Applied Physics Research
http://ccsenet.org/apr
Vol. 1, No. 2
November 2009

Study on Fault Diagnosis of Fuel Injection Based on Vibration Signal Analysis of High-pressure Fuel Injection Pipe

Zhiqiang Wang
School of mechanical and electronic engineering, Tianjin polytechnic university
Tianjin 300160, China
E-mail: XiaoKing_ky@yahoo.com.cn

Abstract

An accurate fuel injection advance angle is an important parameter to obtain better fuel combustion index and emission index. Fuel injection advance angle is always deranged because of the wear of the injection nozzle matching parts, which has serious impact on diesel engine performance. How to measure the fuel injection advance angle easily and accurately is a problem for fault diagnosis of high-pressure fuel injection pipe. In this paper, the vibration signals of high-pressure fuel injection pipes' nozzle of different cylinders with different fuel injection advance angles were measured by external oil pressure sensor. Through the theoretical analyzing and calculating the above-mentioned experimental data, the characteristic curves were established, which described the relationship between the fuel injection advance angles and the vibration characteristic quantities of high-pressure fuel injection pipes' nozzle. The characteristic curves were the judgment basis of fuel injection system fault diagnosis. It can be applied to diagnose the fault that caused by fuel injection advance angle change which induced by improper adjustment and matching parts abrasion.

Keywords: Fuel injection advance angle, Fault diagnosis, Vibration signal, Frequency analysis

1. Introduction

The diesel engine has been widely used in freight cars and some private cars because of its good economy and dynamic performance. An accurate fuel injection advance angle not only is very important for diesel engine to obtain good combustion and normal working condition but also is an important parameter to obtain better fuel combustion index and emission index, so it has great influence on the overall performance of diesel engine. If the fuel injection advance angle is too large, the air temperature in cylinder will be lower, the mixture formation condition will become worse, and the combustion preparing time will get longer, accompanied with the increase of fuel consumption, the reduction of power and the unstable idle speed. However, if the fuel injection advance angle is too small, the fuel combust incompletely at the top dead center and the posterior combustion period get longer. Furthermore, the combustion temperature increase and the pressure in cylinder decrease. Ultimately, the thermal efficiency of diesel engine decreased significantly (Sen, Souling, Zhang, Yingtang, & Zhen, Haiqi, 1999, pp.48-52. Bai, Shuzhan, 2007, pp.49-52. Shiozaki & Matsumoto, 1987, pp.521-533. Kang, Jing, & Hu, Hongying, 2004, pp.127-129). Therefore, the accurate measurement of the fuel injection advance angle is an important part of diesel engine fault diagnosis.

In this paper, the vibration signal of the high-pressure fuel injection pipe's nozzle was measured by external oil pressure sensor. Then through signal processing and analysis, an important parameter — the fuel injection advance angle was extracted, which was used to identify the state of fuel injection. In a word, a new method was presented to measure the fuel injection advance angle, which achieve the nondestructive detection and fault diagnosis of diesel engine without disintegration.

2. Experimental principle

2.1 The measurement of fuel injection advance angle α

As shown in figure 1 (John, 1988, chapter 6), the fuel injection advance angle is the interval between the fuel injection starting point from the top dead center. During this process, the injection rate raise continuously. That is to say, when the crankshaft rotates to top dead center, the fuel injection rate and the corresponding nozzle pressure are maximum. In another word, the time history that the nozzle pressure raises continuously from zero to maximum is the time corresponding to fuel injection advance angle. It is very difficult to measure the time corresponding to fuel injection advance angle directly. In this paper, a new method was presented. The *i*th cylinder's fuel injection advance angle was measured by extracting the duration Δt_i from the first cylinder starting work to the *i*th cylinder finishing work. During this process, the crankshaft-flywheel rotates with homogeneous angular speed, so the value of crank angle β_i from the first cylinder beginning work to the *i*th cylinder finishing work is proportional to Δt_i. The angle is 720° corresponding to the time of crankshaft rotating two circles, so the relationship is given as follows

$$\frac{\beta_i}{\Delta t_i} = \frac{720°}{T} \quad (i=1,\ 2,\ 3,\ 4,\ 5,\ 6) \tag{1}$$

Because WD615.77 diesel engine is four-stroke engine, the crankshaft rotated every two circles is one working cycle, and every injection pump supplies oil to combustion chamber once. The working order of cylinders is 1-5-3-6-2-4. Therefore, the crank angle from the 1st cylinder beginning doing work to each other cylinder beginning doing work are $\varphi_1=0°$, $\varphi_2=480°$, $\varphi_3=240°$, $\varphi_4=720°$, $\varphi_5=120°$, $\varphi_6=360°$, respectively. Then the fuel injection advance angle α can be obtained as following:

$$\alpha = \beta_i - \varphi_i \tag{2}$$

Where φ_i is the crank angle from the first cylinder begin doing work to the *i*th cylinder begin doing work, and the β_i is the crank angle from the first cylinder begin doing work to the *i*th cylinder finish doing work.

2.2 The extraction of Δt_i

The high-pressure fuel injection pipe connected to fuel injection pump and injector. The fuel pressure in pump chamber of fuel injection pump is pulse load, so the exciting force of fuel injection pump also has pulse duration properties, and the vibration frequency as equation (3) (Tang, Daming, 1993, chapter 3).

$$f_k = \frac{mj}{60\tau} k \qquad (k = 1,2,3 \cdots n) \tag{3}$$

Where k is the harmonic number, m is the crankshaft speed of diesel engine, j is the number of cylinder (in the experiment, j=6), and τ was coefficient of stroke (the diesel engine WD615.77 is four-stroke, so τ=2).

Fundamental vibration frequency of high-pressure fuel pipe's nozzle is mainly caused by the harmonic which produced by fuel injection pump's pulse exciting force. The Fourier transformation of the vibration signal X(t) of the *i*th cylinder's nozzle is expressed as

$$X(f) = \int_{-\infty}^{\infty} X(t) e^{-j\omega t} dt \tag{4}$$

The Parseval's equation is given as (Alan, V. O., 2005, chapter 4)

$$E = \int_{-\infty}^{\infty} f^2(t)dt = \frac{1}{2\pi}\int_{-\infty}^{\infty} |F(j\omega)|^2 d\omega \tag{5}$$

According to equation (5), it can be known that the energy of the same signal in time-domain and frequency-domain is equivalent. A new correlation of amplitude spectrum $|X(f)|$ with power spectrum $S_x(f)$ was derived as following

$$S_x(f) = \frac{1}{T}|X(f)|^2 \tag{6}$$

Where T was sample length of signal X(t). Because $S_x(f)$ is even function, so its values is symmetric at origin. Therefore the power spectrum can be expressed as equation (7) in the frequency range of (0,∞).

$$G_x(f) = 2S_x(f) \tag{7}$$

Where $S_x(f)$ and $G_x(f)$ are the bilateral power spectrum and unilateral power spectrum, respectively. In engineering practice, the root-mean-square spectrum $\sqrt{G_x(f)}$ is usually adopted. The $\sqrt{G_x(f)}$ can be calculated by combing equation (4), (5) and (6), then it was filtered by using the Chebyshev I low-pass filter. The characteristic function of Chebyshev I low-pass filter is given as

$$|H(j\omega)|^2 = \frac{1}{1+\varepsilon^2 V_N^2(x)} \tag{8}$$

Where N is the filter order, ε is the ripple factor that determines the magnitude of pass-band ripple fluctuation. $V_N(x)$ is defined as:

$$V_N(x) = \begin{cases} \cos(N\cos^{-1}x) & x\le 1 \\ \cosh(N\cosh^{-1}x) & x\ge 1 \end{cases} \tag{9}$$

By substitution of the simulation technology indexes into the equation (9), the Chebyshev I low-pass filter which meets the requirement of the performance indicator was established. It was used to extract the first harmonic from $\sqrt{G_x(f)}$, denoted by $g_x(f)$. Further, with the help of the inverse Fourier transform of $g_x(f)$, the corresponding time-domain signal $g(t)$ was obtained according to the equation (10).

$$g(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} g_x(f) e^{j\omega t} d\omega \tag{10}$$

The time when the first peak of $g(t)$ appears is the duration from the first cylinder starting work to the *i*th cylinder finishing work, namely Δt_i. The corresponding crank angle calculated from equation (1). Finally, the fuel injection advance angle α was gained according to equation (2).

3. Example

WD615.77 Bosch pump diesel engine was used in this experiment. Its normal fuel injection advance angle φ is 20±2°. The vibration signal of high-pressure fuel pipe was measured by external oil pressure sensor, and then was analyzed by dynamic signal analyzer called RT Pro Focus. The whole test flowchart is shown in figure 2.

As shown in figure 3, the external oil pressure sensor is fixed on the high-pressure fuel injection pipe's nozzle of the fifth cylinder to obtain the vibration signal. In the experiment, the engine speed is 800r/min and the sample frequency is 20000Hz. The vibration signal X(t) of fuel injection pipe's nozzle is presented in figure 4.

The vibration of the fuel injection pipe's nozzle is mainly caused by the harmonic response generated by the pulse exciting force of fuel injection pipe. Normally, the second vibration harmonic or higher harmonic can be ignored because of its weak influence on the whole vibration, so only the first order harmonic of pulse exciting force is considered. The method stated in section 2 is used to establish the root-mean-square spectrum $\sqrt{G_x(f)}$ of X(t). Then the Chebyshev I band-pass filter is used to filter out the first and the second order harmonic of $\sqrt{G_x(f)}$, which is shown in figure 5

As shown in figure 5, the frequency of the first and second order harmonic is 39.1Hz and 58.6Hz, respectively, which gives the same results as that of equation (3). So the first order harmonic of $\sqrt{G_x(f)}$ is caused by the pulse exciting force of fuel injection. The time-domain signal $g(t)$ (shown in figure 6) is obtained according to equation (9). It showed that the value of Δt_5 is 0.029s (the time from the first cylinder beginning doing work to the fifth cylinder finishing doing work). Finally, the injection advance angle α of the fifth cylinder is calculated to be 20° by combing equation (1) and equation (2). Because the test result is the same as the normal state of WD615.77, the fifth cylinder's fuel injection advance angle is without any faults. Continuing to collect the vibration signals of others cylinders' nozzle, and the injection advance angles were calculated by using the method stated in section 2.1~2.2. The results listed in Table 1.

According to the results, the following conclusions can be reached:

1) The 1st, 3rd, 4th, 5th cylinder's injection advance angle are healthy.

2) The 2nd cylinder's injection advance angle is smaller than the normal value;

3) The 6th cylinder's injection advance angle is larger than the healthy value.

The above-mentioned results are agreed with the real state of experiment.

4. Conclusion

(1). In this paper, a novel fault monitor technique for diesel engine was presented. The time-frequency characteristic of the nozzle's vibration signal was used to identify the fault modes of fuel injection advance angle. It is found that the time of fuel injection advance angle can be extracted from the first harmonic caused by pulse exciting force of fuel injection.

(2). The proposed method is verified by experiments. The results of these studies show that the method can be applied in engineering practice as well as develop a process for nondestructive detecting techniques for diesel engine

References

Alan, V. O. (2005). *Signals and systems*. Beijing: Tsinghua University Press, (Chapter 4).

Bai, Shuzhan. (2007). Analysis of damage of engine fuel injection pipe based on vibration test. *I.C.E&Powerplant*, 163, 49-52.

John, H. (1988). *Internal combustion engine fundamentals*. New York, (Chapter 6).

Kang, Jing, & Hu, Hongying. (2004). Vibration detection & diagnosis for high-pressure fuel pipe of diesel engineer. *International conference on information acquisition*, pp.127-129.

Sen, Souling, Zhang, Yingtang, & Zhen, Haiqi. (1999). Study on fuzzy diagnosis for fuel injection system fault of diesel engine using wavelet analysis. *Vehicle Engine*, 19(4), 48-52.

Shiozaki, T., & Matsumoto, T. (1987). Low emission combustion influences durability of fuel injection pipe line and treatment of the pipe. *SAE international off-highway & powerplant congress & exposition*. USA, pp.521-533.

Tang, Daming. (1993). *Vibration control of internal combustion engine*. ChenDu: Southwest Jiaotong University Press, (Chapter 3).

Table 1. The diagnosis results of each cylinder's fuel injection advance angle

Fuel injection advance angle	1st cylinder	2nd cylinder	3rd cylinder	4th cylinder	5th cylinder	6th cylinder
Experimental value	20^{o}	16^{o}	21^{o}	18^{o}	20^{o}	25^{o}
Normal value	20^{o}					

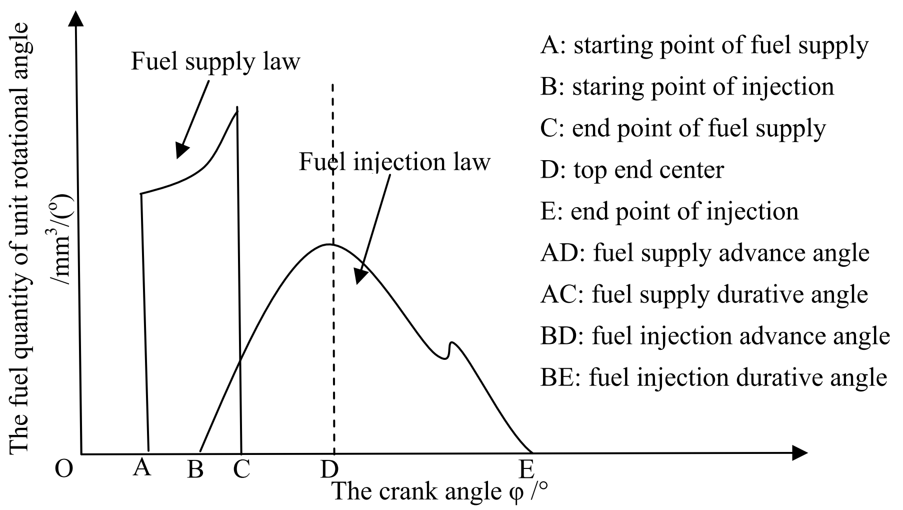

Figure 1. The Fuel Supply Law and Fuel Injection Law

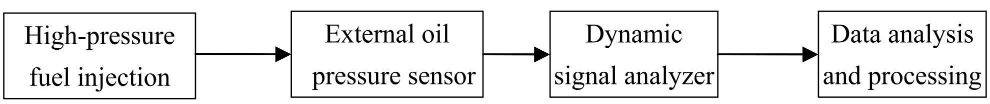

Figure 2. The Test Flowchart

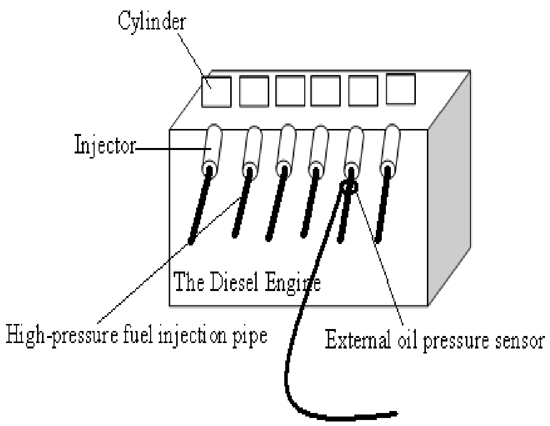

Figure 3. The Location of Sensor

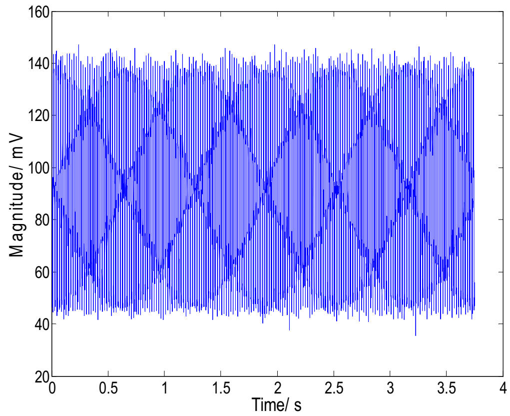

Figure 4. The Vibration Signal X(t) of Fuel Injection Pipe's Nozzle

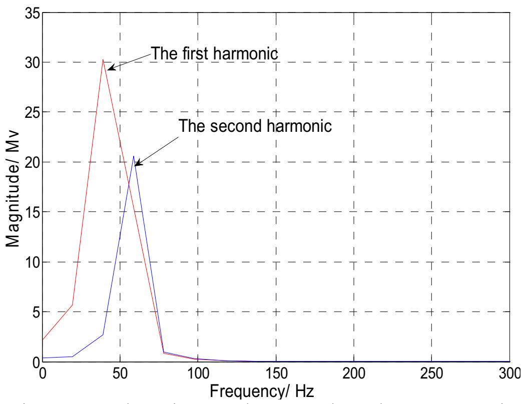

Figure 5. The First and Second Order Harmonic of $\sqrt{G_x(f)}$

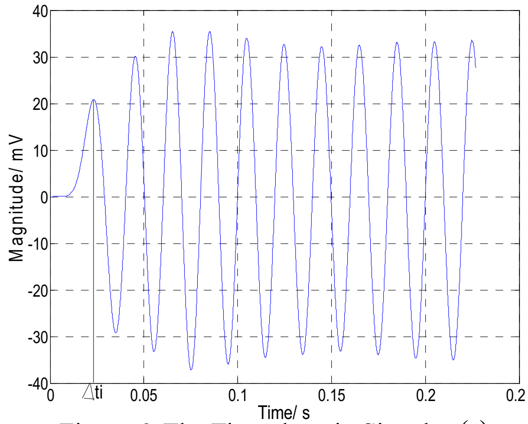

Figure 6. The Time-domain Signal $g(t)$