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Aerodynamic multi-objective integrated optimization based on principal component analysis

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Abstract Based on improved multi-objective particle swarm optimization (MOPSO) algorithm with principal component analysis (PCA) methodology, an efficient high-dimension multi-objective optimization method is proposed, which, as the purpose of this paper, aims to improve the convergence of Pareto front in multi-objective optimization design. The mathematical efficiency, the physical reasonableness and the reliability in dealing with redundant objectives of PCA are verified by typical DTLZ5 test function and multi-objective correlation analysis of supercritical airfoil, and the proposed method is integrated into aircraft multi-disciplinary design (AMDEsign) platform, which contains aerodynamics, stealth and structure weight analysis and optimization module. Then the proposed method is used for the multi-point integrated aerodynamic optimization of a wide-body passenger aircraft, in which the redundant objectives identified by PCA are transformed to optimization constraints, and several design methods are compared. The design results illustrate that the strategy used in this paper is sufficient and multi-point design requirements of the passenger aircraft are reached. The visualization level of non-dominant Pareto set is improved by effectively reducing the dimension without losing the primary feature of the problem.

1. Introduction

Multi-objective design methods mainly include weighted average optimization and non-dominated optimization based on Pareto idea. The former is actually a single point optimization method, and the design results strongly depend on the choice of weight function. Its main deficiency is that the selection of reasonable weight function is becoming more and more difficult with the increasing number of object. Improper weight may lose some important information as the design problem is going to be more complex. As a consequence, numerical

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optimization based on Pareto idea has played an important role in multi-disciplinary and multi-objective design of aircraft. However, the research mainly focuses on low dimensional multi-objective problems with simple shape and single design point. The application of Pareto in high dimensional optimization has several major problems[1–3]:

(1) The Pareto front would advance extremely slowly and is not reliable. With the increasing number of object (when $\geqslant 3$, in the following, it is named as multi-objective problem), the dimension of Pareto optimal front surface increases, and the number of point in the Pareto fronts would rise exponentially, which makes the time consumption and space complexity of the algorithm deteriorate greatly.
(2) The number of the non-dominated solution will grow dramatically. When the object reaches to a certain number, almost all individuals are non-dominated solutions, which will lead to serious weakening of performance based on Pareto dominance ranking and selection. For a given external group with fixed size, excellent individuals may not be preserved in the evolutionary process, making the entire algorithm search become slow and difficult to reach a reasonable Pareto front. So, the traditional optimization method is powerless in dealing with multi-objective problems.
(3) Wide design space and huge grid scale of complex configuration result in large computation expense and requirement of high population diversity.
(4) For designers, the visualization level of non-dominated solution set is not sufficient, which leads to a difficulty to make reasonable decisions. So, the traditional optimization method is powerless in dealing with multi-objective problems.

Aerodynamic design of wide-body aircraft is a typical multi-point integrated design process, in which the multiple design requirements such as the cruise lift-to-drag ratio, the buffer boundary and the drag divergence characteristic should be considered. At the same time, wide-body aircraft often use the crane wing-mounted engine configuration. For this type of configuration, the existence of pylon and nacelle will affect the pressure distribution of supercritical wing to a certain extent by a positive correlation with the sweep angle of wing, which may change some crucial aerodynamic characteristics. Therefore, for the fine design of wing-mounted engine configuration, influence of pylon/nacelle on the wing must be considered. In addition, in order to maintain excellent aerodynamic performance after trimming the pitch moment, it is necessary to carry out integrated design considering the nacelle interference and the horizontal tail trimming. With the rapid development of computer, it is possible to conduct multi-objective and refine integrated design for full aircraft configuration, which, however, has not been deeply investigated in industrial field at present.

According to the above problems, in the large scale distributed parallel computing environment, multi-objective aerodynamic integrated design for wing, fuselage, pylon, nacelle, horizontal and vertical wing on cruise configuration of wide body aircraft is studied based on improved multi-objective particle swarm optimization (MOPSO) algorithm coupling with principal component analysis (PCA) method. Validity of the design method in this paper is verified and the optimized results are discussed.

2. PCA-MOPSO optimization platform

2.1. Redundant object identification and dimensional reduction

The search process of Pareto-based algorithm slows down dramatically in multi-objective optimization, and the visualization level of non-dominated solutions is not conducive to make decision for designers. In data analysis, the data with less variables and more information is always expected. Actually, there is always a certain correlation between the variables in practice, and when there is a correlation between two variables, it can be explained that the information reflected by these two variables has a certain overlap, and then the dimension reduction can be achieved. PCA[4,5] has been widely accepted in image processing and data reduction because of its ability of correlation analysis, variable identification, target recognition and the abnormal value grouping.[6–8] However, the application of PCA in aerodynamic multi-objective optimization is still rare. PCA method can identify the principal components as well as "redundant components" or "sub components". Using the analysis results, we can regard "sub components" as a constraint or redundancy for the further dimension reduction. Based on the PCA method, the dimension reduction of multi-objective optimization can be realized by the following steps[9,10]:

(1) Initialize the iteration counter $I = 0$, the target set $M = \varnothing$, and the threshold TC.
(2) Initialize population randomly, and optimize to obtain a set of Pareto solution P.
(3) Perform principal component analysis on the Pareto solution P, and the redundant target can be eliminated by the specified threshold TC. The specific implementation strategies are as follows:
    (A) Normalize the target vector to calculate the correlation matrix $\boldsymbol{R}(I, J)$ and the eigenvector $\boldsymbol{V}(I, J)$, and extract the first and second principal components via PCA analysis.
    (B) For the first vector, select two targets with the most positive and negative elements into the set M; if all the elements have the same sign, select two corresponding targets with the maximum absolute value.
    (C) For next component, check the threshold. If the threshold is met, end the cycle; otherwise, if the eigenvalue < 0.1, select corresponding target with the largest absolute value $|\max(\boldsymbol{V}(I, J))|$ into the M. Otherwise.
        (a) Select two corresponding objects with the most positive and negative elements into the set M.
        (b) If all the elements have the same sign, select two corresponding targets with the maximum absolute value into the set M.
(4) If $M = M(I-1)$, stop and output the optimal solutions; otherwise, $I = I + 1$ and return to step (2).

After PCA analysis, we can identify the relationship between the targets so as to extract the principal target from the high dimensional object space and eliminate the redundant objects. The original design problem can be simplified without