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Performance Evaluation of Guidance and Control System Based on Improved Latin Hypercube

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Abstract: Aiming at the low efficiency and the poor space-filling property in the aircraft performance evaluation combined with simulation experiment, *a novel aircraft performance evaluation method based on the improved LHD (Latin hypercube designs) was investigated*. The six-DOF (Degree of Freedom) rigid aircraft model was built. C*onsidering the characteristic of BTT (bank-to-turn) vehicle in dive phase, the performance evaluation index system of its guidance and control system was set up*. *The optimal LHD was applied to the performance evaluation of the aircraft guidance and control system*. The improved algorithm can quickly construct a good design of experiments given a limited computational resource. The instance of performance evaluation verifies that the proposed approach is effective and feasible.

Keywords: experimental design; guidance and control system; performance evaluation; improved Latin hypercube design

基于改进拉丁超立方的制导控制系统性能评估

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摘要：针对结合仿真试验的性能评估存在运算效率低、充满空间特性差问题，*提出了一种改进拉丁超立方试验设计的飞行器性能评估方法*。建立了飞行器刚体六自由度模型；*结合 BTT 飞行器俯冲段制导控制系统特点，构建了其性能评估指标体系*；*将改进拉丁超立方试验设计方法运用到飞行器制导控制系统性能评估中*。该算法能够在资源受限的情况下，快速构造出“充满空间”特性较好的试验设计方案。性能评估实例验证了该方法在飞行器制导控制系统性能评估中的可行性。

关键词：试验设计; 制导控制系统; 性能评估; 改进拉丁超立方

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Introduction

The vehicle guidance and control system is the brain and nervous center of the vehicle, which has a great influence on the guidance performance and accuracy[1]. And the vehicle is a class of strong-nonlinearity, strong-coupling, complex nonlinear system with the un-modeled dynamics and external disturbances. Thus, this brings about many difficulties to the design of guidance and control system that guarantees the vehicle to possess a high terminal accuracy and strong robustness. In order to obtain the reasonable plan satisfying performance

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requirement, learn about the performance of the designed guidance and control system. Then optimize the design scheme based on the performance information. Performance evaluation is an effective way to obtain the system performance information. Rapid and reasonable assessment of vehicle guidance and control system can shorten the design period and cut the design cost. The robustness of the control system is an important indicator of vehicle guidance and control system performance evaluation. And it can measure the system's anti-perturbation capability and guarantee vehicle to complete specific mission in the complex flight conditions. Parameters-bias simulation experiment is a common method to measure the robustness of vehicle guidance and control system. There are two experimental design methods to verify the system's robustness in the design of guidance and control system. One is full factorial experiment design based on extreme value of parameter deviation. The other is Monte Carlo experiment design, sampling randomly in the sample space. However, the sampling points obtained by the above methods can't represent the sampling space in view of the space-filling property.

Latin Hypercube Design (LHD) is a hierarchical sampling method, extracting the same number of sample points from subintervals of equal probability in a certain way. The method is mainly used for multi-factor, multi-level simulation experiment design and makes it possible to obtain satisfactory experiment result with fewer experimental times. Thus, it improves greatly the efficiency of experiment. On account of appearing possibly correlation and colonization in the process of sampling, LHD changes sometimes for the better and sometimes for the worse. Therefore, some efforts to improve space-filling property need to be made. Optimal Latin Hypercube Sampling (OLHS) takes optimal criterion as optimal objective and searches an optimal design in a given design class, which optimizes a given optimality criterion. Adopt method of exhaustion to obtain the optimal design, leading to a large computational cost. The more effective solution is to find the feasible optimization method. To solve the problem, many scholars have conducted correlational research. Morris and Mitchell[2] adapted a version of simulated annealing (SA) algorithm for constructing optimal LHDs; Park[3] developed a rowwise element exchange algorithm for constructing optimal LHDs; Ye[4] used the columnwise-pairwise (CP) algorithm for constructing optimal symmetrical LHDs; Fang[5] adapted the threshold accepting algorithm in constructing optimal LHD. [6-8] attempted to adopt genetic algorithm (GA) to construct optimal LHDs; [9-11] introduced particle swarm algorithm for constructing optimal algorithm. The optimal designs constructed by these algorithms have been shown to have a good space-filling property. However, the computational cost of experimental designs is high and it is easier to get into local optimal solution.

Considering the above problems, this paper investigates the Latin hypercube experiment design based on Enhanced Stochastic Evolutionary (ESE) algorithm. Then, a more uniform experimental design method is proposed to conduct the performance evaluation of vehicle guidance and control system.

1 Vehicle Model

This paper mainly evaluates robustness of the vehicle guidance and control system in dive phase. Firstly, the dynamics and kinematics model of centroid motion is established.

$$\begin{cases} m\dfrac{dV}{dt} = P\cos\alpha\cos\beta - X - mg\sin\theta \\ mV\dfrac{d\theta}{dt} = Y\cos\gamma_V - Z\sin\gamma_V - mg\cos\theta + \\ \qquad P(\sin\alpha\cos\gamma_V + \cos\alpha\sin\beta\sin\gamma_V) \\ -mV\cos\theta\dfrac{d\psi_V}{dt} = Y\sin\gamma_V + Z\cos\gamma_V + \\ \qquad P(\sin\alpha\sin\gamma_V - \cos\alpha\sin\beta\cos\gamma_V) \\ \dfrac{dx}{dt} = V\cos\theta\cos\psi_V \\ \dfrac{dy}{dt} = V\sin\theta \\ \dfrac{dz}{dt} = -V\cos\theta\sin\psi_V \end{cases} \tag{1}$$

Where m is the mass of the vehicle, V the velocity of the vehicle, θ the trajectory inclination angle, ψ_V the trajectory deflection angle, α the attack angle, β the sideslip angle, γ_V the angle of bank, X,Y and Z represent the aerodynamic lift, drag, and lateral force acting on the vehicle respectively. The aerodynamic force X,Y and Z are given as the following:

$$\begin{cases} X = c_x qs \\ Y = c_y qs \\ Z = c_z qs \end{cases} \tag{2}$$

Where q is the dynamic pressure (q=0.5 ρV^2, ρ the atmospheric density), s the aerodynamic reference area, c_x,c_y and c_z represent the aerodynamic drag coefficient, the aerodynamic lift coefficient and the aerodynamic lateral force coefficient.

Then, the dynamics and kinematics model of around centroid motion is established.

$$\begin{cases} J_x\dfrac{d\omega_x}{dt} + (J_z - J_y)\omega_z\omega_y = M_x \\ J_y\dfrac{d\omega_y}{dt} + (J_x - J_z)\omega_x\omega_z = M_y \\ J_z\dfrac{d\omega_z}{dt} + (J_z - J_y)\omega_y\omega_x = M_z \\ \dfrac{d\vartheta}{dt} = \omega_y\sin\gamma + \omega_z\cos\gamma \\ \dfrac{d\psi}{dt} = \dfrac{1}{\cos\vartheta}(\omega_y\cos\gamma - \omega_z\sin\gamma) \\ \dfrac{d\gamma}{dt} = \omega_x - \tan\vartheta(\omega_y\cos\gamma - \omega_z\sin\gamma) \end{cases} \tag{3}$$

Where ϑ,ψ and γ represent pitch angle, yaw angle and roll angle respectively, ω_x,ω_y and ω_z represent the roll angular velocity, the yaw angular velocity and the pitch angular velocity respectively, M_x, M_y and M_z represent the roll moment, the yaw moment and the pitch moment. The aerodynamic moment M_x, M_y and M_z are given as the following:

$$\begin{cases} M_x = m_x qsl \\ M_y = m_y qsl \\ M_z = m_z qsl \end{cases} \tag{4}$$

Where l is the reference length, m_x, m_y and m_z represent the roll moment coefficient, the yaw moment coefficient and the pitch moment coefficient respectively.

The research focuses on performance evaluation of the vehicle guidance and control system, and the design of guidance and control law can reference [12].

2 Improved LHD

An experimental design with N runs and d factors is usually written as an N×d matrix $X_d^N = [\mathbf{x}_1, \mathbf{x}_2, \cdots, \mathbf{x}_n]^{\mathrm{T}}$, where each row $\mathbf{x}_i = [x_{i1}, x_{i2}, \cdots, x_{id}]$ stands for an experimental run and each column stands for a factor. The optimal experimental design problem we are interested is to search a design $\mathbf{X}^*$ in a given design class $\mathbf{Z}$, which optimizes (for simplicity, minimization is considered) a given optimality criterion f:

$$\min_{\mathbf{X}\in\mathbf{Z}} f(\mathbf{X}) \tag{5}$$

2.1 Optimality Criteria

The distance criteria between sample points are the measure metric of space-filling property. The common distance criteria consist of maximin distance criterion, ϕ_p criterion (a variant of maximin distance criterion) and so on.

(1) Maximin Distance Criterion

For vector $\mathbf{X}_i,\mathbf{X}_j$, define

$$d_{ij}=d(\mathbf{X}_i,\mathbf{X}_j)=\left[\sum_{k=1}^{m}\left|x_{ik}-x_{jk}\right|^p\right]^{1/p},\ p\geqslant 1 \quad (6)$$

where, d_{ij} is the Minkowski distance.

A design is called a maximin distance design if it maximizes the Minkowski distance:

$$\max\left[\min_{1\leqslant i,j\leqslant n,i\neq j} d(\mathbf{X}_i,\mathbf{X}_j)\right] \quad (7)$$

where m is the number of combinations of two sample points, and p=1or2.

(2) ϕ_p Criterion

Morris and Mitchell proposed an intuitively appealing extension of the maximin distance criterion. For a given design, by sorting all the inter-sited distance $d(\mathbf{x}_i,\mathbf{x}_j)$, a distance list $(d_1,d_2,\cdots,d_s)$ and an index list $(J_1,J_2,\cdots,J_s)$ can be obtained, where d_i is distinct distance values with $d_1<d_2<\cdots<d_s$, s is the number of distinct distance values. A design is called a ϕ_p -optimal design if it minimizes:

$$\phi_p=\left[\sum_{i=1}^{s}J_i d_i^{-p}\right]^{1/p} \quad (8)$$

2.2 Algorithm of improved LHD

The ESE algorithm consists of double loops, the inner loop and the outer loop, as shown in Fig 1 While the inner loop constructs new designs by element-exchanges and decides whether to accept them based on an acceptance criterion, the outer loop controls the entire optimization process by adjusting the threshold T_h in the acceptance criterion[13].

3 Performance Evaluation of Guidance and Control System

Firstly, this section mainly focuses on guidance and control system of a class of BTT vehicle and establishes its performance evaluation index system, as shown in Fig 2. In dive phase, the vehicle adjusts the attack angle, sideslip angle and angle of bank to generate the corresponding aerodynamic forces by controlling the elevator, aileron and rudder. The performance evaluation index system consists of state saturation index, state smoothness index, command tracking index, robustness index and terminal constraint index. State saturation index includes the saturation of flow angles, the saturation of overload and the saturation of elevator angle, measuring the vehicle's ability to cope with complex operational environment. Smoothness index comprises the attack angle smoothness, the sideslip angle smoothness and the overload smoothness, which can weigh indirectly the robustness of control system during the course of the flight. Terminal constraint index is composed of the terminal missile-target distance constraint, the terminal velocity constraint and the terminal fall-angle constraint. Thus, it can evaluate vehicle attacking accuracy and destruction.

Then, apply the proposed ESE-based LHD to performance evaluation of vehicle guidance and control system in dive phase. Compared to Monte Carlo experiment design, performance evaluation instance verifies that ESE-based LHD is effective to evaluate guidance and control system.

The vehicle usually requires to possess the ability to perform specific task in complex operational environment. Hence, the guidance and control system must be robust to atmosphere turbulence. Considering the vehicle simulation model, select the aerodynamic coefficients, the aerodynamic moment coefficients, the atmospheric density and the moment of inertia as experimental factors, as shown in Tab. 1.

According to experimental factor information, generate 200 groups of Monte Carlo experiment design and ESE-based LHD experiment design respectively, obeying uniform distribution, as shown in Tab. 2 and Tab. 3.

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The frequency distribution histogram shows clearly the probability distribution of each experimental factor in different intervals. It is the most suitable to analyze and compare the probability distribution of each factor in different experimental design.

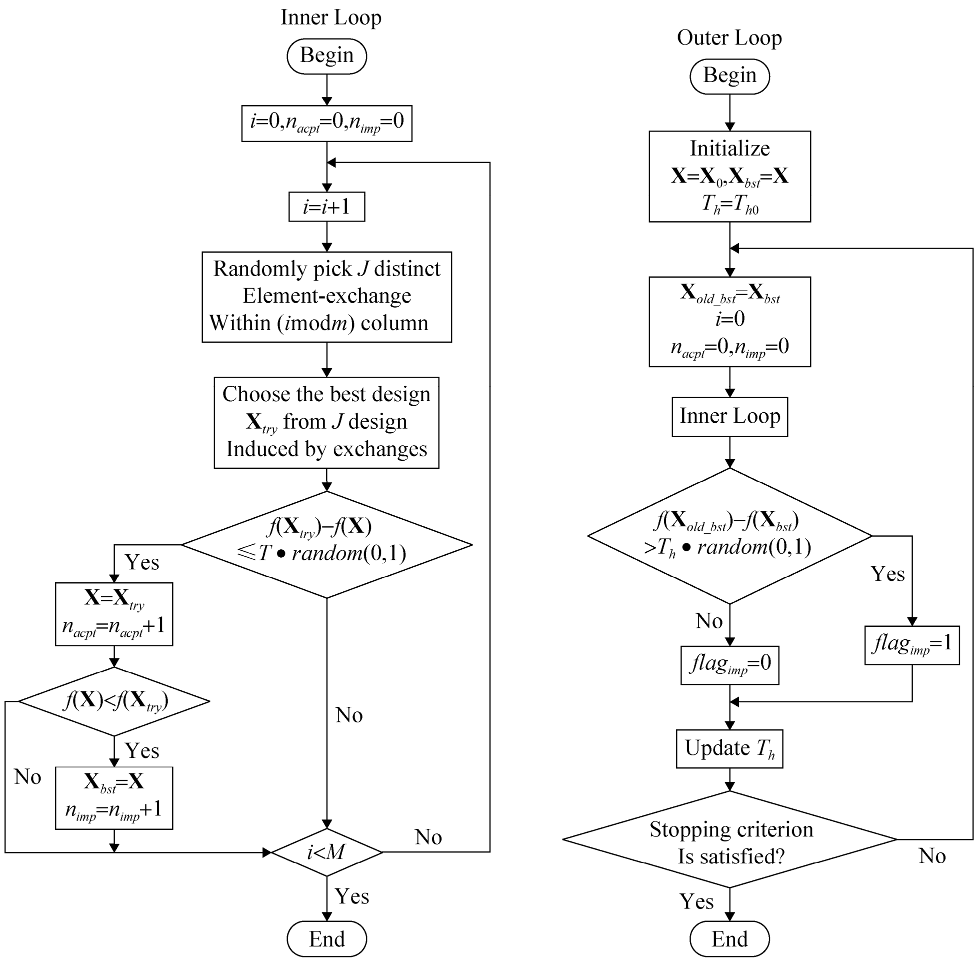


Fig. 1 Flowchart of the ESE algorithm

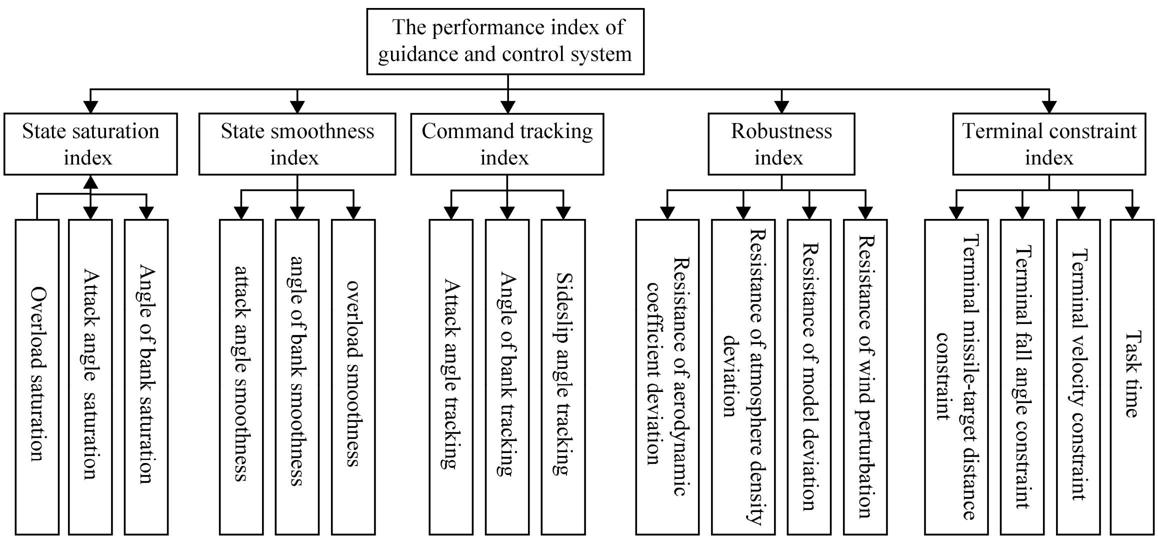


Fig. 2 Performance evaluation index system of vehicle guidance and control system

Tab. 1　Factors information

index	factor name	Symbol	pull range
1	aerodynamic coefficient	C	[–0.15,0.15]
2	aerodynamic moment coefficient	M	[–0.3,0.3]
3	moment of inertia	J	[–0.1,0.1]
4	atmospheric density	ρ	[–0.15,0.15]

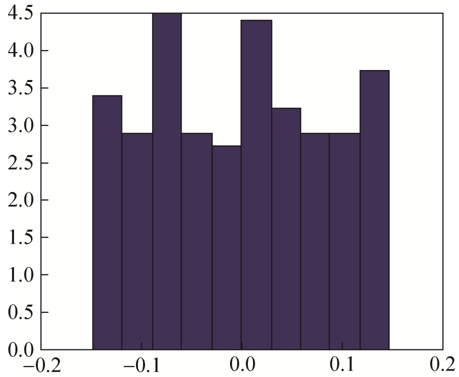
Tab. 2　Monte Carlo experiment design

index	factor1	factor2	factro3	factor4
1	0.054 553	–0.093 150	0.014 312	–0.016 636
2	0.045 227	–0.270 716	–0.036 755	–0.052 026
3	–0.078 797	–0.164 878	0.061 899	–0.063 812
4	–0.006 779	0.048 608	–0.026 900	–0.001 064
5	0.130 926	0.060 825	0.039 758	–0.095 488
…	…	…	…	…
196	0.037 684	0.048 305	0.049 372	–0.088 654
197	–0.136 883	0.075 662	0.033 992	–0.131 144
198	0.089 377	–0.233 311	0.059 118	0.036 716
199	0.145 863	–0.171 783	–0.045 491	0.056 406
200	–0.018 977	–0.278 178	–0.043 217	–0.060 964

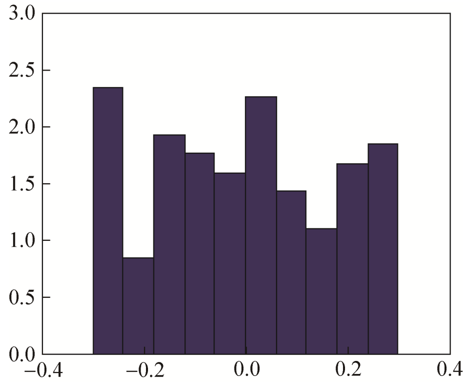
Tab. 3　ESE-based LHD experiment design

index	factor1	factor 2	factor 3	factor 4
1	0.118 313	0.221 646	0.046 253	0.072 345
2	–0.043 727	–0.123 936	–0.089 065	0.118 295
3	0.097 547	–0.042 192	–0.082 883	0.142 13
4	0.100 76	0.168 582	–0.088 114	–0.115 934
5	–0.003 482	–0.022 756	0.089 635	0.016 438
…	…	…	…	…
196	0.149 989	0.026 600	0.099 975	0.053 667
197	0.087 519	0.043 562	0.067 494	–0.145 678
198	–0.087 012	–0.191 771	0.021 267	0.001 071
199	–0.057 094	0.161 572	0.031 955	–0.126 32
200	0.114 67	–0.050 483	–0.093 862	0.121 279

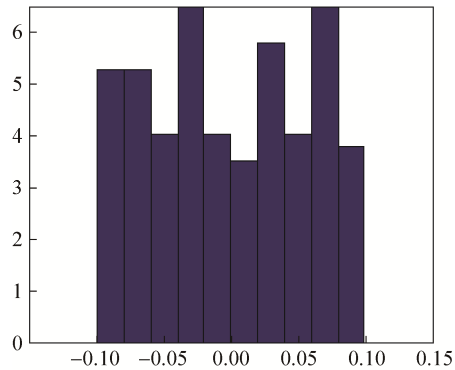
Make use of the generated experiment design scheme to get the frequency distribution histograms of experimental superiority-inferiority in sampling uniformity. The frequency distribution histograms of aerodynamic coefficients, aerodynamic moment coefficients, the atmospheric density and the moment of inertia belonging to Monte Carlo experiment design are shown in Fig. 3.



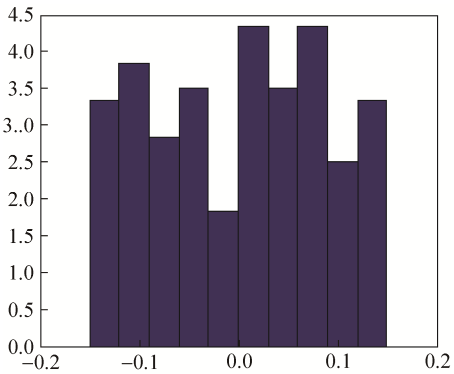
(a) Frequency distribution histogram of factor 1



(b) Frequency distribution histogram of factor 2



(c) Frequency distribution histogram of factor 3



(d) Frequency distribution histogram of factor 4

Fig. 3　Frequency distribution histograms of Monte Carlo experiment design factors

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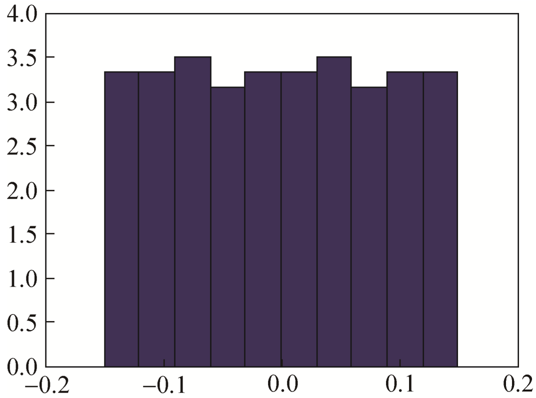
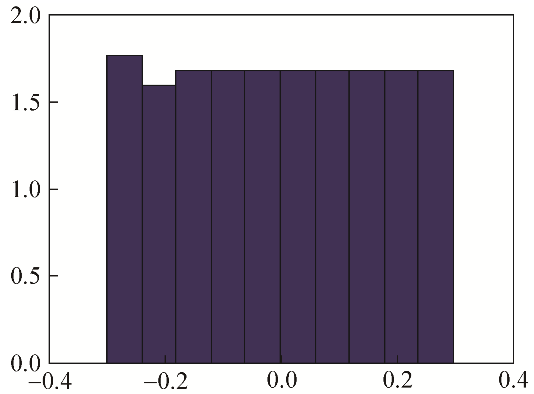
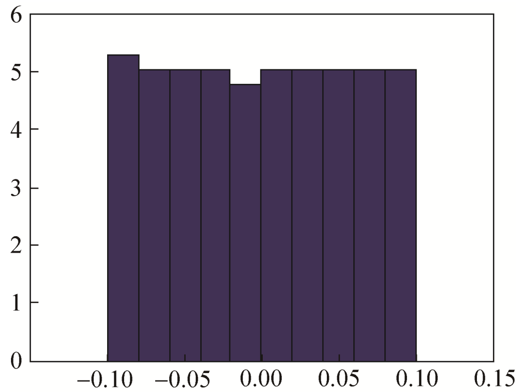
The frequency distribution histograms of aerodynamic coefficients, aerodynamic moment coefficients, the atmospheric density and the moment of inertia, belonging to ESE-based LHD are shown in Fig. 4. Obviously, the experimental factors sampling uniformity of ESE-based LHD is superior to that of Monte Carlo experiment design. Thus, the former can represent better the sampling space.



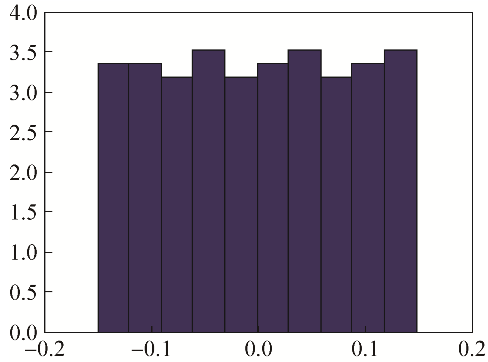
(a) Frequency distribution histogram of factor 1



(b) Frequency distribution histogram of factor 2



(c) Frequency distribution histogram of factor 3



(d) Frequency distribution histogram of factor 4

Fig.4 Frequency distribution histograms of ESE-based LHD factors

Combining the experimental factor information, this paper generates 200 groups of the ESE-based LHD and Monte Carlo experiment design schemes respectively. Then, employ the generated design schemes as the input of system and run simulation program repeatedly to acquire simulation result data. The terminal velocity improving the destruction of aircraft as indicator measures the robustness of guidance and control system. The scatter diagram of the terminal velocity, is shown in Fig. 5.

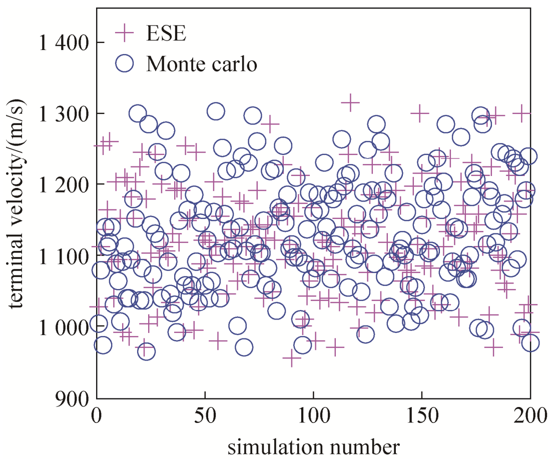


Fig. 5 Terminal velocity of vehicle

One which can obtain the maximum terminal velocity of the ESE-based LHD is slightly larger than that of Monte Carlo experimental design from Fig. 5. Besides, the minimum terminal velocity of the

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ESE-based LHD is marginally smaller than that of Monte Carlo experimental design. In other words, the simulation data obtained by the ESE-based LHD can cover the extreme case.

Compared to Monte Carlo experiment design, the sample points obtained by the ESE-based LHD are more uniform and cover more comprehensively the situations of experimental factors' combination. Therefore, it is suitable to adopt the ESE-based LHD to evaluate the performance of guidance and control system.

4 Conclusion

Aiming at the low efficiency and the poor space-filling property in the aircraft performance evaluation combined with simulation experiment, this paper proposes a novel aircraft performance evaluation method based on experiment design. The method is able to quickly construct a good design of experiment given a limited computational resource. In performance evaluation instance, the scatter of the terminal velocity obtained by ESE-based LHD scheme is more uniform, compared to the Monte Carlo experiment design. It can measure better the robustness of guidance and control system. The ESE-based LHD is feasible and effective to evaluate the performance of the vehicle guidance and control system.

References:

[1] Sun S, Zhang H M, Zhou D. A Survey of Terminal Guidance Law [J]. Aerospace Control(S1006-3242), 2012, 30(1): 86-96.

[2] Morris M D, Mitchell T J. Exploratory designs for computational experiments [J]. Journal of Statistical Planning and Inference (S0378-3758), 1995, 43(4): 381-402.

[3] Park J S. Optimal Latin-hypercube designs for computer experiments [J]. Journal of Statistical Planning and Inference (S0378-3758), 1994, 39(1): 95-111.

[4] Ye K Q, Li W, Sudjianto A. Algorithmic construction of optimal symmetric Latin hypercube designs [J]. Journal of Statistical Planning and Inference (S0378-3758), 2000, 90(1): 145-159.

[5] Fanf K T, Ma C X, Winker P. Centered L2- discrepancy of random sampling and La tin hypercube design, and construction of uniform designs [J]. Journal of Statistical Planning and Inference (S0378-3758), 2002, 71(237): 275-296.

[6] Bates S J, Sienz J, Toropov V V. Formulation of the optimal Latin hypercube design of experiments using a permutation genetic algorithm [C]// Proc. of the 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference. Palm Springs, California, USA: AIAA Press 2004: 2004-2011.

[7] Husslage B G M, Rennen G, Hertog D, et al. Space-filling Latin hypercube designs for computer experiments [J]. Optimization and Engineering(S1389-4420), 2011, 12(4): 611-630.

[8] Schubert J, H Rling P. A comparative study between using A*-search, Latin Hypercube and geneticalgorithm in design of experiment for simulation of military operational plans [C]// Proc. of 2014 IEEE International Conference on System, Man, and Cybernetics. San Diego, CA, USA: IEEE Press 2014: 372-379.

[9] Chen R B, Hsieh D N, Hung Y. Optimizing Latin hypercube designs by particle swarm [J]. Statistics and Computing(S0960-3174), 2013, 23(5): 663-676.

[10] Leatherman E, Dean A, Santner T. Computer Experiment Designs via Particle Swarm Optimization [J]. Topic in Statistical Simulation(S2194-1009), 2014, 114(10): 309-317.

[11] Phoa F K H. A Swarm Intelligence Based (SIB) method for optimization in designs of experiments [J]. Natural Computing (S1567-7818), 2016: 1-9.

[12] Sun X Y, Chao T, Wang S Y, et al. Integrated Guidance and Control Design Method Considering Channel Coupling [J]. Journal of Astronautics (S1000-1328), 2016, 37(8): 936-945.

[13] Jin R C, Chen W, Sudjianto A. An Efficient Algorithm for Construction Optimal Design of Computer Experiments [J]. Journal of Statistical Planning and Inference (S0378-3758), 2005, 134(1): 268-287.