DESIGN AND IMPLEMENTION OF AN AUTOMOBILE MULTI-FUNCTIONAL TESTER BASED ON USB DATA ACQUISITION CARD

Lijin ZHANG[1], Miaozhong SUN[1], Yuanli XU[1]

In order to meet the requirements of automobile vibration signal processing, analysis and automobile performance parameter testing, an automobile multi-functional tester is realized by using Matlab and Delphi mixed programming technology based on USB data acquisition card, which possesses such functions like eight-channel signal data acquisition and storage, signal processing and analysis(specially time-frequency combination methods). By using the Component Object Model (COM) technology, M Matlab files can be compiled and become the dynamic link library (DLL) files. The DLL files can be installed and called on the Delphi platform to carry out nearly 30 signal processing and analysis methods for the tester. Some novel time-frequency combination methods are proposed and implemented to be used to analyze non-stationary signal to effectively extract signal frequency characteristic information. The developed tester is used to test four sensors of the PASSAT automobile electronic control test-bed, and analyze a simulation signal, and analyze the vibration signals sampled from a FOTON type engine. Through comparing their results, the tester is validated to be effectiveness. This tester can also be applied to other fields of vibration signal processing and analysis.

Keywords: Data acquisition, Mixed programming, Time-frequency analysis, Time-frequency combination method, Automobile multi-functional tester.

1. Introduction

Engine faults are usually diagnosed by analyzing engine vibration signals to extract frequency characteristic information, and increasingly by making use of modern signal processing and analysis methods. Engine vibration signals have characteristics of multi-component and non-stationary. Time-frequency analysis methods are effective to localize time and frequency characteristic information [1]. How to improve the effectiveness of vibration signal analysis and develop an automobile multi-functional tester that owns data acquisition, multi-functional signal processing and analysis methods has always been a technical key issue for

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scientific researchers. In recent years, research on automobile testers has brought about some achievements in vibration test analysis system after continuous hard study. For example, A.K.Desai et al [2] developed an automobile engine vibration test system based on LabVIEW, which possessed functions including signal acquisition, historical data reading, data filtering and some signal analysis methods with the help of a PC platform, but there are not any time-frequency analysis methods in the system. Yuanfeng Gu et al [3] exploited a vibration test system for the internal combustion engine also based on LabVIEW. The system only had some analysis methods like FFT, Winger distribution and Wavelet analysis. But there are few reports on automobile multi-functional testers, which have such functions combining automobile performance parameter detection with more time-frequency signal analysis methods in scientific journals. The above developed vibration test systems were carried out with the LabVIEW programming platform, while other systems adopted VB, VC++ and other programming platforms. These platform languages are very difficult to program for the various signal processing and analysis methods.

MATLAB toolbox contains many calculation algorithms (functions) such as signal processing, wavelet analysis, image processing, and time-frequency analysis etc. The corresponding functions can be directly called to implement complex signal processing and analysis. But these functions cannot run independently from the MATLAB environment and have poor performances on running speed and visual programming interface [4]. Delphi is an object-oriented programming language for visual interface. Delphi's control components are used to quickly build a visualization interface. But Delphi is very difficult to program for signals processing and analysis. By using mixed programming, these advantages between Delphi and Matlab will be complemented fully, realizing the test systems more easily and shortening the development cycles more effectively [5].

In this paper, the Delphi platform is first applied to program and design to achieve the functions including 8-channel large-capacity continuous data acquisition, real-time waveform display, data storage and data playback. Then, by using Matlab and Delphi mixed programming, the tester is designed to realize nearly thirty methods of signal processing and analysis for vibration signals. And in this tester, some novel time-frequency combination methods are proposed and implemented, which increase the analysis abilities of current automobile testers.

2. The structure of the test system

The structure of the test system is shown in Fig. 1, consisting of hardware and software.

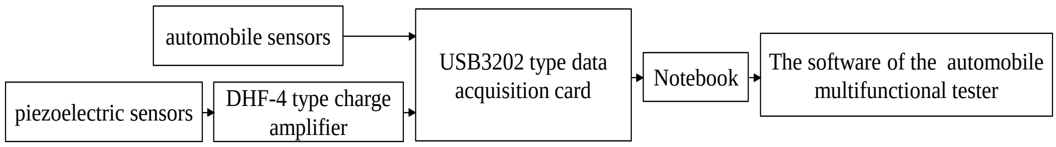


Fig. 1. The structure of the test system

A USB3202 type data acquisition card manufactured by Art Beijing Science and Technology Development Co., Ltd. is used, which possesses the FPGA core at the high asynchronous speed, 16-bit resolution, eight-channel input, single channel sampling speed up to 250 KHz and internal 4K data buffer. It is able to connect with a computer at the USB high speed up to 480MB/s, and support the mode of plug and play, and link to a notebook to be carried more conveniently.

Two testing methods are used in this structure: (1) Automobile sensors connected with the data acquisition card are tested by the automobile multi-functional tester through the USB bus. (2) Vibration signals are sampled first by piezoelectric acceleration sensors, and then the sampled signals are amplified by the DHF-4 type charge amplifier, and the amplified signals are finally analyzed by the software of the automobile multi-functional tester through the data acquisition card.

During the signal analysis, the signals can be displayed, storage in real time, processed and analyzed (including time-frequency analysis). In order to verify the effectiveness of the tester, these two testing methods will be performed later.

3. Programming framework and system software interface

A programming framework of the automobile multi-functional tester is shown in Fig. 2. It is divided into four parts: parameter setting module, data acquisition module, data analysis module and data playback module. Signal processing and analysis can be performed at the same time during signal acquisition and data playback. The signal processing and analysis methods include digital filtering methods, stationary signal analysis methods, non-stationary signal analysis methods and combined time-frequency analysis methods. The running interface of the automobile multi-functional tester is shown in Fig. 3. The sequence numbers of each part of the interface are marked in the figure, and the names corresponding to these sequence numbers are displayed below the figure.

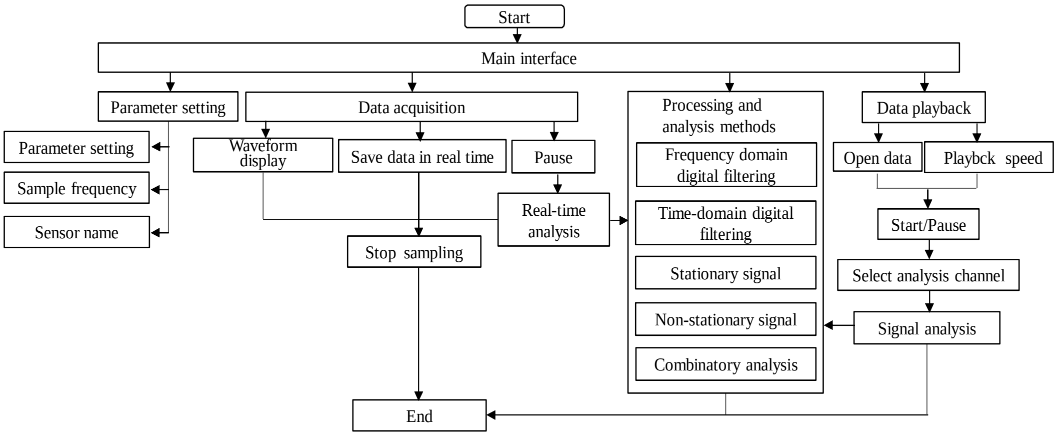
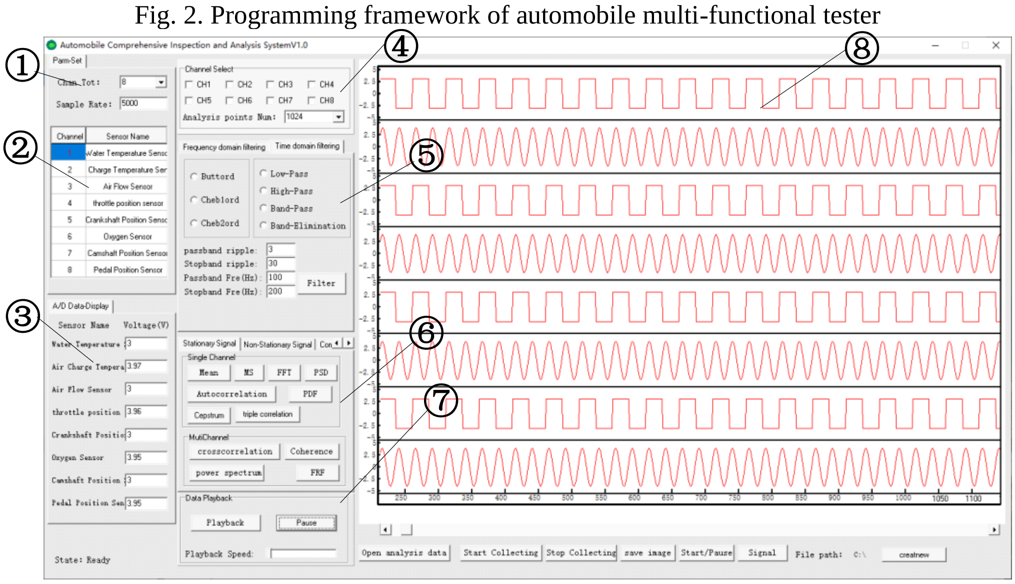


Fig. 2. Programming framework of automobile multi-functional tester



① Acquisition parameter selection module ② Sensor name setting module
③ A/D data numeric display module ④ Channel selection and analysis point setting module
⑤ Digital filter module ⑥ Signal analysis method module ⑦ Data playback module
⑧ the module of Waveform display, data playback and signal analysis
Fig. 3. Software interface of automobile multi-functional tester

3.1 Data acquisition module

The automobile multi-functional tester supports 8-channels large-capacity continuous acquisition, which can display real-time waveforms and storage the real-time data to the hard disk. The maximum storage data capacity depends on the size of the hard disk. Before data acquisition, it is necessary to set the parameters such as the sampling frequency and the total sampling channel number. The channel sensor names can be modified according to the testing sensors. Click New File button to create a file to storage the sampled data.

3.2 Data playback module

Replaying the tested data is an important function used to observe the history state of the signal. Data playback can be performed in real time through waveform display and numerical display. During playback, the playback speed can be adjusted at any time, and the signal data can be replayed to any data point to check the reliability of the signal.

The storage data are played back by clicking the Open Analysis Data button. Fig 3 shows the data playback process of four rectangular waves and four sine waves generated respectively by a SF-DDS type signal generator. The generator channel A outputs a 100Hz rectangular wave with peak-to-peak value of 6V and the channel B outputs a 200Hz sine wave with peak-to-peak value of 8V. Channels 1, 3, 5 and 7 of the acquisition card are connected with the rectangular wave signal, and channels 2, 4, 6 and 8 are connected with the sine wave signal. The sampling frequency is set 5000Hz. Fig. 3 displays the all sampled signals are replayed completely, and there are no missing points. In the waveform display window, the abscissa shows the position of the data point; the ordinate shows the voltage value of each channel signal. At the same time, the voltage value of the playback point of each waveform is displayed in the corresponding number box of the A/D data display module. During data playback, the playback speed can be adjusted by moving the slider bar.

3.3 Signal processing and analysis module

A block diagram of signal processing and analysis methods is shown in Fig. 4.

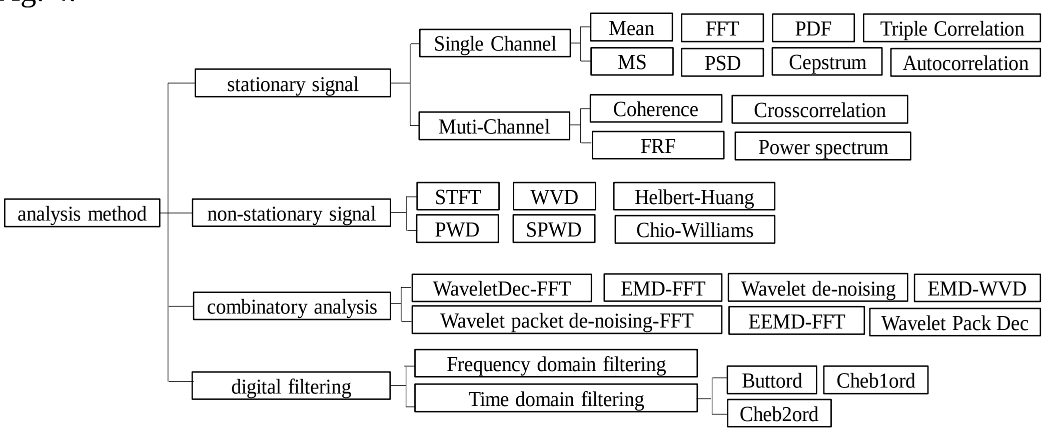


Fig. 4. Block diagram of signal processing and analysis methods

The signal processing and analysis module is designed to be the core module of the automobile multi-functional tester. It is divided into four sub-modules that are digital filtering, stationary signal analysis, non-stationary signal analysis, and combinatory analysis. Input the analysis channel numbers and analysis points in the channel selection box. Click required method button to carry out corresponding signal processing and analysis.

4. Design for system programs

In programming, Delphi drivers and functions of the USB3202 type data acquisition card provided by the manufacturer are chosen to control the port interfaces of the acquisition card and perform data acquisition, data storage and data playback.

4.1 Data sampling and Playback programming

The driving functions of the data acquisition card are called to realize data sampling. The block diagram of data sampling programming is shown in Fig. 5. First, call the AI_InitTask () function to initialize the acquisition card according to the sampling parameters, then call AI_StartTask () to start the sampling task, and call the AI_ReadBinary () function to read the sampling data (from the data acquisition card) in a binary mode and write them to the computer's ring buffer. Before reading the sampling data again, it is necessary to determine whether the sampling parameters are the same. If they are the same, continuous sampling is performed without interruption. Otherwise, the AI_StopTask () is called to stop the sampling task, then re-initialize or stop sampling, and release the device object.

Data playback is the playback of the saved signal data. Some part data is read from the data file into the data ring buffer area by Delphi programming. The timer control component in Delphi is used to implement the programs for data reading and waveform drawing.

4.2 Delphi and Matlab mixed programming

The COM technology of Matlab programming platform provides a unified communication protocol for the Windows programming, through which implements mixed programming with the Delphi, VB, VC++ and other platforms. And the shortcomings of each compiler platform are made up by the mixed programming. In Matlab platform, the VC6.0 compiler is carried out to compile the M files into files of dynamic link library (DLL) by the Matlab COM Builder, and the DLL files are registered on Windows system. Then in Delphi platform, the registered DLL files are installed in Delphi development environment through the Import type library. Once the DLL files are installed successfully, they can be used as same as the other control components of Delphi. Using the above DDL files, the mixed programming of Delphi and Matlab can be realized [6]. The Flow chart of mixed programming is shown in Fig. 6.

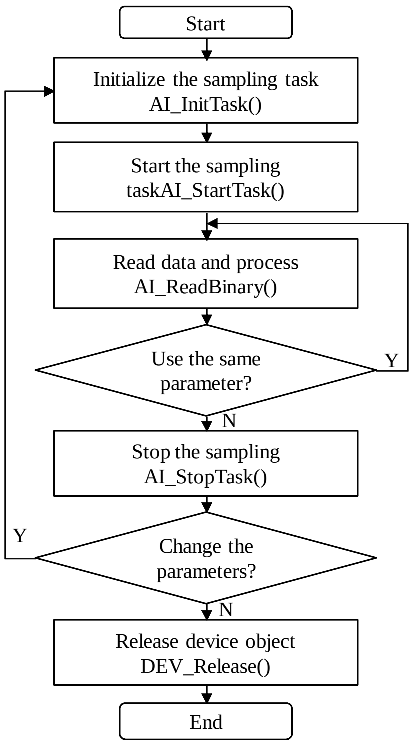


Fig. 5. Flow chart of data sampling

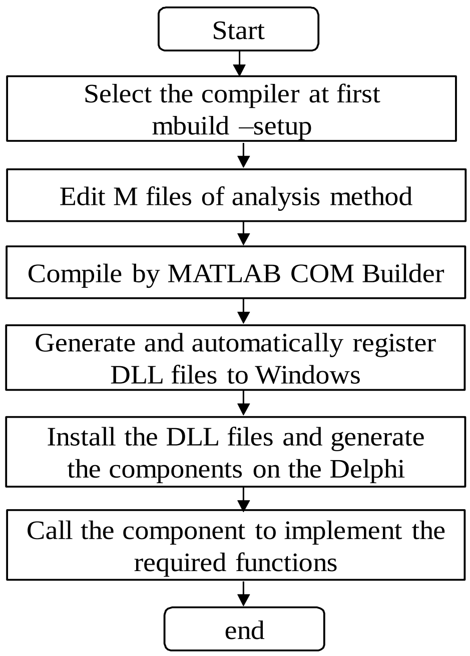


Fig. 6. Flow chart of mixed programming

4.3 Programming for time-frequency combination methods

In order to better extract the frequency characteristic information of non-stationary signals, two or three time-frequencies methods are combined to analyze signal to make the analysis result more accurate and clearer, for example, wavelet decomposition and FFT, EMD-WVD, and EEMD-FFT. The EMD-FFT combination analysis method is taken as an example to illustrate its implementation process.

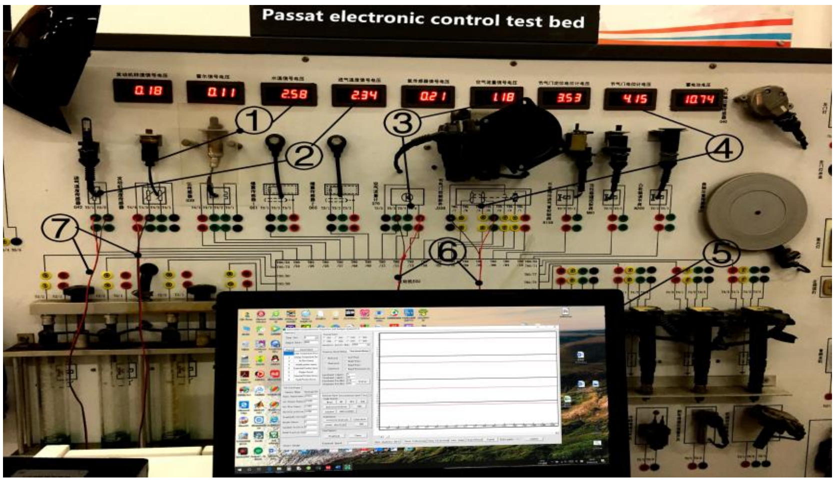
By using the EMD filter characteristics, a complex signal can be decomposed into IMF components and a simple trend term. Then the FFT method is used to analyze each of them to obtain their spectrums. As shown Fig. 10(c), EMD-FFT analysis method is used to decompose the simulation signal into 8 IMFs and a trend term. Through FFT analysis, the spectrum results can distinguish effectively which are the interference signals and which are the feature signals.

5. Tester effectiveness verification

In order to verify the effectiveness of the automobile multi-functional tester, three methods are used: (1) to sample and analyze the sensor signals of a test-bed of PASSAT electronic control. (2) A non-stationary simulation signal is set up to be analyzed using the relative tester analysis methods; (3) to test and analyze vibration signals of a FOTON BJ493ZQ3 type engine.

5.1 Testing on a test-bed

Fig. 7 shows the testing case of the PASSAT electronic control test-bed. Four sensors including the intake air temperature sensor, the engine water temperature sensor, the air flow sensor and the throttle position sensor are connected respectively with the four channels from NO.1 to No.4 of the data acquisition card. Their voltages are displayed on the test bed in the case of the idling running. At the same time, the automobile multi-functional tester starts to sample the four sensor signals. The sampling frequency is chosen 5000Hz, and total number of channels is set 4. In Fig. 8, the four channel sampled data are displayed in the left module of the A/D data display, and the names of the four sensors are showed accordingly above the module. The four real-time waveforms are displayed clearly in the main window.



① Intake temperature sensor ② Engine temperature sensor ③ Air flow sensor④ Throttle position sensor ⑤ Automobile multi-functional tester ⑥, ⑦ Data cables
Fig. 7. Field testing case of PASSAT electronic control test-bed

Table 1 lists the result comparison between the four sensor signal voltages showed by the PASSAT electronic control test-bed and the corresponding voltages tested by the automobile multi-functional tester. Through the result analysis, it can be seen that the errors are below 5%. Thus, the effectiveness of the developed tester is verified. During a common engine test, data collection can be carried out simply by connecting the sensor under test to the data acquisition card and setting sampling parameters, then Click the start collection button and the collection will begin.

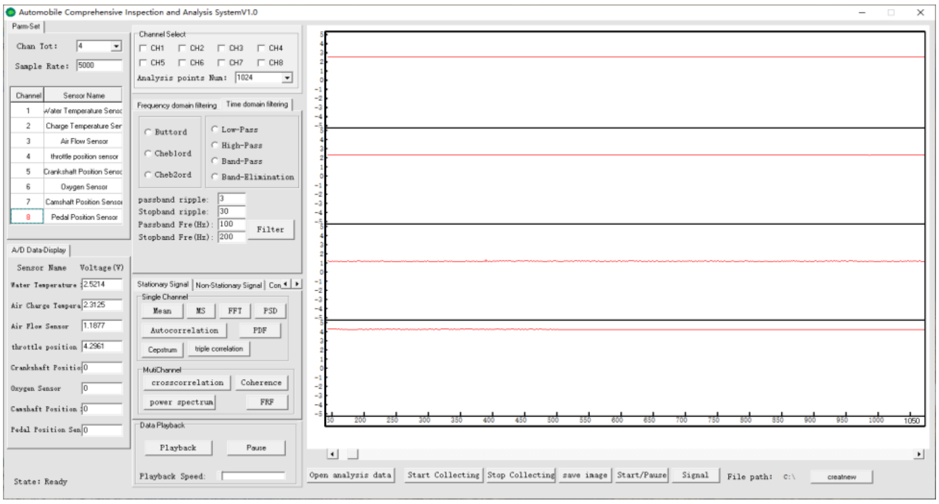


Fig. 8. Waveform and numerical display of the automobile multi-functional tester

Table 1

Comparison of the voltages displayed on the test-bed and the voltages tested by the tester

Sensor name	voltage displayed on the test- bed (V)	voltage tested by the tester (V)	Error (%)
Water temperature sensor	2.58	2.52	2.33
Intake air temperature sensor	2.34	2.31	1.28
Air flow sensor	1.18	1.19	0.85
Throttle position sensor	4.15	4.30	3.61

5.2 Simulation signal analysis

The vibration signals of the engine are non-stationary signals, which usually contain multiple frequency modulation (FM) components and periodic components [7]. A simulation signal needs to be established to imitate the engine vibration signal for checking the correctness of the analysis results.

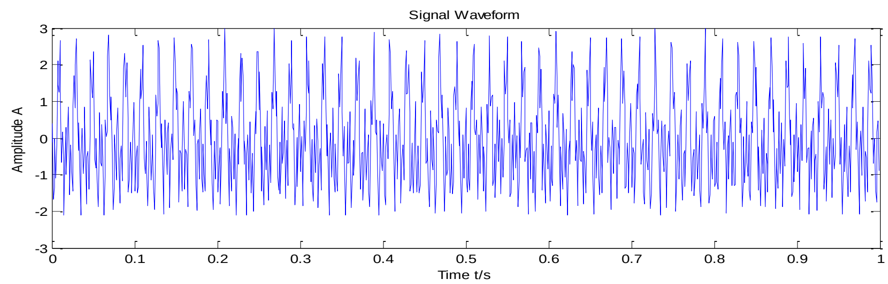
Set the simulation signal a $x(t) = x_1(t) + x_2(t) + x_3(t)$, $x_1(t)$ is a FM signal with a center 300Hz frequency and modulated by a $2\sin 20t$ sine wave, $x_2(t)$ and $x_3(t)$ are two cosine wave signals with frequencies of 50Hz and 100Hz, respectively.

$$x_1(t) = \sin(2\pi(300t + 2\sin 20t)) \quad (1)$$

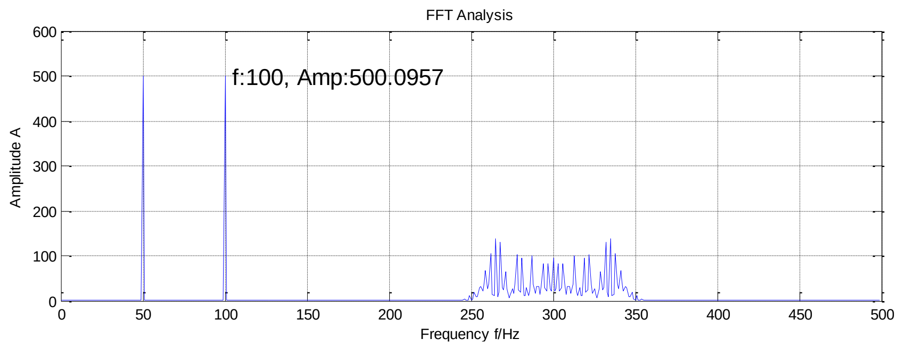
$$x_2(t) = \cos(2\pi \times 50t) \quad (2)$$

$$x_3(t) = \cos(2\pi \times 100t) \quad (3)$$

The sampling frequency is chosen 1000Hz, and the sampling points are 1000. The waveform of the simulated signal and its FFT result are shown in Fig. 9.



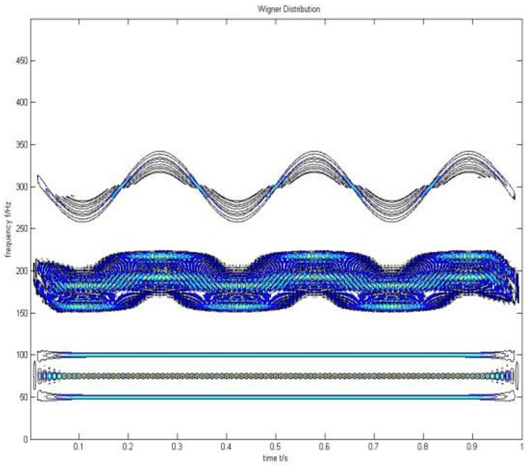
(a) Simulation signal



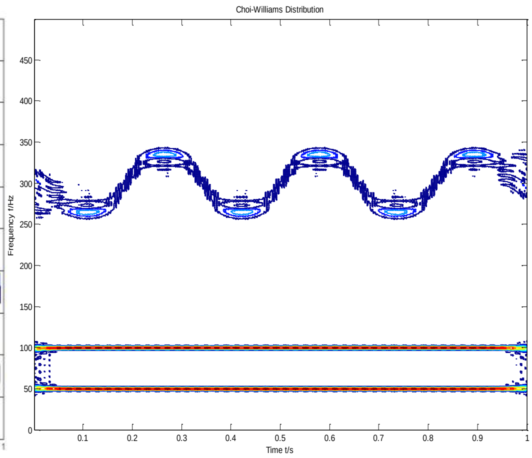
(b) The FFT result

Fig. 9. Simulation signal waveform and its FFT result

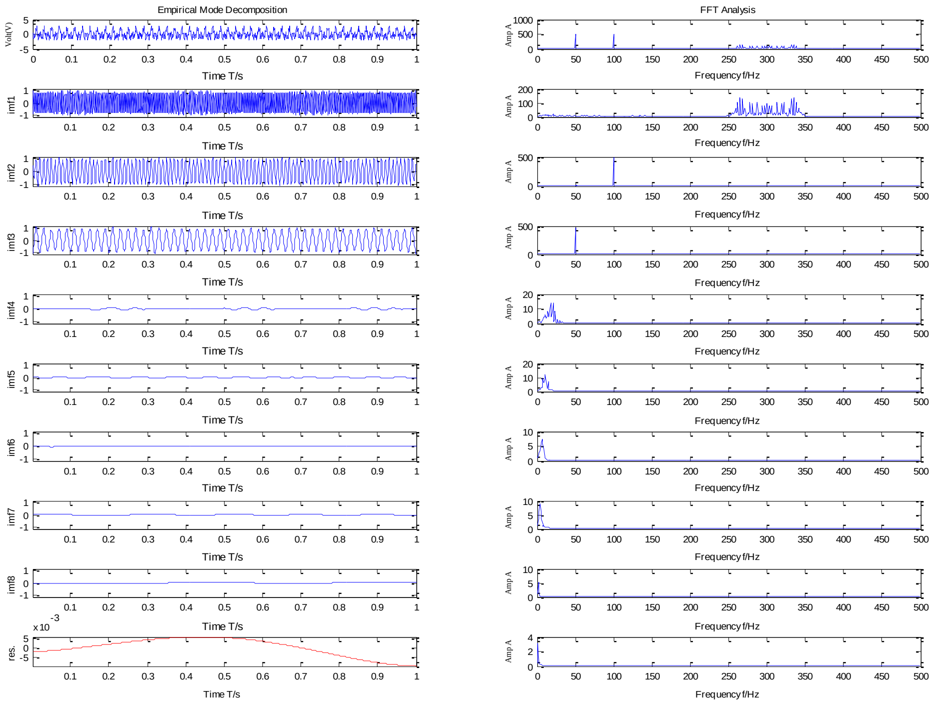
From the spectrogram, the three center frequencies of 50Hz, 100Hz and 300Hz are easy to be seen, which are consistent with their original signal frequency components. But the modulated frequency components around the 300Hz frequency are expressed to be fuzzy. Therefore, the FFT cannot clearly describe the non-stationary signal frequencies varying with the time. Fig. 10 shows the three results of the simulation signal using Wigner-Ville distribution (WVD), Choi-Williams distribution (CWD) and the combination method of EMD-FFT respectively.



(a) Wigner-Ville distribution



(b) CWD distribution



(c) EMD-FFT analysis

Fig. 10. Results of three signal analysis methods

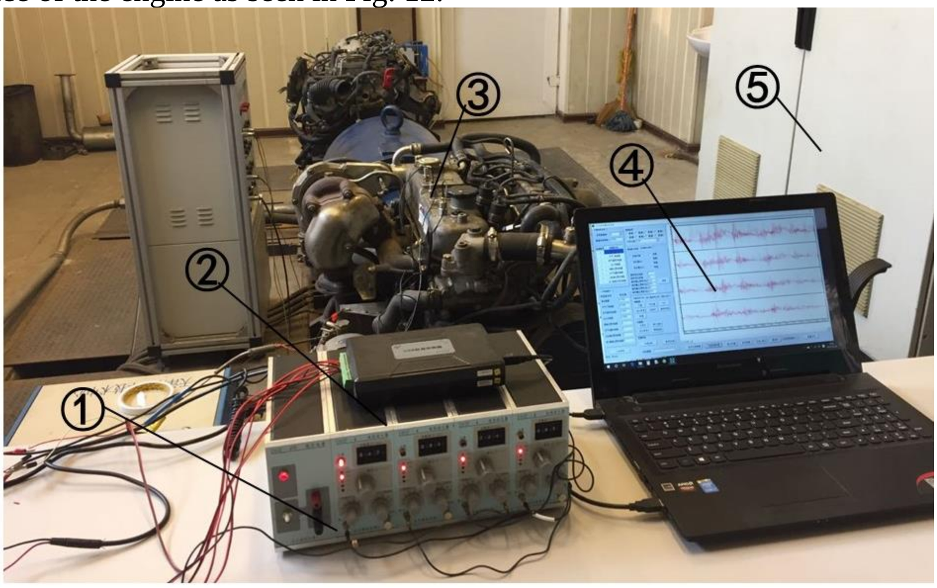
In Fig. 10(a), the Wigner-Ville distribution has a good time-frequency resolution. Due to the existence of multi-component signals, serious cross terms appear which lead to the ambiguous time-frequency characteristics of the signals. Fig. 10(b) shows that the CWD distribution can effectively suppress the interference of the cross terms, and has a better time-frequency resolution [8].

At the left of Fig. 10(c), the simulation signal is decomposed by EMD into 8 intrinsic model functions (IMFs) and a trend term. And at the right the FFT is used to analyze each IMF to show their corresponding results. It is clear that IMF1 is the frequency component of the FM signal; IMF2 and IMF3 are respectively the components of 100Hz and 50Hz frequencies. Due to the over decomposition of EMD, the pseudo components from IMF4 to IMF8 were generated. Correlation analysis method is also carried out respectively between these IMFs and the original signal; finally, the four false IMFs from IMF4 to IMF8 and the trend term can be eliminated because of their too small correlation coefficients [9, 10]. Through the above analysis results, the accuracy and the reliability of the automobile multi-functional tester are verified.

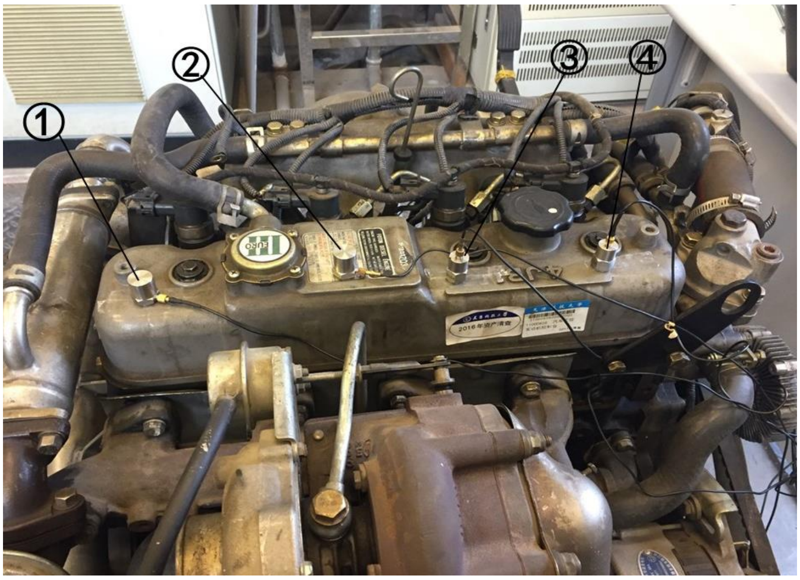
5.3 Testing and analysis for a engine vibration signal

Engine vibration can aggravate the serious wears and the fatigue damages of engine parts, leading to shortening greatly the life span of the engine. Engine vibration signals contain rich information on the vibration sources of engine running parts. Therefore, the novel analysis methods of vibration signals are important for engine performances to be researched.

Fig. 11 shows the testing case of a FOTON BJ493ZQ3 type diesel engine. The testing process is corresponding to the second method shown in Fig. 1. Four YD-12 type piezoelectric acceleration sensors are installed suitably on the top surface of the engine as seen in Fig. 12.

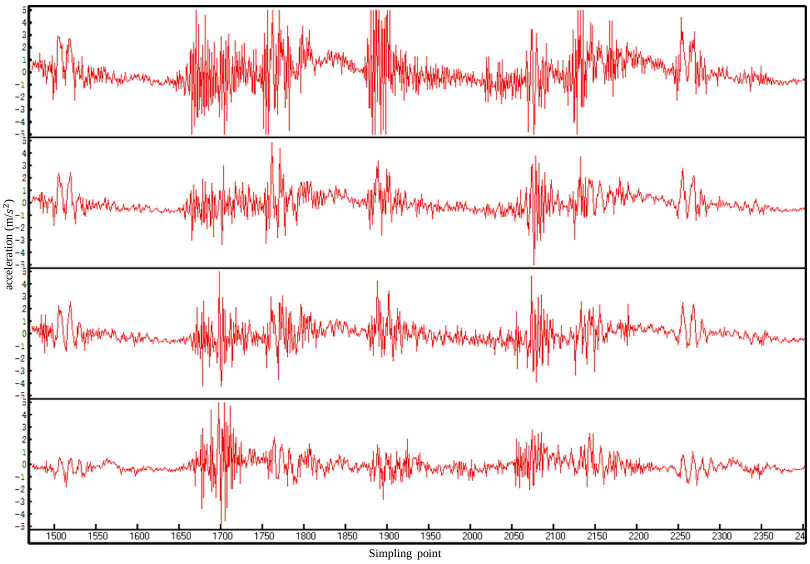


① Charge amplifier ② USB data acquisition card ③ piezoelectric acceleration sensor
④ Automobile multi-functional tester ⑤ Dynamometer
Fig. 11. Field testing case of engine vibration signals

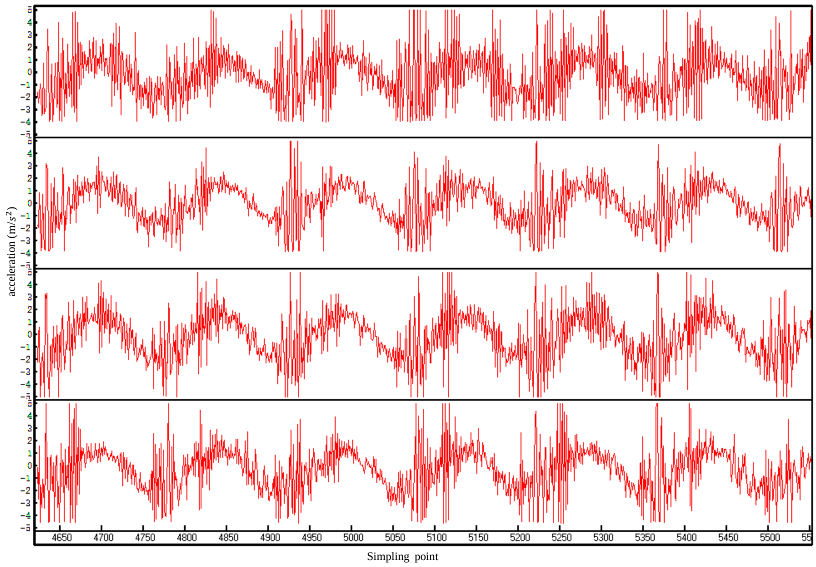


Mark①, ②, ③, ④ are the piezoelectric acceleration sensors for the corresponding channels.
Fig. 12. Installation positions of piezoelectric acceleration sensors

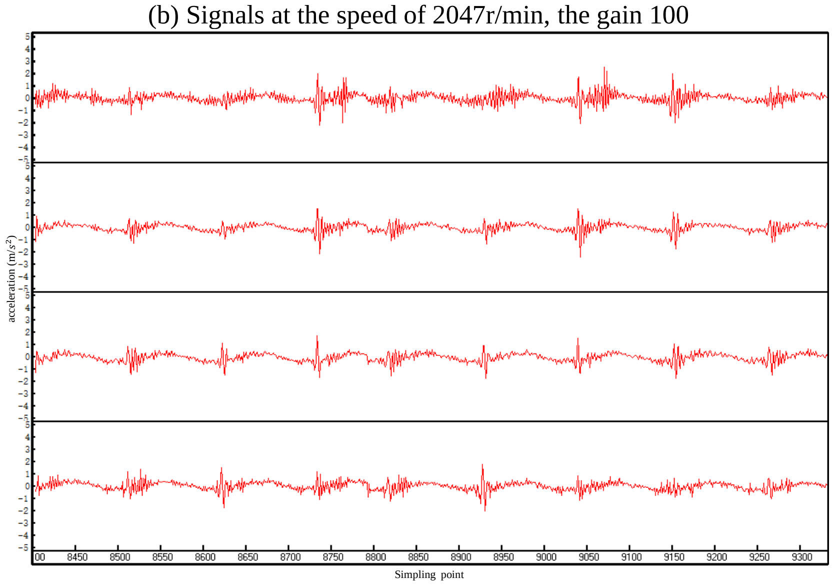
The test is performed under three running conditions of the 800r/min rotation rate, the 2047r/min rotation rate and the 2682r/min rotation rate. The sampling frequency is selected 10000Hz. Fig.13 shows the real-time waveform of engine vibration signals sampled by the four Piezoelectric acceleration sensors under the above three kinds of engine speed. At the speed of 800r/min and 2047r/min, the four channel gain values of the DHF-4 type charge amplifier are selected as 100, and the gain values at the 2682r/min speed are 10 due to bigger vibration.



(a) Signals at the speed 800r/min, the gain 100



(b) Signals at the speed of 2047r/min, the gain 100



(c) Signals at the speed of 2682r/min, the gain 10

Fig. 13. Vibration signal waveforms of four channels at three engine speeds

During the running period of the engine, the cylinder system mainly bears the cylinder pressure, the shock of the valve seats moving down and up, the inertia forces of unbalance reciprocating pistons, the unbalanced rotating inertia moments of the crankshaft and other random exciting forces. The cylinder system will generate the resonance under the action of a variety of exciting sources [11].

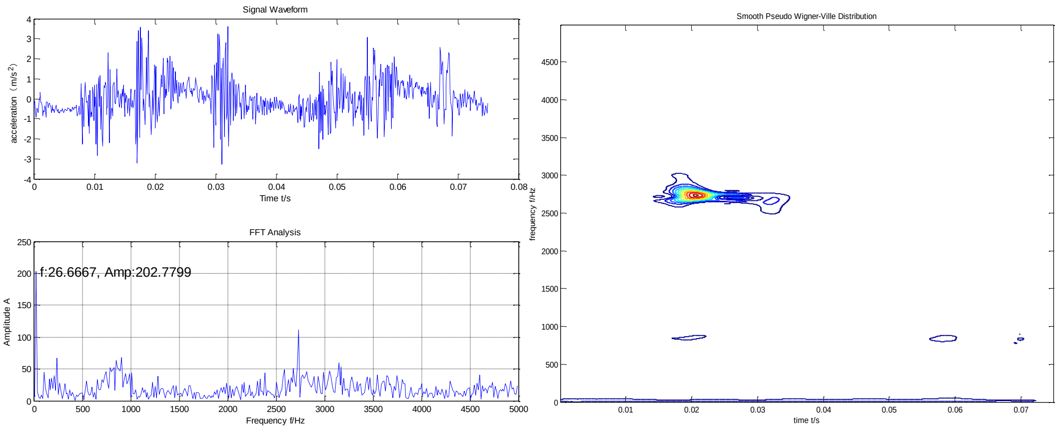
With regards to an inline four-cylinder diesel engine, the frequency of the first-order inertial force is equal to the rotating frequency of the crankshaft; the frequency of the second-order inertial force is twice of the rotating frequency of the crankshaft. The mass of the reciprocating parts of each cylinder are all same. According to the ignition sequence, the first-order inertial forces of the four cylinders are counteracted each other, and the second-order inertial forces are modulated with each other. The expression of the force amplitude is $4\lambda M_j R\omega^2$. When the force is applied on the engine body, serious vibrations will be produced. This force is the one of the main vibration sources of the engine [12, 13].

The frequency of the second-order inertial force can be calculated by the following formula

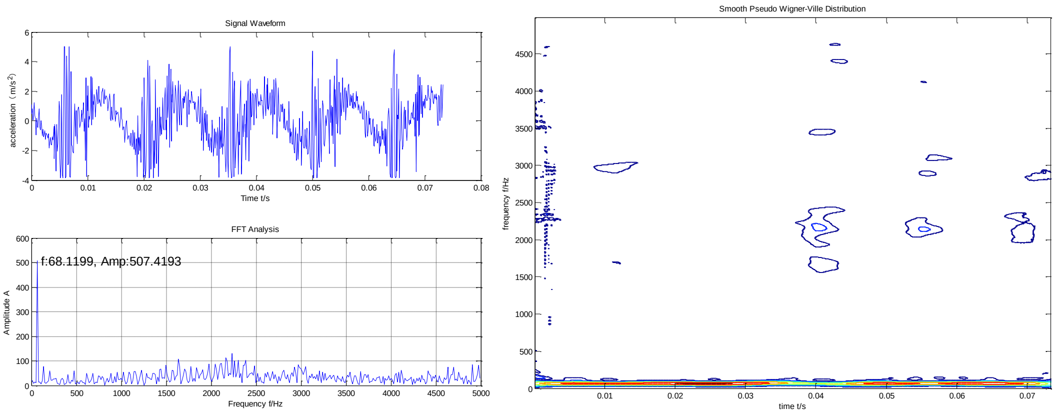
$$f = \frac{Qn}{60} \tag{4}$$

Q is the proportional coefficient, Q=1 when the first-order inertia force is calculated, Q=2 when the second-order inertia force is calculated, n is the crankshaft rotation speed.

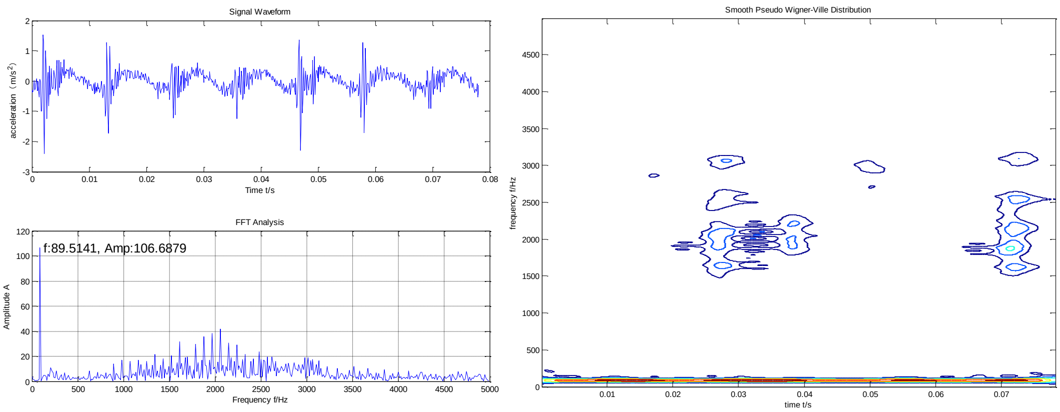
According to the formula (4), when the engine rotation speeds are 800r/min, 2047r/min, 2682r/min, the frequencies of the second-order inertial force are 26.67Hz, 68.23Hz, and 89.40Hz respectively. The sampling frequency is 10Hz. According to the expression of $n = \frac{fs}{f}$, the sampling points of 750, 734 and 782 were selected. Fig. 14 shows the waveforms of the second channel vibration signal, the results of FFT analysis, and the results of smoothed pseudo winger distribution (SPWD) under the three rotation speeds.



(a) 800r/min



(b) 2047r/min



(c) 2682r/min

Fig. 14. Vibration signal waveforms, FFT analysis and SPWD analysis results of the fourth channel at three speeds

According to the three spectrums in Fig. 14, there are tree large peaks corresponding to the three double frequencies that are 26.67Hz, 68.12Hz and 89.51Hz (obtained by the mouse capture, as shown in the figure) in each spectrum. Too small errors exist by comparing with the above theoretical frequencies (seen in Table 2). These three results indicate that the main vibration source of the engine comes from the second-order inertial force of reciprocating motion. According to the fault diagnosis theory [14], the appearance of this double frequency can explain that the engine crankshaft has a serious misalignment. In addition to the strong vibration caused by the second-order inertial force, there are also other vibration sources of engine parts. Fig. 14(a) shows the SPWD analysis result; there are frequency components of 700Hz, 1000Hz to 2750Hz at about time 0.2s point. Fig. 14(b) and Fig. 14(c) meanwhile indicate that there are abundant frequency components around 2000Hz.

The above analysis results provide the data for recognizing the vibration sources of engine parts. Through the field test and analyzing engine vibration signals, the effectiveness of the tester is verified further.

Table 2

Comparison of theoretical second-order frequency and tested second-order frequency

Engine speed (r / min)	Theoretical second-order frequency (Hz)	Tested second-order frequency (Hz)	Error (%)
800	26.67	26.67	0.00
2047	68.23	68.12	0.16
2682	89.40	89.51	0.12

5. Conclusion

Based on a USB3202 type data acquisition card and by using the Delphi and Matlab mixed programming technology, an automobile multi-functional tester integrating signal acquisition, multi-function processing and analysis is developed. Based on the COM technology, Matlab platform can carry out the programming for the powerful signal processing and analysis and achieve the DLL files. Delphi platform can perform the programming for the tester interface and install the DLL files in own platform to achieve nearly 30 kinds of methods of signal processing and analysis (especially time-frequency combination methods) with the help of its flexible and efficient programming. The advantages of the two platforms are complementary. The developed tester has enriched the functions of the current automobile testers, and can run independently in the Windows system without the Matlab platform, and can be carried easily with a notebook. The effectiveness of the automobile multi-functional tester is verified by testing four sensors of the PASSAT electric control test-bed, analyzing a simulation signal and vibration signals of a FOTON type engine. The developed tester can also be applied to other areas of signal processing and analysis such as bearing vibration signal analysis.

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