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Application of Meta-heuristic Optimization and Gaussian Process Regression to Predict the Performance of a Pantograph-Catenary System

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Abstract

It is important to evaluate the contact force between pantograph and catenary for stable energy supply to the trains. The magnitude and variation range of contact force determine the quality of current receiving and safe operation of the train. Therefore, a rapid and accurate prediction of contact force is of great significance. However, collecting contact force data through experiments is challenging, and obtaining timely results using numerical simulations is not always feasible. In this study, we propose an efficient simulation-based surrogate approach based on Gaussian process regression, combined with meta-heuristic optimization, to predict key parameters of pantograph-catenary system, which are responsible for the energy transfer quality. A pantograph-catenary model is established and validated using Finite Element Method, which serves to generate training and test data. Gaussian process regression (GPR) is utilized for estimation. A new developed meta-heuristic optimization, i.e binary Hunger Game Search (HGS), is applied on feature selection. To enhance the performance of HGS, chaos mechanism is embedded, resulting in Chaos-HGS GPR (CHGS-GPR). It is found that the proposed CHGS-GPR provides rather accurate prediction for the mean value of contact force, and can be extended to the preliminary design of railway lines, real-time evaluation and control of train operations.

Keywords: pantograph-catenary system, contact force, Gaussian process regression, surrogate model, physical-based model, computational fluid dynamics

1 Introduction

The pantograph serves as the interface for energy transfer from the overhead contact line. Consequently, the quality of contact between the pantograph and catenary assumes paramount importance in maintaining a stable power supply. The contact force is a significant parameter used to evaluate the quality of the pantograph network [1]. On one hand, an excessively high contact force accelerates wear and tear on the contact strip and pantograph network, leading to an undesirable reduction in its service life and increased maintenance costs. On the other hand, an insufficient contact force results in inadequate energy supply to the train and arcing between pantograph, which severely impacts the transmission quality. Hence, maintaining a consistently proper contact force is crucial for pantograph-catenary system.

Measurement of the contact force between the catenary and pantograph can be achieved through two primary methods: field measurements and numerical simulations. Field tests tend to be more expensive and challenging to carry out. Therefore, numerical simulation methods have gained wider adoption in recent decades. FEM is primarily employed to model the catenary, while lumped mass and multi-body models are commonly utilized to represent pantograph. However, there is a limit to improve the computational efficiency of numerical methods based on physical models. They are unable to meet the requirements for rapid design and prediction of the pantograph-catenary system.

In recent years, there has been a growing interest in machine learning-based surrogate models, which are being increasingly explored to address complex real-world phenomena. In the context of the pantograph-catenary system, Huang et al. [2] started to evaluate the energy transfer quality of the system using a combination of a tree-based surrogate model and eight machine learning-based regression models. Their findings indicated that the multi-layer feed-forward deep residual neural network (MLF-DNN) model demonstrated the best performance.

Recently, stochastic surrogate models incorporating probabilistic analysis have exhibited impressive performance across various engineering domains. For instance, Hejazi et al. [3] utilized GPR to predict failure risks in steel catenary risers, yielding promising outcomes. In another study, Alruqi et al. [4] employed a GPR model to predict engine performance and exhaust emissions, achieving convincing results. Gautam et al. [5] conducted an experimental investigation on different geotechnical properties and modelled them using Artificial Neural Network (ANN) and GPR models. Both machine learning methods demonstrated prediction errors within 10%, but the GPR-based model outperformed the ANN-based model in terms of percentage error.

Building upon the advantages of the GPR model discussed earlier, we apply it to the pantograph-catenary system performance prediction, which, to the best of our knowledge, has not been attempted before. The objective of this paper is to evaluate the feasibility of adapting GPR to quantitatively predict the contact force between pantograph and catenary. If the constructed approach is error-acceptable with affordable computational cost, then they are promising alternatives to traditional numerical simulation methods for pantograph and catenary energy transfer evaluation.

2 Methods

Pantograph-catenary system modelling: FEM is a widely used method to simulate the pantograph-catenary system, which has been well documented in many literature [6, 7]. In this paper, the finite element software Abaqus [8] is used to build the model and simulate the system. Details are as follows:

Catenary is mainly composed of message wire (MW), contact wire (CW), suspensions, steady arms, and droppers. The sketch is shown in Figure 1. MW and CW are modeled by beam units. In order to approximate the real situation, droppers are designed as a non-linear spring that can only be extended but not compressed. The structural damping of the contact network is modeled using a proportional damping model with values of ff=0.0125 and β=0.0001 [9]. To simplify the calculations, a commonly used three lumped mass model is adopted to represent the pantograph. The model parameters are chosen in line with those in the workbench presented in [9]. The contact between pantograph and CW is modeled using a penalty function and is assumed to be frictionless. In this paper, a total of 10 spans of catenary are selected. In order to eliminate the influence of boundary effects, for the statistics of the results only the data of spans 5 and 6 are adopted.

The FEM model established in this paper is validated. Firstly, the accuracy of the model in predicting the initial sag length of CW has been verified. Figure 2(a) compares the results of present study with those of ten research institutes in the workbench [9] and the results are consistent with the reference. Secondly, the dynamic performance of the simulation has been verified. Figure 2(b) shows the dynamic contact forces and again the results agree very well with those in benchmark [9]. The statistical results are shown in Table 1. The difference of the minimum value is caused by the different modeling methods of steady arms, which falls into the acceptable range.

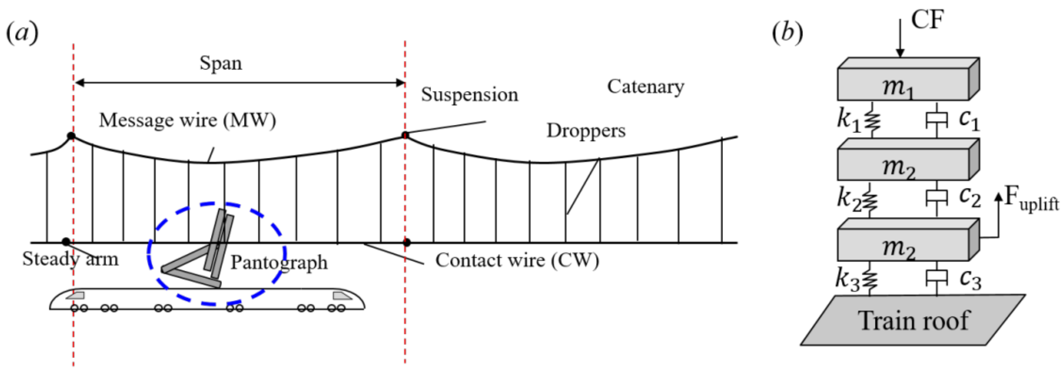

Figure 1: Description of: (a) the catenary model and, (b) the three lumped mass model of pantograph.

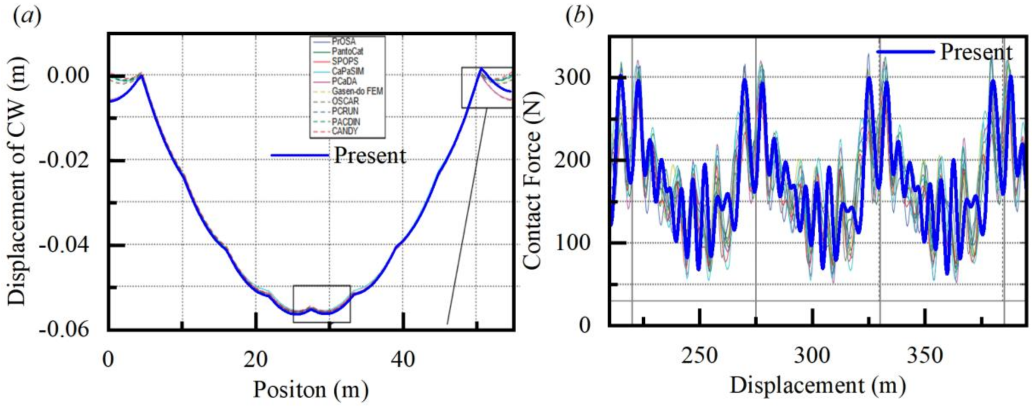

Figure 2: Verification of the present model against the results from benchmark: (a) the contact wire pre-sag and (b) contact force.

	Benchmark	Present	Error
Fm(N)	169	168.6	0.2
Std. (0-20 Hz) (N)	53.9	53.9	0%
Std. (0-2 Hz) (N)	38.3	38.9	1.6%
Std. (0-5 Hz) (N)	41.0	41.1	0.2%
Std. (5-20 Hz) (N)	34.8	35.0	0.5%
Max. (N)	313.2	299.4	4.4%
Min. (N)	60.4	67.7	12%

Table 1: Present statistical results against the benchmark.

Simulation based surrogates: Figure 3 illustrates the general framework of simulation based surrogates used in this paper. The purpose of building the simulation based surrogates in this paper is to make fast predictions of the quality of the pantograph-catenary energy transfer.

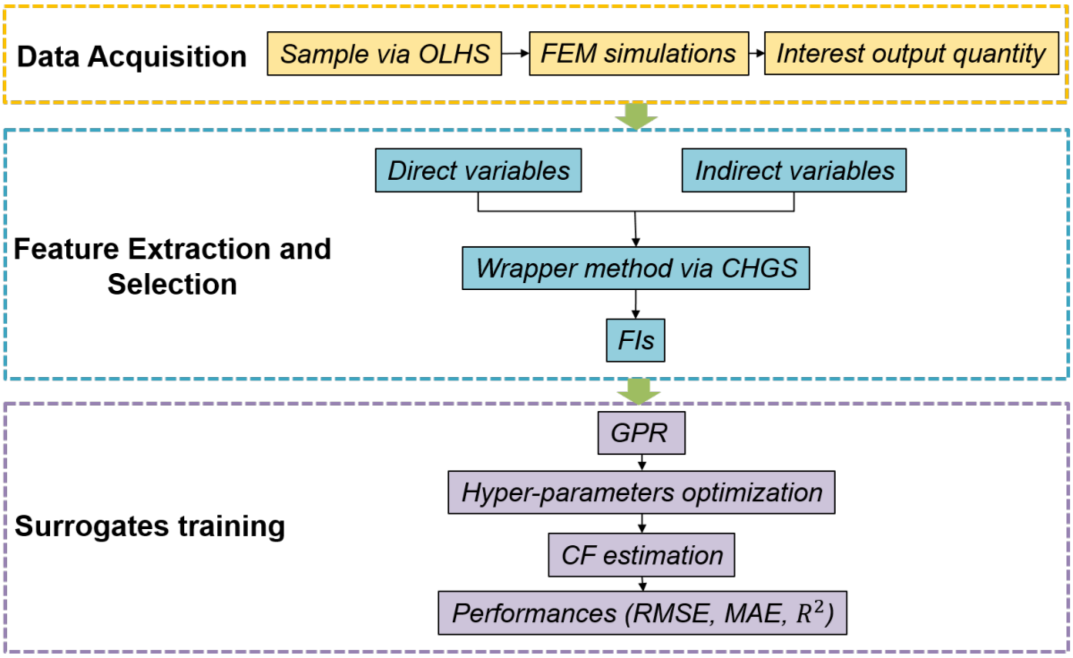

Figure 3: Framework of developing the simulation based surrogates.

The first thing that needs to be clarified for simulation based surrogates is to identify the variables to be predicted. Here, the objective of this paper is to predict the statistics of the dynamic contact forces between pantograph and cate-nary under a given system. According to the recommendations of the standard [10], the five basic parameters contain the mean contact force (Fm), standard deviation (σ), maximum value (Fmax), minimum value (Fmin) and the uplift of the CW (Uplift) are the key indicators to judge the performance of the system. The choice of input parameters and the calibration of their ranges have a great impact on the predictive and generalization capabilities of the surrogate models. In this study, independent variables (CW tension Tc, MW tension Tm, and train running speed v) are chosen to be input parameters. Also, the lifting force (Fuplift) applied to the pantograph is also taken into account. It is important to note that the range of values of Fuplift is related to the train speed [11], as shown in the following:

$$F_{m,min} = 0.00047v^2 + 60 \tag{1}$$

$$F_{m,min} = \begin{cases} 0.00047v^2 + 90, & if\ v \leq 200 \text{ km/h} \\ 0.00097v^2 + 70, & if\ v > 200 \text{ km/h} \end{cases} \tag{2}$$

Input	Tc	Tm	v	Fuplift
Range	10-30kN	10-30kN	50-400km/h	70-90N

Table 2: Value range of independent input values.

According to some preliminary descriptions in the literature [12, 13], the key parameters responsible for the influence of contact force may be the coefficients related to the reflection and transmission at the steady arms and dropper structures. With that under considered, this study derivates the CW reflection coefficient (Ccr), CW transmission coefficient (Cct), MW transmission and reflection coefficient (Cmr) through the spectral analysis, and considers them as input parameters as well. The detailed derivation process is in ??. In addition, the wave speed utilisation ratio of CW (defined as =v⁄c c=$\sqrt{T\rho}$, c is the CW wave speed, T and ρ are CW tension and line density, respectively) is also added to input parameters. It should be noted that the three coefficients and η are related to the catenary inherent characteristics and the train operating conditions, therefore they are not independent variables here. In summary, the vector of input parameters used as an initial pre-selection for the training model is $\overrightarrow{X}$ = *Tc, Tm, v, Fuplift, Ccr, Cct, Cmr, η*.

As can be seen from the above, in present study, Tc, Tm, v, and Fuplift are chosen as independent input parameters. Ccr, Cct, Cmr, and η are associated with at least two of the variables mentioned above. The value ranges that is determined according to the actual operations which may be encountered are shown in Table 2.

3 Results

Model training results: Firstly, a comparison of the convergence capabilities of CHGS-GPR assembled with different chaotic maps is presented, as shown in Figure 4. The black line represents the original random mechanism of HSG. It can be observed CHGS-GPR with tent chaotic map yields the best search performance. The optimal solution is found after five iterations. Therefore, tent map is adopted in this paper. In the following discussion, when referring to CHGS-GPR, it specifically refers to the CHGS-GPR with tent chaotic map. Table 3 provides a comparison of the results CHGS-GPR and GPR without feature selection. From the results of R2, RMSE, and MAE, it can be concluded that the prediction results of CHGS-GPR are better than that of the original model.

Validation and analysis: Then, CHGS-GPR are used to predict test sample sets. R2, RMSE and MAE results of the test results are shown in Figure 5. Predictions of Fm and σ perform better compared with Fmax and Uplift.

Pantograph-catenary system is non-linear [14], and the default assumptions (such as the Gaussian distribution output used in GPR) may not hold, resulting in differences between FEM results and predictions. Nevertheless, as shown in Table 4, the absolute prediction error of CHGS-GPR is acceptable, especially as for the prediction of Fm performs the best. Therefore, CHGS-GPR for CF prediction used physics outputs trained proposed in this paper can be considered feasible. Considering that present results are obtained just through such a few training data sets (17 sets), it is entirely possible to obtain more accurate CHGS-GPR if the time and calculation costs increases.

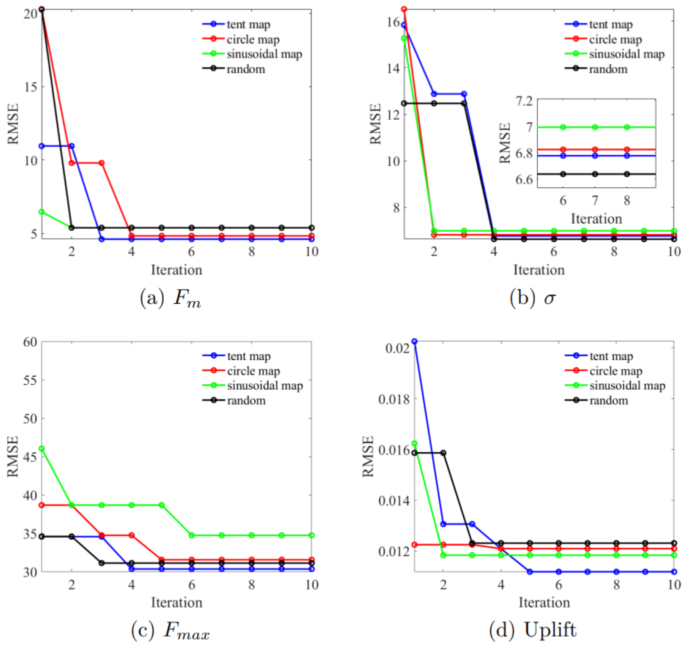

Figure 3: RMSE convergence curve for CHGS-GPR assembled with different chaotic maps.

		FIs	R2	RMSE	MAE
Fm	Origin	Tc, Tm, v, Fuplift, Ccr, Cct, Cmr, η	0.984	5.38	0.029
	CHGS-GPR	Tc, Fuplift, Cmr, η	0.988	4.61	0.023
σ	Origin	Tc, Tm, v, Fuplift, Ccr, Cct, Cmr, η	0.851	13.45	0.21
	CHGS-GPR	Tc, Fuplift, Cmr, η	0.961	0.677	0.209
Fmax	Origin	Tc, Tm, v, Fuplift, Ccr, Cct, Cmr, η	0.930	40.11	0.21
	CHGS-GPR	Tc, Fuplift, Cmr, η	0.957	30.36	0.140
Uplift	Origin	Tc, Tm, v, Fuplift, Ccr, Cct, Cmr, η	0.902	0.012	0.396
	CHGS-GPR	Tc, Fuplift, Cmr, η	0.918	0.011	0.323

Table 3: Value range for independent input values.

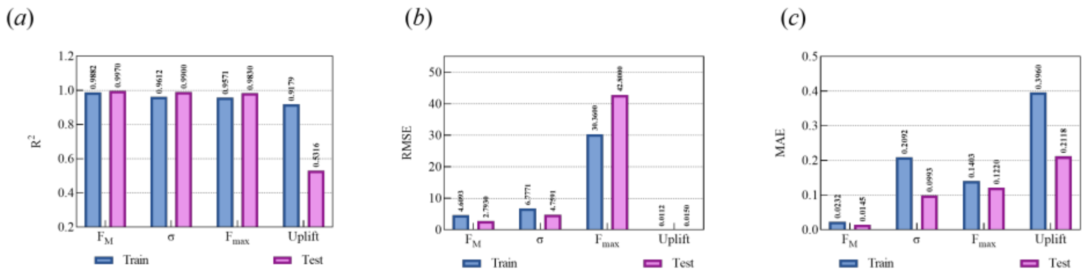

Figure 5: Model evaluation: (a)R^2 (b) RMSE (c) MAE.

	Fm	σ	Fmax	Fuplift
Absolute Value of Error (%)	1.45	9.93	12.2	9.02

Table 4: Individual prediction error with test data set.

4 Conclusions and Contributions

In this paper, Gaussian process regression combined with meta-heuristic optimization on feature selection is used to predict the contact force of the pantograph-catenary system and its feasibility is discussed. To improve the regression, chaotic mechanism, tent map, is added to the search algorithm. FEM simulations of the pantograph-catenary system are established to generate training and testing data sets. The input variables relate to eight design parameters of the pantograph-catenary system. The output includes various statistics of contact force and lifting displacement of contact wire. The results show that CHGS-GPR predicts well on Fm, ff, Fmax and Uplift, especially Fm. However, Fmin cannot be accurately predicted. This may be due to the fact that none of the current input parameters is the key factor affecting the minimum contact force. Moreover, Fuplift and η are the most important parameters affecting pantograph-catenary transmission quality, compared with other parameters.

Among the obtained CHGS-GPR, the prediction for the Fm is the best, with R^2 = 0.997, RMSE=2.793, and MAE=0.0145. The outcomes obtained from CHGS-GPR using only 17 sets of training samples offer considerable reassurance. These results not only validate the feasibility of the proposed method but also demonstrate its effectiveness. This work shows the potential and viability of the approach.

The Gaussian process regression model, distinguished by its probabilistic nature, exhibits remarkable suitability for probability and risk-based engineering assessments, offering notable advantages in engineering prediction tasks. To the best of our knowledge, for the first time, GPR is introduced into the pantograph-catenary system, and its feasibility is discussed. The established method demonstrates acceptable accuracy and efficiency, surpassing FEM methods and potentially even replacing costly field tests for evaluating the pantograph-catenary interaction.

Acknowledgements

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