Wheel Speed Signal Time-Frequency Transform and Tire Pressure Monitoring System Design

Wang Liqiang[1], Meng Hui[2], Han Zongqi[3]

[1](College of Vehicle and Energy Engineering, Yanshan University, China)
[2](College of Electrical Engineering, Yanshan University, China)
[3](College of Vehicle and Energy Engineering, Yanshan University, China)

ABSTRACT: *This article designed a tire pressure monitoring system with time-frequency conversion function, the system can convert wheel speed time signal into frequency signal, can filter in the frequency domain to obtain pure wheel speed signal, and use it to determine tire pressure. This article described the wheel speed signal sampling frequency calculation methods, filter mode selection methods, Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) algorithm and its implementation within the microcontroller, and the implementation of frequency domain filtering within the microcontroller. We designed the tire pressure monitoring system based on XC2336A microcontroller; vehicle road test showed that after the time-frequency conversion, the tire pressure monitoring system can effectively improve the monitoring accuracy at a high speed.*

Keywords: Tire Pressure Monitor, Time-frequency Conversion, Sample Frequency, FFT/IFFT

I. Introduction

Tire is the only parts contact with the road when a car in moving process and the tire pressure is an important parameter [1] directly related to the car driving performance and the safety. Tire Pressure Monitoring System (TPMS) is an ideal device to maintain the tire pressure to be normal. Accordance to the working principle, TPMS can be divided into Direct and Indirect categories. Direct TPMS can accurately monitor the tire pressure, but because of its complex structure, so many alters on the wheels, installation difficulties, high price and other shortcomings, it is only used in a few advanced cars. Indirect TPMS can infer the level of tire pressure indirectly by collecting and processing the ABS wheel speed sensor signal, calculating and analyzing the rolling radius of the wheels, wheel speed, and tire deformation parameters. Because of its simple structure, low cost, easy to implement, the Indirect TPMS has attracted much more attention. However, in the existing indirect TPMS, when the speed is bigger than 100km / h, since the incretion of the noise of wheel speed signal, signal processing methods are simple; the monitoring accuracy is reduced significantly.

This article provided indirect TPMS with a more pure wheel speed signal which went through the time-frequency conversion and filtering. The road test showed that after video conversion, the tire pressure monitoring system can effectively improve the monitoring accuracy at a high speed.

II. Sampling Cycle, Acquisition Cycle And The Definition Of Monitoring Cycle

Acquisition cycle is an interval for a system to determine a tire pressure. If each acquisition cycle performs wheel speed signal acquisition for only once, by memory limitation of the selected microcontroller, each wheel speed signal acquisition can not collect too much wheel speed signal; by the limited accuracy of tire pressure monitoring and alarm, the number of wheel speed signal pluses used to determine tire pressure can not be too small. Therefore, each acquisition cycle is divided into ten sampling periods, so that the wheel speed signal of each sampling period does not exceed microcontroller memory; add the number of pulses of ten sampling period to determine the tire pressure so that tire pressure detection alarm accuracy can not be affected by the small pulse number.

The number of calculation pulses for each sampling period will produce ± 1 pulse error [2], so the maximum error of ten sampling period namely a collection cycle is ± 10, it does not affect the judgment of tire pressure.

Monitoring cycle is the time interval to determine whether to alarm. A monitoring cycle consists of five acquisition cycles, the cycle decides whether to alarm according to the judgments of these five system acquisition cycles on the tire pressure. After each new acquisition cycle generated, we discard the earliest recorded data, so that we can ensure each monitoring cycle contains only the five most recently recorded pulse data.

III. Tire Speed Signal Sampling Frequency And Filter Mode

3.1 determine of the number of speed signal samples

Real vehicle experiments shows that, to determine the tire pressure that is an acquisition cycle, each wheel takes about 5000 pulses, if we take 5120 pulses, and then four wheels require a total of $5120 \times 4 = 20480$ wheel speed signal pulses. The sampling period is one tenth of the acquisition cycle, that is each sample periods needs to collect $20480/10 = 2048$ pulses. Assuming the sampling frequency is 4 times of the wheel speed signal frequency, so that each sampling period needs to collect $2048 \times 4 = 8192$ wheel speed signal. During the Fast Fourier Transform (FFT) process, each wheel speed signal consists of the real and imaginary parts of two integer variables, each integer variable consists of two bytes, then the FFT process requires namely 32K RAM**,** in this article the model of selected SCM is SAF-XC2336A-56F80L of the Infineon company, the chip RAM is 50K, which meets the requirements.

3.2 determine of the wheel speed signal sampling frequency

In each sampling period, the sampling frequency is determined by the output of the wheel speed signal frequency. Diameter of the rolling tires :

$$D = (L \times H) \times 2 + d \times 25.4 \qquad (1)$$

Wherein, D is the wheel diameter, L is the tire width, H is the aspect ratio, d is the diameter of the hub. The wheel speed signal output frequency is:

$$f_1 = \frac{V \times Z}{\pi \times D} \qquad (2)$$

Wherein, V is the vehicle speed, Z is the ring gear teeth of the wheel speed sensor. Take JETTA models as an example, the tire model is 185/60R14, wheel speed sensor ring gear teeth Z is 40, when the vehicle speed is 20km / h, the sensor output signal frequency is 122HZ, speed is 200km / h, the sensor output signal is 1220Hz

By the limitation of microcontroller memory, the number of wheel speed signal collected by each sampling period is fixed, if the sampling frequency is constant, the number of pulses collected at 200km / h is the tenth of number collected at 20km / h. When setting the sampling frequency, if we determine the frequency according to the output frequency of wheel speed signal at a high speed, the sampling frequency is too large, resulting in the number of pulses collected in the low speed is too small, and the measurement accuracy of tire pressure monitoring is reduced. If we determine according to the output frequency of the low wheel speed signal, the sampling frequency is too small, it can not meet the sampling theorem at high speed, leading to the distortion of the signal collected.

This article presents a frequency collection method which can change frequency automatically according to the wheel speed. Wheel speed signal acquisition is carried out in the real-time interrupt function, at the end of each sampling period, 4 paragraph wheel speed signals can be obtained. Set the real-time interrupt interval as t1, the number of real-time interrupt of each sampling period is N.SO the sampling time for each sampling period can be calculated is:

$$T = N \times t_1 \qquad (3)$$

At the end of sampling, the number of pulse of 4 paragraph wheel speed signals can be calculated, according to the cycle method [2] the wheel speed at this time can be calculated for:

$$V = \frac{(n_1 + n_2 + n_3 + n_4)\pi D}{4ZT} \qquad (4)$$

Wherein, n_1、 n_2、 n_3、 n_4 are the number of pulses of four wheels during each sampling period. The interval of each sampling cycle times is very short; it can be assumed that the wheel speed variation for the next sampling period is not big. The interval of next sampling period real-time interrupt can be stetted based on the calculated wheel speed. Set the expectation numbers of pulses collected is n_0, the real-time interrupt interval is:

$$t_1 = \frac{n_0 \pi D}{4ZNV} \qquad (5)$$

Thus, the number of pulses for each sampling period is similar. Thus, according to the previous wheel speed of sampling period to determine the sampling frequency of the next cycle, can not only ensure the number of pulses for each sampling period be too small to affect the measurement accuracy of tire pressure monitoring, but also can prevent signal distortion.

3.3 filter mode selection

When the wheel speed is 100km / h or less, the interference of wheel speed signal is very small, the clutter can be good removed by a hardware filter and software filtering is unnecessary. Meanwhile, in order to ensure the tire pressure of indirect TPMS can detect when the vehicle is started (at this point the speed is low),In order to minimize low speed detection cycle as much as possible, which also requires no further software filtering at low speed. Before filtering the software each sample period selects the filter mode according to the wheel speed calculated when setting the frequency sample. If the wheel speed is greater than 100km / h, then the collected wheel speed signal will be software filtered. If the wheel speed is less than 100km / h, then software filtering is no longer carried out, directly calculate the number of pulses.

IV. SCM Software Filtering

The wheel speed signal collected through fast Fourier transformed (FFT) converted into frequency domain signal, then be filtered, and finally through inverse fast Fourier transform (IFFT) converted into time domain signals.

4.1 FFT and IFFT algorithm principle

The idea of FFT algorithm is: continually decomposing the long sequence of DFT into short sequences of the DFT, and using the periodicity and symmetry of rotation factor to reduce the number of calculations of DFT.

Set the length of sequence X(n) is N, and satisfying: M is a natural number, The sequence X(n) is divided into x1(n), x2(n) two sequences by n is odd or even, with 2 N / 2 point DFT to complete a N-point DFT calculations:

$$\begin{cases} x_1(r) = x_1(2r) \\ x_2(r) = x_1(2r+1) \end{cases} \qquad (6)$$

Wherein r = 0, 1, 2,…,N/2-1,substituded into DFT conversion formula:

$$X(k) = DFT[x(n)] = \sum_{n=0}^{N-1} x(n) W_N^{nk} \qquad (7)$$

Among them $0 \le k \le N-1$, W_N^{nk} is the rotation factor, we have:

$$X(k) = \sum_{r=0}^{N/2-1} x_1(r) W_N^{2rk} + W_N^k \sum_{r=0}^{N/2-1} x_2(r) W_N^{2rk} \qquad (8)$$

Since the rotation factor:

$$W_N^{2n} = e^{-j\frac{2\pi}{N}2n} = e^{-j\frac{2\pi}{N/2}n} = W_{N/2}^n \qquad (9)$$

Substituted into (8), we obtain:

$$\boldsymbol{X(k) = X_1(k) + W_N^k X_2(k)} \qquad (10)$$

Since the cycle of X1 (k) and X2 (k) is N / 2 , and X (k) can be expressed as:

$$\begin{cases} X(k) = X_1(k) + W_N^k X_2(k) \\ X(k+N/2) = X_1(k) - W_N^k X_2(k) \end{cases} \qquad (11)$$

Wherein, $k = 0,1,\cdots N/2-1$.So that the N-point DFT is decomposed into two N / 2 point DFT. Break down x1 (r) and x2 (r) continually by odd or even. This decomposition continues until it can no longer be decomposed.

4.2 FFT and IFFT algorithm implemented in the microcontroller

FFT and IFFT algorithm achieved in the microcontroller mainly consider the real-time of system and the microcontroller RAM limitation. Experimental results show that when the length of sequence X(n) N is 8192, with the microcontroller clock frequency 80MHz, It takes about 600ms for FFT / IFFT, namely tire pressure detection system detects the time of the tire lack of gas is delayed by 600ms, which has little effect to the tire pressure detection systems.

Therefore FFT / IFFT algorithm achieved within microcontroller mainly considered the RAM limitation.

In order to achieve FFT/IFFT algorithm within microcontroller, we use the following three ways to save RAM needed by the FFT algorithm.

(1) The sequence of length N = 2M point FFT, has a total of M-class butterfly computation. At the same level,

the two input data of each butterfly is only useful for the butterfly itself. After calculating a butterfly, the output data resulted can be stored in storage unit immediately, which is occupied by original input data. After M-class operation, the original input data stored in N memory cells may be sequentially stored in the output data of the N values. Such using the same storage unit stores the butterfly calculated input and output data, can save more storage space.

(2) In the FFT algorithm, we can see from the Euler equation:

$$W_N^r = e^{-j2\pi r/N} = \cos(2\pi r/N) - j\sin(2\pi r/N) \qquad (12)$$

When W_N^r is multiplied, we should make the corresponding sin and cos calculation. In programming, one method is to attribute each step directly. From the symmetry of the rotation factor, during calculation we should define N / 2 variables to memorize, this takes more RAM, and slow the computing speed [3]. Another method is to calculate W_N^r in advance, the values are stored in the ROM, which is equivalent to set up a sine and cosine function table. This will not only improve the operation speed, and also save the RAM space. Considering indirect TPMS wheel speed signals collected have already occupied a larger RAM, this article adopts the second way to save RAM space.

(3) when performing wheel speed signal acquisition, the data through the A/D conversion is not the actual wheel speed voltage signal, but needs to be multiplied by a constant, and then transferred into a voltage signal expressed by a decimal, so we should use floating point type of data to storage, float data in MCU will occupy 4 bytes, which occupied too many bytes. Therefore, during the A/D conversion, we no longer calculate the voltage signal, but directly use the integer data after A/D conversion for FFT and filtering, the integer data type only occupy 2 bytes, it saves the chip RAM and does not affect filtering results.

4.3 frequency domain filtering implementation in single-chip within

After FFT conversion, the real wheel speed signal energy amplitude increased, while the amplitude of noise energy decreased. In the frequency domain,"filtering" process is to keep the real amplitude of the signal energy, to attenuate the amplitude of the noise energy component. Set after the FFT transform, wheel speed signal sequence of each frequency component and the corresponding energy amplitude of the series are shown in Table 1.

Table 1 frequency of the signal with the corresponding energy value

Frequency f	f_0	f_1	…	f_m	…	f_n
Energy Amplitude Y	Y_0	Y_1	…	Y_{max}	…	Y_n

Before filtering we must first determine the highest energy value Y max and corresponding center frequency fm. Shown in Fig4.
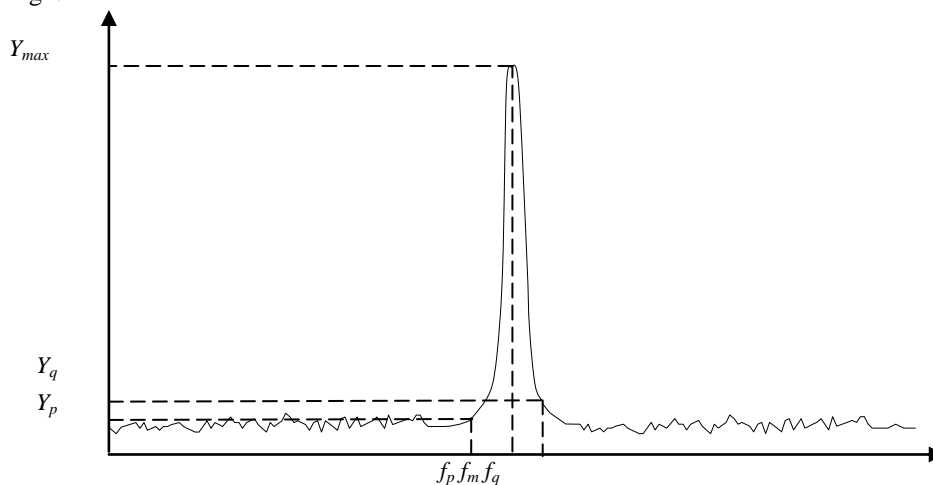

Figure 4 the division of filter frequency bands

The output frequency of wheel speed signal is approximately equal to the center frequency fm; we can estimate the center frequency by using frequency of the wheel speed signal which is calculated when setting the sampling frequency. Since the wheel speed of the wheel speed signal acquisition cycle is not fixed, and the

wheel speed calculated by the cycle method has some error [2], so the wheel speed signal output frequency is not equal to the center frequency fm, but must in the vicinity of the center frequency. So when we looking for the highest energy value Y max, is not required to calculate the maximum energy amplitude of the overall situation, just calculate the local maximum near the wheel speed signal output frequency. After determining the center frequency fm, it is required to determine the "binding site" of the wheel speed signal and the noise fp and fq, shown in Figure 4. fp and fq are determined by the coefficients of the signal / noise amplitude ratio a and b:

$$\begin{cases} f_p = f_m/a \\ f_q = f_m/b \end{cases} \qquad (12)$$

Signal to noise ratio coefficient is obtained by experiment. Finally respectively fit both sides of the binding sites secondary:

$$[Y_0, Y_1, ..., Y_p] = F_1[f_0, f_1, ..., f_p]$$
$$[Y_q, Y_{q+1}, ..., Y_n] = F_2[f_q, f_{q+1}, ..., f_n] \qquad (13)$$

After fitting Substitute the data into the frequency value, obtaining the corresponding energy amplitude. Fit the corresponding spectrum shown in Fig.3, of which the vehicle speed is 160Km / h. After fitting, the spectral curve and the IFFT time-domain graph are respectively restored in Fig.5 and Fig.6.
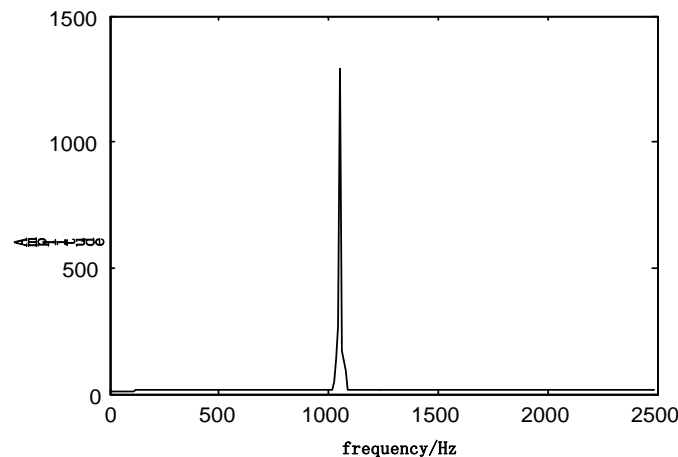

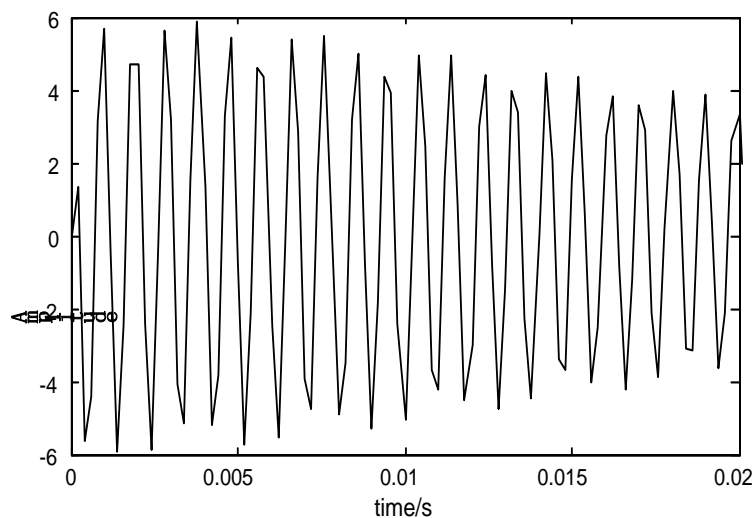Figure 5 the frequency domain spectrum after treatment

Figure 6 the IFFT time domain graph after the inverse transform

Comparing Fig.3 with Fig.12, it can be seen that the wheel speed signal after filtering can eliminating the noise basically.

V. Design Of Tire Pressure Monitoring System

5.1 hardware design of tire pressure monitoring system

System consists of wheel speed signal input module, a central processing module, abnormal tire pressure alarm module and serial communication module. Shown in Fig.7,

```
            Wheel speed signal input module
          ┌──────────────────────────────────────┐
          │  Limiter  →  Low-pass  →  Voltage     │
          │  circuit     filter       follower    │
          │              circuit                  │
          └──────────────────────────────────────┘
                          ↓
          ┌──────────────────────────────────────┐
          │         XC2336A-56F80L                │
          │         MCU module                    │
          └──────────────────────────────────────┘
             ↕                        ↓
      ┌──────────────┐      ┌──────────────────┐
      │    Data      │      │   Low pressure   │
      │ communication│      │   alarm module   │
      │    module    │      │                  │
      └──────────────┘      └──────────────────┘
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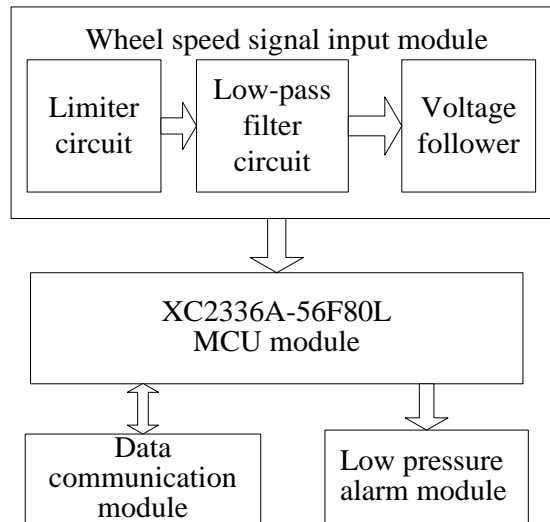
Figure 7 system component modules

When using a magnetic wheel speed sensor, in order to prevent the voltage of wheel speed signal exceeds the tolerance range of microcontroller, we must reduced voltage after a limiter circuit.

After the limiter circuit, the wheel speed signal to be filter out portion of the noise in the signal through the filter circuit. In order to prevent signal acquisition affects ECU, the wheel speed signal after processing should go through the voltage follower to be isolated. Final design is completed and the in or out of the wheel speed signal module circuit is shown in Fig.8.
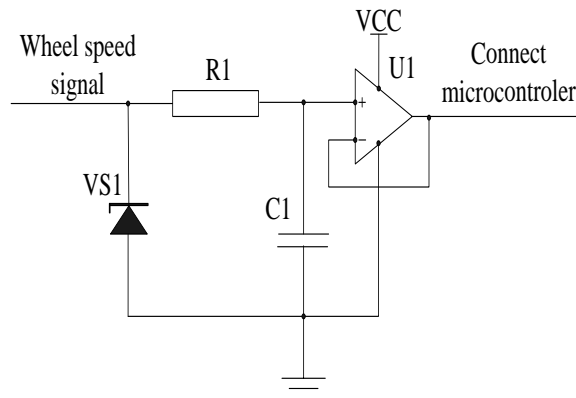
Figure 8 speed signal input module

Wherein the Zener diode VS1 formed the limiter circuit.R1 and C1 form a low-pass filter circuit, U1 is a voltage follower.

System uses XC2336A asynchronous / synchronous serial interface USIC0, achieving the bidirectional communication between PC and microcontroller. Abnormal tire pressure alarm module consists of a buzzer and a fault light.

5.2Tire pressure monitoring system programming

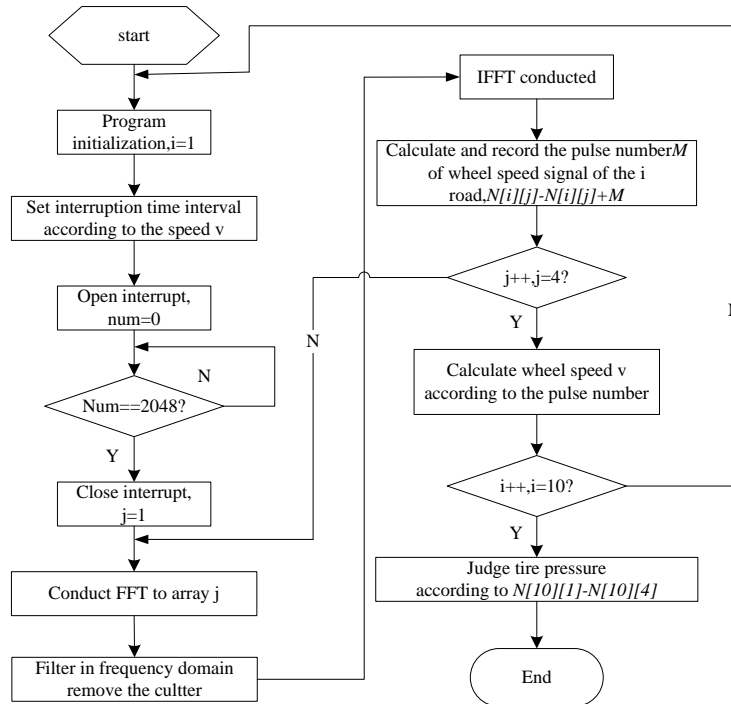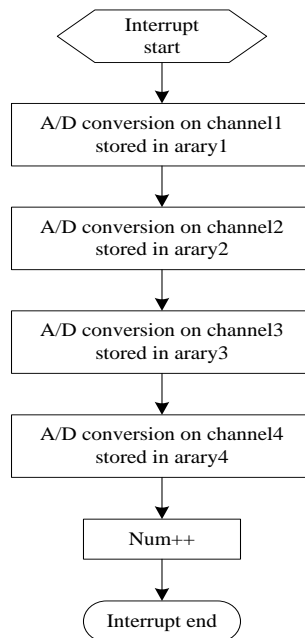Tire pressure monitoring system flow chart as shown below:

Figure 9

Figure 10

5.3 abnormal tire pressure warning module

In this paper the alarm module designed two level thresholds and three level alarm modes according to reference [4]. In each monitoring cycle, the system calculated 5 relative errors and 5 absolute errors according to the number of pulses of five acquisition cycles, a total of ten data. Systems can determine if the tire pressure is abnormal based on the number of times these 10 data exceeds to the threshold value. Assume that the number of alarm which is more than one level is X, more than two levels is Y, then the alarm conditions and alarm manner are shown in Table 2.

Table 2 alarm conditions and manner

Alarm type	Alarm condition	Sound alarm method
Lecel one alarm	X≥6	Frequency 1.0Hz
Level two alarm	X≥8andY≥4	Frequency 0.5Hz
Level three alarm	X=10andY≥8	Continous beep
Error	X＜Y	Fault light on

VI. Road Comparison Test

We installed a tire pressure monitoring system with software filtering function and another tire pressure monitoring system with no software filtering function on the same sedan to take a comparison test. During the experiment, two systems always use the same wheel speed signal. The test tire model is 185/70R14. When tested coefficients of the ratio of signal / noise amplitude a and b are respectively set to 1.05 and 0.95, i.e. fp = fm / a = 0.95fm, fq = fm / b = 1.05fm. In the first test, four tire pressures is normal, which is 0.25MPa; in the second test the left rear tire pressure was reduced to 0.15MPa, the remaining three rounds were unchanged. Tests were respectively finished under 120km / h, 140km / h, and 160km / h four kinds of speed. During the test the number of alarm which is more than one level X and which is more than two levels Y, were transferred to a PC via the serial port for analysis comparing, the test results are shown below.

Table 3 alarm condition of tire pressure monitoring system with no software filtering feature

Vehicle speed	Tire pressure normal			Left rear tire pressure(0.15Mpa)		
	X	Y	Alarm	X	Y	Alarm
120km/h	1	0	No	7	0	Level one
140km/h	3	0	No	9	2	Level one
160km/h	7	0	Level one	10	6	Level Two

Table 4 alarm condition of tire pressure monitoring system with software filtering feature

Vehicle Speed	Tire pressure normal			Left rear tire pressure 0.15MPa		
	X	Y	Alarm	X	Y	Alarm
120km/h	0	0	No	7	0	Level one
140km/h	0	0	No	7	0	Level One
160km/h	1	0	No	8	0	Level one

Comparison Table 3 with Table4 ,we can concluded that at high speed the tire pressure monitoring system with no filtering software was easy to produce false or wrong reports, and filtered with a tire pressure monitoring system software basically eliminate this situation, and the tire pressure monitoring system with a filtered software can basically eliminate this situation.

VII.   Conclusions

Wheel speed signal after FFT transformation filtered in the "frequency domain", and then after IFFT transformation converted to the time domain, the interference signal is substantially eliminated. Road comparison test proved that the tire pressure monitored by the tire pressure monitoring system with the time-frequency conversion function is more accurate, especially when a car at high speed, it can effectively eliminate the noise caused by false or wrong reports.

Acknowledgements

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