PRELIMINARY STUDY OF EMA LANDING GEAR ACTUATION

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Abstract

This research studies the preliminary design of an EMA(Electro-Mechanical Actuator) system used for landing gear actuation on a large passenger aircraft. With the development of more electric technology, aircraft actuation systems such as flight control, braking system and nose wheel steering system have been extensively researched, leveraging EMA technology. However, landing gear actuation, which is the largest actuation payload on board a passenger aircraft, receives little attention. The purpose of this research was to explore the possibility of EMA landing gear actuation, and to provide guidance for further R&D efforts. This research follows a near to real engineering process using the case study method, which consists of several stages such as requirement definition, configuration study, parametric study, structural design and analysis, and finally discussion and conclusion. The requirements of EMA landing gear actuation were generated, in which design constraints such asthe subjects of actuation, actuation time, redundancy level, structural constrains are derived through analysis. In the stage of configuration study, systems of different configurations were identified as candidate solutions. As a unique feature, landing gear kinematics concepts were also optimized, as EMA solutions do not necessarily favor the same kinematics as their hydraulics counterparts. Various kinematic concepts were proposed and analyzed in detail, to provide favorable loading and geometrical conditions for the actuation systems. Design guidelines of kinematics are proposed in the discussion section. Different drive components such as BDCM (brushless DC motor) and PMSM (permanent magnetic synchronous motor) were evaluated for use. In the parametric study stage, the various solutions were modeled and optimized. The multi-discipline optimization method has been extensively used in the process. Firstly, each node of the actuation systems was optimized. Then optimizations were made to the systems to ensure an overall balanced system. Parametric study results revealed that the kinematic concepts and optimization methods used on existing civil aircraft are still applicable to the EMA solutions. As for the electrical motors, the PMSM solutions and BDCM solutions do not differ much in terms of dynamics(see figure 1) and power penalty. The BDCM solution has been chosen as the favorable solution, and brought into engineering phase for evaluation. Based on the results of parametric study, the main components of the BDCM solution have been engineered for weight and structural compatibility evaluation. Extensive analysis of the system has been made. A fault tree analysis was also made to evaluate failure modes. Based on the above results, a conclusion is drawn that a EMA solution for landing gear actuation is possible, however with several problems yet to be solved.

Keywords: EMA, landing gear, actuation

Nomenclature

BDCM	Brushless direct current motor
DC	Direct current
DOC	Direct operational cost
DRESS	Distributed and Redundant Electrical nose gear Steering System
EBHA	Electrical backup hydrostatic actuator

EDP	Engine driven pump
EHA	Electro-hydrostatic actuator
EMA	Electro-mechanical actuator
EMP	Electrical motor pump
LEHGS	Local electro-hydraulic generation system
MTOW	Maximum takeoff weight
PMSM	Permanent magnetic synchronous motor
POA	Power optimized actuator
RAT	Ram air turbine
R&D	Research and Development

1 General Introduction

The movement towards more-electric or all-electric aircraft has been the biggest trend in the domain of aircraft systems in recent years. Aircraft manufacturers and researchers have endeavored for decades trying to unify the three types of secondary power into one, namely electrical power. Recent improvements in the domains of motor and power electronics give a chance to change the whole picture of aircraft control domain. For more-electric aircraft (or all-electric aircraft), most of the secondary power users will be driven by electrical motors. This will dramatically reduce system complexity, power consumption, logistics and thus operational & acquisition cost. More over, researches have predicted that possible weight reduction could be expected. And because of elimination of engine bleeding, the engine performance can be improved significantly. All these should contribute to a much lower DOC when compared with existing aircraft [1].

Electrically- driven actuation systems, such as electro-hydrostatic actuator (EHA), electrical backup hydrostatic actuator (EBHA) and electric-magnetic actuator (EMA) have been extensively researched and tested for the purpose of flight control actuation [2]. EHA and EBHA have already been used on A380 and Boeing 787 as backup flight control actuators. I The Boeing 787 and various other aircraft have used EMA actuators for brakes. On both Boeing 787 and Airbus A380, electrically driven actuators are used on landing gear locks. On Airbus A380, a local electro-hydraulic generation system (LEHGS) is utilized in backup mode for nose and main landing gear steering system.

Landing gear actuation is the largest short period power user of hydraulic system on current transport aircraft. In the context that flight control system is shifting from central hydraulic power to electrical power, landing gear actuation has no reason to remain on central hydraulic power supply.

Various project reports suggest that aerospace manufacturers have been studying possible more-electric landing gear actuation solutions for some time. Research projects such as POA and Power-By-Wire [3] projects use EHA for landing gear actuation purpose. Messier-Dowty is currently evaluating electrical solutions of landing gear retraction [4]. Messier-Bugatti is leading an EU research project named DRESS (Distributed and Redundant Electrical nose gear Steering System) [5]. The Boeing 787 landing gear actuation is driven by two 270V DC driven EMP in normal operation, and a RAT in emergency [6]. No EDP power is used for landing gear operation. So the Boeing 787 is actually the first wide body civil jet which features “more-electric landing gear actuation”, although its configuration remains conventional.

EMA system is believed to have the biggest potential for actuation. It works in a similar philosophy as EHA. The speed of EMA is also controlled by modulating the motor speed. The difference is that in EMA, a mechanical gearbox is used for power transmission rather than hydraulic circuit. As a result no leakage or fire hazard, as for an EHA, will happen on EMA. Also the maintenance of EMA could be much simpler. However up until now, EMA is criticised for its tendency of jamming. This potentially unsafe failure mode has limited its usage in safety critical applications. Also, the power density of EMA is still not comparable to EHA. Large investment has been made worldwide to make the EMA technology safer and more powerful.

EMA landing gear actuation is not new for the aerospace industry. The British “Vulcan”, “Victor” and “Vickers” bombers are of this kind. In those days, the electrical drives were heavy and inefficient, and gave way to hydraulic systems which had much higher power density.

Currently no concrete consensus exists on what EMA landing gear actuation solutions will look like in future. This study tries to provide more information on this question. The main objectives of this study are as follows:

- To demonstrate the feasibility of using EMA actuators as landing gear actuation drives.
- To explore different actuator configurations, and to find out the best solution.
- To identify technological difficulties and problems in realising EMA landing gear actuation.
- To derive a set of requirements for EMA landing gear actuation.

This study presents the results of a research into the problem of EMA landing gear actuation system design. Case study and multi-domain optimization methods have been used in the study. The study discusses the landing gear actuation system together with landing gear kinematics. Several synergies containing actuation systems and landing gear linkages are identified. And through discussion, the best solution has been targeted.

2 Requirement analysis

2.1 Actuation subject and loading

An aircraft which has a MTOW of 238t has been chosen as the study case [7]. Each of the two main landing gear units weights 3767kg. It swings proximately 75degrees into the landing gear bay. The aircraft and its main landing gear are quite similar to Boeing 787 [8] and A330-200.

During landing gear actuation, various loads are effective. Major load are of the following four kinds:

- Load by gravity force
- Load by aerodynamic force,
- Load by friction force,
- Dynamic load.

There are also other forms of loads, such as brake torque loads and gyroscopic loads. These loads are very small when compared with the above ones, and not considered in this study.

Figure 1 shows the results of static load torque.

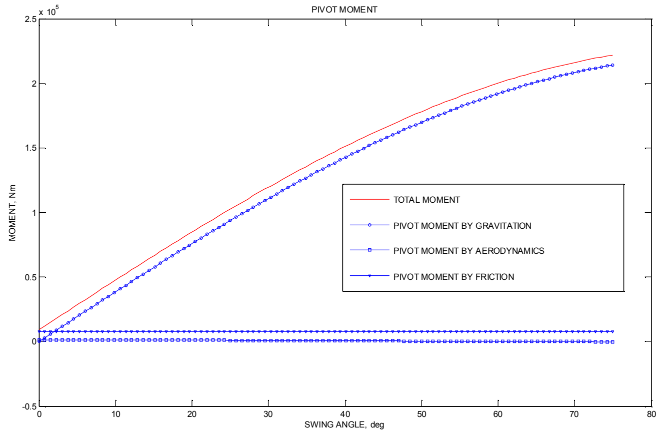

Fig.1. MLG actuation static loads

From the above figure, the load caused by gravitation dominates. Analysis shows that energy stored in landing gear inertia is small when compared with the energy counteracting static loads. It implies that static load is far larger than dynamic load. Because of this, the total static load, was used in sizing components in this study.

2.2 Design Requirements

The design requirements of landing gear actuation are many. High reliability and safety, low cost, minimum weight, high level of integrity, and good maintainability are all demanded. These requirements are conflicting in several aspects. However, certain priorities exist. Because of the serious consequences of failure, safety requirements prevail in the landing gear actuation system design.

Landing gear actuation on current aircraft normally has several hydraulic power sources. The Boeing 787 has the least power source redundancy level in wide body aircraft. Its landing gear actuation is driven by two 270V DC driven EMP in normal operation, and a RAT in emergency. From the above analysis, the conclusion has been made that a least mechanical power source redundancy level of two should be enough for safety, and may provide enough credit to satisfy the airworthiness authorities. For landing gear actuation purposes, the following fail-safe design feature shall also be incorporated:

- One motor should have enough torque ability to raise and lower the gear.
- With two motors, the retraction time requirement shall be fulfilled.

Focuses will be put on the retraction mode for its severity. Extension mode performance will be checked for validity. Two methods are used to estimate the retraction time requirement. One method contains summarizing the requirements of existing aircraft [9]. The other method calculates the time requirement through aircraft performance simulation [10]. The result suggested by these two methods is 15-20s. The retraction time requirement was fixed to 15s for this study. This gives some allowance to the actuation of landing gear subsidiary components such as locks and doors.

Due to the sizing constraint of the landing gear bay, effort must be made to minimize the volume of actuators. The landing gear actuation system has to survive severe vibration and ambient environments. Human error is another major cause of malfunctions and shall be considered in system design.

3 EMA System Design

Based on the requirement listed above, an EMA system for the subject landing gear has been designed and modeled. All the possible design synergies are investigated, with the design selection made through comparison over system weight, dynamic performance, power consumption and other factors.

3.1 EMA System Synergies

The EMA system is composed of two motors driving a single speed reduction gearbox. A clutch is used to free the landing gear from the actuator when jamming happens. Two motors are used to ensure the minimum redundancy level. The gearbox contains one screw and two pair of spur gears. The designed EMA cross section view was shown in figure 2.

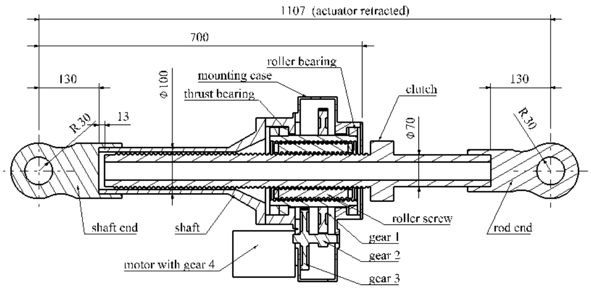

Fig.2.EMA cross section view

Two types of motors, namely brushless direct current motor (BDCM) and permanent magnetic synchronized motor (PMSM) are considered in the design.

Two types of screws are normally used in linear EMA to transmit rotary motion to linear motion: roller screw and ball screw. Roller screw has advantages in terms of size, weight, and load carrying capability; while ball screw is superior in output speed and price For landing gear actuation purposes, high load carrying capability is desired, while high accuracy is not the emphasis. As a result, the planetary roller screw type was chosen for EMA actuators in this study.

Kinematics plays an important role in landing gear actuator design. With in mind that current kinematics design may not necessarily be compatible with EMA actuators, various kinematics concepts both of past experience and of innovation are investigated. Selection of kinematics and their parameters were made through comparison of actuator geometry and loading characteristics.

3.2 System Modeling and Optimization

System mathematic models were built for simulation, to facilitate design synergy comparison and parameter optimization. Certain optimization philosophies were identified through analysis.

The landing gear actuation system could be divided into three parts: motor, transmission, and load. Transmission can be further divided into gearbox and landing gear kinematics. System dynamic equation is produced as follows.

$$\underbrace{\frac{T_{static}}{R_f}}_{1}+\underbrace{\frac{J_{mlg}\times\omega_{mlg}{}'}{R_f}}_{2}+\underbrace{J_{motor}\times\omega_{motor}{}'}_{3}+\underbrace{\frac{m_{actuator}\times v_{actuator}{}'}{R_{f\_actuator}}}_{4}+\underbrace{\frac{F_{drag}}{R_{f\_actuator}}}_{5}=\underbrace{T_{motor}}_{6} \quad (1)$$

Part 1 stands for the torque on motor shaft by static load; part 2 stands for the torque on motor shaft by landing gear inertia; part 3 stands for the torque on motor shaft by motor inertia; part 4 stands for the torque on motor shaft by actuator inertia; part 5 stands for the torque on motor caused by actuator drag force; part 6 stands for the motor electromagnetic torque.

3.3 System Optimization

All the possible design synergies are optimized through simulation to verify their relative advantages.

In order to achieve a fair comparison, the design of each system must be optimized according to its own characteristics. Past experiences on optimizing the hydraulic system driven landing gear actuation system may no longer be applicable in this situation, because EMA actuation system is different in nature. As a result the optimization objects have to be generated. Each node of the system was analyzed first. Then optimization targets were extracted through summarizing requirements from each node. Optimization results are summarized in table 1.

Table.1. EMA synergies comparison

Parameters	BDCM		PMSM	
	Kinematics 1	Kinematics 2	Kinematics 1	Kinematics 2
Gear ratio	52.37	49	52.37	52.37
Maximum motor speed, [rpm]	6063	7110	5619	8250
Average motor speed, [rpm]	5600	6200	4850	6400
Maximum torque, [Nm]	80	80	37.5	35
Average torque, [Nm]	31	27	30	25
Maximum power, [kW]	19.7	19.8	17.2	16.8
Average power, [kW]	18	16.3	16	16

Kinematics optimization research indicates that kinematics optimization methods of EMA solution follow the same rules as their hydraulic counterparts. The kinematics as shown in figure 3 is considered superior in terms of efficiency, load shaping characteristics and actuator fault segregation.

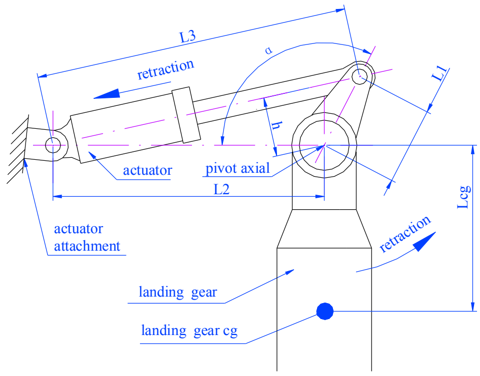

Fig.3. Landing gear kinematics

The actuator speed reduction gearbox consists of roller screw and gear pairs. Roller screw weight and volume are defined by the maximum output force. The screw rod length is defined by the maximum stroke. Larger speed reduction ratio reduces the required motor torque, but induces more complexity, size and weight on the gearbox. Gearbox and motor design must be balanced, which is different from that of hydraulic circuits.

With fixed speed reduction ratio, the gearbox size and weight are determined by the maximum load. The EMA design is not as sensitive to the stroke length as hydraulic actuators, because the rod can be lengthened to accommodate a larger stroke. So the primary target of optimization was to minimize the maximum load. However, the screw rod also contributes a large proportion of unit weight. So, minimized the product of maximum load and stroke is also important.

EMA gearbox sizing study showed that large gear ratio causes excessive size and weight penalties. For the given force and stroke requirement, a gear ratio of around 50 is reasonable. Increasing this ratio would result in large size and weight increment. And reducing this ratio would not get much benefit.

Dynamic simulation results have shown that when suitably optimized, EMA actuators with BDCM and PMSM here have similar dynamic performance. The speed reduction ratio should be tailored according to motor torque and power curves to make full use of the motor, to ensure the minimum motor design while fulfilling the retraction time requirement. Dynamic simulation indicated that for a given motor, a neutral value of gear pairs speed reduction ratio exists, under which condition motors work around their maximum power point for the majority of time. This yields the maximum retraction speed and the most efficiently used motors. Simulation activities indicated that for a given motor, the maximum retraction speed happens when the motor speed is 6500rpm to 7000rpm and the maximum load torque equals approximately two third of motor maximum torque capacity.

Because of the need of one motor operation, motors will actually be over powered. As a result the retraction time will be shorter than required.

3.8 Optimization Results

The optimized EMA design parameters are listed in table 2.

Table.2. EMA parameters

Parameters	Value
Gear ratio	52.37
Number of motors	2
Motor maximum torque, [Nm]	29.2
Motor capacity, [kW]	14.24
Normal retraction time, [s]	12.5
One motor fail retraction time, [s]	18.8

The speed to torque curve and speed to power curve of PMSM with the above parameters are shown in figure 4, in both normal condition and one motor inoperative condition.

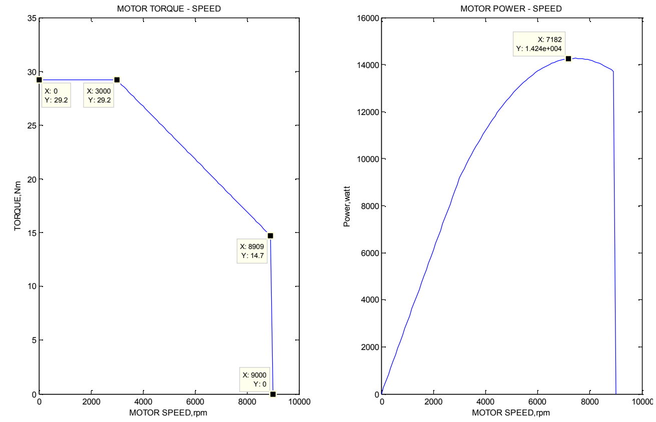

Fig.4. EMA Motor speed-torque and speed-power curves

The optimized system dynamic simulation results are presented below. Figure 5 illustrates landing gear dynamics during retraction. Figure 6 illustrates actuator speed, force and stroke during retraction.

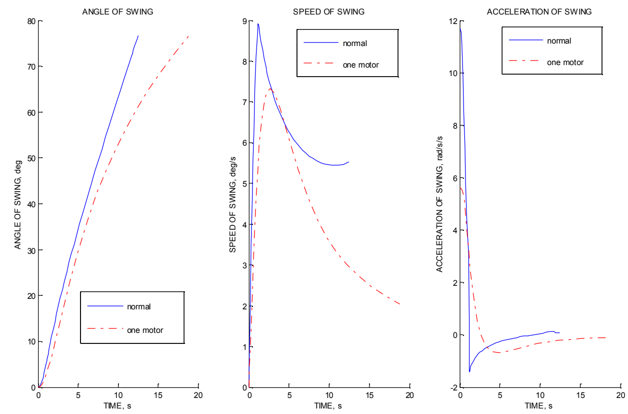

Fig.5. EMA landing gear swing dynamics

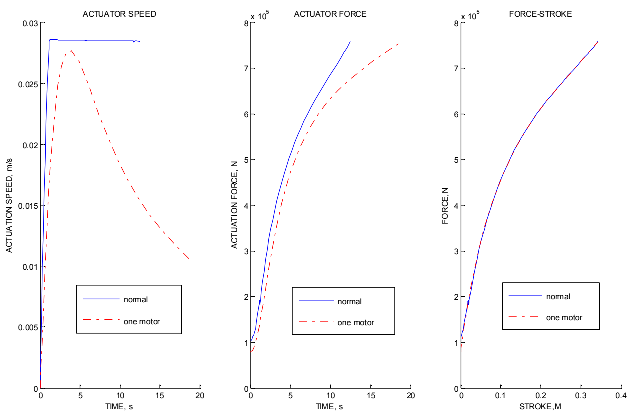

Fig.6. EMA actuator dynamics

Table 3 summarizes the dynamic performance.

Table.3. EMA dynamic performance

Parameters	Normal Operation	One Motor Inoperative
Maximum swing speed, [degree/s]	8.9	7.33
Maximum acceleration, [degree/s^2]	11.71	5.63
Maximum actuator speed, [m/s]	0.029	0.028
Average actuator speed, [m/s]	0.027	0.017
Maximum force, [kN]	757	757
Average force, [N]	550	530

The simulation results suggested that EMA has smoother dynamic performance. A sensitivity study showed that increasing the maximum motor torque yields better dynamic behavior. However, this approach increases both the power consumption and weight.

Power requirements during landing gear retraction and extension are presented in figure 7.

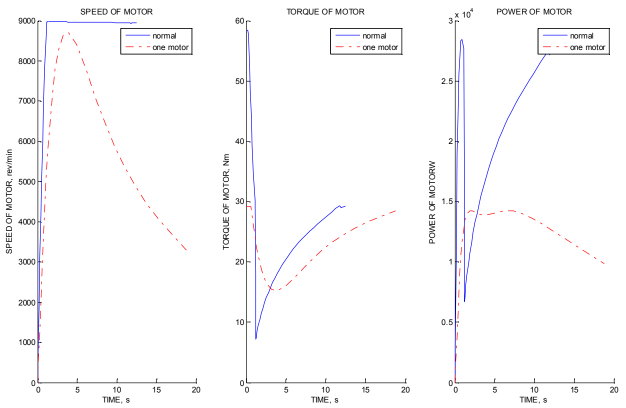

Fig.7. EMA motor dynamics

Power related parameters are listed in the table 4.

Table.4. EMA power consumption

Parameters	Normal Operation	One Motor Inoperative
Actuation time, [s]	12.5	18.8
Motor capacity, [kW]	14.24×2	14.24
Maximum output power, [kW]	14.23× 2	14.24
Motor average output power, [kW]	10× 2	12
PMSM output energy, [kJ]	261.81	235.81
Reducer efficiency	67.04%	74.43%
Motor efficiency	95%	95%
Electrical energy consumption, [kJ]	275.59	248.22
System efficiency	63.69%	70.71%

The total system efficiency is low when compared with hydraulic solutions. One reason is the low efficiency of EMA mechanical transmission, another is the over powered motor.

For EMA, landing gear extension was proved to be a difficult problem. A sink device such as resistor or capacitor has to be incorporated in the system to damp the generated electrical power. Otherwise the motor could not provide any resistant force. These devices will bring in additional weight.

4.6 Components and Weight

Motor weight and power electronics weight are calculated by their power densities and the motor power capacity. Transmission and clutch were designed to accommodate the loadings.

The EMA was mounted on the landing gear for space check. The figure 8 and figure 9 illustrate the installation conditions.

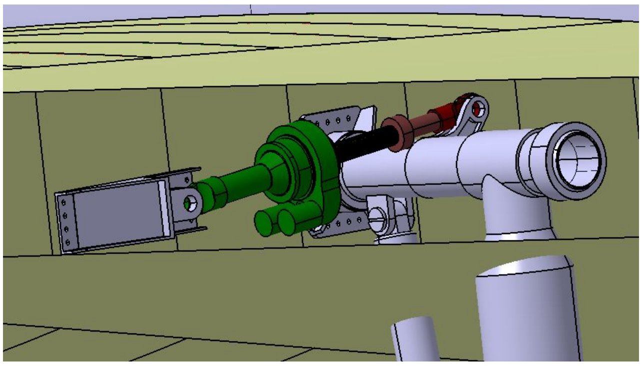

Fig.8. EMA installation-landing gear lowered

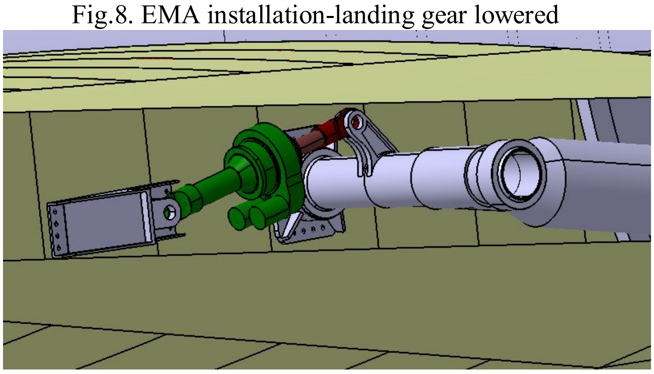

Fig.9. EMA installation-landing gear retracted

The major components parameters and weight are listed in the table 5. The transmission takes most of the weight.

Table.5. EMA component parameters

Parameters	Value
PMSM maximum output torque, [Nm]	29.2× 2
PMSM maximum output speed, [rpm]	9000
PMSM motor weight, [kg]	6.78× 2
Actuator minimum length, [m]	1.069
Actuator stroke length, [m]	0.228
Roller screw pitch [mm]	10
Gear ratio	52.37
Transmission weight, [kg]	87.67
Power electronics weight, [kg]	14.24
Total weight, [kg]	115.472

4.7 Safety, Reliability and Maintainability

The landing gear extension fault tree analysis is shown in figure 10.

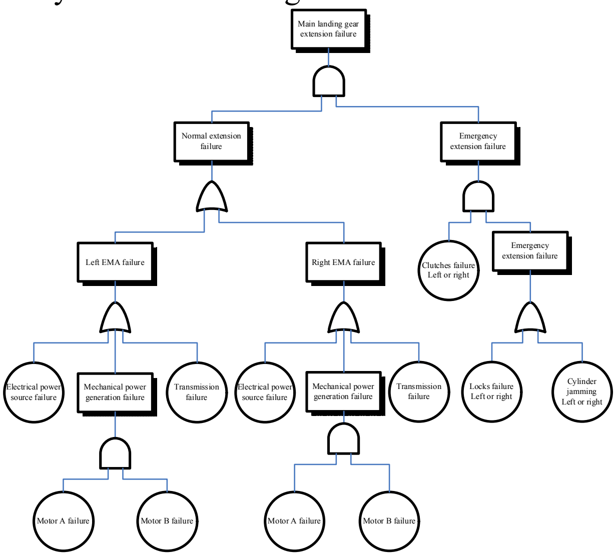

Fig.10.Fault tree analysis

From the above analysis, EMA architecture is much simpler than hydraulic systems and EHA. Two major concerns were found in the fault tree: transmission jamming and clutch failure. Jamming is the major problem affecting EMA usage on aircraft. The probability of jamming is not necessarily high, but the failure consequence is unsafe. Roller screw operating experiences have shown that jamming is most probable to happen when driven by the load. In this application, a clutch was mounted on the output rod to segregate the actuator when jamming happens. Clutch releasing operation is not reversible in the air. So activating the clutch should be regarded as a last resort.

Landing gear emergency extension is another problem of EMA. After the separation, landing gear is extended with help of gravitation. In this circumstance, no swing speed limitation is engaged. So, more attention should be paid on landing gear down locks. Also, the actuator cannot be reset in the air, which makes the landing gear free-fall a hard choice for pilots. Another problem is, after separation from the landing gear, the actuator will have a free end. Under the effects of gravity and shock, this free end can punch through the wing skin. Possible solution may include using sleeve rods or cables to provide additional support.

The EMA architecture is fairly simple, which implies that electro-mechanical actuators are more reliable in nature when compared with their hydraulic counterparts. No fluidic material is needed, so problems of leakage and fire hazard do not exist. Maintenance work on an EMA mainly involves greasing and visual checking. When compared with hydraulic solutions, EMA maintenance requirement is greatly relaxed. However, the transmission could be very complex. Also, subsidiary components like brakes and clutches tend to increase the complexity.

Calculation suggested that EMA dispatch reliability level fulfills requirement.

4.8 Discussion

In this paper, the EMA system was evaluated for landing gear actuation purpose. Firstly, an EMA system diagram was built. Then the combination of PMSM and kinematics 1 was chosen through analysis. Combined with mechanical parts - sizing activities, system parameters were decided. After that, system dynamic simulation was run to discover various performance parameters. System components were sized. Then safety, reliability and maintainability analyses were carried out.

The results showed that EMA is applicable for landing gear actuation application. Its design differs from hydraulic solutions in several aspects. The EMA system was over powered. Under normal conditions, it retracts the landing gear in 12.5s. If one of the two motors in one EMA fails, the retraction time is 18.8s. Potentially unsafe failure modes are still a concern for EMA application, but possible solutions have been proposed. Regenerative power dissipation is a potential problem. However, the EMA system is much better in terms of maintenance. EMA dispatch reliability fulfills requirement.

5 Conclusions

This report tries to answer the question of whether EMA (electro-mechanical actuator) landing gear actuation is possible, and which EMA system synergy is the best for landing gear actuation application.

Information concerning this topic was reviewed and past experiences were understood. EMA landing gear system design requirements were generated. Many possible systems were analyzed for their viability. All the major components of EMA landing gear actuation system were analyzed. Analyses were made both on aircraft level and actuation system level.

The EMA system has been designed in detail, with important characteristics such as dynamic performance and power requirements simulated. Their components are sized, and the weight of systems has been derived. Reliability, safety and maintainability of these systems are checked. Space checks of these systems showed that they did not interfere with other components.

Through this study, the feasibility of EMA landing gear actuation has been demonstrated. EMA is applicable and promising for landing gear actuation application. However, more researches and tests should be performed to make it safer, lighter and more efficient.

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