Methods of Misfire Detection

Using Knock Sensors

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This article presents a summary of investigations carried out within the framework of a thesis at the Institute for Measurement and Automation Technology of the Technical University of Berlin. It deals with misfire detection using knock sensors and points out which components are present within the knock sensor signal and how components relating to combustion can be extracted. It demonstrates that the application of the methods introduced will yield good identification results using real knock sensor signals.
noise and vibration components, i.e. components which propagate through the cylinder wall and those which result from changes in the motion of the engine housing.

Figure 1 shows a sectional diagram through a cylinder and illustrates the causes of various KS signal components. The grey fields show quantities which excite structure-borne noise. The white components represent external excitation.

Many components of the signal are directly or indirectly associated with the combustion, and therefore carry information about the state of the combustion process. In particular, these are the cylinder pressure, which excites the cylinder wall and results in pulse-like components of the KS signal, and the forces due to inertia. These depend on the engine speed and are therefore also associated with the pressure distribution.

For example, the derivation of the torque due to inertia at the crankshaft of a four-cylinder engine leads to Eq. (1).

$$M_D = m \cdot \omega^2$$

where \(M_D\) designates the torque due to inertia, \(m\) is the mass of the pistons, the piston rings and part of the connecting rod, \(r\) is the crank radius, \(\omega\) the angular frequency and \(\lambda\) the connecting rod ratio [10].

Using this equation, both the dependence of the torque on the speed (\(\omega^2\)) and the dependence on the harmonic components of \(\sin 2\omega t\) and \(\sin 4\omega t\) can be seen.

A misfire results in the absence of the typical increase in the cylinder pressure and thus to an absence of the pressure-related pulses.

The lack of combustion also causes the engine speed to fluctuate. According to Eq. (1), this leads to a decrease in the amplitude of the rotational harmonics, in other words to a change in the envelope of harmonic vibrations [5].

Figure 2 shows some typical knock sensor signal distributions in engines from three different manufacturers under the same conditions, i.e. the same speed and load.

Some model-dependent differences can be observed for the signal characteristics. In the first figure (Figure 2a) for example, pressure-related pulses can be clearly seen at the places marked by arrows.

It must be emphasized here that capacitive or inductive influences of the ignition or injection devices can be virtually ruled out, since technical precautions were taken to prevent them having an influence (shielding, application of charge amplifiers etc.).

In Figure 2c, the pressure-related pulses cannot be clearly observed. Instead, the speed harmonic components are the carriers of information on the state of the combustion in this engine, as will be shown by the experimental results in section 4.

Thus, the task of the misfire detection system is to extract the pulse-like components and the envelope of speed harmonics from the knock sensor signal [7].

In the following two sections, two methods which have been developed within the framework of these investigations are described.

3 Pulse Detection Using Non-Linear Polynomial Filtering

This section describes a method for extracting and detecting the pressure-related pulses which can be clearly observed within the signals in Figures 2a and 2b.

In the following, this method is explained and the experimental results which were obtained are presented.

Figure 2 shows that the pressure-related pulses are characterised by strong slopes. This fact can be used to reconstruct the pulses. A so-called non-linear polynomial filter has been developed for the purpose of extracting the pressure-related pulses and suppressing noise and higher rotational harmonics.

This filter is based on the polynomial filter developed by Savitzky and Golay [9]. It applies a moving window over the signal and fits a polynomial of arbitrary order over the signal within the windowed section. The polynomial coefficients represent the output of the filter. It can be shown that this filter type can be implemented by using the same number of FIR filters as the order of the polynomial [4].

The filter was expanded in two steps for the purpose of misfire detection. The first step was to develop the polynomials from the resulting polynomial coefficients. For example, if the length of the window is five, five different polynomial values of the neighbouring signal sections can be obtained at each point. The output of this so-called expanded polynomial filter is the mean value of all the polynomial values which make a contribution at one point.

As an example, Figure 3 shows the result of this filter type applied to a signal with a strong negative slope.

The broken line represents the input signal. The polynomial values at the various points are marked by circles. The mean values — i.e. the output of the filter — are represented by a solid line.

It can be seen that, on the one hand, the polynomial values at the place of an abrupt change in the input signal show a higher variance, while on the other hand it can be seen that the peaks of the pulse are smoothed by the filtering procedure. The higher variance of the polynomial values at the jump can be used to reconstruct the pulse-like components (i.e. the peaks of the signal and the strong jump). A certain value is added to the output signal of the expanded polynomial filter depending on the variance of the polynomial values at one place. An extensive calculation leads to a non-linear or adaptive filter type [4], [6], which will be abbreviated as the NLPF (non-linear polynomial filter) in the following.

Figure 4 shows the result of the NLPF applied to the signal in Figure 2a. It can be clearly seen that both the noisy parts and higher rotational harmonics of the signal are suppressed and the shape of the pulses remains unchanged.

Thus, the non-linear polynomial filter is suitable for extracting the pressure-related pulses from the knock sensor signal and for predicting the existence of misfires.

Figure 5 shows the application of the NLPF for misfire detection. The knock sensor signal is applied to the NLPF. Disturbances (noise and rotational harmonics) are removed from the signal, whereas the shape of the pulses remains unchanged.

After each combustion, a feature is extracted from the filtered signal (Matched Filter), by means of which a decision can be made on whether a misfire (MF) occurred or not (no MF).

The pulse response of the matched filter depends on the engine speed and was determined from cycles without misfires [4].

Table 1 shows identification results obtained using the method described above. The results are based on a four-cylinder production engine (engine I). A data set of 100 combustion events containing 25 misfires in one cylinder was available for each operating point.

The Table shows excellent identification results over the whole speed and torque range. The percentages include all those cases in which the right identification decision was made, i.e. a misfire was detected as a misfire and, vice versa, combustion was detected as combustion.

4 Methods for Detecting Non-Stationary Harmonic Vibrations

Section 2 showed that, besides the pressure-related pulses, the envelopes of rotational harmonics also carry information about the state of the combustion. It was also emphasized that the energy distribution of the signal components can vary considerably from engine type to engine type. Thus, the pulse detection method may work very well for some models, whereas...