Analysis of Vehicle-Bridge Coupling Vibration in Large-Span Combined Road-Rail Arch Bridges

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Abstract: The paper systematically analyzes the coupled vibration characteristics of the long-span dual-use arch bridges under vehicles, using the Caiyuanba Yangtze River Bridge in Chongqing as an example. The paper analyzes the structure characteristics and important role in urban traffic through the current development of dual-use arch bridges. The paper analyzes the main influencing factors and the strategy of modeling based on the fundamental laws of coupled vibration of vehicles and bridges. The paper integrates the national and foreign research achievements, and summarizes the current latest theoretical achievements and practical outcomes. The paper analyzes its dynamic response under the compression effects of highway and track loads through numerical simulation for the Caiyuanba Yangtze River Bridge. The paper discovers the vibration characteristics of the Y-shaped rigid frame and mid-span under coupled loads, and the effect of road surface roughness and the speed of the trains on the amplitude of the vibration. The paper discovers that dual-use arch bridges have strong nonlinear characteristics in the aspect of coupled vibration under complex loads. The structure with the steel-box tied-arch is beneficial in terms of force-distributing, while there is the stress concentration problem that should be overcome. The paper provides the fundamental theoretical support and practical reference on the aspect of the vibration control and structure optimization of dual-use arch bridges, with high application value in terms of practical engineering.

Keywords: Road-Rail Arch Bridge; Vehicle-bridge Coupled Vibration; Caiyuanba Yangtze River Bridge; Dynamic Response; Numerical Simulation

1. Introduction

1.1 Research Background and Significance

As an important part of modern urban transportation infrastructure, the long-span road-rail arch bridge takes into account both road and rail transportation functions and meets the demand for efficient transportation networks in the process of urbanization. Its unique structural design and complex mechanical behavior make it of great value in the study of vehicle-bridge coupled vibration. Vehicle-bridge coupled vibration refers to the vibration phenomenon caused by the dynamic interaction between vehicles and bridges, which directly affects the safety, comfort and service life of the bridge. In recent years, with the increase in urban traffic flow and the rapid development of rail transportation, the vibration problem of road-rail bridges has become increasingly prominent, and in-depth research is urgently needed to optimize the design and operation and maintenance. As a typical road-rail arch bridge, the Caiyuanba Yangtze River Bridge, with its complex structural form and high load characteristics, provides an ideal case for vibration analysis [1]. Domestic and foreign scholars have conducted extensive research on vehicle-bridge coupled vibration, covering theoretical modeling, numerical simulation and experimental verification. For example, Wang et al. analyzed the response characteristics of long-span bridges under dynamic loads by establishing a vehicle-bridge coupling model [2]. However, the vibration mechanism of dual-use arch bridges is more complex due to their double-layer structure and the combined effect of multiple types of loads, and related research is relatively insufficient. This study takes the Caiyuanba Yangtze River Bridge as the object and systematically sorts out the theory and method of vehicle-bridge coupling vibration, aiming to provide theoretical support and practical reference for the design and safety assessment of similar bridges, which has important academic and engineering significance.

1.2 Research Content and Method

This study focuses on the vehicle-bridge coupling vibration analysis of long-span dual-use arch bridges. Taking the Caiyuanba Yangtze River Bridge as a case, its vibration characteristics and influencing factors are systematically explored. The research content includes: first, reviewing the structural characteristics and development status of dual-use arch bridges, clarifying their application value in urban transportation; second, sorting out the basic theory and modeling method of vehicle-bridge coupling vibration, and analyzing the key influencing factors; finally, through numerical simulation and case analysis, the vibration response characteristics of the Caiyuanba Yangtze River Bridge under road and rail loads are explored.

The research method adopts a combination of literature review and numerical simulation. By reviewing relevant domestic and international literature, we summarized the theoretical framework and research progress of vehicle-bridge coupled vibration. Using finite element analysis techniques, we developed a vehicle-bridge coupled model for the Caiyuanba Yangtze River Bridge, simulating the bridge's dynamic response under various load conditions. Through case studies, we validated the model's accuracy and summarized its vibration characteristics. This study aims to provide a scientific basis for vibration control and optimized design of dual-use arch bridges by integrating theory and practice.

2. Overview of the Development of Dual-Use Arch Bridges

2.1 Types and Characteristics of Long-Span Arch Bridges

Long-span arch bridges, with their superior mechanical properties and unique aesthetic appeal, are widely used in river-crossing projects. They convert loads into pressure through arch rings, effectively reducing material consumption and making them suitable for large-span applications. According to the structural form, long-span arch bridges can be divided into stone arch bridges, steel arch bridges, concrete arch bridges and steel tube concrete arch bridges. Among them, steel tube concrete arch bridges are particularly prominent in modern bridges due to their high strength and convenient construction [3]. Such bridges have the characteristics of large span, high stiffness and good landscape effect, but they also face the challenges of complex high-altitude assembly and high vibration control requirements. In recent years, the progress of materials science and construction technology has promoted the breakthrough of the span of long-span arch bridges. For example, the Baisha Bridge in Liuzhou, China adopts a steel tube concrete arch structure and demonstrates excellent bearing capacity and vibration resistance [4]. The design of long-span arch bridges needs to comprehensively consider the deadweight, wind load and dynamic loads caused by vehicles and rail transportation, especially the impact of vehicle-bridge coupling vibration on structural safety and durability. In response to the dynamic response of such bridges, researchers have optimized the design method through theoretical analysis and numerical simulation to ensure long-term stability and safety.

2.2 Design and Application of Dual-Use Bridges

Dual-use bridges integrate the functions of highways and rail transportation and are key structures for solving urban traffic bottlenecks and improving transportation efficiency. Its design needs to take into account both the random dynamic loads of road vehicles and the periodic vibrations of rail traffic, and its structural complexity is significantly higher than that of single-purpose bridges. Dual-use bridges usually adopt a double-deck structure, with the upper deck being the road lane and the lower deck being the rail traffic, and it is necessary to achieve the coordinated operation of the two modes of transportation within a limited space [5]. The design should focus on the stiffness, damping characteristics and fatigue life of the bridge to cope with the coupling effect of road and rail loads. For example, the Douro River Bridge in Portugal successfully achieved dual-use functions by optimizing the steel box girder and tie arch structure [6]. In terms of application, dual-use bridges are mostly deployed in city centers or across river areas, which can effectively alleviate traffic pressure and promote regional economic development [7]. However, due to the difference in load characteristics, vehicle-bridge coupling vibration has become a core issue in design and operation, and accurate mechanical analysis and vibration control technology are required to ensure the safety and comfort of the bridge [8].

3. Overview of Vehicle-Bridge Coupled Vibration Theory

3.1 Basic Principles of Vehicle-Bridge Coupled Vibration

Coupled vibration of vehicles and bridges is the dynamic response effect due to the contact action of the bridge and the vehicle along the contact line when the automobile is traversing through the bridge. The bridge's vibration is caused through the movement of the automobile, while the vibration of the bridge in response contributes to the dynamics of the automobile as well, forming a complicated coupled system. The underlying principle is the dynamic equilibrium, such as the suspension system of the car, the bridge's stiffness and damping properties, as well as the mutual interaction of the two [9]. The automobile's load is usually given in terms of moving distributed force or concentrated force in movement, and the bridge responds with dynamic excitation under an elastic structure. The basic nature of coupled vibration is the contact interaction interface between the wheel and the bridge, usually modeled with the Hertz contact principle. The frequency and amplitude of the coupled vibration of the vehicles and bridges is determined to be of significant relation with the bridge's natural frequency, the automobile's velocity and the rougher road surface [10]. For dual-use arch bridges like the Caiyuanba Yangtze River Bridge, the automobile's random force of road vehicles and the periodic force of rail traffics act with each other, so the mechanism of the coupled vibration is more complex. The nature of the vehicle-bridge coupled vibration is beneficial in the optimized design of the bridge, alleviating the negative influence of the coupled vibration on the durability of the structure and the driving comfort of the automobile's automobile, as well as the basis of the following numerical analysis and coupled vibration suppression.

3.2 Influencing Factors and Modeling Methods

The characteristics of vehicle-bridge coupled vibration are affected by many factors, including vehicle parameters (such as mass, suspension stiffness, speed), bridge parameters (such as stiffness, damping, span), and external conditions (such as road surface roughness and wind load) [11]. For example, high-speed vehicles or trains will significantly amplify the dynamic response of the bridge, and road surface roughness may induce additional excitation. Modeling methods mainly include analytical methods, numerical methods, and experimental methods. The analytical method solves the vibration response of the coupled system by establishing the dynamic equations of the vehicle and bridge, and is suitable for simple models; numerical methods, such as the finite element method and multi-body dynamics method, can simulate the dynamic behavior of complex bridge structures and are often used in the analysis of dual-use bridges for road and rail [12]. When modeling, the nonlinear characteristics of the vehicle-bridge system, such as the nonlinear stiffness and damping of the wheel-bridge contact, must be considered. In recent years, the integrated modeling method combining finite element software (such as ANSYS, ABAQUS) with multi-body dynamics software has gradually become a research hotspot. It can more accurately simulate the vibration response under actual working conditions and provide a reliable tool for the dynamic analysis of dual-use arch bridges.

3.3 Research Progress at Home and Abroad

The study of vehicle-bridge coupling vibration at home and abroad has progressed significantly. Overseas research began earlier and emphasized the development of theoretical models and experimental verification. For instance, Fryba established a classic analytical model of vehicle-bridge coupling vibration, which served as the foundation of later research [13]. Over the past few years, research tended to be oriented toward the vibration control of high-speed bridge railways. Overseas scholars have discussed the dynamic response of the train-bridge system via the application of real-time monitoring technology [14]. Domestic research emerged rapidly through the drive of large-scale bridge projects, particularly in the application of dual-use arch bridges. For large-span arch bridges, researchers have established the model of coupling in multiple forms of loads and experimentally verified the model in combination with field measurements.

The case study on the vibration analysis of the Caiyuanba Yangtze River Bridge reflects that the road and rail interacting loads have an important effect on the bridge's dynamic performance [15]. Nevertheless, the current research remains inadequate in some aspects, for example, the nonlinear vibration under multiple forms of complicated loads needs to be further optimized in terms of the effect in model accuracies, and the application of real-time online monitoring technology needs to be further promoted.

4. Case Analysis

4.1 Structural Parameters and Load Characteristics of the Caiyuanba Yangtze River Bridge

The Caiyuanba Yangtze River Bridge is an important dual-use arch bridge for road and rail in Chongqing, China. The total length of the line is 7 kilometers, the main bridge is 800 meters long, and the span layout is (88+102+420+102+88) meters. The main bridge's steel truss girder is 11.2 meters high, 39.8 meters wide at the top, 13 meters wide at the bottom, and 16 meters long for standard sections. The main arch ring is 2.4 meters wide and 4.0 meters high, with a horizontal projection of 16 meters for standard sections. The main piers range in cross-section from 14 meters x 9 meters to 12 meters x 6.2 meters. The clear width of the bridge deck is 30.5 meters, arranged in a (2.5+12.25+1.0+12.25+2.5) meter configuration, with a clear width of 8.6 meters for rail transit on the lower deck. The upper deck of the bridge serves as a six-lane, two-way highway with a design speed of 60 km/h, while the lower deck serves as a double-track rail transit with a design speed of 75 km/h. The bridge utilizes a concrete-filled steel tube arch design, combining a "Y"-shaped rigid frame and a steel box tied arch structure, resulting in high rigidity and load-bearing capacity. In terms of load characteristics, the highway section bears the random dynamic loads of vehicles on urban arterial roads, including heavy trucks and light cars; the track section bears the periodic train loads of Chongqing Metro Line 3, with relatively regular frequency and amplitude. The combination of these two creates complex dynamic excitations that significantly affect the bridge's vibration response, providing a typical case for vehicle-bridge coupled vibration analysis.

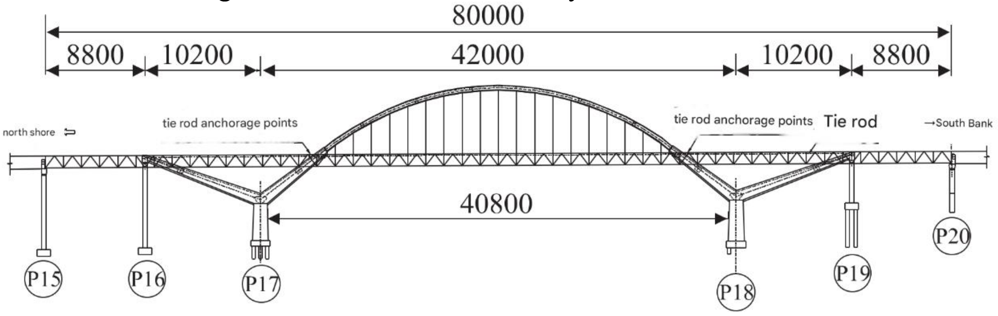

Figure 1. Elevation Layout of Caiyuanba Yangtze River Bridge (units: cm)

The steel-concrete-filled arch bridge structure and its two-deck design (a six-lane, two-way highway on the upper deck and a two-track rail transit on the lower deck) of the main bridge shown in Figure 1 are closely related to the analysis of vehicle-bridge coupled vibration. The span arrangement and structural properties of the "Y"-shaped rigid frame directly influence the dynamic response caused by highway vehicle and rail train loads. The stiffness of the steel trusses and the supporting role of the arch rings are crucial for controlling vibration propagation and amplitude.

4.2 Vehicle-Bridge Coupled Vibration Simulation Method

The numerical simulation methodology mainly utilizes the combination of the numerical simulation (see Figure 2) and the finite element analysis. Firstly, the bridge is established with the finite element. Based on the geometrical attributes and material characteristics of the main bridge, the mechanical properties of the steel trusses, the arch rings, and the "Y"-shaped rigid frame are accurately established. Secondly, the vehicle model and the train model are built in order to simulate the suspension system of the highway automobile and the wheel-rail contact attributes of the rail locomotive, respectively, with the consideration of the parameters such as the mass, the stiffness, and the damping. The coupled model utilizes the dynamic interaction at the wheel-bridge contact point, and the contact force is modeled with the nonlinear contact theory. During the simulation, the road surface roughness and the high-speed travel speed of the train are the crucial inputting parameters, so as to input the excitation condition under the real working condition. The bridge's dynamic response is deduced with the outputting the displacement, the acceleration, and the internal force with the use of the finite element software. Meanwhile, with the comprehensive action of the road and the track loads taken into account, the condition of the single and the comprehensive load is simulated in order to investigate the influence of the various combination of the loads on the vibration characteristics. The methodology is efficient in the capturing of the bridge's dynamic characteristics, laying the foundation of the following vibration control as well as the structure optimization.

Figure 2. Three-Dimensional Finite-Element Model of Caiyuanba Yangtze River Bridge

4.3 Vibration Analysis Results of the Caiyuanba Yangtze River Bridge

The vibration analysis results of the Caiyuanba Yangtze River Bridge show that its dynamic response is significantly influenced by both road and track loads. Under road load alone, the bridge's vibration is primarily manifested as vertical displacement and local acceleration of the main girder, with a peak occurring when heavy vehicles pass the midpoint of the main span. Under track load, the periodic excitation caused by train operation results in relatively regular vibrations of the bridge, with frequencies approaching the bridge's natural frequency, potentially inducing resonance risk. When road and track loads act simultaneously, the bridge's dynamic response exhibits nonlinear superposition, with amplified maximum displacements and accelerations, particularly at the midpoint of the main span and at the arch ring connections. The analysis indicates that road surface roughness and train speed significantly influence the vibration amplitude, requiring optimization of damping devices and road maintenance to mitigate the vibration effects. Furthermore, the steel box tied arch structure performs well in distributing loads, but stress concentration in the "Y" rigid frame requires particular attention. These results provide data support for the operation, maintenance, and vibration control of the Caiyuanba Yangtze River Bridge and offer a reference for the design optimization of similar dual-use arch bridges.

5. Conclusion

5.1 Research Summary

Based on the Caiyuanba Yangtze River Bridge, this paper systematically summarized long-span dual-use arch bridges' vehicle-bridge coupled vibration characteristics in terms of theoretical summaries, structural characteristics and case studies. By systematically analyzing the development status of the dual-use arch bridges at the current stage, the paper cleared up the importance of the dual-use arch bridges in urban means of transportation and complex mechanical properties. Theoretical calculations of vehicles-bridge coupled vibration reveal that the dynamic interaction among vehicles and bridges is involved in many factors like the vehicles' parameters, bridge flexibility and exterior excitation conditions. Based on the Caiyuanba Yangtze River Bridge, the paper used numerical simulations to reveal the bridge's dynamic response characteristics under the highway and track loads' comprehensive action. The paper concluded that the mid-span and Y-shaped rigid frame's vibration response was particularly remarkable, and the road surface roughness and the train speed had significant effects on the amplitude of the vibration. These results are consistent with the dual-use arch bridges' vibration mode under complex loads, providing the scientific evidence on the bridge design, run and maintenance. Through the combination of the theories with practices, this paper expands the cognition of the mechanism of the vehicle-bridge coupled vibration and provides important reference on the structure's optimal design and the dual-use arch bridges' vibration control.

5.2 Limitations and Future Prospects

Although this study has made some progress in vehicle-bridge coupled vibration analysis, it still has limitations. First, the vibration analysis of the Caoyangba Yangtze River Bridge is mainly based on numerical simulation, lacking support from long-term field monitoring data. Future research should combine field monitoring data to verify the accuracy of the model. Second, the nonlinear vibration characteristics of combined road-rail bridges and the combined effects of multiple types of loads still need further exploration, especially their dynamic response under extreme conditions. Looking ahead, the research can incorporate big data and artificial intelligence technologies to develop real-time vibration monitoring and prediction models, thus improving the safety and efficiency of bridge operation. Furthermore, combining new materials and damping technologies to optimize the vibration resistance performance of combined road-rail arch bridges will provide a new path for the sustainable development of urban transportation infrastructure. The results and methods of this study can serve as a reference for vibration analysis and design optimization of similar bridges, promoting technological advancements in the field of bridge engineering.

References

[1] Zhang, N., Xia, H.: Dynamic analysis of coupled vehicle-bridge system based on inter-system iteration method. Computers & Structures, 114-115, 26-34 (2013).
[2] Wang, T., Song, G., Liu, S.: Dynamic interaction analysis of vehicle-bridge system with uncertain parameters. Journal of Sound and Vibration, 332(25), 6873-6888 (2013).
[3] Chen, B. C., Wang, T. L.: Overview of concrete filled steel tube arch bridges in China. Structural Engineering International, 19(2), 165-172 (2009).
[4] Liu, J. P., Zhang, Z. H.: Design and construction of large-span concrete-filled steel tubular arch bridges. Journal of Bridge Engineering, 18(8), 781-790 (2013).
[5] Yang, Y., Yau, J. D.: Dynamic response of a railway bridge to a moving train with random track irregularities. Engineering Structures, 56, 1397-1407 (2013).
[6] Reis, A. J., Pedro, J. J. O.: Design of composite and steel bridges for high-speed railways. Journal of Constructional Steel Research, 66(8-9), 1069-1080 (2010).
[7] Li, Y., Cai, C. S.: Dynamic analysis of a large span railway bridge under moving train loads. Advances in Structural Engineering, 16(5), 873-886 (2013).
[8] Kim, S. H., Ahn, J. H.: Dynamic behavior of a steel-concrete composite railway bridge under high-speed train loading. Journal of Structural Engineering, 139(12), 04013007 (2013).
[9] Yang, Y. B., Wu, Y. S.: A versatile element for analyzing vehicle–bridge interaction response. Engineering Structures, 23(5), 452-469 (2001).
[10] Deng, L., Cai, C. S.: Development of dynamic impact factor for performance evaluation of existing bridges. Journal of Bridge Engineering, 15(3), 252-260 (2010).
[11] Zhang, Z. C., Lin, J. H.: Dynamic response analysis of a bridge–vehicle coupled system with uncertain parameters. Journal of Sound and Vibration, 336, 216-234 (2015).
[12] Cantero, D., OBrien, E. J.: The dynamic response of bridges to moving vehicles: A review. Shock and Vibration, 2014, 1-13 (2014).
[13] Fryba, L.: Vibration of solids and structures under moving loads. Springer Science & Business Media (1999).
[14] Zhai, W. M., Xia, H.: Train–track–bridge dynamic interaction: A state-of-the-art review. Vehicle System Dynamics, 54(12), 1657-1674 (2016).
[15] Wang, S. J., Xu, Z. D.: Dynamic response of a long-span railway bridge under simultaneous train and traffic loads. Advances in Structural Engineering, 19(6), 975-987 (2016).

