CRANFIELD UNIVERSITY

MENG FANLIANG

ACTUATION SYSTEM DESIGN WITH ELECTRICALLY POWERED ACTUATORS

SCHOOL OF ENGINEERING

MSc BY RESEARCH THESIS

Academic Year: 2010 - 2011

Supervisor: Dr. C. P. Lawson
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ABSTRACT

This project addresses the actuation system architecture of future All-electric aircraft (AEA) with electrically powered actuators (EPA).

Firstly, the information of EPAs is reviewed, and then an electro-hydrostatic actuator (EHA) and electro-mechanical actuator (EMA) are selected for further system research. The actuation system architecture of Boeing and Airbus is then presented as a conventional design where the new design concepts are also researched and the distributed architecture was proposed as another design trend. To find out which one is better, both of them are selected for further research.

The easily available data makes the Flying Crane a better choice for the case study. Stall load, maximum rate and power are the main elements for electric actuator requirements and power consumption, weight, cost and safety are the most important aspects for civil aircraft actuation systems.

The conventional and distributed flight actuation system design considered the redundancy of systems and actuators, and also the relationship of the power, control channel and actuator work mode. But only primary flight actuation control system specifications are calculated since this data has better precision and also the limited time has to be taken into consideration. Brief comparisons of the two system specifications demonstrate that the higher power actuator have has higher efficiency and distributed actuators could reduce the system weight through reduce the system redundancy with a power efficiency decline.

The electrically powered actuation system for future aircraft design is a balance between actuator number, system weight and power consumption.

Keywords:

EHA, EMA, conventional, distributed, architecture, PWR

ACKNOWLEDGEMENTS

I would like to express my sincere thanks to my supervisor, Dr. Craig Lawson, and other aerospace staff for their help in the group design program and the individual design program.

I would like also to give special thanks to my friends Du Yongliang, Ma Qinglin, and Yang Wangfeng for their help and friendship during my year in Cranfield.

And I would like to say thankyou to the Special Vehicle Aviation Institute, the China aviation industry and the China Scholarship Council for providing me with the opportunities for my study.

Finally, the last words are for my family, my mother, and my father for their support during my overseas study.

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NOTATION

Symbols

F	force
FoS	factor of safety
L	aircraft length
M	mass
P	power
q''	surface heat flux
Q	Posterior failure probability
$\dot{Q}$	heat transfer rate
R	reliability
s	actuator stroke
SR	safety reliability
t	time
T	torque
v	velocity
V	voltage
α	control surface deflect angle
λ	failure rate
η	efficiency

Acronyms

ACP	actuator channel part
AEA	all-electric aircraft
APA	amplified piezoelectric actuator
ACE	actuator control electronics
DC	direct current

EBHA	electro-backup-hydraulic actuator
EHA	electro-hydrostatic actuator
EHA-FPVM	variable pump fix motor electro-hydrostatic actuator
EHA-VPFM	variable pump fix motor electro-hydrostatic actuator
EHA-VPVM	variable pump variable motor electro-hydrostatic actuator
EHSV	electro-hydraulic servo valve
ELP	electronics part
ELACs	elevator/Aileron Computers
ELMC	electric load management centre
EMP	electro- mechanical part
EMA	more-electric aircraft
EPA	electrically powered actuator
FBL	fly-by-light
FBW	fly-by-wire
FCC	flight control computer
FH	flight hour
GDP	group design program
IAP	intergraded actuator package
MEA	more-electric aircraft
MTBF	mean time between failure
PBW	power-by-wire
PLC	power line communication
PWR	power to weight ration
RAT	ram air turbine
SECs	spoiler/elevator computers

1 Introduction

1.1 Introduction

This report investigated electrically powered actuators (EPA) and used these actuators to architecture actuation systems on future more-electric aircraft (MEA) or all-electric aircraft (AEA). Two different architectures were compared to find out which design trend has more advantage.

This chapter introduced the project background and description which showed the motivation, scope and objective.

1.2 Background

At first, aircraft were directly controlled by manpower. A power actuator was used to position the aircraft control surface since the pilot was unable to comfortably apply sufficient force to control the aircraft when airplanes became bigger and larger [1]. The most widely used power source is hydraulic. Electromechanical Actuator (EMA) has also been used in low-power functions such as trim tab driving and secondary fight control for many years [2].

For the reason of improving system efficiency, aircraft have become more electric, and main actuation principles have moved forward in the recent years with electric actuators (EMA, EHA) and piezoelectric actuators [3]. The electrically powered actuation system function and interfaces are shown in Figure 1-1. It uses 280V DC to drive the actuator and 28V DC to power the electronics.

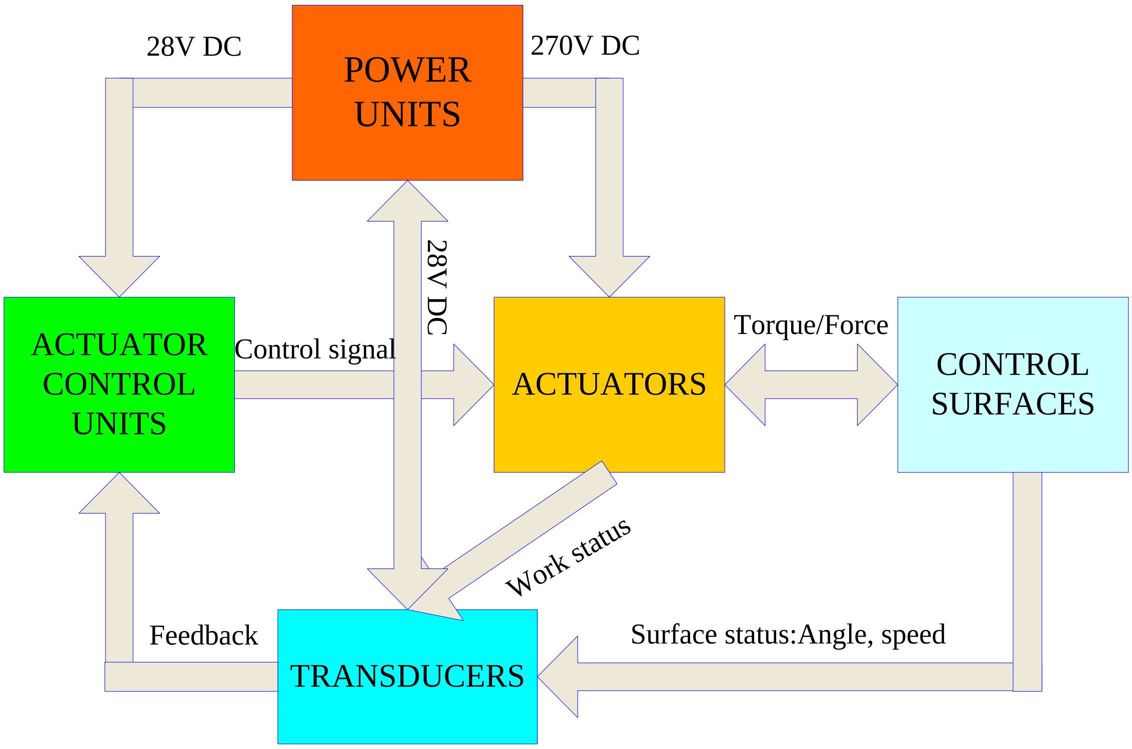

Figure 1–1 Electrically powered actuation system function and interfaces

1.3 Project Description

1.3.1 Project scope

The majority of aircraft control forces generating research focus on two directions which are using the mechanical method or aerodynamic method. The aerodynamic method is based on the Coanda effect [4] to develop circulation control airfoil. Some researchers in Cranfield University are also working on these subjects such as dual slotted circulation control actuator [5] . The other research of this method is using stream ejection to generate control force. The mechanical method is quite a traditional way of using mechanical actuators which are driven by the pilot or hydraulics or another power source to control the aircraft. All aircraft in serve use this control method. As aircraft are becoming more electrical and efficient, the way to address this is by using high-power EHA, EMA and piezoelectric actuators. Since using EPA to design a whole commercial aircraft actuation system is impossible for an MSc project because of limited time, human power and the fact that only quite limited information could be gathered due to commercial confidential reasons, the design was mainly limited to flight control surface actuation design.

1.3.2 Project objectives

The following objectives were established for the project and are reflected in the content of this report:

1. Review EPA's technologies and compare them in complexity, weight, reliability, efficiency, maintenance and thermal qualities, and after that use the appropriate EPAs for the actuation system.

2. Research the modern aircraft actuation system design strategy and the new design concept proposed from new actuator technologies.

3. Actuation system architecture with the strategies and appropriate actuators.

4. Compare the actuation system designs between performance, cost, and airworthiness and give recommendations for future actuation system design.

1.4 Summary

This chapter briefly introduced an actuation background and its state of the art stage. The project scope defined the research area and limitations. The aim of the project is to investigate new actuator and actuation architecture strategies and to find out the direction of future actuation system design. The comparison of different architecture was between performance, cost and the airworthiness certificate. Before the research started, the literature review was presented in the next chapter.

2 Review of the literature

2.1 Introduction

This chapter reviewed four kinds of EPAs, namely EBHA, EHA, EMA and amplified piezoelectric actuators (APA), as well as the actuation system design strategy and the new trend. The most suitable EPAs and design strategies were chosen for the next research step.

2.2 Electrically powered actuator

2.2.1 Electrical Back-Up Hydraulic Actuator

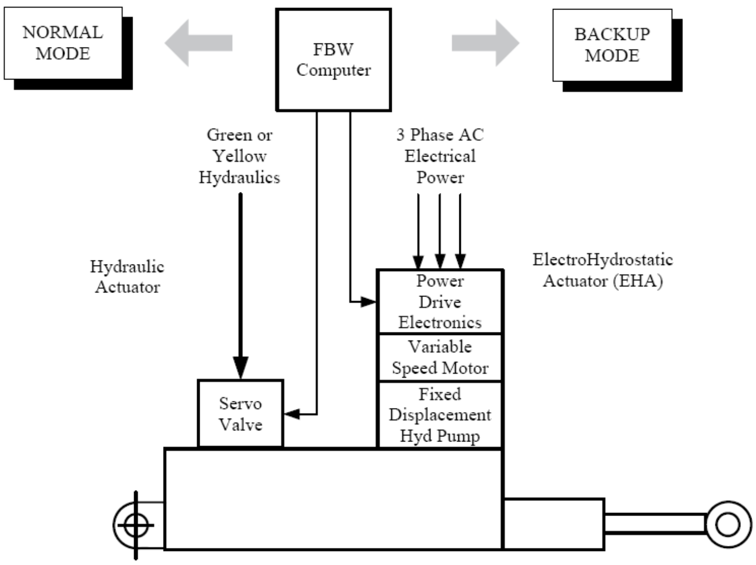

Figure 2–1 A380 EBHA diagram and modes of operation [6]

Electrical Back-Up Actuator (EBHA) is a combination of the FBW actuator and EHA as shown. The EHA just exists as a backup of the FBW actuator and it was firstly developed by Airbus and used in A380 spoiler control. The EBHA diagram and operation modes are shown in Figure 2-1.This actuator is a technology transition from FBW to power-by-wire (PBW) and therefore it is not strictly an EPA. It is good for todays aircraft design in terms of high reliability but it will not be suitable for future aircraft design since there is no hydraulic power.

2.2.2 Electro-hydrostatic Actuator

The initial motivation of EHA design was hydraulic backup and the first prototype was finished in the 1970s. EHAs have since replaced hydraulic actuators as there are more advantages in cost, weight, reliability, maintenance, etc. Also it is the key technology for MEA and AEA and so is developing widely in the world nowadays. The main diagram of this actuator is shown below in Figure 2-2. The pilot or flight computer sends control signals to the actuator via data bus, the actuator receives this data and checks it and then sends it to the electronic control part. After converting it to the appropriate analogue mode, it is used to command motors/pumps. The motor generates control force and transfers it to the control surface by hydraulic circuit.

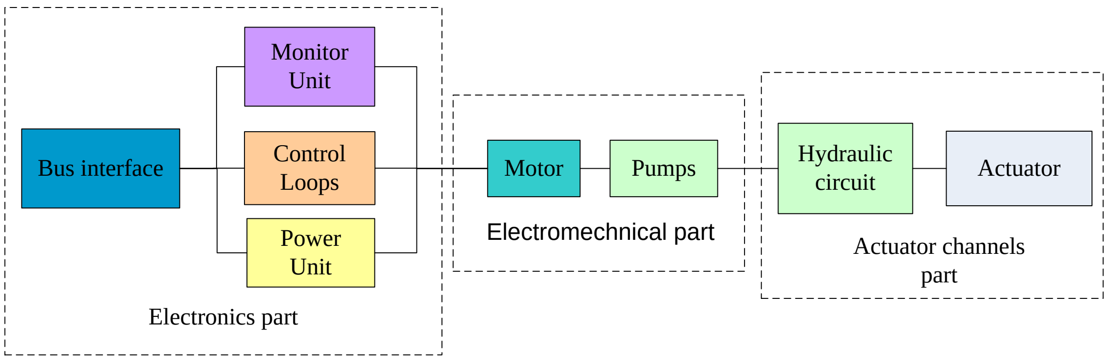

Figure 2–2 EHA diagram

Through different control components, EHA can be divided into three categories: fixed pump variable motor (EHA-FPVM), variable pump fixed motor (EHA-VPFM) and variable pump and variable (EHA-VPVM). The EHA-VPFM is developed based on FBW actuator technology. The control of them all is put through the electro-hydraulic servo-valve (EHSV) and the difference between them is the power source where one is hydraulic and the other is electricity. EHA-FPVM controls motor speed and direction and EHA-VPVM controls motor and pump flux together. EHA-VPFM promises better efficiency for high power requirements while EHA-FPVM is more adequate for low and medium actuator power levels [7]. The EHA-VPVM has medium efficiency both on high power and lower power.

Since the primary flight surface control actuator is a key component for aircraft safety, fault tolerant function must be required. The electronics part (ELP) failure rate is the highest followed by the electro-mechanical part (EMP) while the actuator channels part (ACP) has the lowest failure rate. Also ELP or EMP failure is a critical failure lead to a channel shut down. Not all failure modes associated with an ACP are critical failures (e.g., seal, leak) [8]. So there are two/three/four separate ELP and EMP set up together for fault tolerance. This tandem actuator, as shown in Figure 2-3, was tested in F16 [6] and used in B787 design [9].

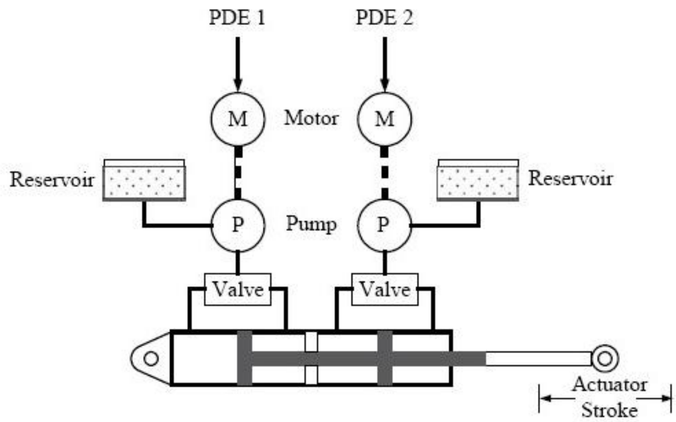

Figure 2–3 Dual-tandem actuator schematic [6]

Figure 2–4 Quadruplex EHA [10]

EHA could provide linear or rotary output through different ACP which is rod or rotary vane. However, the utilisation of rotary vane actuators on main aircraft control surface is quite limited nowadays.

2.2.3 Electro-mechanical Actuator

The principle of EMA is the same with EHA but uses the gearbox to connect the motor and actuator rod instead of hydraulics. The diagram of EMA is shown below.

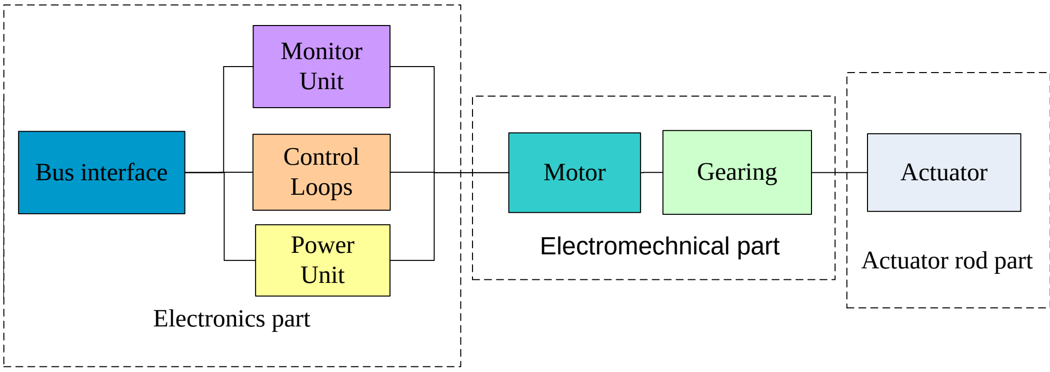

Figure 2–5 EMA Diagram

EMAs have been used for several years on low power aircraft trimming and other functions as mentioned before. High power EMA was quite big and heavy and the low efficiency was not suitable for aircraft before. However, with the technology improvement, permanent magnet brushless motors [11][12] and new materials have changed this situation. The efficiency of big EHAs has been greatly improved and its weight also can fit the aerospace and aviation requirement with fault tolerant architecture also involved in EHA design for the utilisation of aircraft control.

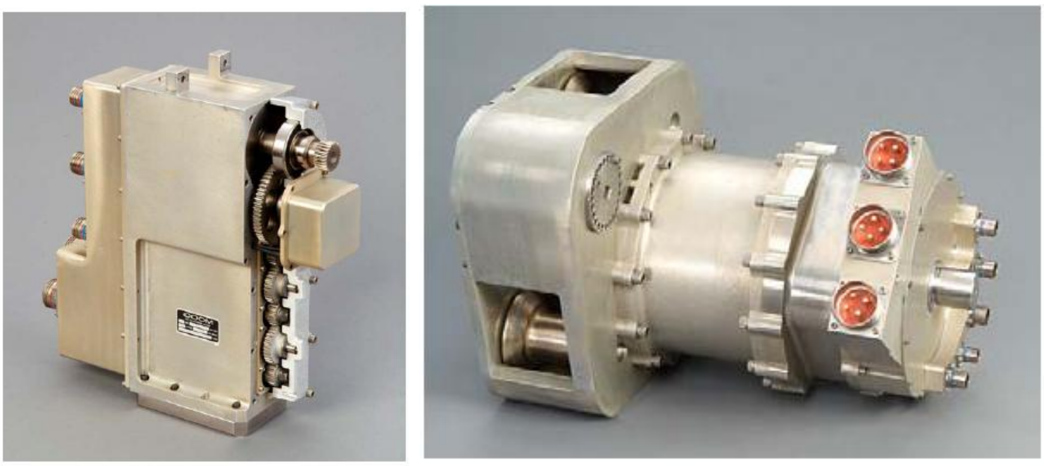

Figure 2–6 Two-Fault Tolerant, Triple Redundant Body Flap EMA [10]

2.2.4 Amplified piezoelectric actuation

The piezoelectric actuator is becoming increasingly prevalent in aircraft industries. It is based on the reverse piezoelectric effect which submits an electric voltage to piezoelectric material and then gets an output force and displacement. However, the output force and stroke is quite limited so the appropriate solution is to pile them up together if there is no material technology revolution even though the output still cannot meet aircraft control surface position requirement. Figure 2-7 gives a panoramic illustration of all kinds of piezoelectric actuators specifications.

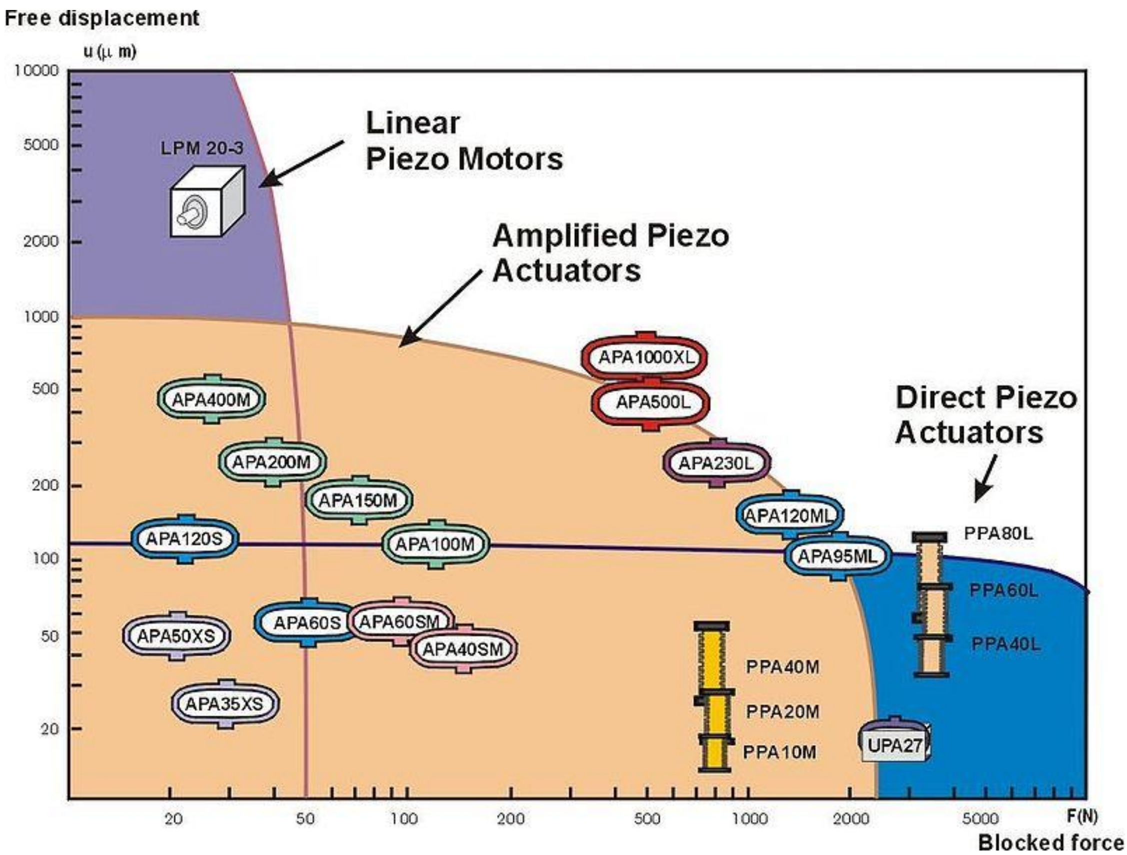

Figure 2–7 Panoramas of piezoelectric actuators [13]

2.2.5 Actuators comparison and discussion

Before using these actuators to design aircraft, the characteristics of them should be discussed as well as something should be noticed in design. The comparison shown below is all in same output level.

The most important terms of aircraft design is weight. According to Nicolas Bataille's research [14], APA could produce a stall force of 11.66kN for a total weight of 6kg (1.94kN/kg) while the EHA on A380 [15] produce a stall force of 18T for a total weight of 80 kg (2.2kN/kg). This shows APA power to weight ratio (PWR) is lower than EHA in this stage. But APA is quite a new technology while EHA is a relatively mature since it has been researched for more than 20 years and the data of APA is just a rough estimation. The weight of APA will be reduced after several years' development. The weight differential of different types of EHA is in a quite small scale; because the structures of them are nearly the same architecture. Lots of simulations and experiments [16][7] [17] have showed EMA have advantage over EHA in weight. The EBHA weight is the lowest one because it shares some hydraulic parts with the hydraulics system. But it also can be the heaviest one for different definition.

The complexity means the risk for aircraft. The EHA-VPVA is the most complex one for its control part is a combination of valve control pump cooperation control [18; 19]. FBW actuator is a mature technology so EHA-VPFM and EBHA all based on it and therefore the complexity of them is relatively low. The key technology of EHA-FPVM and EMA is motor control and this needs a lot of new research for a primary control surface using. So the complexity of it is higher than EHA-VPFM and EBHA and lower than EHA-VPVM. The technology of APA is not complex but it is not mature, so it can be presumed that the complexity of it is medium.

The requirement of civil aircraft and military aircraft are slightly different. The reliability is the most important character for civil aircraft and efficiency is at the first place for military aircraft. Fault tolerant architectures [8; 10] and healthy management technology [20] of EMA and EHA make the reliability of them higher than traditional hydraulic actuators universally. The hydraulic system removal reduced the aircraft level weight and the efficiency of the electric motor is higher than the hydraulic system. EMA is expected to have the highest efficiency but it has a mechanical jamming problem [8; 10]. EHA-VPFM is more adequate for high power requirements and EHA-FPVM promises a better efficiency for small or medium power levels [7]. A power regulator was proposed for improving the high power efficiency of it [21]. EBHA has the highest reliability but the lowest efficiency. The APA energy consumes quite low energy during stable status so it might have the highest efficiency overall.

The maintenance requirement influences aircraft operating cost and usability. EBHA and APA maintenance is quite simple and has no special needs. EHA need to fill the hydraulic liquid due to the leakage of it. EMA need to maintain mechanical transmissions parts wear. So EBHA and APA maintenance cost is relatively low and EMA is relatively high. EHA is on the medium level.

Table 2-1 Actuator brief comparison

Actuator	Complexity	Weight	reliability	Efficiency	Maintenance	Thermal
EBHA	low	low	high	medium	low	medium
EHA-VPFM	low	medium	high	High(high power)	Medium	low
EHA-FPVM	medium	medium	medium	High(low power)	Medium	high
EHA-VPVM	high	medium	low	medium	medium	high
EMA	medium	low	low	high	high	high
APA	medium	high	medium	high	low	low

The thermal characteristic is also quite important for EHA and EMA because the motor and gears generate a lot of heat and this may lead to thermal problems. However, the heat produced by APA is quite limited. EBHA could use hydraulic liquid circulation to cool it. So EHA and EMA need an extra cooling system.

2.2.6 EPA utilisation

A lot of EHA actuators have been flight tested on A320, A340, F16, F18, etc. Robert Navarro [22] tested EHA on F18 research aircraft. The test results show that EHA and actuator control electronics (ACE) performance is in compliance with the airworthiness requirement. And there are some problems that should be noticed during the design process. Actuators have slight differences between each other, and any replacement needs modification to the software. Therefore, a self-rigging and self-calibrating function should be designed. Open phase detection and power transient also need to be seriously-considered in the design process.

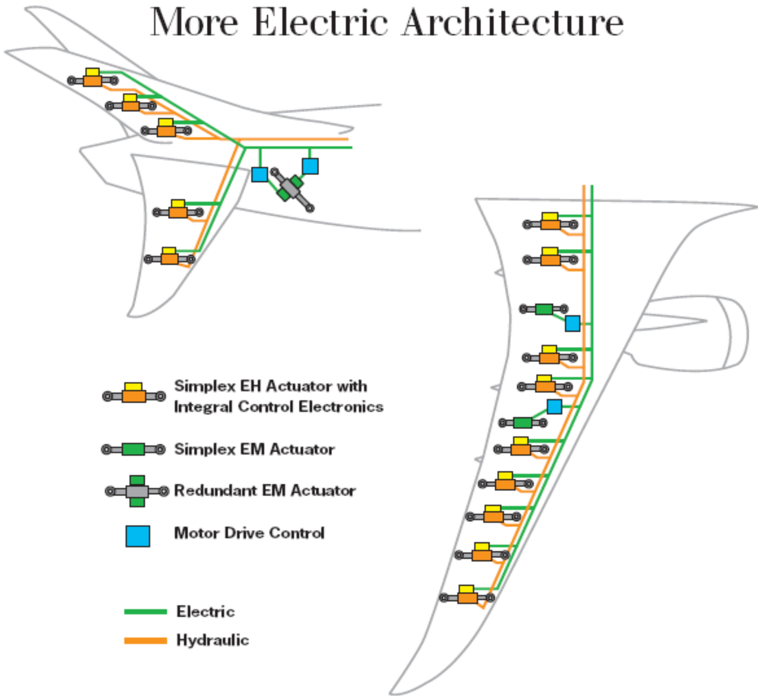

Figure 2–8 B787 actuation system architecture [9]

F35 is the first aircraft using EHA on the primary flight control system and A380 is the first civil aircraft using EHA and EBHA in the control system design. The architecture is shown in Figure 3-3. Compared to 3H, 2H+2E architecture saved 1 ton mass for primary flight control system [15]. If using 3E in the actuation system design, more mass will be reduced.

Boeing next generation aircraft B787 use a smart actuator to control primary surface. This actuator is a FBW actuator and includes failure diagnosis and health management functions. The horizontal stabilizer and mid-board spoilers employ EMAs with associated motor drive control.

2.3 Civil aircraft actuation system architecture analysis

2.3.1 A320 actuation system architecture

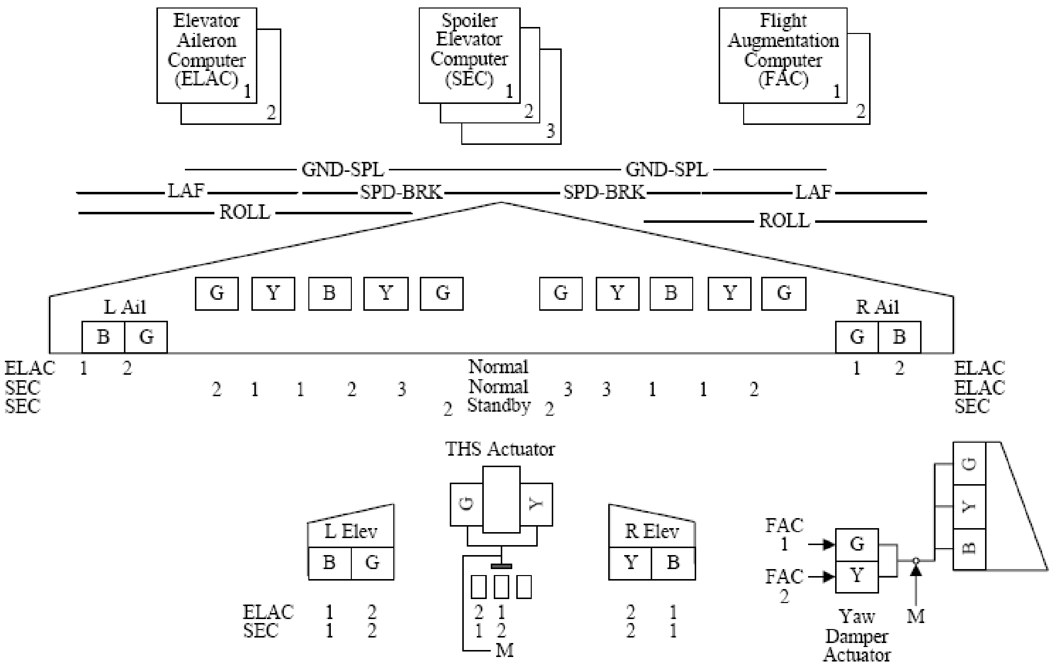

Figure 2–9 Actuation Architecture of Airbus A320 [23]

It can be seen from the architecture figure that the A320 is a triple redundancy actuation system. Power is supplied by three different hydraulic systems; blue, green and yellow. Two pairs of actuators on each aileron and one pair of central spoiler actuators work together forming a triple redundancy roll control channel. The control signals are provided by two Elevator/Aileron Computers (ELACs) and Spoiler/Elevator computers (SECs). The pitch function is given by one pair of actuators at the first channel and two actuators which work at the second and back up channel. Elevators are controlled by two ELACs and two SECs. As the first all-digital control aircraft, it also kept the mechanical channel in the most important yaw control function and horizontal stabilizer.

2.3.2 A330/A430 actuation system architecture

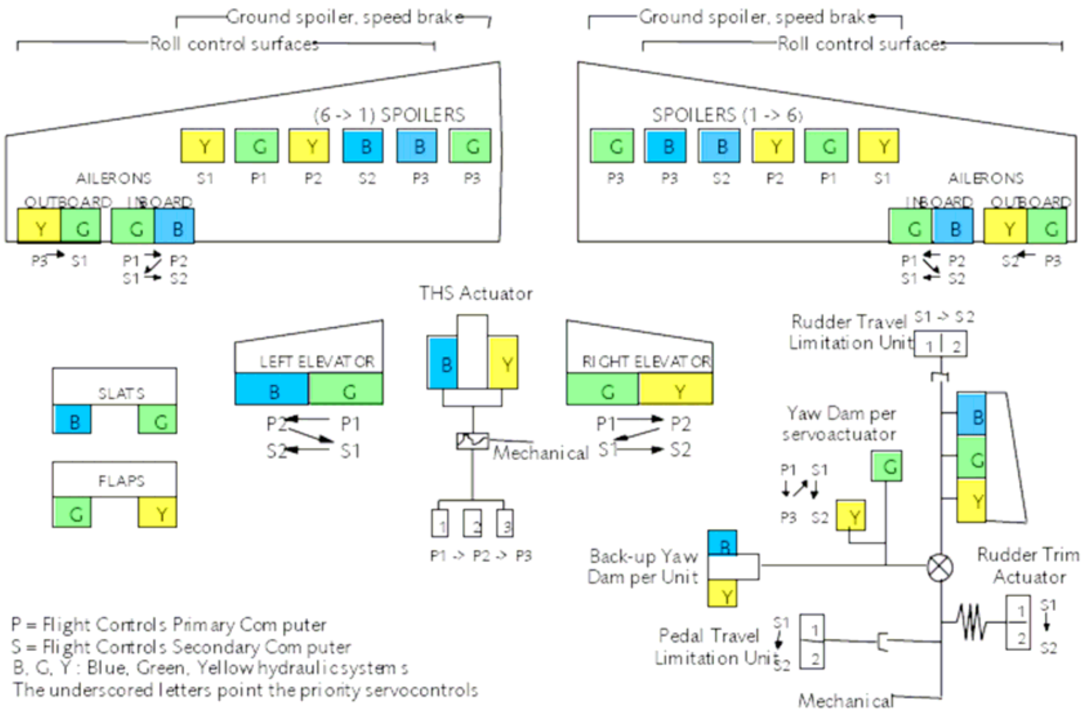

Figure 2–10 Actuation Architecture of Airbus A340 [11]

The A330/340 actuation system bears many similarities to the A320 heritage. The power system is the same as the A320. There are two pairs of inboard and outboard ailerons because the outboard ailerons are not used during high speed flight. As the A330/A340 are quite big aircraft, the aerodynamic force at the wing tip is quite high in a high speed flight scenario which will lead to wing twist. And wing twist will cause aileron control reversal. Therefore, the outboard ailerons are locked during high speed flight. However, inboard ailerons on their own cannot fulfill the roll mission in low speed flight and that is the reason why outboard ailerons exist. Airbus duplicates the control signal of inboard ailerons compared to A320.

2.3.3 A380 actuation system architecture

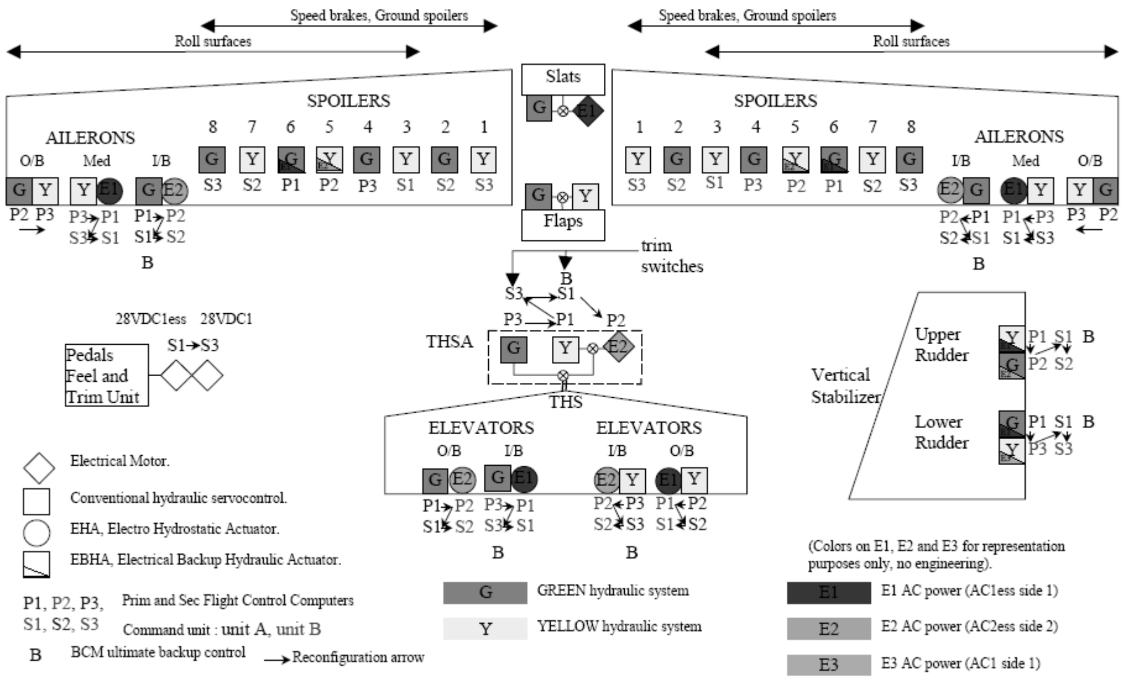

Figure 2–11 Actuation Architecture of Airbus A380 [15]

The A380 is the first civil aircraft using EHA in primary flight control systems and also the first Airbus aircraft which removed all mechanical control channels. The A380 belongs to the very large aircraft category. The control surfaces are quite big in order to provide enough control force. But big control surfaces need relatively big control forces which are given by huge actuators. Huge output actuators will result in structure design problems and by using several medium actuators to work together, this will generate force fight problems. Airbus chose to divide the big control surface into two medium ones. This strategy avoids all the problems and the A330/A340 design experience and component can also be used on it.

The actuators' power systems are 2H+2E. Each primary control actuator has two control signal channels as A330/340 except for the outboard ailerons actuators.

2.3.4 B777 actuation system architecture

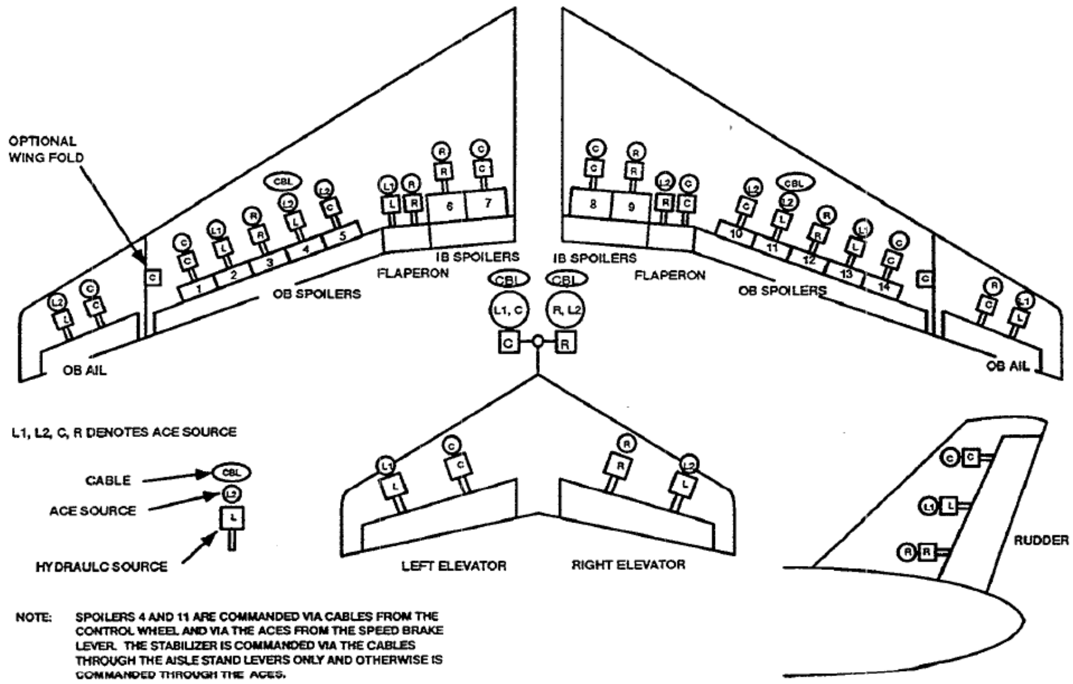

Figure 2–12 Actuation Architecture of Boeing 777 [24]

Boeing777 is the first Boeing Fly-By-Wire (FBW) aircraft. The actuation system is a hydraulic powered actuator control electronics (ACEs) controlled FBW actuators system. The power supply is the same as Airbus. Instead of using the flight control computer to control the actuator directly, it added ACEs between them. Each actuator only has one control signal except for two spoiler actuators and two horizontal stabilizer actuators.

2.3.5 Sum up

The conventional actuation system design character is summarised and shown below:

1. Each aileron and elevator have two actuators and the rudder has three actuators.

2. The main control function roll, pitch and yaw power supply have triple redundancy.

3. The main control function roll, pitch and yaw control signal have triple redundancy.

4. The actuators are divided and work at triple redundancy on each function.

5. Each power system power has nearly the same amount of actuators which means the power sources have the same amount of output.

2.4 New design trends

2.4.1 Remote concept

The remote actuator control concept comes from the Boeing777 [13] aircraft flight control system. ACEs are used for actuator control for the advantage of function separation. Pilots could control the aircraft in direct mode when all

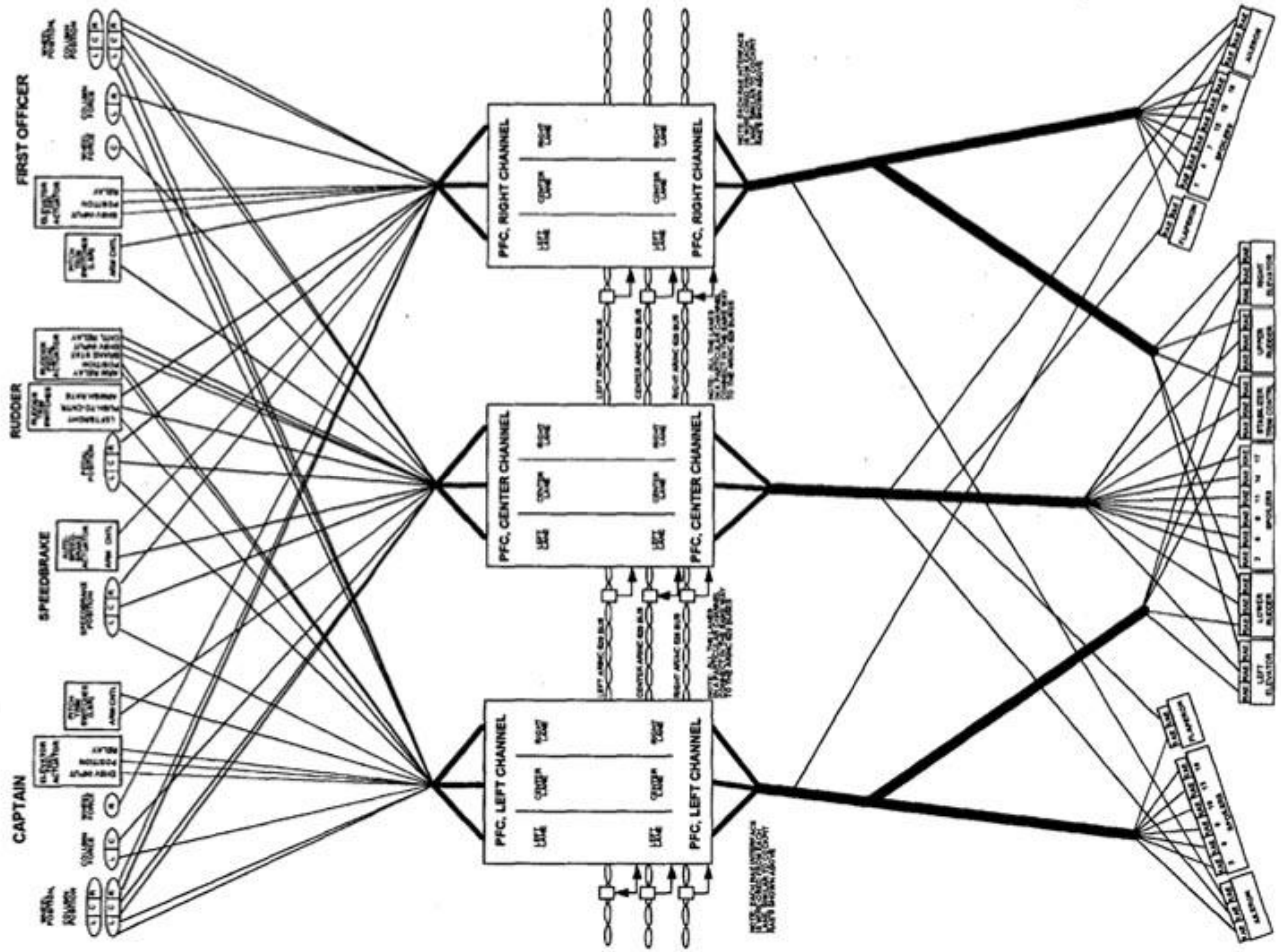

Figure 2–13 B777 remote actuation system control architecture [25]

flight control computers have failed. However, ACEs also introduced disadvantages such as around 15-19 wires are required for the actuator to communicate with ACEs and the high bandwidth's actuator will lead to more complex actuator control loops.

Erik L. Godo [25] proposed a remote actuation control system design based on B777and it shows a tremendous weight and cost saving. Three actuators are located on each primary control surface to keep the triple redundancy actuators working well and reduce the electronic parts used to monitor actuators. Moog engineer John O'Brien [26] researched using power line communication (PLC) to design a flight control system. His research shows that PLC can save weight significantly but lots of new hardware and software would need to be developed.

2.4.2 Distributed concept

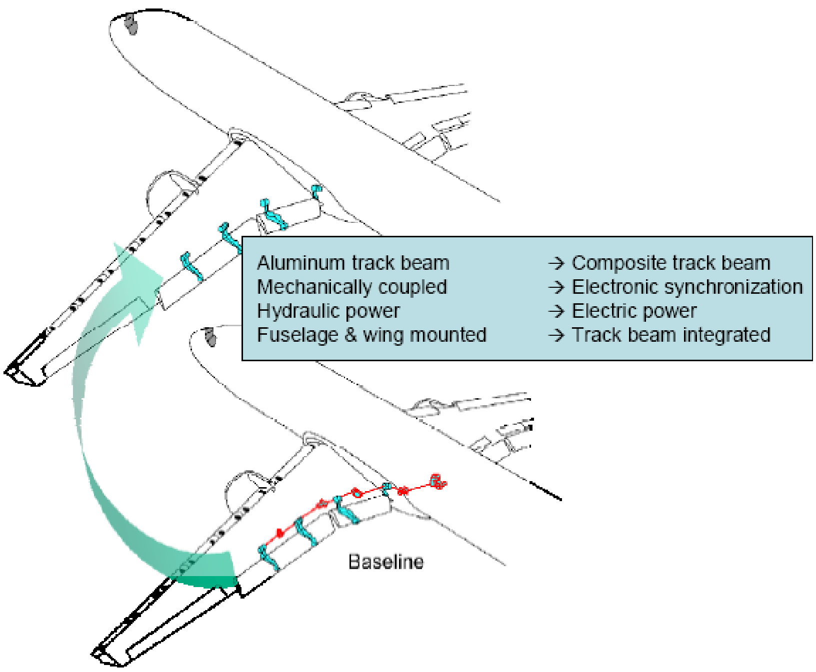

Figure 2–14 New track integrated Electrical Flap drive system [16]

Airbus is researching distributed flap actuation system technology to substitute the centralised flap control system [27]. The new flap system can be used for roll trim and roll augmentation. The weight of the actuation system is greatly reduced because the connection part between each joint is removed. And the cost is reduced also. By reason of a simplified assembly, the maintenance efficiency is improved. The most challenging part of the distributed actuation system design is the control law design.

2.4.3 Distributed effectors concept

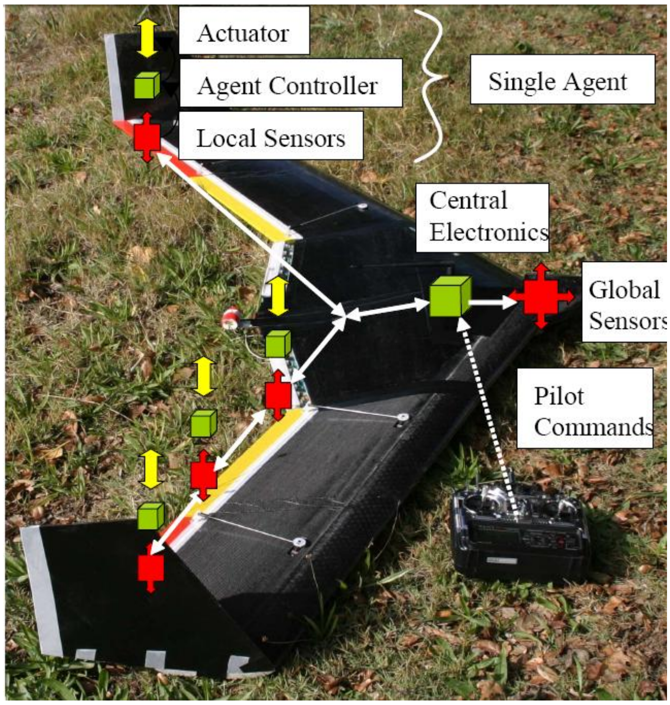

Figure 2–15 distributed flight architecture [28]

The distributed effectors concept is a combination of mechanical control and aerodynamic control. It uses small simple actuators to affect the flow field to generate control force. And also some others use actuators to morph the airfoil slightly to generate control forces [29]. This kind of design can greatly reduce the actuator weight and power consumption. Furthermore, quite small drag is involved. However, this is a fairly undeveloped technology, and before it is used commercially, a lot of experiments will need to be carried out to test every flight case and the influence of other systems. Figure 2-15 shows a miniature-trailing edge effecter unman demonstrator.

2.4.4 Sum up

All the new design trends show more actuators are required on each control surface. The remote concept proposed three actuators on each control surface for the reason of reducing electronics weight. The distributed flight control system design has two meanings, which are the distributed flight computer function design which means remote control as suggested in 2.4.1 and the distributed actuation system design which means using more small actuators on each surface to replace the big actuators. Airbus is developing the use of two actuators on each flap to substitute the centre motor, and this shows the distributed concept. Additionally, the new actuator technology also supports this such as distributed effectors concept design. This also shows the distributed actuation system will be a potential choice for future aircraft design.

2.5 Summary

The information presented in this chapter highlights the EPA review, comparison and implementation. And also the conventional aircraft actuation system characteristics and new actuation system design trends.

The EHA-FPVM has higher efficiency and also reliability, so it is a better choice for primary flight control systems. EMA has the highest efficiency but it does have inherent problems so the best choice is secondary flight control surfaces driving.

The Boeing and Airbus aircraft actuation system architecture have been investigated and the same design points have been summed up. The new design concepts have also been reviewed. For future AEA actuation system architecture, there are two directions. The first one is the conventional one which substitutes FBW actuation system hydraulic actuators with EPA. The other one is using the distributed concept to design an actuation system.

3 Research methodology

3.1 Introduction

Chapter 2 reviewed all EPAs and summarised conventional actuation system architecture characteristics and new design trends. In addition, two system architecture strategies were presented for further research. To find out which strategy has more advantages, the method and design flow was developed in this chapter.

3.2 Research design

The simplest way to find out which design strategy has more advantages is to compare the design results of them in the same case based on the same aircraft and meeting the same requirements.

For the conventional actuation system design, it is the utilisation of characteristics summarised in Chapter 2. For the distributed actuation system design, the first thing is to determine the number of actuators on each control surface. To simplify the problems, three actuators on each aileron and elevator was selected for further research, and also two actuators on each flap were used to replace centre motors.

Before the design starts, the design case should be defined. For the representative reason, the dominant aircraft in future markets is a better choice. After the aircraft was selected, all requirements for the system design are analysed. The requirement analysis is to focus on airworthiness regulations [30], specification design criteria [31] and customer requirement. Then the two actuation systems have been designed based on the requirement, and finally the main parameters of the two systems were compared to find out the advantages and disadvantages between them.

3.3 Comparison principle

The comparison of the two systems is between the same requirement areas. The requirements of a civil aircraft design mainly have three aspects which are performance requirement, airworthiness requirement and customer requirement.

And the key characteristics of performance are reliability, weight, power consumption, and heat rejection. These four parts represent the most important characteristics of aircraft since the principle of commercial and industrial aircraft design is to minimise cost and maximise value [32] . Cost is a design parameter coequal or superior to other design attributes. Aircraft designers always struggle to trade reliability versus cost and performance versus cost.

The most important requirement of airworthiness is safety and the most important aspect of customer requirement is cost.

Detailed analysis of them will be shown in Chapter 4.

3.4 Design process flow

The design process flow is shown in Figure 3-1. Aircraft study case defines and requirement analysis is started at first. The two separate actuation systems with distributed and conventional concepts will be designed later. The final stage is the system comparison.

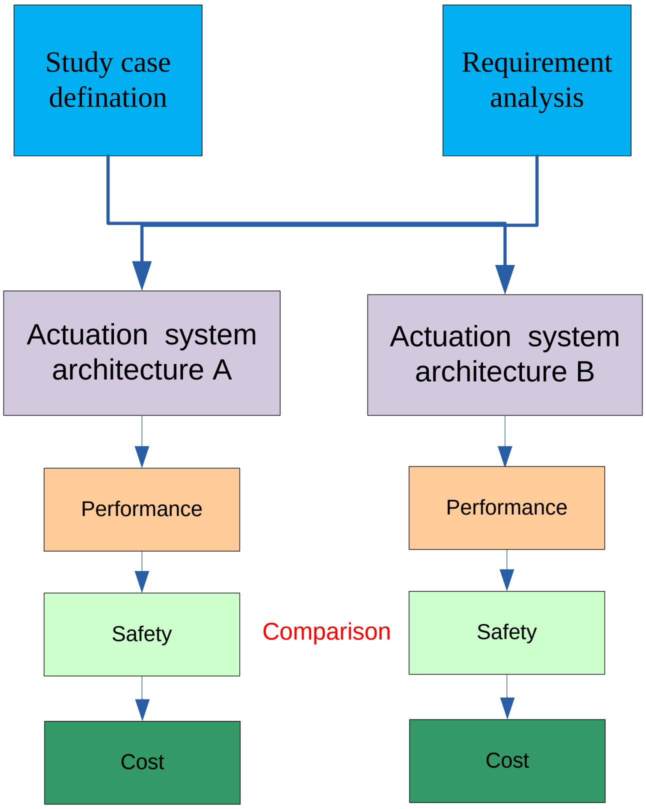

Figure 3-1 Design process flow chart

3.5 Summary

This chapter divided the whole research into three stages. The first stage is information gathering and system definition, the second stage is system architecture and the final stage is system comparison. The main comparison characters are between performance, airworthiness and cost. The next stage of research in Chapter 4 is the case study.

4 Case study

4.1 Introduction

After the design process flow chat and comparison aspects have been set, the next step is to define the aircraft used for research. The dominant aircraft in the future was selected as the research aircraft. , The data from the same size aircraft currently serving is used for an approach. Compare these aircrafts to choose one for further research.

4.2 Aircraft selection

This project evaluated the PBW actuators and uses these actuators to design a new generation aircraft actuation system. Therefore, this aircraft is a new designed aircraft to substitute the mainline carriers.

The 100 to 149-seat segment aircraft are the cornerstone in the development of the mainline carriers of today. Bombardier forecasts that nearly 60% of today's 100 to 149-seat fleet will be retired by 2027 [33]. New generation aircraft, specifically designed for this segment will boast superior economics, comfort, lightweight design and built-in operational flexibility. These new designs will advance the retirement of older aircraft, such as B737 and A320 etc, and stimulate demand for new services using aircraft of this capacity.

Consequently, the best approach of future aircraft is the A320 and B737. Also, the A320 had been chosen for case study aircraft by Pointon [34] and Bataille [14]. The data of the A320 is more easily available than the B737. Therefore, the A320 is a better choice for further research. And compared to another candidate, Flying Crane, which is a medium sized aircraft designed in the author's group design progress (GDP), the data of the A320 is more reliable. But although the data of the A320 can be accessed easier than the B737, it is still a commercial aircraft. Some key data is also kept commercially secret and if it was chosen for the case study, these data can only be estimated. The data of Flying Crane is easy to get but the accuracy of it may have some problems. Considering it was used for two kinds of actuation architecture comparison, the error of it has a limited influence to the final result. Finally, Flying Crane was chosen as the case study aircraft.

Figure 4–1 Flying Crane

4.3 Case Study Aircraft Definition

The Flying Crane is a twin-engine wide-body traditional aircraft designed to replace the A320 and B737. It is an all electrical aircraft without engine bleeding. The basic specification is shown in Table 4-1.

Table 4-1 Flying Crane specification [35]

Parameter	Data	Unit
Passenger Capacity	128 (mixed class)/ 150 (single class)	/
Range	2000	nm
Maximum Take-off Mass	64582	kg
Operational Empty Mass	37844	kg
Design Payload	12160	kg
Maximum Payload	17000	kg
Design Fuel Capacity	14978	kg
Maximum Fuel Capacity	17560	kg
Cruise Speed	0.78	M
Cruise Altitude	39000	ft
Service Ceiling	43000	ft
Fuel Tank Configuration	one centre tank, two inboard wing tanks and two outboard wing tanks	
Engine	Geared Turbofan (GTF) engine	

Table 4-2 Flying Crane control surface specification [36]

Control surface	No	Deflection Angle (°)	Torque (KN.M)
Elevators	2	±25	10.19
Rudder	1	±20	8.96
Ailerons	2	±20	3.17
Horizontal Stabilizer	1	±12	5.94
Flaps	2	40	1.39
Slats	10	25	0.98
Spoilers (inside)	2	50	3.34
Spoilers (outside)	4	50	1.79

Table 4-2 lists the control surfaces of the Flying Crane and the deflect angle. The torque of each surface is collected from Yang Yongke's [36] calculation.

4.4 Case Study Assumptions

The aircraft performance, size and configuration data collected from other members' GDP reports are all assumed correct. And control surface optimization was not considered in this project. The secondary flight control surface stall load estimate is difficult to work out and there is still not a better method to solve it. The engineers get these data by wind tunnel experiments. This cannot be given to a student GDP at this stage. And also to avoid the repetitive work, only the main flight control system characteristic will be calculated, the second flight control system only will be designed and no specific performance calculation proceeded.

4.5 Summary

This chapter investigated the dominant aircraft in the future aviation market. The medium sized aircraft selected as case study aircraft is the Flying Crane which is designed in the author's GDP and has more detailed data than the A320 and B737. After the Flying Crane was selected, the actuation system design requirement was analysed which is discussed in the next chapter.

5 Design requirement

5.1 Introduction

After aircraft selection, the system requirement should be analysed before system architecture. The requirements come from three aspects: performance, airworthiness and customer. As discussed in Chapter 2, 4, the weight, power, power consumption, safety, and cost are all the most critical aspects for aircraft, so the other requirements besides this will be discussed in this chapter. The priority of each parameter was then estimated. The high priority parameters will be used for further research.

5.2 Performance requirement

Since there is no published EPA actuators design information due to reasons of commercial confidence and quite a few aircrafts used that, so these requirement are basically derived from hydraulic actuators requirement.

5.2.1 Stall load

Stall loads are based on the maximum aerodynamic hinge moment predicted at any point in the flight envelope. Using this number means the pilot can operate aircraft at any flight situation and prevent two big output forces which would damage structures. According to different architecture the stall load has three parts:

Minimum required output thrust.

Minimum single-system thrust.

Maximum static-output thrust.

The stall loads of the Flying Crane were calculated by a second cohort and shown in Table 5-1 which will be used in the next step calculation.

Table 5-1 primary control surface stall loads

Control surface	No	Torque (KN.M)
Elevator	2	10.185
Rudder	1	8.964
Aileron	2	3.168

5.2.2 Maximum rate capability

The required actuator rates are usually defined at no-load conditions and about 60 to 70 per cent of the stall load, for two-system and single-system operation. It has to have satisfactory pilot-handling qualitiesas well as the requirements of automatic flight control systems. While it is in this state of the art design stage both actuator factories and flight quality designers cannot provide this requirement. Therefore, the author has to estimate this number based on civil aircraft hydraulic actuators. Later in the chapter will provide a detailed estimate progress.

5.2.3 Frequency response;

For the handling quality sake the actuator must achieve the required performance for the specified range of frequencies and amplitudes. It is invariably intended that the characteristics are as close to linear as possible.

The basic first-order response is the primary factor in determining the actuation-system response bandwidth. The higher-order terms cause variations from the basic response, and can result in undesirable resonances which amplify response at some frequencies. Such linear properties will be evident throughout the broad mid-range of amplitudes.

In specifying the required performance it is necessary to set frequency response gain and phase-lag boundaries which must not be violated and meeting these criteria will determine the feedback control gain. Variations from linearity occur throughout the working range, but these are normally small enough to be acceptable; it is at extremes of input amplitude that significant deviations from linearity become evident on the frequency response.

5.2.4 Dynamic stiffness

The criteria usually specified for dynamic stiffness are based on the need to avoid control-surface flutter. There are no specific criteria set out for the lower frequency range associated with flight control system design, as the impedance which is present in the basic design is generally sufficient and no design constraints need be imposed.

At the higher frequencies associated with flutter it may be critical that the actuation system contributes enough stiffness, in conjunction with the stiffness of the backup structure, to the control-surface rotation mode so that the flutter-speed margins are met. The margins with a fully operational actuation system will be greater than when failures are present.

The overall dynamic stiffness includes the effects of attachment and output structural stiffness. Here is a picture of typical impedance-response boundaries.

5.2.5 Failure transients

Actuators failure transients' requirements are defined as boundaries on the ram-to-body displacement following the occurrence of the failure. Different classes of failure must be considered, including electrical-lane failures, hardover failures (for example, one lane of a multilane electric motor demands full current, requiring the other lanes to compensate, until the failure is confirmed and isolated, as well as to control the actuator) and power-supply failures. The actuation system is assumed to be in a state of steady equilibrium prior to the failure, with or without a steady applied force. The class 1 boundaries apply to a first failure or a second failure if the first failed lane has been switched out. The class 2 boundaries apply to a first electrical power failure and subsequent electrical control signal failures. Failure transients are particularly affected by intersystem force fight and actuator motor characteristics, requiring a high-fidelity actuator model to predict results accurately.

The main requirements for actuator specification are stall load, maximum rate capability, frequency response, dynamic stiffness and failure transients. The stall load is the maximum output force which is determined by control surface torque. Maximum rate capability is a requirement for flight quality, if the rate of actuator is quite low the control response of aircraft will be slow and the aircraft will be quite hard to control. This figure can be obtained from the flying quality designer. Frequency response defined the response speed and the accuracy of the actuator. The dynamic stiffness is a requirement from control surface structure. If this number is too low, it will cause control surface flutter. In EPA, failure transient means it loses its power or control signal in a relatively short time. It has a significant influence in flying quality and safety.

5.3 Airworthiness requirement

For a civil aircraft, it must be in compliance of the airworthiness requirement. And the main market is China, so first we consider China Civil Aviation Regulation 25(CCAR 25). After reading through the CCAR25, the author's actuation system has to comply with these requirements below.

5.3.1 CCAR-25.671 General

This is the original form mechanical control system requirement. Mechanical control passes control signals through pulley cables or rods which will lead to lots of friction force and has the possibility of getting stuck somewhere in the transfer process. The control force becomes bigger and bigger and consequently over human force range as the aircraft become bigger. This regulation is designed to prevent this kind of situation which will lead to hazard accidents. However, the Flying Crane control system is electrically signalled and so does not have these kind of problems. EHA and EMA are independent actuators. Actuator Control Electronics (ACE) receive signals from flight control computers and transform digital signals to analogue signals which are then passed to the actuator. This process will not involve any friction or sticking. Therefore, this regulation is not applicable for a Flying Crane actuation system. The only control unit in the Flying Crane need to consider this side-stick as because of limited human source, nobody is in charge of that part.

The main components of the actuation system are actuators cables and ACE. In order to avoid misassemble every cable and ACE and ACE port will first use the prevent misinsertion method to design. Different actuators use different cables and combine cables together to reduce the chances of misassemble.

The actuation system is a relatively important system for flight safety, especially now that no aircraft is designed fully with PBW. Therefore, the design process should contain both analysis and tests to ensure safety.

5.3.2 CCAR-25.672 Stability augmentation and automatic and power operated systems.

This plane doesn't have damper actuators for stability augmentation. It uses FCC to control surface actuator to simulate this function. Therefore, the author does not need to consider this point.

5.3.3 CCAR -25.675 Stops

In the hydraulic actuation system, by using control the servo-valve holds the pressure in the hydraulic actuator to stop surface movingusing stroke to limit the surface motion range. EHA has an integral hydraulic package so it uses the same strategy to achieve the stop function, while it is a little difficult for EMA. There are two methods in engineering. First: using a ratchet wheel and pawl mechanism. When the actuator starts rotating it only runs in one direction and after it stops the ratchet wheel and pawl mechanism lock it. Another method is using the brake lock. Unlock the brake lock and run the actuator and then lock it after it has finished. These two methods both have disadvantages.

Consequently, the stop function of the EMA needs to be considered seriously in the design process.

5.3.4 CCAR-25.681 Limit load static tests.

The components needed to satisfy this requirement is the actuator and attachment. The actuator stall load required bigger than maximum aerodynamic load. The attachment structures have to bear the force of the actuator. And also stiffness of those structures needs to be strong enough to prevent structure morphing and oscillation. These aspects all need to be tested by experiment.

5.3.5 CCAR-25.683 Operation tests

This regulation is for the mechanical control system whereas the electrically signalled system will not have this problem. Instead of this it will have problems such as frequency response and response rate, etc. This has to be considered during the design process.

5.3.6 CCAR-25.685 Control system details

The Flying Crane is FBW flight control system, so it will not have this problem.

5.3.7 CCAR-25.697 Lift and drag devices, controls

The actuation system must have the function to maintain lift and drag devices at certain positions given by stability and control performance requirements.

To prevent inadvertent operation, the ground spoiler and other control surface which will not be used in flight should be locked in flight and other mechanism used to limit the surface deflection angle.

The actuation system must have a high frequency response to satisfy the flight quality requirement.

The actuation system must have the ability to retract the high lift devices at any speed below V_F + 9.0 (knots).

5.3.8 CCAR-25.701 Flap interconnection

According to different flap or slat control designs the flap or slat must account for the applicable unsymmetrical loads or the motion of flaps or slats on opposite sides of the plane of symmetry must be synchronisedas well as the one side engine failure and one side flap or slat jamming.

5.4 Customer requirement

The customers consider cost as the highest priority. How to reduce the cost and maintenance time is the only request. The aircraft cost includes design cost, manufacture cost and operating cost. For an actuation system, the cost is made up of product price, installation cost and operating cost while in aircraft lift time, the maintenance is the biggest part. The failure actuator not only leads to repair costs but also the aircraft cannot be used for flying to create profit.

The reducing of actuation system mass and power consumption will reduce the fuel consumption and increase the load capacity. These also can reduce the aircraft maintenance costs and increase the profit.

5.5 Summary

This chapter reviewed all actuation system requirements in three categories which are specification, airworthiness and customer.

For the performance load, stall load and maximum rate is the dominant requirement. With these two factors, the power of the actuator and power consumption of the system can be obtained. The frequency response, dynamic stiffness and failure transient requirements and other parameters are too detailed for this design stage.

Table 5-2 Specification priority

Category	Specification	Priority
Performance	Stall load	H
	Maximum rate	H
	Power consumption	H
	Power	H
	Weight	H
	Size	L
	Thermal	H
	Frequency response	L
	Dynamic stiffness	L
	Failure transients	L
Airworthiness	Safety	H
	Design requirement	L
Customer	Cost	H
	Reliability	H

Priority scale: C = Critical importance, H = High importance, L = Low importance

The airworthiness requirements are to make sure of the aircraft's safety. For the actuation system, the highest safety is the main requirement. No design requirement suit for this stage.

Reducing system mass and failure rate and increasing the efficiency will make the aircraft more competitive which will attract more customers. Therefore, these parameters should be noticed at the conception of aircraft design.

6 Conventional Actuation design

6.1 Introduction

After the requirement analysis and aircraft selection, this chapter begins with the conventional actuation system design of the Flying Crane. It was designed based on different Airbus and Boeing Flight control actuation system architecture evaluations, as discussed in Chapter 2. After that, reliability, power, weight and thermal were calculated for next step research.

6.2 Flying Crane actuation system architecture

6.2.1 Actuator layout

As discussed in Chapter 2, triple redundancy EHA-FPVM was chosen for the primary control system because of its high reliability. EMA was selected to design the secondary flight control system because of the high efficiency.

For the primary flight control surface, following the Boeing and Airbus design, the Flying Crane is also a triple redundancy control system. The roll function is performed by ailerons and the middle two spoilers. The aircraft is controlled by ailerons at normal situation, spoilers are used for control when the speed is quite high which means the ailerons are generating too many control forces and also a supplement for when speed is too low that the aileron cannot generate enough control force. There are two actuators located on each aileron forming two channels. And the middle two spoilers are the third channel. The pitch is performed by elevators which are used for short-term pitch control and the horizontal stabilizer is used for long-term aircraft trimming. Horizontal stabilizers also can be used as pitch control in emergency situations. Elevators have the same two actuators, each surface structure with aileron, while using the horizontal stabilizer as the triple redundancy. Three actuators are set on the rudder of Boeing, Airbus and other aircraft. These surfaces are all driven by EHA-FPVM.

The secondary flight control system has a less severe influence than the primary flight control system. So EMAs are used on the slat, flap, spoiler and horizontal stabilizer control. Slat and flap are using centralised control as conventional design and one actuator on each inner and outer spoilers. Since the horizontal stabilizer is fairly important for aircraft trimming, there are three actuators located there.

6.2.2 Power source

The power of the Flying Crane is provided by two engines, ram air turbine (RAT) and fuel batteries. The left engine power generator supplys power through electrical load manage centre 4 (ELMC4) to actuators and the right engine power generator supplys power through ELMC5. The RAT generator power is managed by ELMC6. These three energy parts formed a triple redundancy power supply.

RAT power can only used as a backup power, so the normal control power is from two engines. Each actuator of rudder and horizontal stabilizer just uses one of the power sources separately. The ailerons are powered by two engines for normal flight mode and one pair of the middle spoiler powered by RAT. This design keeps triple power redundancy of roll control. Although horizontal stabilizers can control aircraft pitch, the speed of it is quite low. Therefore, ELMC6 was used instead of one ELMC5 to form a triple redundancy. When two engine failures occur, only the right hand elevator can be powered by RAT. The roll moment generated by elevator deflection can be balanced by spoiler control. For the secondary flight control system, considering the power source and balancing each generator output, the power was set, as shown in Figure 6-1.

6.2.3 Actuator control

The Flying Crane flight control system was designed based on Boeing 777 since the FCC and ACE function separation of it shows a lot of advantage in safety and reliability. Four ACEs provide the interface between the FBW analogue domain (crew controllers, EHAs and EMAs) and the FBW digital domain (digital data buses, primary flight computers, auto flight data computers, etc.) and also provide excitation and demodulation of all actuators. The transducers located in EHA and control surfaces measure the status of actuators and control surface then transfer them to ACEs. The ACEs convert analogue data to digital data and then feedback to the flight control computer to build a control circle.

The connection design between ACEs and actuators' principle are nearly the same with power source design. Firstly, triple redundancy should be promised in all three axes. And then the power consumption balance and control balance. The power requirement for each engine should be nearly the same and the task of each flight control computer should be equal. According to these principles the actuation system control interface architecture is shown in Figure 6-1.

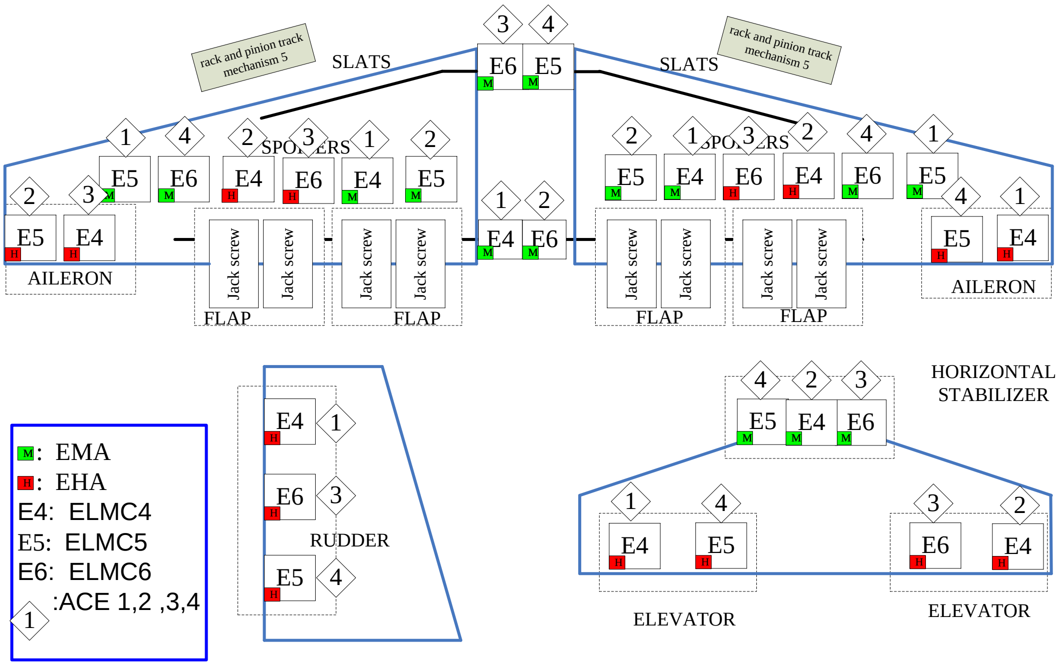

Figure 6–1 Conventional actuation system architecture

6.2.4 Actuator work mode

The work mode of each control surface actuators are active-active mode [17]. The upper and lower rudder actuators work together on normal mode. Both of the actuators can drive the rudder individually. This means the rudder can be controlled without performance deduction when one engine fails. The other actuator work mode and peak power also complies with these rules.

Table 6-1 Actuator work mode

Control surface	Actuator	Work mode
Aileron	Left outside	Active
	Left inside	Active
	Right outside	Active
	Right inside	Active
Elevator	Left outside	Active
	Left inside	Active
	Right outside	Active
	Right inside	Standby
Rudder	Upper	Active
	Middle	Standby
	Lower	Active

6.3 Safety reliability estimation

The most important aspect of the flight control system is safety. Before safety reliability calculation, the EHA failure rate should be calculated, and then using the flight control system FMES model to estimate it.

As discussed before, EHA-FPVM was chosen for the system design, while the redundancy of this EHA has not been decided. For reasons of the two faults tolerant, triple redundancy EHA is a better choice. The failure rate of this chosen actuator is 1.38E-4/FH. A detailed calculation process is shown in Appendix A. This number is higher than expected compared to [37] research from June 1990 to December 1992 which predicted the failure rate of the EHA is 73.668 E-6 / FH. The safety reliability of roll function is 2.22E-11/FH, pitch function is 6.48E-12/FH and yaw function is 1.22E-12/FH. This result satisfied the Extremely Improbable 1E-9/FH requirement.

6.4 Power estimate

For an aircraft actuator, it should fulfill the operation task at any point in the flight envelope and output acceptable force at the most severe situation. The stall load of the actuator should not be less than the peak torque of the control surface. For safety consideration, this peak torque usually multiplied by tge factor of safety 1.1 [38] as the actuator stall load input. This is in opposition with Pointon's research, where he estimated actuator peak power through actuator characteristic whereas we use peak torque to estimate actuator characteristic [34][38].

EHA actuator is a motor with a hydraulic converter. EMA is the same structure but a mechanical converter. And the peak power of an EPA output is determined by its load control surface peak torque. To generate this output, the actuator needs more power than this because of loss of energy. For EHA, the energy depletion is simplified only in the motor and converter process. Typically, motor efficiency increases as the power, for a 50kW motor, the factor of efficiency is 0.9 and the hydraulic pump (converter) is 0.85 [39; 40].

The time estimated for the actuator can be estimated on SAE report [41] and the research of Jean Jacques Charrier [11]. The time of rudder and elevator actuator spent on full stroke at the highest maximum rate is 1s. And aileron is half second faster than this. A detailed estimation process is shown in Appendix D.

With the data calculated above and equations below, the power of the actuation system can be estimated and the figure is shown in Table 6-1. Detailed information is shown in Appendix D.

$$P_{peark-power} = 0.7 \times FoS \times F_{stall-load} \times V_{\max umum-rate} = 0.7 \times T_{peaktoque} \times FoS \times 2 \times \pi \times \frac{2\alpha}{360} \times \frac{1}{\mathrm{t}}$$

$$P_{consumption-power} = 0.7 \times T_{peaktoque} \times 2 \times \pi \times \frac{2\alpha}{360} \times \frac{1}{\eta_{motor}} \times \frac{1}{\eta_{pump}} \times \frac{1}{\mathrm{t}}$$

The elevator actuator peak power is 3.73kW, the rudder actuator peak power is 2.63 kW and the aileron actuator peak power is 1.86 kW. The power consumption of them is 4.43kW, 3.12kW, and 2.21kW separately.

6.5 Weight estimate

The method used for weight estimation is power-to-mass ratio (PMR) [42]. Compared to the method used by Ajit Singh Panesar [43] which is to estimate each part of the actuator then add them together, the PMR is more easier to use. And the information of EHA is quite limited, so it is hard to determine the size of each part and also the structure of it whereas the PWR method compares the weight with the EHA. So, the latter method has no advantage in accuracy also compared to PMR method.

The first step is the power weight ratio calculation. To find out the relationship between PWR and power, using the quite limited data collected, the PWR equation was obtained by two level fitting methods. The result shows PWR is increasing with the power. Compared with others' research, this number seemed a litter higher [43; 44][34]. The detailed calculation is shown in Appendix D.

6.6 Heat rejection estimate

According to law of conservation of energy, the heat generated in EHA is the power lost. The nominal power consumption of the actuator has been calculated. However, it cannot be used as output since it is output multiplied a 1.1 factor of safety. The output can be obtained from the control surface maximum torque.

Table 6-2 Actuator heat rejection

Control Surface	Actuator power consumption (kW)	Actuator peak power(kW)	Output power(kW)	Heat rejection(kW)
Elevator	4.43	3.73	3.39	1.04
Rudder	3.12	2.63	2.39	0.73
Aileron	2.21	1.86	1.69	0.52

Actuator output power:

$$P_{out} = T_{peaktoque} \times 2 \times \pi \times \frac{2\alpha}{360} \times \frac{1}{\mathrm{t}}$$

Heat rejection:

$$\dot{Q} = P_{consumption-power} - P_{out}$$

The actuators work modes are active-active. So each elevator heart rejection is 0.52kW. And the Rudder actuator gives up 0.36kW heat. The aileron is 0.26kW.

Heat flux:

$$q'' = \dot{Q} / A$$

The average actuator heat rejection surface is 0.0965m^2. Therefore, the heat flux of each control surface is 5389W/m^2, 3730W/m^2 and 2694W/m^2.

6.7 Summary

This chapter designed a conventional actuation system based on the Boeing 777. The power, actuator layout and actuator control have been seriously considered. For the architecture validation and comparison, safety requirement, power, weight and heat rejection also have been calculated.

7 Distributed actuation system design

7.1 Introduction

Chapter 6 designed an EHA system with conventional concept. This chapter designed a new system with distributed and remote concept. Additionally, the system parameters will be calculated later.

7.2 System architecture

The actuator used here is the same as the conventional actuation system design except that the redundancy changed to tandem.

The distributed concept attempt is using plenty of actuators to replace the concentrate actuators such as only two actuators located on aileron. For the first step attempt, one pair of actuators were added to the aileron and elevator. This designed can also solve the problems of electronics penalty lead by only two pairs of actuators on the aileron and elevator. The actuators added on elevators can also figure out the roll moment at the backup working model. The whole flaps which are driven by two concentrated EMAs are also changed to individual control. Each piece of flap is positioned by two EMAs build up by the motor and jack screw.

The utilization of smart EHAs [45] achieved the remote control aim. The control signal is a digital command sent by the flight control computer directly without ACEs conversion needed. This will reduce the weight of wires.

The power and control logic follows the same rules as discussed in Chapter 6.

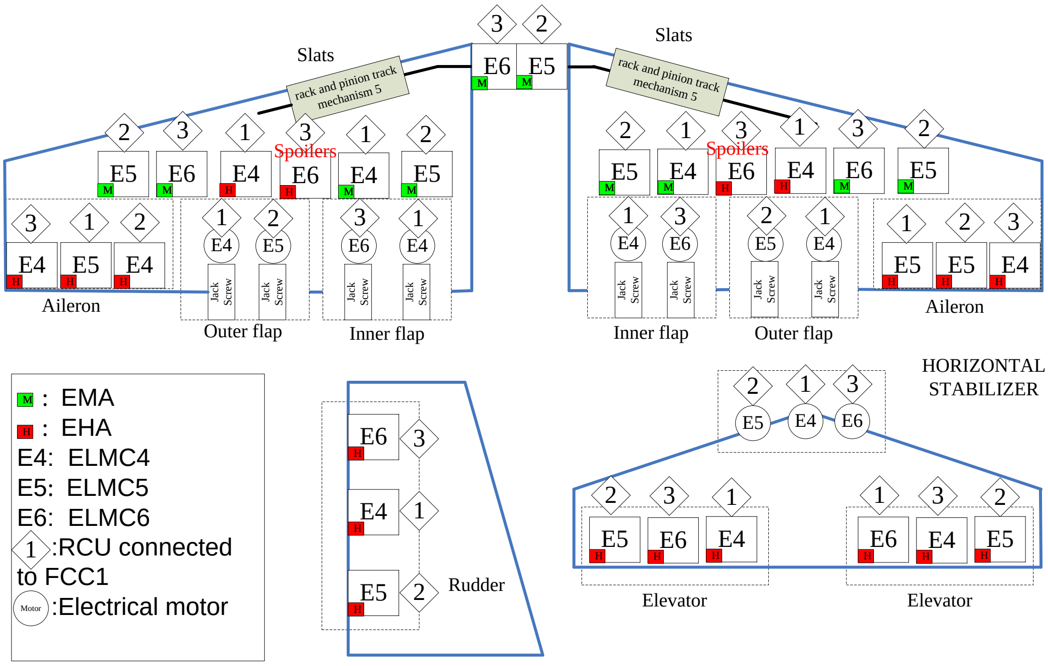

Figure 7–1 distributed actuation system architecture

7.3 Safety reliability estimation

The safety reliability is based on the tandem actuator failure rate calculated in Appendix A. The control surface failure rate is also calculated in Appendix A. The distributed flight control system FMEA model was then established. Following the FMEA model and tandem actuator failure rate, the whole flight control system reliability and actuation system safety reliability can be calculated.

7.4 Power estimation

For safety consideration, each actuator can drive the control surface individually. So both the peak power of each actuator is equal to the control surface peak power.

7.5 Mass estimation

The actuators used in this design only have two redundancies, so each actuator lane power is higher than the triple redundancy actuator used in the conventional design. Comparing the PWR to power curve, this actuator has higher efficiency than the conventional one. Each lance weight can be obtained and then the whole system weight can be calculated.

7.6 Heat rejection

Each elevator, rudder aileron operating peak heat rejection is 1.04kW, 0.73kW, and 0.52 kW. The actuator heat rejection of elevator is 0.35kW, and the rudder actuator is 0.24kW, and the Aileron actuator heat rejection is 0.17kW.

7.7 Summary

The distributed actuation system has been designed in this chapter and system reliability, safety, failure rate and power consumption, mass and heat rejection all have been calculated. After having obtained all these design data, it is ready for the next step research and the comparison of these two kinds of architecture.

8 Discussion

8.1 Introduction

Chapter 6 presents the conventional actuation system design with EPA and Chapter 7 demonstrates the design with distribute strategy. To find out which one has more advantage, the comparison was preceded in this chapter.

The main comparison is between performance, cost and airworthiness certificate three part. These three aspects represent the main design requirement of actuation system design. The results are summarised in the end.

8.2 General comparison

8.2.1 Performance

Both these two systems can satisfy the requirement of stall load, maximum rate, frequency response, dynamic stiffness and failure transient requirement with a weight penalty although some aspects are not discussed in this research for the reason of being too specific while this is only a conceptual design.

Table 8-1 Weight comparison

Control Surface	Conventional system		Distributed system	
	Actuator weight(kg)	Total weight(kg)	Actuator weight(kg)	Total weight(kg)
Elevator	29.84	119.36	29.6	177.6
Rudder	21.21	63.63	21.21	63.63
Aileron	15.12	60.48	15.	90

For the weight comparison, it can be clearly seen from Table 8-1 that the distributed system actuator weight is slightly lighter than the conventional system actuator while the system weight is 30% heavier with the exception of the rudder because the rudder used the same design. The reason of these results is caused by actuator task definition. Both these two system actuators need to position the control surface itself. So the peak power of each actuator is the same with the surface peak power it controlled. From the single lane PWR to power curve shown in Appendix E, the triple lane actuator PWR is less than the two lane tandem actuator. Therefore, this is where the actuator weight differential is generated as well as the number of actuator decided for the total system weight. If we suppose the actuators on one surface work together to meet the peak torque requirement, the best results will be the distributed system weight which will be slightly less than the conventional one for the reason that the PWR number of each actuator lane is less than the conventional one. If more actuators were added to control surface, it would lead to the same answer. The main factors of the system weight depend on the whole system power and the PWR number. The best strategy for system architecture is concentrating the actuator as much as possible, since this will improve the PWR number because it increases with the power.

Although the two system power consumption results seemed the same, the distributed system power consumption will be actually less than the conventional one. The reason of the same results was caused by the same motor and hydraulic pump efficiency. According to the motor design data, motor efficiency increases as the power increases [40]. Hydraulic pumps also obey this rule. Therefore, bigger EHA means better efficiency. This is a basic result based on the same design level, if the company technology is more advanced than another company, this possibly results in concluding that small actuator have the same or higher efficiency as a high power actuator designed by the latter company.

Table 8-2 Heat rejection comparison

Control surface	**Conventional system**		**Distributed system**	
	Heat rejection (kW)	**Heat flux (W/cmW/cm^2)**	**Heat rejection(kW)**	**Heat flux** W/cm^2
Elevator	0.52	0.539	0.35	0.363
Rudder	0.36	0.373	0.24	0.249
aileron	0.26	0.269	0.17	0.176

The heat rejection and heat flux of two systems have been shown in Table 8-2. Figure 8-1 shows both these two systems needed thermal management. The heat flux of them is similar. So there is no weight advantage between them.

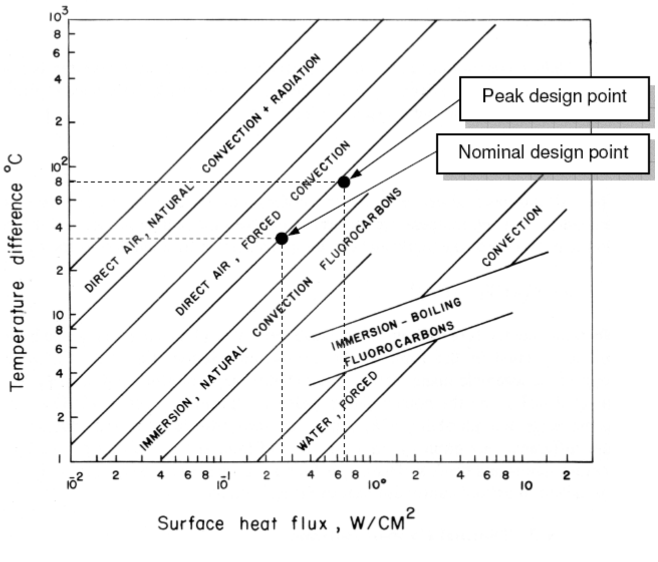

Figure 8–1 Cooling Method comparison [46]

8.2.2 Cost

Cost is the primary requirement for customers. The maintenance cost is the main cost. The work load of installation of the distributed system is heavier since it needs one more actuator to install on each surface. And we can see from Table 8-3 that the distributed system actuator failure is higher than the conventional system actuator. And the system failure rate is also higher than conventional especially in the elevator system. The elevator is triple redundancy architecture, while there is only one actuator on the second and third channel. So more actuators lead to more failure rate and more failure rate results in more maintenance time and cost and less operating time. From a customer's point of view, less actuator is a better choice.

Table 8-3 Failure rate comparison

Control surface	Conventional system		Distributed system	
	Actuator failure rate (FH)	Actuator system failure rate (FH)	Actuator failure rate (FH)	Actuator system failure rate (FH)
Elevator	1.27E-4	0.8E-4	1.38E-4	1.50E-4
Rudder	1.27E-4	0.75E-4	1.38E-4	0.75E-4
aileron	1.27E-4	1.69E-4	1.38E-4	1.50E-4

8.2.3 Airworthiness certification

For airworthiness certification, the number one requirement is safety. The safety reliability results show both these two system can fit the 10E-9/FH requirement. From Table 8-4 we can see that the distributed system actuators safety reliability is much higher than other component in the flight control system. This makes the system safety reliability total decided by other components. The failure rates of the actuator used in distributed and conventional systems are nearly the same. Through adding more actuators in the system, the system safety will greatly improve, especially in the parallel mode.

Airbus has got the certificate to use EHA A380. The EHA-VPFM actuator passes the certificate easily because there is no more new technology used there. But the EHA using FPVM will have a little risk for the new motor control technology. For the smart actuator used in the distributed system, it is harder to get the certificate than the conventional system for the reason that no such kind of actuator has been used before.

Table 8-4 Safety reliability comparison

Control surface	Conventional system		Distributed system	
	Actuators safety reliability (FH)	System safety reliability (FH)	Actuators safety reliability (FH)	System safety reliability (FH)
Pitch	5.26E-12	6.48E-12	1.30E-19	1.22E-12
Yaw	2.10E-11	2.22E-11	2.10E-11	2.22E-11
Roll	1.67E-11	1.89E-11	5.80E-15	1.22E-12

8.3 Discussion

It seemed conventional design has more advantages than distributed design from the general comparison. While to make two comparisons at the same level, both the two systems are designed in 6 channel. The actuator used in conventional design was a triple redundancy actuator. Each redundancy takes the 33% task of the whole actuator. The distributed one was a dual redundancy actuator. Each redundancy takes 50% task of the whole actuator. So, it can be seen as 6 small actuators work together to drive the control surface. While the motors of distributed actuators take 50% task, so the power of it is higher than conventional actuator motors (33% task). So the efficiency of it is higher. However, the conventional design is lighter than distributed design. The reason of it is that conventional design is two redundancy systems but the distributed one is a triple redundancy system. Reducing the system redundancy could reduce the system weight greatly.

The electrically powered actuation system for future aircraft design is a balance between actuator number, system weight and power consumption.

8.4 Summary

This chapter has compared the conventional actuation system and the distributed actuation system on performance, cost and airworthiness.

The results analysis uncovered that these two design are not the best design. For the system does not need backups, the more concentrate the better at the situation it can satisfy other requirement. While for a aircraft system design, it is a tradeoff between safety, actuator efficiency, weight and numbers.

9 Conclusion

9.1 Conclusion

The work carried out during this project has proved that concentrate architecture has more advantages than distributed architecture with EHA-FPVM actuator for primary flight control actuation system and EMA for secondary flight control actuation system.

EHA and EMA is the most mature technology for all electric aircraft design in the near future. EHA suits primary control surfaces for high reliability and EMA suits secondary control surfaces for high efficiency. If EMA solves the sticking problems, it will be the one for the whole actuation system design. The APA actuator is not available for aircraft control at the current stage due to the limited stroke and force. To achieve the required stroke it needs about 2000V electric voltage. However, it is a potential actuator for future design.

For a medium sized or bigger sized aircraft, triple redundancy EHAs system has the best equivalence between safety and performance. Too much actuator added on the control surface could improve the safety but also reduce the efficiency of actuators which leads to higher weight and more power consumption. At the same time, more actuators will also increase the difficulty of actuator control design and fault diagnosis and prediction. Less actuators also cannot satisfy the safety deadline even though the new actuator technology has greatly improved the actuator reliability.

While for a future MEA or AEA, the actuation system design should consider the efficiency decline and weight increase with the actuator size and weight decline with the redundancy reduce. So the design is a tradeoff between them.

For the reason of limited time, the data of the aircraft and actuators are all based on assumption and brief calculations. A lot of the influence between systems and detailed failure mode and different flight cases were neglected. These may mean that the research does not accurately represent the realism.

9.2 Recommendations for Future Work

At the end of this research, there are still a lot of interesting works which remain to be done in the future.

Firstly, further reliability analysis is required. The safety reliability analysed in this research is only the baseline requirement constrained the hazard failure which is probability of loss of control. For detailed analysis, the failure coverage model should be built to analyse the system failure at the first time and second time.

Secondly, the influence of smart actuator utilises on aircraft. This actuator can be controlled by digital signal directly, so ACEs are no longer needed. A further analysis should be done to estimate the influence of ACE removing. Because the data of ACEs is hard to get, a conceptual ACE design may be required for further specification estimate and comparison.

Thirdly, a secondary flight control system calculation should be done especially with regard to the flap control system. The distributed control architecture will reduce the motor efficiency; the weight of system will increase. Applying new material and removing the mechanical connection parts between each flap will also reduce the system weight and add new functions. Therefore, the distributed flap system design should be researched.

Fourthly, for a long-term research, the concept of using an actuator to influence flow filed to generate control forces shows a great potential in weight and power reduction and therefore deserves further investigation.

Finally, the influence of actuator monitor and diagnose electronics design to actuation system should be considered in further research. Adding more electronics to diagnose the system failure may reduce the failure rate of the actuator. And less actuator will be needed on each function control.

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Appendices

Appendix A Reliability estimation

Appendix B Distributed actuation system architecture Safety reliability calculation

Appendix C Conventional actuation system architecture safety reliability calculation

Appendix D Power estimation

Appendix E Weight estimation

Appendix F Group design report

Appendix A Reliability estimation

A.1 Safety calculation principle

The failure rate of a component has three different stages during the lifetime, It is very high at first and then drops down dramatically as debugging continues. The second stage corresponds to an essentially constant and low failure rate and failures can be considered to be nearly random. This is the useful lifetime of the component. The last stage corresponds to wear out or fatigue phase with a sharply increasing failure rate. The failure rate follows exponential distribution at the second stage and it is a constant value.

For the EPA reliability estimation below, it is all supposed that the component failure rate follows the exponential distribution. The relationship between reliability, failure rate and posterior failure probability is shown below.

Reliability: $R(t) = \mathrm{e}^{-\lambda t}$

Failure rate: $\lambda = \dfrac{1}{MTBF}$

Posterior failure probability: $Q(t) = Q_c(t) = 1 - e^{-\lambda t}$

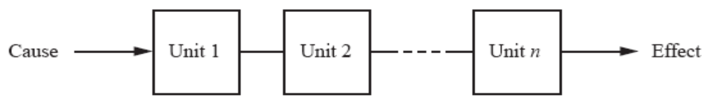

Figure A–9–1 Series or chain structure

Series structure reliability equation: $R_s = \prod_{i=1}^{n} R_i$

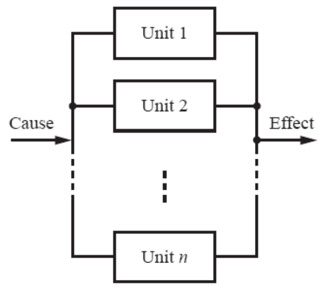

Figure A–9–2 Parallel structure

Parallel structure reliability: $R_i = 1 - \prod_{i=1}^{n} Q_i$

A.2 Tandem EHA model

The EHA model shown below is a two control loop tandem actuator. It is a simplified model which contains the most basic parts. The relationship of parts in each channel is series. And the two channels are parallel structure. With the structure of EHA and reliability structure equations, each component failure rate, the reliability, failure rate of EHA can be calculated.

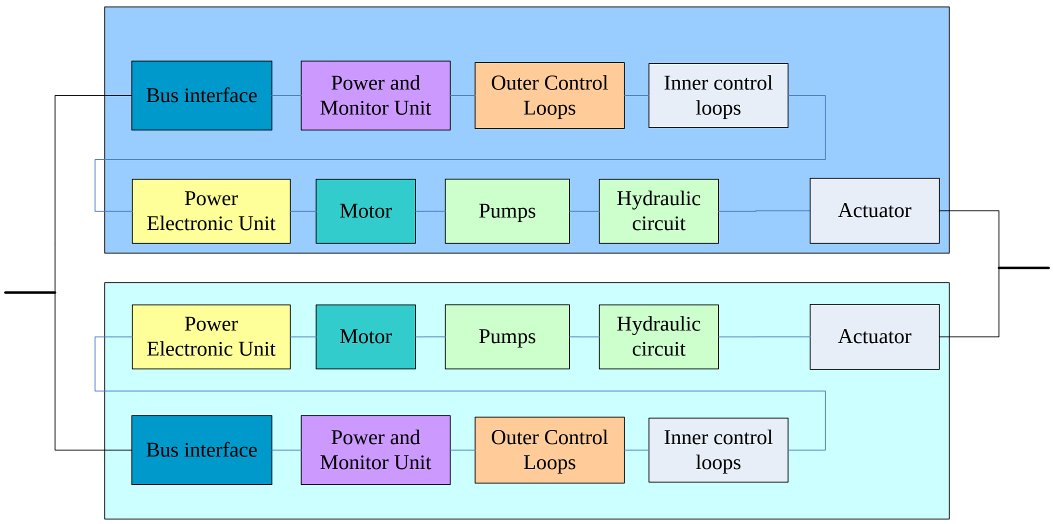

Figure A–9–3Tandem EHA Diagram

The EHA reliability diagram can be established by Figure 9-3:

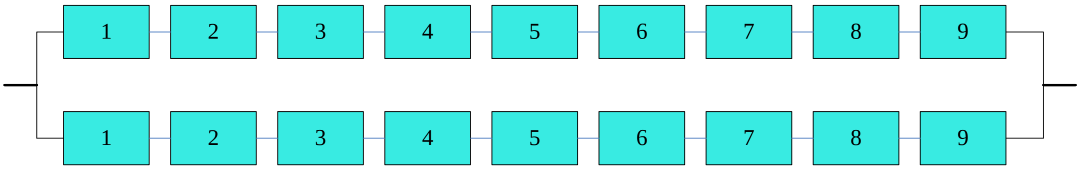

Figure A–9–4 EHA reliability Diagram

The failure rate of each part can be calculated individually. By using reliability prediction of electronics equipment [47], the electronic part failure rate can be obtained. This is hardest part of whole process because the architecture of control electronics are quite different. The hydraulic circuit can be calculated by the method of Liu CengXing [48] . For saving time, each part failure rate can be derived from Ma JiMing's result [49].

Table A-1 EHA Parts Failure Rate

Part	**BI**	**PMU**	**OCL**	**ICL**	**PEU**
Failure Rate Per FH	13E-6	26E-6	3E-6	13E-6	96E-6
Part	**Motor**	**pump**	**HC**	**AC**	**GEAR**
Failure Rate Per FH	15E-6	12E-6	28E-6	0.4E-6	12E-6

A.3 EPA failure rate

Tandem redundancy EHA failure rate:

$$\mathrm{R}_{eha} = 1 - \prod_{i=1}^{n} Q_i = 1 - (1 - \prod_{i=1}^{9} R_i)^2 = 2\prod_{i=1}^{9} R_i - \prod_{i=1}^{9} R_i^2 = 2 * e^{-(\sum_{i=1}^{9} \lambda_i t)} - e^{-2(\sum_{i=1}^{9} \lambda_i t)}$$

$$\mathrm{MTBF}_{eha} = \int_0^\infty \mathrm{R}_{eha}(t)\mathrm{d}(t) = \int_0^\infty 2 * e^{-(\sum_{i=1}^{9}\lambda_i t)} - e^{-2(\sum_{i=1}^{9}\lambda_i t)} \mathrm{d}(t) = \frac{2}{\sum_{i=1}^{9}\lambda_i} - \frac{1}{2(\sum_{i=1}^{9}\lambda_i)} = \frac{3}{2(\sum_{i=1}^{9}\lambda_i)}$$

$$\lambda_{eha} = \frac{1}{MTBF_{eha}} = \frac{2(\sum_{i=1}^{7}\lambda_i)}{3} = 1.38E\text{-}4/FH$$

Triple redundancy EHA have the same structure as tandem EHA but have one more channel. So the failure rate of it can be calculated by the same method:

Triple redundancy EHA failure rate:

$$R_{eha} = 1 - (1 - \prod_{i=1}^{9} R_i)^3 == 3e^{-(\sum_{i=1}^{9}\lambda_i t)} - 3e^{-2(\sum_{i=1}^{9}\lambda_i t)} + e^{-3(\sum_{i=1}^{9}\lambda_i t)}$$

$$MTBF_{eha} = \int_0^\infty R_{eha}(t)d(t) = \int_0^\infty (3e^{-\lambda_{EHA}t} - 3e^{-2\lambda_{EHA}t} + e^{-3\lambda_{EHA}t})d(t) = \frac{11}{6(\sum_{i=1}^{7}\lambda_i)}$$

$$\lambda_{eha} = \frac{1}{MTBF_{eha}} = \frac{6(\sum_{i=1}^{7}\lambda_i)}{11} = 1.27E\text{-}4/FH$$

The EMA have the same structure with EHA, the failure rate of gear part can can be accessed from an actuator research book [7].

EMA failure rate:

$$\lambda_{ema} = \frac{1}{MTBF_{ema}} = \frac{2(\sum_{i=1}^{7}\lambda_i)}{3} = 1.37E\text{-}4/FH$$

A.4 Distributed actuation system control surface failure rate

The calculation presented here is the distributed actuation system control surface failure rate; the process is the same with the actuator failure rate.

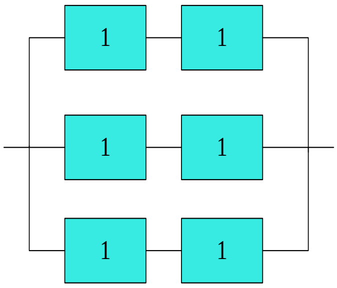

Figure A–9–5 Ailerons actuator reliability diagram

Ailerons reliability:

$$R_{aileron} = 1-(1-R_{EHA}^2)(1-R_{EHA}^2)(1-R_{EHA}^2) = 1-(1-3R_{EHA}^2+3R_{EHA}^4-R_{EHA}^6)$$
$$= 3R_{EHA}^2 - 3R_{EHA}^4 + R_{EHA}^6 = 3e^{-2\lambda_{EHA}t} - 3e^{-4\lambda_{EHA}t} + e^{-6\lambda_{EHA}t}$$

Ailerons mean time between failures:

$$MTBF_{aileron} = \int_0^\infty R_{aileron}(t)d(t) = \int_0^\infty (3e^{-2\lambda_{EHA}t} - 3e^{-4\lambda_{EHA}t} + e^{-6\lambda_{EHA}t})d(t)$$
$$= \frac{3}{2\lambda_{EHA}} - \frac{3}{4\lambda_{EHA}} + \frac{1}{6\lambda_{EHA}} = \frac{11}{12\lambda_{EHA}}$$

Aileron failure rate:

$$\lambda_{aileron} = \frac{1}{MTBF_{aileron}} = \frac{12}{11}\lambda_{EHA} = 1.50E-4/FH$$

Rudder failure rate:

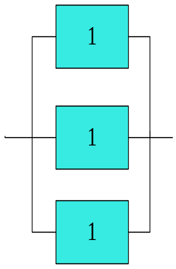

Figure A–9–6 Rudder reliability diagram

Rudder reliability:

$$R_{rudder} = 1-(1-R_{EHA})(1-R_{EHA})(1-R_{EHA}) = 3R_{EHA} - 3R_{EHA}^2 + R_{EHA}^3$$
$$= 3e^{-\lambda_{EHA}t} - 3e^{-2\lambda_{EHA}t} + e^{-3\lambda_{EHA}t}$$

Rudder mean time between failures:

$$MTBF_{rudder} = \int_0^\infty R_{rudder}(t)d(t) = \int_0^\infty (3e^{-\lambda_{EHA}t} - 3e^{-2\lambda_{EHA}t} + e^{-3\lambda_{EHA}t})d(t)$$
$$= \frac{3}{\lambda_{EHA}} - \frac{3}{2\lambda_{EHA}} + \frac{1}{3\lambda_{EHA}} = \frac{11}{6\lambda_{EHA}}$$

Rudder failure rate:

$$\lambda_{rudder} = \frac{1}{MTBF_{rudder}} = \frac{6}{11}\lambda_{EHA} = 7.49E-5/FH$$

The elevators and ailerons actuators are in the same architecture, so the failure rate of them are also the same.

A.5 Conventional actuation system control surface failure rate

Based on the same method,

Aileron failure rate:

$$\lambda_{aileron} = \frac{1}{MTBF_{aileron}} = \frac{4}{3}\lambda_{EHA} = 1.69E-4/FH$$

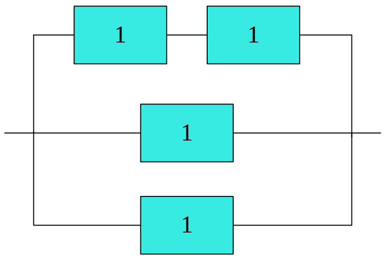

Figure A–9–7 Elevators reliability diagram

Elevator failure rate:

$$R_{elevator} = 1-(1-R^2{}_{EHA})(1-R_{EHA})(1-R_{EHA}) = 2R_{EHA} - 2R^3_{EHA} + R^4_{EHA} = 2e^{-\lambda_{EHA}t} - 2e^{-3\lambda_{EHA}t} + e^{-4\lambda_{EHA}t}$$

Elevator mean time between failures:

$$MTBF_{elevator} = \int_0^\infty R_{elevator}(t)d(t) = \int_0^\infty (2e^{-\lambda_{EHA}t} - 2e^{-3\lambda_{EHA}t} + e^{-4\lambda_{EHA}t})d(t)$$

$$= \frac{2}{\lambda_{EHA}} - \frac{2}{3\lambda_{EHA}} + \frac{1}{4\lambda_{EHA}} = \frac{19}{12\lambda_{EHA}}$$

Elevator failure rate:

$$\lambda_{elevator} = \frac{1}{MTBF_{elevator}} = \frac{12}{19}\lambda_{EHA} = 8.02E-5/FH$$

Rudder failure rate is the same with distributed design because of using the same triple redundancy actuators.

Appendix B Distributed actuation system architecture Safety reliability calculation

The FMEA analysis of distributed actuation system is shown below. The failure rate of control command signal is 1.60E-13 / FH, the failure rate of flight control computer is 5E-4 /FH [42], the failure rate of electrical system is 4E-7/FH, and the failure rate of EHA is 1.37E-4 /FH.[44]. The safety reliability results were calculated below.

Roll function safety reliability calculation:

$$SR_{roll} = \lambda_{FCC}{}^4 + \lambda_{cg} + 2\lambda_{ema}(2\lambda_{eha})^3 * + \lambda_{db}{}^3 + \lambda_{es}{}^3 = 1.22\text{E-}12/\text{FH}$$

$$SR_{Roll-actuator} = 2\lambda_{ema}(2\lambda_{eha})^3 = 16\lambda_{ema}\lambda_{eha}{}^3 = 5.80\text{E-}15/\text{FH}$$

$$SR_{aileron} = (2\lambda_{eha})^4 = 8\lambda_{eha}{}^3 = 2.10\text{E-}11/\text{FH}$$

Pitch function safety reliability calculation:

$$SR_{pitch} = \lambda_{FCC}{}^4 + \lambda_{cg} + 3\lambda_{motor}(2\lambda_{eha})^3 * + \lambda_{db}{}^3 + \lambda_{es}{}^3 = 2.22\text{E-}11/\text{FH}$$

$$SR_{elevator} = (2\lambda_{eha})^2 = 8\lambda_{eha}{}^3 = 2.10\text{E-}11/\text{FH}$$

Yaw function safety reliability calculation:

$$SR_{yaw} = \lambda_{FCC}{}^4 + \lambda_{cg} + (2\lambda_{eha})^3 + \lambda_{db}{}^3 + \lambda_{es}{}^3 = 1.22\text{E-}12/\text{FH}$$

$$SR_{Yaw-actuator} = (2\lambda_{eha})^3 = 8\lambda_{eha}{}^3 = 2.10\text{E-}11/\text{FH}$$

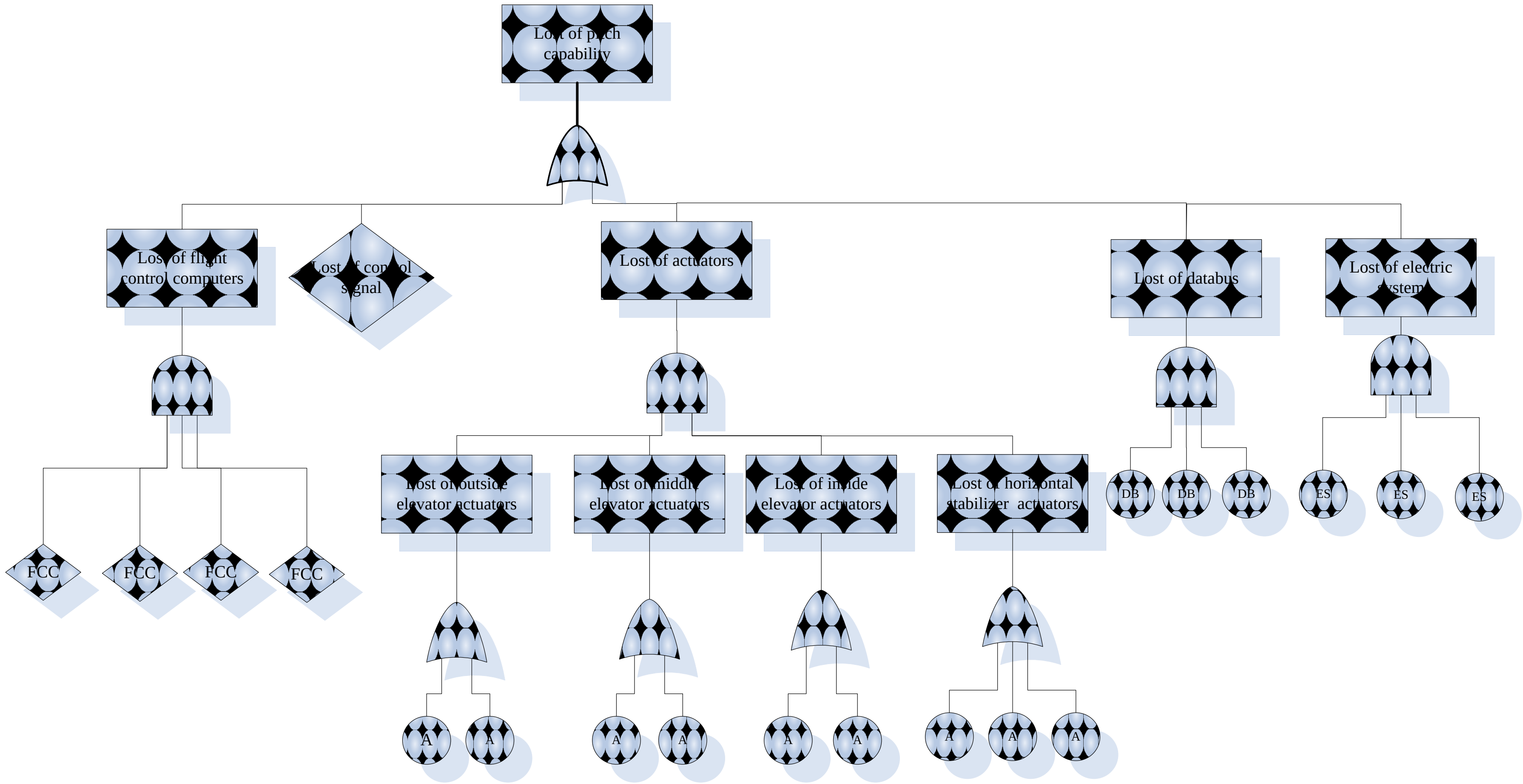

Figure B–1 Pitch function FMEA analysis

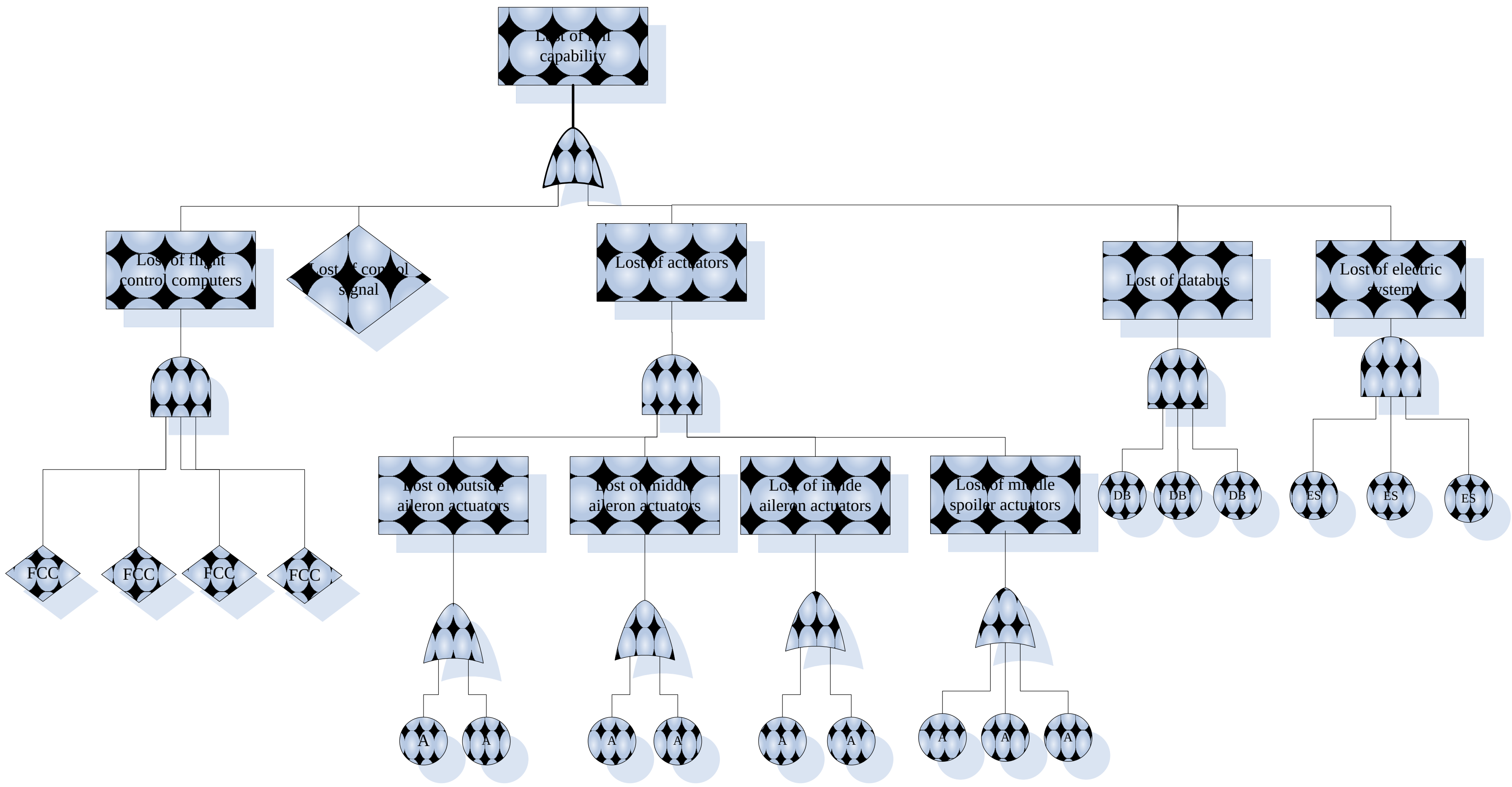

Figure B–2 Roll function FMEA analysis

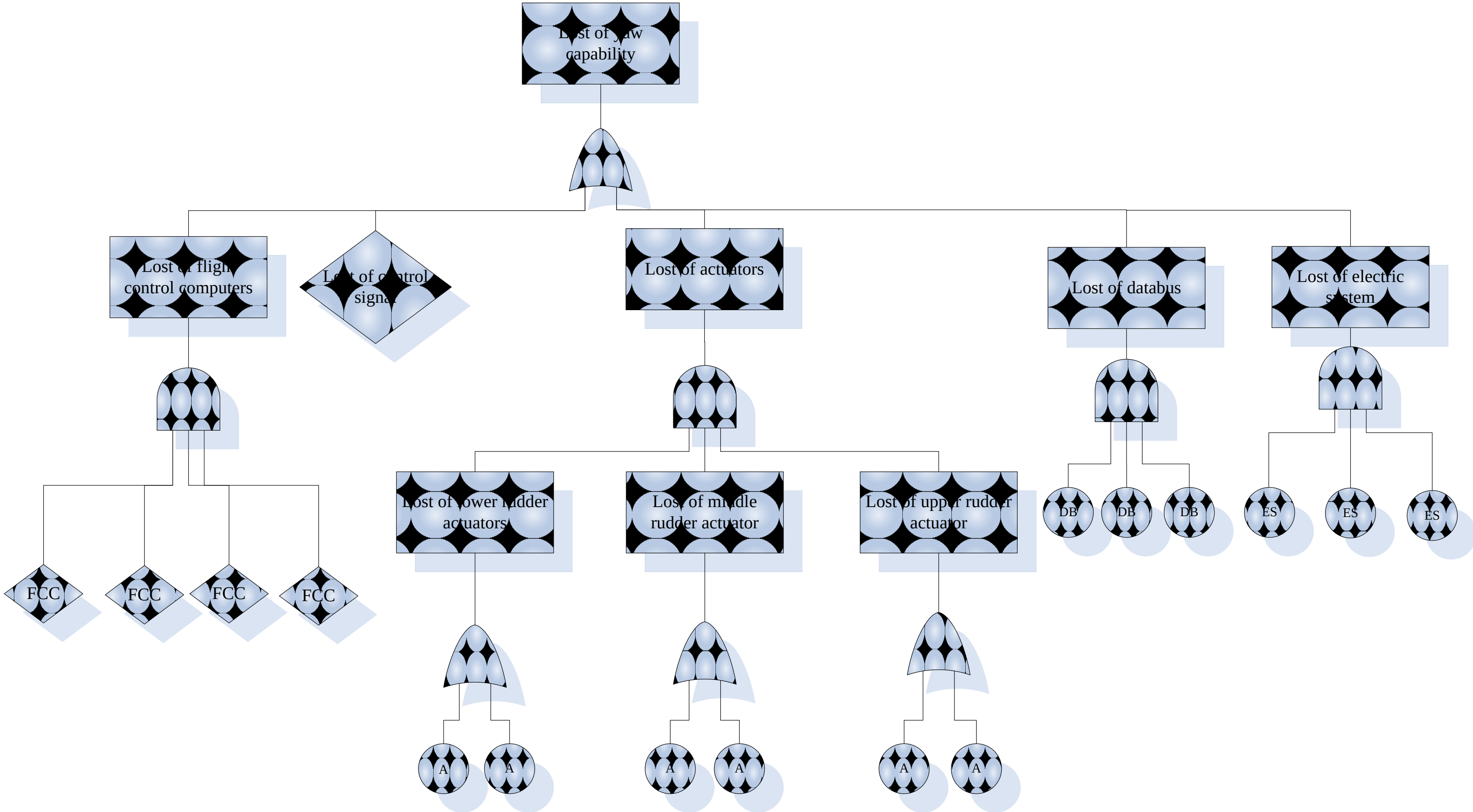

Figure B–3Yaw function FMEA analysis

Appendix C Conventional actuation system architecture safety reliability calculation

With the same method and data discussed previously, the conventional actuation system reliability was calculated.

Roll function safety reliability calculation:

$$SR_{roll} = \lambda_{FCC}{}^{4} + \lambda_{cg} + 2\lambda_{ema}(2\lambda_{eha})^{2} * + \lambda_{db}{}^{3} + \lambda_{es}{}^{3} = 1.89\text{E-11/FH}$$

$$SR_{Roll-actuator} = 2\lambda_{ema}(2\lambda_{eha})^{2} = 8\lambda_{ema}\lambda_{eha}{}^{2} = 1.67\text{E-11/FH}$$

$$SR_{aileron} = (2\lambda_{eha})^{2} = 4\lambda_{eha}{}^{2} = 7.62\text{E-8/FH}$$

Pitch function safety reliability calculation:

$$SR_{pitch} = \lambda_{FCC}{}^{4} + \lambda_{cg} + 3\lambda_{motor}(2\lambda_{eha})^{3} * + \lambda_{db}{}^{3} + \lambda_{es}{}^{3} = 6.48\text{E-12/FH}$$

$$SR_{pitch-actuator} = SR_{elevator} = 2\lambda_{eha} * \lambda_{eha} * \lambda_{eha} = 2\lambda_{eha}{}^{3} = 5.26\text{E-12/FH}$$

Yaw function safety reliability calculation:

$$SR_{yaw} = \lambda_{FCC}{}^{4} + \lambda_{cg} + (2\lambda_{eha})^{3} + \lambda_{db}{}^{3} + \lambda_{es}{}^{3} = 1.22\text{E-12/FH}$$

$$SR_{Yaw-actuator} = (2\lambda_{eha})^{3} = 8\lambda_{eha}{}^{3} = 2.10\text{E-11/FH}$$

Appendix D Power estimation

D.1 Time

The velocity required of military aircraft and civil aircraft are different; military aircraft actuator should be no less than 10 in/sec at no load and 120deg/sec. while for civil aircraft, 60 deg/sec rates can meet the requirement [11]. The Flying Crane actuator working at this speed will need about 0.8 s for full stroke running.

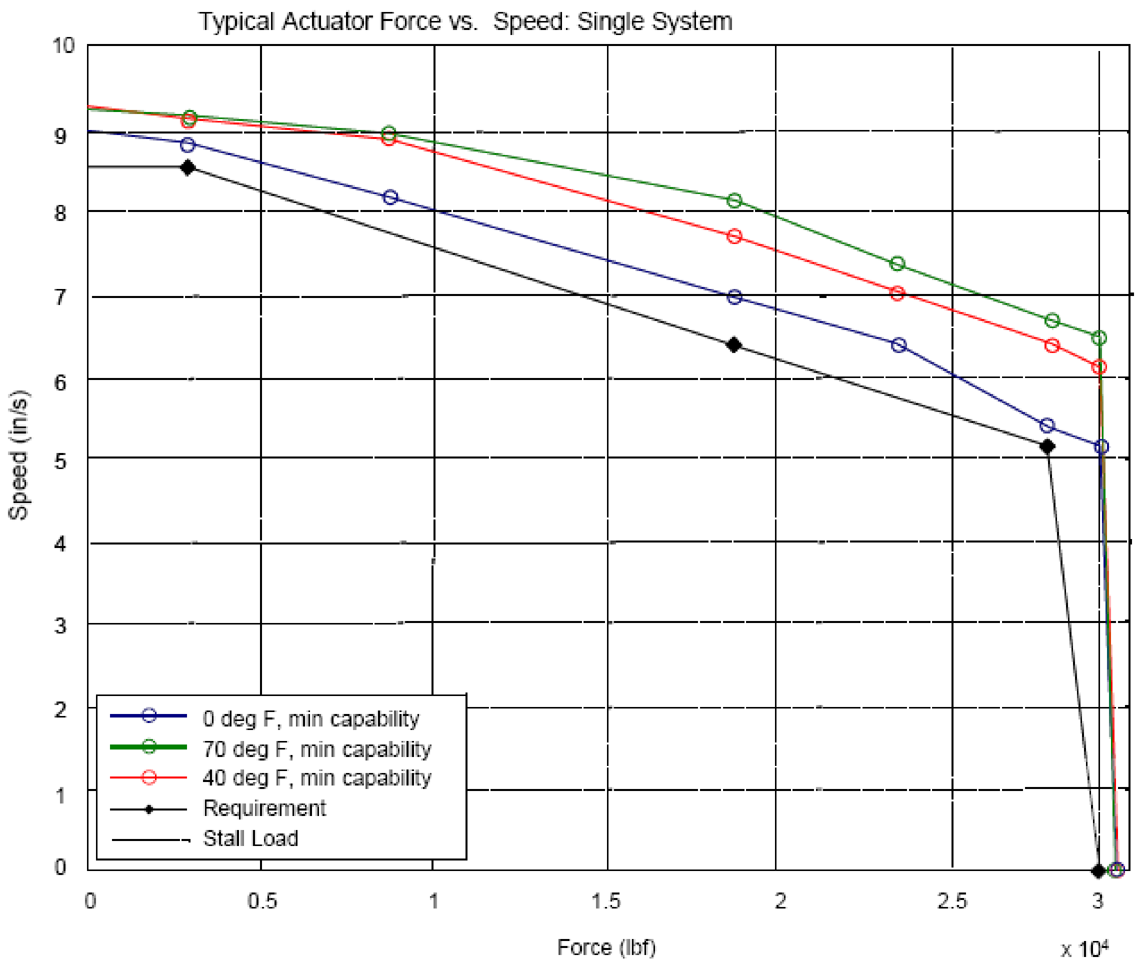

Figure D–9–8 Typical Load/Speed Curve for Actuator [11]

Table D-1 Actuator full stroke time

Control Surface	Rate (deg/sec)	Angle (°)	Time (s)
Elevator	60	±25	0.83
Rudder		±20	0.66
Aileron		±20	0.66

With the SAE report date calculation [41], the elevator and rudder actuator running time of A320 and A340 is about 1 second for total stroke at max rate. And the aileron time is about 0.5 second.

Table D-2 Airbus A319/320/321 actuator characteristics [41]

Characteristics	Elevator	Rudder	Aileron	Spoiler
Max.Rate(in/sec)	2.4	4.3	3.5	3.9
Total Stroke(in)	2.4	4.3	1.7	3.3
Time(s)	1	1	0.4857	0.8462

Table D-3 A330/340 Actuator characteristics [41]

Characteristics	Elevator	Rudder	Inboard aileron	Outboard aileron	Spoiler
Max.Rate(in/sec)	4.7	5.3	4.3	4.3	2.4
Total Stroke(in)	3.9	6.2	3.3	3.0	2.8
Time	0.8298	1.1698	0.7674	0.6977	1.1667

By comparing these two different times, the first Flying crane running time is a little too short, and the size of Flying Crane and A320 are nearly the same time. The A320 time was used for the next step calculation. The full stroke running time for the aileron and rudder was set to 1 sec and the aileron running time was set to 0.5 sec.

D.2 Power estimate

EHA actuator is a motor with a hydraulic converter. EMA is the same structure but a mechanical converter. And peak power of the EPA is a constant number determined by control surface load. After looking through the Internet I chose 0.9 and 0.85 as the motor efficiency and converter efficiency.

Actuator nominal power estimate:

$$P_{peark-power} = 0.7 \times FoS \times F_{stall-load} \times v_{\max umum-rate} = 0.7 \times T_{peaktoque} \times FoS \times 2 \times \pi \times \frac{2\alpha}{360} \times \frac{1}{\mathrm{t}}$$

$$P_{consumption-power} = 0.7 \times T_{peaktoque} \times 2 \times \pi \times \frac{2\alpha}{360} \times \frac{1}{\eta_{motor}} \times \frac{1}{\eta_{pump}} \times \frac{1}{\mathrm{t}}$$

$P_{peak-peakpower}$: Actuator peak power

$T_{peaktoque}$: Control surface maximum torque

$P_{consumption-power}$: Actuator power consumption at peak load.

FoS: Factor of safety.

η_{motor}: Motor efficiency

η_{pump}: Hydraulic pump efficiency

α: Control surface deflect angle.

The results of actuator peak power, power consumption and total power consumption of each control surface is shown in the table below.

Table D-4 Actuator peak power and power consumption

Control Surface	**Torque kN.m**	**Angle (°)**	**Time (s)**	**Actuator peak power(kW)**	**Actuator power consumption (kW)**	**Total power consumption**
Elevator	10.19	±25	1	3.73	4.43	8.86
Rudder	8.96	±20	1	2.63	3.12	6.24
Aileron	3.17	±20	0.5	1.86	2.21	4.42

Appendix E Weight estimation

E.1 Power-to-mass ratio calculation

The data of EPA is quite sensitive so only limited data can be found. Some A380 EHA is provided in the presentation of Xavier,Le tron. For this reason no speed or any related information was provided in the presentation slides [15], so the author decided on using the A330 data to estimate. The velocity of actuator depends on the flying quality requirement. The pilot said the A380 is quite easy to fly so it is assumed that it spends the same time to deflect the control surface to the ordered position with A330. The A330 actuator speed and stroke have got been obtained from the SAE report [41]. The length of the A380 is 79.75 meters and the length of the A330 is 60.3. Assuming the A380 and A330 has same proportion the A380 actuator maximum velocity can be calculated.

E.1.1 A380 Elevator EHA

A380 elevator EHA stroke:

$S_{380} = S_{330} * L_{380}/L_{330}$=3.9*79.75/60.3=5.16inch

A380 elevator EHA velocity:

$$v_{380} = S_{380} * \frac{v_{330}}{S_{330}} = 5.16 * \frac{4.7}{3.9} = \frac{6.22\text{in}}{\text{sec}} = 0.158\text{m/s}$$

A380 elevator EHA peak power:

$$P = 0.7 * F * v_{380} = 0.7 * 18 * 9.8 * 0.158 = 19.51\ \text{kW}$$

A380 elevator EHA power to weight ratio:

$$\text{PWR} = \frac{\text{P}}{\text{M}} = \frac{19.51}{80} = 0.244\text{kW/kg}$$

E.1.2 A380 Aileron EHA:

A380 aileron EHA stroke:

$$S_{380} = S_{330} * L_{380} / L_{330} == 3.9 * 79.75 / 60.3 = 5.16\text{inch}$$

A380 elevator EHA velocity:

$$v_{380} = S_{380} * \frac{v_{330}}{S_{330}} = 4.36 * \frac{4.3}{3.3} = \frac{5.68\text{in}}{\text{sec}} = 0.1443\text{m/s}$$

A380 aileron EHA peak power:

$$\text{P} = 0.7 * \text{F} * v_{380} = 0.7 * 13.5 * 9.8 * 0.1443 = 13.364\text{kW}$$

A380 aileron EHA power to weight ratio:

$$\text{PD}_2 = \frac{\text{P}}{\text{M}} = \frac{13.364}{65} = 0.2056\text{kW/kg}$$

E.2 PWR curves

Table E-1 EHA power and weight data

	EHA1	EHA2	EHA3	EHA4	EHA5
Power(kW)	13.36	19.51	-	(4.2KN)	1.62
Weight(kg)	65	80	-	17.2	12
PWR(kW/kg)	0.2056	0.244	0.186	-	0.135

EHA1 and EHA2 is A380 EHA calculated before. EHA3 is coming from Long xian Xue’s thesis while no power and weight data was found [44]. EHA4 lack of stroke and PWR could not be found [50]. EHA5 is from an EHA validation program [7].

Only EHA1, EHA2 and EHA5 have enough data for PWR to power curve fitting.

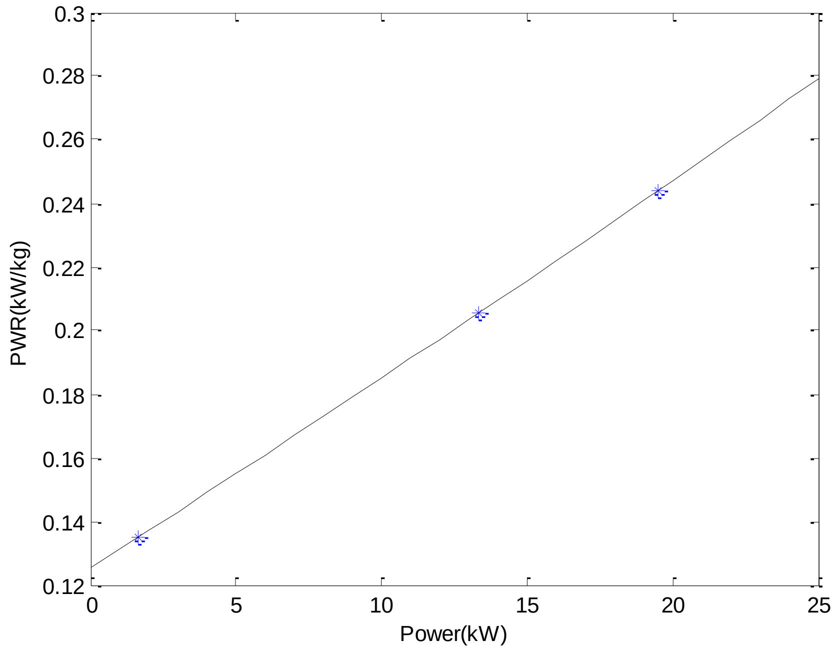

Figure E–1 Single lanes PWR to Power curve

The PWR to Mass curve also plotted for further research.

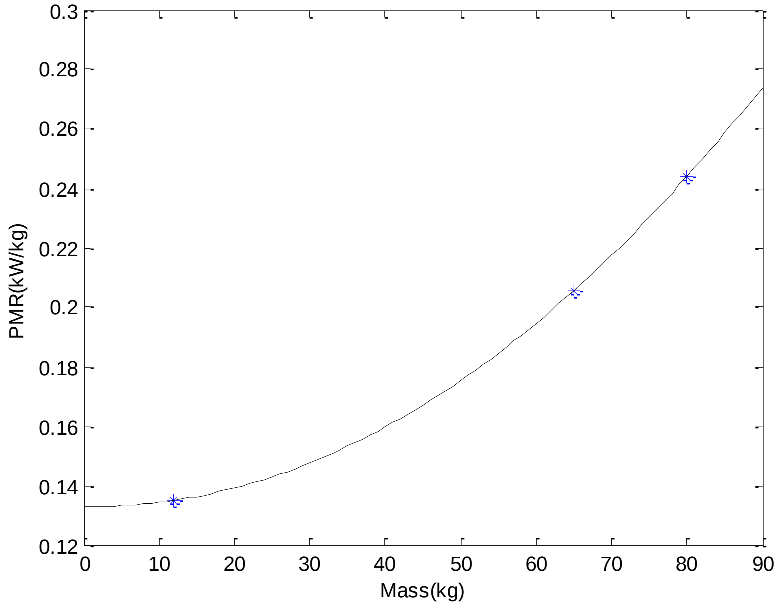

Figure E–2 Single lanes PWR to Mass curve

E.3 Weight calculation

It can be clearly seen that the EHA actuator of A380 is a one lane actuator. And there is no need to backup the backup actuator.

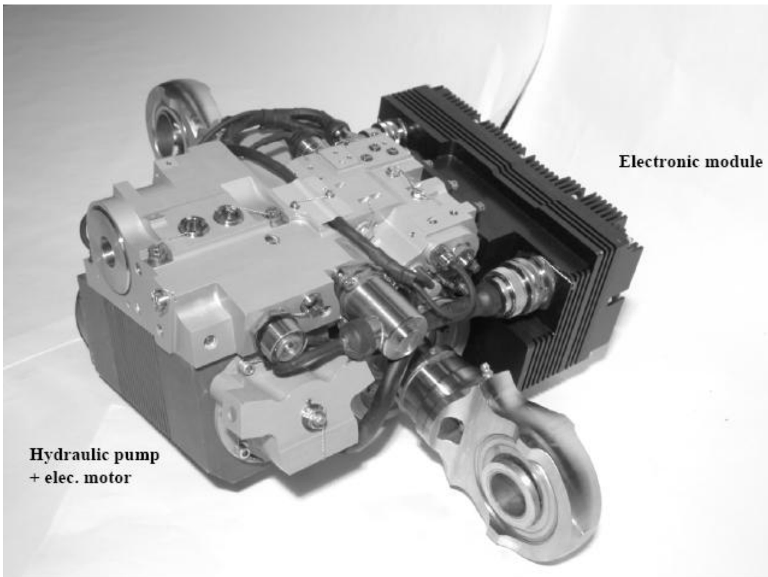

Figure E–3 EHA on A380 [15]

While EHA used here is a triple redundancy actuator, so the one lane power should be calculated at first. Then the PMR number can be read from Figure 9-12, after that, the actuator and system weight was calculated.

Table E-2 conventional system weight

Control Surface	Actuator Power (kW)	One lane actuator power(kW)	PMR (kW/kg)	Actuator weight(kg)	Total weight(kg)
Elevator	3.73	1.24	0.125	29.84	119.36
Rudder	2.63	0.88	0.124	21.21	63.63
Aileron	1.86	0.62	0.123	15.12	60.48

With the same method, the tandem actuator weight and distributed system weight is calculated.

Table E-3 Distributed system weight

Control Surface	Actuator Power (kW)	One lane actuator power(kW)	PMR (kW/kg)	Actuator weight(kg)	Total weight(kg)
Elevator	3.73	1.87	0.126	29.6	177.6
Rudder	2.63	1.31	0.125	21.21	63.63
Aileron	1.86	0.93	0.124	15.	90

Appendix F Group design report

Flying Crane actuation system design and flight simulation platform design

ABSTRACT

This report presents a design of 3-electrical (3E) actuation system design. The designer investigates the airworthiness requirement and the performance requirement for civil aircraft. Then adjust the second cohort actuation system design. During the detail design procedure, it is impossible to find any actuator information because that is quite sensitive so it's all confidential. So the designer researched the method for weight, power and heat rejection method and then gives a briefly estimate about this characters.

The flight simulation is using Matlab to create aircraft 6-DoF model and perform simulation with aerodynamic data from Datcom, then output the simulation results to visual platform FlightGear. The visual platform is designed with Flying Crane 3D model to make the simulation result reliable. The design procedure is export Catia model to AC3D and then converts it to .AC model which can be used in Flight Gear. Then writing XML files to drive the models.

Keywords:

CCAR25, 3E， EHA, EMA, power density，heat rejection， heat pipe, AC3D, flight simulation, visual platform.

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1 Introduction

1.1 Introduction

This report gives a preliminary design of actuation system for Flying Crane which is a 130-seat level civil aircraft based on AVIC GDP program.

1.2 Project description

1.2.1 Design status

First cohort designer demonstrated that the EHA system and the variable area actuation system are both feasible for FCS in civil aircraft applications [1]. While the second cohort designer chose EHA to design actuation system, and also abandoned hydraulic system to design this aircraft as a all-electric aircraft (AEA) [2]. The designer already give a briefly design, so my work is to complete this work based on him.

1.2.2 Specification

According the reports of first and second cohort, the author found the data of specification of control surfaces while the Torque are found in Tang Kebing's report.

Table 1-1control surfaces specifications

Control surface	No	Deflection Angle (°)	Torque (KN.M)
Elevator	2	25	10.185
Rudder	1	20	8.964
Aileron	2	20	3.168
Horizontal Stabilizer	1	12	
Flap	2	40	1.391

Slat	10	25	0.9757
spoiler(inside)	2	50	
spoiler(outside)	4	50	

1.2.3 Project objectives

1) Analysis the requirement of actuation system
2) Modify the architecture
3) Estimate the actuation system power
4) Estimate the actuation system weight
5) Heat rejection system design

1.3 Summary

This chapter introduced the background of this actuation system design and showed the objectives of design. Next chapter will address on the requirement analysis for the system.

2 Requirement analysis

2.1 Airworthiness requirement

For a civil aircraft, it must compliance the airworthiness requirement. And the main market is China, so first we consider China Civil Aviation Regulation 25(CCAR 25). After read through CCAR25 [3], the author Actuation system has to compliance these requirements below.

2.1.1 CCAR-25.671 General

This is original form mechanical control system requirement. Since mechanical control pass control signal through pulley cables or rods which will leads to lots of friction force or stuck somewhere in the transfer process. And the control force become bigger and bigger even over human force range as aircraft become bigger. This regulation is designed to keep this kinds of situation which will lead to hazard accident won't appear. While Flying Crane control system is electrically signaled that don't have this kind of problems. EHA and EMA are independent actuators, Actuator Control Electronics (ACE) receive signal from flight control computers and transform digital signal to analog signal them pass it to actuator. In this progress will not involve any friction or stuck. So this regulation is not applicable for a Flying Crane actuation system. The only control unit in Flying Crane need to consider this is side-stick in this stages nobody in charge of that part because of limited human source.

(a) The main components of actuation system are actuators cables and ACE. For avoid misassemble every cables and ACE and ACE ports first will use prevent misinsertion method to design. Different actuator use different cables and combine cables together to reduce the chances of misassemble of Mark the parts can't use prevent misinsertion.

(b) Actuation system is quit important system for flight safety. Especially now no aircraft designed fully with PBW. Therefore during the design progress it should be contain both analysis and test to ensure the safety.

2.1.2 CCAR-25.672 Stability augmentation and automatic and power operated systems.

This plane doesn't have damper actuators for stability augmentation. It uses FCC to control surface actuator to simulate this function. So author doesn't need to consider about this.

2.1.3 CCAR -25.675 Stops

In hydraulic actuation system, through control the servo-valve to hold the pressure in hydraulic actuator to stop surface moving. Using stroke to limited the surface motion range. EHA has a hydraulic package inside so it uses the same strategy to achieve stop function, while it is a little hard for EMA. There are two methods in engineering. First: using ratchet wheel and pawl mechanism. When actuator starts rotating it just only run one direction and after it stops ratchet wheel and pawl mechanism lock it. Another one is using brake lock. Unlock brake lock and run the actuator and the lock it after finished. These two methods both have disadvantages. So the stop function of the EMA need consider seriously in design progress.

2.1.4 CCAR-25.681 Limit load static tests.

The components need to satisfy this requirement is actuator and attachment. The actuator stall load required bigger than maximum aerodynamic load. The attachment structures have to bear the force of actuator. And also stiffness of those structures need strong enough for preventing structure morphing and oscillation. Those all need to be tested by experiment.

2.1.5 CCAR-25.683 Operation tests

This regulation is for mechanical control system while electrically signalled system won't have this problem. Instead of this it will have problems like frequency response and response rate etc. This has to be considered during design progress.

2.1.6 CCAR-25.685 Control system details

Flying Crane is FBW flight control system, so it won't have this problem.

2.1.7 CCAR-25.697 Lift and drag devices, controls

The actuation system must have the function for maintain lift and drag devices at certain position given by stability and control performance requirements.

For prevent the inadvertent operation, the ground spoiler and other control surface which won't use in flight should be locked in flight and other mechanism to limit the surface deflection angle.

The actuation system must have high frequency response for satisfy the flight quality requirement.

The actuation system must have the ability to retract the high lift devices at any speed below V_F + 9.0 (knots).

2.1.8 CCAR-25.701 Flap interconnection

According different flap or slat control design the flap or slat must account for the applicable unsymmetrical loads or the motion of flaps or slats on opposite sides of the plane of symmetry must be synchronized. And also the one side engine failure and one side flap or slat jamming.

2.2 Reliability and safety requirement

Flight control is an extremely important system; any control loss of aircraft will lead to catastrophic accident. The author use the follow philosophy to design for satisfies the reliability requirement.

(1) System won't have common mode/common area faults

(2) System component separation

(3) System functional separation

(4) Dissimilarity

(5) High reliability

2.3 Maintainability requirement

Aircraft operating costs is much higher than design and manufacture fees. Considering the maintain requirement in design process is a most effective method to reduce this cost.

Use Line Replaceable Units (LRU) in design to reduce the repair time.

Arrange the components near openings.

Design the attach components easy to disassemble.

Design the system for easy find out failure components and where it located.

2.4 Function requirement

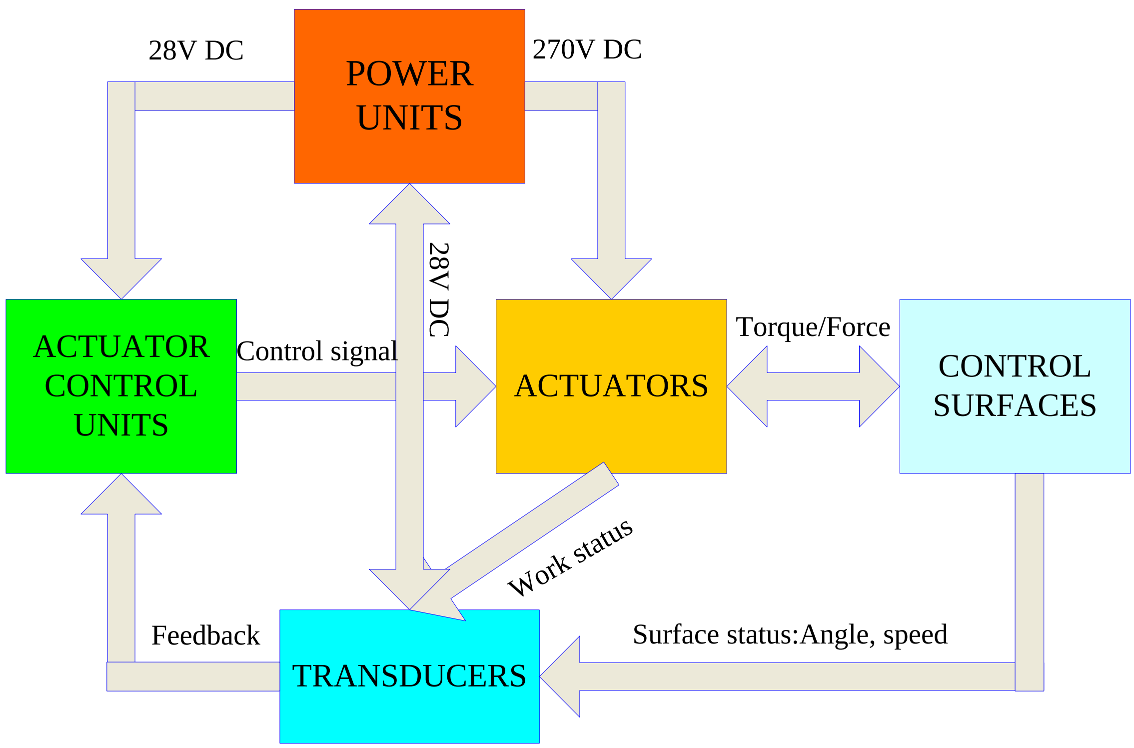

Figure 2–1 Actuator system function and interface

Table 2-1 Actuator control surfaces and stalk

Control surface	No	Deflection Angle (°)
Elevators	2	25
Rudder	1	20
Ailerons	2	20
Horizontal Stabilizer	1	12
Flaps	2	40
Slats	10	25
spoilers(inside)	2	50
spoilers(outside)	4	50

The actuation system function figure showed in Figure2-3. It includes 5parts. Actuators control units sent control signal to actuators and put through the power of actuators and then actuators follow the command to drive control surfaces. Transducers at actuators and control surface sent feedback signal to control units. According to the task allocation, the actuation system mainly includes flight control actuators. So the actuators for landing gear is belong to landing gear designer. The maximum surfaces deflect angles have been defined by previous students. Detail information given in Table 2-1.

2.5 Specification requirement

Since there is no published EPA actuators design information for the reason of commercial confidence and quite a few aircrafts used that, so the author has to derive those requirements from hydraulic actuators.

2.5.1 Stall load

Stall loads are based on the maximum aerodynamic hinge moment predicted at any point in the flight envelope. Using this number makes pilot can operate aircraft at any flight situation and prevent two big output forces to damage structures. According to different architecture the stall load has three parts:

Minimum required output thrust.

Minimum single-system thrust.

Maximum static-output thrust.

The stall loads of Flying Crane were calculated by second cohort and still some haven't finished.

Table 2-2 control surface stall loads

Control surface	No	Torque (KN.M)
Elevator	2	10.185
Rudder	1	8.964
Aileron	2	3.168
Horizontal Stabilizer	1	
Flap	2	1.391
Slat	10	0.9757
spoiler(inside)	2	
spoiler(outside)	4	

2.5.2 Maximum rate capability

The required actuator rates are usually defined at no-load conditions and about 60 to 70 per cent of the stall load, for two-system and single-system operation. It has to satisfactory pilot-handling qualities. Also, the requirements of automatic flight control systems. While in this state of art and design stages both actuator factories and flight quality designer cannot provide this requirement. So the author has to estimate this number based on civil aircraft hydraulic actuators. In later chapter will provide detail estimate progress.

2.5.3 Frequency response;

For the handling quality sake the actuator must achieving the required performance for the specified range of frequencies and amplitudes. It is invariably intended that the characteristics are as close to linear as possible. The basic first-order response is the primary factor in determining the actuation-system response bandwidth. The higher-order terms cause variations from the basic response, and can result in undesirable resonances which amplify response at some frequencies. Such linear properties will be evident throughout the broad mid-range of amplitudes.

In specifying the required performance it is necessary to set frequency response gain and phase-lag boundaries which must not be violated and meeting these criteria will determine the feedback control gain. Variations from linearity occur throughout the working range, but these are normally small enough to be acceptable; it is at extremes of input amplitude that significant deviations from linearity become evident on the frequency response.

For the limited data, the author choose to use the typical frequency-response boundaries.

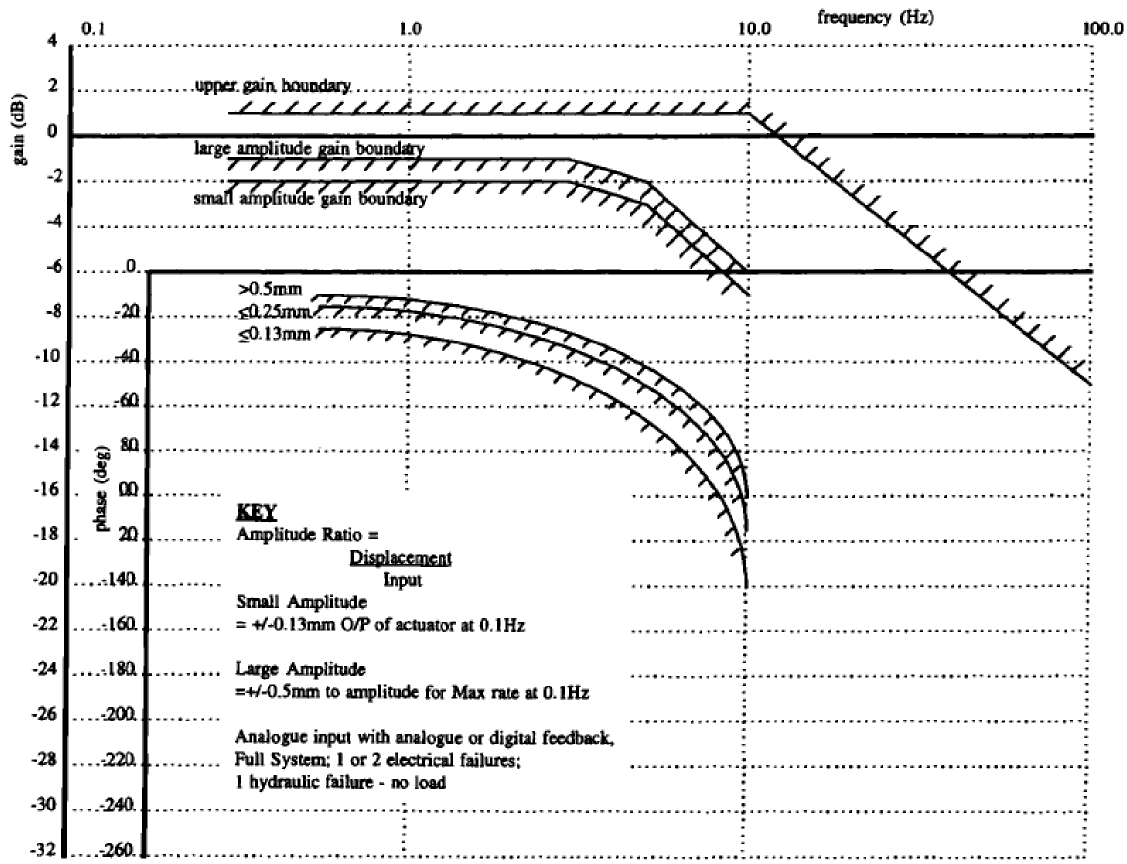

Figure 2–2 Typical frequency-response boundaries [4]

2.5.4 Dynamic stiffness

The criteria usually specified for dynamic stiffness are based on the need to avoid control-surface flutter. There are no specific criteria set out for the lower frequency range associated with flight control system design, as the impedance which is present in the basic design is generally sufficient and no design constraints need be imposed.

At the higher frequencies associated with flutter it may be critical that the actuation system contributes enough stiffness, in conjunction with the stiffness of the backup structure, to the control-surface rotation mode so that the flutter-speed margins are met. The margins with a fully operational actuation system will be greater than when failures are present.

The overall dynamic stiffness includes the effects of attachment and output structural stiffness. Here is a picture of typical impedance-response boundaries.

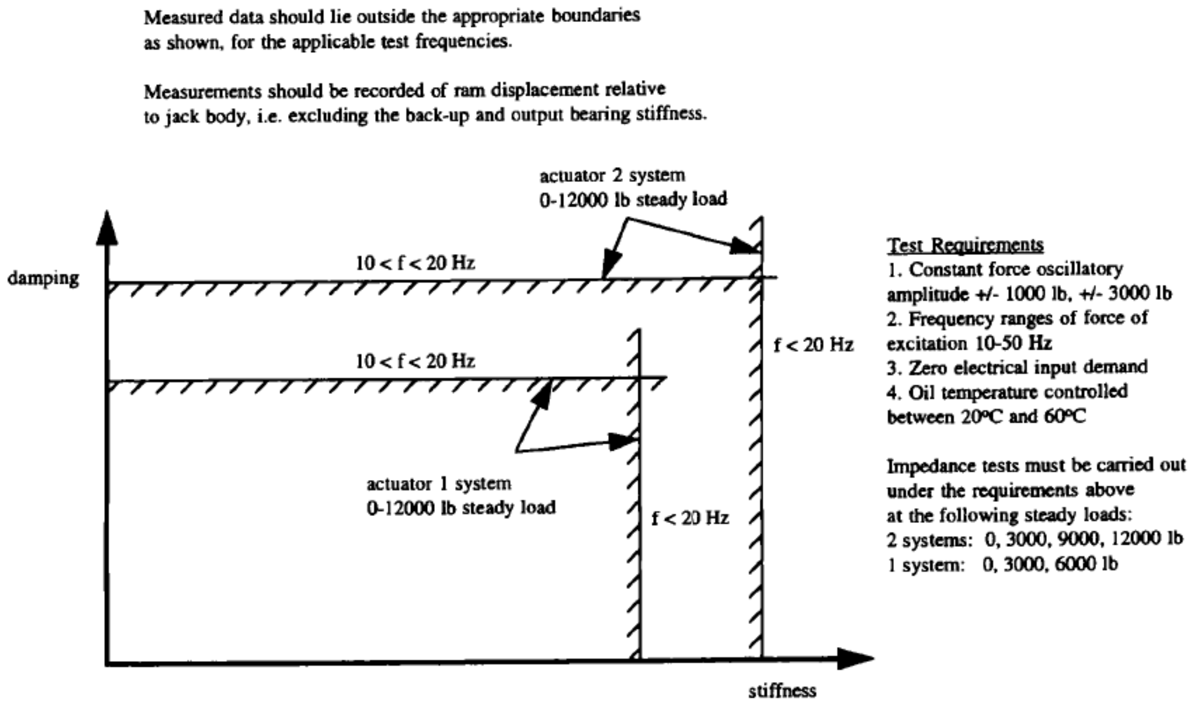

Figure 2–3 Typical Impedance-response boundaries [4]

2.5.5 Failure transients

Actuators failure transients' requirements are defined as boundaries on the ram-to-body displacement following the occurrence of the failure. Different classes of failure must be considered, including electrical-lane failures, hardover failures (for example, one lane of a multilane electric motor demands full current, requiring the other lanes to compensate, until the failure is confirmed and isolated, as well as to control the actuator) and power-supply failures. The actuation system is assumed to be in a state of steady equilibrium prior to the failure, with or without a steady applied force. The class 1 boundaries apply to a first failure or a second failure if the first failed lane has been switched out. The class 2 boundaries apply to a first electrical power failure and subsequent electrical control signal failures. Failure transients are particularly affected by intersystem force fight and actuator motor characteristics, requiring a high-fidelity actuator model to predict results accurately.

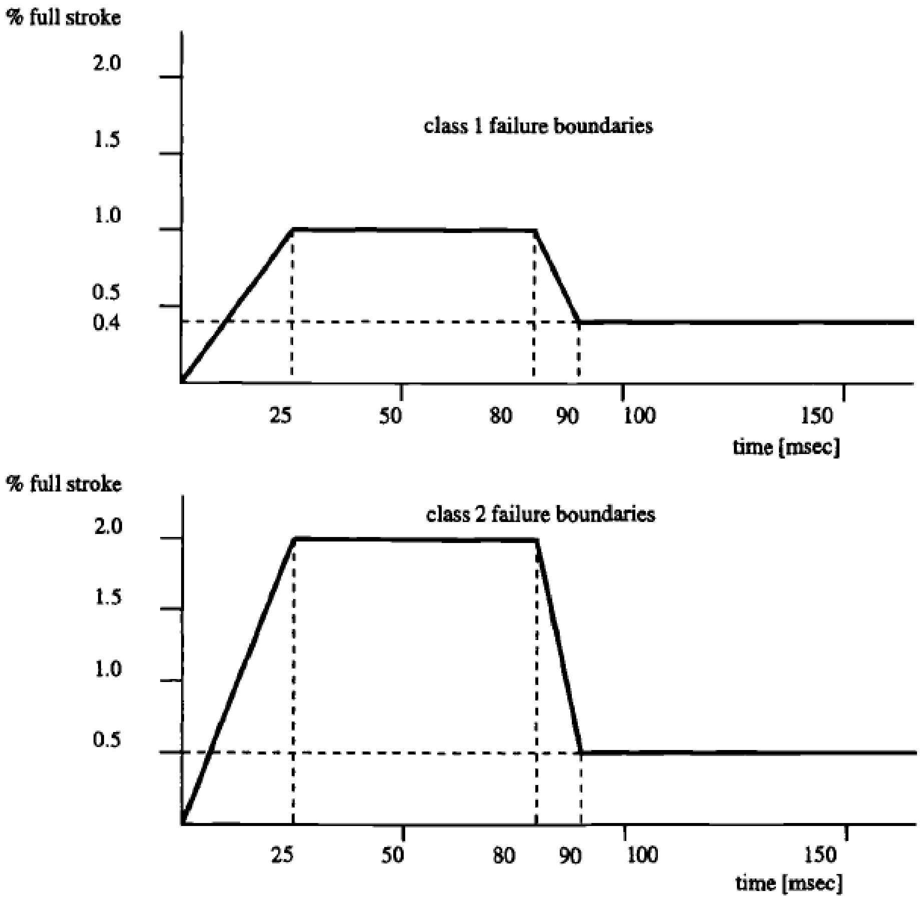

Figure 2–4 Typical failure-transient boundaries [4]

2.6 Summary

This chapter defined the requirements for actuation system design. In those different categories they have some similar entry.

3 Actuation system architecture

3.1 Introduction

Since Flying Crane is the same size as A320 and B737 but used EPA instead of hydraulic actuator. While no aircraft using EPA as primary control actuators so it need to investigate both traditional actuation system and new aircraft using EPA as secondary actuators. Boeing and Airbus are the most successful aircraft company in the world and they use different actuation system. Then author chose A320, A340, A380 and B777 to research before architecture.

3.2 Civil aircraft actuation system architecture analysis

3.2.1 A320

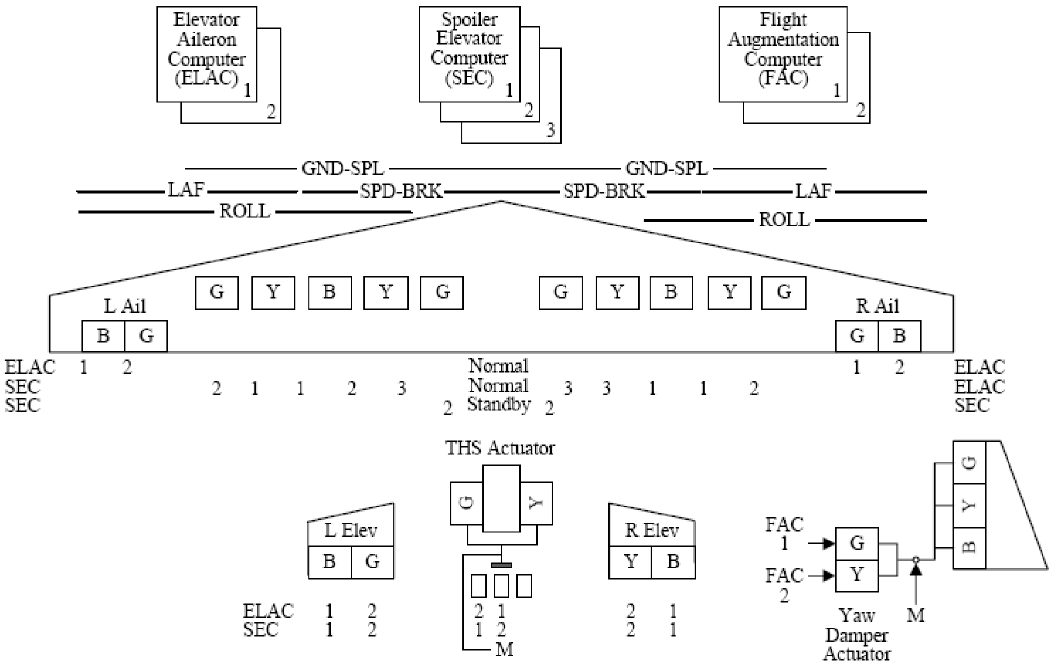

Figure 3–1 Actuation Architecture of Airbus A320[5]

It can be seen from the architecture figure that A320 is a high redudancy actuation system. Power is supplied by three different hydraulic system blue green and yellow. Two pairs acatuators on each aileron and 4 pairs spoiler worked together as roll control surfaces. The control signals are provided by two

Elevator/Aileron Computers (ELACs) and Spoiler/Elevator computers (SECs). The pitch function is given by two pair elevators and horizontal stabilizer. Elevators controlled by two ELACs and two SECs and horizontal stabilizer controlled by mechanical channal. Yaw control surfaces are also driven by mechanical channel. As the first all digital control aircraft A320 have a one backup in low reliability parts as control units. And it also kept mechanical channel in the most important yaw control function.

3.2.2 A330/A430

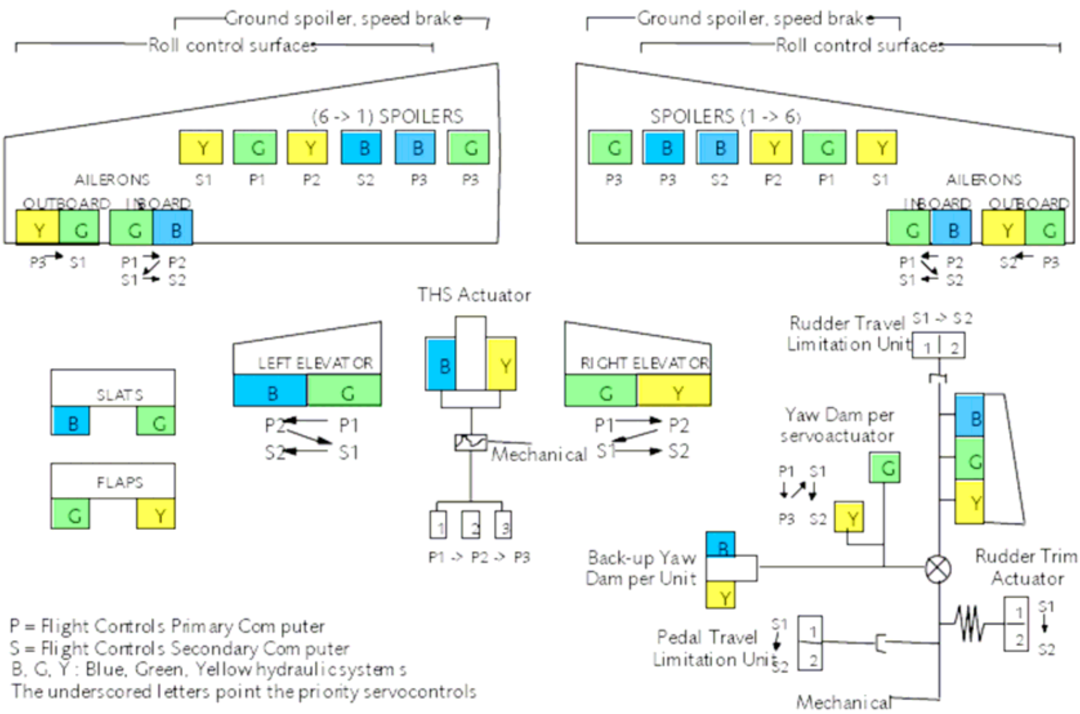

Figure 3–2 Actuation Architecture of Airbus A340 [6]

The A330/340 actuation system bears many similarities to the A320 heritage. Power system is the same as A320. There are two pair inboard and outboard ailerons because the outboard ailerons are not used during high speed flight. The A330/A340 are quite big aircraft, the aerodynamic force at wing tip is quite high in high speed flight scenario which will lead to wing twist. And wing twist will cause aileron control reversal. So the outboard ailerons are locked during high speed flight. While only inboard ailerons cannot fulfill the roll mission in low speed flight and that is the reason why outboard ailerons exist. Airbus duplicates the control signal of inboard ailerons compared to A320.

3.2.3 A380

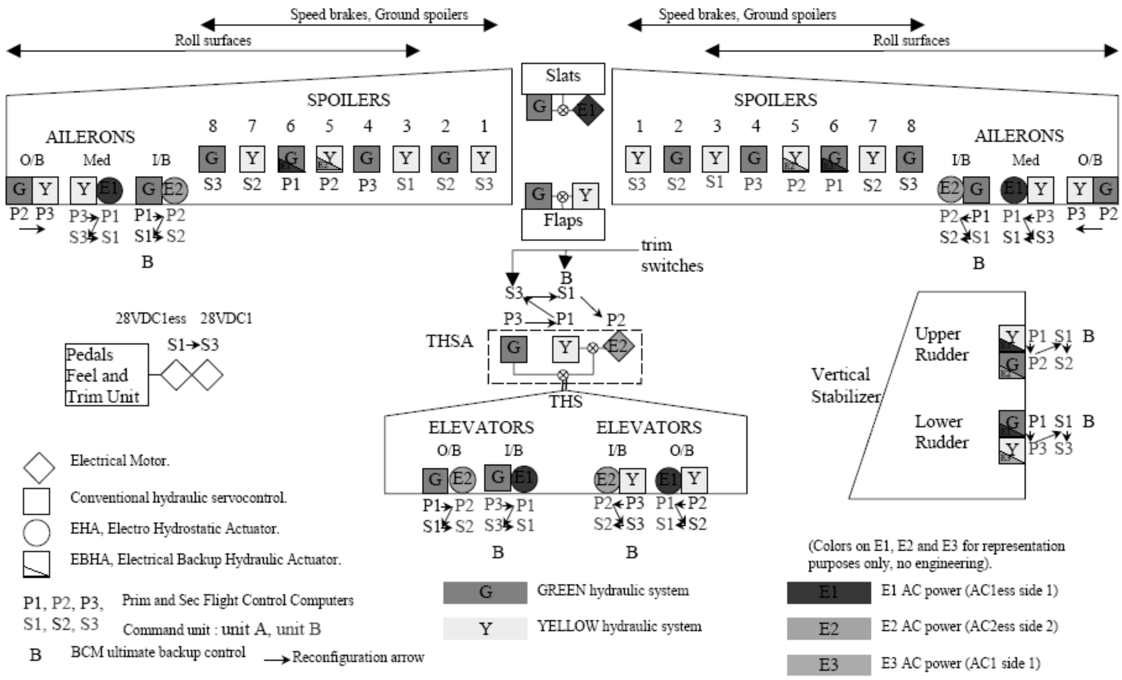

Figure 3–3 Actuation Architecture of Airbus A380 [7]

A380 is the first civil aircraft using EHA in primary flight control systems and also the first Airbus aircraft removed all mechanical control channels. A380 belongs to the very large aircraft. The control surfaces are quite big for provide enough control force. But big control surfaces need quite big control force which given by a quite huge actuators. Huge output actuators will result in structure design problems and using several medium actuators work together will generate force fight problems. Airbus chose divide the big control surface into two medium one. This strategy avoids all the problems and also can use A330/A340 design experience in it.

The actuators power systems are 2H+2E. each primary control actuator has two control signall except outboard ailerons acatuators as A330/340.

3.2.4 B777

The Boeing777 is the first Boeing Fly-By-Wire (FBW) aircraft. The actuation system is a hydraulic powered ACE controlled using FBW actuators system. The power supply is the same as Airbus. Instead of use flight control computer it uses ACE to control actuators. Each actuator only has one control signal except two spoiler's actuators and two horizontal stabilizer actuators.

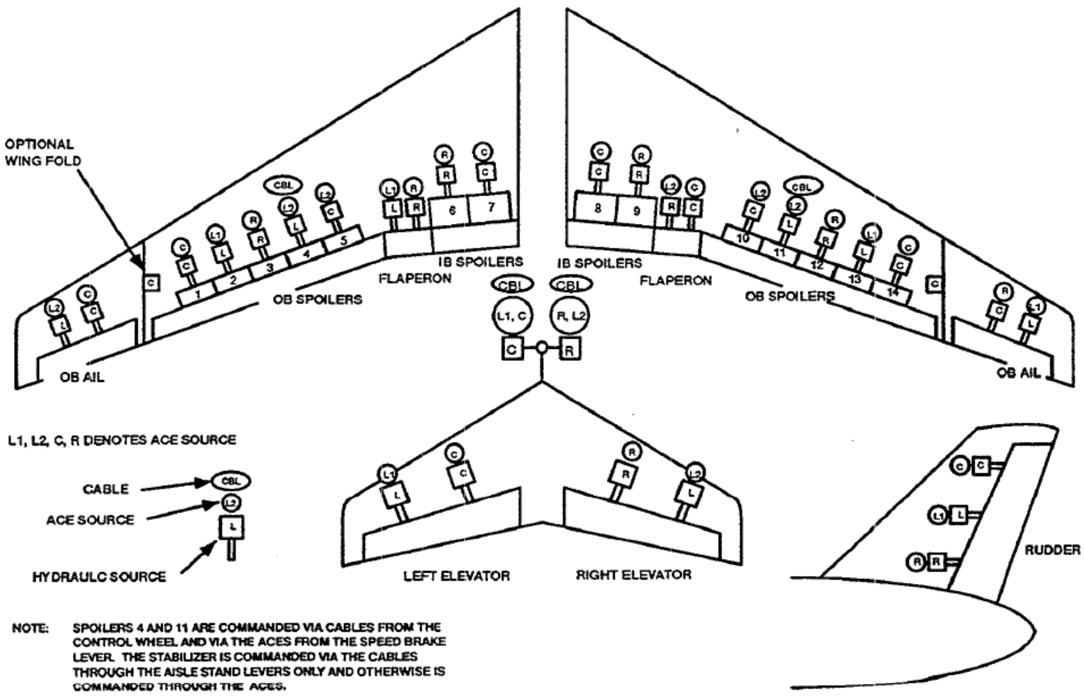

Figure 3–4 Actuation Architecture of Boeing 777 [8]

3.2.5 Conclusion

1 each control surface can have two actuators.

2 main control function roll pitch yaw power supply have triple redundancy

3 main control function roll pitch yaw control signal have triple redundancy

4 each power system power nearly the same amount actuators

5 each actuator system control nearly the same amount actuators

The Boeing actuation system is simpler and more integrate than Airbus.

3.3 Flying Crane actuation system architecture analysis

The Flying Crane actuation system architecture designed by second cohort is based on A340. The primary actaution system is designed well but the high lift devices system has some disadvantages.

First of all, so many flaps drived respectly hard to keep them work sysmmetrily. And the flaps didn't work designed to have a roll augmatal function. So I use a centralized EMA to position the flap system.

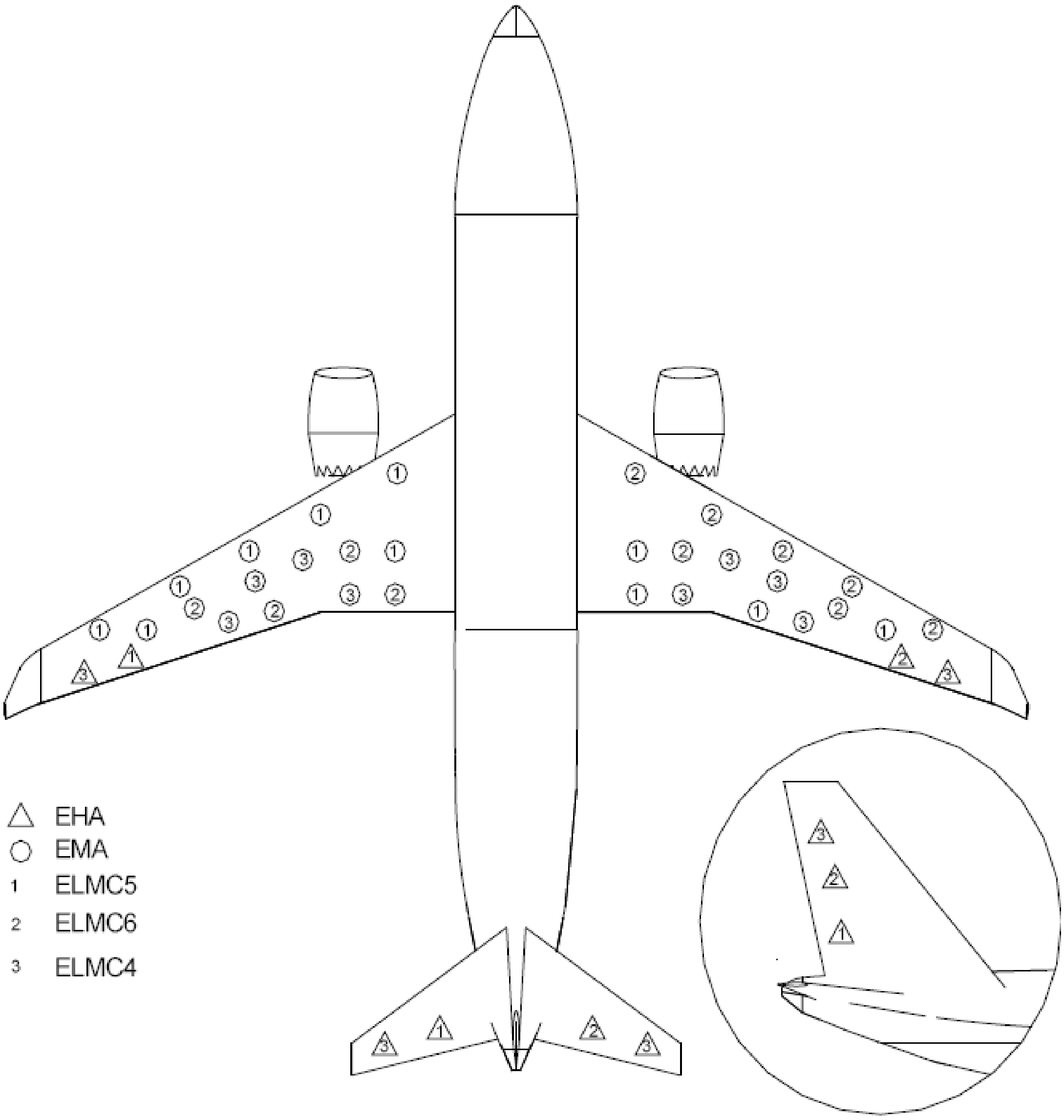

Figure 3–5 Actuation Architecture of Flying Crane [2]

3.4 Flying Crane actuation system modification

3.4.1 High lift system adjust

Flying Crane Flaps and designed to generate more life during takeoff and landing stage. It doesn't have other functions like roll augmentation. So use distributed actuation design will greatly increase the control system design difficulty for compliance CCAR-25.701. So the actuator of each flaps were removed and set two EHAs in the centre to position the all the flaps.

Slats are used on high attack angle to defer airflow separation. So the actuator of each slats were removed and set two EHAs in the centre to position the all the slats for the same reason with flaps.

3.4.2 Horizontal stabilizer adjust

The pitch control is quite important for aircraft safety. In modern aircraft it should have the same reliability with primary control system. Two EMA and one EHA was set there to position it.

3.4.3 Power supply adjust

Aileron is used for roll control, on the scenario the outside actuator of left aileron is failure, we can not control the right side outside actuator for the reason it will lead to uncertain roll response. So it's better to design the power supply summarily.

Centre Spoilers on each side are used for roll augmentation during flight, so the power supply of these spoilers should considered with aileron together.

3.4.4 Control channel design

Flying Crane has four ACEs which are located in the electronics bay. Four ACEs provide the interface between the FBW analogy domain (crew controllers, electrohydraulic actuators and electric actuators) and the FBW digital domain (digital data buses, PFCs, AFDCs, etc.). The ACEs provide excitation and demodulation of all position transducers and the servo loop closure for all flight control surface actuators and the variable feel actuators. Each ACE contains three terminals which comply with the AFDX specification to communicate with the data buses. In Direct Mode, the ACEs do not respond to commands on the digital data bus but instead provide simple analogy control laws to command the surface actuators directly. Figure 3 shows the functions performed by the ACEs. Figure 3-6 shows the electrical power distribution for PCUs to which ACEs provide electrical control.

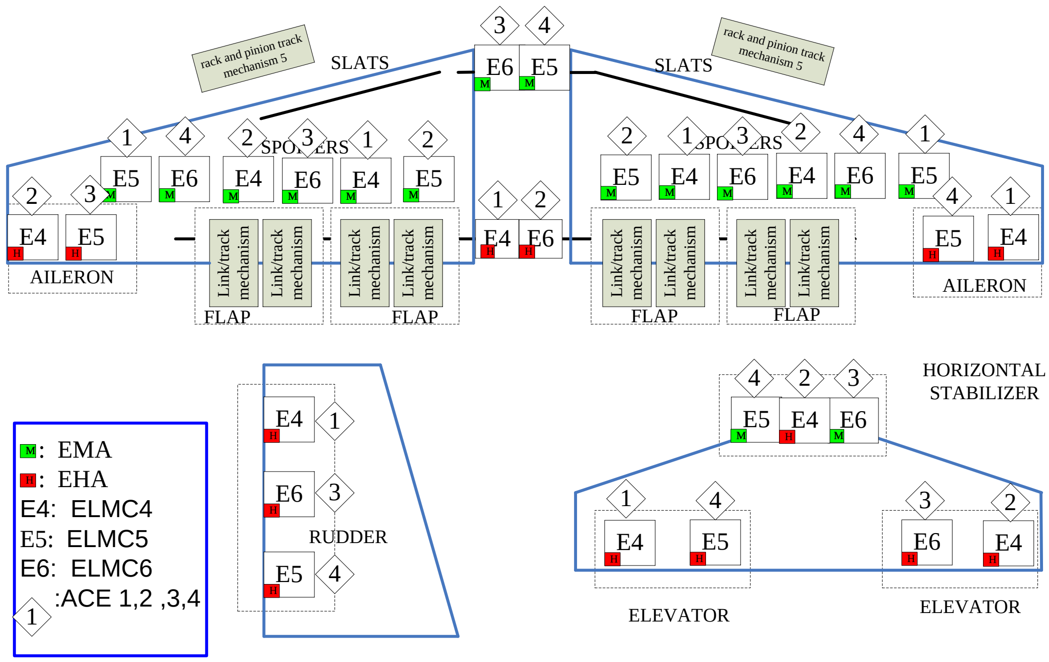

Figure 3–6 Actuation Architecture of Flying Crane 2

3.5 FHA analysis

According to system development processes which is required by SAE4754, Safety design is an indispensable part of the system. The following graph shows the system design process:

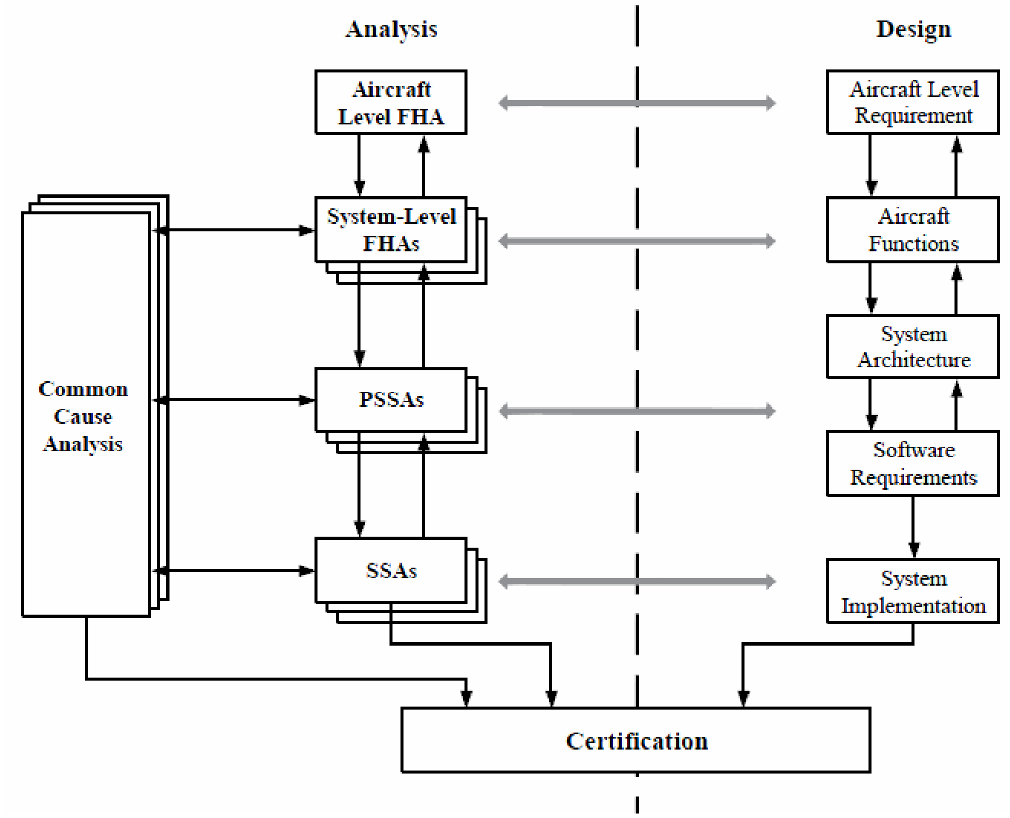

Figure 3–7 simplified portrayal safety processes [9]

According to Figure 3-7, the right side of this graph illustrates the system development process; the left side of the graph demonstrates the safety design process. The FHA is used to identify system failure mode and the effects which were caused by these failures. The PSSAs is used to examine the failure conditions according to system architecture, and direct the system design to meet the safety requirement. During the safety assessment, the method we used is based on ARP4761, the first step is system function allocation and requirement analysis, the next step is system architecture design and system function hazardous assessment based on the results of the first step, followed by PSSA which will examine the system architecture whether it can meet the safety requirement or not, In the PSSA analysis, the FTA method will be used. The results of FHA can be seen in Appendix F. Here, we chose one case to demonstrate the process of safety assessment. From the results of FHA, it can be found that the function of loss of essential loads power supply control effects flight safety, its functional hazard has been defined as category Ⅰ (catastrophic) .

So, this function is chosen for demonstration. The detailed fault tree analysis can be seen as follow.

3.6 Summary

Airbus and Boeing aircraft actuation system was analyzed in this chapter. And second cohort Flying Crane actuation system design has some disadvantages compared with Boeing and Airbus design. So the designer amended the actuation system design to a centralized high lift control system and 3H primary flight control system. It integrated with ACEs and power supply system to make each control and power channel have the same work load.

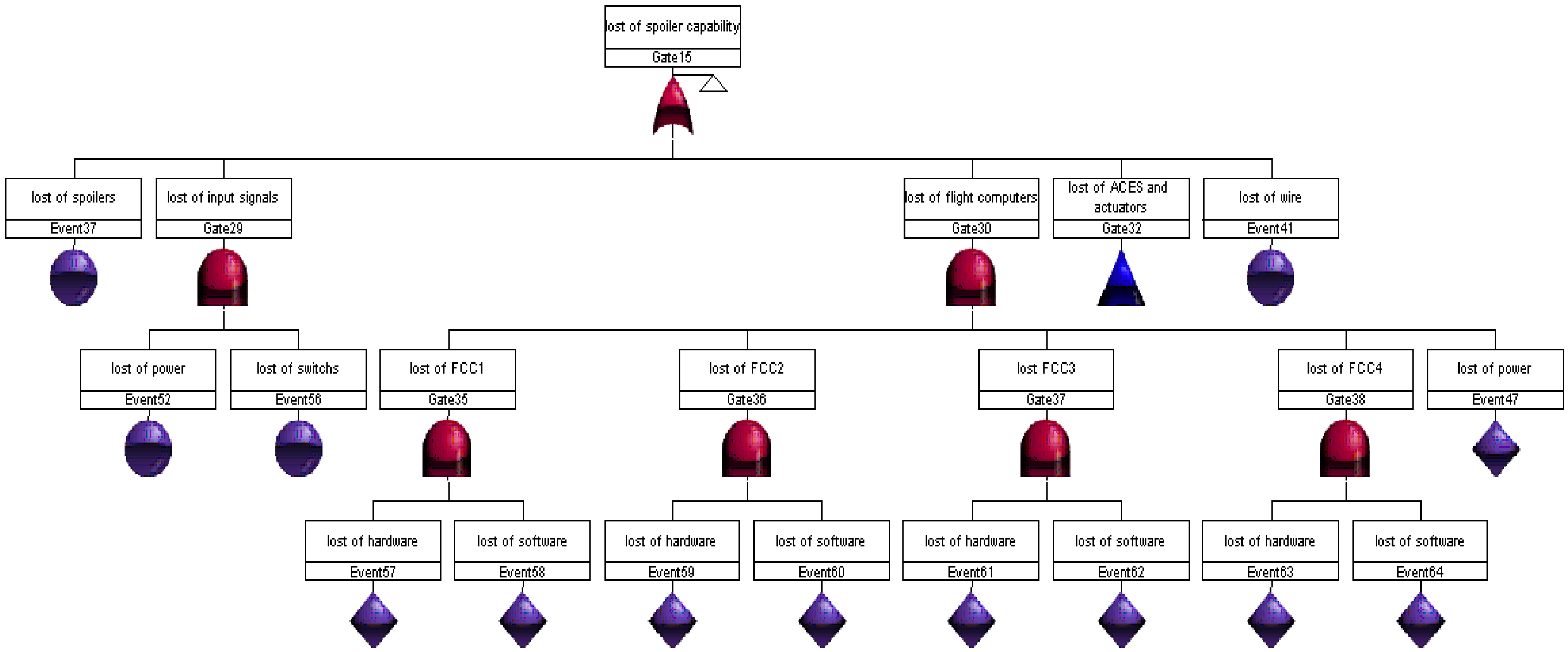

Figure 3–8 Roll function EHA analysis 1

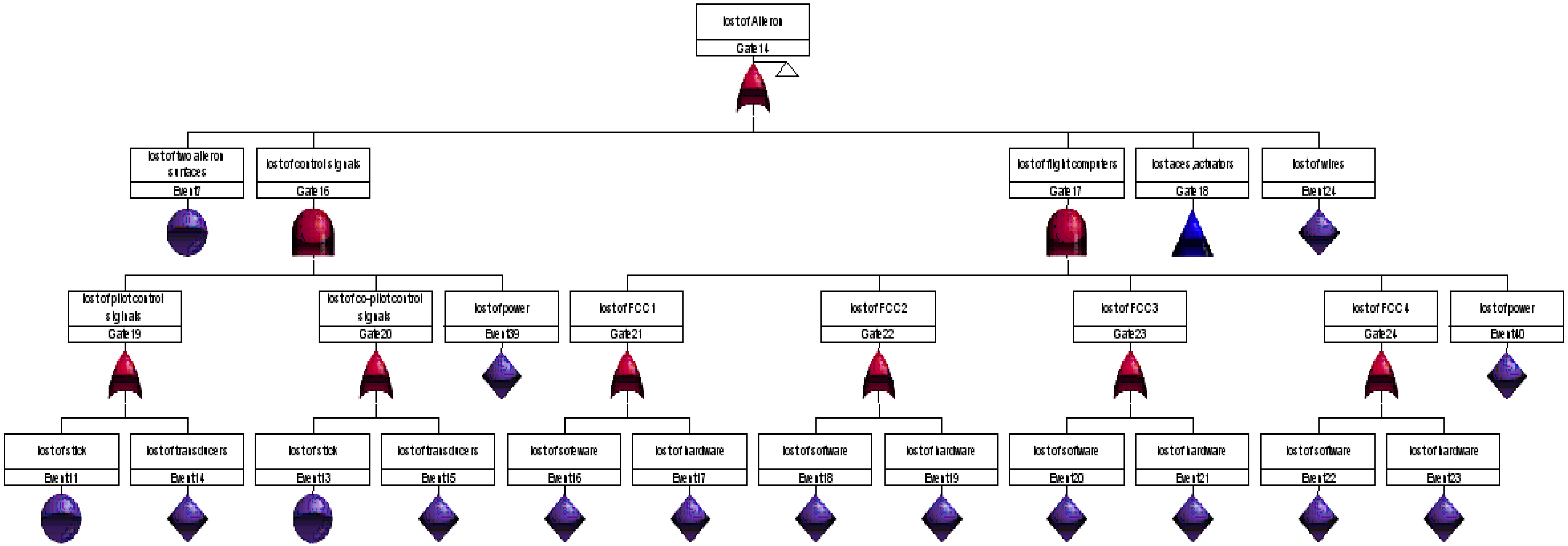

Figure 3–9 Roll function EHA analysis 2

4 Power estimate

EHA actuator is a motor with a hydraulic converter. EMA is the same structure but a mechanical converter. And peak power of the EPA is a constant number determined by control surface load. After looked through internet I chose 0.8 as motor efficiency and converter efficiency.

Table 4-1 Flying Crane power estimate

Control Surface	Torque kN.m	Angle (°)	Time (s)	Power(one side)(kW)	Total power(kW)	Last year (kW)	No.
Elevator	10.19	25	2	3.47	6.94	6.8	4
Rudder	8.96	20	2	2.44	2.44	4.4	3
Aileron	3.17	20	2	0.86	1.727	3.52	4
HS	5.94	12	10	0.19	0.19	1.56	3
flap	11.09	40	5	2.41	4.83	9.2	2
Spoiler (inside)	3.34	50	5	0.91	1.82	18	6
Spoiler (outside)	1.79	50	5	0.48	0.97		6
slat	0.975	25	5	0.133	0.266	10	2

The table showed the comparison between this year and the last year calculation with the method of Ahit Singh Panesar. The rudder, aileron and flap power is half of last year. This is because we use the peak control surface torque to size the actuator and in normal mode only one actuator works, so the peak power consumption should just one actuator's peak power. While in last the designer doubled it for there are two actuators on the surface. No one in charge of high lift system, spoiler and horizontal stabilizer design, in this year, the designer tried to calculate the torque with exiting data while the answer is too small. In the last year the designer chose to estimate the system power by compare to the size of Flying Crane with other aircraft. And the results are too big.

Power estimate:

Assume time =2s

$$P = T \times 1.1 \times 2 \times \pi \times \frac{\alpha}{360} \times \frac{1}{\eta_1} \times \frac{1}{\eta_2} \times \frac{1}{t}$$

P: actuator power output

T: control surface maximum toque

η_1=0.8

η_2=0.8

α: Control surface deflect angle.

The result is showed in table 4-1.

5 Weight estimate

The method used for weight estimation is power density (PD). The first step is power weight ratio calculation. Because the data of actuators are quite sensitive so quit few data was founded. The author found some EHA data of A380 comes from SAE report [10] and Airbus engineer presentation [6].

Table 5-1 A380 actuator characteristics

Control surface	Stall load	Weight	A340/330
Ailerons	13.5T	35/65kg	15.7/10t
Spoilers	22/14.5T	25/65kg	11/8.6t
Elevators	18T	40/80kg	10.2t
Rudders	22.5T	100kg	9.4t
THSa*	85T	380kg	32.5t
*:Loads on trim screw			

A380 has two kinds of EHA used in elevator and aileron control which will be calculate individually.

Elevator EHA:

For the reason no speed or any related information was provided in the presentation slides, so the author decided using A330 data to estimate. The velocity of actuator depends on the flying quality requirement. The pilot said A380 is quite easy to fly so I assume it spends the same time to deflect the control surface to the ordered position with A330. The A330 actuator speed and stroke have got form SAE report.

$S_{380} = S_{330} * L_{380}/L_{330}$ =3.9*79.75/60.3=5.16inch……………………………….(1)

$$V_{380} = S_{380} * \frac{V_{330}}{S_{330}} = 5.16 * \frac{4.7}{3.9} = \frac{6.22\text{in}}{\text{sec}} = 0.158\text{m/s}$$

$$P = 0.7 * F * V_{380} = 0.7 * 18 * 9.8 * 0.158 = 19.51 \text{ kW}$$

$$PD_1 = \frac{P}{M} = \frac{19.51}{80} = 0.244\text{kW/kg}$$

Aileron EHA:

$S_{380} = S_{330} * L_{380}/L_{330}$=3.9*79.75/60.3=5.16inch

$$V_{380} = S_{380} * \frac{V_{330}}{S_{330}} = 4.36 * \frac{4.3}{3.3} = \frac{5.68\text{in}}{\text{sec}} = 0.1443\text{m/s}$$

$$P = 0.7 * F * V_{380} = 0.7 * 13.5 * 9.8 * 0.1443 = 13.364\text{kW}$$

$$PD_2 = \frac{P}{M} = \frac{13.364}{65} = 0.2056\text{kW/kg}$$

$$PD_{avr} = \frac{PD_1 + PD_2 + PD_3}{3} = 0.212\text{kW/kg}$$

The EHA used in JSF aircraft PD number is 0.186. These three numbers are a little different so take the average number as Flying Crane actuator weight estimate.

Table 5-2 actuator system weight estimate

Actuator	Peak Power Output(kW)	Weight (kg)	No	Total weight(kg)	Total power (kW)
Aileron	3.02	14.25	4	56.98	12.08
Spoiler	3.14	14.81	12	177.74	37.68
Elevator	1.16	5.47	4	21.89	4.64
Rudder	3.41	16.08	3	48.25	10.23
Slat	2.42	11.42	2	22.83	4.84
Flap	2.42	11.42	2	22.83	4.84
HS	0.97	4.58	3	13.74	2.91

Total weight: 364.25KG. Total power: 77.22 KW

Table 5-3 A330/340 Actuator characteristics

characteristics	elevator	rudder	Inboard aileron	Outboard aileron	Spoiler
Actuators per surface	2	3	2	2	1
Hydraulics pressure (psi) Fluid	3000 A	3000 A	3000 A	3000 A	3000 A
Hydraulic system Failure capability	Fail-Op/Fail-safe	Fail-op/Fail Safe	Fail-Op/Fail-Safe	Fail-Op/Fail-safe	Fail-Safe
Electrical System Failure Capability	Fail-Op/ Fail-Op/ Fail-Op/ Fail-Safe	Fail-Op/ Fail-Op	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Safe
Fail-Safe Modes	Centering/ Damped Bypass	Damped Bypass	Damped Bypass	Damped Bypass	Surface Down
Servovalves	B	B	B (Yaw damper)	B	B
Output Force(lb)	22900	21100	37100	23800	25000

Extend Retract	22900	21100	37100	23800	19400
Max.Rate(in/sec)	4.7	5.3	4.3	4.3	2.4
Total Stroke(in)	3.9	6.2	3.3	3.0	2.8

A – type IV phosphate ester

B – 2-stage single inlet servovalve

*- Capability at surface level

6 Flight simulation visual platform design

6.1 Flight simulation methodology

Flying Crane flight simulation is using Datcom to generate aerodynamic coefficient and then transfer to Matlab, Matlab using these data and aircraft control law and aircraft 6-DoF model to simulation. The result will input to FlightGear visual platform. The author was in charge of visual platform design.

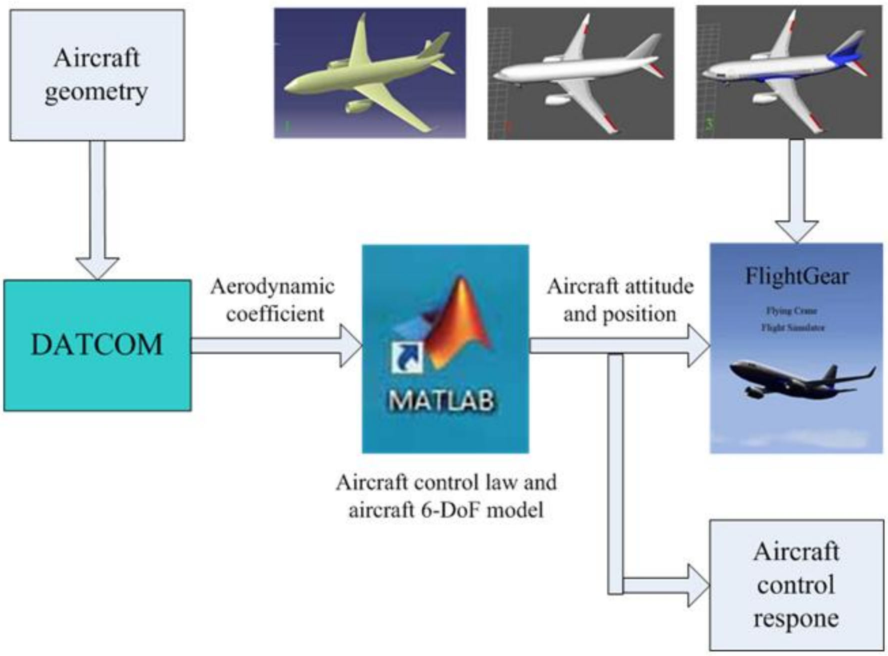

Figure 6–1 Flight simulation architecture

6.2 Visual platform design

Before we design the visual platform, we need to analyze the file configuration.

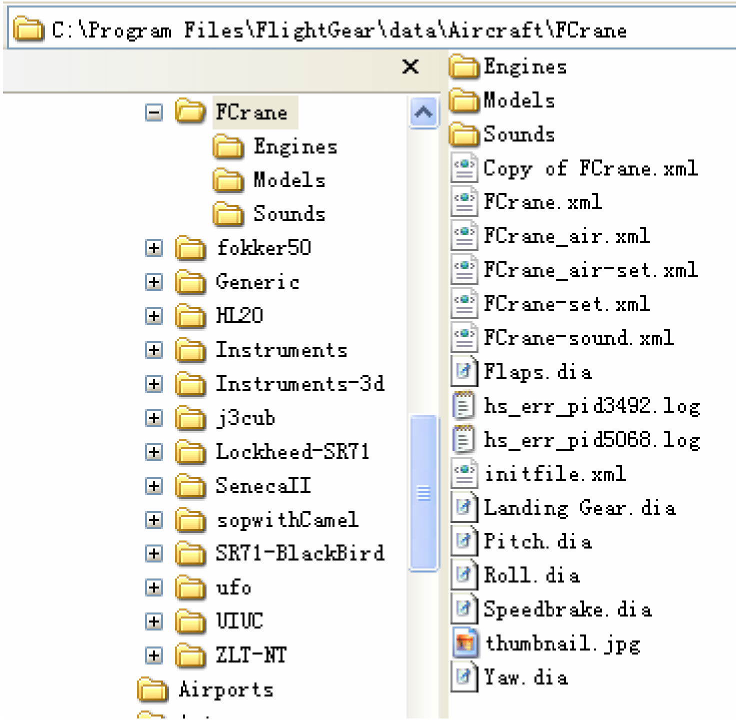

Figure 6–2 file system

As is shown in the **Fig. 6-2**, aircraft model was put into a folder. For Flying Crane the folder named FCrane (as the aircraft root path). There are several information files and folder in side this. **Table 1** list most files in the aircraft model.

Table 6-1 file list

No	Path	Description
1	FCrane\FCrane.xml	The main aircraft data are stored in this file. It curtains mass inertia data, Ground reactions, propulsion, flight control, aerodynamic, and output setup information
2	FCrane\FCrane_set.xml	Initial setup file, it includes the initial position, autopilot setup, engine condition and

		configuration
3	FCrane\Model\FCrane.xml	1) 3D model file name 2) Flight deck display setup 3) Animation (To realized the live display panel)
4	FCrane\Model*.ac	3D model in format of ac This model included: 1) aircraft model 2) FFD display model 3) ENA display model 4) Airspeed indication model
5	FCrane\Enginel*.xml	Engine characteristic setup file
6	FCrane\Sound*.wav	Some necessary sound files

Since we use Matlab to simulation and use FlightGear to show the result. So the work we need to do is No.3 andNo.4. Other files just need to amend slightly.

6.3 Aircraft AC model design

The design process is showed below the same as second cohort:

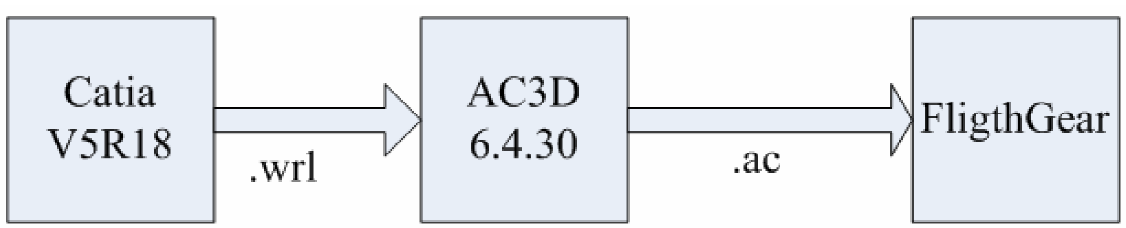

Figure 6–3 model design flow

6.3.1 Convert Catia model AC3D model

The Catia model we used is Flyingcrane_surface_v5. The model doesn't have doors and landing gear and other parts. So we discussed with Catia model team leader Liu Yifei.

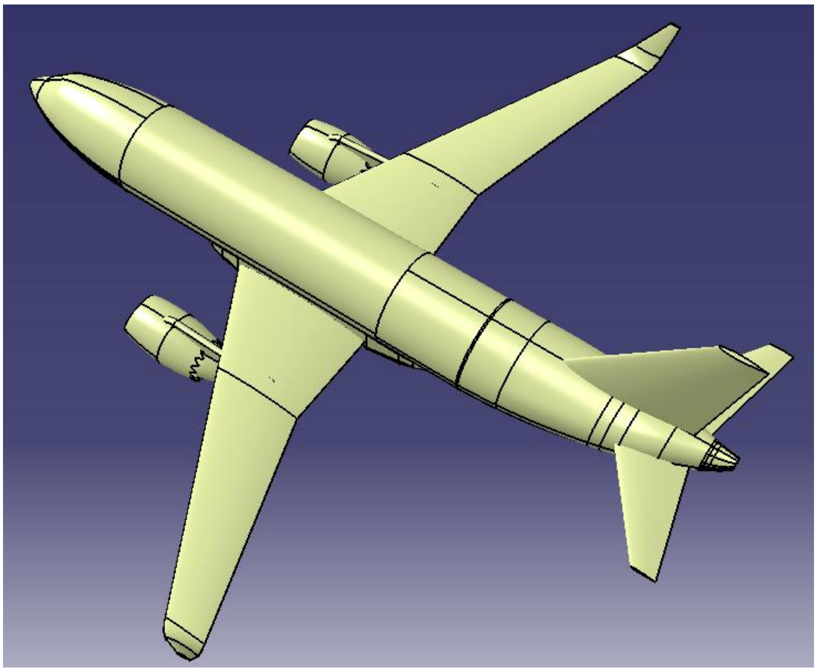

Figure 6–4 Flying Crane Catia model

With the help of Liu and other designers the Catia model was prepared well.

6.3.2 AC3D model design

When we transfer the models to Ac3D, the first problem we met is the Catia model was:

Figure 6–5 AC3D flying crane model

many faces connected together. And in Ac3d it will shows a lot of curves and lines on the model. And we use the optimize surfaces command to regenerate the surfaces, after regeneration all faces will connected together to one face. Then delete the original model, we got an integrated model. Run the command again to reduce the size of model, so FlightGear can run faster with this smaller model.

Then the second problem was met: we can’t separate the moving parts with aircraft. So we have to separate the Catia model first before transfer.

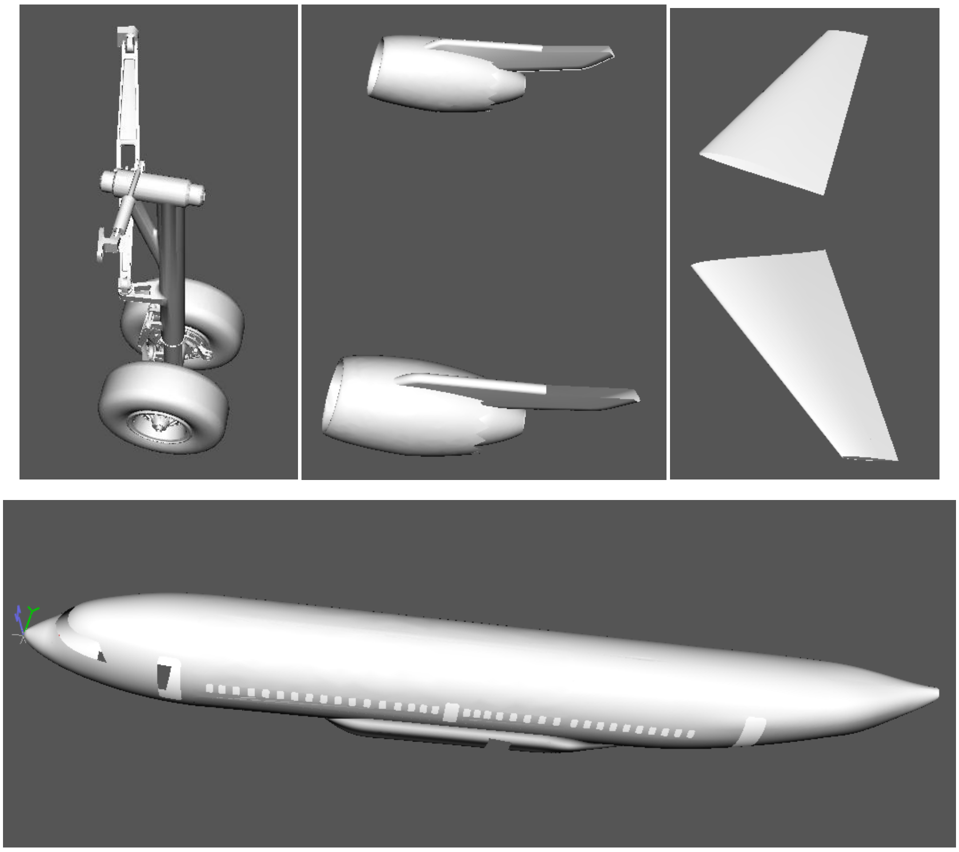

Figure 6–6 Flying Crane parts model

After all parts all transferred individually, the author assembled them together in Ac3D.

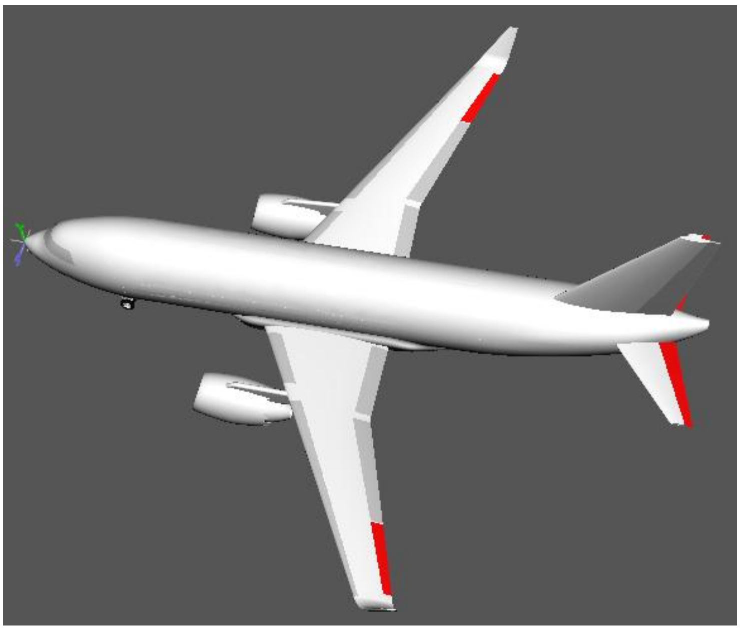

Figure 6–7 Flying Crane assembled model

6.3.3 AC3D model painting design

For saving time we used a B737 painting model to design Flying Crane painting in Photoshop.

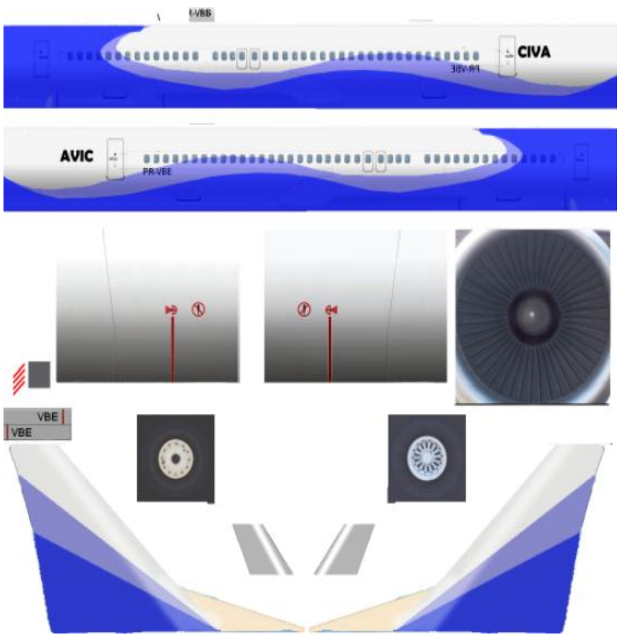

Figure 6–8 Flying Crane painting

Apply the painting on Flying Crane.

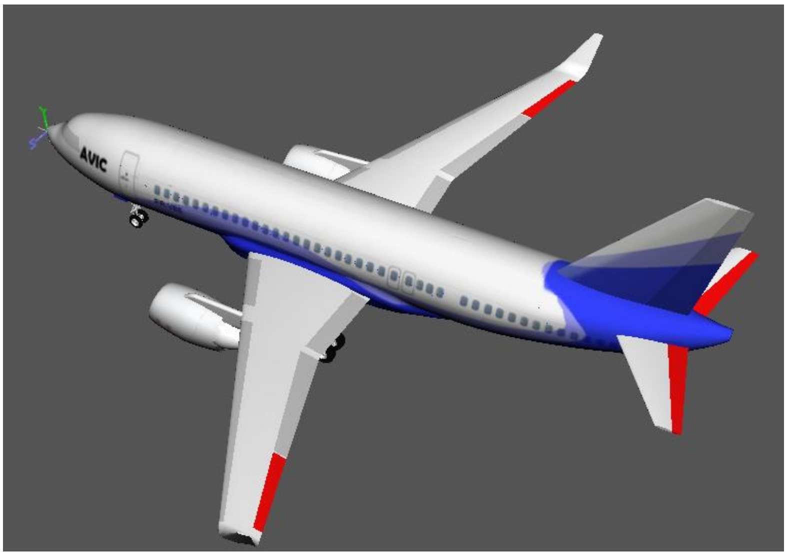

Figure 6–9 aircraft with painting

6.4 Aircraft animation design

Flying crane animation types and method is shown in following tables and details in appendix.

Table 6-2 animation method [12]

Animation parts	Animation method	Examples
Aileron	Rotate	<animation> <type>rotate</type> <object-name>Rudder </object-name> <property> controls/rudder </property> <factor>18</factor> <center>
Rudder	Rotate	
Elevator	Rotate	
Front landing gear	Rotate	
Front Landing gear doors	Rotate	
Left main landing	Rotate	

gear doors		<x-m>5.45</x-m> <y-m>0.0</y-m> <z-m>0.0</z-m> </center> </animation>
Right main landing gear doors	Rotate	
Left main landing gear	Rotate/rotate	
Right main landing gear	Rotate/rotate	
Flaps	Rotate	
Front landing gear wheels	Spin	<type>**spin**</type> <object-name>**FrtWheel** </object-name> <property>**gear/gear/rollspeed-ms**</property> <factor>**10**</factor> - <axis> <x>**0**</x> <y>**-1**</y> <z>**0**</z> </axis> - <center> <x-m>**5.05**</x-m> <y-m>**-0.36**</y-m> <z-m>**-3.75**</z-m> </center>
Left main landing gear wheels	Spin	
Right main landing gear wheels	spin	
Left engine fan	spin	
Right engine fan	spin	

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