A Study on Tire Pressure Monitoring System Based on Comparison of the Standard Pulse Number

Han Zong-qi, Wang Li-qiang, Liu quan-you, Zhang zhong-xiao Ju Xue-kun
College of Vehicle and Energy, Yanshan University, Qinhuangdao City, 066004,China

Abstract: The abnormal tire pressure is one of the main reasons for tire blow-out. Monitoring the tire pressure and alarming when it is abnormal is an important means to improve the automobile active safety and prevent malignant accidents. The pulse number from wheel speed sensors reflects the rolling radius and the tire pressure directly. Recording and analyzing the pulse number of the wheel speed sensors in a certain distance; we can inspect the tire pressure indirectly. Based on the tire pressure test on road, the author proposed a theory and method which can indirectly monitor the tire pressure using the standard pulse number. The method includes the signal processing, the tire calibration, the pulse number standardization, the standard pulse number comparison, the abnormal tire pressure judgment, and the warning methods. The samples of tire pressure monitoring system are designed and made. Many real vehicle tests on road show that the samples have favorable effect.

Keywords：Standard pulse number, Tire pressure monitoring system, Tire calibration, Alarm

1 Introduction

According to relevant statistics, the traffic accidents caused by tire blow-out accounted for 70% of the total number of accidents on China's highway. Tire explosion is the major factor of malignant traffic accidents[1]. When the tire is running at low pressure, the tires deformation increased, the contact area with the road surface increased, the rolling resistance increased, friction and temperature rise sharply. In addition, standing wave may occur when running at high-speed. So that the strength of the tire drops, eventually it lead to the tire cord breaking and the tire blow-out. Low pressure has become the most important factor of tire blow-out[2~6]. At present, Tire Pressure Monitoring System (TPMS) can be divided into two types: direct-TPMS and indirect-TPMS[7]. The direct-TPMS using pressure sensors installed inside of tires to detect the tire pressure. This type of TPMS alarms accurately and timely. But installation of sensors inside the tire will destroy the wheel equilibrium. At the same time, it is difficulty to supplying electricity power [8]. Therefore it costs expensively. The author has designed a kind of indirect-TPMS which is set up on basis of the comparison of the standard pulse number.

This kind of TPMS makes full use of the signals, which come from the wheel speed sensors of the automobile Anti-lock Braking System (ABS). And it monitors the tire pressure by comparing the pulse number of wheels. The system works without installing any extra mechanical parts in wheels. It costs low. The road test shows that the system has accurate and timely alarming function and works well.

2 Basic Principle of Monitoring the Tire Pressure Using the Pulse Number of Wheels

2.1 The relationship between the pulse numbers of wheel and tire rolling radius

The rolling radius of a tire [9] is:

$$r = S/(2\pi n) \tag{1}$$

Where: r=Rolling radius (m)

S= Rolling distance of the wheel (m)

n = Revolution number of the wheel

Suppose the teeth number of the wheel speed sensor is Z, then the pulse number is Z when the wheel rotated a lap. When the wheel rolling distance of S, it will give the pulse number of N, the rolling radius r is:

$$r = ZS/(2\pi N) \tag{2}$$

and

$$N = ZS/(2\pi r) \tag{3}$$

From sq. (3), we know that the pulse numbers of wheel speed sensor(N) and the rolling radius are inversely proportional in the certain rolling distance.

2.2 Influencing factors of the pulse number of wheels

The Influencing Factors of the rolling radius usually are wheel speed, wheel load, and tire inflation pressure, as well as the wear of the tire. So the pulse number of a wheel speed sensor when the wheel passing one kilometer is also affected by the speed, the load, the tire inflation pressure, as well as the abrasion of the tire.

The tests data shows that the pulse number per kilometer reducing with the speed increasing, and the relationship of the two variables is approximately l**inear. As shown in Figure 1.**

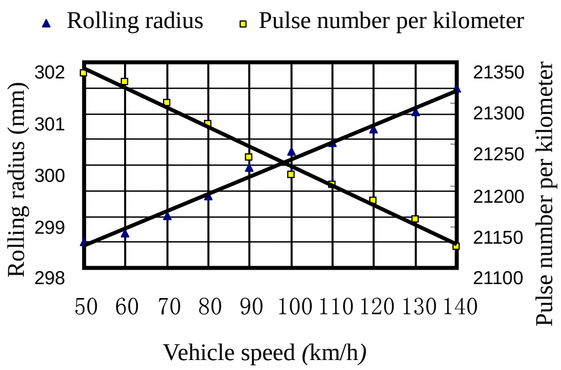

Figure 1 Curves of the rolling radius and the pulse number per kilometer with the vehicle speed

At the same time, the tests show that the pulse number per kilometer reducing with the tire pressure increasing, and two variables are a good linear relationship. Shown in Figure 2.

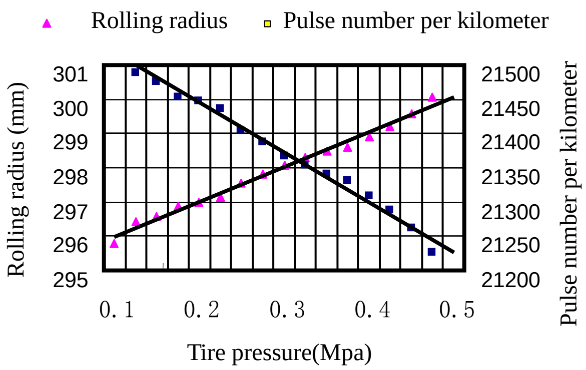

Figure 2 Curves of the rolling radius and the pulse number per kilometer with the tire pressure

According to the above 2 figures, we can fit for the tire rolling radius as bellow:

$$r = k_v V + k_{pv} P + r_0 \tag{4}$$

the pulse number per kilometer can be expressed as:

$$N = ZS / (2\pi(k_v V + k_{pv} P + r_0)) \tag{5}$$

Where: V= Speed of the vehicle(km / h)

P=Tire inflation pressure(Mpa)

k_v= Influencing coefficient of wheel speed for rolling radius (mm/km/h)

k_{pv}= Influencing coefficient of air pressure for rolling radius (mm / Mpa)

r_0=Rolling radius when speed and inflation pressure of wheel are 0 (mm).

In fact, under the normal load, the influencing effect of the load for rolling radius and the pulse number per kilometer is very small, as shown in Figure 3.

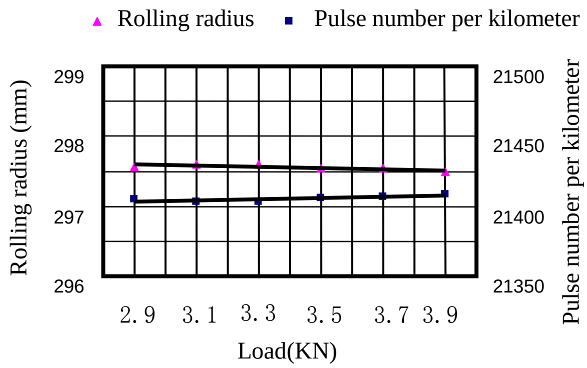

Figure 3 Curves of the rolling radius and the pulse number per kilometer with the load

For tires of a car, under the normal load, the effect of load to pulse number could be ignored. As we know, as the tire wear increasing, the rolling radius reduces and the pulse number per kilometer increases. But the tire wears gradually, so that we can consider rolling radius as invariable in the relatively short period of time.

Assuming the distances of the four wheels are equal when vehicle running at a higher speed. If the teeth number of the wheel speed sensors are same, the pulse numbers of wheel speed sensors and there tire pressure are inversely proportional relationship when vehicle running at a certain speed and under a certain load. Therefore the smaller the tire pressure, the bigger the pulse number of wheel speed sensor. As a result, comparing and analyzing the pulse numbers of four wheel speed sensors , we can determine the tire pressure of four wheels.

3 Processing of the Signal and the Pulse Number

3.1 Signal processing

The wheel speed signal comes from the ABS wheel speed sensors. The wheel speed sensor yields a series of sine wave signal with the wheel rotating. The voltage and frequency of signals relate with the wheel rotating speed only. Wheel speed signals must be protected with insulation method. With the filtering, amplifying and modulating, the signals turn to square waves. These are dealt with by a micro-controller. The signal processing circuit should meet the following conditions:

(1) The square wave must has same frequency with the sine wave, and duty cycle is 50%;

(2) Exporting the square wave in the largest scope of the speed;

(3) Good electromagnetic compatibility and less noise[10,11]

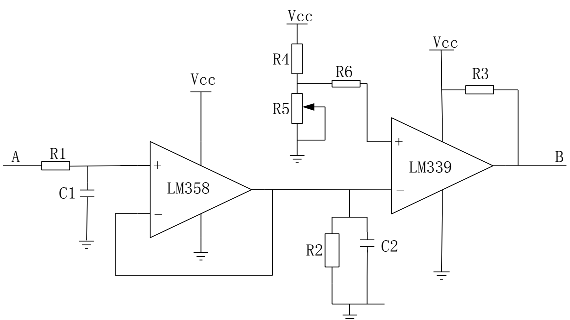

Figure 4 Wheel-speed signal processing circuit

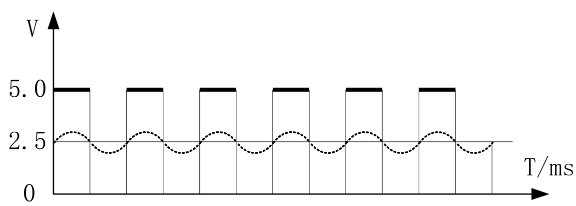

Figure 5 Wheel-speed signal waveform translation

The wheel-speed signal processing circuit is given in Figure 4. The circuit is constituted by the LM358 op amp, the LM339 comparator, the resistors and the capacitors etc. Point A is linked to the anode of the wheel speed sensor signal, point B import the transformed pulse signal into the controller. The wheel speed signal waveform is shown in Figure 5.

3.2 Tire calibration

The purpose of tire calibration should be to eliminate the effect on the pulse number due to the manufacture, the wear and tear, and the difference standard pressure. After calibration, we can monitor normally the tire pressure even if the tires have different radius. The calibration method is followed: vehicle runs through the same section of a good surface and straight road at least one round-trip at a common speed, and with normal load, prescriptive tire pressure by the tire manufacturers. Record the pulse number of all wheel speed sensor.

Set the pulse number of 4 wheel sensors as N_1, N_2, N_3, N_4 (the suffix 1 stand for the left-front wheel, the 2 for the right-front wheel, the 3 for the right-rear wheel, and the 4 for the left-rear wheel). Thus the correcting coefficients for each wheel are:

$$k_i = \sum N_i \Big/ 4N_i \qquad \text{i = 1～4} \tag{6}$$

3.3 Pulse number standardization

Each wheel gains a correcting coefficient (k_i) of the pulse number after the calibration. The standard pulse number equal to the pulse number multiplied by the correcting coefficient corresponded to the tire.

$$SN_i = k_i \times N_i \qquad i = 1～4 \tag{7}$$

Where: SN_i = Standard pulse number, $i = 1 \sim 4$

In a car, the standard pulse numbers of four wheels should be equal nearly when the air pressures of four tires are normal, despite the difference between the rolling radius of wheels.

4 Comparative method of the Standard Pulse Number

The standard pulse number of tire directly reflects the quality of the tire pressures So long as comparing and analyzing the standard pulse numbers of all of tires, we can determine the tire pressure whether or not abnormal.

4.1 Four-mean comparative method

Four-mean comparison is defined as relative error between every standard pulse numbers with the mean of the 4 standard pulse numbers. This result reflects how their own tire pressure deviate from the average level. Using the result we can judge that a tire pressure may be normal or not.

Calculation:

$$\overline{SN} = \sum SN_i / 4 \qquad i = 1～4 \tag{8}$$

$$\Delta SN_i = \left| \frac{SN_i - \overline{SN}}{\overline{SN}} \right| \times 100\% \tag{9}$$

Where: $\overline{SN}$ = Mean of the standard pulse number of the 4 wheels

SN_i = Standard pulse number of tire *i*, 1~4 respectively stand for the left-front, the right-front, the left-rear and the right-rear wheel

ΔSN_i = Relative error for the standard pulse number of *i*- tire with the mean

When ΔSN_i more than a set value, the *i*-tire pressure may be abnormal.

4.2 Three-mean comparative method

Three-mean Comparison is defined as relative error between every standard pulse number with the mean of the other three standard pulse numbers in one sample.

Calculation:

$$\overline{SN_i} = \frac{1}{3} \sum_{j=1}^{4} SN_j \qquad j \neq i \text{, i = 1～4;} \tag{10}$$

$$\Delta SN_i^{'} = \left| \frac{SN_i - \overline{SN_i}}{\overline{SN_i}} \right| \times 100\% \tag{11}$$

Where $\overline{SN_i}$ =Mean of the other three standard pulse number except the pulse number of *i*-tire

$\Delta SN_i^{'}$ = Relative error for the standard pulse number of *i*-tire with $\overline{SN_i}$

If $\Delta SN_i^{'}$ is more than a set value, the tire pressure will be determined to be abnormal. The $\Delta SN_i^{'}$ eliminates the effect of it own pulse number and enlarges the relative error. It is easer to determine an abnormal pressure tire in this method than the four mean comparisons.

4.3 Front-rear wheels comparative method

Calculating:

$$\Delta N_{1/4} = \frac{SN_1 - SN_4}{SN_4} \times 100\% \tag{12}$$

$$\Delta N_{2/3} = \frac{SN_2 - SN_3}{SN_3} \times 100\% \tag{13}$$

Front-rear wheels comparative method can be used to judge front-wheel or rear-wheel whether or not sliding when running. If $\Delta N_{1/4}$ and $\Delta N_{2/3}$ are greater than a designed value at the same time, we can know that the front-wheel is slipping. On the contrary, if $\Delta N_{1/4}$ and $\Delta N_{2/3}$ are less than a designed value at the same time, the rear-wheel is slipping.

4.4 Left-right wheels comparative method

Calculating:

$$\Delta N_{1/2} = \frac{SN_1 - SN_2}{SN_2} \times 100\% \tag{14}$$

$$\Delta N_{4/3} = \frac{SN_4 - SN_3}{SN_3} \times 100\% \tag{15}$$

This Comparative method can determine the vehicle whether or not turning a corner. If $\Delta N_{1/2}$ and $\Delta N_{4/3}$ are greater than a designed value at the same time, that means that the vehicle is turning right. The other way round , if $\Delta N_{1/2}$ and $\Delta N_{4/3}$ are less than the negative value at the same time, the vehicle is turning left.

4.5 Cross-wheel comparative method

Calculating:

$$\Delta X = \left| \frac{(SN_1 + SN_3) - (SN_2 + SN_4)}{\overline{SN}} \right| \times 100\% \tag{16}$$

This Comparative method is used to judge whether there is any abnormal pressure tire in vehicle turning. If ΔX is greater than a certain value, there may be a tire which air pressure is abnormal.

5 Judge for Tire Pressure Abnormal

5.1 Estimating a tire pressure may be abnormal

We can use the four or three mean comparative method above to estimate a tire pressure that may be abnormal. Before that, we research the sensitivity of the two comparative methods by road tests. We reduce the tire pressure of the left-rear wheel to 1/4 to 1/2 of normal value and keep the other three wheel tires as normal value. The test results are illustrated in table 1. From the tests, we know that the three-mean comparative method works better than the four-mean comparative method. The three mean comparative method has high-accuracy and less-mistake.

Table 1. Proportion of the left-rear tire pressure is estimated abnormal

Percentage of the left-rear tire pressure	Proportion of abnormal estimated	
	Three-mean method	Four-mean method
0	0	7%
25%	58%	41%
35%	81%	69%
50%	100%	94%

We can say from the table 1 that three mean comparative method is more sensitive than the four mean method. So that we prefer the three mean comparative method to the four to determine a tire pressure normal or abnormal.

5.2 Confirming a tire pressure abnormal

If we use the three or four mean comparative method to confirm a tire pressure, we may make errors. Either a normal pressure were considered abnormal or a abnormal were failed to report. To avoid these and improve alarming accuracy, we use a small sampling statistic work to eliminate the effect of random factors. That is adopting the statistical probability method to judge the tire pressure whether or not abnormal indeed.

Set a positive integer M as the statistical sample capacity. Microprocessor records the last results of M-sample. Set a positive integer A_i (i = 1 ~ 4) as the frequency of i-tire pressure judged abnormal. If $C_i = A_i / M \geqslant q$, the microprocessor will conclude that the pressure of i-tire as abnormal indeed, and gives alarming.

Where: C_i = Ratio of abnormal frequency to M

A_i =Abnormal frequency

M = Statistical sample capacity

q = Set value for the tire pressure is judged abnormal indeed.

6 Test Result

According to the theory and the method, we design and make the sample of TPMS and do tests in a Jetta GIX sedan on road. The tire model is 185/60R14. In one sampling process, the maximum value of the original pulse number identified as 4000, the set value of three-mean comparative method identified as 0.55%, the statistical sample capacity identified as 5, the set value for q is 0.6 (or 60%). Reduce the tire pressure of the left-rear wheel to 2/3 normal value and keep the other three Wheel's pressure normal. The test results show in table 2. In the table, A_4 is the time that the left rear wheel pressure is estimated abnormal, and C_4 is the ratio of A_4 to M.

Table 2 shows the system alarms at speed range from 40 to 100 km/h. But one time is not able to determine the left-rear tire pressure is abnormal at the speed 40km/h. If determining the tire pressure abnormal only could accord to the comparative result of one detecting data, we would leave out an alarm. The statistical probability method designed by this article can eliminate the impact of random factors in car running.

Table 2 Test results on road

Speed of vehicle	A_4	C_4	Alarm	Time of fail to alarm
40 km/h	4	80%	Y	1
60 km/h	5	100%	Y	0
80 km/h	5	100%	Y	0
100 km/h	5	100%	Y	0

7 Conclusion

1、The TPMS designed in this paper belongs to indirect TPMS, it has a simple structure, easy to implement, and low cost.

2、The comparative methods of the standard pulse numbers are built on the linear relationship between the standard pulse number and the vehicle speed as well as the tire pressure and the experimental data.

3、Under certain conditions, the pulse number of each wheel speed sensor and its tire pressure are inversely proportional relationship, the standard pulse numbers reflect the relationship indirectly between the tire pressures, it is accurate and feasible.

4、According to the comparative results of the standard pulse number, it is easy to judge whether or not the tire pressure abnormal.

5、The test results show that the statistical probability method proposed by this article can alarm accurately but also prevent false alarm.

References

[1] 张玉琴,唐亚鸣,王锦桥.高速公路上汽车爆胎原因及其防止措施浅探[J].黑龙江交通科技，2007,(1)：92-94

[2] 郑安文.我国高速公路交通事故的基本特点与预防对策.公路交通科技,2002,19(4): 109-112

[3] 胡言.引起爆胎的原因及其预防.北京汽车,2004,(2):45-46

[4] P.I.Dolez, C. Nohile, T. Ha. Anh. Exploring the chemical aspects of truck tire blowouts and explosions[J]. Safety Science, 2008,(46):134-144

[5] J. Rcho, K. W. Kim, H. S. Jeong. Numerical investigation of tire standing wave using 3-D patterned tire model[J].Journal of sound and vibration,2007,(305):795-807

[6] 王振宇.高速公路汽车爆胎的原因与预防[J].2003，（3）

[7] George J. Soodoo. Tire Pressure Monitoring Systems NHTSA Final Rule[R]. Switzerland: 51thGRRF: 1-24

[8] Joshua M. Pearce, Jason T. Hanlon. Energy conservation from systematic tire pressure regulation[J]. Energy Policy, 2007,(35):276-277

[9] 韩宗奇，宋健等.基于滚动半径法轮胎气压异常报警系统设计[J]. 汽车工程，2008，30（8）：721—724

[10] 张集乐，鲁植雄.ABS轮速传感器及其信号处理[J].机械与电子，2007，（12）：48-50.

[11] 陆文昌,毛务本.汽车防抱死制动系统轮速信号处理[J].江苏大学学报，2002，23(4)：36—41.

About the author:

Han Zong-qi, professor of Vehicle Engineering, the president of the Vehicles and Energy College of Yanshan University. Graduated from Tsinghua University in July 1982. He has been engaged in automotive design, research and teaching for a long time. His main research areas are the vehicle dynamics and automotive electronic control technology.

Contact the author:

Han Zong-qi
Address: Vehicle and Energy College ,Yanshan University , Qinhuangdao City, Hebei Province, 066004,China
Phone: 0335-8043036
Fax: 0335-8074682
Mobile phone: 13933586730
E-mail：zqhan@ysu.edu.cn