

Research Article

Optimization Plug Mode of External Fuel and Weapons for Less Changing Aircraft Center of Gravity

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To achieve the minimum change of aircraft center of gravity, plug mode optimization was carried out. Plug mode, including weight and position of external fuel and weapon load, was selected as design mode. Numerical model for calculating aircraft center of gravity was established and used to generate mode samples. Random search algorithm (RSA) was designed and applied for solving the optimization plug mode, and the precise solution of plug mode was determined by full array method (FAM). Compared with typical plug mode, the optimization mode can reach a minimum change in aircraft center of gravity with fewer samples than the solution by FAM. RSA coupled with FAM is an effective scheme for the optimization of aircraft plug mode.

1. Introduction

Demands for more fuel and weapons plug and smaller change of aircraft center of gravity have caused aircraft designers and staff to develop system or model to determine aircraft center of gravity. Han et al. developed an adaptive nonsingular fast terminal sliding mode control for aircraft with center of gravity variations to improve the dynamic and the quality characteristics of the aircraft [1]. Yang et al. established aircraft center of gravity estimation using Gaussian process regression models [2]. An aircraft weight and center of gravity indicator system was developed [3]. Gupta et al. proposed a finite element based structural model of a small flexible aircraft, focusing on obtaining a simple model suitable for control design based on a two-step procedure [4]. Li et al. analyzed the position of center of gravity for an unmanned aerial vehicle based on load task [5].

Much work has been done on the influence of aircraft center of gravity on flight performance and aerodynamic characteristics. Li et al. did research on effects of partial fuel pump failure on center of gravity control for high-speed aircraft to gain potential performance benefits. Besides, the influence of partial fuel transfer line leak on active center of gravity control was analyzed [6, 7]. Jungo et al. investigated the development of the CEASIOM aircraft design environment for novel aircraft configurations and analyzed static and

dynamic stability of the aircraft [8]. Mardanpour et al. did research on engine placement effect on nonlinear trim and stability of flying wing aircraft [9]. Zhen probed into the CG position of minimum drag to check stability boundary and front control boundary for J-7 aircraft [10]. An analytical expression was developed which showed that wing/tail interference drag was determined by wing downwash at downstream infinity [11, 12]. Wang et al. did optimization design of unmanned aerial vehicle with considering the uncertainty of the center of gravity and the influence of the center of gravity on the navigation time is greatly reduced [13]. Diekmann did trim analysis of nonlinear flight dynamics for a civil aircraft with active high-lift system [14]. Tang et al. put forward a calculation and analysis method for aircraft center of gravity to improve flight performance and safety [15].

Developing an efficient design and optimization method for plug systems is attracting more and more attention from researchers. Dancila et al. researched fuel burn prediction algorithm for cruise, constant speed, and level flight segments and considered the continuous fuel burn rate variation with time caused by the gross weight modification due to the fuel burn process itself [16]. Patron et al. put forward low calculation time interpolation method on the altitude optimization algorithm for the FMS CMA-9000 improvement on the A310 and L-1011 aircraft [17]. Ivester et al. worked on compact aircraft galley and lavatory arrangement and articulating

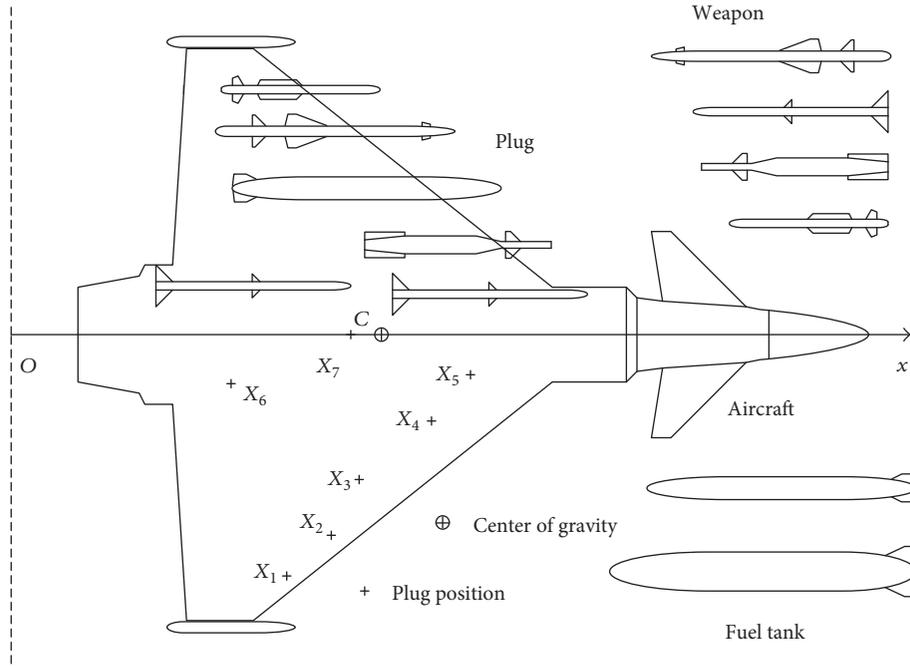


FIGURE 1: Plug and spare load schematic, symmetrical loading.

lavatory partition for an aircraft [18]. Jia et al. developed airborne weapon CAPP system and met the application of an aviation enterprise [19]. Xia et al. investigated the research of release safety analysis method for external stores of weapon [20–22]. Luo developed 1553B bus error correction technique in the management system of aircraft weapon to increase the adaptability between the aircraft and external plug [23].

Concentrating on the plug mode based on various missions for fighters with much heavy fuel load or quite a few weapons, a method based on RSA is designed and used to solve the optimization plug mode for minimum changing aircraft center of gravity.

In this paper, the design mode and objective function are presented in Section 2; and then the method for solving the optimization problem is performed in Section 3; the optimization results are analyzed in detail in Section 4; finally, the manuscript is concluded in Section 5.

2. Design Mode and Objective Function

The plug mode is defined as the corresponding relations between external loads and plug positions where the external loads include fuel and weapons loads such as common size auxiliary fuel tanks, various missiles, and bombs. The schematic of plug and spare load for a fighter on active service in current research is shown in Figure 1. European EF-2000 is selected as the fighter support, with empty weight 11.150 ton, 13 plug positions, and two types of external fuel tank. The coordinate of aircraft center of gravity can be calculated as

$$X_C = \frac{M_e \cdot X_e + M_{if} \cdot X_{if} + \sum_1^p M_{ef_i} \cdot X_{ef_i} + \sum_1^q M_{ew_j} \cdot X_{ew_j}}{M_s}, \quad (1)$$

$$M_s = M_e + M_{if} + \sum_1^p M_{ef_i} + \sum_1^q M_{ew_j}, \quad (2)$$

where X_C is the coordinate of aircraft center of gravity, M_e is the aircraft empty weight, X_e is the coordinate of aircraft center of gravity with empty weight, M_{if} is the total weight of internal fuel, X_{if} is the equivalent coordinate of internal fuel, M_{ef} is the external fuel weight, X_{ef} is the coordinate of the external fuel plug, M_{ew} is the weight of external weapon, M_{ew} is the coordinate of external weapon, M_s is the total weight of the current aircraft.

Generally, the position of aircraft center of gravity is defined as a percentage of mean aerodynamic chord length:

$$C = \frac{X_L - X_C}{L_{mac}} \times 100\%, \quad (3)$$

$$L_{mac} = X_L - X_T,$$

where C is the position of aircraft center of gravity, X_L is the coordinate of the leading edge of mean aerodynamic chord, L_{mac} is the length of mean aerodynamic chord, and X_T is the trailing edge of mean aerodynamic chord.

By using symmetrical loading, there are 7 plug positions to carry weapons or fuel tanks as shown in Figure 1. With specific task, external fuel and weapons can be determined. Then plug mode can be designed as

$$M = [M_1, \dots, M_7],$$

$$M_i \in [M_{ef_1}, \dots, M_{ef_p}, M_{ew_1}, \dots, M_{ew_q}], \quad (4)$$

$$X = [X_1, \dots, X_7].$$

The plug mode, namely, the one-to-one correspondence between M_i and X_i , $i = 1, 2, \dots, 7$, can be solved by

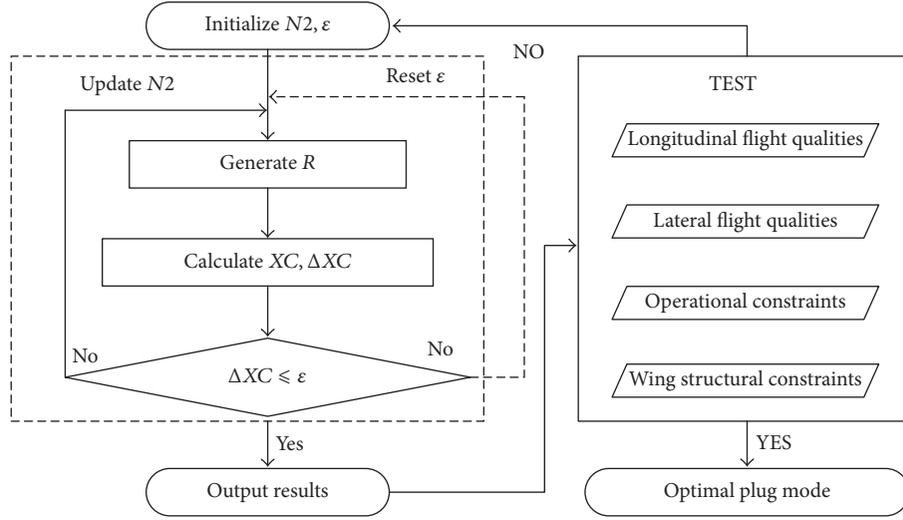


FIGURE 2: The flow chart of the random search algorithm and results test.

determining the array of M_i and the center of gravity can be calculated by the combination of M and X based on formula (1).

3. Methods for Solving Optimization Problem

Because of various types of missiles and different missions, the group of M and X can reach hundreds of thousands or more, from the theoretical perspective regardless of plug position limit, including the fixed position of heavy external fuel tank or some anti-ship missile. Supposing the weight of internal fuel equals zero and all the plug positions mounted with weapons or fuel tanks, the optimization plug mode can be solved by the following methods.

3.1. Full Array Method. For giving mission and fixed type of external fuel load and weapon, the number of the group of M and X is an arrangement number, from the theoretical perspective. And a fixed plug position can be considered as cutting the length of the array of X . Then the matrix of all the group of M and X can be expressed as

$$\begin{aligned}
 F &= \text{FAM}(M), \\
 N_0 &= A_m^n, \\
 N_1 &= A_n^n, \\
 N_2 &\leq \frac{N_0}{10},
 \end{aligned} \tag{5}$$

where FAM is a function to list all the array of M , F is $N_1 \times 7$ matrix, N_0 is the number of plug modes in different missions, N_1 is the number of plug modes in giving missions, N_2 is the number of plug modes by RSA, n is the number of active plugs, and m is the number of all the types of external fuel

tanks and weapons. According to (1)–(3), the center of gravity and minimum change of center of gravity can be calculated as

$$\begin{aligned}
 \Delta X_{C_j} &= X_{C_j} - X_{C_0}, \\
 \Delta X_{C_m} &= \min(\Delta X_{C_1}, \dots, \Delta X_{C_{N_1}}),
 \end{aligned} \tag{6}$$

where X_{C_0} is the aircraft center of gravity with a typical plug mode under the giving mission.

3.2. Random Search Algorithm. Taking into account EF-2000 fighter, the value of m can reach 17; then it is formidable for FAM to couple with the huge number N_0 . Therefore, RSA is designed to search the optimization plug mode in a small samples. For a giving mission and optional types of external fuel load and weapons, RSA is designed and used to solve the optimization plug mode as shown in Figure 2.

Here N_2 is a random number or a giving number, ε is critical error of center of gravity change, and R is $N_2 \times 7$ random matrix by arrangement of M as described in (7). Similarly, the center of gravity and minimum change of center of gravity can be calculated as

$$R = \text{RSA}(M), \tag{7}$$

$$\Delta X_{C_j} = X_{C_j} - X_{C_0}, \tag{8}$$

$$\Delta X_{C_{N_2}} = \min(\Delta X_{C_1}, \dots, \Delta X_{C_{N_2}}). \tag{9}$$

The RSA operator can proceed as follows.

Step 1. Obtain or update N_2 value.

Step 2. For each $i = 1, 2, \dots, N_2$,

$$R_i = t[M_1, M_2, \dots, M_j], \quad 1 \leq j \leq 7; \text{ here } j \text{ is determined by the number and type of plugs}$$

TABLE 1: A typical plug load.

	Weapon			Fuel	
	AIM-9	AIM-120	Paveway	Tank 1	Tank 2
Weight/ton	0.0910	0.1507	0.9070	0.7750	1.1625
Number	2	4	4	2	1

TABLE 2: The distribution of the typical plug load.

X	Typical plug mode						
	1	2	3	4	5	6	7
Plug	AIM-9	Paveway	Tank 1	Paveway	AIM-120	AIM-120	Tank 2

and t is a true random operator to generate a set of nonrepeating permutations to simulate the various plug mode.

Step 3. Calculate C and ε for each R_i .

Step 4. Determine the optimal plug mode with the minimum absolute value of ε among R .

Concerning that the value of N_2 is not large enough to find the optimization solution, N'_2 is used to update N_2 to search one more time until meeting the error test. Even if the above 4 steps still cannot get the answer, resetting ε can be available to continue the algorithm. The updating and resetting operator for N_2 can be described as follows:

$$N'_2 = r \cdot N_2,$$

$$r = \begin{cases} 5 & \Delta X_{C_{n_2}} > \varepsilon \\ 0 & \Delta X_{C_{n_2}} \leq \varepsilon. \end{cases} \quad (10)$$

The optimization plug mode can be determined based on (9) with the termination of the random search algorithm. In addition, the ultimatum solution of the optimal plug mode should pass the results test such as flight qualities and operational and wing structural constrains as shown in Figure 2.

4. Results and Analysis

4.1. The Results of Typical Plug Mode. For comparison of the solutions between RSA and FAM, a typical plug load including 10 missiles and 3 external fuel tanks is given as shown in Table 1. There are 10 missiles and 3 fuel tanks for the fighter to possess plenty of missiles and fuel. By using symmetrical loading, the typical plug mode is presented in Table 2.

Regarding (1)–(3), the center of gravity in the typical plug mode is calculated to be 17.7205%, where $C_e = 19.50\%$. Then $\Delta C_0 = -1.7795\%$.

4.2. The Results and Analysis of FAM. To obtain the precise solution of the typical plug mode, FAM is used to produce

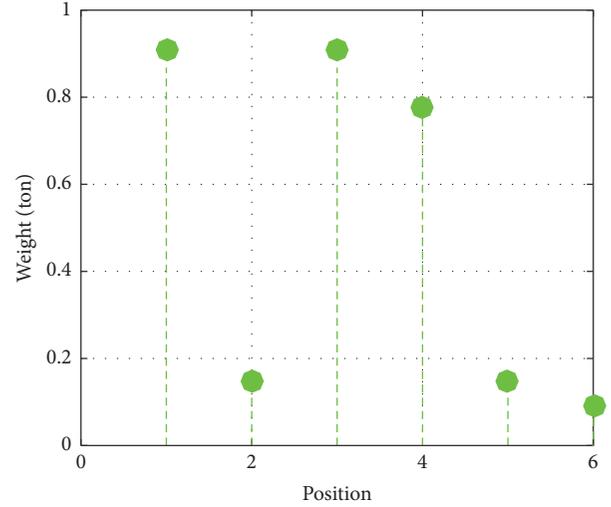


FIGURE 3: Precise plug mode.

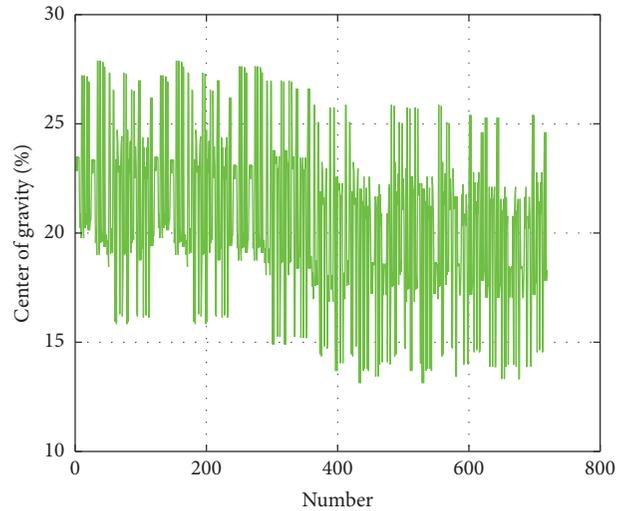


FIGURE 4: Center of gravity by FAM.

all the array of M matrix. Concerning the fact that there is a unique position (X_7) for fuel tank 2 as shown in Figure 1 and Table 2, the value of N_1 is 720. With this in mind, the precise plug mode can be determined as presented in Figure 3. The results of center of gravity are obtained as shown in Figure 4 with a range of 13.143%–27.8909%. The change of C is presented in Figure 5 in the scope $[-6.3657, 8.3909]$. To observe the range of C , the results of center of gravity is sorted as shown in Figure 6. Besides, there are 164 plug modes with less changing of the value of C than the typical plug mode. Then the minimum change of C can be determined as 0.0594% where $C = 19.5594\%$ with the precise plug mode. Because F matrix is a full arrangement of M , the precise solution can be considered reliable.

4.3. The Results and Analysis of RSA. Figure 7 shows that it is formidable to search the robust results of plug mode when the initial size of N_2 is small. Thanks to the action

TABLE 3: Center of gravity generations of the optimization plug mode by RSA.

Generations	1	2	3	4
N_2	4	20	100	500
$C/\%$	22.3846	19.9799	19.5605	19.5605
$\Delta C/\%$	2.8846	0.4799	0.0605	0.0605
$\varepsilon/\%$	14.748	2.454	0.309	0.309

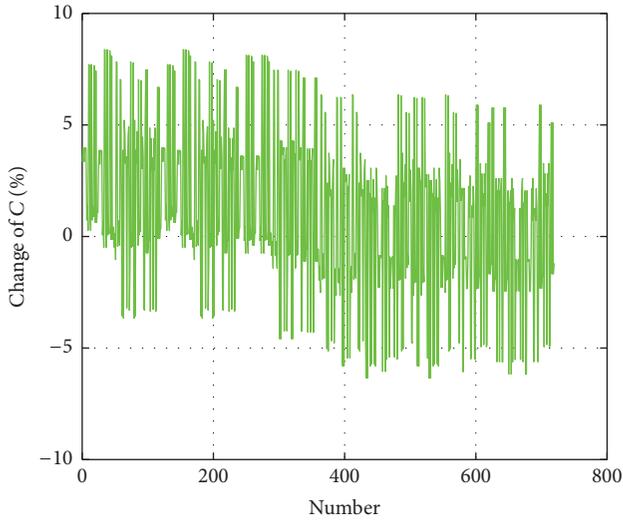


FIGURE 5: Change of C by FAM.

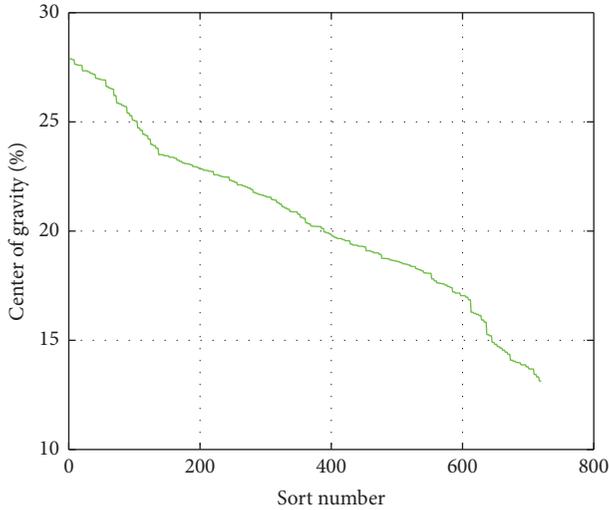


FIGURE 6: Sorting results of center of gravity by FAM.

of updating and resetting operator of N_2 , the relative error of the optimal C is significantly reduced when the value of N_2 increases to 20 as shown in Table 3. Figure 8 presents the fact that there are more solutions close to the value $C = 19.5594\%$ by FAM. In addition, the error is significantly improved when $N_2 \geq 20$ from Table 3 and the proposed algorithm is theoretically and practically convergent. Figure 9 supports the fact that a new plug mode can be applied to

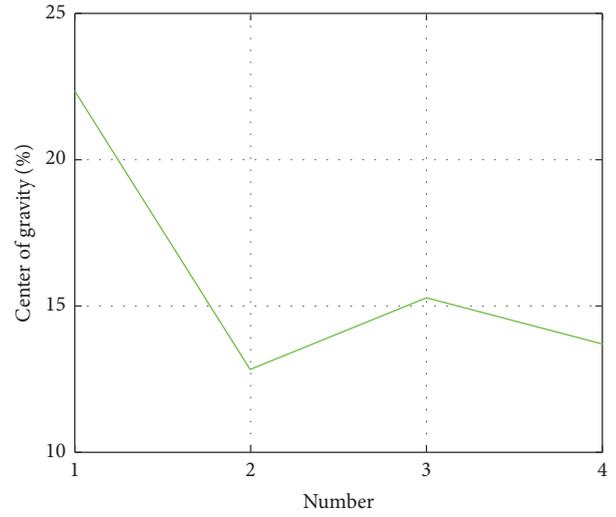


FIGURE 7: Center of gravity by RSA, $N_2 = 4$.

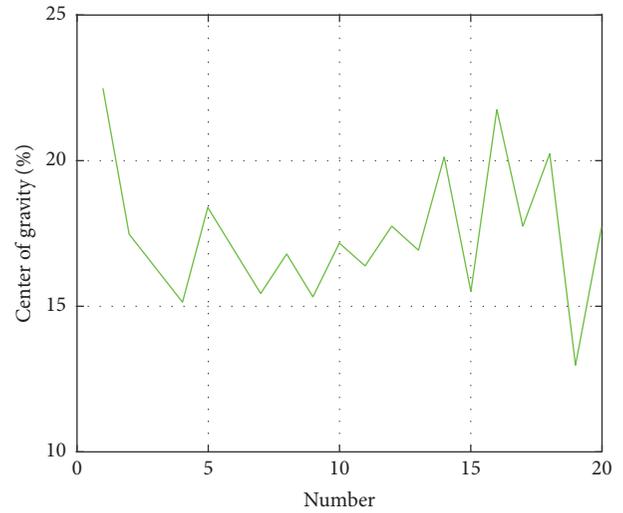


FIGURE 8: Center of gravity by RSA, $N_2 = 20$.

finish the external load distribution when it is suitable for X_6 plug position to carry Paveway missile, including the strength of the plug pylons and the space around the plug point. Unlike the other random search method for producing some single values, the RSA operator concentrates on generating a certain number of nonrepeating combinations to simulate the various and promising plug modes. It can be noted from Figure 10 that the center of gravity ranges from 12.4865% to 22.4288% close to the result by FAM. Figure 11 shows that the value of ΔC is between -7.0135% and 2.9288% . It could be remarkable from Figure 12 that there are 59 plug modes which changes center of gravity less than the typical plug mode by comparing the absolute value of ΔC between RSA and the typical plug mode. The minimum value of center of gravity position can reach 19.5605% with $\Delta C = 0.0605\%$ which is close to the solution by FAM. Furthermore, it just costs RSA 100 initial plug modes to get the optimization solution by searching only one time. Compared with FAM, RSA is really fast and efficient with enough precision.

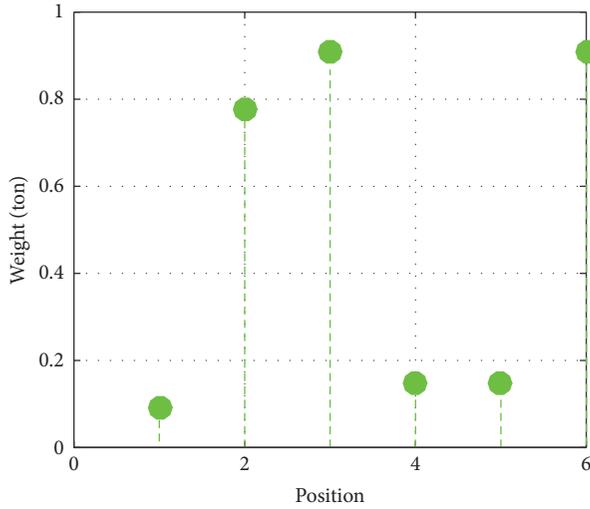
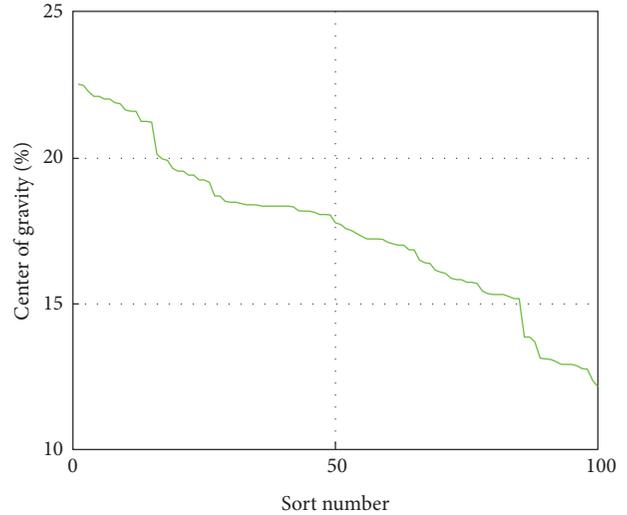
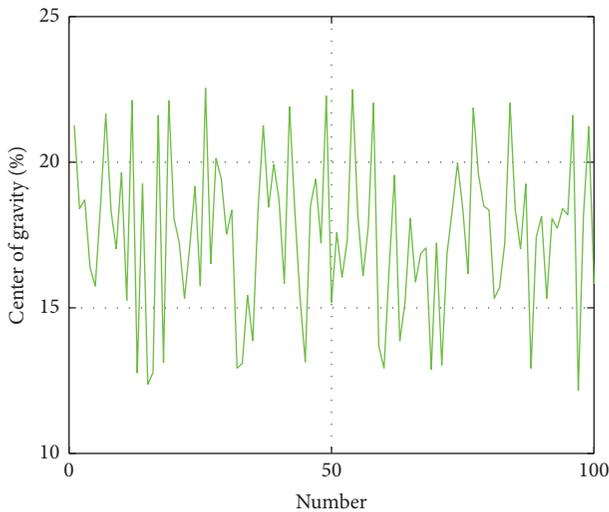
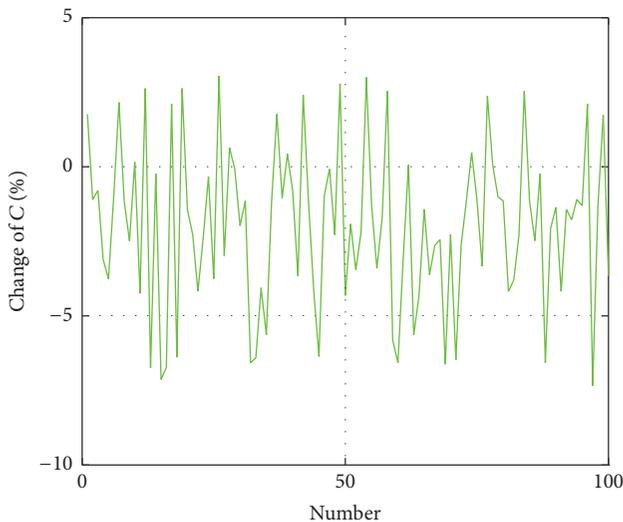
FIGURE 9: The optimization plug mode, $N_2 = 100$.FIGURE 12: Sort center of gravity by RSA, $N_2 = 100$.FIGURE 10: Center of gravity by RSA, $N_2 = 100$.FIGURE 11: Change of C by RSA, $N_2 = 100$.

Figure 13 supports the fact that there are 13 plugs occupying all the plug positions not only to simulate aircraft high payload but also to test the proposed algorithm. By paying attention to the weight of Paveway missile heavier than that of fuel tank 1 in spite of the former volume smaller than the later, X_2 or X_4 plug position is strong enough to carry the other plugs lighter than fuel tank 1 from the perspective of wing structure and this is operable. In addition, the high weight of Paveway plug at X_2 position is not good for rolling manipulation, thus affecting the lateral flight qualities. Figure 14 indicates that a precise plug mode with the minimum changing center of gravity is obtained by FAM. Although the longitudinal flight qualities are improved because of the minimum changing aircraft center of gravity, the heavy weight of Paveway missile at X_1 position is extremely detrimental to the lateral flight qualities as shown in FAM results. In addition, high load often occupying the wing tip is unfavorable for aircraft wing structure and easily leads to structural fatigue along with the aircraft taking off, climbing, and maneuvering. Thanks to the optimal solution by RSA, the disadvantages above are well improved as shown in RSA results. As previously demonstrated, X_2 is strong enough to carry fuel tank 1 lighter than the Paveway missile and the auxiliary tank could be preferentially exhausted and abandoned; thus the flight qualities could be improved significantly. The remaining operation is placing the Paveway missile at X_6 position and this is convenient and feasible.

5. Conclusions

RSA for solving the optimization plug mode was carried out. A typical plug mode was used to be the comparison of reference between RSA and FAM. FAM is precise and comprehensive to calculate the precise solution with computing a large number of the arrangements of M . RSA is accurate and efficient for generating the optimization plug mode with searching among a small number of samples of the arrangement of M . From this research, it can be found that

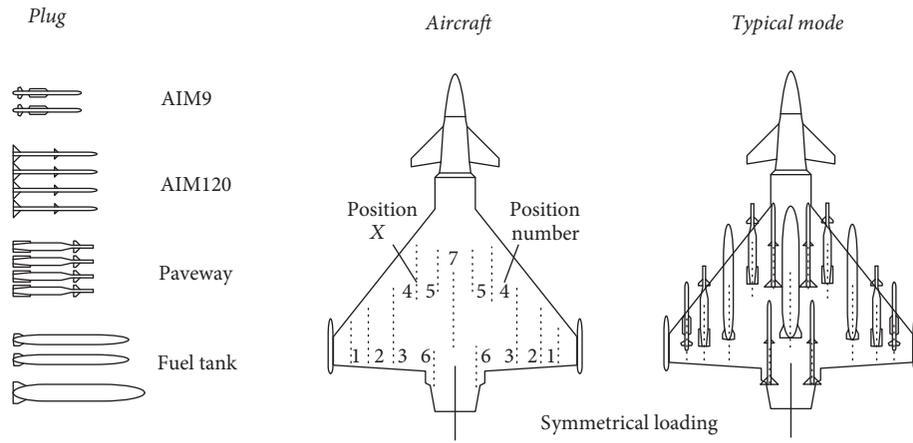


FIGURE 13: The schematic of aircraft, plug, plug position, and typical plug mode.

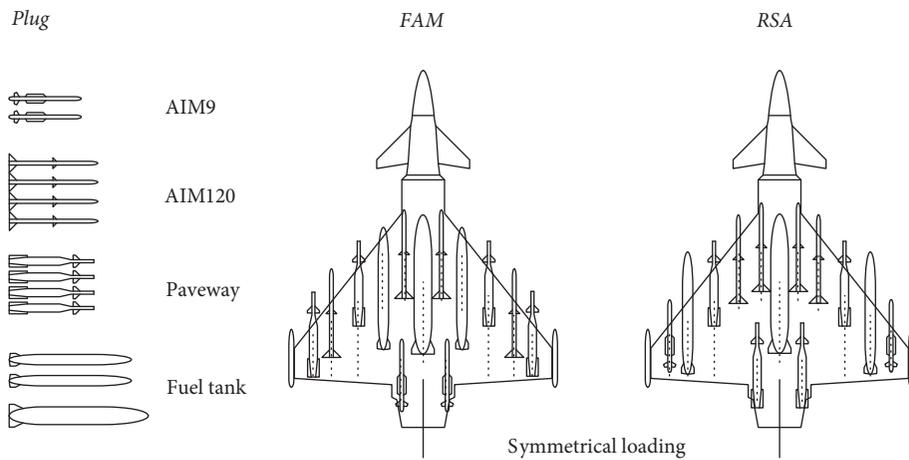


FIGURE 14: Comprehensive analysis and comparison of the results by FAM and RSA.

RSA coupled with FAM is an efficient tool for optimization of aircraft plug mode.

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Conflicts of Interest

The authors declare that there are no conflicts of interest.

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