Redundant electromechanical actuator operation analysis in case of failures

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Abstract. In the modern aircraft control systems electro-hydraulic actuators are used widely, due to structural and elemental redundancy, they remain operational even in case of two heterogeneous failures. However, the hydraulic systems supplying them require regular maintenance and have large overall dimensions. The more electric aircraft concept involves reducing the number of hydraulic systems and replacing part of the actuators with electromechanical ones powered by a centralized electrical system. This requires highly reliable electromechanical actuators development and determines to search for ways to implement their structural and elemental redundancy. The modern elements, including electric motors with rare-earth metals, wave gears and power electronics, has low mass and size specifications. However, the reliability issues associated with structural and elemental redundancy for electromechanical actuators are not well studied and are under development. In this article a redundant electromechanical rotary actuator and its reconfiguration algorithm descriptions are given for in the events of heterogeneous failures. This algorithm is used to compile a mathematical model and conduct simulation experiments. It is shown that by means of structural redundancy the actuator remains operable even in case of two heterogeneous failures.

Keywords: electric aircraft, redundant electromechanical actuator, structure reconfiguration, simulation model.

1. Introduction

Modern aircraft flight control systems mainly use centralized hydropower and electro-hydraulic actuators for power automatic systems. The disadvantage of hydraulic systems are large overall dimensions and regular maintenance that required. At the first stage a partial replacement of centralized hydraulic systems by electrical systems and hydraulic actuators by electromechanical actuators (EMA) is the current task in modern aviation technology. This is consistent with the international concept of creating more electric aircraft (MEA) [1]. The MEA concept requires new solutions and components for EMAs, providing reliability and lifespan similar to hydraulic actuators [2, 3, 4]. At present, electromechanical power mini-actuators constructing features are developed. The electromechanical power mini-actuators includes highly efficient power electronics devices, brushless high-speed motors with highly-reactive rare-earth magnets and mechanical gears with a small moment of inertia, such as wave gear with rolling elements, that converts rotational motion into rotational, or ball screw (or roller screw) with a separator that converts rotational motion into translational [5, 6]. The reliability level required for flight control systems can be achieved by means of structural redundancy [7]. The issues of choosing the EMA structure are analyzed in detail in [8].
This article is devoted to study one of the possible versions for the EMA structure, proposed in [8]. The goal is to develop the reconfiguration algorithms for its structure in cases of heterogeneous failures, and to describe the mathematical model to provide simulation experiments.

2. Materials and methods

The object is rotary electromechanical actuator (EMA) based on hollow rotor torque motors. The EMA’s block diagram is shown in figure 1.

In figure 1: AM – actuator mechanism, EM – electric motor, G – gear, EC – electromagnetic clutch, ES – electrical system, PSS – power supply system, EPSS - emergency power supply system, D – diode, PC – power converter, PFS – position feedback sensor, RPS – rotor position sensor, CS – current sensor, VS – voltage sensor, LM – lever mechanism, CIS – clutch sensor, PSR – power supply relay, DR – damper relay, ICS – integrated control system.

To describe EMAs operation algorithm the following modes are given:
- EMA status with power off
- Turning on
- Normal operation
- Operation in case of failures

In the listed modes, the state of all elements is analyzed. The algorithm for reconfiguring the actuator structure is proposed to ensure the normal operation in case of any possible failures.

To provide simulation based on the structure reconfiguration algorithm, a mathematical model of the EMA was developed. The model is developed in MATLAB by using Simulink environment, Simscape and SimPowerSystems libraries.

![EMA block diagram](image)
3. Results and discussion
Accept that AM1 is the main actuator, and AM2 - the backup actuator. Also, accept that in following we will call the AM channel the set of EM connected to its RPS control system, supplying its PC windings, the corresponding CS, and the controller channel controlling this EM.

3.1. EMA status with power off
The steering surface must be fixed when the power is off (it must be locked or damped). To make it sure, in this mode, the clutches of both AMs are in the “Engaged” position. When the power is off, the ends of the motor windings must be circuit to each other. Then, if the steering surface moves a short circuit current will flow in the EM windings, thereby creating a braking torque that will damp the steering surface. Such circuit may be provided, for example, by relay contacts, or by other switching elements.

3.2. Turning on
First, power and service power must be supplied to all AM channels and to the clutch. The clutch of the main AM is in the “Engaged” stat and, the clutch of the backup AM is set into the “Disengaged” state. After that, the drive is ready for operation.

3.3. Normal operation
During normal operation, two channels of the main AM operate, so two motors - EM1-1 and EM1-2 operate, while EM2-1 and EM2-2 are in standby mode, i.e., the SP2-1 and SP2-2 power converters are powered, but all the keys of the converters are in a closed state, i.e., the windings of EM2-1 and EM2-2 are de-energized. EM1-1 and EM1-2 torques are summarized on the input shaft of the gearbox G1. The C1 clutch is in the “Engaged” state, which means that AM1 total torque is transmitted to the steering surface and the EMA adjusts its position in accordance with the control signal. The clutch C2 is in the “Disengaged” state. Power is supplied from the centralized electrical systems ES1 and ES2 to the power converters through the corresponding fuses and power supply relays. It should be noted that the EMA’s mechanisms are the same and interchangeable, so AM2 may be the main, and AM1 may be the backup. This allows to increase the EMA’s lifetime by periodically reassigning the primary and backup AM.

3.4. Operation in cases of failures
3.4.1. In case of electrical system failure, the failed electrical system is automatically disconnected from the actuator by locking the corresponding decoupling diode, and the actuator receives power from a normally operating electrical system. A battery pack may be used as an emergency power supply.

3.4.2. In case of any failure in one of the working (main) AM channel, namely, in case of failure EM, RPS, PC, CS or the controller channel, the power is switched off from the corresponding PC by disconnecting the contacts of its PSR and the corresponding EM windings becomes de-energized. In this case, a normally operating AM channel takes the external load. After this, the backup AM’s clutch is switched to the “Engaged” position, and both electric motors of the backup AM are switched-on by signal to the corresponding PCs, then the power is switched-off from the main AM by disconnecting the contacts of its remained PSR and the main AM’s clutch sets to “Disengaged” mode. Further operation of the EMA is provided by the backup AM with two motors operational. Further, in case of any failure in any channel of the backup AM (second failure), power is removed from its PC and the corresponding motor’s windings becomes de-energized. One channel of the backup AM remain in operation. Further, if it also fails (third failure), the EMA again switches operation with the main AM (which has on operational cannel left). To do this, first, the power is removed from the failed channel of the backup AM, the clutch of the main AM is switched to the "Engaged" position, then the clutch of
the backup AM is switched to the "Disengaged" and only the operational channel of the main AM is supplied with power. In case of failure of the last operational channel of the EMA (fourth failure), the power is removed from its PC, the damping mode of the EMA is activated by circuiting the windings of the electric motors and the backup AM clutch is switched to "Engaged" position.

3.4.3. When jamming the gearbox or the lever mechanism that is in the operational AM, the windings of the electric motors (or one electric motor, if one channel has already failed) are first de-energized, then the second AM’s clutch is set to “Engaged” position, then the failed AM’s clutch is set to “Disengaged” and both electric motors in operational AM are switched on (or one, if one of the channels has failed before that).

3.4.4. Electromagnetic clutches that used in EMA design are one of the key elements to ensure the operation, so they must have high reliability level, so clutches control system backup is also used. Clutch control block diagram is given on figure 2. Clutches are powered from the power supply network and from the emergency service power supply network through decoupling diodes. Switching electromagnets, contain main coils and backup coils which are connected in parallels to the power supply network by transistor groups to increase the operation reliability. This allows the clutch to operate normally in event of a short circuit or breakage of any transistor group. Clutch engage and release sensors represented by a pair of relay-switches connected in parallel. When the clutch moves to any fixed position (“Engaged” or “Disengaged”), the corresponding relay-switch sent a signal to the integrated control system that position achieved. This will occur even if one of the relay-switches in each group fails. In the event of clutch failure in accordance with the algorithm described above, redundant windings must be included in the operation. Thus, a level of reliability is achieved that allows us to consider the clutch failure to be an almost unbelievable event (the clutch failure rate is less than the AM failure rate).

Figure 2. Clutch control block diagram.
On figure 2: PSR – power supply relay, W – coil winding, SPK – sequential-parallel key, CIS eng-clutch engagement sensor, CIS diseng – clutch disengagement sensor, PSS – power supply system, EPSS – emergency power supply system.

3.4.5. PFS has fourfold reserve, all PFS channels are always active, and position of the steering surface is determined by calculating the average value. In this case, the performance of PFS channels is determined by comparing channel-by-channel signal with the average. If the signal differs by more than an acceptable value from the average, then the PFS channel is excluded from the calculation.

EMA’s structure reconfiguration takes place automatically in case of occurrence of paragraphs 3.4.1 and 3.4.5, but 3.4.2, 3.4.3 and 3.4.4 require continuous data analysis from all sensors. Data from the sensors comes to the integrated control system (ICS), to be analyzed and give out EMA’s reconfiguration signals in case of failures.

Total EMA’s reliability depends on the reliability of the ICS. Data from the sensors comes to all four channels of the controller. Each channel, independently decides whether the actuator is operating normally, whether there are deviations or a failure occurs, and gives commands to reconfigure the actuator. The decision to perform reconfiguration is made by quorumizing the corresponding signals from all the controller channels.

To provide simulation based on the above structure reconfiguration algorithm, a mathematical model of the EMA was developed. The functional diagram of the model is given in figure 3. It is accepted that brushless DC motors will be used in the drive, and their control is provided by pulse width modulation.

ICS receives data from failure simulation block and EMA’s elements and gives reconfiguration signals according to an algorithm. Failures may be set manually by choosing from a list of elements in each channel in failure block.
The main elements (motor, power inverter, clutch, etc.) parameters are set in their blocks based on datasheet or calculated values of the simulated elements. This model allows to determine EMA’s static and dynamic characteristics and the response time of couplings under load and without it and to check required coils forces to guarantee the engaging or disengaging the clutches under load.

Setting failures makes it possible to simulate events and record the operating channels parameters in order to determine their operation modes.

The redundant EMA with similar reliability with the currently used electro-hydraulic and electro-hydrostatic drives will improve the overall dimensions and reduce maintenance and repair costs. The fault-tolerant design in EMAs development is currently at an early stage for implementation in aircraft safety-critical control systems due to insufficient study of reliability issues. The least expensive and fastest way to develop technical solutions in creating new equipment (especially aircraft that requires significant material and time costs) is simulation. Correct simulation of EMA and analysis of real and simulated failures are key aspects for finding out reliability issues. Such an approach will allow to make changes to the developed EMA to reduce the failure probability by evaluating the difference between the predicted and received data at the test rigs.

The mathematical model of the redundant EMA with estimated failure rate $\lambda_{EMA} \leq 10^{-8}$/hour is proposed as a result. The model includes verified models of all elements, describes the structure of the actuator, and allows it to be reconfigured. The developed model is intended to be used as a tool for providing simulation experiments to optimize the parameters selection of the actuator components and its design.

4. Conclusion
It is shown that due to structural and element-wise redundancy, EMA stays operable even in case of two heterogeneous failures.

The model allows to analyze the operation dynamics, set failures, set parameters of the motors, clutches, coils, gear ratios and power supply parameters to provide the required dynamic characteristics of the object.

It allows to increase development efficiency and reduce the time and cost of the design stages.

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