Measurement of Tire Contact Loads and Cornering Stiffness during Turning Maneuvers with a Novel Intelligent Tire

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In recent years, significant efforts have been made to develop technologies for measuring tire contact loads and other parameters while a vehicle is in motion, with the aim of improving automotive safety. By measuring factors such as road surface slip resistance and braking performance, it is possible to improve the performance of Advanced Driver Assistance Systems (ADAS) and conduct detailed analyses of steering and brake control systems during vehicle development. In this study, we propose a method that uses an intelligent tire to measure the triaxial loads acting on the tire-road interface during cornering and to estimate cornering stiffness (C_S).

The proposed intelligent tire measures strain on the wheel surface, using the wheel itself as a sensing element. In this study, strain gauges were attached near the wheel rim edge close to the brake disc to minimize the effects of large wheel deformations during cornering by measuring at a high-stiffness location. As shown in the following equation, the strain $\varepsilon(\alpha, \varphi)$ at a tire rotation angle α and measurement direction φ is expressed as a linear sum of the longitudinal load F_X, lateral load F_Y, and vertical load F_Z. The experimental constants k, l, m and b are determined in advance through calibration experiments using a driving simulation device.

$$\varepsilon(\varphi,\alpha) = k(\varphi,\alpha)\cdot F_X + l(\varphi,\alpha)\cdot F_Y + m(\varphi,\alpha)\cdot F_Z + b(\varphi,\alpha) \qquad (1)$$

Experiments were conducted using a traction bus to evaluate the proposed method on dry and wet road surfaces at a vehicle speed of approximately 20 km/h. The results, as shown in Fig.2, revealed a "crosstalk effect" during cornering, where F_Y caused the measured values of F_X and F_Z to deviate from their true values.

To address this issue, we propose the following the correction formula based on the assumption that the measurement errors of F_X and F_Z are proportional to F_Y. As shown in Fig.3, for studless tires, which are particularly susceptible to crosstalk, this correction significantly improved the root mean square error of F_X on dry pavement from 855 N to 426 N.

$$\begin{bmatrix} F_{XS} \\ F_{YS} \\ F_{ZS} \end{bmatrix} = \begin{bmatrix} 1 & A_{12} & 0 \\ 0 & 1 & 0 \\ 0 & A_{13} & 1 \end{bmatrix} \begin{bmatrix} F_{XK} \\ F_{YK} \\ F_{ZK} \end{bmatrix} + \begin{bmatrix} B_{XK} \\ 0 \\ B_{ZK} \end{bmatrix} \qquad (2)$$

Using the load measurement data, we calculated the cornering stiffness C_S as the slope of F_Y with respect to the slip angle β (within the range $0.5 \le |\beta| \le 1.5$) using the linear least-squares method. The slopes of the solid lines in Fig. 4 represent the cornering stiffness. As shown in Fig. 4, the measured values agree well with the true values. Furthermore, cornering stiffness C_S values for normal tires were generally higher than those for studless tires.

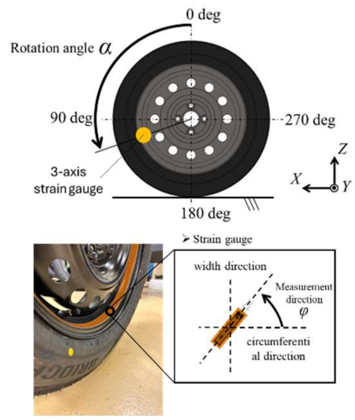


Fig. 1. Strain measurement point and direction

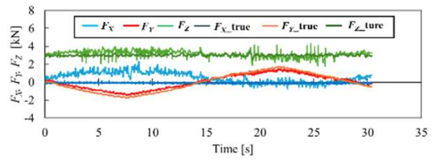


Fig. 2. Measurement results before correction

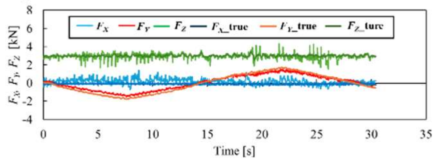
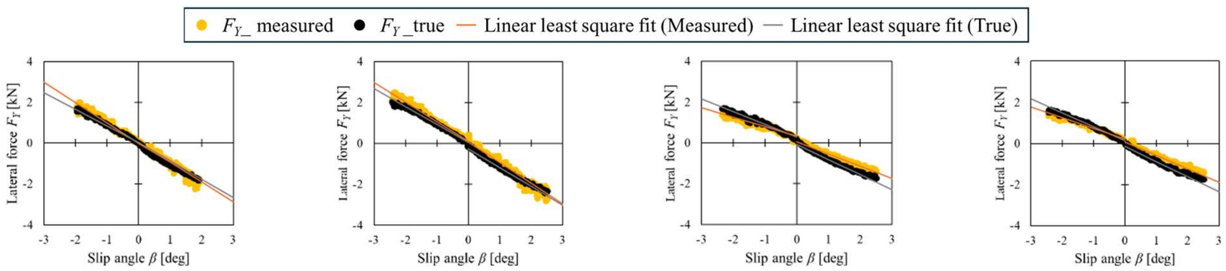


Fig. 3. Measurement results after correction



(a) Normal tire [dry surface] (b) Normal tire [wet surface] (c) Studless tire [dry surface] (d) Studless tire [wet surface]

Fig. 4 Relationship between F_Y with β at F_Z = about 3.0 kN