Monitoring Method of Indirect TPMS Under Steering Situation

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ABSTRACT: Conventional indirect tire pressure monitoring system (TPMS) is mainly designed according to the wheel speed signal of anti-lock brake system (ABS). Four wheels’ velocity change because yaw rate exists when vehicles are under steering conditions. The original tire pressure monitoring method failed which is based on the wheel speed comparison method. As the electronic stability program (ESP) is applied in vehicle, inertial measurement unit that can obtain vehicle’s yaw rate are widely used. In this passage, four-wheel trajectory model is established. Every wheel’s side-slip angle and steering radius can be deduced by using this model when the steering wheel in sinusoidal input and step input. Four wheels’ velocity can be quantified through turning radius, steering angle and yaw rate. On the basis of the original wheel speed comparison method, the indirect TPMS under steering situation can be achieved.

1 INTRODUCTION

Indirect tire pressure monitoring system (TPMS) is based on Anti-lock braking system’s (ABS) wheel speed sensor (Thiriez 2006). Compared with the direct TPMS, It has simple structure, low cost, easy to install and many other advantages. But currently the principle of indirect TPMS installed on the vehicle is based on the following assumptions: four-wheel rolling distance is the same (Gao et al. 2008). Therefore, Indirect TPMS can monitor the tire pressure only when the car is driving straight (or approximately linear-driving). When the vehicle dives on the curve, TPMS lose the monitoring function (Han et al. 2010). Vehicle often meets with consecutive turns driving task in the process of actual driving, such as urban roads and mountain road. Even if vehicle drives in the highway, there are hundreds of meters, or even thousands of meters of arc curve. If TPMS can't play a role in tire pressure monitoring, there is a hidden safe trouble. Therefore, study on the indirect TPMS method under steering condition can perfect the indirect TPMS’s function, which also has important practical value.

In recent years, many scholars did research on indirect TPMS. Specially, Kan Yijie from Yanshan University raises a new algorithm based on extreme value statistics (Kan 2015). Gao Mingqiu, from China automotive technology research center, did a variety of researches on TPMS’s tire pressure monitoring standards and test methods, he also designed the special test device (Gao et al. 2008). Niclas Persson from Department of Electrical Engineering, Linkoping University put forward an indirect TPMS using sensor fusion, he introduced the yaw rate to fix wheel rolling radius (Persson et al. 2002). Professor Zhong Shaohua from Wuhan University of technology use tire’s resonance frequency to monitor tire pressure, and the resonance frequency estimated by analyzing the wheel speed’s frequency spectrum (Luo et al. 2014).

In this passage, we firstly utilize two degrees of freedom vehicle model to calculate the vehicle’s yaw rate and centroid side-slip angle when the steering wheel in step input and sinusoidal input (Chen et al. 2013). Then calculate each wheel’s side-slip angle and steering radius according to the vehicle geometry parameters (Li et al. 2014). So we can establish four-wheel trajectory model based on vehicle’s yaw rate and each wheel’s steering radius. Finally, use four-
wheel trajectory model put forward the revise method for indirect TPMS under steering situation.

2 WHEEL SPEED COMPARISON METHOD FOR INDIRECT TPMS

Average comparison method is to collect sampling values of four wheels comparing with their average values. Their relative errors reflect the degree of the tire pressure deviation from normal, which was used to determine whether a tire pressure is normal.

\[ u = \frac{1}{4} \sum_{i=1}^{4} u_i \]  
\[ \Delta u_i = \left| \frac{u_i - u}{u} \right| \times 100\% \]  

Where \( u_i \) = the i-th wheel’s speed; \( u \) = the average number of four wheels’ speed; \( \Delta u_i \) = the i-th wheel’s relative deviation of the speed and the average.

It can be determined that the tire pressure may be abnormal when \( \Delta u_i \) exceed the setting threshold value.

3 FOUR-WHEEL TRAJECTORY MODEL

In this passage, two degrees of freedom vehicle model is used to calculate the vehicle’s yaw rate and centroid side-slip angle. The model is described as follows:

\[ mu \frac{d\beta}{dt} + 2(C_{af} + C_{ar})\beta + \left[ mu + \frac{2}{u} (aC_{af} - bC_{ar}) \right] \omega = 2C_{af} \delta \]  
\[ 2(aC_{af} - bC_{ar})\beta + I \frac{d\omega}{dt} + \frac{2(a^2C_{af} + b^2C_{ar})}{u} \omega = 2aC_{af} \delta \]  

Where \( m \) = vehicle mass; \( u \) = vehicle speed; \( C_{af} \) = cornering stiffness of front axle; \( C_{ar} \) = cornering stiffness of rare axle; \( \beta \) = centroid side-slip angle; \( \omega \) = vehicle’s yaw rate; \( a \) = the distance from cornering to front axle; \( b \) = the distance from cornering to rare axle; \( I \) = rotational inertia of centroid; \( \delta \) = the steering wheel Angle.

Four-wheel vehicle equivalent model of planar movement is shown in Figure 2.

According to the model and dynamic relationship, front and rare axle’s side-slip angle can be calculated by equation (5) and equation (6). Each wheel’s side-slip angle can be calculated by equation (7) to equation (10).

\[ \beta_f = \beta + \frac{aa_0}{u} - \delta \]  
\[ \beta_r = \beta - \frac{ba_0}{u} \]  
\[ \beta_1 = \arctan\left( \frac{u \sin \beta + aa_0}{u \cos \beta - d_0 \omega / 2} \right) - \delta \]  
\[ \beta_2 = \arctan\left( \frac{u \sin \beta + aa_0}{u \cos \beta + d_0 \omega / 2} \right) - \delta \]  
\[ \beta_3 = \arctan\left( \frac{u \sin \beta - ba_0}{u \cos \beta - d_0 \omega / 2} \right) \]  
\[ \beta_4 = \arctan\left( \frac{u \sin \beta - ba_0}{u \cos \beta + d_0 \omega / 2} \right) \]
Each wheel’s steering radius $R_1$-$R_4$ has strict geometric relationship with centroid steering radius $R$, they can be described as follows:

\[
R_i = \frac{2R \cos(\delta - \beta_i - \beta) + \sqrt{4a^2 + d^2 - 4R^2 \sin^2(\delta - \beta_i - \beta)}}{2}
\]

\[
R_2 = \frac{2R \cos(\beta + \beta_i) + \sqrt{4b^2 + d^2 - 4R^2 \sin^2(\beta + \beta_i)}}{2}
\]

Finally, each wheel’s velocity component in the direction of the rotation plane is shown in equation (13). This equation is called four-wheel trajectory model.

\[
\begin{align*}
    v_1 &= \omega R_1 \cdot \cos \beta \\
    v_2 &= \omega R_2 \cdot \cos \beta \\
    v_3 &= \omega R_3 \cdot \cos \beta \\
    v_4 &= \omega R_4 \cdot \cos \beta
\end{align*}
\]

**4 ANALYSIS OF SIMULATION RESULT**

Both step input and sinusoidal input carry information about that veer influent the wheel speed. In the simulation process, it was assumed that the following conditions:

1. Vehicle speed is constant, the value is 10 m/s;
2. Tire cornering stiffness is constant, lateral force and side-slip angle are in linear relationship.

When the steering wheel angle input is a step input, the final value of step input is about 1 rad (about 60 degree). The simulation is used to simulate small turning-radius and stable situation. Simulation result is show in Figure 3.

The simulation results confirm that when the steering wheel input is in sinusoidal input, each wheel’s speed regularly changes. As can be seen from the figure, if the vehicle turns left, wheel 1 and wheel 3 speed are greater than 10 m/s, however wheel 2 and wheel 4 are less than 10 m/s. If the vehicle turns right, the result is opposite. So the algorithm also can be applied to estimate wheel speed under the continuous steering input.

**5 FOUR-WHEEL TRAJECTORY MODEL APPLIED TO THE INDIRECT TPMS**

Four-wheel trajectory model can estimate every each wheel’s speed when the vehicle’s yaw rate and steering wheel angle change. If the vehicle under the situation of certain steering wheel angle and yaw rate, four-wheel trajectory model estimates the wheel speed respectively $v_1$, $v_2$, $v_3$ and $v_4$. The wheel speed sensor acquisition signals are $u_1$, $u_2$, $u_3$ and $u_4$. Firstly, use average wheel speed comparison method dispose $v_1$, $v_2$, $v_3$ and $v_4$. It will obtain four relative deviation $\Delta v_1$, $\Delta v_2$, $\Delta v_3$ and $\Delta v_4$. Secondly, use average wheel speed comparison method dispose $u_1$, $u_2$, $u_3$ and $u_4$. It will also obtain four relative deviation $\Delta u_1$, $\Delta u_2$, $\Delta u_3$ and $\Delta u_4$. Finally, if the relative deviations satisfy the following relationship:

\[
\left| \frac{v_i - u_i}{v_i} \right| \times 100\% \leq \tau
\]

\[
\left| \frac{\Delta v_i - \Delta u_i}{\Delta v_i} \right| \times 100\% \leq \varepsilon
\]
It can be determined that the tire pressure is normal. Otherwise, the tire pressure maybe abnormal. \( \tau \) and \( \varepsilon \) can be determined according to the experimental data and monitoring precision.

Through the road test, the value of \( \tau \) and \( \varepsilon \) in different monitoring precision are shown in Table 1. Monitoring precision indicates the lack of tire pressure. For example, 20\% means when the tire lose 20\% inflating volume, TPMS raise the alarm. The smaller the value, the higher the precision

Table 1. Road test result.

<table>
<thead>
<tr>
<th>Monitoring precision</th>
<th>Variable ( \tau )</th>
<th>Variable ( \varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>30%</td>
<td>4%</td>
<td>5%</td>
</tr>
<tr>
<td>40%</td>
<td>7%</td>
<td>10%</td>
</tr>
</tbody>
</table>

As for \( \tau \) and \( \varepsilon \), the value is larger when the tire pressure is lower. The difference between theoretical value \( v \) and the actual value \( u \) is also larger because the rolling radius changes a lot.

6 CONCLUSION

After theoretical verification, each wheel’s speed changes a lot in the process of steering. Misjudgment happens under steering condition where the original tire pressure monitoring system doesn’t work.

Four-wheel trajectory model make full use of the vehicle inertial unit and steering wheel angle sensor to monitor tire pressure when the vehicle under steering condition. It can successfully estimate every wheel’s theoretical velocity when the vehicle’s yaw rate and steering wheel angle change. Theoretical wheel velocity has important effect on revise method for indirect TPMS.

The revise method based on the average wheel speed comparison method can successfully accomplish tire pressure monitoring task under steering condition. Through the road test, it can successfully produce the alarm signal when a certain wheel is under-inflated. In the future research, our team will do a lot of road experiment to establish the complete TPMS under steering condition. This paper has important meaning to the later research.

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REFERENCES


