Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 11, No. 1, 2024

Dynamic Response Analysis of Moving Loads over Tension Cables of Connected Tower Cable-Stayed Bridge

Xiyuan Liu [1, *]

[1] School of Civil Engineering, Lanzhou Jiaotong University, 730000, China

[*] Corresponding author: Xiyuan Liu

Abstract: Due to its strong crossing ability, cable-stayed bridges have become the mainstream bridge type for large and medium spans. The connected tower cable-stayed bridge is different from traditional single span cable-stayed bridges, integrating the characteristics of split frame structure and connected tower design, and has better structural mechanical properties. However, the complex cable layout, multi tower structure, and segmented bridge deck of the cable-stayed bridge with connected towers result in essential differences in its mechanical behavior compared to traditional bridges. Therefore, studying the dynamic response of cable-stayed bridge cables when vehicle loads pass through the bridge is of great practical significance. This article comprehensively considers two factors: vehicle weight and vehicle speed, and introduces the parameter of dynamic amplification factor. The numerical simulation method is used to analyze the dynamic response of the cable when a vehicle load passes through a cable-stayed bridge with a connected tower. In order to provide key data support and important references for the construction and operation monitoring of cable-stayed bridges with connected towers.

Keywords: Connected tower cable-stayed bridge, Dynamic response, Vehicle load, Dynamic amplification factor, Numerical simulation.

1. Introduction

In the past, research on the dynamic response analysis of vehicle loads passing through highway bridges mainly focused on beam bridges, while there has been very little research on the dynamic effects of cable-stayed bridges with connected towers under vehicle loads.

OBrien E J and Enright B[1,2] used Monte Carlo method to simulate traffic flow based on a large amount of data measured by dynamic weighing systems in Europe, and calculated and analyzed the impact of vehicle loads on bridge structural effects. Zhao J et al[3] calculated the distribution of bending moment and shear force effects generated by the vehicle load based on the top 5% of the maximum vehicle weight in the data measured by the dynamic weighing system. Green M F et al[4] simulated a truck crossing a bridge and conducted a detailed analysis of the bridge's vibration response. Zhang Q L et al[5] analyzed the influence of bridge deck flatness and vehicle driving position on the dynamic response of bridges. Guo W[6] established a finite element model of a large-span cable-stayed bridge, conducted vehicle bridge coupling vibration analysis under wind load, and considered the dynamic response of the bridge under factors such as wind speed, driving speed, and road surface grade. Nguyen K et al[7] studied the driving safety and comfort of slender arch bridges under wind and vehicle loads by establishing a two axle vehicle model. Li Y et al[8] conducted a dynamic performance study on a new type of hybrid beam bridge, and studied the dynamic characteristics of a special shaped hybrid beam bridge with concrete filled steel pipe arches under the action of moving vehicles through experiments and numerical methods. Zhang Y et al[9] established mechanical models of the vehicle subsystem and bridge subsystem based on the finite element method, and analyzed the dynamic response of the vehicle under uneven conditions.

When vehicles act on a cable-stayed bridge with different operating conditions, there is relatively little research on the cable performance of the cable-stayed bridge under different operating conditions, and further research is needed. This article takes a cable-stayed bridge with a connected tower as an example to explore the influence of different vehicle weights and speeds on the dynamic response of the cables when passing through the cable-stayed bridge.

2. Establishment of Bridge Calculation Model

2.1. Project overview

A large-span cable-stayed bridge is a double tower three span composite beam cable-stayed bridge, with a semi floating bridge system and a total span arrangement of 151m+328m+151m. The main beam is a composite beam composed of steel main beam and reinforced concrete bridge deck, which are jointly subjected to force. The two are combined through shear nails. The steel main beam is made of Q420 steel, and the concrete bridge deck is made of C55 concrete. The bridge tower adopts a diamond shaped connected tower design, with the south tower reaching a height of 152m and the north tower reaching a height of 133m. According to its shape and position, the tower body can be divided into upper and lower tower columns. There are a total of 208 cables in the entire bridge, arranged in a spatial fan-shaped four cable surface form. The overall layout of the entire bridge is shown in Figure 1.

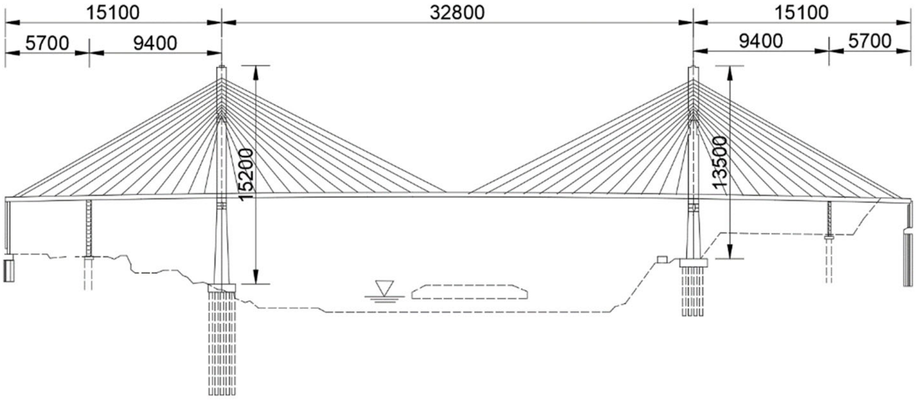


Figure 1. Layout plan of the entire bridge (Unit: cm)

2.2. Model establishment

The origin of the numerical model of the bridge is located at the starting point of the right bridge axis. The positive direction of the x-axis is to the right along the longitudinal direction of the bridge, the positive direction of the y-axis is to rotate 90 ° counterclockwise along the x-axis, and the positive direction of the z-axis is perpendicular to the upward direction of the bridge deck. Due to the fact that cable-stayed cables only bear axial forces and do not need to bear bending moments or shear forces, truss elements are used for simulation, and circular sections are used to establish elements. Each cable is divided into a truss element. The finite element model of the entire bridge is shown in Figure 2.

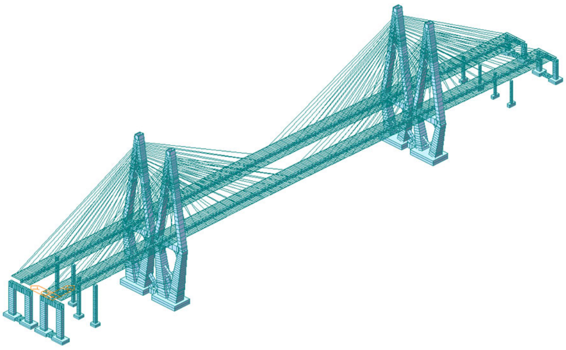


Figure 2. Full bridge model diagram

3. Dynamic Response Analysis of Cable During Vehicle Crossing Bridge

The dynamic response of the cable when the vehicle passes through the bridge is analyzed and studied by selecting the right bridge loading mode and comprehensively considering the vehicle type, vehicle weight and other factors.

The longest and shortest cable in the side span of the right bridge was selected as the research object of the cable and numbered as S1 and S13. The longest and shortest cable in the middle span of the right bridge was numbered as M1 and M13.

In the dynamic response analysis of bridges, the parameter of dynamic amplification factor is also needed to consider the dynamic amplification effect caused by moving vehicles. Here, a method that is commonly used and convenient for calculation and understanding is adopted, as shown in formula (1).

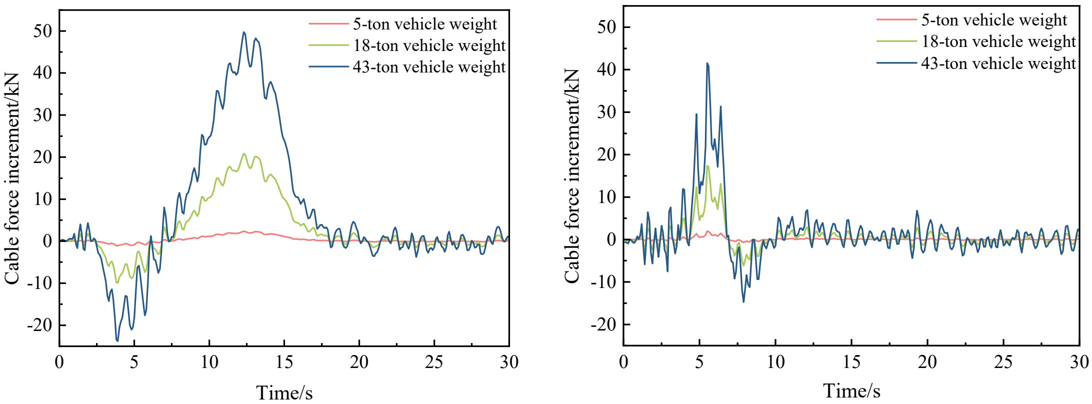
$$DAF = \frac{Y_{d\max}}{Y_{j\max}} \tag{1}$$

Where: DAF is the dynamic amplification factor;
Y_{dmax} is the maximum dynamic response value;
Y_{jmax} is the maximum static effect value.

The calculation of the dynamic amplification factor in the following text adopts the above formula.

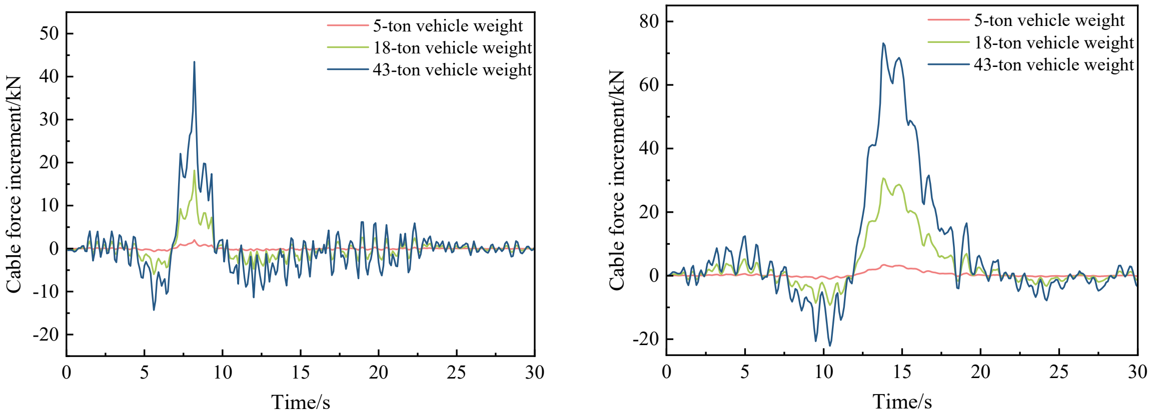
3.1. Influence of vehicle weight on dynamic response of cable

The vehicle weight is 2 tons, 18 tons and 43 tons respectively, and the vehicle speed is 80km/h. The lane loading mode is medium load, that is, the right bridge centerline is used for loading. The dynamic increment of cable force of S1, S13, M1 and M13 cables of the right bridge under different vehicle loads is shown in Fig. 3.



(a) S1 cable

(b) S13 cable



(c) M13 cable

(d) M1 cable

Figure 3. Dynamic increment of cable force under different vehicle weights

It can be seen from the above figure that when vehicles of different weights pass through the right bridge of the cable-stayed bridge at the same speed, there is a significant difference in the cable dynamic increment. Intuitively, the greater the weight of the vehicle, the greater the load on the bridge deck, and the more significant the deformation of the bridge under the vehicle load, resulting in the need for cables to bear more force to maintain the stability of the bridge deck. This kind of vehicle weight directly affects the dynamic response of the cable of cable-stayed bridge, which leads to different peak values of dynamic increment of cable force. In addition, the dynamic increment of cable force is more significant under the dynamic response of vehicle load in the middle span, regardless of the long cable in the side span or the long cable in the middle span; While the short cable is only more sensitive to the cable force response of the vehicle load passing through the cable anchorage zone, and the vehicle load in other areas has little effect on the cable force response.

When different vehicle weights pass through the right bridge, the dynamic increment peak value and dynamic amplification factor of each cable tension of the right bridge are counted. See Table 1 and table 2 for details.

Table 1. Peak value of cable force response under different vehicle weights(Unit: kN)

Diagonal cable number	5-ton vehicle weight	18-ton vehicle weight	43-ton vehicle weight
S1	2.32	20.84	49.79
S13	1.93	17.08	41.54
M13	2.02	18.19	43.46
M1	3.37	30.63	73.16

Table 2. Dynamic amplification factor of cable under different vehicle weights

Diagonal cable number	5-ton vehicle weight	18-ton vehicle weight	43-ton vehicle weight
S1	1.18	1.18	1.18
S13	1.59	1.56	1.59
M13	1.67	1.67	1.67
M1	1.16	1.17	1.17

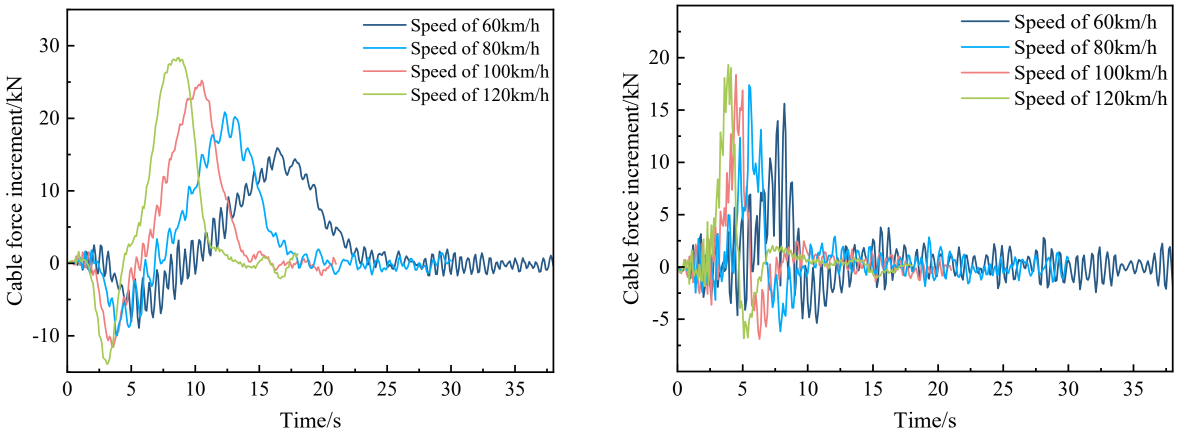
It can be seen from the above table that different vehicle weights have a great impact on the peak value of dynamic increment of cable force. Taking S1 cable as an example, under 2 tons of vehicle weight, the peak dynamic increment of cable force is 2.32kN, while under 43 tons of vehicle weight, the peak dynamic increment of cable force reaches 49.79kN, an increase of 200.46%. Under the condition of the same vehicle weight, the cable force response of the middle span cable is greater than that of the same number of side span cable. Compared with S1 cable and M1 cable, when 43 tons of vehicle weight passes through the cable-stayed bridge, the dynamic increment of the peak cable force of M1 cable is 73.16kN, while the dynamic increment of the peak cable force of S1 cable is 49.79kN, an increase of 46.94%, so the middle span cable shows greater cable force response under dynamic load.

At the same time, it is found that under different vehicle loads, the dynamic amplification factor of each cable force is different from the dynamic increment of cable force, that is, it increases with the increase of vehicle weight, but basically maintains an equal value. In addition, under the same vehicle weight, the dynamic increment of cable force of long cable is larger than that of short cable, but the dynamic amplification factor of cable force of short cable is larger than that of long cable. Compared with S1 cable and S13 cable, the dynamic amplification factor of the latter is 1.45 times of the former. To sum up, there is no inevitable relationship between the dynamic response of the cable and the dynamic amplification factor, but the increase of the vehicle weight will increase the dynamic response of the cable. Even if the dynamic amplification factor does not increase, when the dynamic response value caused by the excessive vehicle weight is too large, it will be harmful to the stress safety of the cable.

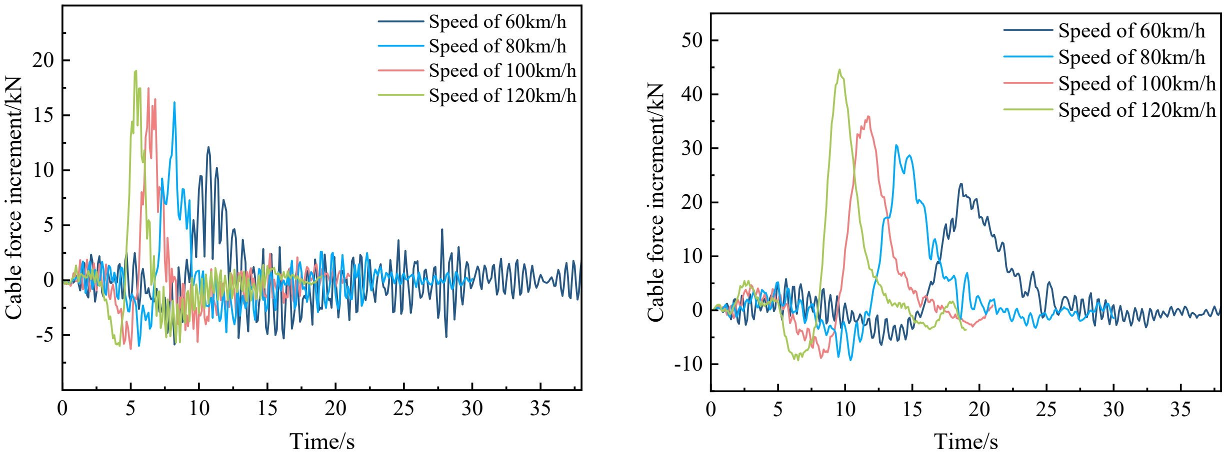
3.2. Influence of vehicle speed on dynamic response of cable

The design speed of this bridge is 80km/h. Considering the overspeed phenomenon, two working conditions of 25% overspeed and 50% overspeed are designed respectively. To sum up, the speed is 60km/h, 80km/h, 100km/h and 120km/h respectively, and the vehicle weight is 18 tons. The right bridge middle load is selected as the lane loading mode.

The dynamic increment of cable force of S1, S13, M1 and M13 cables of the right bridge under different vehicle loads is shown in Figure 4.



(a) S1 cable (b) S13 cable



(c) M13 cable (d) M1 cable

Figure 4. Dynamic increment of cable force under different vehicle speeds

It can be seen from the above figure that with the increase of vehicle speed, the shorter the time the vehicle travels on the bridge, the earlier the peak value of cable tension dynamic increment appears, which means that higher speed can reach the key point causing the maximum cable tension dynamic increment faster and trigger earlier dynamic response. At the same time, the increase of the speed also leads to the increase of the dynamic increment of the peak value of the cable force, but its action time will decrease, that is, the high-speed vehicles will lead to more rapid changes in the cable force. After the peak value, the fluctuation of dynamic increment of cable force at each speed gradually decreases, indicating that when the vehicle passes through the key area, its influence gradually weakens, and the reduction of this fluctuation is related to the reduction of cable force caused by the distance of the vehicle. To sum up, the key area of dynamic increment of cable force of long cables in both mid span and side span sections is in the middle of the bridge mid span, while the key area of short cables is in the cable anchorage area.

When passing through the right bridge at different speeds, the dynamic increment peak value and dynamic amplification factor of each cable tension of the right bridge are counted. See Table 3 and table 4 for details.

Table 3. Peak value of cable force response under different vehicle speeds(Unit: kN)

Diagonal cable number	Speed of 60km/h	Speed of 100km/h	Speed of 120km/h
S1	18.77	25.22	28.35
S13	15.62	18.37	19.34
M13	12.12	17.47	19.06
M1	27.37	35.94	44.61

Table 4. Dynamic amplification factor of cable under different vehicle speeds

Diagonal cable number	Speed of 60km/h	Speed of 100km/h	Speed of 120km/h
S1	1.06	1.42	1.60
S13	1.43	1.68	1.77
M13	1.21	1.60	1.75
M1	1.05	1.38	1.71

It can be found from the above that the faster the speed, the greater the peak value of each cable force response, and the sensitivity of different cables to vehicle speed is also different. Compared with S1 cable, M13 cable and M1 cable, the peak value of S1 cable force response increases by 51.04% from 60km/h to 120km/h, while M13 cable increases by 57.26% and M1 cable increases by 62.99%. On the whole, the peak value of dynamic response of mid span cable is larger than that of side span cable, and the long cable is larger than the short cable. In addition, unlike the vehicle weight, the dynamic amplification factor of each cable increases with the increase of vehicle speed. Taking M1 cable as an example, the dynamic amplification factor increases by 1.63 times from 60km/h to 120km/h. At low speed, the dynamic amplification factor of long cables is smaller than that of short cables, and the maximum value of the latter is 1.36 times that of the former. With the increase of vehicle speed, the dynamic amplification factor of long cables continues to increase, and the increment of dynamic amplification factor of long cables is much larger than that of short cables. At 120km/h, the dynamic amplification factor of long cables and short cables is relatively close. It shows that at low speed, the short cable is already sensitive to the dynamic load of the vehicle, while at high speed, the dynamic response of each cable of the bridge is greatly affected.

4. Conclusion

(1) With the increase of vehicle weight, the peak value of bridge cable dynamic response increases, but the arrival time and action time of each peak value are the same; With the increase of vehicle speed, the dynamic response peak of bridge cable increases, and the arrival time of dynamic response peak is earlier. At the same time, faster vehicle speed will cause more rapid dynamic response of bridge cable.

(2) The longer cable will bear more loads, and the load distribution within its span will be more extensive. At the same time, the stiffness of the short cable is greater than that of the long cable. The cable with higher stiffness can more effectively resist the deformation caused by the load, thus reducing the impact of the load on the cable.

(3) There is no necessary relationship between the dynamic response value and the dynamic amplification factor. For example, the dynamic response value of short cable is smaller than that of long cable, but the dynamic amplification factor is larger than the latter.

References

[1] Nowak A S, Hong Y K.Bridge Live-Load Models[J]. Journal of Structural Engineering, 1991, 117(9):2757-2767.

[2] Nowak A S, Nassif H, DeFrain L. Effect of Truck Loads on Bridges[J]. Journa orTransportation Engineering, 1993, 119(6): 853-867.

[3] Zhao J, Tabatabai H.Evaluation of a Permit Vehicle Model Using Weigh-in-MotionTruck Records[J]. Journal of Bridge Engineering, 2012, 17(2): 389-392.

[4] Green M F, Cebon D. Dynamic interaction between heavy vehicles and highway bridges[J]. Computers & structures, 1997, 62(2): 253-264.

[5] Zhang Q L, Vrouwenvelder A, Wardenier J. Dynamic amplification factors and EUDL of bridges under random traffic flows[J]. Engineering Structures, 2001, 23(6): 663-672.

[6] Guo W. Dynamic analysis of coupled road vehicle and long span cable-stayed bridge systems under crosswinds[M]. Hong Kong Polytechnic University (Hong Kong), 2003.

[7] Nguyen K, Camara A, Rio O, et al. Dynamic effects of turbulent crosswind on the serviceability state of vibrations of a slender arch bridge including wind–vehicle–bridge interaction[J]. Journal of Bridge Engineering, 2017, 22(11): 06017005.

[8] Li Y, Cai C S, Liu Y, et al. Dynamic analysis of a large span specially shaped hybrid girder bridge with concrete-filled steel tube arches[J]. Engineering Structures, 2016, 106: 243-260.

[9] Zhang Y, Li W, Ji Z, et al. Vehicle ride comfort analysis based on vehicle-bridge coupled vibration[J]. Shock and Vibration, 2021, 2021: 1-14.