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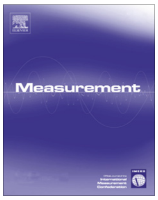

A new method for measuring engine rotational speed based on the vibration and discrete spectrum correction technique

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A B S T R A C T

This paper presents an encoder-less method for measuring the rotational speed of a reciprocating engine. The proposed method obtains the rotational speed of the engine from the lowest harmonic frequency component of its vibration signals, and uses a discrete spectrum correction technique to improve the measurement precision. Results from bench tests and tests on real engines, each having a different number of cylinders, have proven that the proposed method can achieve an extremely high precision when the engine is working in a steady-state or small speed fluctuation condition. As compared to the encoder-based method for measuring engine rotational speed, which is often found in literatures, the proposed method uses a straightforward hardware which is easy to install, and is particularly suitable for use during routine inspection and maintenance of vehicles.

1. Introduction

The rotational speed of an engine poses significant impacts on the dynamic, economy and emissions performances of a vehicle. A precise measurement of the engine rotational speed has become an ongoing concern shared by many scholars. At present, most rotational speed measurement methods require the installation of toothed or notched encoder disks, which rotate synchronously, at the end of the crankshaft [1,2]. Although the characteristics may be different, the underlying principle behind all encoder-based methods is the same. When the crankshaft rotates, the teeth or notches on the toothed or encoder disk trigger a series of pulse signals in the sensor, and the engine rotational speed is then obtained by calculating the time interval between two consecutive pulses or the number of pulses within a designated period [3–5]. These commonly used methods, however, suffer the following drawbacks: (1) require the use of dedicated hardware such as encoders or encoder disks; (2) hardware installation hassles and limited portability; and (3) require the use of an extremely high sampling frequency in order to increase measurement accuracy.

An indirect method based on vibration signals can overcome the aforesaid disadvantages. Such a method transforms the problem of estimating the rotational speed into that of estimating the frequency of a particular spectral component. In Refs. [6,7], the shaft's rotational frequency is obtained by demodulating the mesh frequency of gear vibration signals, whereas in Refs. [8,9], the instantaneous frequency of the useful signal is obtained using the time- and frequency-domain analysis method. Similarly, the new method proposed in this paper also measures the rotational speed of an engine based on its vibration signals. Nevertheless, it is unique, as compared with previously published works, in that it leverages on the dynamic characteristics of the engine crankshaft system, to obtain the lowest harmonic frequency component of the vibration signals accurately through the use of an algorithm. Therefore, it can determine the rotational speed of various gasoline and diesel engines quickly without requiring prior knowledge of the number of cylinders which the engine possesses. The principle behind the proposed method is the same for all reciprocating engines, irrespective of the number of strokes. The only difference is that, the lowest

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harmonic order is 1 for two-stroke engines, and 0.5 for four-stroke engines. For brevity, the discussion in this paper will be based on the four-stroke engine as an example.

The proposed method does not require special device such as encoder, and the only hardware needed is a one-axis acceleration sensor used for acquiring engine block vibration signals which is easy to install, and an commonly signal pickup assembly. In addition, it does not require the parameter of cylinder's number. The two advantages make the proposed method particularly suitable for routine inspection and maintenance of vehicles.

The remainder of this paper is structured as follows. Section 2 briefly introduces the dynamic characteristics of a four-stroke engine, as well as the discrete spectrum correction technique used for improving determination accuracy. Section 3 describes the proposed new algorithm for measuring rotational speed in detail, which is then validated through a simulation procedure. Section 4 presents the results from bench tests and tests on real engines for measuring the engine rotational speed using the new algorithm. Section 5 contains the conclusion of the paper.

2. The principle behind estimating the rotational speed of an engine from its vibration signals

2.1. Dynamic characteristics of crankshaft

When an engine is running, its power is transmitted and transformed through the crank and connecting rod mechanism. The excitation loads acting on the crankshaft of an internal combustion engine are mainly derived from the driving torque due to gas forces generated within the cylinder M_g and the driving torque due to reciprocating inertial forces of the moving parts M_j. As known from the dynamic analysis of the engine crankshaft, the gas pressure torque M_g can be expressed as a summation of harmonic torques comprising different amplitudes, frequencies and phases [10]. Since a four-stroke engine fires once for every two revolutions of the crankshaft, the frequency of change in torque M_g corresponds to half the crankshaft angular velocity ω, and gas pressure torque generated within the ith cylinder can be expressed as:

$$M_{gi} = M_{0i} + \sum_{k=1/2}^{K} [A_{ki}\cos(k\omega t + \varphi_i) + B_{ki}\sin(k\omega t + \varphi_i)] \qquad (1)$$

where M_{0i} is the average torque due to gas forces generated within the ith cylinder; A_{ki} and B_{ki} are the Fourier coefficients; φ is the initial phase of the kth harmonic order of the torque waveform; and K is the highest harmonic order required to represent the torque due to gas forces, which can be set to $K = 24$ for four-stroke engines [11].

Similarly, the reciprocating inertia torque M_j can also be expanded into a Fourier series, but contains only the integer-order sine terms [11]. As compared to the gas pressure torque M_g, the reciprocating inertia torque M_j poses minimal impact on the vibration of the crankshaft, since it only affects the size of vibration and does not generate any useful external power.If the various harmonic components of the gas pressure torque are expressed like rotating vectors on the crankshaft axis, the vector of the kth harmonic order will rotate k times faster than the crankshaft [12]. For an engine with i cylinders, every cylinder's torque due to gas pressure has a phase difference of $4\pi/i$, which varies according to the firing order of the engine. Fig. 1 illustrates the phase angle diagram for the gas pressure torque of a typical four-stroke six-cylinder engine. As it can be seen in the figure, if all cylinders contribute equally to the engine torque, only the main harmonic orders, which are multiples of half the number of cylinders in a four-stroke engine, will survive in the harmonic structure of the resultant torque due to gas forces.

This means the first main harmonic order $k = i/2$ has the largest amplitude on the spectrum of the resultant torque. The engine speed can be worked out according to the first main harmonic order when the number of cylinders is known. Assuming $f_{i/2}$ is the frequency of the first main harmonic order $k = i/2$, f_1 is the rotating frequency of the engine, the engine speed n (r/min) will be:

$$\begin{aligned} n &= 60 \times f_1 = 60 \times f_{i/2}/k \\ &= 120 f_{i/2}/i \end{aligned} \qquad (2)$$

In reality, however, the gas forces in all cylinders can never be totally identical, especially when one cylinder is misfired or when fuel supply to the individual cylinders is not even. Determining $f_{i/2}$ only by searching the peak value of the amplitude spectrum may result in a wrong choice of the first main harmonic order. Besides, the cylinder number i has to be known in order to obtain the engine rotational speed using Eq. (2), thus significantly limiting its use.

As known from the harmonic analysis of the crankshaft system, the half-harmonic order can be considered the basic order for a four-stroke engine, i.e. if the frequency of the half-harmonic order $f_{1/2}$ can be determined accurately, the engine rotational speed can be worked out. Assuming $f_{1/2}$ is the frequency of the half-harmonic order relative to the engine speed n, then:

$$n = 120 f_{1/2} \qquad (3)$$

As seen from a comparison between Eqs. (3) and (2), the method of obtaining engine rotational speed using Eq. (3) allows more flexibility since it does not require any prior knowledge of the number of cylinders.

Given that the first and second natural modes of the crankshaft are negligible at the low frequency band, the crankshaft can be considered a rigid body. It is possible to establish a direct correlation between the equal-order harmonic components of the crankshaft's speed and torque due to gas forces [11]. The proposed method in this paper leverages on this characteristic, to obtain the vibration signals of the engine cylinder through the accelerator sensor, and then look for harmonic information that are related to the rotational speed from within the low frequency bands.

2.2. Discrete spectrum correction technique

As a result of the spectrum leakage effect caused by a finite number of processed samples, the precision of the