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A Highly Robust Tire Contact Load Measurement Method Utilizing Wheel Deformation

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Accurate measurement of tire–road contact loads is essential for advanced vehicle dynamics control. A prior approach using wheel strain to measure longitudinal load F_X, lateral load F_Y and vertical load F_Z required precise measurement of the tire's absolute rotation angle. However, accurately measuring the rotation angle during vehicle operation is challenging, and its errors directly degrade load estimation accuracy. To overcome this limitation, this study proposes a new measurement method that eliminates the need for absolute tire rotation angle, thereby achieving higher robustness against measurement noise.

As shown in Fig.1, strain gauges are attached at the wheel rim, using three-axis gauges capable of measuring strain in any direction. The relationship between the wheel strain $\varepsilon(\alpha,\varphi)$ at rotation angle α and measurement direction φ and the three-axis contact loads is expressed as a linear model as shown in Equation(1). $k(\alpha,\varphi)$, $l(\alpha,\varphi)$, $m(\alpha,\varphi)$ and $b(\alpha,\varphi)$ are experimental constants that are determined in advance through calibration experiments.

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

The key innovation is the use of strain summation over one complete tire revolution, rather than instantaneous strain values at known rotation angles. Assuming that contact loads remain approximately constant over one revolution, the sum of absolute strain values over one rotation is shown to be proportional predominantly to the vertical load F_Z as shown in Equation(2). This allows F_Z to be estimated without angular position information.

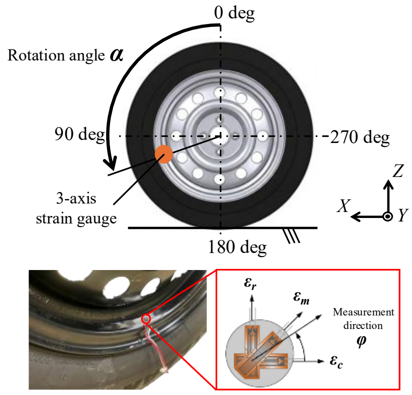


Fig.1 Definition of tire rotation angle and measurement direction

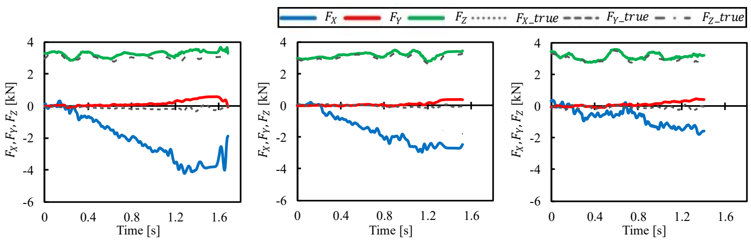
$$\sum_{\alpha=0}^{2\pi}\left|\varepsilon(\alpha,\varphi)\right|\approx\sum_{\alpha=0}^{2\pi}\left|m(\alpha,\varphi)\right|\cdot F_Z \tag{2}$$

Subsequently, the summed strain values under two measurement direction conditions are used to solve F_X and F_Y through simultaneous equations shown in Equation(3). The measurement directions for F_Z and for F_X and F_Y were determined experimentally to minimize measurement errors. This approach effectively decouples the load estimation from precise rotational angle measurement.

$$\sum_{\alpha=0}^{2\pi}\varepsilon(\alpha,\varphi)=\sum_{\alpha=0}^{2\pi}k(\alpha,\varphi)\cdot F_X+\sum_{\alpha=0}^{2\pi}l(\alpha,\varphi)\cdot F_Y+\sum_{\alpha=0}^{2\pi}m(\alpha,\varphi)\cdot F_Z+\sum_{\alpha=0}^{2\pi}b(\alpha,\varphi) \tag{3}$$

The method was validated on a traction test vehicle equipped with a six-axis force transducer as reference measurement. Braking tests were performed on road surfaces representing dry, wet, and basalt (low-μ) conditions, with slip ratio varied from 0 to 100%. In the low-slip range which representative of normal driving on real roads, all three load components tracked the reference values accurately as shown in Fig.2.

The proposed method successfully estimates three-axis tire contact loads without measuring absolute tire rotation angle, demonstrating high accuracy across multiple road surfaces and strong potential for practical on-vehicle deployment.



(a) Dry (b) Wet (c) Basalt (low-μ)

Fig.2 Measurement results on multiple road surfaces

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