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# Dynamic interaction of suspension-type monorail vehicle and bridge: Numerical simulation and experiment

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A B S T R A C T

To evaluate the dynamic behaviour of suspension-type monorail (STM) system, a coupled dynamic model of the STM vehicle-bridge system has been developed based on multibody dynamics and finite element (FE) theory. In the model, both the spatial vehicle model with 21 degrees of freedom and the 3-dimensional FE model of the bridge structure for a particular STM system are established by using ANSYS parametric design language (APDL). The vehicle subsystem is coupled with the bridge subsystem through the contact relation between the vehicle tire and bridge inner surface. Then, a mixed explicit and implicit integration method is used to solve the coupled dynamic model. Finally, the dynamic responses of the vehicle-bridge system are calculated by adopting the established model, which are compared with the field test data. Results show that the simulation with the proposed dynamic model is in good agreement with the filed test data. Some apparent discrepancies can be distinguished when the bridge is treated as rigid body and flexible body, respectively, showing the importance of considering the flexible bridge and demonstrating several modelling advantages of the proposed coupled dynamic model. Overall, the train has good operation stability, and the lateral stability of car body is worse than its vertical stability because of the special vehicle structure. The first-order natural frequencies of the bridge in the vertical and lateral-torsional directions are about 5.60 Hz and 2.27 Hz, respectively. The bridge lateral acceleration is significantly larger than the vertical accelerations at the bridge middle-span section due to the low lateral stiffness of the bridge. These conclusions could provide a useful guidance for design of the STM system.


## 1. Introduction

With the recent fast development of urban traffic, many types of the urban rail transit systems have been employed to solve the serious problem of traffic jam [1-4]. The suspension-type monorail (STM) transport system is an active technological solution, which has the advantages of stronger climbing ability, lower turning radius, lower running noise, lower cost and shorter construction period compared with subway and light railway [5,6]. It not only can be used as a supplement of the large-scale urban rail transit system, but also can be used as a main transportation power for small and medium-sized cities. The earliest representative countries in the world that studied the STM system and put it into operation are Germany and Japan, and they have accumulated systematic technology and experience through its continuous development and improvement. In recent year, China successfully completed the first test line for the STM system with the new energy of high

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capacity lithium battery under independent research and innovation. Due to its natural mechanism, the STM system could also be considered as one of coupled vehicle-bridge systems, which has special vehicle structure, bridge structure and steering system employing rubber tires. To ensure the health and reliability of the STM transit system, it is necessary to systematically research the running safety and ride comfort of the vehicle, and the dynamic behavior of the bridge structure should also be evaluated.

Considering the general concept of railway vehicle-bridge interaction, a number of literatures can be found [7–20]. In contrast with the conventional railway bridge, a limited number of studies have been carried out for monorail system which utilizes a different interaction mechanism with the bridge structure. Boehm and Frisch [5] summarized the composition, the operation mode and the main feature of the sky train in German Dortmund in detail. Goda [21] studied a curving dynamics for a straddle-type monorail car based on multi-body dynamics method. Lee et al. [22] studied the vehicle-bridge interaction of the straddle type monorail system based on numerical simulation and the ride comfort of running vehicle is estimates using 1/3 octave band spectral analysis. Naeimi et al. [23] investigated the coupled vibration characteristics of the straddle type monorail vehicle-bridge by combining multibody dynamic (MBD) and finite element (FE) modelling, and further gives an overview about the dynamic forces and reactions that can appear in bridge structure due to the vehicle movement. It can be seen that the investigation objective of most existing studies focus on the straddle type monorail system. However, a limited number of literatures have been carried out for the dynamic behaviour of the STM system. Meisinger [24,25] developed a vehicle dynamic model with four degrees of freedom to research the lateral dynamic of STM train with periodic irregularities. Bao [26] investigated the coupled vehicle-bridge vibration of the STM system under different track irregularities based on a co-simulation method; the bridge model is condensed into a single super element to consider main low-order modes of the bridge, and it is input into the SIMPACK to realize the vehicle-bridge interaction analysis. However, high-frequency local vibrations of the STM bridge could be induced by local defects or irregularities. In order to obtain the accurate analysis results of the bridge local vibrations, high-order modes of the bridge should be considered in studying the vehicle-bridge interaction. Further, the strength check of the bridge is an essential work for the consideration of the bridge operational reliability, but it is difficult for the co-simulation method to obtain the local dynamic stress of the bridge structure. In addition, the current researches are also lack of validation by field tests. Actually, the STM bridge is the steel box-beam with an open bottom, whose fundamental natural frequencies in the vertical and lateral direction are in the low range. If the vibration frequencies of the bridge subsystem are close to the natural frequencies of the vehicle subsystem, the resonance or larger vibration of vehicle-bridge coupled system will be induced, thus reducing ride safety and comfort of the monorail vehicle. Moreover, the vehicle running part of the bridge is a steel plate structure, which will appear high-frequency vibration under the vehicle load. Therefore, it is significant for the STM system to develop a coupled vehicle-bridge dynamic model considering a full-mode FE model of the bridge.

This paper proposes a framework based on computer simulation to study the vehicle-bridge dynamic interaction for the STM system. First, both the spatial vehicle model with 21 degrees of freedom and the 3D FE model of the bridge structure for a particular STM system are established based on ANSYS parametric design language (ADPL). The vehicle and bridge subsystems are coupled through the contact relation between tire and bridge inner surface. Further, the fast explicit integration method is used to solve simultaneous differential equations of the multibody model of vehicle subsystem, and the finite model of bridge is solved using an implicit integration method. On this basis, dynamic responses of the coupled vehicle-bridge system are investigated and validated with the field test data. Finally, some useful conclusions are obtained, which provide an important insight for the design and safety assessment of vehicle-bridge interaction of the STM system.

## 2. Vehicle–bridge dynamic interaction model of STM system

Fig. 1 presents a STM transport line in China, and it was built in 2016. Due to its natural mechanism, the STM system is a type of coupled vehicle-bridge system, which is composed of the bridge subsystem and the moving vehicle subsystem using the lithium battery to provide the driving force.

### 2.1. Vehicle model of STM system

A STM vehicle has special structure, whose dynamic model is different from that of traditional railway vehicle. Figs. 2–4 show the dynamic model of the STM vehicle subsystem, which consists of two bolsters, two bogies, two central pins and a car body.

Each bogie consists of four driving tires and four guiding tires, which is placed inside the box-beam bridge. The driving tires act as the bogie primary suspension and carry the load of the whole vehicle. The guiding tires provide the lateral guide. The bolster is supported on the bogie with the secondary suspensions, and the central pin is connected to the bolster by using a rotating hinge. Further, an articulated four-linkage mechanism is used to connect the central pin and the car body, which releases the lateral constraint of the car body to a certain degree and reduces lateral impact of the body. In addition, a lateral shock absorber (c1) and two rubber blocks ($k_3$ and $k_4$) are installed inside the four-linkage mechanism, which can play an important role in decreasing the lateral vibration of the car body and limiting the lateral displacement of the car body, respectively.