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Optimization design for aerodynamic elements of high speed trains

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ABSTRACT

The complex wake flow of high speed trains severely influences the running safety and amenity of the trailing car. In this paper, based on the streamlined shape of CRH380A high speed train, taking the aerodynamic lift force of the trailing car and the volume of the streamlined head as the objectives, an efficient multi-objective optimization process based on the response surface has been constructed. The Kriging model has been constructed based on the cross-validation method and genetic algorithm (GA). This approach could decrease the number of training samples and improve the optimization efficiency while without decreasing its generalization. After the Pareto optimal solutions being obtained, four design points are chosen for comparative study with the original shape, and one of these points is chosen for the unsteady aerodynamic study together with the original shape. The results reveal that the variation trends of the lift force and the side force of the trailing car are the same as that of the drag of the whole train. After optimization, the volume of the streamlined head is almost the same as that of the original shape. Compared to the original shape, the lift force of the trailing car decreases by 27.86% of and the drag of the whole train decreases by 3.34% in conditions without crosswind, and the lift force of the trailing car decreases by 5.43%, the side force of the whole train decreases by 72.09% and the drag of the whole train decreases by 2.1% in the crosswind conditions. The optimal train benefits from low fluctuations of lift and side force of the trailing car. Besides, better wake flow could be obtained, and the wake vortices are suppressed, too. Consequently, the running safety and amenity of HST are improved a lot after optimization.

1. Introduction

As a large length-to-diameter ratio transportation vehicle, high speed trains (HST) run quicker and quicker. The speed of HST that running on the Beijing–Shanghai railway has already reached 300 km/h. In high speed conditions, the flow around the train reveals distinct unsteady characteristics due to the influence of the exposed structures (bogies, pantographs, etc.) and the ground effect [1]. Furthermore, the unsteady characteristics of the wake flow for a slender body are more predominant, which may lead to high fluctuations of aerodynamic loads, especially for the lift and side force of the trailing car. Large aerodynamic lift force will decrease the contact force between the wheels and the rail, which will lead to derailment in certain circumstance. For the flow around a slender body, asymmetric wake flow will emerge in crosswind conditions, and the shedding vortices around the nose of the trailing car will result in high lift and side force. Meanwhile, enough space should be ensured not only for the placement of equipments but also for the operation convenience of the drivers. Consequently, it is very necessary to ensure enough space of the streamlined head during the shape optimization of HST.

The streamlined part is very essential to the aerodynamic performance of HST. The aerodynamic performance could be effectively improved by optimizing the train shape [1]. However, the running environment of HST is very complex, and lots of design objectives (such as the aerodynamic drag force, the aerodynamic lift force of the trailing car, aerodynamic side force of the trailing car, the aerodynamic overturning moment of the trailing car, the aerodynamic rolling moment of the trailing car, the micro-pressure wave generated when the train pass a tunnel, the pressure wave generated when two trains crossing each other on a double railway and the aerodynamic noise.) have a serious effect on the running safety and amenity of HST. Dozens of design parameters are needed to accurately control the geometry of the high-speed train head, and several geometric constraints are also required to ensure the usefulness of the train head. Meanwhile, the aerodynamic shape optimization needs large amount of computational cost and hundreds of thousands times of flow field calculations should be required for one optimization. Thus, it is unbearable to take all of the design objectives into consideration when optimizing a train head. Limited by the computer technique and optimization

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algorithms, early studies on the streamline shape optimization of HST mainly rely on wind tunnel experiments and numerical simulations [2]. Meanwhile some methodology studies on two-dimensional profile of the streamlined head have been performed with gradient algorithms [3]. In order to reduce the computational cost and shorten the optimization cycle, some scholars introduce the response surface method (RSM) into the aerodynamic optimization [2–10]. In recent years, great progress has been obtained both for the response surface technique and the computer technique, which greatly improves the optimization efficiency and makes the engineering optimization of HST be possible.

Jongsoo and Junghui [3] conducted a two-dimensional optimization on reducing the micro-pressure wave with the RSM technique and sequential quadratic programming algorithm. Vytla et al. [4] performed a two-dimensional optimization study on minimizing the aerodynamic drag and noise based on the Kriging model and GA-PSO hybrid algorithm. In order to obtain the micro-pressure wave when the train passes by tunnel, both Jongsoo and Vytla [3,4] used axial symmetric equations to simulate the flow field. Combined with GA and arbitrary shape deformation technique, Sun et al. [11] performed a three-dimensional aerodynamic shape optimization of HST. In order to reduce the computational cost, only the streamlined head has been considered in Ref. [11], which may decrease the computational accuracy of the flow field. Ku et al. [5] utilized the polynomial RSM to optimize the micro-pressure wave and obtained the optimal cross-sectional area distribution. Taking this distribution as the constraint, they then performed the three-dimensional optimization on minimizing the aerodynamic drag based on Kriging model. However, the whole process still belongs to a single objective optimization. Krajnovic [6] took the drag force coefficient, rolling moment coefficient and yawing moment coefficient as objectives to optimize a very simple train front for crosswind stability. Three kinds of RSM are adopted to reduce the CFD cost in his work. Because of difference of the three RSM methods prediction accuracy, Krajnovic found that the performance of the combination of RBNN and polynomial functions is better than the two others (polynomial functions and radial basis neural networks). Besides, in Ref. [6], Krajnovic also optimized the vortex generators to reduce the drag of the train. The study inspires us to make full use of RSM to reduce the CFD cost. In conclude, the aerodynamic shape optimization of HST found in the above references mainly focus on two-dimensional profiles or very simple three-dimensional shapes, and they mainly belong to methodology study and could hardly be used to engineering problems.

Thus, the main propose of our work in this paper is to introduce the popular optimization algorithms and RSM technique into engineering problems with amounts of CFD cost, adopt a procedure to shorten the design cycle of new streamlined parts of HST as much as possible, and shed light on aerodynamic shape design based on the unsteady flow field. Aerodynamics design objectives that seriously influence the running safety and amenity of HST (such as the aerodynamic lift force of the trailing car, aerodynamic side force of the trailing car, the aerodynamic overturning moment of the trailing car, the aerodynamic rolling moment of the trailing car, the pressure waves generated when the train pass a tunnel) are considerate in this paper. Besides, the aerodynamic drag force is also considerate in our work to make sure that the optimal train is friendly to environment. However, some other design objectives (such as two trains crossing each other on a double railway and the aerodynamic noise) are not discussed in this paper. Only the lift force of the trailing car and the volume of streamlined part are taken to be optimal objectives so as to reduce the CFD cost and make the optimal problem be practical. So we mainly take the shape of the trailing car into consideration in this paper and discuss the influence of the leading car shape to pressure waves in Section 6.4 carefully. The Kriging model is adopted together with the multi-points criterion based on minimum response surface method to reduce the CFD cost and improve the optimization efficiency. Meanwhile, a cross-validation training approach has been proposed in this paper which greatly reduces the number of training samples. Based on the Kriging model of which the accuracy meets the engineering requirement, the Pareto front has been obtained with NSGA-II. Then four typical design points are chosen from the Pareto solutions for comparative study with the original shape known as CRH380A, and one of these points is chosen for the unsteady aerodynamic study together with the original shape.

2. Optimization process

Although the RSM has been utilized, the design cycle of the streamlined parts of HST is still very long. Any unreasonable operating during the optimization process may deteriorate the optimization solutions, even result in disagreeable solutions. Thus, the optimization process should be designed reasonably and reduce unnecessary steps as many as possible. The whole optimization process in the present paper is listed as below, as Fig. 1 shows:

(1) Determine the design variables and their ranges based on the optimization problems.
(2) Determine the number of training samples which could meet the requirement of the RSM model, sampling in the design space with the use of central Latin hypercube sampling method with maximin criteria, obtain the initial value of the design variables for each training sample.
(3) Get the exact value of objectives for each training sample with CFD tools; the values of some objectives could be obtained by other approaches, the volume of the streamlined part, for instance.
(4) Train the Kriging model based on the cross-validation method and the real-coded GA.
(5) Based on the Kriging model, optimization is performed with the multi-objective non-dominated sorting genetic algorithm, and the Pareto front is obtained.
(6) Choose some samples from the Pareto solutions as the testing samples, and CFD validation is performed to judge whether the predicting accuracy has been achieved.
(7) If the predicting accuracy of the testing samples is not met, these samples should be added to the training sample set, return to step (3), and reconstruct the Kriging model.
(8) If the predicting accuracy is achieved, the Kriging model is recognized as correctly constructed. The Pareto solutions are then the final optimal solutions.

3. Parametric methods

3.1. Geometry

Optimization of the head of HST mainly focuses on the streamlined part, of which the key design variables are as follows: the cross-sectional area distribution and the slenderness ratio of the streamlined part, the longitudinal-type line and horizontal-type line of the streamlined part, the drainage around the nose, the cab perspective and the bogie shield. In the present paper, a CRH380A 1:1 model with three carriages has been utilized for aerodynamic shape optimization. The connection part between adjacent carriages is completely eliminated. Meanwhile, the cavities around the bogies are all closed for simplification. Considering that the bogie below the trailing streamlined part is crucial for the wake flow and the flow below the trailing car, this bogie is