

# An Improved PSO Algorithm with Object-Oriented Performance Database for Flight Trajectory Optimization

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**Abstract**—In order to improve accuracy and convergence speed for flight trajectory optimization program in flight management computer and enhance its maintainability, an improved particle swarm optimization (PSO) algorithm with object-oriented performance database is proposed. Firstly, an object-oriented performance database is built by Microsoft Visual C++ and MATLAB/SIMULINK mixed software development environment. Through synthetically use class hierarchy and specialized function library, the flight performance data is retrieved and its data file can be replaced with adapt for different aircraft types. Secondly, the mass point motion mathematical model is built according to mass point dynamics and energy states. Objective functions for trajectory optimization in vertical flight profile are acquired by the Minimum Principle of Pontryagin. Thirdly, adaptive inertia weight is introduced, the equality constraints is processed using the penalty function method. Finally, trajectory in vertical flight profile is optimized through using the improved PSO based on the object-oriented performance database. Meanwhile, the PSO algorithm flow for vertical flight profile trajectory optimization is given. Through using of the improved PSO, trajectory optimization of Boeing 737-800 aircraft in vertical flight profile is carried out. Comparison results between optimization results and flight test data show that the calculated results of proposed algorithm rapidly converges to optimal solution with higher precision.

**Index Terms**—object-oriented technique, particle swarm optimization, flight trajectory optimization, local optima, flight simulator, convergence speed, penalty function

## I. INTRODUCTION

As standard equipment on commercial transport vehicles [1], flight management computer (FMC) plays an important role in business transportations. The main functions of the FMC are flight planning, trajectory optimization, performance prediction as well as guidance, navigation and control. With the performance optimization of FMC, the economy of operation is improved considerably [2]. Thus, it is significance to study the flight trajectory optimization with the transition of the flight state.

The performance database is the data source of trajectory optimization which provides aerodynamic coefficients, engine thrust and fuel flow rate etc. Peng built aircraft performance model (APM) according to flight manual [3]. The author studied the searching method of the database under non-real-time circumstances and the feasibility of data searching in the context of real-time environment. Wang also construct APM on the basis of the flight manual and designed a sub-optimal trajectory based on the flight profile data acquired from flight manual [4]. NASA cooperates with Boeing for updating and improving the performance data of CTAS [5]. BADA (base of aircraft data) developed by the Euro control Experimental Center provided a set of ASCII code including parameters of aircraft performance and running procedures [6]. These parameters are used to calculate aerodynamic forces, engine thrust and fuel flow in order to figure out all the flight parameters needed. Furthermore, trajectory optimization techniques have been investigated by a large number of academicians [7-9]. Whereas, no matter which kind of trajectory optimization techniques are adopted, the authentic and maintainable performance database is the presupposition.

As closely related to the operating costs of airline, trajectory optimization in vertical profile is also studied by many researchers. Wu studied on the guidance

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technique for optimal vertical flight trajectory with Fibonacci search method based on a total energy control system [10]. Zhou researched the vertical profile flight trajectory of heavy military airlift with the time cost based on the simple genetic algorithm [11]. Wang solved the trajectory optimization problem using simple optimization algorithm based on cost function with the fuel economy [12]. Although these algorithms solved optimal trajectory problem, but the disadvantages of slow convergence and sinking into local optima may infect the real-time capability.

With originally developed by Kennedy and Eberhart in 1995 based on social behavior, such as bird flocking, fish schooling [13], particle swarm optimization (PSO) is widely used in optimization problems. With respect to genetic algorithm (GA), PSO algorithm possesses the ability of adjusting search strategy dynamically according to the current searching information. Besides, the complicated genetic manipulation can be avoided with the velocity-displacement model. Many search and optimization problems involve a number of constraints which the optimal solution must satisfy. The most common approach adopted to dispose constrained search space is the use of penalty functions [14, 15]. Nevertheless, their application in constraint optimization is limited [16-18]. The main reason is they lack an explicit mechanism to bias the search in constrained search space.

This paper describes the work on behalf of computations of optimal flight trajectory in vertical profile using modified particle swarm optimization algorithm with object-oriented performance database. First, based on object-oriented programming method, a maintainable and extensible performance database is built. Then, the point mass dynamical model with energy-state is built. According to minimum principle, the objective functions of each flight phrase are given. With adaptive inertia factor, the standard PSO is modified and through penalty function method, the equality constraints are processed. By the improved PSO, trajectory Boeing 737-800 aircraft in vertical flight profile is optimized and flight test are carried out with Boeing 737-800 flight simulator. Finally, the work is concluded and its effectiveness is indicated.

II. OBJECT ORIENTED PERFORMANCE DATABASE

The function of aircraft performance database involves the aerodynamic coefficients model and engine performance model which provides essential data for trajectory optimization. The purpose of performance database design using object oriental technique is to provide applicable and reliable performance data for optimal trajectory search corresponding to specified airplane. In performance database, each sub-module should be independent and cooperate in harmony. The class inheritance, dispatching method, the definition of model and data management of performance database are discussed as follows.

A. Class and Class Inheritance

Each sub-model is derivate from the parent class named CModel, as shown by figure 1. The parent class provides abstraction interface to access derived class.

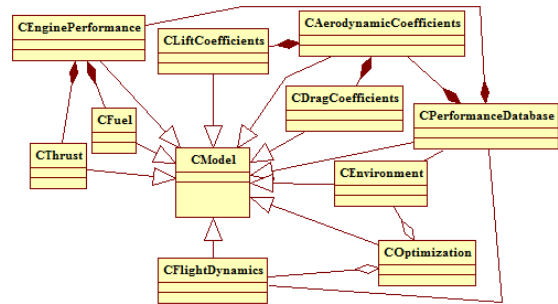


Figure 1. Base class and component classes for performance database.

Figure 2 shows the functions and attributes in the parent class-CModel. In CModel, by using the function Run(RunMode mode, double TimeStep), the initialization, data receiving, data transfer, results output and destructor of the derived classes are realized. These functions are virtual functions and protected in the parent class. For each derived class, the virtue functions are overloaded to describe various characteristic. Meanwhile, data can be processed and stored by the parent class.

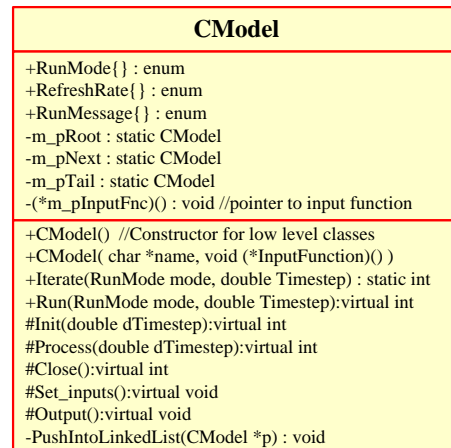


Figure 2. Diagram of the parent class.

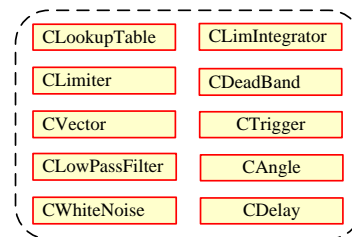


Figure 3. Algorithmic classes in the class of performance database model.

B. Operating Functions

As the functions in Standard Template Library (STL) in C++ cannot accomplish the mathematical operations during optimization, a special operating function database is built. Figure 3 reveals a part of the function library.

Through these algorithmic classes, the performance database modeling is much convenient based on C++. For example, in practice, aerodynamic data and engine performance data composed of a great quantity of data tables are hard to process. By using the function CLookupTable, the data tables can be disposed. In the aerodynamic coefficients model, the relationship between flight parameters and aerodynamic coefficients are classified and organized into several data tables. Figure 4 gives an example of the 2-Dimensional data table of the aerodynamic coefficients.

```
[clbas]      # clbas = f(alfad, dfef)

dfef = 7.6   13.2
-8 =  -0.826359  -0.720113
-7 =  -0.696642  -0.583841
-6 =  -0.556547  -0.447569
-5 =  -0.42683   -0.313956
```

Figure 4. The 2-Dimensional data table.

In figure 4, clbas is the dependent variable of alfad and dfef. The first line involves the name of dependent variable. The second line refers to the second corresponds to the values of the second independent variable. And the column on the left side of the equal mark involves all the values of the first independent variable in this mapping.

For the established data tables, the desired data is acquired by interpolating function of CLookupTable. The mathematical expression of the function CLookupTable is shown as follows

- a) Suppose y is the dependent variable of x. Each value of y mapped to x can be acquired from the adjoining coordinates. To ensure the rationality of the results, the interval of data table can be unequal.
- b) If  $x_2 < x < x_3$ , the interpolation formula is

$$y = y_2 + (y_3 - y_2)(x - x_2)/(x_3 - x_2). \quad (1)$$

```
[NICorr_PLA] ← keywords
Altitude = 0.0 10000.0 20000.0 30000.0 40000.0
[Altitude_0] ← keywords
Mach ← variable name
= ← separator
0.0 0.2
-109.2 = 82.12 82.32
-103.8 = 82.12 82.32
-97.8 = 74.50 74.68
-62.2 = 18.0 20.0
0.0 = 18.0 20.0
4.8 = 18.0 20.0
16.97 = 51.88 51.94 ← variable value
29.0 = 69.70 69.77
41.45 = 82.93 83.00
44.0 = 84.45 84.50
52.0 = 88.25 89.94
54.8 = 90.50 91.18
57.6 = 93.98 94.66
60.65 = 94.48 95.16
```

Figure 5. The 3-Dimensional data table.

### C. Data Structure of Performance Database

During the process of trajectory optimization, the aerodynamic coefficients, engine performance data and aircraft geometric parameters are essential. As the objective of optimization is specific airplane, extensible markup language (XML) in JSBSim is unnecessary. In the data file, the data tables include keywords, variable name, separator and variable value. All the aerodynamic data and engine performance data are stored in Aero.dat and Engine.dat respectively. Figure 5 shows a part of 3-Dimensional data table in the file Engine.dat.

### D. Implementation of Performance Database

In FMC, as the data basis of the optimization program, the performance database provides lift coefficients, drag coefficients, fuel flow, thrust and wing area for the aerodynamic model. And, the lift force, drag force which calculated by the aerodynamic model and fuel flow are transferred to optimization program. The data flow relationship is shown in figure 6.

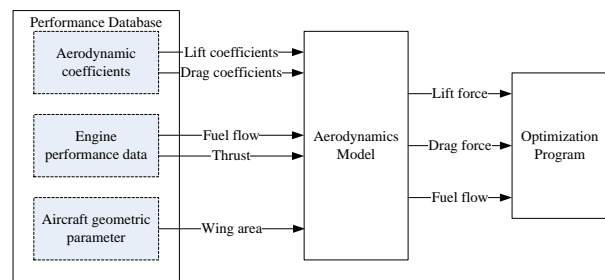


Figure 6. Data flow relationship between optimization program and performance database.

The FMC performance database is implemented by

```
Harbin Institute of Technology.
Boeing ***Level-D Flight Simulator FMS program --HIT
Version: PD.01 -- Build: [NOV 11 2009:18:18:10]

Success! Logging enabled.
cFMS_pd::init: Performance data transmission...
```

Figure 7. Running results of program debugger for performance database.

Microsoft Visual C++ and MATLAB/SIMULINK mixed software development environment. In order to validate the correctness of the data structure, the performance database is called by FMC. The results of the program are shown by figure 7.

## III. TRAJECTORY OPTIMIZATION IN VERTICAL PROFILE

In trajectory optimization, mass point and rigid body dynamics equations are used to describe aircraft motion [19]. In practice, to reduce complexity and enhance the real-time performance in online computation, a simplified point mass performance model is adopted by flight management system for optimal trajectory generation.

### A. The Mass Point Model with Energy-state

The mass point dynamics in vertical flight profile is described as

$$\begin{cases} \dot{m}V = T \cos \alpha - D - mg \sin \theta \\ \dot{m}V \dot{\theta} = T \sin \alpha + L - mg \cos \theta \\ \dot{h} = V \sin \theta \\ \dot{x} = V \cos \theta + V_w \end{cases} \quad (2)$$

$$V \dot{\theta} = 0. \quad (7)$$

where,  $m$  is the weight of aircraft;  $V$  the flight velocity;  $T$  the engine thrust;  $\alpha$  the angle of attack;  $D$  the Drag force;  $L$  the lift force;  $\theta$  the flight path angle;  $h$  the flight altitude;  $x$  the flight distance;  $V_w$  the velocity of the wind. The variables in (2) are calculated by the following equations.

$$\begin{cases} f = f(TLA, h, V) \\ \dot{m} = -f \\ T = T(TLA, h, V) \\ L = \frac{\rho V^2 C_L S_w}{2} \\ D = \frac{\rho V^2 C_D S_w}{2} \end{cases} \quad (3)$$

$$C_z = C_t t + C_f m_f. \quad (9)$$

where,  $\rho$  represents the air density,  $S_w$  the wing area,  $C_L$  the lift coefficient,  $C_D$  the drag coefficient,  $T$  the engine thrust force,  $f$  the fuel flow,  $M$  the Mach number,  $TLA$  the thrust level angle.

In flight, each point of the trajectory corresponds to a certain amount of energy states. In relation to potential energy, the rotational energy is too small so as to be neglected. Thus, the total energy per unit mass of the aircraft is defined as follows.

$$E = h + \frac{1}{2g} V^2. \quad (4)$$

Combined (4) into (2), the mass point model with energy state is acquired.

$$\begin{cases} \dot{x} = V \cos \theta + V_w \\ \dot{E} = \frac{T \cos \alpha - D}{mg} V \end{cases} \quad (5)$$

Furthermore, based on the replacement of variable  $dE$  and  $dt$ , (5) can be simplified as follows

$$\frac{dx}{dE} = \frac{V \cos \theta + V_w}{(T \cos \alpha - D)V} mg. \quad (6)$$

For there is no violent maneuver in airline operation, the normal acceleration of mass point can be neglected, that is

Constraint equation act on aircraft in flight trajectory is converted into (8).

$$T \cos \alpha + L - mg \cos \theta = 0. \quad (8)$$

**B. Cost Function**

Solving the flight state corresponds to the minimum operation cost is an important approach to reduce direct operation cost (DOC) and enhance air transportation economic. Thus, DOC is adopted as the performance index in the trajectory optimization problem. The definition of DOC is shown as follows

where,  $C_z$  is the direct operation cost;  $C_t$  the coefficient of time cost;  $t$  the total time cost in flight;  $C_f$  the coefficient of fuel economic;  $m_f$  the total fuel consumed in flight.

Taking the functional equation of (10) as performance index of the optimization problem, namely

$$J = \int_{t_0}^{t_f} (C_t + C_f f) dt. \quad (10)$$

where,  $t_0$  is the start time of the flight;  $t_f$  the completion time of the flight;  $f$  the specific fuel consumption.

**C. The Principle and Analysis of the Problem**

Suppose that, the whole vertical flight profile consists of three phases which are climb, cruise and descent phase respectively. The total energy per unit mass of the aircraft  $E$  is increasing monotonically in climb phase, decreasing monotonically in descent phase, and keeping constant while cruising.

In cruise, the aircraft maintain steady flight, that is, the flight path angle  $\theta$  is equal to zero and the flight velocity  $V$  maintain constant. Thus, the equations of static equilibrium of the aircraft are

$$T \cos \alpha - D = 0. \quad (11)$$

$$T \cos \alpha + L - mg = 0. \quad (12)$$

Taking the flight cost per unit flight distance as the performance index in cruise. The expression of optimization is shown as

$$\lambda(E_c) = \min_v \frac{C_t + C_f \cdot f}{V}. \quad (13)$$

where,  $\lambda$  is the operation cost per unit flight distance in cruise;  $E_c$  the total energy per unit mass of the aircraft in cruise.

For the total energy per unit mass of the aircraft  $E$  is increasing monotonically in climb phase and decreasing monotonically in descent phase, state equation and performance index in climb and descent phase can be described as follows

$$\frac{dx}{dE} = \frac{V_c \cos\theta + V_{wc}}{(T \cos\alpha - D)V / mg} \Big|_{E>0} + \frac{V_d \cos\theta + V_{wd}}{|(T \cos\alpha - D)V / mg|} \Big|_{E<0} \quad (14)$$

$$J = \int_{t_0}^{t_{ci}} (C_t + C_f f) dt + \int_{t_{cf}}^{t_f} (C_t + C_f f) dt + (d - d_c - d_d)\lambda \quad (15)$$

where,  $V_c$  is the flight velocity while climbing;  $V_{wc}$  the velocity of wind while climbing;  $V_d$  is the flight velocity in descent;  $V_{wd}$  the velocity of wind in descent;  $d$  the total flight distance;  $d_c$  the total climb distance;  $d_d$  the total descent distance.

Converting the total energy per unit mass as an independent variable in performance index, (15) can be written as

$$J = \int_{E_0}^{E_f} \frac{(C_t + C_f f)}{E} dE + (d - (d_c(E_c) + d_d(E_c)))\lambda + \int_{E_0}^{E_c} \frac{(C_t + C_f f)}{E} dE \Big|_{E>0} + \int_{E_f}^{E_c} \frac{(C_t + C_f f)}{|E|} dE \Big|_{E<0} \quad (16)$$

Based on the analysis discussed above, the problem of solving optimal trajectory in vertical profile can be converted into calculating the minimum value of (16) under the constraint conditions of (14). The Hamiltonian function defined as shown in (17).

$$H = \frac{(C_t + C_f f)}{E} \Big|_{E>0} + \frac{(C_t + C_f f)}{|E|} \Big|_{E<0} + \chi(E) \left( \frac{V_c \cos\theta + V_{wc}}{(T \cos\alpha - D)V / mg} \Big|_{E>0} + \frac{V_d \cos\theta + V_{wd}}{|(T \cos\alpha - D)V / mg|} \Big|_{E<0} \right) \quad (17)$$

where,  $\chi(E)$  is the covariant.

In (17), the end-point condition  $E_0$  is constant, whereas,  $E_c$ , as well as  $d_c(E_c)$  and  $d_d(E_c)$  are free of restraints. According to the Minimum Principle of Pontryagin [20], the transversality condition is acquired.

$$\chi(E_c) = \frac{\partial(d - d_c - d_d)\lambda}{\partial(d_c + d_d)} \Big|_{E=E_c} = -\lambda(E_c) \quad (18)$$

Based on the minimum principle, the optimum control variable  $V$  and  $TLA$  should minimize (18), namely

$$L = \min_{V, TLA} H(E, \lambda, V, TLA) = L_{climb} + L_{descent} \quad (19)$$

where,  $L_{climb}$  and  $L_{descent}$  correspond optimization model in climb phase and descent phase, in which the initial energy of climb  $E_0$  is decided by the initial flight altitude and velocity in climb, the initial energy of descent  $E_f$  is acquired based on the termination flight altitude and velocity in descent. The expressions of  $L_{climb}$  and  $L_{descent}$  in (19) are shown as follows.

$$L_{climb} = \min_{V, TLA} \left[ \frac{(C_t + C_f f)}{E} \Big|_{E>0} - \lambda \frac{V_c \cos\theta + V_{wc}}{(T \cos\alpha - D)V / mg} \Big|_{E>0} \right] \quad (20)$$

$$L_{descent} = \min_{V, TLA} \left[ \frac{(C_t + C_f f)}{|E|} \Big|_{E<0} - \lambda \frac{V_d \cos\theta + V_{wd}}{|(T \cos\alpha - D)V / mg|} \Big|_{E<0} \right] \quad (21)$$

#### IV. IMPLEMENTATION OF THE MODIFIED PARTICLE SWARM OPTIMIZATION ALGORITHM

##### A. Population Initialization of Particle Swarm

In the flight management system, the outputs from trajectory optimization calculation module to the automatic flight control system (AFCS) are objective airspeed and objective altitude, which is used to the control of vertical flight profile. Thus, the Mach number  $M$  and the flight altitude  $h$  are adopted as the particles of the population. Suppose that, the size of population is  $l$ , the population described as follows.

$$X = \begin{bmatrix} M_1 & h_1 \\ M_2 & h_2 \\ \dots & \dots \\ M_l & h_l \end{bmatrix}_{l \times 2} \quad (22)$$

In order to reduce the search space, accelerate the convergence rate, based on the Boeing 737-800 flight plan and performance manual [21], the search space  $S$  is set as

$$S = \begin{bmatrix} M_{\min} & M_{\max} \\ h_{\min} & h_{\max} \end{bmatrix} = \begin{bmatrix} 0 & 0.85 \\ 6000 & 41000 \end{bmatrix} \quad (23)$$

##### B. Objective Function Construction

According to the analysis of the optimization principle, the problems of solving optimal trajectory in each flight phase are a class of optimization problem with constraints. In this paper, the penalty function method is used to convert the optimization problem with constraints into the

one without constraints. Then the fitness function of cruise is obtained.

$$fitness = \frac{C_t + C_f \cdot f}{V} + (T \cos \alpha - D)^2 + (T \cos \alpha + L - mg)^2 \quad (24)$$

The fitness function of climb and descent are shown as (25) and (26).

$$fitness = \frac{(C_t + C_f f)}{E} - \frac{\lambda(V_c \cos \theta + V_{wc})}{(T \cos \alpha - D)V / mg} + (T \cos \alpha + L - mg \cos \theta)^2 \quad (25)$$

$$fitness = \frac{(C_t + C_f f)}{|E|} - \frac{\lambda(V_d \cos \theta + V_{wd})}{|(T \cos \alpha - D)V / mg|} + (T \cos \alpha + L - mg \cos \theta)^2 \quad (26)$$

C. Inertial Factor

As the procedure of searching the optimal solution in search space is nonlinear. To balance the ability of global search and local search, a nonlinear adaptive inertial factor is introduced into the standard PSO to improve the searching performance. In the modified PSO, the fitness value of particles can be adjusted dynamically. When the fitness value of each particle trends to local optimal solution, the inertial factor increases, whereas, when the fitness value of each particle trends to be scattered, the inertial factor decreased. Meanwhile, if the fitness value is superior to the average level, the particle is protected, otherwise, inertial factor of the particle corresponds to the worse fitness value should be increased to make the particle close to a better solution. The adaptive inertial factor can be described as (29).

$$w = \begin{cases} w_{\min} + \frac{(w_{\max} - w_{\min})(f - f_{\min})}{f_{\text{avg}} - f_{\min}} & f \leq f_{\text{avg}} \\ w_{\max} & f > f_{\text{avg}} \end{cases} \quad (27)$$

where,  $w$  is the inertial factor;  $w_{\max}$  the maximum value of  $w$ ;  $w_{\min}$  the minimum value of  $w$ ;  $f$  the fitness value of particle;  $f_{\text{avg}}$  the average value of total particles;  $f_{\min}$  the minimum value of the whole population.

D. Population Updating

Suppose that, the velocity of  $i$ -th particle in population  $X$  denoted as  $V_i = [v_{i,1}, v_{i,2}, \dots, v_{i,l}]$ , the best position the particle experienced and the optimal position the whole population experienced are describe as  $P_i = [p_{i,1}, p_{i,2}, \dots,$

$p_{i,l}]$  and  $P_g$  respectively. Then the evolution equation of the population is shown as (26).

$$v_{ij}(t+1) = wv_{ij}(t) + c_1 r_{1j} [P_{ij}(t) - x_{ij}(t)] + c_2 r_{2j} [P_{gj}(t) - x_{ij}(t)] \quad (28)$$

where,  $i$  is the serial number of the particle;  $j$  represents the dimension of the particle;  $t$  the iterations;  $w$  the inertial factor;  $c_1$  and  $c_2$  the acceleration constants;  $r_1$  and  $r_2$  the random numbers of stochastic distribution.

In (28), the best position the particle experienced at  $t$  is calculated as (29).

$$\begin{cases} P_i(t) = P_i(t-1) & \text{if } f(x_i(t+1)) \geq f(P_i(t-1)) \\ P_i(t) = X(t-1) & \text{if } f(x_i(t+1)) < f(P_i(t-1)) \end{cases} \quad (29)$$

The iteration expression of the optimal position the whole population experienced can be revealed as shown in (30).

$$P_g(t) = \min \{ (f(P_0(t-1)), f(P_1(t-1)), \dots, f(P_s(t-1))) \} \quad (30)$$

The iteration equation of the particle position is obtained.

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1) \quad (31)$$

E. Algorithm Procedure

First, the optimal solution of cruise phase is calculated and the optimal cost of cruise is acquired. The process is as follows.

- a) The population is initialized according to (22) and (23).
- b) The fitness value of each particle is calculated by (24) and the inertial factor is updated through (27).
- c) The local optimum is obtained by (29).
- d) The global optimal solution is acquired according to (30).
- e) The velocity and position of each particle are evolved based on (28) and (31) respectively.
- f) If the iterations reach the max number of iterations and satisfy the tolerance of termination 10-5, the algorithm is terminated and the optimal solution is output. Otherwise, step a to e are repeated.

Then, the optimal cost of cruise is substituted into (25) and (26) and the computing process of optimal trajectory in climb and descent phrase is shown as follows.

- a) The population is initialized according to (22) and (23).
- b) The fitness value of each particle in climb and descent phrase are computed according to (25) and (26) respectively, the inertial factor is updated through (27).
- c) The local optimum is obtained by (29).
- d) The global optimal solution is acquired according to (30).

- e) The velocity and position of each particle are evolved based on (28) and (31) respectively.
- f) If the iterations reach the max number of iterations and satisfy the tolerance of termination 10<sup>-5</sup>, the algorithm is terminated and the optimal solution is output. Otherwise, step a to e are repeated.

V. TRAJECTORY OPTIMIZATION AND DISCUSSION

By invoking the functions defined in the parent class CModel, the optimization procedure can be executed. Take program initialization as an example, after the objects are instantiated, the function *Iterate()* of the object cOptimization is called to initialize of each object. During the process, each sub-classes are initialized through invoking the function Run(RunMode *mode*, double *TimeStep*) by their parent classes. The sequence diagram of the program initialization is shown as figure 8.

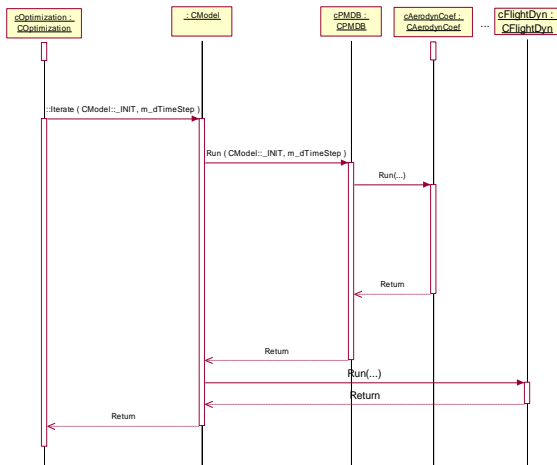


Figure 8. Initialization sequence diagram for optimization procedure.



a) The interior of the flight simulator. b) Waypoints in flight on the Navigation Display.

Figure 9. The Boeing flight simulator.

According to the modified PSO algorithm, the optimal trajectory is calculated. The performance data used in trajectory optimization is derived from the performance database specified for Boeing 737-800. The flight experiment is carried out on Boeing 737-800 flight

simulator. Figure 9 shows the interior of the flight simulator and the waypoints of the air route in flight.

A. The Search Performance Comparison

Taking the optimization trajectory in cruise as an example, the GA algorithm, the simple PSO algorithm and the modified PSO algorithm are used to solve the optimal vertical trajectory respectively. The iteration parameters of the modified PSO algorithm are shown in

TABLE I. ITERATION PARAMETERS IN THE IMPROVED PSO ALGORITHM

Denotation	Parameters	Values
$w_{min}$	The minimum inertia factor	0.4
$w_{max}$	The maximum inertia factor	0.9
$N$	The size of the population	30
$D$	The dimensions of the population	1
$maxgen$	The maximum iterations	50

table 1 and the convergence performance of the various algorithms is indicated in figure 10.

As shown in figure 10, in the simulation, using the same iterations, the modified algorithm is trapped in to local best once, whereas, the standard PSO algorithm reaches local best three times and the GA algorithm experiences four local best solutions. It can figure out that the modified PSO possesses faster converge rate and better ability of avoid local optima.

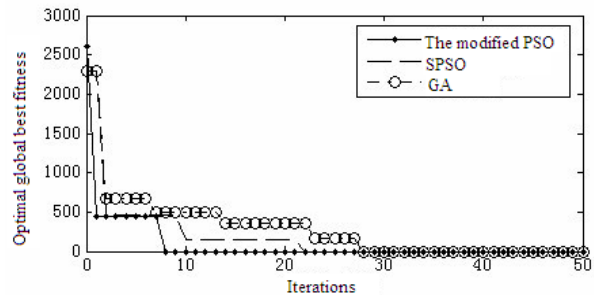


Figure 10. Convergence comparison.

B. Optimization Results

The GA, the standard PSO and the modified algorithm are adopted to solve flight trajectory respectively. All of the optimization results are used to flight test on the simulator platform. Figure 11 and 12 reveal optimal TAS at various altitude in cruise on flight simulator platform and the optimal solution comparison between the GA, the standard PSO and the modified PSO algorithm. Figure 13 shows the optimal TAS at various altitude while climbing on flight simulator platform and the optimal solution comparison between the GA, the standard PSO and the modified PSO algorithm.

In figure 11, at the cruise altitude of 35700 feet, the optimal true airspeed on flight simulator is 456 knots,



whereas, according to the modified PSO, the standard PSO and the GA, the results of computation are 455.5, 455 and 454.4 knots respectively.

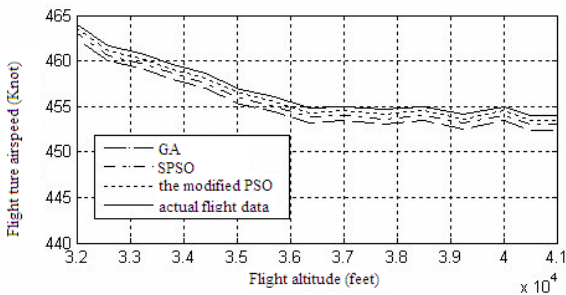


Figure 11. Optimal TAS at various altitudes in cruise and the optimal solution comparison.

In figure 12, when the aircraft weight is 150 kilo lbs, the low pressure rotor speed is 88.6 on the flight simulator platform, whereas, through the modified PSO, the standard PSO and the GA, the results of optimization are 88.5114, 88.3785 and 88.4671 respectively.

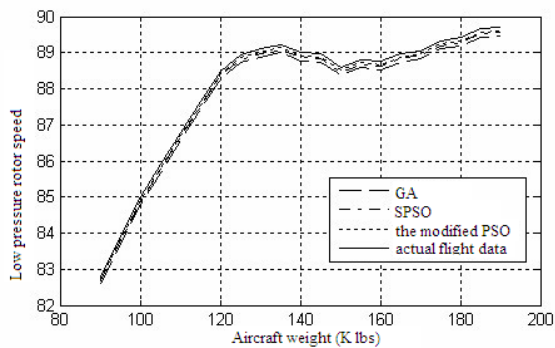


Figure 12. Optimal N1 at various altitudes in cruise and the optimal solution comparison.

In figure 13, at the climb altitude of 30000 feet, the optimal true airspeed of the simulator is 376 knots, whereas, by the modified PSO, the standard PSO and the GA, the results are 371, 368 and 374.5knots respectively.

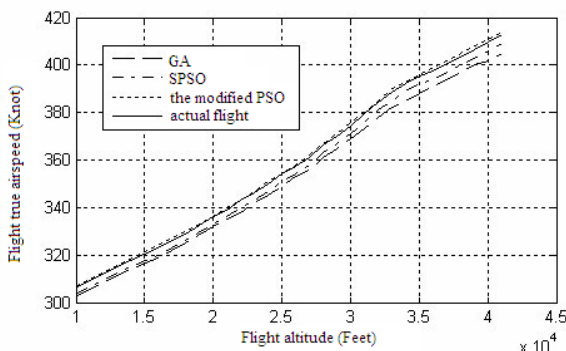


Figure 13. Optimal TAS at various altitudes while climbing and the optimal solution comparison.

VI. CONCLUSION

In this paper, the performance database for FMC is built by object oriental technique and the aircraft optimal flight trajectory in vertical flight profile is solved by

using the modified particle swarm optimization algorithm. According to object-oriented principle, the class and their inheritance are designed. Through designs the operating function library for data table processing, the complicated performance data can be disposed and calculated conveniently. Based on the proposed data structure, the data files are reorganized and classified into a unified format which can be easily stored and maintained. And by replacing the data file, the performance database can be expanded into different types for various airplanes. The particle swarm optimization algorithm is modified by introducing adaptive inertia factor. Meanwhile, by combination with the penalty function method, the trajectory optimization with constraint conditions is converted into unconstrained optimization problem. Based on the modified PSO algorithm, the optimal vertical trajectory of Boeing 737-800 is calculated. Comparison between optimization and experiment results reveal that the optimal solution acquired by modified PSO algorithm is approximately equal to actual flight data and the modified algorithm convergence faster than other algorithms.

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