DIAGNOSTIC INTERNAL COMBUSTION ENGINE BASED ON CRANKSHAFT ANGULAR ACCELERATION

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Abstract

Internal combustion (IC) engine is a complex power generating machines and used widely in automotive industry, which the failure rate is high. Carrying out the IC engine fault diagnostic methods have been studied and still a lasting topic for scientists. Crankshaft instantaneous angular acceleration, which evaluated by second derivative of the crankshaft rotation respect to time contains a little information for fault diagnostic. In this paper, phase modulation signal is derived from the phase of an analytical signal which evaluated by using the Hilbert Transform technicque. To verify the signal analysis technique, the engine model created originally by John J. Moskwa needs to be extended to produce fluctuation of the crankshaft angular acceleration and to implement the extended model into the dSPACE equipment to control and diagnose the IC engine.

Key words: Engine diagnostic, crankshaft angular acceleration, phase demodulation.

I. INTRODUCTION

Diagnostics engine is a very important field in manufacturing, using and developing automobile and it has a long history. Since the first automotive engine in the 19th century, there has been a need for finding faults in engines, but the diagnostics was performed manually and off-board. By the time, when the field of automotive engine control develops and becomes very important because it yields benefits on several front such as fuel efficiency, exhaust emission reduction, better delivery, and so that, on-board diagnosis also develops very quickly. Many methods of fault diagnostics for internal combustion engine have been found such as vibration spectrum analyzing, vibration wavelet theory, instantaneous rotary speed analyzing, lubrication oil iron-microboulde spectrum analyzing, lubrication oil copper-microboulde spectrum analyzing, etc. However, fault diagnostics model-wise, there are many advantage controlling theory and algorithm models, such as neural network, expert system, heredity algorithm, fuzzy algorithm, etc. In this paper, the internal combustion engine fault diagnostics technique based on instantaneous crankshaft angular acceleration measurement will be used.

II. FAULTS DIAGNOSTIC METHOD

A. Introduction of the method

In some literatures, the signal of crankshaft instantaneous rotating speed is utilized in IC engine fault diagnosis. In fact, the instantaneous angular acceleration and rotating speed have something in common; they both are on the basis of the rotating speed of crankshaft. However, instantaneous angular acceleration can reflect the state of applying work of IC engine more powerfully than instantaneous rotating speed does. According to Newton’s Second Law, the angular acceleration of rotating body is proportional to the moment of couple which is acted on. It’s well known that the course of working of the IC engine is that each cylinder fires according to certain ignition order and at the interval of certain degrees of crankshaft turn angle, and each cylinder intermittently in the explosion stroke impulses crankshaft and supplies moment of couple to drive crankshaft, then the crankshaft gain energy and angular acceleration. So the instantaneous angular acceleration can directly reflect the state of applying work and current pressure in each cylinder. By means of analyzing the angular acceleration signal, the instantaneous engine running state and a lot of related faults can be discovered. Under the normal working conditions, the motive force performance of each cylinder is unanimous basically, the spark ignition engine operates steadily. Its angular acceleration always fluctuates in a normal range and presents certain regularity. The operation when a certain cylinder is working abnormally, the consistency of motive force is destroyed, the engine becomes bad to the stationary of operation, and angular acceleration signal will be out of shape. By observing its fluctuation, the working process in each cylinder can be evaluated.

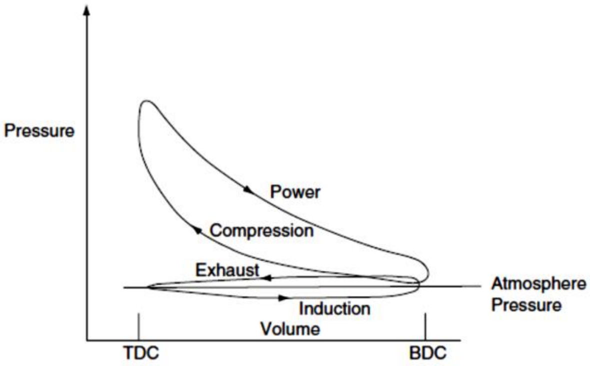
B. The relation between volume and pressure in the cylinder of IC engine

As mentioned above, pressure in compression and power stroke in each cylinder effect directly to the instantaneous angular acceleration and depend on the volume of cylinder. This relation can be displayed by a pressure–volume diagram which represents the pressure and volume at different stages of a process of power and compression and satisfied Boyle's law.

$$p_1V_1^n = p_2V_2^n = C \text{ or } pV^n = C \tag{2.1}$$

Work done during power:

$$W = \frac{p_1V_1 - p_2V_2}{n-1} \tag{2.2}$$



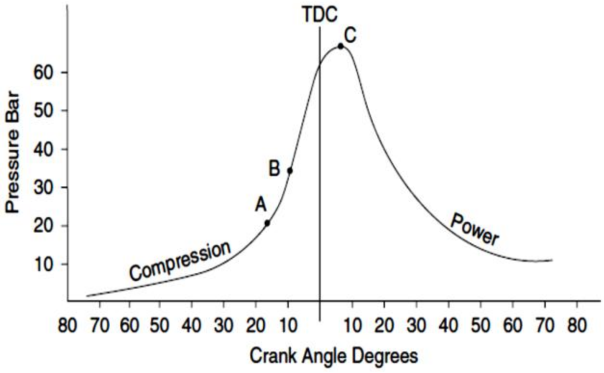


Figure 1: Indicator diagram for a 4-stroke engine Figure 2: Cylinder pressure vs. crankshaft angle

The peak value time of the pressure and also angular acceleration of IC engine is almost overlapped with the beginning of power stroke, by the right of this; the peak of the wave of angular acceleration can be associated with the top dead center of certain cylinder's power stroke, so the state of applying work can be directly known. In fact, the peak value time would lag behind the top dead center by certain degrees. According to the kinematics of IC engine, when piston is on the top dead center, the arm of force is small to crankshaft, so the moment of couple is small. Only after the beginning of power stroke, the corresponding wave peak would occur.

C. Torque Generation and Acceleration

Engine torque is a function of the air charge, the air/fuel mixture ratio, the spark advance, the engine speed and determined by the equation:

$$T_e = -181.3 + 379.36m_a + 21.91\left(\frac{A}{F}\right) - 0.85\left(\frac{A}{F}\right)^2 + 0.26\sigma - 0.0028\sigma^2 + 0.027\omega$$

$$-0.000107\omega^2 + 0.00048\omega\sigma + 2.55\sigma m_a - 0.05\sigma^2 m_a \tag{2.3}$$

where,

m_a- mass of air in cylinder for combustion (g)

A/F- air to fuel ratio

σ- spark advance

T_e- torque produced by the engine (running output torque) (Nm)

The engine torque less the net load torque results in acceleration.

$$J.\frac{d\omega}{dt} = J.\varepsilon = T_e - T_l \tag{2.4}$$

where,

J- engine rotational moment of inertia (kg-m^2),

ε - engine acceleration (rad/s^2),

T_l - running torque of receiver, including resistance connected to receiver inertia.

If the energy receiver is detached ($T_l = 0$), the equation (2.4) will present the engine torque change caused for example by the quick increase of the fuel dose supplying the cylinders:

$$T_e = J.\frac{d\omega}{dt} = J.\varepsilon \quad (2.5)$$

But in case of engine supply switched off ($T_e = 0$), the equation (2.4) will present the internal resistance change during engine retardation started at high initial rotational speed:

$$T_l = -J.\frac{d\omega}{dt} = J.(-\varepsilon) \quad (2.6)$$

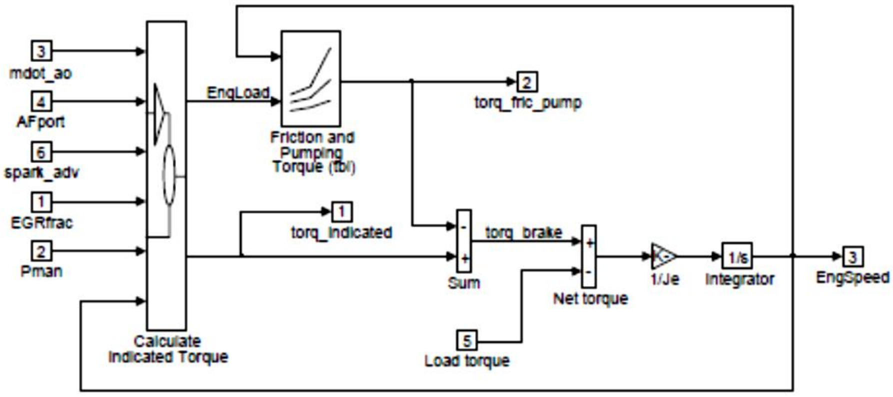


Figure 3: Torque Generation block

D. Phase Demodulation using Hilbert Transform

The phase modulation signal can be derived from the phase of an analytical signal that is evaluated using the Hilbert Transform technique. To compound the complex analytical signal $z(t)$ the real sampled signal $x(t)$ must be extended by an imaginary part $y(t)$ that is the mentioned Hilbert Transform of the real signal.

$$z(t) = x(t) + jy(t) = |z(t)|exp\,(j\varphi(t)) \quad (2.7)$$

The relation between the FFT of $y(t)$ and $x(t)$ with the length N can be determined:

$$N_i = jsign\left(\frac{N}{2} - i\right)X_i \quad (2.8)$$

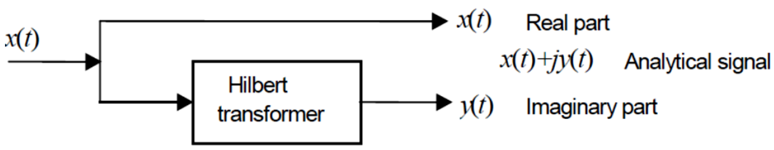


Figure 4: Evaluation of the analytical complex signal in real time

The angle range of the complex values from -π to +π, the true angle of the analytical signal as the function with jumps at -π to +π, must be obtained by unwapping which is based on the fact that the absolute value of the difference between two consecutive angles is less then π.

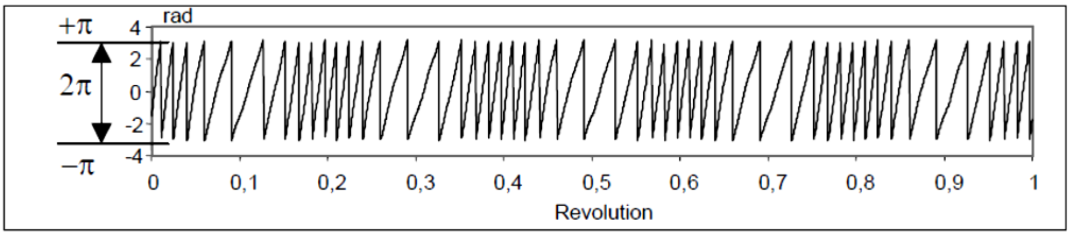


Figure 5: Phase of analytical signal ranging in interval from –π to +π

The relation between phase of the analytical signal and phase of the modulation signal $\Delta\varphi(t)$:

$$\varphi(t) = arctan(y(t)/x(t)) = \omega_0 t + \Delta\varphi(t) \quad (2.9)$$

Where ω_0 is angular frequency of the carrier component. Phase modulation signal is the fluctuation of phase angle around the linear term $\omega_0 t$. First derivative of the linear term corresponds to the steady – state rotational speed, while first derivative of the modulation signal gives the fluctuation of the rotational speed around zero value. Second derivative of the analytical signal phase is the same as the first derivative of the fluctuation part of the rotational speed, which is known as angular acceleration.

III. THE MEASUREMENT SYSTEM

A. *Crankshaft angular acceleration measurement*

Rotational speed of the 4-stroke / 4-cylinder engines running at idle varies in a certain range at the average level of 800 RPM. The purpose of measurements is to explain the source of the rotational speed non-uniformity. The first step of analysis is to identify the rotational speed variation of not only in term of the complete revolutions but also in terms of the basic operational stages of the engine under the test. This goal of tests requires the measurement of the instantaneous rotational speed and angular acceleration.

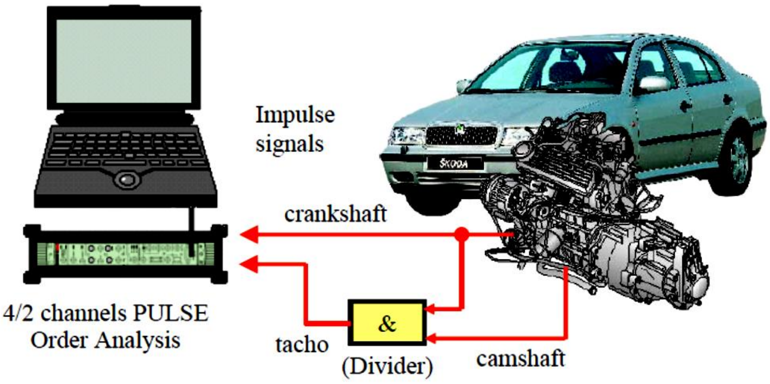
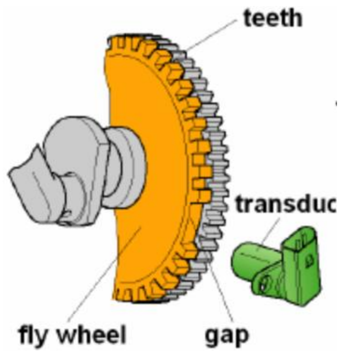


Figure 6: Rotational speed measurement of the engine

Measurements were restricted only to the time history of a pulse train that is generated by a transducer that is connected to the engine control unit. Any special device or encoder is not supposed to attach to the engine crankshaft. The transducer that is a part of engine generates 58 pulses between the gaps of 2 missing pulses. All the 58 pulses are distributed in the period of a revolution uniformly in 60 positions situated proportionally to the rotational angle. As the operational cycle consists of two revolutions, the time history of a pulse signal is shown in figure 8. To improve accuracy of the modulation signal evaluation, a computer program incorporates the missing pulses.



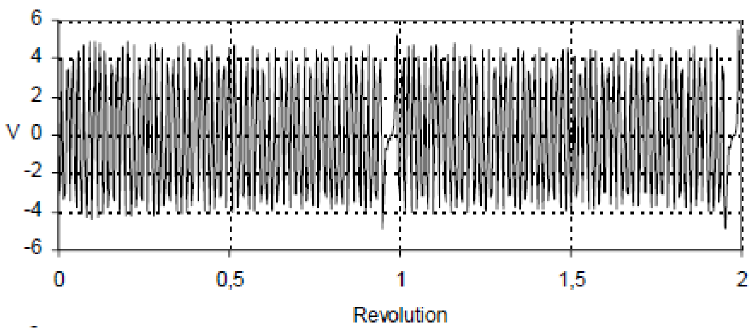


Figure 7: Engine speed measurement

Figure 8: The waveform of engine speed sensor

B. *Evaluating crankshaft angular acceleration*

Angular velocity and acceleration were evaluated using the first and second derivative of the crankshaft angle with respect to time, respectively. Differentiation was performed in the frequency domain in such way that the FFT angle spectrum was multiplied by the term of $j\omega$ or $(j\omega)^2$. As multiplication by mentioned terms amplifies the high frequency noise in the measurement data proportionally to the frequency or even proportionally to the square of the frequency the filtration in the time domain was employed. The spectrum components with the frequency higher than the 6th order of the rotational frequency were put to the zero.

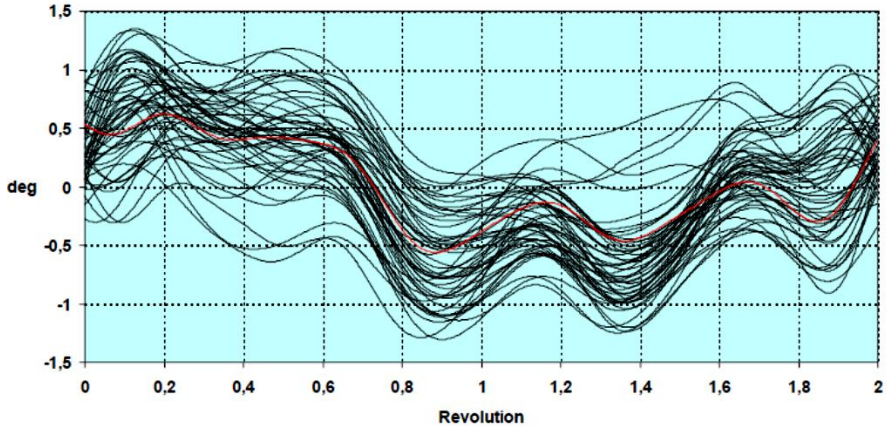


Figure 9: Crankshaft angular variation

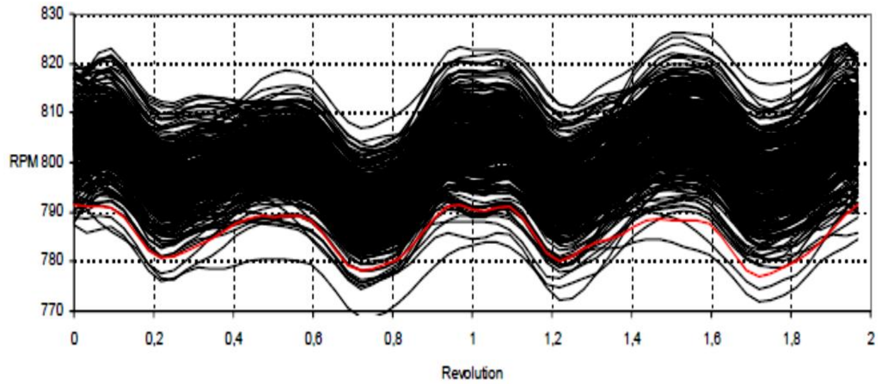


Figure 10: Crankshaft angular velocity

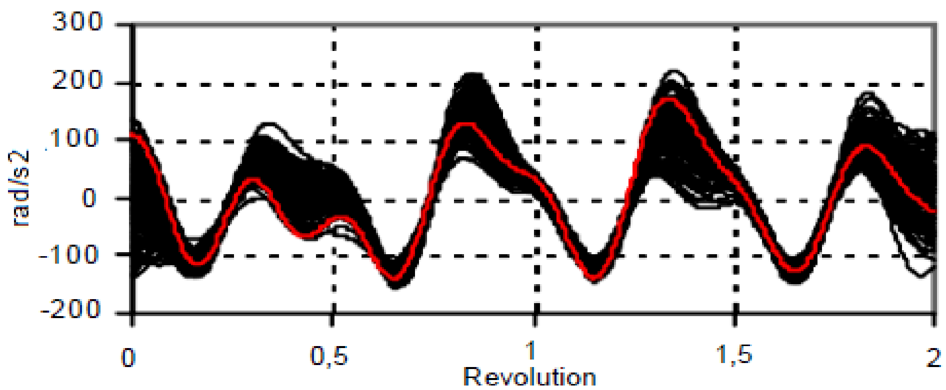


Figure 11: Crankshaft angular acceleration

IV. CONCLUSION

As we knew that there are three grades of fault diagnostic. First of all is to make sure whether there is fault or not, the second grade is to find out the location of fault and the third is to find the specific part which occurred fault. Using the technique of based on crankshaft instantaneous angular acceleration to diagnose the internal combustion engine can be competent for the first two grades. At first, measuring and analyzing the instantaneous angular acceleration of the crankshaft, to evaluate the overall state of applying work in each cylinder of internal-combustion engine and to find out whether there is fault or not, Then finding out the specific abnormal cylinder to guide fault diagnosis and reduce the range of fault diagnosis, so the technique of fault diagnosis based on angular acceleration signal has practicable significance. In this IC engine, as the firing order is 1-3-4-2. From the result of the evaluation, it is very easy to recognize that the angular acceleration of the first cylinder is less than the others. It means that the pressure in the first cylinder is lower. The information is very necessary for the manufacturer to find out and fix the problems. The disadvantage of this method is that it can locate the abnormal cylinders, but cannot find out the direct reason for malfunction. Anyway, this still is a good technique.

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