Analysis of the power part architecture for short-medium-range aircraft control system with local hydraulic systems by reliability criterion

S Postnikov, A Trofimov* and D Smagin

Department of Aircraft Design and Certification, Moscow Aviation Institute (National Research University), 4 Volokolamskoye Highway, Moscow 125993, Russian Federation.

*E-mail: trofimovaa@mai.ru

Abstract. This article provides a comparative analysis of the traditional control system power part for a short-medium-range aircraft with a control system power part with local HS. Comparison is based on the criterion of reliability. As initial data, statistics on the probability of failures of the electrical system and hydraulic system and actuators. The considered architecture of the control system power part with local HS fully complies with the required standards for the control system reliability given in regulatory documents, such as AR-25 and CS-25. The considered architecture of the control system power part with local HS is commensurate with the reliability of a typical version of the control system power part architecture. The considered architecture of the control system power part with local HS fully complies with the required standards for the control system reliability given in regulatory documents, such as AR-25 and CS-25. The considered architecture of the control system power part with local HS is commensurate with the reliability of a typical version of the control system power part architecture and in some cases it is an order of magnitude superior.

1. Introduction

When designing new types of civilian aircraft, the developers are faced with the task of increasing fuel efficiency and reducing operational maintenance costs to maintain the competitiveness of the aircraft. The usage of complex digital electronics as part of on-board equipment as well as the development of new design solutions is one of the main principals for increasing fuel efficiency and reducing costs. Also, the main task in the development of aviation systems is to achieve a given level of reliability. Analysis of newly developed systems by the criterion of reliability is an obligatory stage of design. The requirements of ARP 4754 oblige the developer from the very early design stage to prepare materials for the analysis of system fail-safety. Reliability assessment is used not only to confirm that the system meets the requirements of certification bodies in terms of reliability, but also for maintenance planning, calculation of parameters such as mean time between failures (MTBF) or average cycles between failures (MCBF) [1].

At this article a control system (CS) for a short-medium-range aircraft (SMRA) is considered as an object of study. At the moment, most aircraft of this dimension use three centralized hydraulic systems, and electro-hydraulic servo actuators are used as surface actuators. An example of CS typical version is presented in figure 1.
As an alternative, in this article the control system architecture with three distributed local hydraulic systems (HS) is considered. The use of local hydraulic systems will reduce the length of pressure and drain pipelines and, accordingly, reduce the pipelines weight [2], simplify maintenance and reduce power take-off from aircraft engines [3].

The first local HS is located in the left wing console and is connected to a hydraulic pump mounted on the left engine. The second local HS is located in the right wing console and is connected to a hydraulic pump mounted on the right engine. The third local HS is located in the back of the fuselage and receives hydraulic energy from a pumping station located in the back of the fuselage, as well as in the case of an abnormal situation, from a ram air turbine (RAT).

The block diagram of control system with local HSs is shown in figure 2.
In the proposed architecture version of the control system power part, besides electro-hydraulic servo actuators powered by the corresponding local HSs, EHA powered by two independent power supply systems are used. The use of EHA allows to reduce the control system energy consumption [4], to scale back the number of HSs [5], to simplify HSs installation on aircraft, to simplify HSs testing, as well as to reduce the time of maintenance and operating costs of HSs [2].

Currently, various versions of the control system architecture are offered, for example, TsAGI experts proposed four variants of the control system architecture as part of the "Safety & Energy Efficiency Research on Advanced More Electrical Flight Control Actuation Systems for Short / Middle Range Passenger Aircraft" [6]. These options are based on the use of EMA drives to control ailerons. At the moment, the main drawback of EMA drives is the lack of damping mode. An alternative to EMA is proposed to use electrohydrostatic actuator (EHA). Airbus Corporation engineers also preferred EHA instead EMA for controlling internal ailerons A350 XWB [7]. Also, at the moment, EMA is a more expensive drive compared to hydraulic drives [8], but it is advisable to make a final cost estimate only at the level of the entire aircraft life cycle.

It is worth noting that the assumption is made at this work that roll control is carried out by two surfaces of ailerons and three external surfaces of spoilers on each wing console, all surfaces of spoilers and ground spoilers (GS) participate in braking. The use of interceptors in roll control is a well-known solution and improves not only dynamic characteristics, but also increases the reliability of roll control [1].

2. Calculations
Reliability analysis, as a rule, by the manufacturer using the Fault Tree Analysis (FTA) method built on the basis of the system architecture. In this study, fault trees are replaced by equivalent mathematical expressions.

Based on the data provided in open sources, the average failure rate indicators of HS, ES, and also the main elements of the control system were calculated.

The average probability of one aircraft hydraulic system failure is $4.06 \cdot 10^{-5}$ [9–12].

The average probability of one aircraft power supply system failure $1 \cdot 10^{-4}$ [9–11].

The average failure probability of EHSA is $1.38 \cdot 10^{-5}$ [7, 9, 12].

The average failure probability of EHA is $3.27 \cdot 10^{-5}$ [13, 14].

The average failure probability of EMA is $7.6 \cdot 10^{-5}$ [15, 16].

The average failure probability of high lift power drive unit (PDU) for two electric channels is expertly estimated to be $9 \cdot 10^{-5}$, and for two hydraulic channels $2.7 \cdot 10^{-5}$.

In the framework of this work, failures of the “Jamming” type were not considered as a common cause of control loss of one surface. The SMRA dimension aircraft control system reliability is considered as the sum failure rate for each control channel (roll, pitch, yaw, braking), high lift, THSA and a complete failure (failure of three control channels). Also, as an assumption, the calculation does not take into account the main digital part architecture of the control system. Based on the initial data, the sum failure rate for each channel was obtained, taking into account the considered control system architecture variant, shown in Figure 2. The sum failure rate of the roll, pitch or yaw channel indicates the reliability of the hydraulic and electrical systems in general, the electro-hydraulic servo actuator and electro-hydrostatic actuators involved in roll, pitch or yaw control, respectively.

3. Results and discussion
The main result of this work is to determine the probability of failure of control channels, as well as an analysis of compliance with the power variant of the architecture of the remote control system of aviation rules.

The sum failure rate is:
The proposed architecture with local HSs (figure 2) leads to the organization of control of the first and third section of spoilers from EHA, the control of the second and fourth section of spoilers from EHSAs. Ground spoilers in this architecture are controlled by EHA.

The PDU of the flaps and slats control system is controlled by two electric channels.

The complete failure of the control system calculation does not take into account the failures of high lift and THSA, since in the conditions of failure of all surface actuators, safe completion of the flight with the working high lift and THSA is impossible.

The failure rate calculation of each channel demonstrates that the considered failure conditions leading to the emergence of a catastrophic situation are estimated as extremely improbable events and do not occur due to a single failure of one of the system elements. Thus, the considered architecture of the power part shown in Figure 1. The sum failure rate of the roll, pitch and yaw channel of a typical variant with local hydraulic systems can be made by comparing it with a typical version of the control system (AR-25 or CS-25) section A-0 [17]. The final conclusion on the power part architecture of the control system fully meets the reliability requirements presented in Aviation rules number 25 (AR-25) or CS-25 section A-0 [17].

The complete failure of the control system calculation does not take into account the failures of high lift and THSA, since in the conditions of failure of all surface actuators, safe completion of the flight with the working high lift and THSA is impossible.

The failure rate calculation of each channel demonstrates that the considered failure conditions leading to the emergence of a catastrophic situation are estimated as extremely improbable events and do not occur due to a single failure of one of the system elements. Thus, the considered architecture of the power part shown in Figure 1. The sum failure rate of the roll, pitch and yaw channel of a typical variant is:

\[
\lambda_{\text{roll channel}} = \lambda_{HS1} + \lambda_{EHSA \text{aill}. \text{left out}} + \lambda_{EHSA \text{sp}.4 \text{right wing}} + \lambda_{EHSA \text{sp}.2 \text{left wing}} + \lambda_{EHSA \text{sp}.3 \text{left wing}} + \lambda_{EHSA \text{sp}.4 \text{right wing}} \]

\[
(\lambda_{EHSA \text{aill}. \text{left out}} - \lambda_{EHSA \text{sp}.3 \text{left wing}} + \lambda_{EHSA \text{sp}.4 \text{right wing}} - \lambda_{EHSA \text{sp}.3 \text{left wing}}) = 9.58 \cdot 10^{-13}
\]
The THSA calculation is carried out according to the example described for the power part architecture CS with local HS.

\[ \lambda_{\text{THSA}} = \left( \lambda_{\text{stab. actuator}} + \lambda_{\text{ES1}} + \lambda_{\text{ES2}} \right) = 1.58 \times 10^{-8} \]  \hspace{1cm} (13)

The control system complete failure of a typical variant is calculated according to the example described for the power part architecture CS with local HS.

\[ \lambda_{\text{complete failure}} = \left( \lambda_{\text{HS1 left out.}} + \lambda_{\text{left wing left out.}} \cdot \lambda_{\text{EHSA ail.}} \cdot \lambda_{\text{EHSA sp.1}} \cdot \lambda_{\text{EHSA sp.2}} \cdot \lambda_{\text{EHSA sp.3}} \right) + \left( \lambda_{\text{HS2 right out.}} + \lambda_{\text{left wing left out.}} \cdot \lambda_{\text{EHSA ail.}} \cdot \lambda_{\text{EHSA sp.1}} \cdot \lambda_{\text{EHSA sp.2}} \cdot \lambda_{\text{EHSA sp.3}} \right) = 6.69 \times 10^{-14} \]  \hspace{1cm} (14)

More clearly, the calculation results for a typical version CS and CS with local HS are presented in table 1.

| Control channel | Typical case | Local HS case |
|-----------------|--------------|---------------|
| Roll channel    | 6.69 \times 10^{-14} | 6.69 \times 10^{-22} |
| Pitch channel   | 1.2 \times 10^{-13} | 7.15 \times 10^{-13} |
| Yaw channel     | 1.61 \times 10^{-13} | 9.58 \times 10^{-13} |
| Braking         | 6.69 \times 10^{-14} | 1.65 \times 10^{-17} |
| High lift       | 7.29 \times 10^{-10} | 1.81 \times 10^{-8} |
| THSA            | 1.58 \times 10^{-8} | 1.58 \times 10^{-8} |
| Complete failure| 6.69 \times 10^{-14} | 6.69 \times 10^{-22} |

As can be seen from table 1, the power part reliability with local HS is comparable in reliability with the typical architecture, and in some cases it is an order of magnitude superior. The increase in reliability during roll channel and in the braking channel is associated with an increase in the number of energy sources for power surface actuators. It is also worth noting a not significant decrease in the reliability of high lift system, this is due to a statistically lower reliability of the high lift electric drives.

The results obtained in this study are comparable in value with other well-known architecture options for the power part of the control system [7, 18], which allows us to conclude that the presented option is competitive.

4. Conclusion
The average probability of failure of the control system elements obtained in this study can be used in the development of various versions of the control system architecture, as well as the data obtained can be used in the development of the Preliminary System Safety Assessment (PSSA) and other reporting documents to confirm the reliability of the system. Since the obtained values are based on a large amount of statistical data, we consider them to be more relevant when assessing the architecture of a control system according to the reliability criterion in the early stages of design. The considered architecture of the control system power part with local HS fully complies with the required standards for the control system reliability given in regulatory documents, such as AR-25 and CS-25. The considered architecture of the control system power part with local HS is commensurate with the reliability of a typical version of the control system power part architecture and in some cases it is an order of magnitude superior. The increase in reliability during roll channel and in the braking channel is associated with an increase in the number of energy sources for power surface actuators. The considered architecture requires further comparison with the standard version and optimization by mass and energy efficiency criterion since the implementation of the option with local hydraulic units will reduce the capacity of pumping stations compared to the standard version by reducing the number of consumers and exclude the laying of hydraulic pipes along the fuselage. These measures reduce the weight and increase the reliability of the HS by reducing the number of elements, but lead to an increase in the required power of the power supply system and generators.
References

[1] Beaverstock C, Maheri A, Richardson T, Lowenberg M and Isikveren A 2009 Methods for Conceptual Flight Control System Design. 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition (Orlando, USA) doi: 10.2514/6.2009-1620

[2] Shumilov I S 2014 Hydraulic Actuators with Autonomous Hydraulic Supply for the Mainline Aircraft. Science and Education Bauman MSTU 8 139 doi:10.7463/0814.0724446

[3] Erofeev E V, Kuvshinov V M, Steblinkin A I, Terehov R I and Khaletsky L V 2016 Local hydraulic system with adaptive pressure control for long-haul aircraft. Conf.: Recent Adv. in Aerospace Actuation Systems and Components (R3ASC) (France, Toulouse) pp 67-74

[4] Postnikov S E, Trofimov A A and Baikov S V 2018 Architecture options estimate for the near-medium-haul aircraft control system by the reliability, mass and power consumption criteria. Aerospace Systems 2(1) 33 doi:10.18698/2308-6033-2017-12-1711

[5] Ermakov S A, Karev V I and Mitrichenko A.N 2010 Systems of surface actuators of passenger aircraft, their development and ensuring trouble-free operation. Aerospace MAI Journal. 17(3) 18 [in Russian]

[6] Kuvshinov V, Khaletsky L, Steblinkin A, Erofeev E and Skryabin A 2015 Safety & Energy Efficiency Research on Advanced More Electrical Flight Control Actuation Systems for Short/Middle Range Passenger Aircraft. Conf. More Electric AircraftAt (Toulouse, France) pp 1-3

[7] Aircraft EHA, MOOG Company, available at: https://www.moog.com/products/actuators-servoactuators/actuation-technologies/electrohydrostatic/aircraft-eha.html

[8] Jianming L, Zhiyuan , Yuping H and Zhiguo L 2016 Review of electromechanical actuation system for more electric aircraft. IEEE/CSAA International Conf. on Aircraft Utility Systems (Beijing China) pp 490-497 doi: 10.1109 / AUS.2016.7748100

[9] Baikov S V, Bliznova T B and Obolenskiy Y G 2012 Trends in the development of the architecture of the executive part of the modern aircraft control system. Scientific Herald State Research Institute of Civil Aviation Collection of Scientific Paper 2 15 [in Russian]

[10] Alekseenkov A S 2014 Improvement of dynamic properties and study of working processes of the aircraft steering hydraulic actuator with combined speed control with increasing external load. PhD thesis, Moscow [in Russian]

[11] Redko P G 2002 Increased reliability and improved performance of electro-hydraulic actuators (Moscow: MSTU Stankin Publishing Center Janus-K Moscow) p 57 [in Russian]

[12] Mare J C 2016 Aerospace Actuators: Needs, Reliability and Hydraulic Power Solutions (Wiley-ISTE) p 51 doi: 10.1002/9781119307662

[13] Xue L 2010 Actuation Technology for Flight Control System on Civil Aircraft. MSc thesis, Cranfield University

[14] Weiss J 2014 Control Actuation Reliability and Redundancy for Long Duration Underwater Vehicle Missions with High Value Payloads, Underwater Intervention 2014 pp 3-4

[15] Hyssain Y, Burrow S, Henson L and Keogh P 2016 Benefits Analysis of Prognostics and Health Monitoring to Aircraft Maintenance using System Dynamics. 3rd European Conf. of the PHM Society - PHME16 (Bilbao, Spain) p 11

[16] Actuation-EMA-Series, CIRCOR Aerospace, available at: http://www.circoraerospace.com/downloads/bodet/Bodet-Electromechanical-Actuation-EMA-Series.pdf

[17] Certification Specification. Part 25 (CS-25). The norms of flight of the aircraft of the transport category. Section A-0 – “General requirements for the airflow of the aircraft when functional system failure” pp 14-16

[18] Postnikov S E, Trofimov A A and Smagin D I 2017 Options of control system architectures for short-medium haul aircraft. Eng. J. Sci. Innovat. 12 12 doi: 10.18698/2308-6033-2017-12-1711