

A Study on TPMS Pre-warning Threshold Algorithm Based on Multi-sensor Data Fusion

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Abstract

In order to improve the precision of the tire pressure monitoring system, the Bayes method is applied to establish its mathematical model of multi-sensor information fusion. The temperature and pressure in the tire, which are the complementary information, are integrated in the model through analyzing the mechanism of tire burst generated by temperature and pressure. Through the temperature compensation of tire burst pressure threshold value, the false alarm and false negative are avoided to the hilt. The experimental results show that compared with the traditional TPMS, the accuracy of the measuring results of this model is improved and thus the system's monitoring ability is improved so that the traffic safety is guaranteed.

Keywords: temperature, pressure, multi-sensor data fusion, false alarm, false negative, TPMS

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1. Introduction

Tire is an important safety component of automobile. If the tire is operated under heavy load, for a long time or under high pressure, it may blow out or leak and even it may cause traffic accidents, casualties and property losses [1]. The tire pressure monitoring system can monitor the tire pressure and temperature in real time and give an alarm when the tire is over-pressured or under-pressured and the temperature is too high so as to avoid tire burst [2]. At present, the tire pressure monitoring system applies the single sensor to collect the tire pressure and temperature from the same direction, leading to low precision of measuring result, misinformation and false negative. Based on the above problems, the TPMS pre-warning threshold algorithm based on multi-sensor data fusion is put forward in this paper.

2. Tire Burst Mechanism

2.1. Influence of Inflation Pressure on Tire Burst

When the tire pressure is lower than the standard value during the driving process at high speed, the bending deformation of the tire sidewall may be increased, the tire temperature may rise sharply and it may delaminate and the tire strength and loading capacity may be impaired, resulting in loosing and rupture of cord thread on the inner wall of tire and air leakage or tire burst. When the tire pressure is higher than the standard value, the contact area between tire and road surface decreases and the pressure borne by the central area of the tire tread increases so that the abrasion becomes severe and bottom of the tread pattern cracks; since the tire rigidity increases at this moment and does not have the function of buffering, the dynamic load between tire and road surface is increased and thus the automobile smoothness becomes worse and the handling quality reduces [3, 4]. From Figure 1, we can see the influence of tire pressure on tire performance.

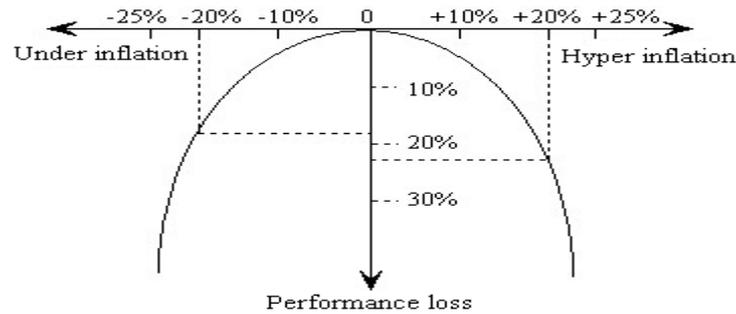


Figure 1. Influence of Tire Pressure on Tire Performance

2.2. Influence of Temperature on Tire Burst

During the driving process, the tire temperature may rise sharply due to the heat dissipating, leading to rubber and cord thread strength reductions. When the tire temperature is rising from 0°C to 100°C, the cord thread strength of nylon tire may reduce about 20% and its rubber strength may reduce about 50%; when the tire temperature is higher than the critical temperature (within 100°C belongs to normal temperature, between 100 and 121°C belongs to critical temperature, and above 121°C belongs to dangerous temperature), the rubber and cord thread strength may reduce greatly, therefore, the tire temperature rise may exert a tremendous influence on its service life [5]. Figure 2 shows the influences of temperature and speed on tire performance during driving.

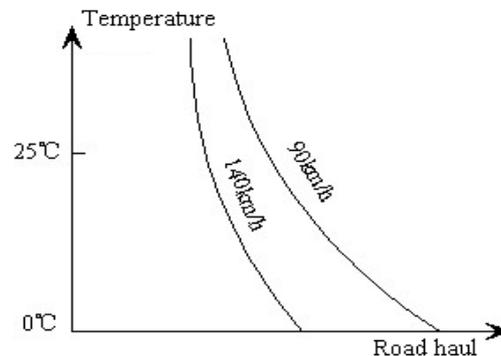


Figure 2. Influences of Temperature and Speed on Tire Performance

3. Multi-sensor Data Fusion Model

Even though certain or several sensors in a certain plane domain fail when using the multi-sensor data fusion technology to measure the pressure and temperature data of the tire in a limited time, the accurate results can still be obtained through the information offered by other non-failure sensors. The multi-sensor data fusion of pressure and temperature in the tire includes failure data rejection and valid data optimization and fusion [6].

3.1. Failure Data Rejection Method Based on Compatibility Matrix

When using several pressure temperature sensors to measure pressure and temperature in the tire, let the measured data of the i th and j th sensors be X_i and X_j and they should comply with Gaussian distribution. In order to reflect the deviation between X_i and X_j , the confidence distance measure (probability metrics) d_{ij} is introduced.

$$d_{ij} = \operatorname{erf}\left(\frac{x_j - x_i}{\sqrt{2\sigma_i}}\right) \quad (1)$$

σ_i is the mean square error of the measured data of the i th sensor; the smaller the value of d_{ij} , the closer the measured values of the i th and j th sensors, or otherwise, the deviation is big, therefore, d_{ij} is called the fusion degree of the i th and j th sensors.

If measuring the same index parameter through m sensors, the confidence distance measure $d_{ij} (i, j = 1, 2, \dots, m)$ forms a matrix D_m :

$$D_m = \begin{bmatrix} d_{11} & d_{12} & \dots & d_{1m} \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ d_{m1} & d_{m2} & \dots & d_{mm} \end{bmatrix} \quad (2)$$

When using several sensors to measure a parameter from different directions, give the threshold value $\beta_{ij} (i, j = 1, \dots, m)$ of d_{ij} based on the experience or the test results and suppose

$$r_{ij} = \begin{cases} 0, & d_{ij} \leq \beta_{ij}, \\ 1, & d_{ij} > \beta_{ij}, \end{cases}$$

Compose relation matrix R_m by r_{ij} :

$$R_m = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1m} \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ r_{m1} & r_{m2} & \dots & r_{mm} \end{bmatrix} \quad (3)$$

If $r_{ij}=1$, it is considered that the compatibility of the i th and j th sensors is bad or they do not support each other. If $r_{ij}=0$, it is considered that the compatibility of the i th and j th sensors is good or they support each other. If a sensor can only be supported by few sensors, the data of this sensor should be failure data which should be rejected. If the reading number of this sensor is invalid in a long period, the sensor should be checked.

3.2. Multi-sensor Data Fusion Method Based on Bayes Estimation

Definition 1: (Bayes estimation): let the parameter Q in the aggregate distribution function $F(x, Q)$ be random variable, and for the decision function $d(x_1 \dots x_n)$, if $B(d^*) = \min(B(d))$ is obtained through any decision function $d^*(x_1 \dots x_n)$, then d^* is called as Bayes estimation value of parameter Q and $B(d)$ is called as the Bayes risk of decision function $d(x_1 \dots x_n)$ [7].

Theorem 1: if quadric expression is taken for the loss function:

$$\lambda(Q, d) = [Q - d(x_1 \dots x_n)]^2$$

Then the Bayes estimation value of parameter Q is:

$$d(x_1 \dots x_n) = E(Q | x_1 \dots x_n) = \int Q P(Q | (x_1 \dots x_n)) dQ$$

Hence, in order to evaluate the Bayes estimation of Q , the probability density curve $P(Q | x_1 \dots x_n)$ should be evaluated firstly.

Based on Bayes estimation theory [8], the optimal fusion pressure and temperature data of the four pressure temperature sensors are obtained:

$$T = \frac{\sum_{k=1}^L \frac{T_k}{\sigma_k^2} + \frac{T_0}{\sigma_0^2}}{\sum_{k=1}^L \frac{1}{\sigma_k^2} + \frac{1}{\sigma_0^2}} \quad P = \frac{\sum_{k=1}^L \frac{P_k}{\sigma_k^2} + \frac{P_0}{\sigma_0^2}}{\sum_{k=1}^L \frac{1}{\sigma_k^2} + \frac{1}{\sigma_0^2}} \quad (4)$$

Thereinto : $L \leq 4$

P_k : observed value of the k th pressure sensor;

σ_k : standard deviation of measured value of the k th pressure sensor;

P_0 : mean value of observed value of the L th pressure sensor;

σ_0 : standard deviation of observed value of the L th sensor;

T_k : observed value of the k th temperature sensor;

σ_k : standard deviation of measured value of the k th temperature sensor;

T_0 : mean value of observed value of the L th temperature sensor;

σ_0 : standard deviation of observed value of the L th temperature sensor.

4. Temperature Compensation of Tire Burst Pre-warning Threshold

In order to obtain the scientific and accurate threshold value, the causes that may change pressure threshold value should be analyzed; in the part, the main focus is on the influence of environment temperature on tire pressure.

Let the upper and lower limits of tire pressure threshold value be P_{max} and P_{min} , the pressure data of the tire measured in time be P_r and measured temperature data be T_r ; when the temperature is T_r , the adjusted pressure value that needs temperature compensation is ΔP_r , then the upper and lower threshold values of pressure after temperature compensation are $P_{max} + \Delta P_r$ and $P_{min} + \Delta P_r$.

If the system does not provide temperature compensation, the pre-warning should be judged as follows:

When $P_r \geq P_{max}$ or $P_r \leq P_{min}$ and $P_{min} + \Delta P_r < P_r < P_{max} + \Delta P_r$, false alarm may occur if the system alarms, when $P_{min} < P_r < P_{max}$ and $P_r \geq P_{max} + \Delta P_r$ or $P_r \leq P_{min} + \Delta P_r$, false negative may occur if the system does not alarm.

The experiment proved that [9] when the environment temperature is between 0 and 24°C, there is no need to revise the inflation pressure; however, when the environment temperature is higher than 24°C or lower than 0°C, the tire pressure may change with the environment temperature and the basic inflation pressure should be revised. When the environment temperature is higher than 24°C, its influence degree on tire pressure is shown in table 1. When the environment temperature is between -1°C and -40°C, the basic pressure of 0.025Pa should be added once the temperature is reduced by 1°C, starting from 0°C.

Table 1. Test Data Table of Tire Pressure Increment Rate under Different Environment Temperature

| Environment Temperature(°C) | Tire Pressure Increment Rate(%) |
|------------------------------|----------------------------------|
| 25~29 | 4 |
| 30~34 | 6 |
| 35~39 | 8 |
| 40~45 | 10 |

According to United States Standard [10], when the tire pressure is higher than 1.2 times of the standard tire pressure or lower than 85% of the standard tire pressure, alarm should be given and the temperature compensation of tire burst pressure threshold value is shown in Figure 3. When the temperature within the tire is higher than 85°C (the normal temperature is between 60°C and 70°C), the system alarms. In this paper, the pressure value that is 1.2 times of the standard tire pressure is set as "upper limit value of pressure pre-

warning threshold” and the pressure value that is 85% of the standard tire pressure is set as “lower limiting value of pressure pre-warning threshold”; 85°C is set as “temperature pre-warning threshold value”.

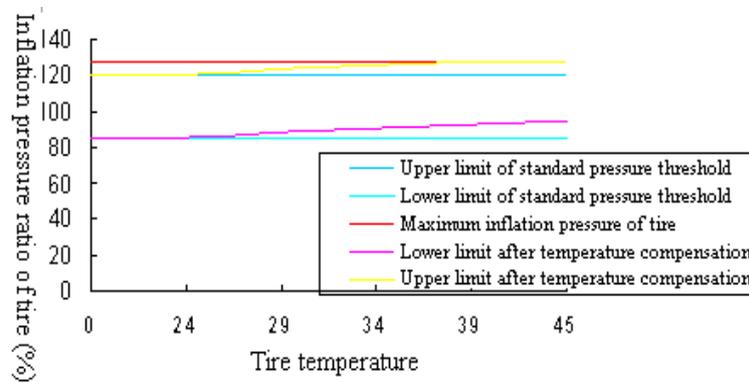


Figure 3. Temperature Compensation of Pressure Threshold Value

5. Measured Data Fusion Experiment

Bora automobile tire is taken as an example in the experiment. According to the experience of Bora engineers, the pressure of front wheel should be 230KPa and that of back wheel should be 250KPa if running at high speed (fully loaded). If the intermediate value of 240 KPa is taken for the front and back wheels during air inflation, then the upper limit of tire pressure pre-warning threshold and the lower limit of tire pressure pre-warning; the tire temperature pre-warning threshold.

Put the four MENS sensors in a tire uniformly and monitor its pressure and temperature. In order to enhance the measurement accuracy and facilitate calculation, each sensor needs four data, as shown in table 2. Since the measured data should be subject to Gaussian distribution, the expectation E (T) and variance D (T) should be:

$$E (T) = \frac{1}{4} \sum_1^4 T_i$$

$$D(T) = \frac{1}{4} \sum_1^4 T_i^2 - E(T)^2$$

Table 2. Test Data Table of Pressure Temperature Sensor (unit: kg/cm, °C)

| Sensor | 1 | 2 | 3 | 4 |
|-------------|---------------|--------------|---------------|--------------|
| Data1 | 292.6(85.4) | 289.7(84.3) | 291.5(84.9) | 300.3(92.4) |
| Data2 | 292.1(86.1) | 289.4(83.1) | 292.2(83.4) | 302.1(91.2) |
| Data3 | 292.8(85.4) | 290.1(84.5) | 291.8(83.1) | 301.2(90.1) |
| Data4 | 292.3(83.7) | 293.2 (86.2) | 291.6 (82.4) | 299.2(89.7) |
| Expectation | 292.45(85.15) | 290.6(84.53) | 291.77(83.45) | 300.7(90.85) |
| Variance | 0.0725(0.78) | 0.232(0.37) | 0.072(0.833) | 0.115(0.11) |

From Table 2, we can get the confidence distance matrix Dmp formed by the confidence distance measure dij of pressure data:

$$D_{mp} = \begin{bmatrix} 0.000 & 0.023 & 0.011 & 0.032 \\ 0.041 & 0.000 & 0.006 & 0.043 \\ 0.002 & 0.061 & 0.000 & 0.021 \\ 0.022 & 0.008 & 0.021 & 0.000 \end{bmatrix}$$

Get the threshold value $\beta_{ij}(i, j = 1, 2, 3, 4) = 0.1$ of dij based on experience or test results, and the matrix of relation is:

$$R_{mp} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Then the measured data of the four sensors are all valid data, the optimal fusion number is L=4 and Bayes optimal fusion data P of the measured pressure is:

$$P = \frac{\sum_{k=1}^L \frac{P_k}{\sigma_k^2} + \frac{P_0}{\sigma_0^2}}{\sum_{k=1}^L \frac{1}{\sigma_k^2} + \frac{1}{\sigma_0^2}} = 290.84(KPa)$$

The confidence distance matrix formed by the confidence distance measure dij of temperature data is:

$$D_{mt} = \begin{bmatrix} 0.000 & 0.032 & 0.021 & 0.212 \\ 0.041 & 0.000 & 0.026 & 0.143 \\ 0.072 & 0.041 & 0.000 & 0.351 \\ 0.432 & 0.238 & 0.314 & 0.000 \end{bmatrix}$$

Take the threshold value $\beta_{ij}(i, j = 1, 2, 3, 4) = 0.1$ of dij, and the matrix of relation is:

$$R_{mt} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{bmatrix}$$

Then the measured data of the four sensors are all valid data, the optimal fusion number is L=3, and Bayes optimal fusion data T of the measured temperature is:

$$T = \frac{\sum_{k=1}^L \frac{T_k}{\sigma_k^2} + \frac{T_0}{\sigma_0^2}}{\sum_{k=1}^L \frac{1}{\sigma_k^2} + \frac{1}{\sigma_0^2}} = 85.32(^{\circ}C)$$

After calculation, P=290.84 kPa and T=85.32°C; at this time, both pressure and temperature exceed the set pre-warning threshold. The system should warn the driver of tire burst; if it continues to rise, raise the alert level; if it tends to decline, stop alarming.

6. Conclusion

In this paper, the decision model on TPMS pre-warning threshold based on multi-sensor data fusion is put forward. Compared with the traditional tire pressure monitoring system, this model has the advantages of information integrity, uniformity, diversity and fault

tolerance. The experiment results show that the system can achieve the function of pre-warning for tire burst and it can effectively avoid false alarm and false negative and prevent the tire burst during driving so that the driver's life and property safety can be guaranteed.

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