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Optimization of longitudinal viscous dampers for a freight railway cable-stayed bridge under braking forces

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Abstract. Under braking forces of a freight train, there are great longitudinal structural responses of a large freight railway cable-stayed bridge. To alleviate such adverse reactions, viscous dampers are required, whose parametric selection is one of important and arduous researches. Based on the longitudinal dynamics vehicle model, responses of a cable-stayed bridge are investigated under various cases. It shows that there is a notable effect of initial braking speeds and locations of a freight train on the structural responses. Under the most unfavorable braking condition, the parameter sensitivity analyses of viscous dampers are systematically performed. Meanwhile, a mixing method called BPNN-NSGA-II, combining the Back Propagation neural network (BPNN) and Non-Dominated Sorting Genetic Algorithm With Elitist Strategy (NSGA-II), is employed to optimize parameters of viscous dampers. The result shows that: 1. the relationships between the parameters of viscous dampers and the key longitudinal responses of the bridge are high nonlinear, which are completely different from each other; 2. the longitudinal displacement of the bridge main girder significantly decreases by the optimized viscous dampers.

Keywords: cable-stayed bridge; braking forces; viscous damper; freight train; optimization

1. Introduction

As the railway construction forward in China, there are more and more large span cable-stayed railway bridges. Under braking forces, there are great structural responses on such floating-type bridges without any longitudinal constraint between their main girder and pylons.

There have been many studies on bridge responses caused by emergency braking forces. However, most of them focused on highway bridges. Kishan and Traill-Nash (Kishan and Traill-Nash 1977) studied the braking effect on a simply supported beam bridge. Gupta and Traill-Nash (Gupta and Traill-Nash 1980) presented impact factors through a ramped braking function of two-axle vehicles. Law and Zhu (Law and Zhu 2005) studied the dynamic behavior of a multi-span non-uniform continuous bridge suffered from the vehicles braking. Based on the routine bridge weight-in-motion (B-WIM) results, Zhao and Uddin (Zhao and Uddin 2013) proposed a method to predict bridge safety and integrity if heavy trucks experience emergency braking on the bridge. In order to reduce the excessive longitudinal vibration of a suspension bridge induced by vehicle braking forces, Yang and Cai developed a mixed control methodology using magnetorheological dampers (Yang and Cai 2016). About railway bridges, Liu etc. (Liu *et al*. 2010) studied the Tianxingzhou Yangtze River Bridge, the longest highway and railway floating-type cabled-stayed bridge in the world, subjected to train braking forces. Yin (Yin 2000) analyzed longitudinal dynamic responses of the Wuhan Yangtze River Bridge under a heavy haul train . The effect of initial braking speeds and positions of the heavy haul train were illustrated. But the most unfavorable braking condition was not clearly given.

It can be seen that braking forces have an enormous impact on floating-type bridges. To reduce the longitudinal responses, it is strongly necessary to install viscous dampers. The working performances of the viscous dampers are closely linked to their parameters. There are many optimization researches on building structures (Shukla and Datta 1999, Wongprasert and Symans 2004) or on bridges under seismic forces (Vader and McDaniel 2007). However, the probability of the earthquake is smaller than that of the braking of heavy haul trains. Compared to the passenger express railway, the train loads of a long span freight railway cable-stayed bridge are much bigger resulting to significant dynamic responses. About the optimization works on a floating-type cable-stayed bridge suffered from braking forces of heavy haul trains, there were little similar systematically studies (Long and Li 2015).Meanwhile, the influence about initial braking speed and position of heavy haul trains has not been investigated.

Faced to such problems, dynamic responses of a freight railway cable-stayed bridge under braking forces of heavy haul trains are studied herein. Firstly, the most unfavorable braking condition about initial braking speed and position of heavy haul trains is investigated in detail. Next, under the most negative case, the effects of viscous damper parameters on the structure responses are systematically

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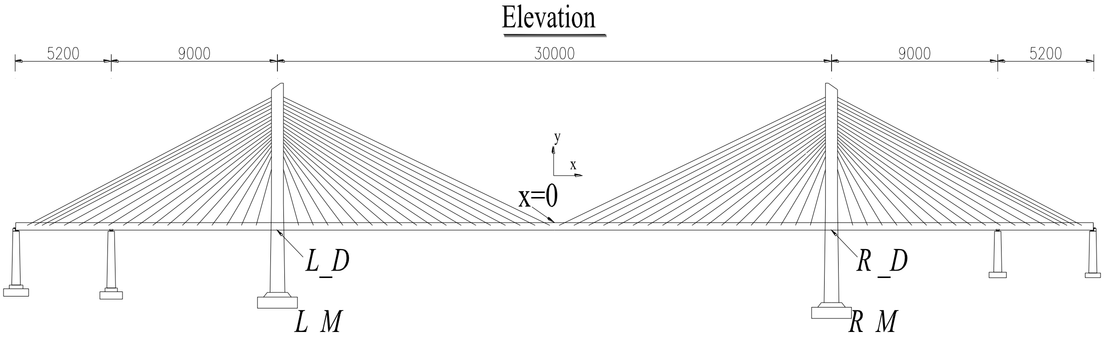
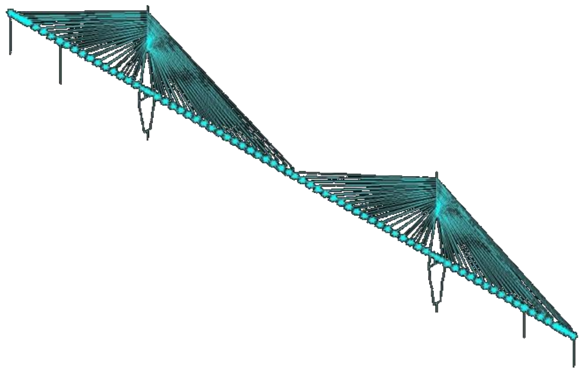


(a) General layout (Unit: cm)

(The relative longitudinal displacement between the left / right tower and the main girder is abbreviated as by *L_D* and *R_D* respectively. And the longitudinal bending moment at the root of the left / right tower is abbreviated as *L_M* and *R_M* respectively)



(b) Three-dimensional finite element model

Fig. 1 Cable-stayed bridge studied in the paper

discussed. Finally, different from the traditional method, a new hybrid model combined with the Back Propagation neural network (BPNN) and the Non-Dominated Sorting Genetic Algorithm With Elitist Strategy(NSGA-II), called BPNN-NSGA-II, is proposed to optimize the parameters of viscous dampers.

The rest of this paper is organized as: section 2 introduces analysis models, section 3 searches the most unfavorable braking condition, section 4 makes sensitivity analysis of parameters for viscous dampers, and section 5 proposes optimization models for viscous dampers and makes discussions on the results.

2. Analysıs model

2.1 Cable-stayed bridge

The general layout of the bridge studied in this paper is shown in Fig. 1(a). Its system is a longitudinal-floating-type one. The concrete-box main girder is 300 m, which is 13.0 m in width and 4.0 m in height with single track for freight railway. The design vehicle speed is 80 km/h. Three-dimensional finite element model of the bridge is established in ANSYS as Fig. 1(b) shows, where the girders, towers and piers are simulated by Beam4, and cables are simulated by Link8.

2.2 Viscous damper

There are four longitudinal viscous dampers installed in the junction of the main girder and the pylons. The mechanism model of viscous damper can be illustrated by Eq. (1) and simulated through the Combin37 in ANSYS (Liu and Lan 2011).

$$F = C_v \left| v \right|^n \mathrm{sgn}(v) \tag{1}$$

Where F is the damping force; C_v is the damping coefficient; v is the relative velocity; n is the velocity power function.

2.3 Braking forces of heavy haul trains

Heavy haul trains consist of locomotives and trailers connected by couplers and draft gears. It is difficult to build the refined model for that there are many geometric and contacting nonlinearities existing in heavy haul trains. The subject of the study is more concerned with the longitudinal responses of the bridge, instead of the vehicles themselves. Hence, they can be abstracted as a multi-mass spring-damping system (Chou *et al*, 2007, Cole 2006). For heavy haul trains, the force condition of a unit (locomotive or trailer) in longitudinal direction can be illustrated as shown in Fig. 2. Balance equation of that is established as follows

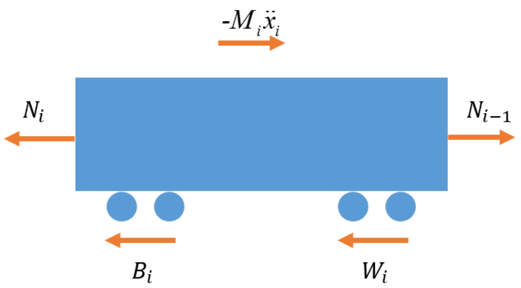


Fig. 2 Dynamic model of a unit of train in the longitudinal direction

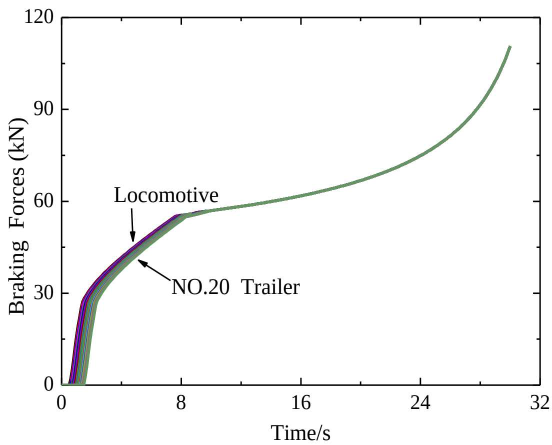


Fig. 3 Time history of braking forces (initial braking speed= 80 km/h)

$$M_i\ddot{x}_i = N_{i-1} - N_i - W_i - B_i (i = 1 \cdots m) \tag{2}$$

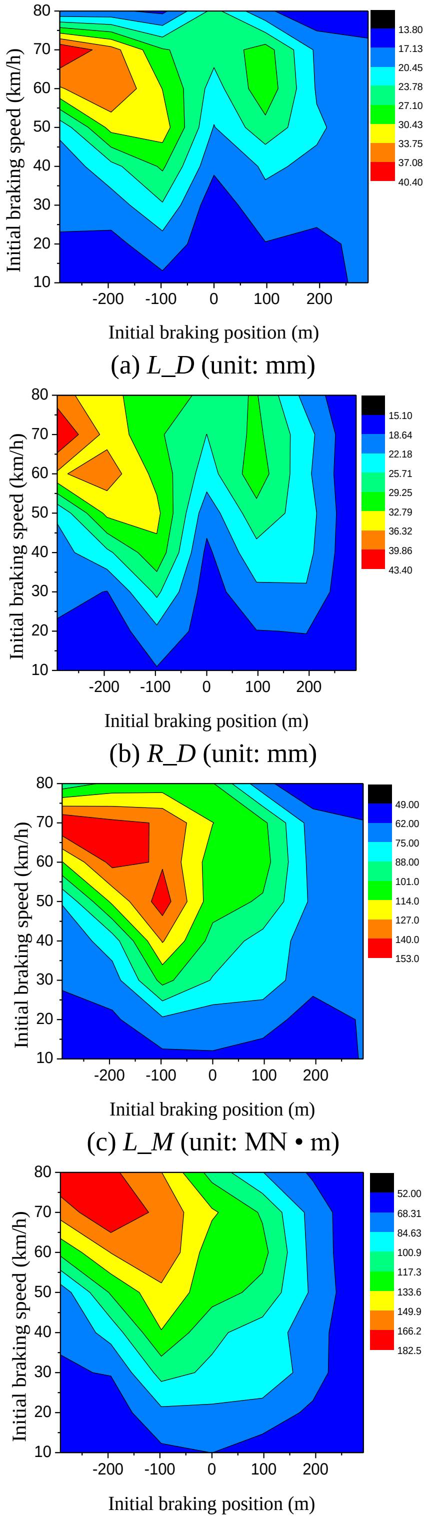
where M_i, $\ddot{x}_i$, B_i and W_i are the mass, the acceleration, the braking force and the basic resistant force of the i^{th} vehicle, N_{i-1} and N_i are coupler forces of the i^{th} adjacent vehicles.

In this study, the freight train consists of 1 DF4 locomotive and 20 C62 trailers. More information could be referred to the references (Ministry of Railways in China 1998). After calculation, the time histories of the heavy haul train braking forces for all vehicles is shown in Fig. 3 when initial train breaking speed is 80 km/h.

3. Unfavorable braking condition

There are great responses of the bridge subjected to the train braking forces, especially the longitudinal displacement (Long and Li 2015). But for comprehensive consideration, the relative longitudinal displacement between the tower and the main girder and the longitudinal bending moment at the tower root, respectively abbreviated as *L_D*, *R_D*, *L_M* and *R_M* as shown in Fig. 1, are all taken as indexes to find the most unfavorable braking case.

The effect of braking forces on the bridge is related to the initial braking speed and position of heavy haul trains. The orthogonal experiments are designed to find the influence factors. The initial speeds are from 10 km/h to 80km/h in 10km/h intervals. The coordinate of the bridge is shown in Fig. 1.



(a) *L_D* (unit: mm)

(b) *R_D* (unit: mm)

(c) *L_M* (unit: MN • m)

(d) *R_M* (unit: MN • m)

Fig. 4 The effect of initial braking speed and position on the relative longitudinal displacement between the towers and the main girder and the bending moment at the root of the towers

The initial positions are at -291.7 m, -217.5 m, -150 m, 0 m, 150 m, 217.5 m and 291.7 m, respectively corresponding to: the entrance, the 1/8 of the span, the junction of the main girder and the left tower, the mid-span, the junction of the main girder and the right tower, the 1/8 of the span and the exit. So there are 56 braking typical cases in total. Since the braking process is dynamic and time-varying, the maximum responses are extracted for analysis. The effect of initial braking speed and position on bridge responses are given in Fig. 4.

From (a) and (b) in Fig. 4, the responses, the relative longitudinal displacements between the towers and the main girder, are similar at speeds smaller than 50 km/h, when the trains starts braking in the bridge entrance. With the initial braking speed increasing, the responses become larger. However, it is not true that the higher speed the larger response is. When the initial braking speed is near 70 km/h, there is a maximum for *L_D* and *R_D* respectively. As the train moves forward and brakes, the responses decrease gradually. The responses fall into the minimum when the initial braking position is near the exit, and the initial braking speed has little impact.

From (c) and (d) in Fig. 4, when the trains starts braking in the bridge entrance, there is the maximum of the longitudinal bending moment at the root of towers. The same situation is that when the train moves forward and brakes, *L_M* and *R_M* decrease gradually. And the responses also reach the minimum when braking near the exit. The initial braking speed has little impact.

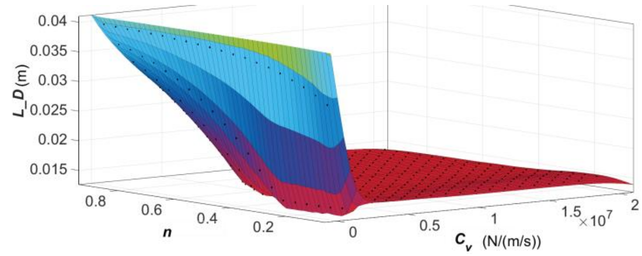
From the above analysis, it can be seen that the effect of the initial braking speed and position on the key longitudinal responses of the bridge is great. The higher the speed, does not mean that the larger the structural response is. The initial braking position has a greater effect on the bridge response. After calculation, the most unfavorable braking condition is found: the initial braking speed is 71.9 km/h and the initial braking position is -290.9 m. All the follow-up study is under this case.

4. Sensitivity analysis

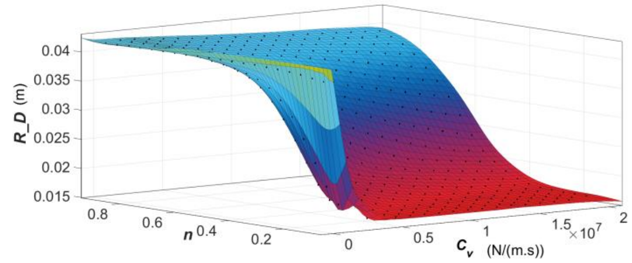
Based on the most unfavorable braking condition, the parameter sensitivity analyses of viscous dampers acting on the bridge responses are performed in this section. As shown in Eq. (1), there are two variables of a viscous damper, including C_v and n. Another orthogonal test is designed: $C_v \in$ [100, 20000] kN/(m/s), $n \in$ [0.1, 0.9]. Both of the intervals are divided into 20 groups and the total amount of cases is 400. The effect of the viscous dampers on the key longitudinal responses of the bridge, including *L_D*, *R_D*, *L_M* and *R_M* are shown in Fig. 5.

It can be seen that: a. when C_v is very small, *L_D* is about 0.04m; when C_v is smaller than 14000 kN/(m/s), there is a small range of n making *L_D* dramatically decrease; when C_v is bigger than 14000 kN/(m/s), the transformation of *L_D* is very minor regardless of changes of the parameter n; b. when C_v is bigger than 2000 kN/(m/s) and n is smaller than 0.3, *R_D* is at the minimum in stable. *R_D* increases nonlinearly with the raise of n, while C_v has little impact; c. there is a minimum of *L_M* when C_v is in the interval from 1500 to 8000 kN/(m/s) and n is in the range from 0.2 to 0.4. Outside this interval, *L_M* changes nonlinearly; d. there are two areas to minimize *R_M*, where the change law is highly irregular. The general scopes are that n is smaller than 0.15 or between 0.25 and 0.4 while C_v is close to or bigger than 4000 kN/(m/s).

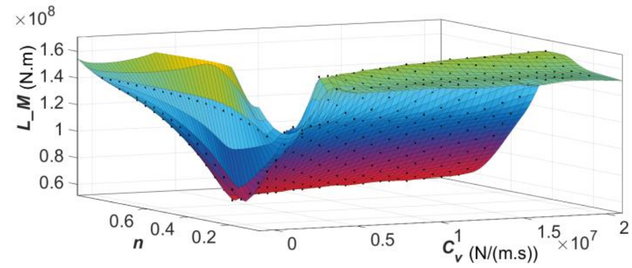
On the whole, there is an obvious nonlinear relationship between the parameters of viscous dampers and the key longitudinal responses of the bridge, including *L_D*, *R_D*, *L_M* and *R_M*. What's more, the impact of the parameters of viscous dampers is very different among different responses. Parametric selection of viscous dampers should be over-all consideration and proper management, otherwise unsuitable parameters may yet cause large responses.



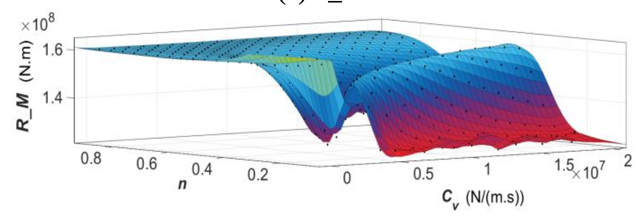
(a) *L_D*



(b) *R_D*



(c) *L_M*



(d) *R_M*

Fig. 5 The effect of initial braking speed and position on the relative longitudinal displacement between the towers and the main girder and the bending moment at the root of the towers

5. Optimization

5.1 Optimization model

As mentioned above, the key longitudinal responses of the bridge, including *L_D*, *R_D*, *L_M* and *R_M* are taken as the optimization goals, as shown in Eq. (3). The optimization objectives in Eq. (3) are complicated implicit functions with highly non-linearity, which should be simulated accurately in an appropriate manner. What's more, since the change laws of the four responses are very different and even inconsistent from each other, the process is a multi-objective optimization.

$$\begin{cases} \text{Min } (L\_D(C_v,n), R\_D(C_v,n), \\ \qquad L\_M(C_v,n), R\_M(C_v,n)) \\ \text{s.t.:} \\ 100<C_\text{v}<20000\left(\text{kN/(m/s)}\right) \\ 0.1<n<0.9 \end{cases} \tag{3}$$

5.2 BPNN-NSGA-II

In order to search the optimum parameters of the viscous dampers, a hybrid method BPNN-NSGA-II combined with BPNN and NSGA-II is proposed. In this hybrid method, BPNN is employed to simulate the key longitudinal responses of the bridge and taken as the objective functions, while the NSGA-II is applied to do multi-objective optimization.

5.2.1 BPNN

BPNN is the one of the most popular and widely used artificial neural networks with quite completely theory system and learning mechanism. The typical structure topology of BPNN is shown in Fig. 6. BPNN is capable of dealing with complex and nonlinear problems. Hence, BPNN is utilized to simulate objective functions involving $L\_D(C_v,n)$, $R\_D(C_v,n)$, $L\_M(C_v,n)$ and $R\_M(C_v,n)$ shown in Eq.(3). For each objective function, the structure of BPNN is the same as shown in Table 1. More details to determine the structure can be referred to the references (Dai and MacBeth 1997, Ghose *et al*. 2010).

5.2.2 NSGA-II

NSGA-II (Deb *et al*. 2002, Srinivas and Deb 1994) is a representative and efficient algorithm for multi-objective optimization. Based on NSGA, the modified version NSGA-II was developed which has a better sorting algorithm and incorporates elitism with the new concept of crowding distance. The flowchart of the NSGA-II algorithm is shown in Fig. 7. In the study, the number of initial population and the maximum generation is 100 and 6000, respectively.

5.3 Results and analysis

The optimization is performed by the hybrid method BPNN-NSGA-II, where the four BPNNs with good performances are taken as the objective functions in Eq. (3), then NSGA-II is utilized to do optimization process. After calculation, the Pareto optimal solutions to the parameters of the viscous dampers are shown in Fig. 8.

Table 1 Important parameters of the BPNN in the study

	Input	Hidden -1	Hidden -2	Output
Number of neurons for each layer	2	14	13	1
Active function	Sigmod function			
Learning process	Gradient descent algorithm with variable learning rate and momentum			

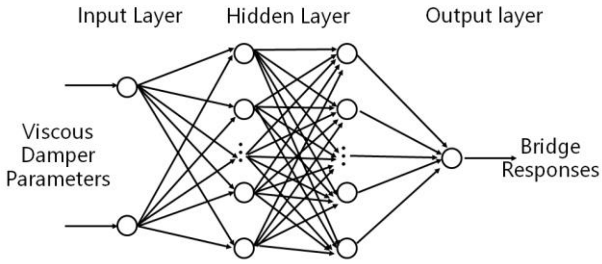


Fig. 6 Structure of BPNN

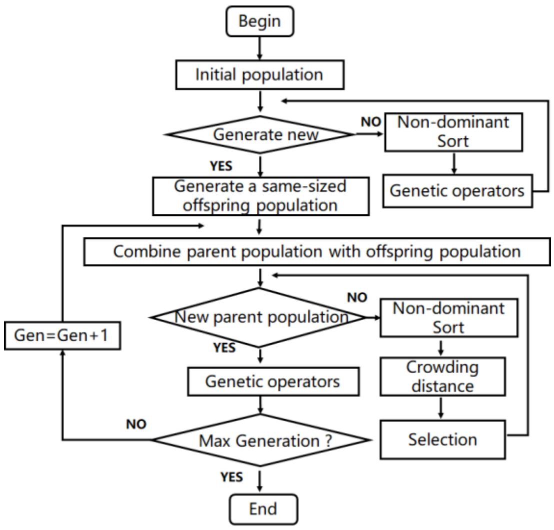


Fig. 7 Flowchart of the NSGA-II algorithm

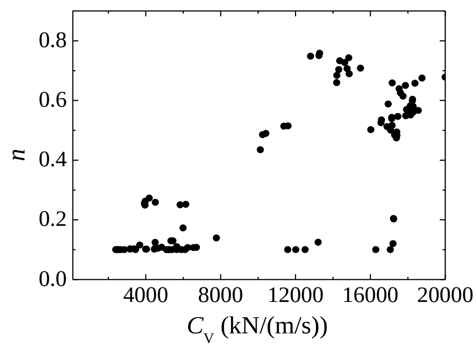


Fig. 8 Pareto optimal solutions to the parameters of the viscous dampers

Table 2 Relative reductions of the responses after selection

Solution	I	II	III	IV	V	VI
C_v (kN/(m/s))	10123	4517	4186	3967	3961	3932
n	0.434	0.259	0.273	0.262	0.249	0.255
R_L_M (%)	25.63	12.52	15.51	14.75	13.16	13.91
R_L_D (%)	65.05	63.82	63.95	63.62	63.29	63.41
R_R_M (%)	14.59	10.91	12.68	12.30	11.45	11.82
R_R_D (%)	50.85	54.95	52.93	53.27	54.35	53.83

To filer the Pareto optimal solutions and find the final optimum one, the relative reduction of each response, derived from the bridge with and without the optimized viscous dampers, is defined as Eq. (4), where the subscript 0 represents the response without viscous damper.

$$
\begin{aligned}
R\_L\_M &= \frac{Abs(L\_M - L\_M_0)}{L\_M} \times 100\% \qquad \text{(a)} \\
R\_L\_D &= \frac{Abs(L\_D - L\_D_0)}{L\_D} \times 100\% \qquad \text{(b)} \\
R\_R\_M &= \frac{Abs(R\_M - R\_M_0)}{R\_M} \times 100\% \qquad \text{(c)} \\
R\_R\_D &= \frac{Abs(R\_D - R\_D_0)}{R\_D} \times 100\% \qquad \text{(d)}
\end{aligned} \tag{4}
$$

Obviously, the relative reduction of each response should be set properly. On the one hand, there will be no suitable solutions if the relative reductions are too large. On the other hand, with small relative reductions, a valid selection could not be conducted. After many trails, all the relative reductions is defined as Eq. (5). Six selection results are shown in Table 2.

$$
\begin{aligned}
&R\_L\_D \geq 50\% \quad \text{and} \quad R\_R\_D \geq 50\% \\
&R\_L\_M \geq 10\% \quad \text{and} \quad R\_R\_M \geq 10\%
\end{aligned} \tag{5}
$$

About solution I, all the relative reductions except R_R_D are smaller than those of other solutions. But the value of C_v is too large to be acceptable with too high cost. Since the larger the value of C_v, the more expensive the viscous dampers are. The relative reductions derived from solution II to solution VI are close to each other. Integrated with the purpose of the less-cost, the solution VI is chosen as the optimum choice, in which C_v =3932 kN/(m/s), n = 0.255. From Table 2, it can also been that all the relative reductions of relative displacement is always bigger than that of the bending moment at the root of the tower. It means that the relative displacement is more sensitive to the viscous damper. With the optimum viscous dampers, the longitudinal displacement of the bridge main girder significantly decreases.

6. Conclusions

Based on the longitudinal dynamics vehicle model, the influence of initial braking speed and position on the key responses of a cable-stayed bridge are systematically investigated. To reduce the responses, parameter sensitivity of viscous dampers is performed. Optimization model is established and the proposed hybrid method BPNN-NSGA-II is utilized to find the optimum parameters. The results show that: a. the effect of the initial braking speed and position on the key longitudinal responses of the bridge is great. The higher the speed, does not mean that the larger the structural response is. The initial braking position has a greater effect on the bridge response; b. the relationships between the parameters of viscous dampers and the key longitudinal responses of the bridge are high nonlinear, which are completely different from each other. Through proposed hybrid method BPNN-NSGA-II, the optimum parameters are found: C_v =3932 kN/(m/s), n = 0.255. The longitudinal displacement of the bridge main girder significantly decreases by the optimized viscous dampers.

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