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A Redundant Electromechanical Elevator System

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Abstract. Current trend towards sustainable aviation has led to development of more- and all-electric aircraft and its systems. However, the usage of electrical alternatives in flight still limited due to safety and reliability concern, especially jamming failure. Hence, this paper proposed an architecture for redundant electromechanical elevator systems (EMA) and a decoupling method to release an actuator from the entire system at jamming failure. This paper also discusses the potential advantage of using EMA over existing hydraulic actuator system in aircraft. It is shown that EMA system proposed in this paper satisfy the regulatory requirements to power aircraft elevator system. The comparison to other type of actuator also shown improvement in reliability, with failure rate for the proposed EMA systems around 2.25×10^{-8} failure per flight hour.

Keywords*:* ***e****lectromechanical actuator; aircraft elevator systems; redundant system.*

1 Introduction

In the 21st century, a move towards sustainable aviation has led to development of more- and all-electric aircraft (MEA/AEA). This calls for new technologies using electrical power for aircraft subsystems that traditionally uses other energy types such as mechanical, hydraulic, and pneumatic [1]. A Power-by-Wire (PbW) systems can be ysed, in which electricity directly powers the systems without any mechanical, hydraulic, or pneumatic intermediate [2]. One of such technology is the electromechanical actuator (EMA).

EMA has been used to power the flight control systems of many unmanned aerial vehicle (UAV). However, the usage of EMA in commercial aviation is still limited. Even newer aircraft such as Boeing 787 and Airbus A380 uses EMA only in secondary flight control and non-safety critical systems such as flaps, slats, spoilers, and horizontal stabilizer. Hydraulic power still dominates the primary control systems (elevator, aileron, and rudder) [3]. Although EMA has several advantages in weight and overall complexity compared to hydraulic actuators [4], safety and reliability issues still raises concern for the use of electromechanical actuator in primary flight control systems. This technology is not mature yet and still lacking experience from past usage, and failure probability of EMA is much higher than current hydraulic actuator used in aircraft systems [5].

This paper presents a system-based approach to meet the challenge of electromechanical actuator reliability for aircraft elevator control systems. A dual-redundant architecture for each elevator surfaces is created, with an active-standby backup mechanism. A decoupling method to release an actuator from the entire system at a jam is also developed. Other than that, this paper also reviews the electromechanical actuator as a system, its advantages and disadvantages, and its comparison with existing hydraulic actuator system in aircraft.

2 Background Review

2.1 Electromechanical Actuator

Electromechanical actuator, abbreviated as EMA, is a device to transform electrical power into mechanical action. In general, EMA comprises of two elements: an electric motor and a mechanical transmission [6]. The motor generates rotational motion by using electrical power source to drives an array of magnets or coils. This rotational motion is transferred to a mechanical transmission, usually gear systems or jackscrew, to move another part, such as elevator surfaces. Figure 1 describes the general structure of an EMA.

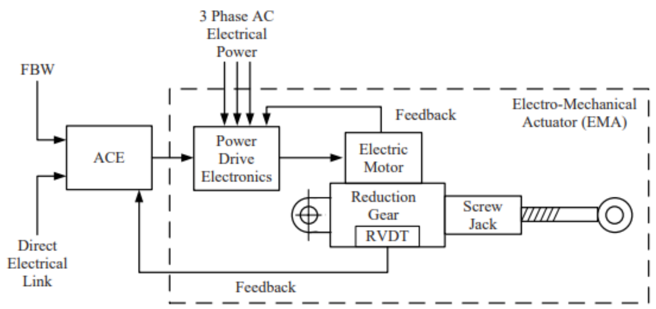

Figure 1 A scheme of linear electromechanical actuator system with jackscrew (adapted from Moir and Seabridge [6])

2.1.1 Types of EMA

Electromechanical actuator can be divided into several types based on the direction of mechanical action. Usually, EMA are divided into two types: linear and rotational [7]. Linear-type EMA produces a linear motion by converting motor rotation using jackscrew, while rotational-type EMA uses series of gears to produce a rotational motion by lowering the speed of motor. Linear-type is further divided into direct drive actuator which directly connects the motor to jackscrew and geared actuator that uses gear transmission to connect the motor to jackscrew. Each of these EMA types has its own advantages and disadvantages.

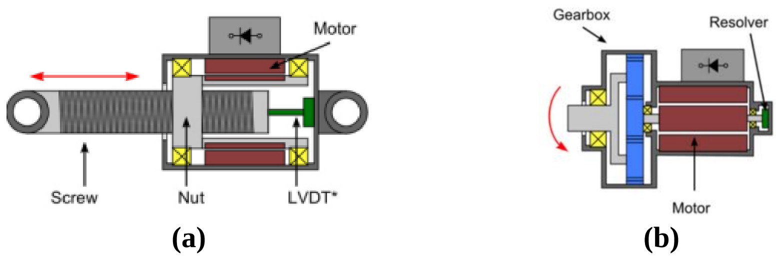

Figure 2 Example of electromechanical actuator types: (a) linear-type and (b) rotational-type (adapted from Wagner et al. [7])

Actuators for aircraft systems require large forces at low speeds, while electric motors generate relatively small forces at high rotational speeds. In addition, the actuator must be as small as possible due to space and weight constrain. In this regard, rotational-type electromechanical actuators are unsuitable as this type generally produce high rotation speed but low torque, and the need to directly attach actuator to the control surfaces means larger space needed. Linear actuator can be a solution, with direct drive actuator offering compact and simple systems while geared actuator can generate larger forces at cost of greater weight [8].

2.2 Elevator Flight Control System

Aircraft elevator is one of the primary flight control systems for a conventional aircraft. This system is used to control the pitch motion of aircraft using two control surfaces, deflecting symmetrically to each other. This deflection manipulates aerodynamic forces and moment, therefore generating rotational moment required for pitch maneuver. The typical aircraft elevator system consists of control surfaces, linkage, controller, and actuator [9]. Typical methods of actuation in commercial aircraft are fully mechanical actuator, hydraulic-assisted mechanical actuator, and hydraulic-powered actuator.

2.2.1 Regulation Considerations

Every aspect of aircraft system must follow certain standards of airworthiness. Elevator control system in a transport category aircraft is regulated in Civil Aviation Safety Regulation part 25.143, 25.671, and 25.1309. These regulation covers the function and safety requirements of flight control system.

Regulation states that the aircraft must be capable of continued safe flight and landing after any of the following failures or jamming in the flight control system and surfaces. As a critical system, any failure that can led to total loss must be extremely improbable. Quantitively, the probability of failure that led to catastrophic failure in aircraft elevator system is less than 1×10^{-9} per flight hour, or at most one failure per billion flight hour [6]. Any jamming failure potential must be shown to be extremely impobable and can be alleviated. Meanwhile, the probability of failure other than jam must be improbable, or less than 1×10^{-5} per flight hour.

2.3 Comparison of EMA to Hydraulic Actuator

Electromechanical actuator is a relatively new technology for aircraft systems. Therefore, a comparison to existing solution is needed, to identify the advantages and disadvantages of EMA and its problem for use as substitution of hydraulic systems.

Some of EMA advantages is given by Rosero, *et al.* in [2], Fu, *et al.* in [3], Qiao, *et al.* in [4], and Maré in [8]. Uses of EMA reduces overall system complexity and weight compared to hydraulic system, as EMA eliminates the need for pump system, hydraulic reservoir, and pipeline. Elimination of pump also means that EMA is important for more/all electric aircraft, as aircraft electric generator is the only system needed to power other systems. EMA also has higher energy efficiency on system level compared to hydraulic actuator, as EMA directly transfer energy from generator to drive the actuator by means of electricity using wire which minimize energy loss in transformation and transfer process. Stiff jackscrew rod used in EMA can produce more accurate and controllable output compared to compressible fluid in hydraulic actuator, where the dynamic is more complex. Usage of EMA also reduces fire hazard and environmental concern regarding toxicity of hydraulic fluid. Also, EMA enables high modularity in systems that making maintenance easier, as diagnostic and replacing an electrical component is simpler than finding leakage or constantly replacing hydraulic fluids due to contamination.

However, with all the advantages listed previously, EMA is still not used as primary flight control system usage in commercial aircraft. These systems are still dominated by hydraulic actuator as their main driver. This is due to issues in EMA that affect safety and reliability. Several of these issues is presented by Fu, *et al.* in [3], Gaile and Lue in [5], and Maré in [8] is mainly regarding reliability of electromechanical actuator. Current reliability of hydraulic actuator is higher than equivalent EMA, with failure rate of EMA that can be up to 100 times higher. Jamming in motor and jackscrew is the main issue in EMA. In addition, this failure will result in a cascade as other mechanical components will also be locked in their position. As jamming is the main concern in airworthiness regulation for flight control system discussed previously, this means that it is hard to fulfill standards of airworthiness using EMA in aircraft elevator systems. While hydraulic actuator can also have jamming failure, it can be easily bypassed by redirecting hydraulic fluids to other non-jammed section using series of control valves. The same cannot be done for EMA .

Other issues in EMA are heat resistance and electromagnetic interference in the electronic components. In addition, some secondary characteristic of hydraulic fluid such as dynamic damping, back-driving, and overload protection is harder to be duplicated in EMA. Bigger EMA system with gear transmission is usually needed to generate similar forces comparable to a piston in hydraulic actuator as power generation of EMA in component level is lower, although the elimination of hydraulic systems as advantages of EMA can offset this difference. Lastly, there are concerns regarding the maturity of EMA systems. This technology is relatively new with many problems still yet to be identified. On the other hand, hydraulic actuator has been used for decades in commercial aviation and there are a lot of experience in design, production, and maintenance of hydraulic actuator. Hence the reluctance to switch to EMA.

With all advantages and disadvantages of EMA mentioned above, it can be summarized that use of electromechanical actuator in aircraft systems is important in more-/all- electric aircraft design, as this technology potentially reduce in weight and system complexity while increasing the efficiency in performance and energy usage. However, several issues with EMA needs to be addressed to make a safe and reliable system. The key issue is regarding how to alleviate jamming problem in EMA.

3 System Design

Based on the discussion regarding advantages and disadvantages, an EMA system design for aircraft elevator control system needs to address two issues: reliability and case of jamming failure. The issues of reliability can be solved by using a dual-redundant architecture for the system design. Charrier and Kulshreshtha in [10] gives the general layout for dual-redundant EMA as presented in Figure 3.

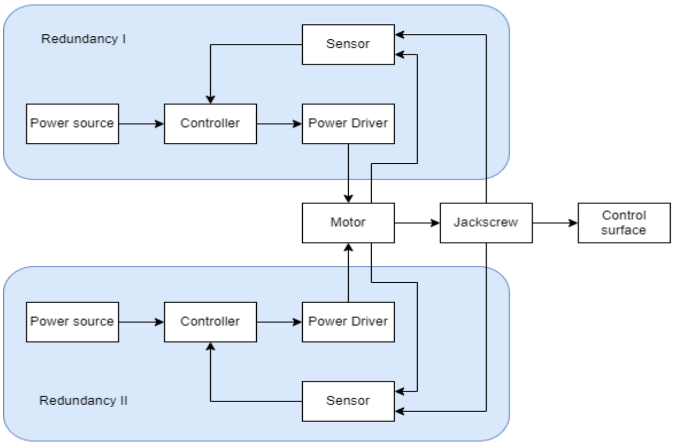

Figure 3 Dual-redundant EMA architecture.

The architecture in Figure 3 is still does not enough to address the jamming potential in the jackscrew, which can be up to 8.1×10^{-6} failure per flight hour according to Giagrande, *et al.* in [11]. Hence, a system with two EMA, each with its own jackscrew, working in active-standby mode, connected to the elevator surface by a common shaft and a decoupling system is created. The proposed system can be seen in Figure 4. This system is proposed for one side of elevator surface. Since transport category aircraft generally has two elevator surfaces, there will be four EMA working in pair for each aircraft. Both pairs are independent. A geared motor will be used as the core of EMA.

Since this architecture works in active-standby mode, both EMA works at the same time. One of them works with load connected to the common shaft while other working without load. When the active system jammed, its coupling system will disconnect it from the elevator. After that, the standby EMA coupling engaged and this will take over the elevator control system. If both EMA jammed, then both EMA will be released from the common shaft, and the elevator will be in free floating. Decoupling mechanism and logic between each EMA pair and its common shaft are described in subsection 3.1.

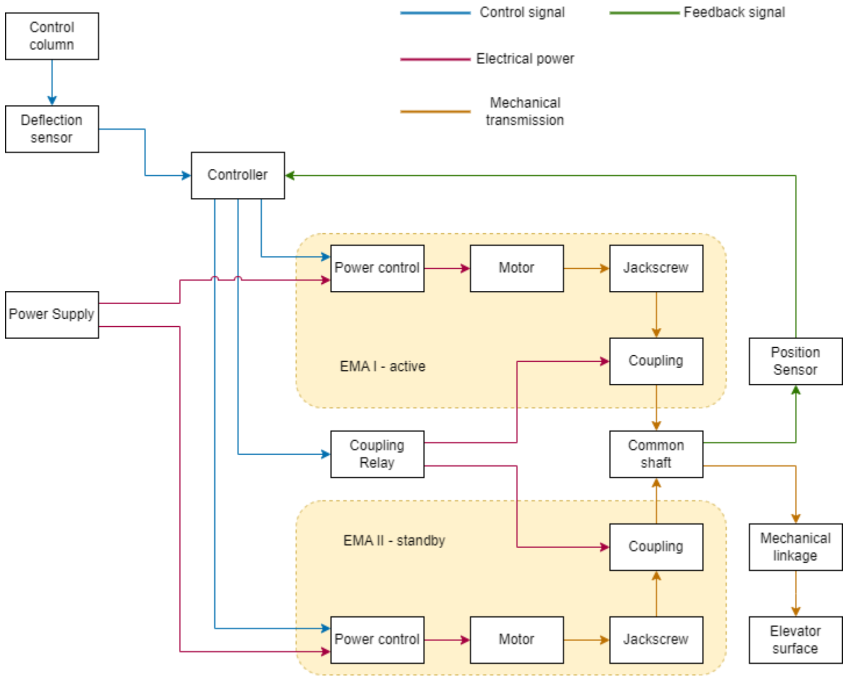

Figure 4 System design for electromechanical elevator systems.

3.1 Decoupling Mechanism

Each elevator surface has a pair EMA operates in an active-standby mode. Each EMA is connected to the mechanical linkage and elevator surface by a common shaft. To prevent jammed EMA to block the entire system, a coupling mechanism is added between each EMA's jackscrews and common shaft. This coupling mechanism uses a spring and an electromagnet to lock jackscrews to common shaft. The schematics for this coupling mechanism can be seen in Figure 5.

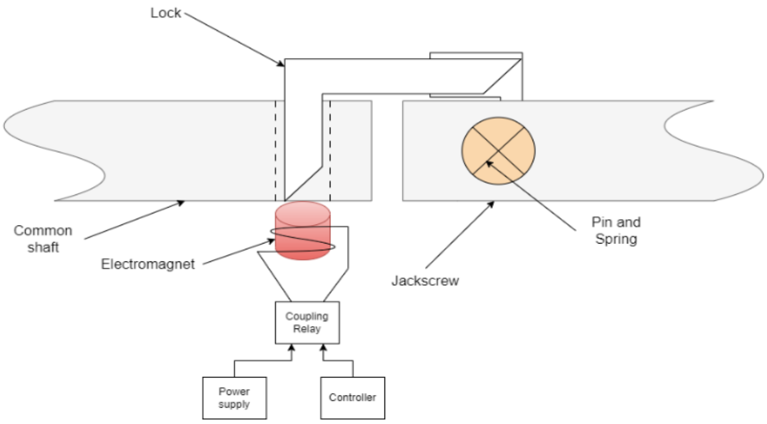

Figure 5 Decoupling mechanism between EMA and common shaft

At unpowered condition, the spring will pull the lock bar open, so that common shaft and jackscrew is not connected. When the system is powered, supply of electricity from power supply will activate the electromagnet and pull the lock to connect jackscrew and common shaft. Should a jam occur, there will be a sudden increase in power demand from motor but no motion detected by position sensor in common shaft. This signal is used by controller to make the relay cut the power to electromagnet in the jammed EMA, therefore releasing the lock and disconnect common shaft from the jammed jackscrew. Combined with the active-standby mode of this EMA architecture, the flowchart of coupling logic can be seen in Figure 6.

4 Reliability Analysis

The reliability analysis for the elevator systems with architecture described in Section 3 is carried out using the fault-tree analysis (FTA) method. In this analysis, only the electromechanical actuator part is considered for the probability of failure calculation on FTA, with assumption that other components are standard to elevator systems regardless of its actuator type. Hence, the components to be analysed is as shown in Figure 7 for one EMA set.

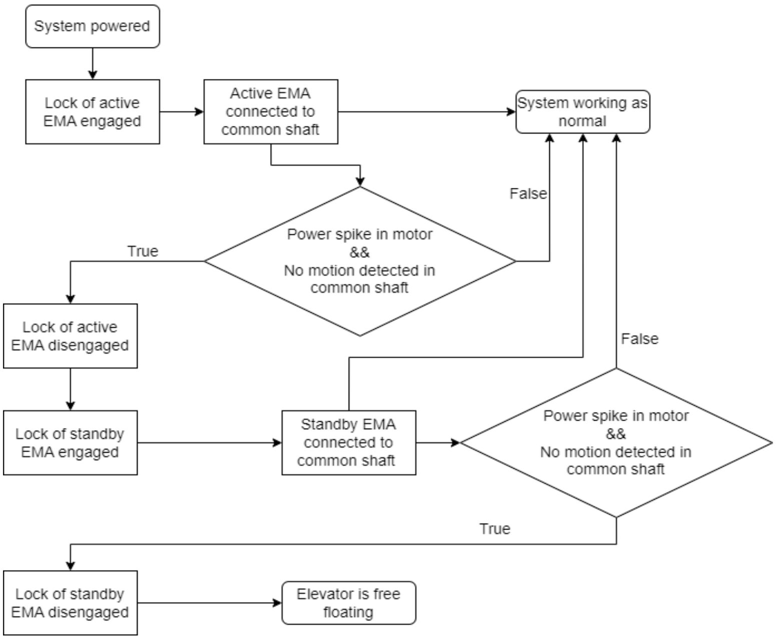

Figure 6 The logic of decoupling mechanism

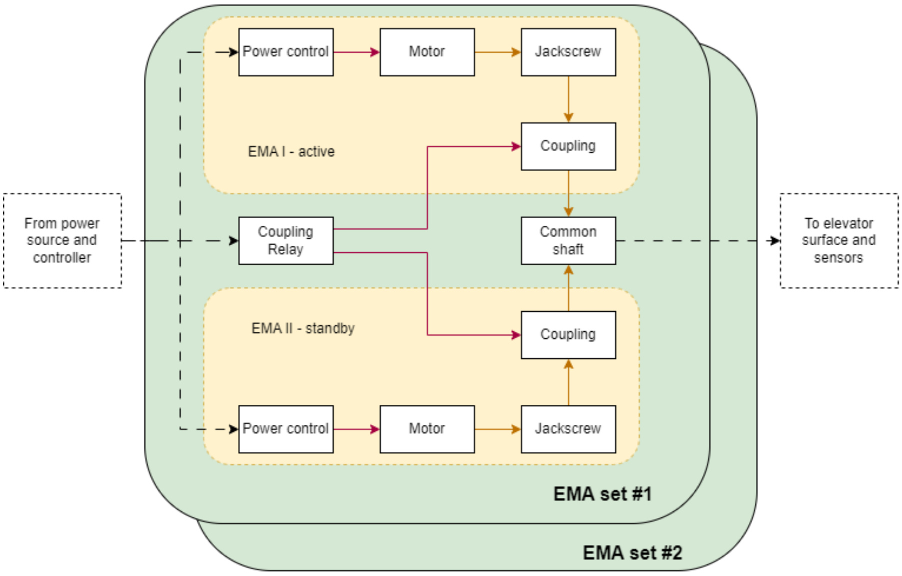

Figure 7 EMA set for reliability analysis

4.1 Fault Tree Analysis

In order to analyse the reliability of this EMA architecture, a fault tree analysis (FTA) is done. The probability of failure of each component will be defined using figures described by several sources. For the power control unit, the number assigned for similar systems in electrohydraulic actuator (EHA) systems by Sadeghi and Lyons in [12], while study of industry survey by Tavner and Hasson in [13] regarding rotating electrical machine is used as to determine the probability of failure for the electrical motor. The probability of failure for a jackscrew is obtained from analysis of failure probability of rotary screw with planetary gear done by Lemor in [14]. Failure figure for the coupling mechanism is also based on probability for a system consisted of electromagnetic-controlled actuation mechanism described by Zhu, *et al.* in [15]. Meanwhile, the failure probability for the controller and relay to switch is based on data given by Zhu, *et al.,* but modified to typical triplex architecture for electronics. The common shaft is left out in this FTA as this is part of mechanical linkage that similar with other type of actuator for aircraft elevator, hence the probability is already should be below 1×10^{-9}. To summarize, Table 1 lists the probability of failure for each component.

Tabel 1 Probability of Failure for each EMA component

No	Components	Probability of Failure (per Flight Hour)
1	Power control	5.4×10^{-5}
2	Motor	6.0×10^{-6}
3	Jackscrew	1.5×10^{-6}
4	Coupling mechanism	1.5×10^{-4}
5	Coupling switch mechanism	3.6×10^{-10}

The FTA for one side of the elevator then constructed based on these numbers, as shown in Figure 8. From this figure, the failure probability of an actuator with this architecture is around 2.25×10^{-8} per flight hour, which was still higher than the maximum allowed by regulation for total loss of elevator flight control system. However, this is still within the requirements for operation that would reduce the ability of the crew to cope with adverse operating conditions.

The FTA showed that the most critical component is the coupling mechanism. When the coupling mechanism fails, a jammed jackscrew cannot be released from the common shaft, creating failure in the entire system regardless whether the other component is still operational. In addition, the coupling mechanism has the lowest reliability compared to the other mechanism in this EMA architecture.

This EMA architecture cannot be used to power the entire aircraft elevator system, as its reliability does not meet the airworthiness standard. However, redundancy can be added by duplicating this architecture. The proposed system for use in aircraft elevator is a duplex system each containing the EMA architecture described in Section 3. Each system works and powered independently to move one control surface. Should one system fail, the elevator surface powered by that system will be in free floating mode. The other system that still works will only power the other control surface. The fault tree for the proposed aircraft elevator system is shown in Figure 9. From this figure, it is shown that the total loss of elevator control by using two independent system of EMA based on the proposed architecture has fulfilled the regulatory requirement of failure probability level at extremely improbable.

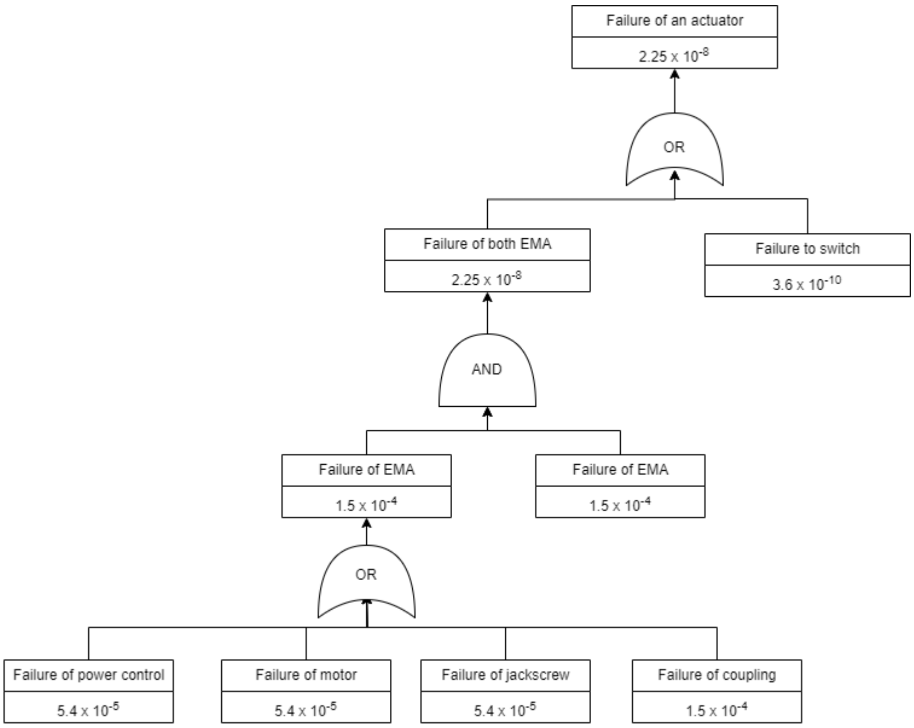

Figure 8 Fault tree analysis of the EMA architecture for one side of aircraft elevator.

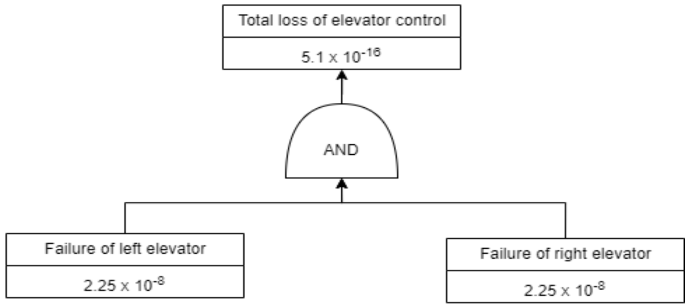

Figure 9 FTA for entire aircraft elevator system

4.2 Comparison to Reliability Data

The reliability of EMA architecture described in the previous section is then compared to reliability of other flight control actuator systems. Three different systems and architecture are used as comparison: EMA with two motor and single jackscrew, single EHA system, and tandem electrohydraulic system with one mechanical backup. The reliability data for EMA with two motor and single jackscrew is given by Giagrande, *et al*. in [11] while the reliability data for both EHA system is given by Sadeghi and Lyons in [12]. The comparison can be seen in Table 2. Note that this comparison is only for single actuator, not for entire aircraft elevator systems.

Table 1 Comparison of probability of failure between actuator type.

No	Actuator Type	Probability of Actuator Failure (per Flight Hour)
1	EMA with two motor and two jackscrews	2.25×10^{-8}
2	EMA with two motor and single jackscrews	8.12×10^{-6}
3	Single EHA	4.48×10^{-7}
4	Tandem EHA with mechanical backup	1.304×10^{-9}

The probability of failure for the proposed EMA architecture as shown in Table 2 is improved significantly compared to EMA with only single jackscrews. It can also be seen that the probability of failure is slightly better than single EHA system. However, the failure probability is still lower than tandem EHA with mechanical backup system.

5 Conclusion

In this paper, a study of EMA architecture for use in aircraft elevator system has been created. This study covers the design of electromechanical actuator, its advantages of its use in context of more- and all-electric aircraft, and the issue of EMA that prevents current use in aircraft control system. A duplex system, each containing two electromechanical actuator is proposed to increase the reliability of this system. Another feature proposed in this architecture is the use of a decoupling method to release a jammed EMA to prevent blockage and failure of entire actuator system. It is shown using fault tree analysis that the proposed system can be used as actuator for aircraft elevator system, as the system probability of failure based on the fault-tree analysis is at 5.1×10^{-16} per flight hour, well below the maximum probability for system that must have extremely improbable failure at 1×10^{-9} per flight hour. The proposed EMA architecture has considerable reliability improvement compared to EMA with only single jackscrew EMA (failure rate about 360 times than the proposed systems) and also slightly better than single electrohydraulic actuator (failure rate about 20 times the failure rate for the proposed systems). This means that from reliability aspects, the proposed EMA can be used to substitute hydraulic actuator in primary flight control systems, and improved reliability compared to existing EMA systems. However, the proposed architecture still has higher probability of failure than a tandem EHA system with mechanical backup.

The next step in this research is to build a working model of this actuator system and verification by experiment. For future works, a coupling mechanism design with higher reliability can be created, as this is the major source of failure to the proposed EMA architecture in this research.

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