Estimation of Maximum Tire-Road Friction Coefficient Using Electric Power Assist Steering

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1. Introduction

In general, on a snow-covered or otherwise slippery road, an abrupt steering change will cause unstable vehicle behavior, or excessive speed will make the vehicle deviate from the intended path. The vehicle stability control (VSC) system detects such conditions and stabilizes the vehicle. Although the use of VSC has begun to increase, it is not yet widely seen in inexpensive cars, partly because of its high cost. This paper proposes a low-cost method for estimating the tire-road friction coefficient using only standard signals from the sensors installed in the electric power assist steering (EPAS) system.

2. Method for Estimating Tire-Road Friction Coefficient

When making a turn, the reaction given to the steering wheel varies depending on the vehicle speed, steering wheel angle and road surface conditions. The tire-road friction coefficient can be estimated from this feedback reaction, simply by detecting a road surface-derived component using the EPAS system. The principle of this detection method is described below with the relevant background.

2.1 Fiala Tire Model

The Fiala tire model is well known for explaining the side force exerted on the tire\(^{(1)}\). The direction of the tire's rolling motion seemingly coincides with the actual direction of travel. However, there is a slight difference when the vehicle is going around a curve or during similar situations. The Fiala tire model demonstrates how the angle between the two directions generates a side force on the tire. This angle is called the “tire sideslip angle”, and the dimensionless quantity converted from this sideslip angle with correction for the influence from the load, the tire’s own gripping property, and other factors is called the dimensionless sideslip angle, \(\psi\).

According to the Fiala tire model, if the dimensionless sideslip angle \(\psi\) is increased by turning the steering wheel, as shown in Fig. 1, the tire side force \(F\) gradually increases up to the limit of the friction, whereas the tire self-aligning torque \(M\), which makes the tire turn about the tire center axis, saturates at a certain angle and then decreases.

2.2 Influence of Steering Wheel

It should be noted that the torque \(M\) of the Fiala model does not correspond to the reaction given to the steering wheel. In the actual steering system, as shown in Fig. 2, the kingpin axis is inclined from the tire’s center axis, and thus the self-aligning torque about the kingpin, \(M_z\), which corresponds to the reaction given to the steering wheel, differs from the torque \(M\), where the “kingpin axis” refers to the axis around which the tire is turned by the steering wheel.

Mitsubishi Electric has conducted extensive research on the torque about the kingpin axis.

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\[^{(1)}\] Mitsubishi Electric ADVANCE December 2010 13
(self-aligning torque) that indicates the reaction given to the steering wheel, and found that this torque also has a local maximum value similar to the tire self-aligning torque \( M \), and the local maximum value is proportional to the tire-road friction coefficient (Fig. 3).

By detecting this local maximum value and using the proportionality relationship, the tire-road friction coefficient can be estimated.

2.3 Estimation of Self-Aligning Torque

The self-aligning torque is obtained by considering the balance between the forces acting on the steering system. That is, the self-aligning torque is estimated based on the sum of the steering torque given by the driver and the torque assisted by the EPAS. In this estimation, signal processing is performed to remove noises\(^2\).

2.4 Detection of Local Maximum Value of Self-Aligning Torque

Under normal conditions, the local maximum value of the self-aligning torque should be detected by the maximum condition on the dimensionless sideslip angle \( \psi \). Instead, the maximum condition on the steering wheel angle \( \theta \) is used for the detection, because this reduces the number of sensors. It should be noted, however, that a slight correction is added to avoid any erroneous detection of the local maximum value due to external disturbances on the road\(^3\).

2.5 Self-Aligning Torque Conversion Coefficient

The proportionality relationship between the local maximum value of the self-aligning torque about the kingpin, \( M_{z\text{max}} \), and the tire-road friction coefficient \( \mu \) is expressed by:

\[
M_{z\text{max}} = \frac{1}{512\pi^3} (d + 6\xi_c)(2\xi_c + 1344\xi_c^2 - 1560\xi_c^3 + 72\xi_c^4)\mu w \mu
\]  

where \( d \) is the tire contact length, \( \xi_c \) is the caster trail, and \( \mu \) is the tire vertical load.

This relationship was verified using an actual car: the verification result (Fig. 4) shows that the proportionality relationship holds true. However, the linear regression line does not pass through the origin, indicating that the actual proportionality relationship differs from Eq. (1) with a non-zero constant term, which is due to the influence of a friction component in the steering system. The value of the x-intercept corresponds to the amount of friction torque.

By reverse calculation using this relationship, the tire-road friction coefficient \( \mu \) is obtained from the local maximum value of the self-aligning torque about the kingpin \( M_{z\text{max}} \).

2.6 Verification of Estimation Accuracy

The accuracy was verified for the proposed estimation method of the tire-road friction coefficient.

2.6.1 Estimation Accuracy under Nominal Conditions

The estimation accuracy of the tire-road friction coefficient under nominal conditions was verified under the same driving conditions used to set up the parameters described in Section 2.5 (Fig. 5). The horizontal axis represents the measured value of the tire-road friction coefficient, which was obtained from the maximum value of the lateral-acceleration sensor reading; the vertical axis represents the estimated value using the proposed method; and each point corresponds to each verification cycle. As clearly seen from the chart, the estimation error was within \( \pm 0.1 \).

2.6.2 Estimation Accuracy under Varying Vehicle Weight and Tire Conditions

The estimation accuracy was also verified under conditions different from those used to set up the parameters shown in Section 2.5 (Fig. 6). In this estimation method, the model parameters, i.e., tire contact length and tire vertical load, are set as constants, and thus when these parameters vary, there is a concern about deterioration in estimation accuracy. In this verification, as shown in Table 1, the actually changed

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\( \psi \): undimensionalized side slip angle

Fig. 3 Local maximum point of self-aligning torque

Fig. 4 Correlation between tire-road friction coefficient and self-aligning torque
variables were the tire pressure and load conditions, which could alter the model parameters. Under Condition A, the estimated value of the tire-road friction coefficient becomes smaller than the measurement; whereas under Condition B, the estimated value becomes greater than the measurement. It was confirmed that even though the estimation error increases in these cases, the increase remains within about $\pm 0.2$.

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Load</th>
<th>Tire pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal conditions</td>
<td>Driver only</td>
<td>220 [kPa]</td>
</tr>
<tr>
<td>Condition A</td>
<td>Driver only</td>
<td>300 [kPa]</td>
</tr>
<tr>
<td>Condition B</td>
<td>300 [kg]</td>
<td>150 [kPa]</td>
</tr>
</tbody>
</table>

3. Conclusion

We have proposed a method for estimating the tire-road friction coefficient, which uses the proportionality relationship between the tire-road friction coefficient and the maximum value of the self-aligning torque about the kingpin.

The proposed method enables the detection of the maximum value of the self-aligning torque using only the electric power assist steering system, without any additional sensors such as acceleration, yaw rate and steering wheel angle sensors. Also, the computational load is low, resulting in low implementation cost.

References

(1) E. Fiala: "Seitenkrafte am Rollenden Luftreifen", DI Zeitschrift, 96, 1954