Tire Force Estimation through Measurement of Vehicle Body Acceleration and Angular Velocity

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1. INTRODUCTION

Bridge modal parameters are important factors that determine the bridge responses. From structural health monitoring point of view, these parameters need to be known for many purposes, including damage detection (Zhu et al, 2018) and load estimation (Wang et al, 2017). For the identification of some bridge parameters, e.g., modal mass, it is usually necessary to conduct simultaneous measurement on the excitation on the bridge and its corresponding bridge responses. However, traditional methods of the exciting the bridge by a hammer or shaker have many drawbacks including limitation on impact energy, narrow frequency range, as well as other site-specific difficulties. In this paper, an algorithm is proposed to estimate the vehicle normal tire forces from the measurement of vehicle body acceleration and angular velocity of a commercial vehicle using Kalman filter.

2. VEHICLE MODEL

A half-car vehicle model is employed, which represents an ordinary two-axle vehicle. This model has 4 degrees of freedom, including vehicle body vertical movement, two axle movements and vehicle body rotation, as shown in Fig. 1. The equation of motion of the half-car model is shown in Eq. (1).

$$\mathbf{M}\ddot{\mathbf{U}}(t)+\mathbf{C}\dot{\mathbf{U}}(t)+\mathbf{K}\mathbf{U}(t)=\mathbf{P}(t) \tag{1}$$

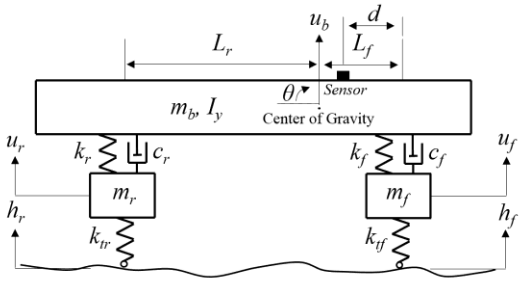

Fig. 1. Half-car model

3. KALMAN FILTER

Kalman filter is usually known as one of the most common real-time data processing methods for measurement (Doumiati et al, 2010). In Kalman filter, the evolution of the state is determined by a system transition matrix, as expressed in Eq. (2).

$$\mathbf{X}_{k+1}=\mathbf{A}_d\mathbf{X}_k+\mathbf{w}_k \tag{2}$$

where $\mathbf{X}_k$ is the system state vector at time step k, $\mathbf{A}_d$ is the system transition matrix which links the system state between time step k and k+1, and $\mathbf{w}_k$ is the system error term following a zero-mean Gaussian distribution.

At each time step, the observation vector is formed by measurement values, which is related with the state vector through the observation equation as Eq. (3).

$$\mathbf{Y}_k=\mathbf{C}_d\mathbf{X}_k+\mathbf{v}_k \tag{3}$$

where $\mathbf{C}_d$ is the observation matrix dependent on the measurement, and $\mathbf{v}_k$ is the observation error following a zeros-mean Gaussian distribution independent with $\mathbf{w}_k$.

With the state matrix and the observation matrix, the state vector is recursively estimated at each time step through a process of prediction and update of the system state. The state vector in this analysis is shown in Eq. (4) and the system matrix $\mathbf{A}_d$ and observation matrix $\mathbf{C}_d$ are determined based on the half-car model and the measurement.

$$\mathbf{X}=\begin{bmatrix} u_b & \theta_b & u_f & u_r & \dot{u}_b & \dot{\theta}_b & \dot{u}_f & \dot{u}_r & F_f & F_r \end{bmatrix}^{\mathrm{T}} \tag{4}$$

where F_f and F_r are the front and rear tire forces, respectively.

4. EXPERIMENTAL VALIDATION

An experiment was conducted to verify the proposed algorithm. A Honda Step-wagon van was equipped with a wheel-load transducer at the front left tire, which can record the contact force between the tire and the ground. Four iPod touch sensors equipped with accelerometers and gyros were attached on the vehicle body just above each vehicle tire to measure vertical acceleration and angular velocity. The iPod data was synchronized with the wheel-load transducer through an accelerometer, which is attached next to the iPod sensor, sharing the same time system with the wheel-load transducer. The sampling frequency of all these devices was set as 100 Hz. In addition, a GPS sensor was attached to the iPod sensor to determine the vehicle driving speed at every second.

(a) equipped test vehicle

(b) wheel-load transducer

Fig. 2. Experimental setup

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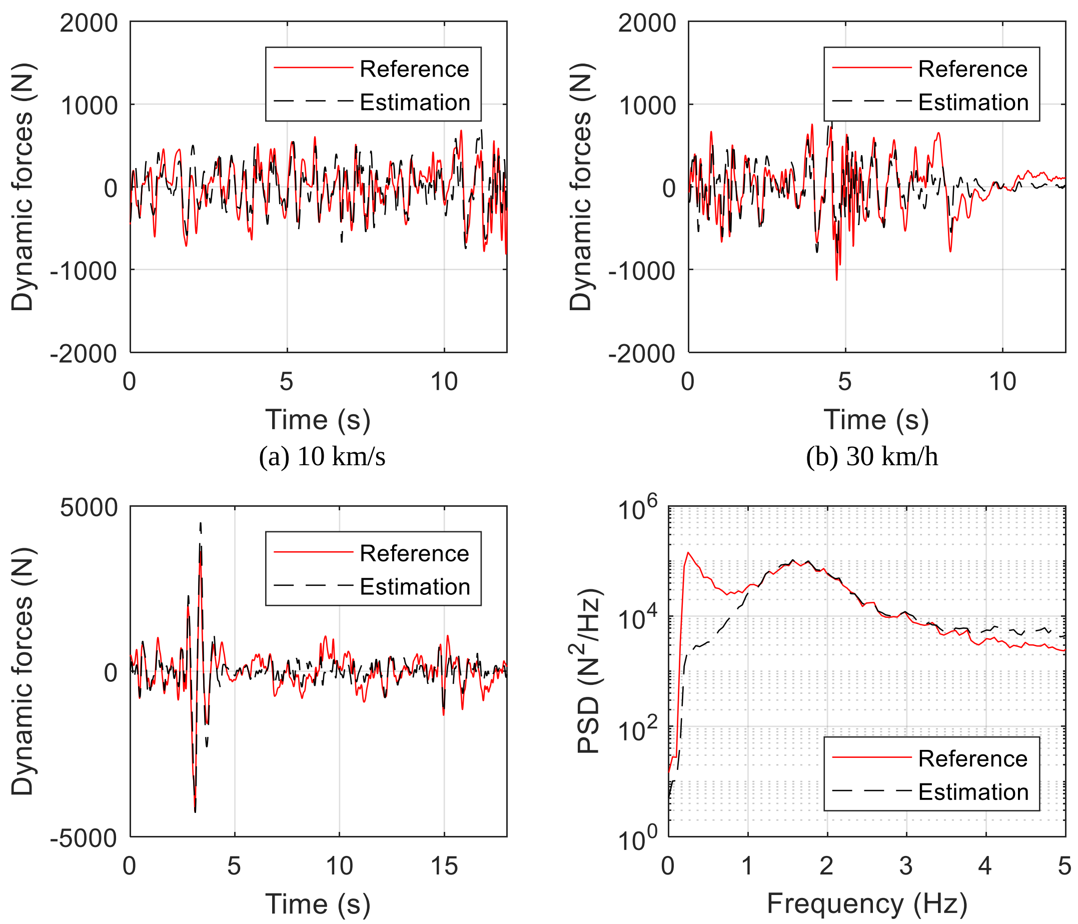
As stated before, the vehicle parameters are necessary for the tire force estimation. A calibration test, in which a known-size hump was used as the input when the test vehicle drove over the hump, was conducted to obtain the half-car model parameters of the test vehicle (Zhao, 2017).

The tire forces were estimated from the measured data and are shown in Fig. 3(a) – (d), in which (a) and (b) show the results for lower (around 10 km/h) and higher (around 30 km/h) driving speed. The tire force estimation when the vehicle passed over a rubber speed hump on the road is shown in Fig. 3(c). The power spectral density (PSD) of the entire time history is in Fig. (d). The measurement last for 16 minutes but the results are extracted in short windows for clear observation. These figures indicate that the proposed algorithm is robust against driving speed and has good performance even when the tire force suddenly changes.



(a) 10 km/s (b) 30 km/h

(c) At hump (d) PSD of entire time history

Fig. 3. Experimental results

5. CONCLUSIONS

A method based on a half-car model to estimate the vehicle tire forces using augmented Kalman filter is proposed. A field measurement was conducted to validate the proposed method through the comparison between the estimation and the wheel-load transducer system. Good results were obtained for different driving speeds and road conditions. The estimated tire forces can be used as the known input for the purpose of bridge monitoring when the smartphone-equipped vehicle passes over the bridge.

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