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Measurement of Vehicle-Bridge-Interaction force using dynamic tire pressure monitoring

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ABSTRACT

The Vehicle-Bridge-Interaction (VBI) force, i.e., the normal contact force of a tire, is a key component in the VBI mechanism. The VBI force measurement can facilitate experimental studies of the VBI as well as input-output bridge structural identification. This paper introduces an innovative method for calculating the interaction force by using dynamic tire pressure monitoring. The core idea of the proposed method combines the ideal gas law and a basic force model to build a relationship between the tire pressure and the VBI force. Then, unknown model parameters are identified by the Extended Kalman Filter using calibration data. A signal filter based on the wavelet analysis is applied to preprocess the effect that the tire rotation has on the pressure data. Two laboratory tests were conducted to check the proposed method's validity. The effects of different road irregularities, loads and forward velocities were studied. Under the current experiment setting, the proposed method was robust to different road irregularities, and the increase in load and velocity benefited the performance of the proposed method. A high-speed test further supported the use of this method in rapid bridge tests. Limitations of the derived theories and experiment were also discussed.

1. Introduction

Bridges, as linkages in transportation infrastructures, play an indispensable role in modern society. Loads such as the wind, earthquake and temperature impose significant effects on the bridge health; however, this paper focuses on the vehicle load, which is one of the most common loads imposed by humans [1–4]. The Vehicle-Bridge-Interaction (VBI) has a long history of theoretical, numerical and experimental studies [5–8]. In recent years, researchers have made contributions to constantly improve the VBI models. For example, although the single-point Spring-Mass-Damper (SMD) model is widely applied because of its simplicity [9,10], Yin [11] and Chang [12] suggested that the classical single-point model might induce unreal contents into bridge responses under distressed bridge deck conditions. They proposed disk models to upgrade the traditional model. Deng [13] further proposed a multi-point tire model to enhance the accuracy and sustain convenience for practical application. The measurement of the VBI force can provide experimental validations to the improved VBI models and support further VBI mechanism studies. From another perspective, measuring the VBI force makes a moving vehicle a suitable excitation for an input-output structural identification. With mechanical modifications of the vehicle to increase its tire forces, this new test method can be more labor-saving than a hammer-impact test. Furthermore, the measurement

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of the VBI force, which is the normal contact force of a tire, is also valuable for road spectrum analyses and vehicle state control.

After recognizing the importance of the VBI force measurement, we should note that there are many developing methods with similar aims in vehicle engineering. They can be broadly categorized into measurements that use vehicle body responses and measurements that only use tire responses.

The first type must consider the mechanical motion of the entire vehicle. For example, Shim and Ghike [14] proposed a 14-Degree-Of-Freedom (DOF) model that considers the rotations and displacements at all three directions of the gravity center: four suspension displacements and four tire displacements. By carefully designing the observers of the Kalman filter, Doumiati et al. [15] proposed an estimation of the vertical tire force that uses low-cost sensors to measure the longitudinal and lateral accelerations, roll angles and suspension deflections of the vehicles. Jiang et al. [16] and Cordeiro et al. [17] extended Doumiati's method to different road geometry (banked roads and inclined roads) and uneven road profiles, respectively.

The second type, i.e., the force measurement that only uses tire responses, is a more direct solution because the tire is the necessary transfer path of the VBI force. A classical method is the Wheel Force Transducer, which uses a specialized hub and measures the multi-axis tire forces and moments based on the hub's deformations [18]. However, this commercialized method is often described as too expensive for broad engineering applications [15,19]. Cheli et al. [19] proposed a new and convenient force measurement method using installed strain sensors on the tire rim. Because of the sensors' eccentric installation positions, this method assumes the same value for the tire force during one rotational turn of the tire. This treatment casts doubts on the accuracy when the tire rolls on uneven roads. Accelerometers [20] or optical sensors [21] were embedded in the air cavity to measure the tire force. These methods were convenient but also faced the disadvantage of Cheli's method.

Wang et al. [22] validated that the tire pressure could estimate the vertical ground acceleration when the vehicle was stationary (and the ground was vibrated by a hammer impact). Because of the continuity of the air cavity, the tire pressure can reflect the real-time force changes during a tire rotation. Inspired by this idea, this paper further attempts to build a relationship between the tire pressure and the normal contact force (VBI force) using the ideal gas law and a basic 1-DOF spring-damper model. Then, unknown model parameters are identified by the Extended Kalman Filter (EKF) based on the calibration data. Finally, the proposed model can estimate the VBI force when only the tire pressure data are dynamically monitored. The estimated force is the normal contact force, whereas the estimated forces in [14–19] are suspension forces or tire inertial forces (to which the static load was added). Strictly speaking, there are differences among a contact force, a suspension force and an inertial force, but the numerical difference remains to be validated. From an installation perspective, the core hardware of the proposed method is a pressure sensor mounted onto the valve stem, so the installation can be convenient.

The structure of this paper is as follows: The second section introduces the theories for the model design, the parameter estimation and a necessary preprocessing of the tire pressure data. The third section introduces a laboratory experiment to verify the proposed theory; it displays the experimental result and discusses the potential of the proposed method in real conditions. The fourth section introduces a high-speed experiment that studied the effect of temperature in rapid bridge tests.

2. Theory

2.1. Framework

The design concept of the VBI force (normal contact force) measurement using the dynamic tire pressure monitoring is shown in Fig. 1. Its theoretical foundation includes three parts, as shown in Fig. 2. The first part, which is the core of the proposed method, is a thermodynamics-based VBI force model that connects the tire pressure and VBI force. The second part uses the EKF to estimate the model parameters based on the calibration data. The third part is a preprocessor that normalizes the non-uniformly distributed tire pressure due to the tire rotation. After the parameter calibration, the proposed model can estimate the VBI force when only the tire pressure is dynamically monitored.

2.2. Thermodynamics-based Vehicle-Bridge-Interaction force model

2.2.1. Vehicle-Bridge-Interaction force model

We assume that the vertical tire motion can be considered a single-DOF spring-mass-damper system in Fig. 3. Since the tire motion is affected by both bridge vibration and suspension vibration, two spring-damper subsystems are used. In this paper, we are interested in the normal contact force (VBI force). Thus, the VBI force change ΔF can be calculated as follows:

$$k\Delta z + c\dot{\Delta z} = \Delta F \tag{1}$$

where k is the vertical rolling stiffness, c is the vertical rolling damping, Δz is the vertical displacement of a rolling tire compared with the state of the static tire and $\dot{\Delta z}$ is its first-order time derivative.