American Journal of Engineering Research (AJER)
e-ISSN : 2320-0847 p-ISSN : 2320-0936
Volume-03, Issue-01, pp-35-42
www.ajer.org

Research Paper Open Access

Fast Fourier Transformation Processing Method for Wheel Speed Signal

Wang Liqiang[1], Meng Hui[2], Han Zongqi[1]
[1](College of Vehicle and Energy Engineering, Yanshan University, China)
[2](College of Electrical Engineering, Yanshan University,China;

Abstract : - At high speed, there are two problems for safety and effective control of vehicles. One is that Signal-to-noise of wheel speed sensors are reduced, and the other is the data calculated by wheel speed signal is emanative. In this paper, wheel speed sensor signal was transformed into a frequency domain by using Fast Fourier Transformation (FFT) or Inverse Fast Fourier Transform (IFFT), waveform features of true signal and noise were studied in a frequency domain. Based on a narrow frequency domain and high energy of true signal, and wide-band signal and low energy of noise spectrum, a new method to process wheel speed signal was presented by using FFT and IFFT algorithms. Namely, transforming wheel speed signal into frequency domain using FFT firstly, "filtering" the wide-band noises in a frequency domain using polynomial fitting method secondly, and transforming waveforms of the noise spectrum into real signal inversely thirdly. The effects of three filtering methods which are electronic current filter, Karman filter and FFT/IFFT filter were compared to each other by road test of automotive vehicle. The test indicates that it can get rid of noises efficiently；improve signal-to-noise ratio clearly by using the processing method of FFT/IFFT filter.

Keywords: **-** *Wheel speed signal, Filter, Signal-to-noise, Fast Fourier Transform*

I. INTRODUCTION

At high speed, collection and procession wheel speed signal of automotive vehicle real-timely and precisely，which are bases of indirect Tire Pressure Monitoring System (TPMS), Anti-lock Brake System (ABS), Acceleration Slip Regulation (ASR), Active Yaw Control (AYC), Electronic Stability Program (ESP), Dynamic Stability Control (DSC) and other active safety control systems. In these safety control systems, processed wheel speed signal are used to calculate vehicle speed, acceleration or deceleration, wheel slip ratio or slip rate, yaw rate, understeer correction, and other important automotive motion parameters. And these parameters are used as a basis for safety control systems estimating vehicle driving state and generating control commands. Therefore, when a car is operated at high speed, it is an important guarantee for safe driving that collection and procession wheel speed signal real-timely and precisely.

However, due to the facts that Signal-to-noise of wheel speed sensors are reduced, and the data calculated by wheel speed signal is emanative when vehicle driving in high-speed, the active safety control systems mentioned above face with a common problem [1]. Traditional Karman filter, noise reduction using wavelet filter, digital Wiener filter and other measures, although these measures are able to reduce noises in wheel speed signal appropriately, and decrease the divergence of vehicle motion parameters based on wheel speed signal, but noises can not be eliminated completely. In order to improve the situation, many domestic and foreign researchers have carried out a lot of work widely and deeply. Including using Karman filter and genetic iterative algorithm to suppress sensor signal errors [2], using fault-tolerant manner based on analytica redundancy to solve the distortion problem of oscillation type sensor signal [3], using adaptive enhancer based on minimum mean square error in a frequency domain to predict wheel speed sensors mean square error in a frequency domain to predict wheel speed sensor signal, and enhance Signal-to-noise [4]. Some domestic scholars had studied in-depth researches about measurement error and filtering techniques of wheel speed signal, in their approach, digital variable gain filter of Karman filter structure was proposed [5]. In addition, during the researches had studied anti-interference processing method of wheel speed signal, the method for smoothing processing data was proposed [6], and the method for processing wheel speed signal by using wavelet algorithm mean squared error threshold quantization based on improved threshold, analyzing wheel speed signal both in time domain and frequency domain at the same time was achieved, the filtering effect of this method is excellent [7].

In this paper, the cause of noises and the problem of signal acquisition were analyzed starting from wheel speed signal in high-speed. Based on narrow frequency domain and high energy of true signal, and wide-band signal and low energy of noise signal, a new method to process wheel speed signal was presented by using FFT (Fast Fourier Transform) and IFFT (Inverse Fast Fourier Transform) algorithms. Namely, transforming wheel speed signal which in a time domain into frequency domain using FFT firstly, "filtering" the wide-band noises in a frequency domain using polynomial fitting method secondly, and transforming waveforms of the noise spectrum into real signal inversely thirdly [8].

II. CHARACTERISTICS OF WHEEL SPEED SIGNAL AND CAUSES OF GENERATING NOISE

In the process of driving vehicles, with increasing speed, stronger signal noises are generated by the interference inside and outside a vehicle. Fig. 1 to Fig. 2 are the output signal waveforms which were collected by magnetic sensors installed in a given vehicle segment in the conventional method, and the three figures correspond to the vehicle speeds at 80 km/h and 160 km/h. Signal frequency and average amplitude increased with speed increasing, but the changes of the waveforms were irregular. The waveform was regular sine wave when the vehicle speed was 80km/h, but the evident distorted waveform which was the superposition of a sine wave and the noise signal, was relatively disorder at the speed of 160km/h.

The waveforms above show wheel speed signal at high speed have following characteristics: (1) Wheel speed signal was prone to appear the situations of pseudo impulses (increasing pulse) or missing impulse signal; (2) The amplitude and the phase position of Signal impulses which was no longer a sine wave had changed obviously; (3) Generation of the case that noise signal was superimposed on normal signal generating was strong randomness.

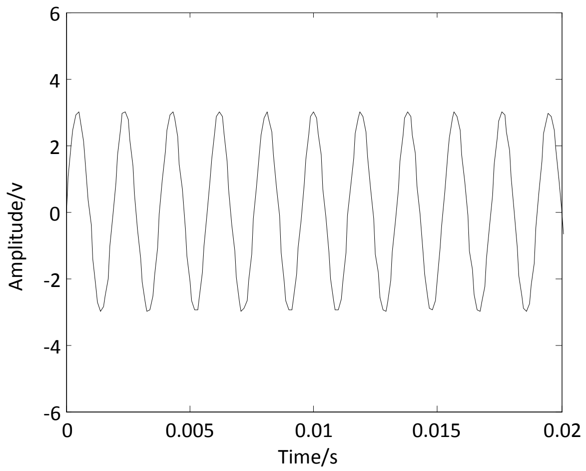


Fig. 1. The wheel speed sensor signal(80km/h)

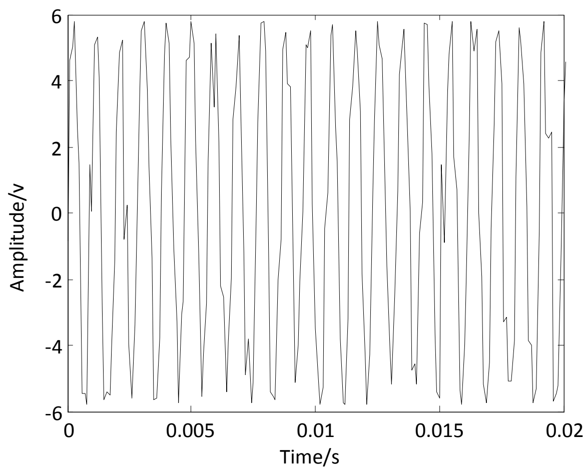


Fig. 2. The wheel speed sensor signal(160km/h)

There are three main causes result in generating wheel speed noise [9]: The first causes are pseudo impulse signal, missing impulse signal and other gross errors, which are caused by wheel vibration or sensor vibration. A change of relative position of the wheel and the sensor is caused at the same time, and the change occurs in the time of the sensor facing to tooth space or tooth crest of the fluted disc. In this situation, pseudo impulses and missing impulse signal are generated possibly. The second cause is narrow band noise whose frequency is low and frequency range is narrow, which is the superposition of normal wheel speed signal and the signal which is caused by the wheel torsional vibration. Road excitation and driveline excitation cause the wheel torsional vibration. The third is wide band noise, which is caused by circuit outside interference and environmental interference. Circuit boards on-vehicle are equipped with a variety of relays, transformers, solenoids and other inductive circuit devices. These devices work frequently in the circuit, thus generate induced noises. Besides, a variety of electromagnetic waves in the atmospheric environment also make induction sensors inducing broadband but small amplitude induced noises.

The noises in the signal make it difficult to obtain the instantaneous wheel speed signal precisely. By acquiring imprecise wheel speed signal, calculated wheel slip ratio or slip rate, yaw rate and other motion parameters also will appear a larger divergence and a larger errors, and thus affecting the effect of security control [10].

III. FAST FOURIER TRANSFORM OF WHEEL SPEED SIGNAL

According to the analysis of collected wheel speed signal and noise signal on the real vehicle, we can see the real wheel speed signal are strong (large amplitude), the change of frequency is small during a relatively short time (for example, an acquisition cycle). On the contrary, noises are small amplitude, the frequency of which ranges in a wide range. Because the features mentioned above of wheel speed signal, processing method for wheel speed signal based on FFT/IFFT was designed, "filtering" noises in a frequency domain, eliminating noises and transforming waveforms of the noise spectrum into a time domain inversely, as shown in Fig. 3.

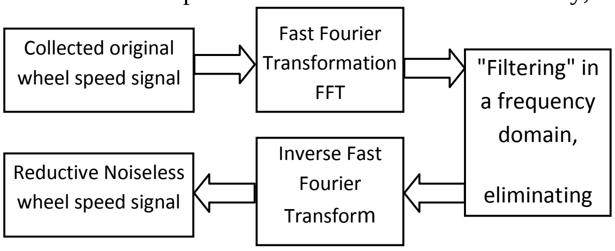


Fig. 3. FFT / IFFT filtering flow

FFT is a fast algorithm of DFT (Discrete Fourier Transform). According to odd, even, true, real and other characteristics of the discrete Fourier transform, FFT is a improved discrete Fourier transform algorithm. FFT is divided to the FFT algorithm by the time and the FFT algorithm by the frequency. The former is decomposing the sequence into two shorter sequences based on the sequence number is odd or even; the latter is dividing the sequence into before and after two sequences, and the numbers of two parts are equal. FFT algorithm is used in this paper [11].

Data collected by electromagnetic induction wheel speed sensors are time data sequence and the voltage value sequence of its corresponding wheel speed signal:

to,t1,t2,…,tn, …,tN

xo,x1,x2,…,xn…,xN

Where N is the total number of collected data, n is a data in the sequence. By the DFT transform above equation:

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

Where $0 \le k \le N-1$, WNnk is twiddle factor.

By dividing x(n) into two groups according to the parity of n, each of whose variable substitution is easy to get:

$$x(2r)=x1(r) \quad x(2r+1)=x2(r) \quad (2)$$

Where r=0,1,2,…,N/2-1

Substituting Eq. (2) into Eq. (1) gives the following equation:

$$X(k)=\sum_{r=0}^{N/2-1} x_1(r)W_N^{2rk}+W_N^k\sum_{r=0}^{N/2-1} x_2(r)W_N^{2rk} \quad (3)$$

thus: $$W_N^{2n}=e^{-j\frac{2\pi}{N}2n}=e^{-j\frac{2\pi}{N/2}2n}=W_{N/2}^{2n} \quad (4)$$

By Eqs. (3), (4), we can get:

$$X(k)=X_1(k)+W_N^k X_2(k) \quad (5)$$

According to the cyclical nature of the coefficient of WN :

$$W_{N/2}^{r(N/2+k)}=W_{N/2}^{rk} \quad (6)$$

then: $$X_1(N/2+k)=\sum_{r=0}^{N/2-1} X_1(r)W_{N/2}^{rk} \quad (7)$$

therefore: X1(N/2+k)=X1(k) (8)

Similarly: X2(N/2+k)=X2(k) (9)

According to the symmetry of WNk :

$$W_N^{r(N/2+k)} = W_N^{N/2}\ W_N^k = -W_N^k \tag{10}$$

therefore: $$X(k) = X_1(k) + W_N^k X_2(k) \tag{11}$$

$$X(N/2+k) = X_1(k) - W_N^k X_2(k) \tag{12}$$

Where k=0,1,2,…,N/2-1

The operations of Eqs. (11) and (12) are usually named after butterfly operation, the operation process as shown in Fig. 4.

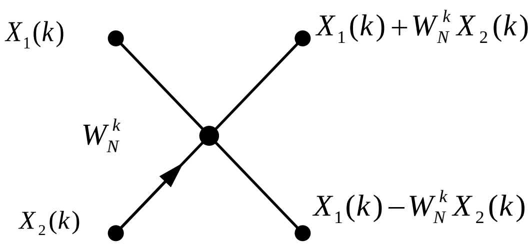


Fig. 4. Butterfly operation

In Fig. 4, the two lines on the left are inputs, and the two lines on the right are outputs. Inputs and outputs are separated by a small circle which represents addition or subtraction (the upper right road for the added output, the lower right road for the subtraction output). If the signal in a branch needs a multiplication, it is a necessary to mark arrows on the branch, and mark the multiplication coefficient on the side. Fig. 5 describes wheel speed signal was transferred into a frequency domain by using FFT in this expressive method.

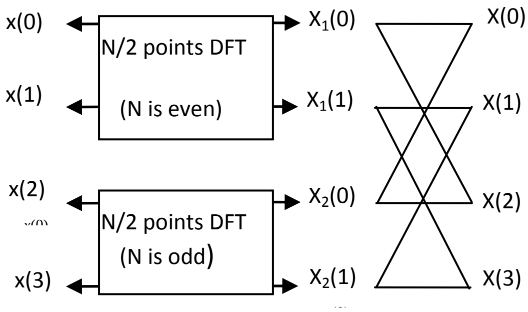


Fig. 5. The algorithm principle of FFT/IFFT (N=4)

By transferring wheel speed signal data in the time domain to the frequency domain using FFT, obtain its corresponding frequency spectrum. Fig. 6 to Fig. 7 are the frequency spectrums, and the three figures correspond to the vehicle speeds at 80 km/h, 120 km/h and 160 km/h.

IV. ELIMINATING SIGNAL NOISES IN FREQUENCY DOMAIN

By analyzing the speed signal spectrums after FFT transform, we can get the conclusion that the real wheel speed signal are narrowband and high-energy signal, while the noises are broadband and low-energy signal. A process of "filtering" in frequency domain means keeping the energy amplitude of the signal frequency components, and attenuating the energy amplitude of the noise components.

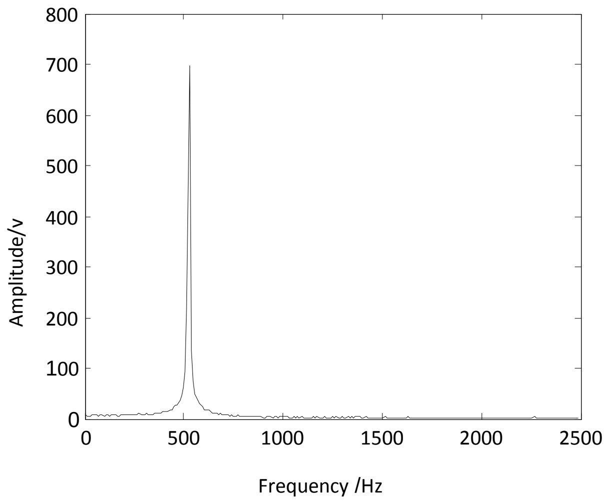


Fig. 6. The spectrums (80Km/h)

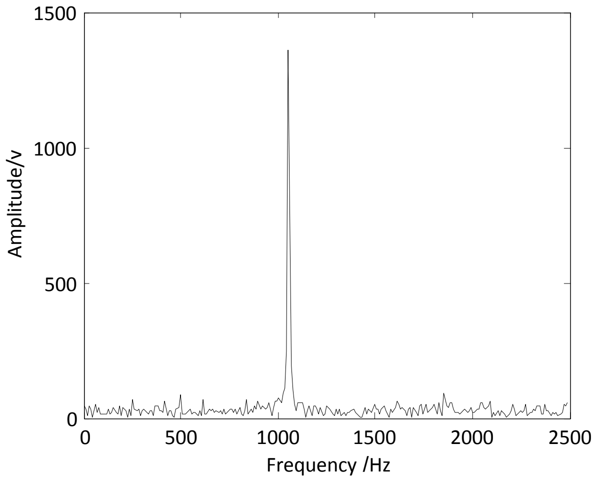


Fig. 7. The spectrums (160Km/h)

Table 1 gives out each frequency component of wheel speed signal sequence which is transferred by using FFT and the corresponding energy amplitude sequence.

Table 1 The frequency of signaland the corresponding energy amplitudes

Frequency/ f	f0	f1	…	fi	…	fn
Energy amplitude/X	X0	X1	…	Xi	…	Xn

The appropriate upper and lower cutoff frequency that the "binding site" of the frequencies of original signal and noise signal, are determined according to the difference of energy between the two signal. The selection of the upper and lower cutoff frequencies are about the frequency range of the real signal, and therefore the highest energy value and the corresponding center frequency should be determined.

At first, the center frequency of signal that is fi, the corresponding energy amplitude Xi is the maximum amplitude, Xmax= Xi; then determining the appropriate coefficients a and b of the amplitude of Signal-to-noise:

Xs/Xmax=a Xx/Xmax=b

The two correspond to the energy amplitude of the upper and lower cutoff frequency respectively, namely, each of the upper and lower cutoff frequency fs and fx is corresponded to the frequency of Xs and Xx. The pass band of wheel speed signal is fs ~ fx, both ends of the band are bands which need to filter noises. As shown in Fig. 8.

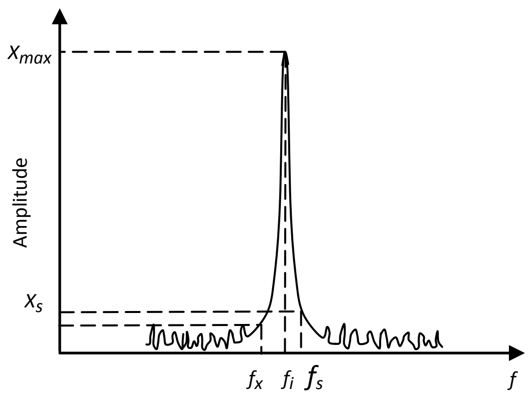


Fig. 8. The division of filtering bands

As you can see by the principle of Fourier transform, any continuous periodic signal can be made up of an appropriate combination of a set of sine curves. Therefore, for the fitting of spectrum curve correctly, it would be necessary to restore the real time domain signal. The principle of curve fitting is constructing new spectrum curve, using the fitted function to reduce the amplitude of the noise component, meanwhile make every frequency component of the new fitted function to satisfy the relationship of Fourier transform, and restore every frequency component to real wheel speed signal after IFFT processing.

Table 1 shows the corresponding relationship of frequency and signal energy; Eq. (13) expresses the function of after curve fitting:

$$[X0,X1,\ldots,Xn]=F[f0,f1,\ldots,fn] \qquad (13)$$

Generally, Eq. (13) is a first-order polynomial or quadratic polynomial. After fitting the signal energy, the noise component of which is suppressed, substituting the frequency value into Eq. (13) again, the sequences of the fitted values of frequency and energy are:

$$f0, f1, f2 ,\ldots\ldots,fi , \ldots\ldots,fn$$
$$X1',X2',X3',\ldots,Xi',\ldots,Xn'$$

The process of filtering in domain frequency of wheel speed signal at speed of 160km/h is shown for illustrating. Looking at the curve within cutoff frequency in Fig. 9, the number of fitting is determined to 2 with a preliminary. The fitted spectral curve and the time domain curve of after IFFT reduction are shown in Fig.9 and Fig.10 respectively.

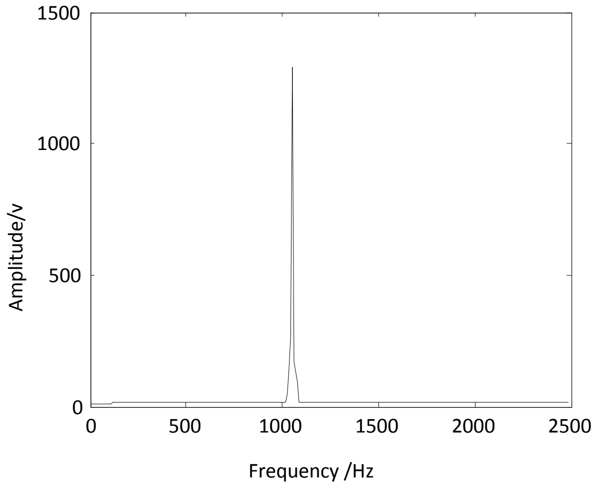


Fig. 9. The spectral curve after filtering in frequency domain

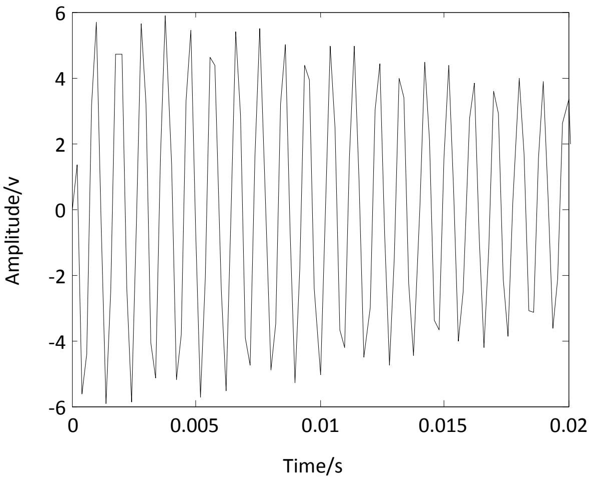
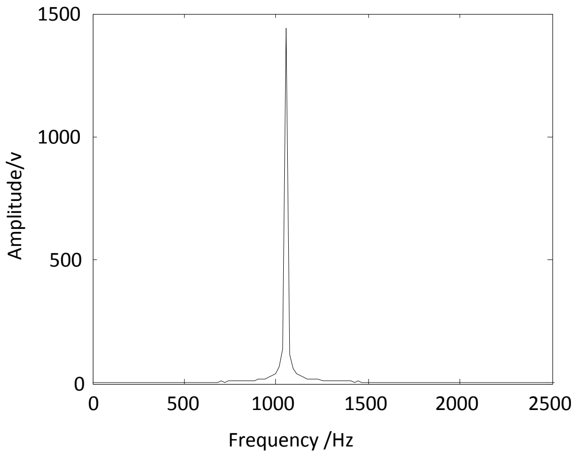


Fig. 10. The time domain graph after IFFT inverse transform

As shown in Fig. 10, the noise signal after fitting in time domain is eliminated substantially, periodic is uniform, but the amplitude of the signal is distortion. The continuous but not differentiable points, that operate in the situation of the fitting part of the spectrum curve at the transition is more abrupt, contribute to a reason why the distorted signal occurs. The noise band is divided into two sections, the section near the center frequency needs a higher order polynomial fitting, so that each section of the curve in continuous conduction. The spectral curve after piecewise fitting and the time domain graph of wheel speed signal after IFFT inverse transform are as shown in Fig.11and Fig.12 respectively.



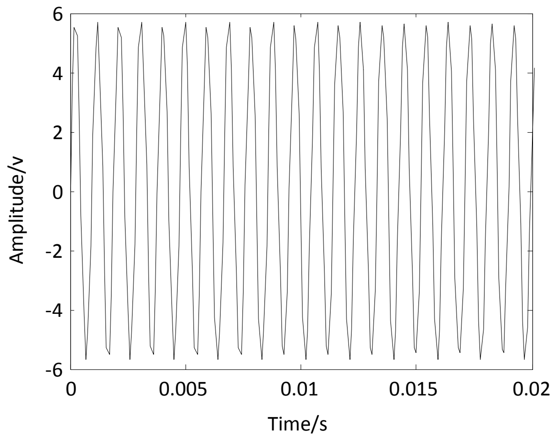


Fig. 11. The spectral curve after piecewise fitting Fig. 12. The time domain graph of wheel speed signal after IFFT inverse transform

According to the plot in Fig.12, the correct spectral curve can be fitted after piecewise fitting, the fitting out of, a true wheel speed signal is restored by using IFFT.

V. ROAD TEST

In order to verify the ultimate effects of processing wheel speed signal using FFT and IFFT, road comparison tests with Jetta sedan are done. The wheel speed sensor signal is directly connected to the number 1 analog channel of data acquisition system; the wheel speed sensor outputs after low-pass filtering and Karman filtering are connected to the number 2 counting channel of the data acquisition system; the output of the true corner which was measured by grating wheel angle / speed sensor wheel in every turn 1000 pulses within a certain distance traveled is connected to the number 3 digital counting channel of the data acquisition system. The frequency of the data acquisition system is 100 KHz. After processing the wheel speed signal collected by analog channel by using FFT and IFFT, writing down the pulse number.

The pulse coefficient of the grating sensor is 0.36°in every pulse. The wheel turned angle φ can be calculated by the pulse number recorded by the counter. The fluted disc of wheel speed sensor has 44 teeth, each pulse corresponds to the wheel rotation of 9 °. The real number of pulses Nz can be calculated according to the rotation angle of four wheels. Comprising the pulse number ND recorded after circuit filtering, the pulse number NK recorded after Karman filtering and the pulse number NF recorded after the processing of FFT/IFFT to Nz respectively, each of filtering effects is judged based on respective corresponding relative error.

Road test chooses three kinds of speed of 80 km/h,120 km/h and 160 km/h as the test speeds, the average of two driven wheels as the collecting data, 200 meters as the collection distance, and when the grating sensor counts to reach 100000, test is over. Actual wheel turns 100 rpm, the number of real wheel speed sensor pulse Nz is 4000. Each of the counted errors after three filters was shown in Table 2.

Table 2 The effects comparison of three kinds of filtering

Items	Units	Wheel speed(km/h) 80	120	160
the pulse number of grating sensor	thousand piece	100	100	100
the pulse number of real wheel speed sensor Nz	piece	4000	4000	4000
the count pulse number after circuit filtering	piece	3998	3994	3990
ND and error	%	0.05	0.15	0.25
the count pulse number after Karman filtering	piece	4000	3997	3995
and error	%	0	0.075	0.083
the count pulse number after FFT filtering NF	piece	4000	4000	3999
and error	%	0	0	0.025

From Table 2 above, compared to hardware circuit filtering and Karman filtering, the error of FFT filtering in frequency domain is smaller, more precise, the filtering effect is obvious.

VI. CONCLUSION

The wheel speed signal of the vehicle and the data based on calculate of the wheel speed signal are foundations for automotive effective security control. However, at high speed, the noise of wheel speed signal and the divergence of calculated data make the control effect reducing.Though using conventional software and hardware filtering in time domain to reduce the wheel speed signal noise can have an effect, but can not eliminate the noise completely.Based on the differences of frequency distribution and energy amplitude of true signal and noise signal, wheel speed sensor signal was transformed from a time domain into a frequency domain for processing by using FFT, then "filtering" the noise frequency by using polynomial fitting method for noise band data, and restoring the filtered noise frequency into time domain to eliminate noise in the signal effectively. Road test shows that the effect of eliminating the noise is quite good.In process of frequency filtering, the selections of cutoff frequency and polynomial fitting method for noise band data have a certain effect on frequency filtering.The processing method of FFT/IFFT for wheel speed signal has a obvious effect on reducing gross error and improving the accuracy of acquisition and other aspects, true signal is well restored. In this paper, the effect of applying the processing method was only carried on the preliminary attempt, the method and technique about frequency domain filtering are still need to conduct a more in-depth discussion.

VII. ACKNOWLEDGEMENTS

This work was financially supported by the National Natural Science Foundation (51175450), Hebei Province Natural Science Foundation (E2012203046).

REFERENCES

[1] Li Pu, Song Jian, Yu Liangyao. Treatment method of anti-interference of ABS wheel speed signal.*Automobile Technology*, 2001, 5. 15-18.
[2] T. Hsiao, M. Tomizuka. Sensor fault detection in vehicle lateral control systems via switching karman filtering . *ACC'05*, 2005. 209-222.
[3] Li Xu, H. E. Tseng. Robust model-based fault detection for a roll stability control system . *IEEE Transaction on Control System Technology*, 2007, 15(3):519-528.
[4] Wilmar Hernández. Improving the response of a wheel speed sensor using an adaptive line enhancer. *Measurement*, 2003, 33(3):229-240.
[5] Liu Guofu, Wang Yueke, Zhang Qi, Zheng Weifeng. Study on the filer technique in ABS wheel speed signal. *Automotive Technology*, 2004, 22 (3).22-24.
[6] Li Pu, Song Jian, Yu Liang-yao A preconditioning algorithm of singular point rejecting for wheel speed signal processing in anti-lock brake system.*Journal of Higyway and Transportation Research and Development*, 2001,8(4):119-123.
[7] Jiang Kerong, Tang Xiangqing, Zhu Dequan. Automobile wheel speed signal processing based on wavelet algorithm of improved threshold. *Journal of Scientific Instrument*, 2010,31(4). 736-740
[8] Cheng Peiqing．*Digital signal processing tutorial*．Beijing：Journal of Tsinghua University, 2007.
[9] Fang Yugu, Ding Nenggen, Pan Weimin. Analysis of the distort of wheel speed pulse signal and the processing of software anti-interference. *Automotive Engineering (Suppl.)*，2003,10：119-120.
[10] Sun Shangzhi, Chen Yanfu, Sun Jun. Study on SNR of wheel speed sensor signal in ABS. *Automobile Parts*, 2010, (12):59-60.
[11] Fang Jie, Zhang Ke, Wang Rui, et al. Study on improved FFT algorithm and Applications. *Sichuan Electric Power Technology*, 2007, 6(30):9-11.