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# Architecture Optimization of More Electric Aircraft Actuation System

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**Abstract**

The optional types of power source and actuator in the aircraft are more and more diverse due to fast development in more electric technology, which makes the combinations of different power sources and actuators become extremely complex in the architecture optimization process of airborne actuation system. The traditional "trial and error" method cannot satisfy the design demands. In this paper, firstly, the composition of more electric aircraft (MEA) flight control actuation system (FCAS) is introduced, and the possible architecture quantity is calculated. Secondly, the evaluation criteria of FCAS architecture with respect to safe reliability, weight and efficiency are proposed, and the evaluation criteria values are calculated in the case that each control surface adopts the same actuator configuration. Finally, the optimization results of MEA FCAS architecture are obtained by applying genetic algorithm (GA). Compared to the traditional actuation system architecture, which only adopts servo valve controlled hydraulic actuators, the weight of the optimized more electric actuation system architecture can be reduced by 6%, and the efficiency can be improved by 30% based on the safe reliability requirements.

*Keywords:* more electric aircraft; power-by-wire; actuation system; architecture; multiobjective optimization; genetic algorithms

## 1. Introduction

The architecture of aircraft actuation system is a collection of control surfaces, flight control computers (FCCs), power sources and actuators, which is organized in a certain form. Flight control can be fulfilled through the coordination and collaboration of these system elements. As the actuating mechanism of flight control system, airborne actuation system is an important part of the aircraft. The performance of actuation system can directly affect the overall flight characteristics of the aircraft [1]. With the rapid development of more/all electric technology, power-by-wire (PBW) actuation system will be widely adopted to improve the reliability, maintainability and survivability of the aircraft and to reduce the whole weight greatly [2-3]. PBW actuator normally has two forms: electro-hydrostatic actuator (EHA) and electro-mechanical actuator (EMA) [3]. However, considering the reliability requirements of the whole aircraft, PBW actuation systems have not been independently applied in the primary flight control surfaces due to their immature technology. The PBW actuators are usually applied together with the traditional servo valve controlled hydraulic actuators (SHAs) which belong to the mode of flight-by-wire and power-by-pipe actuation systems and are supplied by the central constant pressure hydraulic source. The so called "2H/2E" (two hydraulic systems/two electrical systems) actuation system architecture is adopted in the Airbus A380 aircraft [4].

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Combining the backup PBW actuator with the active SHA, this architecture has four sets of independent primary flight control actuation systems (FCASs). Two of them are powered by traditional central hydraulic source, and the others which use PBW actuators to maneuver the control surfaces are powered by electrical source. It is seen that "2H/2E" architecture makes the flight control of A380 aircraft achieve unprecedented levels in aspects of system independence, redundancy and reliability.

Larger quantities of the aircraft control surfaces, alternative power sources and actuators lead to extreme complexity of permutations for the different configurations in the design process of the actuation system architecture when the PBW actuators are adopted in the aircraft actuation systems. This brings great challenges to the former architecture design process [5-6].

For the actuation system architecture, most of the current researches only introduce the existing architecture forms which have been used in the present aircraft [3-4,7], but do not refer to deep study on why it is such a configuration. From the current literature it can be found that only Airbus France and University of Toulouse have a preliminary study with branch-and-bound method on this problem [6,8-9]. So some further study will be done in this paper to provide a valuable way for the future application.

In order to simplify the analysis, this paper focuses on the optimization design of the more electric aircraft (MEA) FCAS architecture. By the advanced optimal design method, the aim is to find an optimal architecture configuration which is combination of FCCs, power sources and actuators in the level of whole aircraft to achieve the purpose of smaller size, lighter weight and higher efficiency on the basis of meeting the safe reliability requirements.

This paper is arranged as follows. Firstly, the composition of MEA FCAS is introduced briefly, and the possible architecture quantity is calculated. Secondly, the evaluation criteria of FCAS architecture in aspects of safe reliability, weight and efficiency are proposed. Finally, multi-objective optimization design (MOD) of the FCAS is carried out by applying genetic algorithm (GA), and the corresponding optimization results are obtained.

## 2. Composition of MEA FCAS

The MEA FCAS mainly consists of control surfaces, FCCs, power sources and actuators [2,10], which will be illustrated separately as follows.

### 2.1. Control surface

Flight attitude control and the lift increase are mainly implemented by control surfaces which are composed of primary flight control surfaces and secondary flight control surfaces. The following discussion will focus on the architecture optimization of primary FCAS to simplify the analysis. Considering the design requirements of large aircraft, it is believed that the primary flight control surfaces are made up of two pairs of ailerons, five pairs of spoilers, two pairs of elevators and one pair of rudders, as shown in Fig. 1. Note that the fifth pair of spoilers do not play the role of primary flight control.

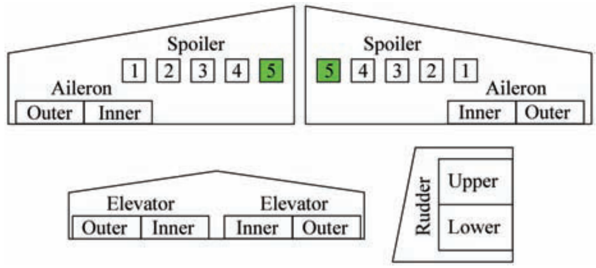


Fig. 1 Schematic of primary flight control surfaces.

### 2.2. FCC

FCC can translate the control commands from pilot or autopilot into input signals for actuators to complete the movement control of the control surfaces. One FCC can master several actuators, and each actuator can be controlled by more than one FCC. In order to meet the reliability requirements of FCC, several FCCs are usually deployed in an aircraft. Here we regard that five FCCs are adopted for the primary FCAS and each actuator is controlled by at least one and up to two FCCs.

### 2.3. Power source

Power source is applied to providing energy for the actuator. As the development of more electric aircraft technologies, power source types of airborne actuation system are more and more diverse. Different actuators need different power sources. Assume that the optional power source types are hydraulic source and electrical source, and both of the power sources have two sets respectively.

### 2.4. Actuator

Actuators are mainly used to drive the control surfaces for completing the aircraft attitude control. The traditional actuators are mainly the SHAs. Along with the rapid development of PBW technologies, there are more optional new actuator types which can be used in the aircraft, such as EHA, EMA and electrical-backup hydraulic actuator (EBHA). In this paper, all of these four types of actuators are in the optional list.

## 3. Possible Architecture of MEA FCAS

For the actuation system of each individual control surface, there are many configuration options which involve several FCCs, diverse power sources and different actuators. The quantity of configuration options $N_{as}$ can be calculated by the following equation according to permutation and combination method [6]:

$$N_{as} = \underbrace{\underbrace{(n_h}_{\text{SHA}} + \underbrace{2n_e}_{\text{EHA/EMA}} + \underbrace{n_h n_e}_{\text{EBHA}})}_{\text{Power sources}} \underbrace{[\underbrace{n_c}_{\text{One}} + \underbrace{n_c(n_c-1)}_{\text{Two}}]}_{\text{FCCs}} \tag{1}$$

where $n_h$ is the number of hydraulic sources, $n_e$ the number of electrical sources, and $n_c$ the number of FCCs.

Based on current experience, two actuators are respectively applied to one piece of aileron, elevator and rudder, and one actuator is usually deployed in one piece of spoiler. Then the quantity of configurations of each control surface can be obtained.

For the aileron, the quantity of configuration options $N_a$ is

$$N_a = N_{as}^2 \tag{2}$$

For the elevator, the quantity of configuration options $N_{ev}$ is

$$N_{ev} = N_{as}^2 \tag{3}$$

For the rudder, the quantity of configuration options $N_r$ is

$$N_r = N_{as}^2 \tag{4}$$

For the spoiler, the quantity of configuration options $N_s$ is

$$N_s = N_{as} \tag{5}$$

If the primary FCAS consists of $n_a$ ailerons, $n_{ev}$ elevators, $n_r$ rudders and $n_s$ spoilers, the total quantity of optional architecture $N$ can be given by

$$N = N_a^{n_a} N_{ev}^{n_{ev}} N_r^{n_r} N_s^{n_s} \tag{6}$$

According to the previous assumptions, we know that $n_h$=2, $n_e$=2, $n_c$=5. So it can be obtained that $N_{as}$=250 according to Eq. (1). And based on Eqs. (2)-(5), we obtain that $N_a$=62 500, $N_{ev}$=62 500, $N_r$=62 500, $N_s$=250. Furthermore, we have $n_a$=4, $n_{ev}$=4, $n_r$=2, $n_s$=8. Finally, the total quantity of optional architectures of MEA primary FCAS can be calculated as $N>1.3\times10^{67}$ by Eq. (6).

Apparently, the total quantity of $N$ derived from the above analysis is a result in the mathematical sense. Actually, many permutation cases in $N$ are not feasible which should be removed in the practical design process because of some technical constraints. In order to meet the relevant technical requirements, the technical constraints in the design of FCAS architecture are proposed as follows [6] based on the previous experience:

(1) Each actuator should be connected to the appropriate power source (e.g. SHA needs to connect to hydraulic source, EHA and EMA should link electrical source, and EBHA should be powered by both hydraulic and electrical sources).

(2) Each actuator should be controlled by at least one and up to two FCCs.

(3) For the aileron, elevator and rudder, two actuators in one piece of control surface should adopt different types.

(4) The spoiler actuator only deploys a single FCC.

(5) The two adjacent spoilers should adopt different architectures.

These constraints can be expressed as the following function:

$$\text{TC}=\begin{cases}1, & \text{Chosen architecture meets the rules}\\ 0, & \text{Otherwise}\end{cases} \tag{7}$$

## 4. Evaluation Criteria of FCAS Architecture

For the FCAS, the evaluation criteria of architecture configuration mainly include safety, reliability, weight, size, efficiency, power consumption, cost and so on. In order to simplify the analysis, we only focus on the safe reliability, weight and efficiency in this paper, because these three indexes are the relatively important ones. The following section will illustrate these three indexes.

### *4.1. Safe reliability* [11-14]

Safety is very essential for the manned aircraft. The reliability of FCAS is usually measured by two indicators, namely flight safe reliability and mission reliability. Presently, the proposed safe reliability indicator of large civil aircraft FCAS in the world is generally $1\times10^{-9}$/h. So redundancy techniques must be used to achieve such a high reliability index. In this paper we also regard $1\times10^{-9}$/h as the safe reliability constraint of the FCAS optimization.

According to the related practical experience, we assume that the failure rates of related FCAS components are shown in Table 1. Note that the failure rates of the hydraulic pipes, wires and signal lines connected to the actuators as well as the sensors are taken into account in the total failure rates of the actuators.

**Table 1 Component failure rates of FCAS**

| Component | Failure rate/($10^{-7}$h$^{-1}$) |
|---|---|
| FCC | 3 300 |
| Hydraulic source | 1 000 |
| Electrical source | 0.02 |
| SHA | 12 000 |
| EHA | 18 000 |
| EMA | 27 000 |
| EBHA | 6 000 |

In order to quantitatively estimate that whether the designed FCAS architecture can meet the flight safe reliability requirements, the safe reliability block diagram of the whole FCAS is built based on the composition, function and principle of FCAS, as shown in Fig. 2 [15-16].

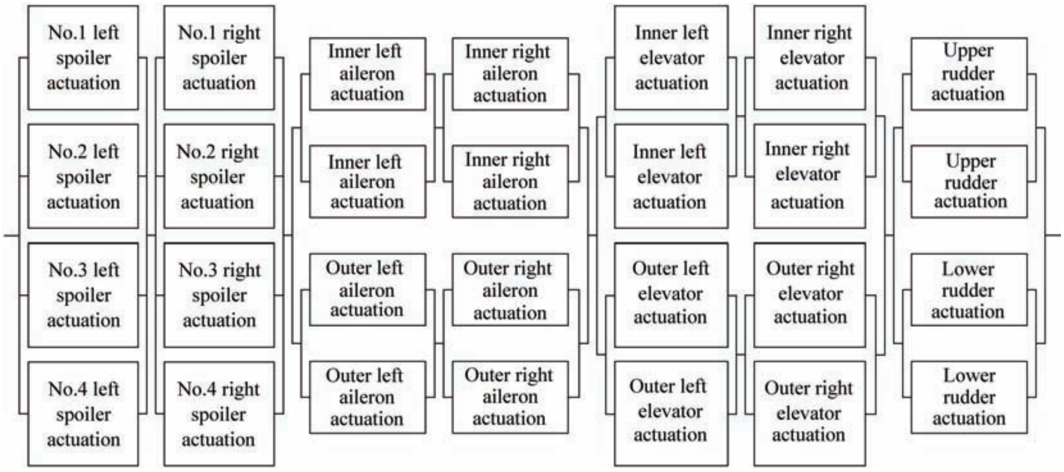


Fig. 2 Safe reliability block diagram of the whole FCAS.

It should be noted that the safe reliability block diagram in Fig. 2 does not suit all the aircraft, and each aircraft has its specific safe reliability block diagram.

Generally, for the MEA, we consider that the performance of the entire FCAS is guaranteed by the collaborative operations simultaneously of spoiler, aileron, elevator and rudder actuation system, so the relations between them are in series.

According to Fig. 2, the failure rate $\lambda$ of the whole FCAS can be written as

$$\lambda = \lambda_{sl} + \lambda_{sr} + \lambda_{a} + \lambda_{ev} + \lambda_{r} \tag{8}$$

where $\lambda_{sl}$, $\lambda_{sr}$, $\lambda_{a}$, $\lambda_{ev}$ and $\lambda_{r}$ are respectively the failure rate of left spoiler, right spoiler, whole aileron, whole elevator and whole rudder actuation system. The specific calculations of $\lambda_{sl}$, $\lambda_{sr}$, $\lambda_{a}$, $\lambda_{ev}$ and $\lambda_{r}$ can be achieved based on the series-parallel system failure rate formula of Fig. 2.

For each type of actuation system, the reliability block diagram is shown in Fig. 3.

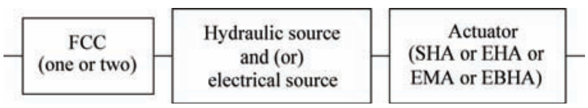


Fig. 3 Reliability block diagram of each actuation system.

Based on Fig. 3, the failure rate $\lambda_{as}$ of each actuation system can be calculated as

$$\lambda_{as} = \lambda_{c} + \lambda_{p} + \lambda_{act} \tag{9}$$

where $\lambda_{c}$, $\lambda_{p}$ and $\lambda_{act}$ are respectively the failure rate of each FCC, each power source and each actuator.

### 4.2. Weight

For aircraft design, weight is undoubtedly a very important indicator. To reduce the weight as much as possible is the goal of the aircraft designers. Therefore, we take weight as an important goal in the whole MEA FCAS architecture optimization.

To facilitate comparative analysis, we use the normalized way to handle the descriptions of weight. The weight of hydraulic source and electrical source is handled by way of conversion based on power mass ratio. The weight sum of hydraulic source, electrical source, hydraulic lines and cables are added to the total weight of actuator. According to the related practical experience, we assume that the normalized weight of each control surface actuator is shown in Table 2.

**Table 2 Normalized weight of each control surface actuator**

| Control surface | Normalized weight | | | |
|---|---|---|---|---|
| | SHA | EHA | EMA | EBHA |
| No.1 spoiler | 0.150 | 0.100 | 0.075 | 0.250 |
| No.2 spoiler | 0.144 | 0.096 | 0.072 | 0.240 |
| No.3 spoiler | 0.138 | 0.092 | 0.069 | 0.230 |
| No.4 spoiler | 0.132 | 0.088 | 0.066 | 0.220 |
| Inner aileron | 0.480 | 0.320 | 0.240 | 0.800 |
| Outer aileron | 0.600 | 0.400 | 0.300 | 1.000 |
| Inner elevator | 0.432 | 0.288 | 0.216 | 0.720 |
| Outer elevator | 0.540 | 0.360 | 0.270 | 0.900 |
| Upper rudder | 0.480 | 0.320 | 0.240 | 0.800 |
| Lower rudder | 0.384 | 0.256 | 0.192 | 0.640 |

Compared to the weight of actuators in Table 2, the normalized weight of FCC can be drawn as 0.080.

In summary, the whole weight $w$ of FCAS can be expressed as

$$w = \sum_{i=1}^{n} w_{ci} + \sum_{i=1}^{m} w_{acti} \tag{10}$$

where $w_{ci}$ and $w_{acti}$ are respectively the weight of the selected FCC and the selected actuator, $n$ and $m$ are respectively the number of the selected FCC and the selected actuator.

### 4.3. Efficiency

For the aircraft design, besides safe reliability and weight of the above indicators, efficiency is also an indicator that cannot be ignored. Improving the efficiency of FCAS can not only reduce the power loss but also reduce the flight cost. Therefore, we also consider efficiency as an index in the whole MEA FCAS architecture optimization, and try to maximize it as much as possible.

The efficiency of FCAS mainly depends on the efficiencies of the actuators. Thus, we just consider the efficiency of the actuator itself to replace the efficiency of the FCAS to simplify the analysis. According to the related practical experience, we assume that the efficiency of various types of actuators is shown in Table 3.

**Table 3 Efficiency of various types of actuators**

| Type of actuators | Efficiency/% |
|---|---|
| SHA | 60 |
| EHA | 85 |
| EMA | 90 |
| EBHA | 70 |

To facilitate the optimal design, we calculate the efficiency of FCAS by way of cumulative average. The optimized objective is to maximize the value. Efficiency $\eta$ can be drawn as follows:

$$\eta = \prod_{i=1}^{m} \eta_{\mathrm{act}i} \Big/ m \tag{11}$$

where $\eta_{\mathrm{act}i}$ is the efficiency of the selected actuator.

### 4.4. Evaluation criteria of single architecture

In order to provide a comparative reference for the optimized architecture, firstly we calculate the evaluation criteria values of each control surface adopting the same actuator type. According to Eq. (8), Eq. (10) and Eq. (11), the calculation results of failure rate, normalized weight and efficiency are respectively shown in Table 4.

**Table 4 Evaluation criteria of single architecture**

| Type of architectures | Failure rate/($10^{-9}h^{-1}$) | Normalized weight | Efficiency/% |
|---|---|---|---|
| Only SHA | 0.618 | 11.464 | 60 |
| Only EHA | 1.800 | 7.776 | 85 |
| Only EMA | 7.350 | 5.932 | 90 |
| Only EBHA | 0.066 | 18.840 | 70 |

We can find some relationships of the above types of actuators in Table 4. In the view of reliability: EBHA>SHA>EHA>EMA, in the view of weight: EMA>EHA>SHA>EBHA, in the view of efficiency, EMA>EHA>EBHA>SHA, where, “>” means “better than”. Therefore, no matter what kind of the single architecture, the indicators are not the optimal. Therefore, the hybrid architecture optimization design is needed.

## 5. Multi-objective Optimization of FCAS

According to the analysis of Section 3, the quantity of possible architectures of MEA FCAS is very large. It is almost impossible to design by employing the traditional exhaustion or “trial and error” method. Furthermore, the optimal design of the architecture is a multi-objective optimization problem. Therefore, it is necessary to select an appropriate optimization algorithm to seek the solution of this problem.

### 5.1. Mathematical description

The optimal design of MEA FCAS is a multi-objective combinatorial optimization problem. It can be described as follows. Find an appropriate architecture $A$ that

$$\begin{gathered} \min w(A) \\ \max \eta(A) \\ \text{s.t. safe reliability constraints} \\ \lambda(A)<1\times10^{-9}/\mathrm{h} \\ \text{and technological constraints} \\ \mathrm{TC}(A)=1 \end{gathered} \tag{12}$$

### 5.2. MOD based on GA

GA, which is formed in the simulation process of genetic and evolution of lives in the natural environment, is an adaptive global optimization probability search algorithm [17]. As a stochastic optimization and search method, GA can produce a group of feasible solutions, with good parallelism. GA is suitable for the optimization of discontinuous multi-peak functions with characters of large-scale and highly nonlinear as well as the optimization of objective functions without analytical expression. Feasible solution sets of GA are encoded, and objective function could be regarded as the fitness values of encoded individuals (feasible solution). GA has good operability and simplicity. GA has the ability of global search in a wide range, and has no relationship with the field to which the problem belongs. GA implements the iterative process by probabilistic search techniques, and the global optimal solution is easy to be obtained by using GA [18-19]. Based on the above merits of GA, we select it to solve the MOD problem of the MEA FCAS. The specific implementation steps are as follows:

(1) Defining the decision variables and various constraints. The decision variables of this problem are actuator types chosen by each control surface. In this paper, the quantity of control surface which needs to assign actuator is 18; ten of these 18 control surfaces need to assign 2 actuators, so the total number of decision variables is 28. The arrange order represents the equipped actuator types in the control surface of No.1 left spoiler, No.2 left spoiler, No.3 left spoiler, No.4 left spoiler, No.1 right spoiler, No.2 right spoiler, No.3 right spoiler, No.4 right spoiler, inner left aileron (2), inner right aileron (2), outer left aileron (2), outer right aileron (2), inner left elevator (2), inner right elevator (2), outer left elevator (2), outer right elevator (2), upper rudder (2), lower rudder (2). The related con-

straints are safe reliability and technical limitations described in Eqs. (14)-(15).

(2) Establishing the optimization model, namely determining the types of objective functions and their mathematical descriptions. The objective functions of this problem are shown in Eqs. (12)-(13), which are respectively the functions of minimal weight and maximal efficiency.

(3) Determining the chromosome encoding method of feasible solutions. Each decision variable has four feasible solutions in this problem. So we can use a binary encoding method, namely each decision variable is coded by 2-bit binary numbers respectively. Then join these binary numbers together to form a 56-bit binary integer to denote a feasible solution.

(4) Defining the decoding method. Before decoding, it needs to cut the 56-bit binary string into 28 2-bit coded binary strings, and then they are converted into the corresponding decimal integer code 1, 2, 3 and 4 respectively. Each code represents one type of actuator, namely "1" represents SHA, "2" represents EHA, "3" represents EMA and "4" represents EBHA.

(5) Choosing the quantitative evaluation method of the individual fitness. For this MOD problem, individual fitness can be determined by parallel selection method. All the individuals are equally divided into two subgroups. Weight objective function is assigned to the first subgroup, and efficiency objective function is assigned to the second subgroup. It should be noted that, the weight objective function is applied to obtain the minimal values, so it needs to be converted to solve the maximal values. This can be fulfilled by the method that using an appropriate large positive number to subtract the weight objective function value as the final value. Thus, these two subgroups can adopt the respectively objective function value as their own individual fitness.

Meanwhile, the particular constraints can be guaranteed by the design of individual fitness in this paper. Namely that if the individual does not meet the constraints, then the fitness will be reduced to 0 and the individual will not be inherited in the next generation.

(6) Designing genetic operators.

Proportional selection operator is used for the selection operator. The sum of all individual fitness in the groups should be calculated firstly. Then, the size of each individual's relative fitness is calculated, which is the probability of each individual being inherited to the next generation. Finally, employing simulated gambling disk operation to determine the number of times of each individual is selected.

Single point crossover operator is used for the crossover operator. First, the individuals in the group are matched to pair randomly. Second, a random position is set as the intersection for each of the matched individual. Finally, the chromosomes of the two matched individual are exchanged after the intersection according to the setting crossover probability, thus two new individuals are created.

Basic bit mutation operator is used for the mutation operation. The mutation point is specified for each individual based on the mutation probability. And then, the negation operator of gene value for each given mutation point is done to produce a new individual.

(7) Determining the relevant operating parameters of GA. In this problem, the operating parameters of GA are: group size $M = 80$; terminated generation $T = 100$; crossover probability $p_c = 0.8$; mutation probability $p_m = 0.05$.

This multi-objective GA can be implemented by MATLAB to obtain the multiple Pareto optimal solutions of the MEA FCAS, as shown in Table 5. Fig. 4 shows the evolution process and results of fitness, reliability, weight and efficiency of the third solution in Table 5.

Fig. 4 illustrates that in the evolution process of the solution, there is a trend of convergence in general although some fluctuations exist in the various indicators of the group. Also, the Pareto optimal solution can be found quickly by GA.

Table 5 shows that, for the MOD of MEA FCAS architecture, there is no absolute optimal solution except the Pareto optimal solution. According to the results in Table 5 and the indicators shown in Table 4 which adopts a single architecture, it can be found that, compared to the traditional actuation system architecture, which only adopts servo valve controlled hydraulic actuators, the weight of the multi-objective optimized architecture can be reduced by 6%, and the efficiency can be improved by 30% based on the safe reliability requirements.

Taking the principle of distributed configuration of the power sources into account comprehensively, the optimized MEA FCAS architecture can be obtained in Fig. 5 based on the third optimization design results in Table 5. Yellow (Y) and green (G) parts respectively represent two hydraulic sources; red and purple respectively represent two electric sources (E).

**Table 5 Results of architecture optimization design based on GA**

| No. | Decision variable value of Pareto optimal solution | Failure rate/($10^{-9}$h$^{-1}$) | Normalized weight | Efficiency/% |
|---|---|---|---|---|
| 1 | 2142432323423442213434423234 | 0.863 | 10.702 | 80.179 |
| 2 | 2424242323423443243242411232 | 0.908 | 10.644 | 80.000 |
| 3 | 2142434224322134244132323224 | 0.981 | 10.560 | 79.107 |
| 4 | 3423132434241442244232322324 | 0.864 | 11.385 | 79.623 |
| 5 | 2434142342423232242123244324 | 0.939 | 10.965 | 79.464 |

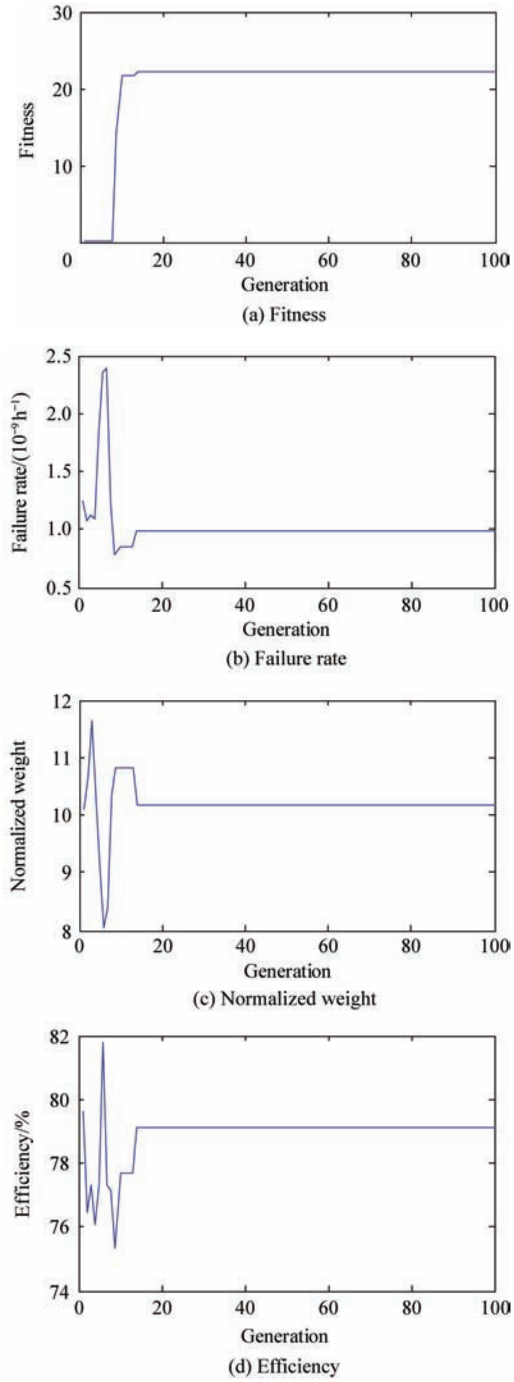


Fig. 4 Evolution process and results of GA.

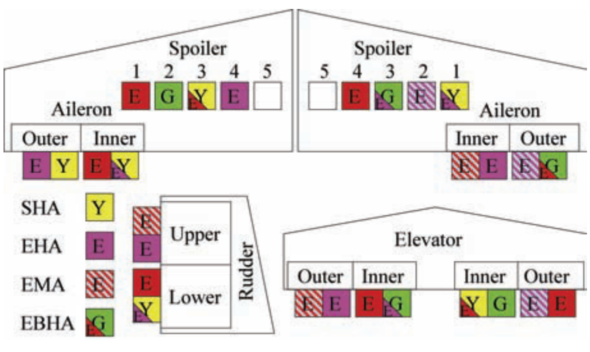


Fig. 5 Optimized MEA FCAS architecture.

## 6. Conclusions

Being “more electric” and “large scale” is the development trend of future aircraft, which will make the design of actuation system architecture more and more complex. Conclusions can be drawn by the analysis of its architecture optimization:

(1) The number of possible architectures of MEA actuation system is very large and traditional design methods cannot complete the design task.

(2) The optimization design of MEA actuation system architecture is MOD.

(3) GA can well solve the MOD problem of MEA actuation system architecture design.

(4) Compared to the traditional actuation system architecture, which only adopts servo valve controlled hydraulic actuators, the weight of the optimized more electric actuation system architecture can be reduced by 6%, and the efficiency can be improved by 30% based on the safe reliability requirements.

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