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Grid fins shape design of a launch vehicle based on sequential approximation optimization

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Abstract

This paper performed the optimization of grid fins shape of a launch vehicle based on Sequential Approximation Optimization (SAO) and Computational Fluid Dynamics (CFD) simulation coupling. An efficient and reliable method is proposed for determining the width of Gaussian functions based on a logical relationship between the width and local density. The performance of the proposed method is evaluated using five classical test functions. The proposed method for width determination generates almost no excessive calculation costs, and improves the accuracy, reliability, and stability of the Radial Basis Function (RBF) surrogate model notably. Based on the improved RBF surrogate model, a framework and detailed procedure for the SAO algorithm is presented, and the performance of the proposed SAO algorithm is tested, with obtained results showing that the proposed SAO algorithm reduces the calling times of the original model and improves the optimization efficiency remarkably. The objective function is strictly deduced and reflects the momentum loss caused by aerodynamic drag directly. Three constraints are imposed to ensure the static stability and controllability of the launch vehicle. Finally, grid fins shape optimization problem of the launch vehicle is solved, with the objective function and constraints calculation tasks accomplished automatically by batch mode CFD simulations. The global optimal solution is obtained after 54 calling times of the original model, and 92 h (3.84 days) of computation on a 96-core cluster. Once the baseline shape is replaced with the optimized shape, it is detected that (1) taking the minimum fuel as an objective function, the take-off mass is 2.07% lighter than the take-off mass of the baseline shape, (2) taking the maximum payload mass as an objective function, the payload mass is 14.3% heavier than the payload mass of the baseline shape.

Keywords: Grid fins; Launch vehicle; Sequential approximation optimization; Radial basis function model; Width of Gaussian functions; Shape optimization

1. Introduction

Grid fins (also known as lattice fins) are non-conventional aerodynamic lifting and control surfaces which consists of outer frames and intersecting grids. The main advantages of grid fins includes; (1) favorable lift characteristics, (2) very high stall angle of attack, (3) low hinge moment due to low chord length, hence small size of needed control actuator, (4) can be easily folded for efficient packaging, storage, and transport, (5) high strength to mass ratio (Theerthamalai, 2007; Peng et al., 2015). Due to its advantages, grid fins have attracted much attention in recent years and have been utilized for a wide variety of missiles and intelligent munition systems successfully, examples which include; the OTR-21 Tochka

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tactical ballistic missile of the Former Soviet Union, R-77 air-to-air missile of Russia, GBU-43/B Massive Ordnance Air Blast (MOAB) of the USA, Falcon 9 rocket, Falcon heavy rocket, etc. Due to its favorable characteristics, grid fins can also be used as stabilizing and control surfaces of launch vehicles appropriately, an example of which the Chinese Kuaizhou 1 and Kuaizhou 11 launch vehicle possess four grid fins installed on the base of the first stage. However, the main disadvantages of grid fins are (1) Its complex shape and structure, (2) higher drag when compared with conventional fins.

Aerodynamic shape design of grid fins are highly essential and presents the major consideration during grid fin designs. A more careful and detailed aerodynamic shape design could further develop and improve the advantages of grid fins, and in so doing, potentially reduce the impacts of its associated disadvantages. Existing studies mainly focused on; grid fins basic aerodynamic characteristics (Dikbas et al., 2018; Kless and Aftosmis, 2011; Hughson et al., 2007; Simpson and Sadler, 1998), effects of geometric variables on grid fins aerodynamic characteristics (Washington and Miller, 1998), special configurations such as curved grid fins (Washington et al., 1993), and local swept back grid fins (Guyot and Schulein, 2007). Meanwhile, studies on grid fins aerodynamic shape design based on modern numerical optimization methods was seldomly found, except for studies by; Yang and Zhang (2013), where they optimized three section shape parameters of grid fins base on Computational Fluid Dynamics (CFD) method, and Ledlow et al. (2015), whom optimized a ten grid fin geometrical parameters based on aerodynamic theoretical prediction algorithms method in order to maximize the target strike area of a missile using grid fins as control devices.

CFD methods proffer a high-fidelity method for computing the aerodynamic parameters of flight vehicles, which could potentially yield more accurate results than theoretical prediction methods when applied towards computing aerodynamic parameters of grid fins. Design methods based on coupling modern numerical optimization algorithms and CFD simulations are favorable methods for grid fins shape design and could potentially lead to improved performance of grid fins design.

Within this paper, grid fins shape is optimized for a launch vehicle based on the coupling of numerical optimization algorithms and CFD simulations. The computational cost of CFD methods could be potentially high. The key point in accomplishing a successful grid fin shape optimization is to increase the efficiency of the optimization methods while reducing the calling times of CFD simulations to as minimal as possible during the optimization procedure. Sequential approximation optimization (SAO) methods are known for their lower computational costs, generality, robustness, and accuracy (Wang et al., 2014a). SAO algorithms require much lesser times for evaluation of original models in order to locate global optimum when compared to evolutionary algorithms (EAs) such as the genetic algorithm (Goldberg, 1989), simulated annealing (Kirkpatrick et al., 1983), particle swarm optimization (PSO) algorithm (Kennedy and Eberhart, 1995), immune algorithm (Yildiz, 2009), and artificial bee colony algorithm (Karaboga and Basturk, 2003). Objectively, SAO algorithms are particularly fit for grid fins shape optimization based on coupling with CFD simulations. Within SAO, the surrogate models are constructed repeatedly by addition of new sampling points, until the terminal criterion is satisfied (Kitayama et al., 2011). Surrogate models construction stage is the most important part of SAO algorithms, and this has been widely studied (Deng et al., 2002; Kitayama et al., 2011; Kitayama and Yamazaki, 2011; Luo et al., 2011). The Radial Basis Function (RBF) model, was originally proposed by Hardy (1971) to fit irregular topographic contours of geographical data. The RBF model has shown to be reliable in terms of accuracy and robustness (Jin et al., 2001), and is extensively used in SAO algorithms. Determination of the width of an RBF model has decisive impacts on the accuracy of the RBF model (Chen et al., 2011; Xu et al., 2013; Yeh et al., 2012; Wu et al., 2016, 2017; Bonte et al., 2010). Nakayama et al. (2002) proposed a determination method of the width for uniform samples. Kitayama et al. (2011) proposed a method for non-uniform and sufficient samples. Wang et al. (2014a) proposed a method based on local densities of sampling points, with the total influence volume as the key parameter for the method, which was obtained by cross validation in a cumbersome approach. Due to the intense non-uniform distribution of samples and progressively increasing samples in an SAO procedure, establishing a reliable RBF width determination method for non-uniform samples with uncertain scale is significantly beneficial for improving the accuracy of surrogate models and the efficiency of SAO algorithms in general.

Multipoint optimization is widely applied in fight vehicles shape optimization (Gallard et al., 2013; Lee et al., 2006a, 2006b; Sunago et al., 2009), which means the status of several flights are considered within the optimization procedure. Therefore, within this paper, a multipoint optimization method is employed for grid fins shape optimization for a launch vehicle based on the SAO algorithm and CFD simulations coupling. A new approach for determination of the width of the RBF model is proposed to enhance the RBF surrogate model during the SAO algorithm, and the performance of the proposed method is evaluated. Based on the improved surrogate model, the framework and detailed procedure of the SAO algorithm are presented, and the performance of the proposed SAO algorithm is tested. Weighted average drag coefficients at several selected trajectory points are used as the objective function, and the weighting factors are determined based on strict deducing. The emphasis of obtaining a reasonable objective function is to determine the design trajectory points and the corresponding weighting factors. Constraints are imposed to ensure static stability and controllability for the launch vehicle. Grid fins shape optimization

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