on the basis of experience or tests. The assumed design values of properties of materials must be suitably related to the minimum properties stated in the material specification" [5].

Hence, materials' qualities need to be proved. In the practice of the industry, this usually means resorting to certified materials, or materials tested in advance, which seriously limits the designer's choice. For instance, as MIL-type connectors are recommended – such were used in the project.

Further restrictions on material quality are related with corrosion resistance and fire safety, and described, respectively, in CS-E 90 *Prevention of Corrosion and Deterioration* and CS-E 130 *Fire Protection* [5].

CS-E 90 states, "(a) Each Engine component and each item of equipment must be protected from corrosion and deterioration in an approved manner. (b) Materials which will render the Engine inherently self-protecting against corrosion, without the use of internal and external corrosion inhibitors must be used wherever possible" [5].

CS-E 130 requires that "(a) The design and construction of the Engine and the materials used must minimise the probability of the occurrence and spread of fire during normal operation and Failure conditions and must minimise the effects of such a fire… (d) An Engine component designed, constructed and installed to act as a firewall must be: (1) Fireproof; (2) Constructed so that no hazardous quantity of air, fluid or flame can pass around or through the firewall; and, (3) Protected against corrosion" [5].

Therefore, selection of materials is narrowed down to this corrosion-proof. or corrosion-protected, and whose use minimizes the risk of ignition and fire spread.

There are also special recommendations for testing electronic systems. These tests were crucial for electronic components and conducted according to RTCA DO-160 [6]. The list of environmental effects to be considered is long:

- Temperature and Altitude,
- Temperature Variation,
- Humidity,
- Operational Shock and Crash Safety,
- Vibration,
- Explosion Proofness,
- Waterproofness,
- Fluids Susceptibility,
- Sand and Dust,
- Fungus Resistance,
- Salt Spray,
- Magnetic Effect,
- Power Input,
- Voltage Spike,
- Audio Frequency Conducted Susceptibility – Power Inputs,
- Induced Signal Susceptibility,
- Radio Frequency Susceptibility (Radiated and Conducted),
- Emission of Radio Frequency Energy,
- Lightning Induced Transient Susceptibility,
- Icing,
- Electrostatic Discharge,
- Fire and Flammability.

The electronic subassemblies are to be designed with the aim of passing these tests. The scope of tests needs to be considered, among others, while selecting materials. In the presented case, the design team had to bear in mind that their creation is to operate, for instance:

a) in low temperatures; the minimum operating temperature was -55ºC, so at least by 10ºC lower than in the case of designing components for automotive industry,
b) in contact with chemicals such as fuels, oils, lubricants, cleaning and de-icing products used in aviation,
c) in contact with salts and fungi,
d) under mechanical stresses such as vibrations and impact,
e) in changing electromagnetic fields, with threat of electrostatic discharge and interference.

This was especially important in the case of the design of control unit casing: custom-made, airtight, made of anodized aluminum and equipped with MIL-38999 type hermetic connectors of nickel alloy (Fig. 4).

Fig. 4. Original design of ignition system control units

If it is necessary to use components that do not conform to a particular requirement themselves, they should be assembled in a way that guarantees that the requirement is met. This possibility was used, among others, in the case of air pressure sensors: the sensors' original body was made of plastic and did not fulfil fire resistance requirements. Therefore, the sensors were put inside a custom-made aluminum casing (Fig. 5), and this method of protection fully satisfied the considered requirement.

Fig. 5. Air pressure sensors in custom-made protective casing

Additionally, putting sensors and control units in hermetic casings is dictated by the DO-160 requirement of waterproofness and airtightness. Moreover, metal casing provides good protection against electromagnetic interference.

4.3 System's software

Software for electronic control devices is also subject to numerous requirements: the CS-E 50 *Engine Control System* states that: "(f) Software and Programmed Logic Devices. All associated software and encoded logic must be designed, implemented and verified to minimise the existence of errors by using an approved method consistent with the criticality of the performed functions" [5]. This means that methodology of software design is to be approved. The RTCE DO-178 *Software Considerations in Airborne Systems and Equipment Certification* [7] is a standard that describes such methodology of software certification for airborne systems on commercial aircraft. In particular, its part DO-178B contains guidance for the planning, development, and verification of airborne software. The guidance comprises several elements:

- A series of *objectives* keyed to the various software life cycle processes,
- The specified *activities* for accomplishing these objectives, and
- The required artifacts (*life cycle data*) that serve as evidence that the objectives have been met.

The intent behind DO-178B is to achieve a degree of confidence in a software component proportional to the component's criticality, i.e., the impact of a software anomaly on the continued safe operation of the aircraft. Criticality is reflected in the component's software level [7]:

A. Catastrophic – Failure may cause multiple fatalities, usually with loss of the airplane.
B. Hazardous – Failure has a large negative impact on safety or performance, or reduces the ability of the crew to operate the aircraft due to physical distress or a higher workload, or causes serious or fatal injuries among the passengers.
C. Major – Failure significantly reduces the safety margin or significantly increases crew workload. May result in passenger discomfort (or even minor injuries).
D. Minor – Failure slightly reduces the safety margin or slightly increases crew workload. Examples might include causing passenger inconvenience or a routine flight plan change.
E. No Effect – Failure has no impact on safety, aircraft operation, or crew workload.

The requirements of DO-178 are to be reflected by the design of particular systems. A restriction on control systems is that they need to be based on responsive algorithms, which excludes those probability-based and adaptive. Therefore, the selection of processors is seriously limited.

However, the core object of interest of DO-178 is the design process. The standard enforces that each step of the design works and each test is carefully documented, which naturally increases workload of the design team and takes considerable amount of time.

5. Summary and conclusions

The design process of any technical system is usually subject to regulation. As aviation is one of the most heavily regulated branches of industry, and a thorough study of regulations and standards is to be made before any venture to design an aircraft system is undertaken. As illustrated by the analysis, restrictions are put on the overall layout of the system (in the analysed case, with respect to safety under single fault condition) as well as particular design solutions (in the analysed case, necessity to duplicate the ignition system). There exist also many requirements towards operation quality of the system: precision, stability, safety under single fault, and many more. Another group of restrictions is related with materials to be used in particular components. Their main subjects are material properties that need to be clearly proved. Therefore, the design team's choice of system ideas and components already present in the market is considerably limited.

Acknowledgements

This work was supported by National Centre of Research and Development, Poland, as a part of „EPOCA Device for power supplying and controlling on-board and ground equipment" INNOLOT/I/1/NCBR/2013. The authors gratefully acknowledge the support.

References

[1] ICAO, *Outlook for Air Transport to the Year 2025*, Circular 313, AT/134, Montreal: International Civil Aviation Organization, 2007.

[2] ACARE, *Strategic Research & Innovation Agenda*, Brussels: Advisory Council for Aeronautics Research, 2012.

[3] ICAO, *Convention on International Civil Aviation*, Ninth Edition, Doc. 7300/9, Montreal: International Civil Aviation Organization, 2006.

[4] Oster, C. V., Strong, J. S., Zorn, C. K., *Analyzing aviation safety: problems, challenges, opportunities*, Research in Transportation Economics, 43, 148-164, 2013.

[5] EASA, Decision No. 2003/009/RM of the Executive Director of the European Aviation Safety Agency of 24 October 2003 on certification specifications, including airworthiness codes and acceptable means of compliance, for European Technical Standard Orders (CS-E), Cologne: European Aviation Safety Agency, with amendments, 2003.

[6] RTCA, DO-160E Environmental Conditions and Test Procedures for Airborne Equipment, Radio Technical Commission for Aeronautics, Washington D.C. 2004.

[7] RTCA, DO-178B Software Considerations in Airborne Systems and Equipment Certification, Radio Technical Commission for Aeronautics, Washington D.C. 1992.

[8] RTCA, DO-254 Design Assurance Guidance for Airborne Electronic Hardware, Radio Technical Commission for Aeronautics, Washington D.C. 2000.

[9] Polish Aviation Act, Ustawa z dnia 3 lipca 2002 r. Prawo lotnicze, t.j. Dz.U. 2013/1393, with amendments, 2013.

[10] EASA, Commission Regulation (EC) No. 216/2008 of the European Parliament and of the Council of 20 February 2008 on common rules in the field of civil aviation and establishing a European Aviation Safety Agency, and repealing Council Directive 91/670/EEC, Regulation (EC) No 1592/2002 and Directive 2004/36/EC, 2008 OJ L 79/1,

[11] EASA, Commission Regulation (EC) No. 1702/2003 of 24 September 2003 laying down implementing rules for the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organizations, OJ L 243/6, 2003.

[12] EASA, Commission Regulation (EC) No. 2042/2003 of 20 November 2003 on the continuing airworthiness of aircraft and aeronautical products, parts and appliances, and on the approval of organisations and personnel involved in these tasks, OJ L 315/1, 2003.

[13] Jakliński, P., *Analysis of the dual control system operation during failure conditions*, Eksploatacja i Niezawodność – Maintenance and Reliability, No. 3, Vol. 15, pp. 266-272, 2013.

[14] Jakliński, P., Wendeker, M., Czarnigowski, J., Duk, M., Zyska, T., Klimkiewicz, J., *The Comparison of the Operating Parameters in an Aircraft Radial Piston Engine Fuelled by 100LL and ES95 Gasoline*, PTNSS-2009-SS1-C064 Combustion Engines Silniki Spalinowe No. 1, pp. 52-59, 2009.

[15] Czarnigowski, J., Jakliński, P., Wendeker, M., *Fuelling of aircraft radial piston engines by ES95 and 100LL gasoline*, Fuel 89, 3568-3578, 2010.