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DIAGNOSTIC GASOLINE ENGINE BY PHASE DEMODULATION METHOD

DIAGNOSTIKA ZÁŽEHOVÉHO MOTORU METODOU FÁZOVÉ DEMODULACE

Abstract

In gasoline (SI) engines, crankshaft instantaneous angular acceleration, which is evaluated by the second derivative of the crankshaft rotation respect with respect to time contains information for fault diagnostics. The instantaneous angular velocity of the crankshaft can be identified from a string of pulses for the engine electronic control unit (ECU). In this paper, the phase modulation signal is derived from the phase of an analytical signal which is evaluated by using the Hilbert Transform technique. 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 SI engines.

Key words: Engine fault diagnostics, crankshaft angular acceleration, phase demodulation.

Abstrakt

Ve vnitřním spalování dosahuje kliková hřídel okamžitého úhlového zrychlení, které je vyjádřeno druhou derivací rotace klikové hřídele vzhledem k času, ta obsahuje málo informací pro diagnostiku poruch. V tomto příspěvku je fáze modulačního signálu derivována z fáze analytického signálu, který je vyjádřen pomocí Hilbertovy transformace. Pro ověření signálu analytickou technikou, musí model motoru vytvořený původně John J. Moskwa být rozšířen na výrobu kolísání klikové hřídele úhlového zrychlení a implementovat rozšířený model do zařízení dSPACE k ovládání a diagnostice spalovacího motoru.

1 INTRODUCTION

Diagnostics of engines is a very important field in manufacturing, operating, and developing automotive engines and it has a long history. In the past, the engine diagnostics was performed manually and off-board. By the time, when the field of the automotive engine control develops and becomes very important because it yields benefits on several ways 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 gasoline engine have been found such as vibration spectrum analyzing, vibration wavelet theory, instantaneous rotary speed analyzing, lubrication oil iron-microparticle and copper-microparticle 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.

Gas pressure in the cylinder of an engine varies throughout the Otto four-stroke engine cycle. Work is produced and consumed by acting of gas pressure at the piston during expansion and compression stroke, respectively. The gases produce energy through the combustion process. These changes in energy combined with changes in the volume of the cylinder lead to fluctuations in gas

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pressure. The ability to accurately predict the pressure allows for better understanding of the processes taking place in the cylinder such as the interactions between the gases, oil film, piston and liner. Cylinder pressure that is generated by engine combustion contains much information related to engine performance such as fuel burning rate, combustion heat release rate, and fuel-air ratio. Not only this, in the gasoline engine, the angle of spark ignition advanced is also a very important factor. It was estimated to be at the angle ranging from 25 to 5 degrees before top dead center (BTDC) and the burn duration is approximately ranging between 60 and 80 degree of the crankshaft rotation. Generally, the burn duration angle increases with load and, with the exception of the quarter load data, the angle spark firing becomes later with increasing load. The delay in spark firing as the inlet pressure increases is expected, however, the increase in burn duration goes against the predicted trend.

In this paper, the engine fault diagnostics technique based on instantaneous crankshaft angular acceleration measurements will be used. Many faults caused by faulty combustion and mechanics in multicylinder engines can be detected through measurement and analysis of the crankshaft's angular acceleration. Using a low-cost magnetic sensor near the flywheel teeth, this method is easily applicable for production, service and on-board diagnosis. Errors in angular acceleration signal due to noise and limitations of the measurement procedure can be minimized by appropriate digital signal processing. The measured waveforms are interpreted based on a model describing the relationship between input variable (pressure in the combustion chamber) and output (angular acceleration).

2 FAULTS DIAGNOSTIC METHOD

2.1 Description of the method

In some literatures, the signal of the crankshaft instantaneous rotating speed is utilized in SI 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 the crankshaft. However, the instantaneous angular acceleration can reflect the state of applying work of the SI engine more powerfully than the instantaneous rotating speed does. According to Newton’s Second Law, the angular acceleration of a rotating body is proportional to the moment of couple which is acted on. It’s well known that the course of working of the SI engine is that each cylinder fires according to the ignition order at the interval of a certain crankshaft rotation angle, and each cylinder intermittently in the explosion stroke acts to the piston and simultaneously to the crankshaft and supplies moment of couple to drive the 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 gasoline 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 the angular acceleration signal will be out of shape. By observing its fluctuation, the working process in each cylinder can be evaluated.

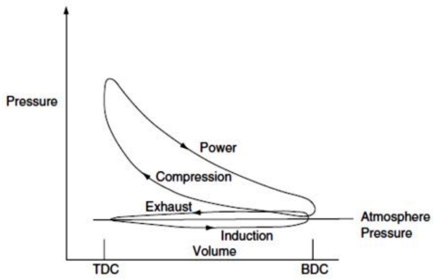
2.2 The relation between volume and pressure in the cylinder of SI engine

As mentioned above, pressure in the compression and power stroke in each cylinder influences 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 dependence of pressure on volume at different stages of the process of power and compression according to the Boyle’s law.

$$p_1V_1^n = p_2V_2^n = C \text{ or } pV^n = C \quad (1)$$

Work done during the power stroke:

$$W = \frac{p_1V_1 - p_2V_2}{n - 1} \quad (2)$$



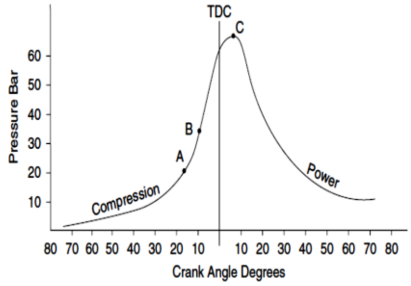


Fig. 1 Indicator diagram for a 4-stroke engine. **Fig. 2** Cylinder pressure vs. crankshaft angle.

The peak value time of the pressure and also the angular acceleration of a SI engine is almost overlapped with the beginning of the power stroke, by the right of this; the peak of the wave of angular acceleration can be associated with the top dead center of a 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 a certain amount of angular degrees. According to the kinematics of the SI engine, when the piston is on the top dead center, the arm of force acting at crankshaft is small, so the moment of couple is consequently small as well. Only after the beginning of the power stroke, the corresponding wave peak would occur.

2.3 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 it is determined by the formula:

$$T_e = -181.3 + 379.36 m_a + 21.91\left(\frac{A}{F}\right) - 0.85\left(\frac{A}{F}\right)^2 + 0.26\sigma - 0.0028\sigma^2 + 0.027\omega$$
$$-0.000107\omega^2 + 0.00048\omega\sigma + 2.55\sigma m_a - 0.05\sigma^2 m_a \qquad (3)$$

where,

m_a- mass of air in cylinder for combustion [g],

A/F- air to fuel ratio,

σ- spark advance [degree],

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

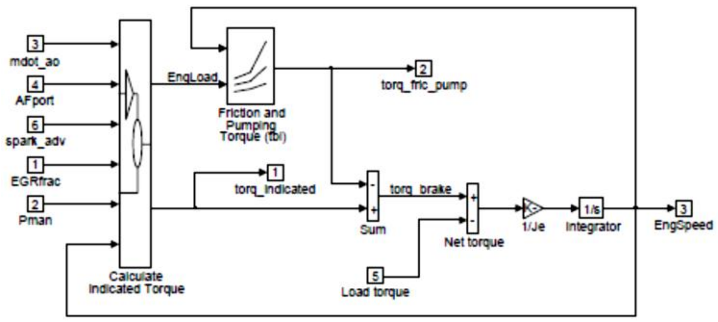


Fig. 3 Torque Generation block.

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

$$J.\frac{d\omega}{dt} = J.\varepsilon = T_e - T_l \qquad (4)$$

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 (4) will present the engine torque change caused for example by the quick increase of the fuel dose supplying the cylinders:

$$T_e = J.\frac{d\omega}{dt} = J.\varepsilon \quad (5)$$

But in case of the engine supply switched off ($T_e = 0$), the equation (4) will present the internal resistance change during the engine retardation started at high initial rotational speed:

$$T_l = -J.\frac{d\omega}{dt} = J.(-\varepsilon) \quad (6)$$

2.4 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.

$$z(t) = x(t) + jy(t) = |z(t)|exp(j\varphi(t)) \quad (7)$$

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

$$N_i = jsign\left(\frac{N}{2} - i\right)X_i \quad (8)$$

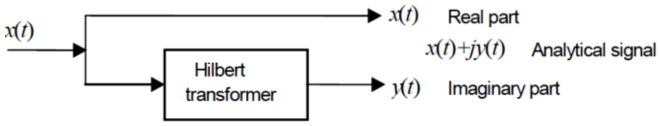


Fig. 4 Evaluation of the analytical complex signal in real time.

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

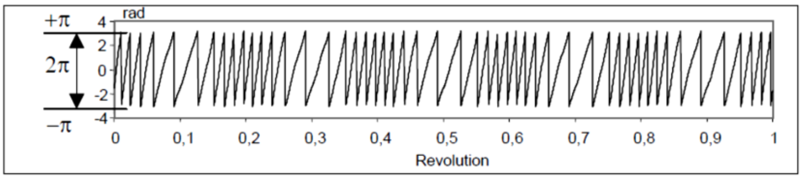


Fig. 5 Phase of analytical signal ranging in interval from –π to +π.

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

$$\varphi(t) = arctan(y(t)/x(t)) = \omega_0 t + \Delta\varphi(t) \quad (9)$$

where: ω_0 is angular frequency of the carrier component.

The phase modulation signal is the fluctuation of the rotation angle around the linear term $\omega_0 t$. The first derivative of the linear term with respect to time corresponds to the steady – state rotational speed, while the first derivative of the modulation signal gives the fluctuation of the rotational speed around the zero value. The second derivative of the analytical signal phase with respect to time is the same as the first derivative of the fluctuation part of the rotational speed, which is known as the angular acceleration.

3 THE MEASUREMENT SYSTEM

3.1 Crankshaft angular acceleration measurement

Rotational speed of a 4-stroke / 4-cylinder engine running at idle speed 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.

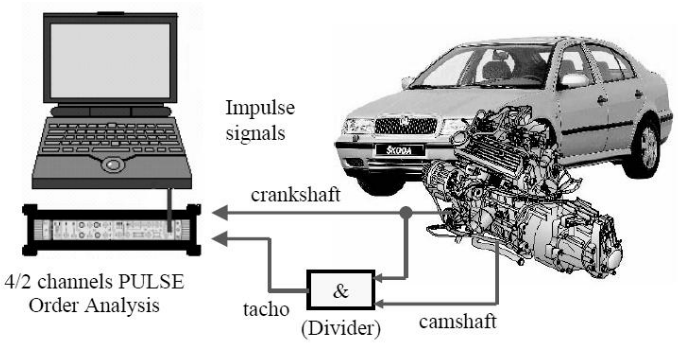
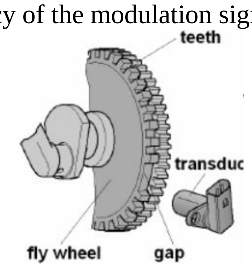


Fig. 6 Rotational speed measurement of the engine.

Measurements were restricted only to the time history of a pulse train that is generated by a transducer that is connected to the engine electronic 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 inserts the missing two pulses.



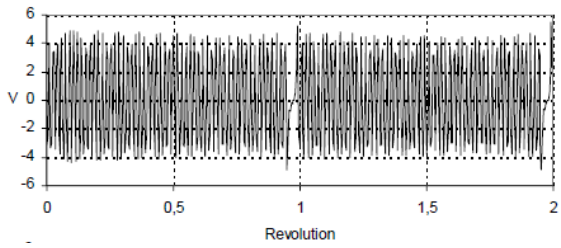


Fig. 7 Engine speed measurement.

Fig. 8 The waveform of engine speed sensor.

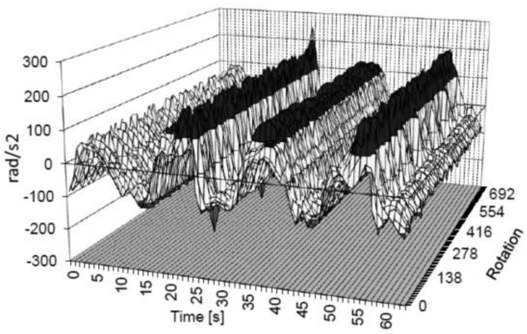


Fig. 9 Crankshaft angular acceleration

3.2 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.

4 CONCLUSIONS

With 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, based on crankshaft instantaneous angular acceleration to diagnose the gasoline 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 the 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 SI 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 than in the others. 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.

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