Research on Key Parameter Optimization Method of High-Speed Railway Vehicle-Bridge System Based on Proxy Model

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Abstract. This paper proposes a key parameter optimization method for a high-speed railway vehicle-bridge system using numerical calculations, proxy models, and optimization design. A three-dimensional vehicle-bridge coupled dynamic model is constructed to calculate the vertical acceleration of the vehicle body under different sampling combinations. Based on this, a Kriging proxy model of vehicle body vertical acceleration is constructed to accurately describe the relationship between vehicle axle weight, bridge creep deflection, and vehicle body vertical acceleration. A matching optimization model for vehicle axle weight and bridge creep deflection is proposed, with the objective of minimizing vehicle body vertical acceleration. The cuckoo search algorithm is utilized to obtain the optimal design parameters. The results show that the sensitivity of vehicle body vertical acceleration to creep deflection is much higher than that to vehicle axle weight. The optimal vehicle axle weight for a high-speed railway is 15 t, and the creep deflection limit for the bridge is 3 mm, resulting in a minimum vehicle body vertical acceleration of 0.4909 m/s^2. This method provides an important basis for controlling bridge creep deflection and vehicle design from a system-level perspective.

Keywords: High-speed railway · Optimization method · Numerical calculation · Vehicle-bridge systems · Proxy model

1 Introduction

Due to the rapid advancement of high-speed railway, higher requirements for its safety and comfort have been put forward. Bridges are widely used in high-speed railways to reduce post construction settlement and unevenness [1, 2]. Simple supported beams are widely used in high-speed railway construction in China due to their advantages such as simple structure, convenient construction, and low cost. Prestressed concrete simply-supported beams are subjected to long-term compressive action of prestress, which often produces a creep compression effect over time [3]. The compression deformation at the lower end is higher than that at the upper end, resulting in creep and camber of the

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simple supported beam, resulting in irregularities in the longitudinal section of high-speed railway lines, seriously affecting the safety of high-speed railway traffic and ride comfort [4, 5]. Research on the vehicle line bridge coupling system shows that the axle load of trains and the creep camber of bridges are important factors affecting the vertical acceleration of the train [6, 7]. Thus, in the bridge intensive high-speed railway design stage, determining reasonable bridge creep camber and train axle load is of great significance for the comfort and safety of high-speed railway design.

The investigation into the dynamic response of creep camber of high-speed railway bridges to train effects has garnered significant interest among researchers. The relevant research mainly focuses on the simulation of bridge creep camber [8, 9], the dynamic response analysis of creep camber to trains, and the study on the limit value of creep camber.

Currently, China has independently and comprehensively constructed a complete technical system with a speed of 350 km/h, and has explored relevant technical issues for high-speed railways with a speed above 350 km/h through comprehensive tests on certain high-speed railways. Currently, the technical parameters of high-speed railways with higher speeds per hour have not been fully determined, and there is a certain coupling relationship between the technical parameters of multiple units and the design parameters of infrastructure. Therefore, it is necessary to further improve the forward design and matching optimization methods of the system, so as to more reasonably formulate the design parameters of a new generation of faster, safer, and more comfortable high-speed railways. Therefore, this paper aims at the vertical acceleration of trains, utilizing proxy models and optimization design theory, to study the key parameters optimization design method of the vehicle bridge system of high-speed railways with speeds above 350 km, providing reference for bridge creep camber control and vehicle design, and has important significance for promoting the development of high-speed railways and improving operational safety and comfort.

2 Construction of Vertical Acceleration Proxy Model for High-Speed Trains

The creep camber of bridges and the axle load of trains are key parameters that affect the vertical acceleration of trains. However, due to the intricate nature of their interactions, obtaining precise analytical expressions is challenging. By utilizing limited sample data, proxy models can accurately describe the interdependencies within vehicle bridge systems, which offer a valuable approach for studying the optimization of key parameters.

2.1 Design Variable Sampling Based on LHS

Latin Hypercube Sampling (LHS) is a constrained random sampling method that generates uniform sample points, which can achieve high computational accuracy with fewer samples. Based on the technology of 350 km/h high-speed railway, the design variables are bridge creep camber and train axle load, and their value ranges are set to [3, 13] mm and [12, 17] t. The combined data of creep camber and train axle load sampled based on the LHS method are shown in Table 1, with a total of 25 different design variable combinations, providing effective input parameter combinations for subsequent virtual simulation of vehicle vertical acceleration.

2.2 Virtual Simulation of Vertical Acceleration of High-Speed Trains

Building a dynamic model of the high-speed railway vehicle bridge system to investigate the vertical dynamic characteristics of trains is currently an effective analysis method. This paper considers the structural characteristics of the CRH380B train, takes a continuous 32m concrete simply supported beam as the object, and based on the input parameter combinations sampled by the LSH method, constructs a three-dimensional vehicle bridge coupling dynamic analysis model to investigate the vertical acceleration of the high-speed trains under the combination of creep camber and axle load, providing reasonable and effective sample data for constructing its proxy model.

(1) **Dynamic Analysis Model and Solution Method of Vehicle Bridge Coupling System**

The three-dimensional vehicle bridge dynamic coupling system comprises of two parts: a vehicle subsystem and a bridge subsystem. The subsystems are connected through a given wheel rail interaction model. The internal self-excitation of the system includes track irregularities, vehicle snake-like movement, and so on.

For the dynamic interaction between wheels and rails, the system employs the linear simplified assumption for wheel-rail tangential creep in the horizontal direction. Additionally, the wheel-rail vertical attachment assumption is applied in the vertical direction. The dynamic equations of the vehicle subsystem and the bridge subsystem, and the equations of the simultaneous vehicle subsystem and the bridge subsystem are established respectively, and the dynamic equations of the vehicle-bridge coupling system can be obtained as:

$$\begin{cases} M_v\ddot{X}_v + (C_v + C_c)\dot{X}_v + K_vX_v = F_v \\ M_b\ddot{X}_b + C_b\dot{X}_b + K_bX_b = F_b \end{cases} \tag{1}$$

In the formula, M_V, X_V, C_{V} and K_V are the mass matrix, displacement vector, damping matrix and stiffness matrix of a single car, respectively; C_C is the additional damping matrix caused by wheel rail creep; F_V is the applied force vector acting on a single car; M_b and K_b are the mass matrix and stiffness matrix of the bridge subsystem, respectively; X_b is the displacement vector of the bridge subsystem; C_b is the damping matrix of the bridge subsystem; F_b is the force vector acting on the bridge subsystem, i.e., the wheel rail force. The method for establishing system equations and each matrix vector is shown in reference [10, 11].

The system equation is solved by using the full process iterative method [12]. Firstly, assuming that the rigidity of the bridge subsystem, the independent vehicle subsystem equation is solved to calculate the time history of the train wheel rail force. Secondly, the wheel rail force is applied to the bridge, and the independent bridge dynamic equation is solved to analyze the dynamic response of the bridge. The obtained bridge deck dynamic response time history and track irregularities are superposed as the new vehicle system excitation for the next iteration.

(2) **Calculation of Vertical Acceleration of Vehicles with Different Samples**

Taking the CRH380B EMU as the object, the time-domain irregularity samples of China high-speed railway ballastless track irregularity spectrum conversion are used as track irregularity excitation for the EMU. Based on the combination of creep camber and axle load parameters sampled by the LSH method, the vertical acceleration of vehicles with different combinations of creep camber and axle load for high-speed railway is obtained by solving the three-dimensional vehicle-bridge coupling dynamics model, as shown in Table 1, providing effective sample data for constructing a vehicle body vertical acceleration proxy model.

Table 1. Vertical acceleration of vehicles based on three-dimensional vehicle bridge coupled dynamic model with different creep camber and axle load combinations

No	Vertical acceleration(m/s^2)	No	Vertical acceleration(m/s^2)
1	0.60	14	0.62
2	0.54	15	0.66
3	0.56	16	0.51
4	0.74	17	0.51
5	0.64	18	0.66
6	0.62	19	0.78
7	0.74	20	0.83
8	0.73	21	0.52
9	0.68	22	0.71
10	0.81	23	0.62
11	0.56	24	0.51
12	0.77	25	0.56
13	0.75		

2.3 Kriging Based Vehicle Body Vertical Acceleration Proxy Model

(1) **Kriging Proxy Model Construction Method**

The Kriging model is a statistical prediction method based on random processes, which excels in precise interpolation and prediction techniques on sample points and models possess great fitting capabilities for highly nonlinear problems. Let $x \in \mathrm{R}^d$ denote a multidimensional input vector, and $y(x)$ denote the corresponding output vector, the following formula can represent a Kriging model:

$$y(x) = \sum_{i}^{p} \beta_i g f_i(x) + Z(x) \tag{2}$$

where, β_i is the coefficient of regression; $Z(\boldsymbol{x})$ represents a normal distribution $N(0,\sigma^2)$: a Gaussian random process with a average value of 0 and a covariance expressed as:

$$cov\left[Z\left(x^i\right), Z\left(x^j\right)\right] = \sigma^2 R\left(\theta, x^i, x^j\right) \tag{3}$$

where, $\boldsymbol{x}_i$ and $\boldsymbol{x}_j$ denote two input design variables. The selected Gaussian correlation function and constant regression term in this paper are as follows:

$$R\left(\theta, x^i, x^j\right) = exp\left[-\sum_{k=1}^{m} \theta_k \left|x_k^i - x_k^j\right|^2\right] \tag{4}$$

where m denotes the dimension of the design variable, while θ_k corresponds to the correlation coefficient for the kth component of the input variable.

The expression for the optimal linear unbiased estimate of the output $y(x)$ is given by:

$$\begin{cases} \hat{y}(x) = \hat{\beta} + r^T(x)R^{-1}\left(y - f\hat{\beta}\right) \\ r^T(x) = \left(R\left(x, x^1\right), R\left(x, x^2\right), \text{L}, R(x, x^n)\right)^T \end{cases} \tag{5}$$

where y is the vector of response values obtain from the sample, f symbolizes the unit column vector with a length of n, and R denotes the matrix of correlation function, which $\hat{\beta}$ represents the maximum likelihood estimate of β, and its expression is:

$$\hat{\beta} = \left(f^T R^{-1} f\right)^{-1} f^T R^{-1} y \tag{6}$$

The estimate of variance is:

$$\hat{\sigma}^2 = \frac{\left(y - f\hat{\beta}\right)^T R^{-1}\left(y - f\hat{\beta}\right)}{n} \tag{7}$$

Both $\hat{\beta}$ and $\hat{\sigma}^2$ are the functions of correlation coefficient vector θ in Eq. (7). To obtain the value of θ, the following equation needs to be solved:

$$\begin{gathered} max\Phi(\theta) = \frac{-n\ln\hat{\sigma}^2 + \ln|\boldsymbol{R}|}{2} \\ \text{s.t}\ \theta \geq 0\ \theta \in R^d \end{gathered} \tag{8}$$

The pattern search algorithm can be applied to solve the aforementioned unconstrained optimization problem.

(2) **Proxy Model Construction Based on Kriging**

Taking the axle load of high-speed trains and the creep camber of bridges as design variables, this paper first obtains a range of data samples of vehicle body vertical acceleration when trains pass through bridges at very high speed by solving a three-dimensional vehicle bridge coupling model; Subsequently, employing the principles of Kriging proxy model construction, a proxy model is developed to encompass the train axle load, bridge creep camber, and vertical acceleration of the vehicle body. Figure 1 displays the normalized response surface. From the figure, it can be seen that the vertical acceleration of the vehicle body has a non-linear relationship with the axle load of the train and the creep camber of the bridge, and its response surface is smooth. The greater the axle load of the train and the smaller the creep camber of the bridge, the smaller the vertical acceleration of the vehicle body of the high-speed train. In addition, the sensitivity of vehicle body vertical acceleration to creep camber is much higher than the sensitivity to vehicle axle load. Minor changes in bridge creep camber are more likely to have a significant impact on vertical acceleration, and the creep camber limit of the bridge should be limited in system design. At the same time, the response surface of the proxy model constructed aligns with the tendency observed in the calculation from the axle dynamics model, thereby demonstrating the efficacy of proxy model comprehensively.

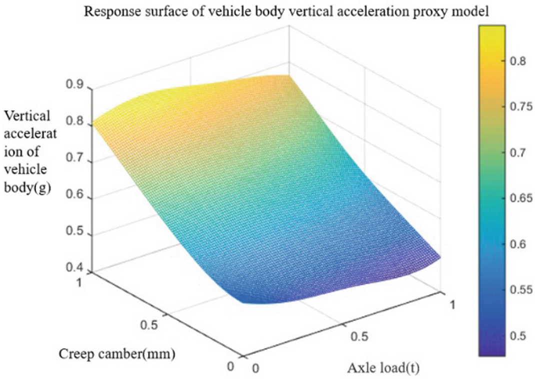

Fig. 1. Response surface of vehicle body vertical acceleration proxy model utilizing Kriging method

(3) **Proxy Model Precision Analysis**

Table 1 presents the parameters and accuracy details concerning the vehicle body vertical acceleration proxy model, which was constructed using Kriging method. The proxy model accuracy reaches 98.96%, and the complex correlation coefficient reaches 0.9953. The results indicate that the Kriging-based vehicle body vertical acceleration proxy model exhibits remarkable precision and correlation, and can effectively capture the nonlinear relationship between the axle load of high-speed trains, bridge creep camber, and vehicle body vertical acceleration. In addition, the parameter vectors of creep camber and axle load are 0.4993 and 0.3164, respectively, which also proves that the change of creep camber has a greater impact on the vertical acceleration of the vehicle body, consistent with the response surface. The reasonable and effective proxy model constructed lays the groundwork for subsequent optimization design using this model.

3 Optimization of Key Parameters of Vehicle Bridge System Based on Proxy Model

3.1 Optimization Model for Vertical Acceleration of High-Speed Trains

Aiming at providing a foundation for the design of bridges and trains during the design phase above 350 km/h high-speed railway system, this paper focuses on high-speed railway, uses the vertical acceleration of the vehicle body as an index to evaluate its safety and comfort, and takes the train axle load and bridge creep camber as design variables, taking the minimum vertical acceleration of the vehicle body as the design goal. Considering the constraints imposed by relevant design specifications for high-speed railway, the key parameter optimization model for the high-speed railway vehicle bridge based on the agent model is:

$$\begin{gathered} minf(x_1, x_2) \\ s.t.\ 12 \le x_1 \le 15 \\ 3 \le x_2 \le 13 \end{gathered} \tag{9}$$

where, x_1 and x_2 denote design variables, respectively representing the axle load of high-speed trains and the creep camber value of bridges; $f(x_1, x_2)$ is a vertical acceleration function of high-speed train body, which is calculated using a proxy model. For the given existing 350 km/h high-speed rail design data, the range of the variation for the train axle load x_1 is set as [12, 15] t, and the range of variation for the bridge creep camber x_2 is set as [3, 13] mm.

3.2 Optimization Model for Vertical Acceleration of High-Speed Trains

Cuckoo Search Algorithm (CSA) is a new evolutionary global optimization algorithm that draws on the nesting and spawning patterns of cuckoo birds in nature and the Levy flight principle. CSA is extensively applied in engineering optimization due to its numerous benefits, which include a reduced number of debugging parameters, good robustness, enhanced global optimization ability and the elimination of the need for parameter rematching. The update of the local random walk position of the ith cuckoo in generation $t + 1$ of the algorithm is expressed as follows:

$$x_i^{t+1} = x_i^t + \alpha s \otimes H(p_a - \varepsilon) \otimes \left(x_j^t - x_k^t\right) \tag{10}$$

where x_i^{t+1} is the position of the ith cuckoo bird of the t + 1 generation; x_i^t is the ith cuckoo position of the tth generation; s is the step size; $\alpha > 0$ is the scale factor of step size; $\otimes$ means dot multiplication of vectors; $H(u)$ denotes the Heaviside function; p_a denotes the likelihood of a host bird discovering an egg belonging to an alien bird, which falls within the range of [0, 1]; ε denotes a random number; x_j^t and x_k^t represent different random sequences.

Based on the Levy flight principle, the position update expression for the global random walk is:

$$\begin{cases} x_i^{t=1} = x_i^t + \alpha L(s, \lambda) \\ L(s, \lambda) = \dfrac{\lambda \Gamma(\lambda) \sin\left(\frac{\pi\lambda}{2}\right)}{\pi} \dfrac{1}{s^{1+\lambda}} \\ s > s_0 > 0, \quad 1 < \lambda \le 3 \end{cases} \tag{11}$$

where, λ denotes the Levi index; $\Gamma(\lambda)$ denotes the λ Function and $L(s, \lambda)$ represents the Levy flight function.

The process of optimization key parameters for high-speed railway vehicle bridge system using the CSA algorithm can be observed in Fig. 2, and the specific steps are as follows.

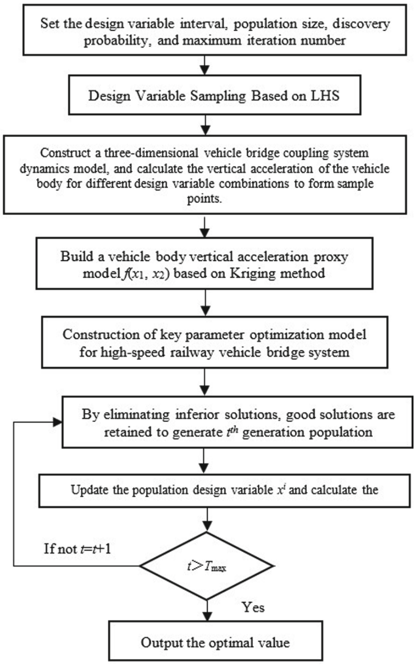

Fig. 2. Optimization process for key parameters of high-speed railway vehicle bridge system based on CSA algorithm

3.3 Result Analysis

Taking vehicle axle load and bridge creep camber as design variables, they are key parameters that determine the performance of the high-speed railway vehicle bridge system. On the basis of the established optimization model for the key parameters of the high-speed railway vehicle bridge system, the CSA is employed to optimize the solution. The algorithm is implemented with 20 bird nests and a discovery probability of 0.25. By initialing the design variables randomly and conducting 100 iterations after debugging, the iterative process for optimizing key parameters of high-speed railway vehicle bridge system using the CSA is illustrated in Fig. 3. As the number of iterations increases, the target function value for the vertical acceleration of the vehicle body gradually stabilizes and eventually converges to 0.4909 m/s^2 in the 100th generation. The vertical acceleration of the vehicle body is far less than the maximum allowable value of 1.3 m/s^2, indicating that the vertical acceleration of the vehicle body can meet the safety and comfort requirements for high-speed railway operation.

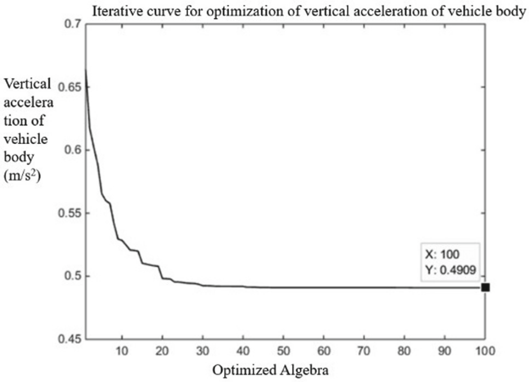

Fig. 3. Iterative process for optimizing vertical acceleration of high-speed railway trains using CSA

The optimized vehicle axle load and bridge creep camber achieve their optimal values with $x_1 = 15$ t and $x_2 = 3$ mm, respectively. Utilizing these design variables, the constructed proxy model is used to minimize the vertical acceleration within the range of design variables. Ultimately, a value of 0.4909 m/s^2 is attained. Notably, the optimal value of design variables derived from proxy models and optimization theory is located at the boundary of the feasible region, which aligns with the properties of the objective function. The optimization iteration process and outcomes presented above clearly validate the efficacy of the proposed approach in optimizing key parameters of high-speed railway vehicle bridge systems.

4 Conclusion

For the problem of complex and challenging optimization of high-speed railway vehicle bridge system modeling, this paper aims at minimizing the vertical acceleration of the vehicle body, and investigates an optimization method for key parameters utilizing proxy model and optimization design theory. The main findings are as follows:

(1) By utilizing the three-dimensional vehicle bridge system dynamics model of a high-speed railway and employing Latin Hypercube Sampling and simulation analysis,

a Kriging proxy model for vehicle body vertical acceleration was established, with an accuracy of 98.96% and a complex correlation coefficient of 0.9953. This model can effectively describe the relationship between vehicle body vertical acceleration and vehicle axle load, as well as bridge creep and camber.

(2) A novel approach was suggested to optimize key parameters for high-speed railway vehicles and bridges with a speed higher than 350 km/h using the proxy model. The proposed method employed a proxy model and optimization theory to identify the optimal vehicle axle load and bridge creep camber limits as 15 t and 3 mm, respectively. At this time, the corresponding vertical acceleration of the vehicle body was the smallest, with a value of 0.4909 $m/s^2 < 1.3$ m/s^2, verifying the accuracy and efficiency of the proposed methodology.

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