

SIGNAL COMPONENT ANALYSIS FOR MISFIRE DETECTION

M. Lindemann, D. Filbert

Institut für Meß- und Automatisierungstechnik, Sekretariat E2
Technische Universität Berlin, Einsteinufer 19, D-10587 Berlin, Germany

Abstract: The misfire detection plays an essential role for the on-board diagnosis of spark ignition engines and is prescribed by law in the United States of America since 1989 (OBDII). According to the last revised edition from 1996, the misfire detection rate must equal 100 percent for the 2002 model year under all operating conditions relating to speed and torque. Actual methods for misfire detection in spark ignition engines base on measuring speed fluctuations. But they don't work reliably even at high speed and low torque. Hence this paper describes a new approach which consists of measuring the vibration at the cylinder walls. The composition of the knock sensor signal is introduced and classified in several elementary parts. All of them carry information about the state of combustion. A new polynomial based signal element decomposition method is proposed to extract features for the misfire detection. Results are given using real knock sensor signals.

Keywords: Engine Misfire Detection, Signal Component Analysis, Polynomial Filtering

1 INTRODUCTION

With the purpose to reduce dramatically the emission of pollutants for SI-engines, in the year 1989 the California Air Resources Board (CARB) passed the so-called OBDII law which requires manufacturers of automobiles to comply with a lot of demands respecting to the surveillance and diagnosis of all exhaust gas cycle components [1]. The most disputed requirement in the law is the misfire detection. Misfires are lacks of combustion due to a faulty or damaged ignition unit, poor fuel metering, poor compression etc. [2]. The consequences of a higher misfire activity can be the combustion of the fuel by contacting the catalyst, or the fuel escapes directly in the environment without being ignited. In either case those occasions damage the environment or the engine. According to the last revised edition of the OBDII law from 1996, the misfire detection rate must equal 100 percent for the 2002 model year under all operating conditions relating to speed and torque [3].

Many efforts have been done to comply with this demand, and many methods have been proposed and investigated. They can be distinguished between direct and indirect methods. Direct methods make use of one or more additional sensors which are installed directly within the cylinders or the exhaust cycle, and which measure the pressure or the temperature in the cylinders or the exhaust gas cycle. Indirect methods make use of already available devices or sensors like speed sensors, spark plugs etc. The direct methods deliver much better results according to the misfire detection rate for the whole load and speed range but have in common that they are more sumptuous in comparison to the indirect methods, because they require additional sensors and therefore constructive modifications of the engine. The indirect methods on the other side are much cheaper to be implemented but have some deficiencies under certain working conditions of the engine.

Due to its cheap integration, the most common method which actually is used for the misfire detection is an indirect method and makes use of the measuring of speed fluctuations [4]. A misfire occurrence leads to speed fluctuations which take some few revolutions of the crankshaft. The higher the load and the lower the speed are, the more obviously the fluctuation is observable. But even for the case of high speed and low torque speed fluctuations can not be related reliably to an origin, i.e., if the reason was a rough road surface, a high load gradient or something else. In these cases the running state of the vehicle must be controlled to switch off the diagnosis tool when the working conditions don't allow a reliable identification of misfires anymore.

Hence there is a need for some new or additional methods which are able to support or replace this system in its critical regions. This paper deals with a new indirect approach for misfire detection using knock sensors. Knock sensors are acceleration sensors which are fixed at the cylinder walls of the engine. Their signal represents the vibration of the engine, and actually they are only tasked with

detecting knocking combustion. For new model years these sensors are installed in quantity, as the knocking detection is another requirement within the frame of the OBDII regulation. Since the knock sensors are directly placed at the cylinder walls, their nearness to the place of combustion suggests their application to the misfire detection as well.

This presentation first describes the composition of the knock sensor signal respecting to physical origins, i.e., of which elementary components the knock sensor signal consists. It will be clearly pointed out, how far the elementary components carry information about the state of combustion. These signal components will be defined and afterwards a new signal component analysis method using polynomial decomposition techniques is derived. From the signal components then it is easy to extract certain features for the misfire detection. The efficiency of the method will be shown using real knock sensor data.

2 THE KNOCK SENSOR SIGNAL

The knock sensor signal represents the vibration of the engine. Fig. 1 illustrates the essential components of the signal. It shows a cross-section through a cylinder of an SI-engine. At the right side at the cylinder wall the knock sensor is placed. For a vertical four cylinder engine there are usually one or at most two knock sensors. For a couple of sensors they are fixed between the 1st and 2nd and between the 3rd and 4th cylinder, for just one sensor it is usually mounted between cylinder 2 and 3.

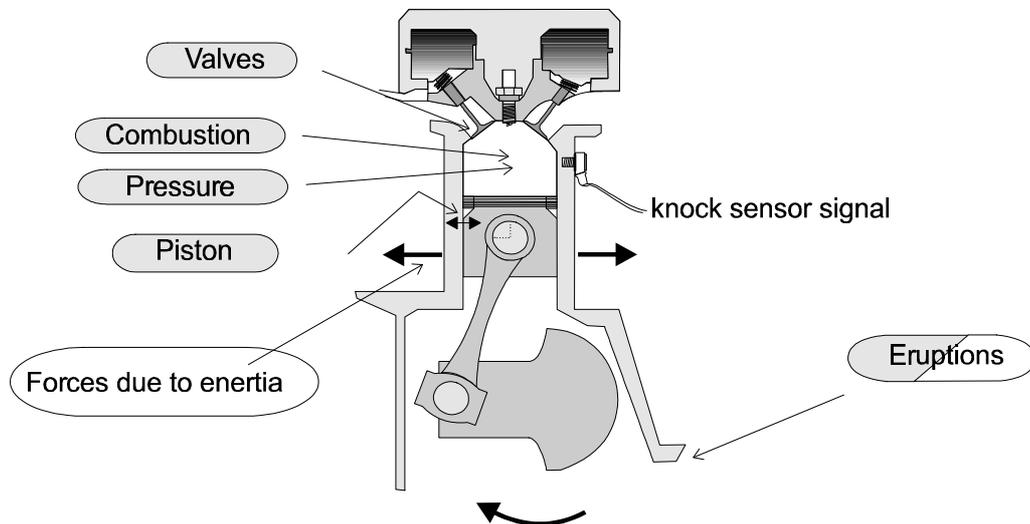


Figure 1. Origins of engine vibration and knock sensor signal

The origins of the vibrations which are measured with the knock sensor can be distinguished between two different groups. One part of the signal is caused by those vibrations which excite the sensor directly running through the cylinder wall. The origin can be a valve clearance, excitations by the pressure distributions within the cylinders, cross-cuts of the piston and so on. The parts which evoke an excitation of the cylinder wall are grey underlined in Fig. 1. The remaining components are vibrations which not really have to pass the cylinder wall but which are causing a motion of the engine in itself. These parts are white underlined.

Some parts of the signal can be determined analytically, at least in a rough approach, like the forces due to inertia and the pressure distribution. This will be done in the following in this section. The remaining parts can't be determined either because their appearance is undeterminable like the eruptions or the physically basics are much too complicate to allow to get good approaches for these signal parts (e.g. the transfer function of the cylinder wall, cross-cuts of the piston etc.) [5].

Fig. 2 shows the principal forces and torques which contribute to the knock sensor signal. The rotation of the crankshaft leads to the torque M_x which tries to overturn the engine against the rotation motion and which accelerates the whole engine block. The friction between the cylinder wall and the piston is represented by the force F_N . This force and the component p_N of the pressure distribution excite the cylinder walls. The component p_z contributes to an additional part of the torque M_x .

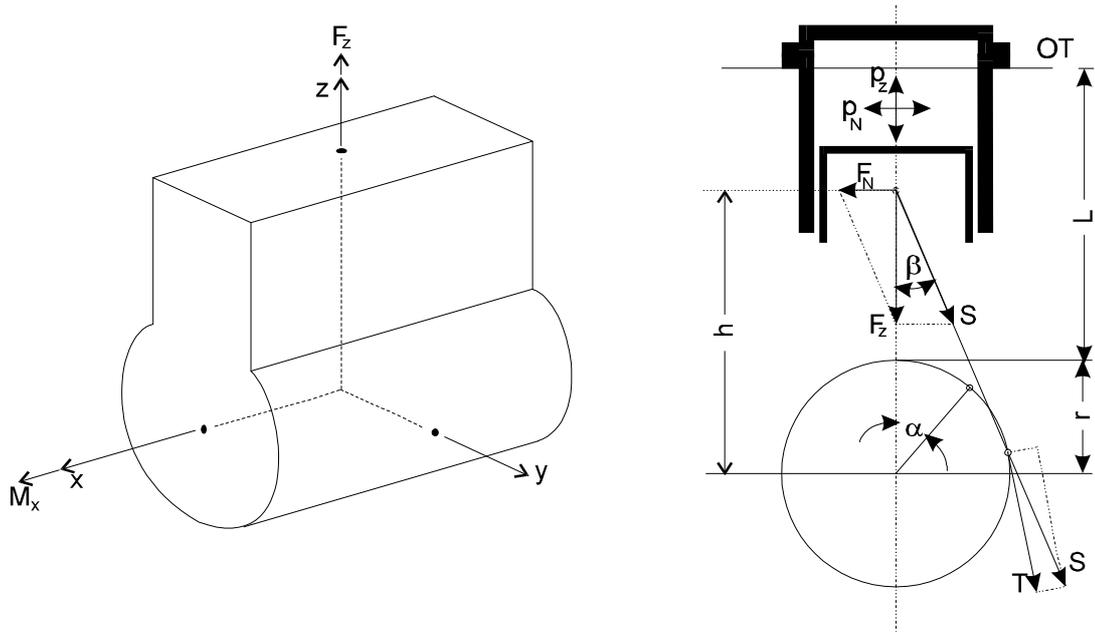


Figure 2. Definition of directions, forces and torques

For a four cylinder engine the torques and forces listed above can be calculated easily [6], [7]. The force F_z can be shown to be

$$F_z = 4m_s r \omega^2 I_p \cos 2\omega t. \quad (1)$$

m_s denotes an equivalent mass for the piston including rings and gudgeon pin and contains around 25% to 33% of the mass of the connecting rod [6], r is half the piston stroke, ω the angular velocity of the crankshaft, and I_p represents the stroke-connecting-rod ratio r/L (see Fig. 2). The torque M_x can be separated in two different parts, one which is caused by mechanical origins (M_m) and another which is due to the combustion (M_c), i.e.

$$M_x = M_m + M_c. \quad (2)$$

The mechanical part can be derived by Fig. 2 to

$$M_m = 4m_s r^2 \omega^2 \left(\frac{1}{2} \sin 2\omega t + \left(\frac{I_p}{2} \right)^2 \sin 4\omega t \right) \quad (3)$$

Using the relation $F_{pz} = p_{cyl} \cdot A_k$ with p_{cyl} denoting the cylinder pressure and A_k the area of the piston top, the combustion part of the torque M_x can be expressed as a Fourier series as

$$M_c = \bar{M}_c + a_2 \sin(2\omega t + j_2) + a_4 \sin(4\omega t + j_4) + \dots \quad (4)$$

which contains only even orders of the rotation frequency. The normal part F_N of the force of the oscillating mass m_s leads to an excitation of the cylinder wall. Using (1) F_N can be represented as

$$F_N = F_z I_p \frac{\sin \omega t}{\sqrt{1 - I_p^2 \sin^2 \omega t}}. \quad (5)$$

A misfire now sets a chain of occurrences going. First, the pressure distribution shows a typical lack in its slope. This may immediately lead to a reduced energy of the knock sensor signal. The misfire evokes a collapse in the torque M_p with the consequence that the rotation speed fluctuates. According to (3) and

(5), this leads to a reduced torque M_m and a reduced excitation of the cylinder wall by the force F_N . Due to (3), (4) and (5), the information of a misfire is hidden in the speed harmonics which de- or increase in time according to the sequence of occurrences. Their exact behaviour strongly depends on speed and load conditions [5].

3 POLYNOMIAL DECOMPOSITION

As shown in section 2, the information about a misfiring cylinder lies in the spectral distribution of the knock sensor signal. Because of the different components which are involved in the knock sensor signal, different spectral behaviours appear at different times. Hence this fact suggests either the application of time-frequency approaches, or methods of signal decomposition which deliver several elementary signal components which carry different informations about the state of combustion. Since all the knock sensor signal elements share the same frequency range (see (3) – (5)), the distribution of the signal in the time domain must be taken into consideration. This can be managed by a polynomial decomposition.

The basic idea of the polynomial decomposition lies in the moving polynomial filtering as proposed in [8]. According to this, for a fitting of a signal by a polynomial of order M over a sliding window of length L , the j -th moving polynomial coefficient can be obtained by a correlation between the input signal y and a vector \mathbf{a}_j by

$$p_j(n) = \sum_{k=0}^{L-1} \mathbf{a}_j(k) \cdot y(k+n) \quad (6)$$

with

$$\mathbf{a}_j(k) = \sum_{i=0}^M \mathbf{S}_x^{-1}(i, j) x(k)^i \quad \text{and} \quad \mathbf{S}_x = \begin{bmatrix} \sum x^0 & \sum x^1 & \dots & \sum x^M \\ \sum x^1 & \sum x^2 & & \\ \vdots & & \ddots & \\ \sum x^M & & & \sum x^{2M} \end{bmatrix} \quad (7)$$

$x(k)$ represents the k -th value of the corresponding x -vector of the regression interval, and \mathbf{S}_x the matrix of the potential sums of the x values. An alternative representation for the polynomial coefficients can be obtained using an FIR filter bank as shown in Fig. 3 with \mathbf{a}^* denoting the filter coefficients mirrored in time.

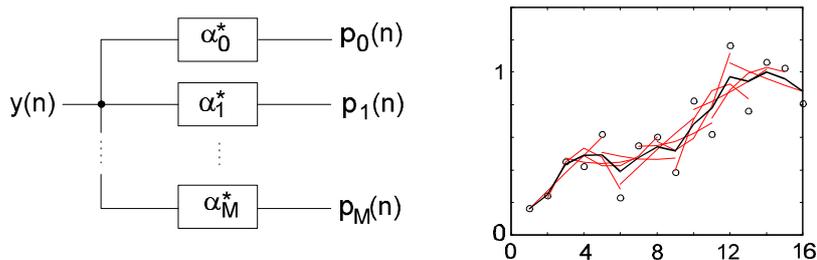


Figure 3. Polynomial filtering as FIR filter bank (left), regression example and approximation (right)

On the right, Fig. 3 gives an example for the moving regression of a signal whose values are illustrated by circles. The regression is done using a second order polynomial over every 5 points ($M = 2$, $L = 5$). It can be seen that at every place L different polynomials exist. Hence an approximation of the signal can be obtained by calculating the mean over all polynomials at one place. Assuming $z_j(n)$ assigns the L values which are contributed by the corresponding regressions, they can be calculated as

$$z_j(n) = \sum_{i=0}^M p_i(n-j) \cdot x(j)^i \quad \text{with } j = 0, 1, \dots, L-1. \quad (8)$$

Taking the mean over L values for j , and writing $\beta_i(j) = 1/L \sum x(j)^i$ yields

$$z^*(n) = \sum_{j=0}^{L-1} b_o(j) \cdot p_o(n-j) + \sum_{j=0}^{L-1} b_1(j) \cdot p_1(n-j) + \dots + \sum_{j=0}^{L-1} b_M(j) \cdot p_M(n-j). \quad (9)$$

$z^*(n)$ is a smoothing approximation of $y(n)$ which consists of $M + 1$ elementary parts. Every part is due to a polynomial power and therefore emphasizes different characteristics of the input signal y . According to (9) the $M + 1$ components can be obtained by filtering the polynomial coefficients with the values $\beta_i(j)$.

4 APPLICATION TO REAL KNOCK SENSOR SIGNALS

The following examples on a real knock sensor signal of a four cylinder engine illustrate the high efficiency of the polynomial decomposition method to extract different signals which share the same frequency range. According to the considerations in section 2 a misfire leads to changings of the spectra of the different signal components at different times, especially to those which are harmonics of the rotation frequency. Fig. 4 shows the behaviour of the second rotation harmonic as a reaction to a misfire. The knock sensor signal was measured at 1200 rpm under full load. A series of misfires at each 25th ignition point was generated. They are marked by the vertical lines. The x axis is scaled in working cycles. One working cycle corresponds to one rotation of the camshaft or two rotations of the crankshaft, respectively.

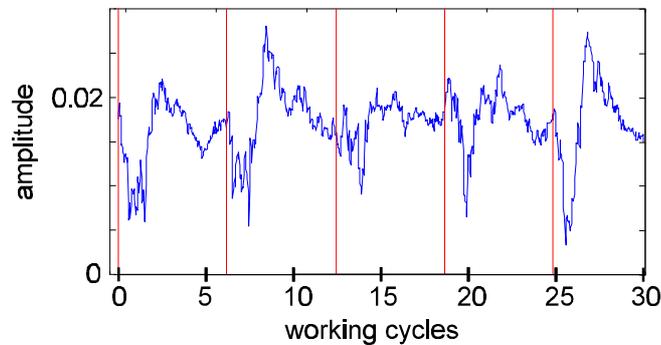


Figure 4. Distribution of the second harmonic under the presence of misfires

It can be seen obviously that in general a misfire leads with a slight delay to a breakdown of the second harmonic which then starts up to increase rapidly after around two working cycles, though it also can be pointed out here, that the increasing of the harmonic is not clearly given for every misfire occurrence. This fact may result in problems when trying to extract features for a classification of the state of combustion.

The knock sensor signal now was applied to the polynomial decomposition method with the parameters chosen to $M = 2$ (3 signal components) and $L \approx 16\%$ of the duration of a camshaft revolution. The signal was prefiltered with a angular synchronous low pass filter to suppress noise disturbances. From the output of the method three different signals are obtained. The distribution of their 2nd harmonic is shown in Fig. 5.

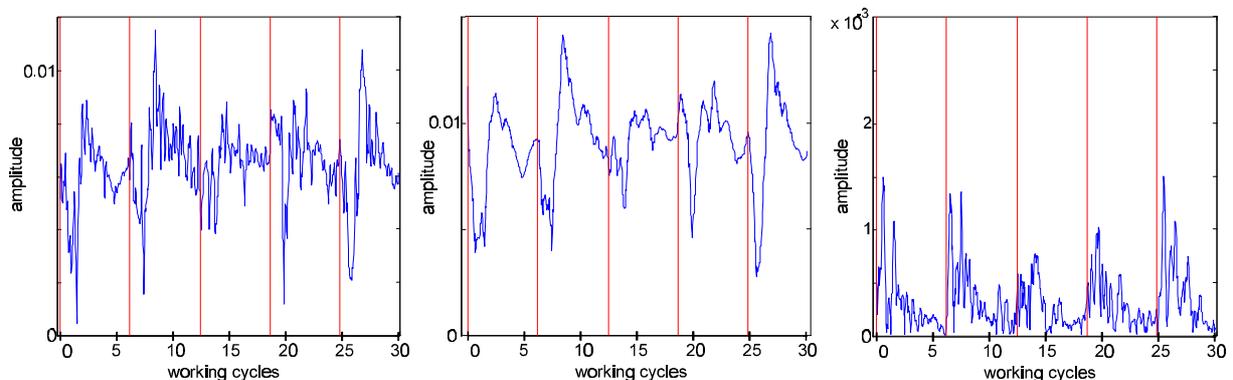


Figure 5. 2nd harmonic distribution of decomposed signals

It can be seen that the first and the second signal principally show the same behaviour for their second harmonic as the knock sensor signal does. The point of interest lies in the third decomposed signal which shows a quite different shape in comparison to the other ones. It is observable that as a reaction to a misfire the 2nd harmonic increases immediately and that the effect remains visible for several working cycles, even longer than the decreasing which can be seen for the first or second decomposed signal. This means that the third decomposition part delivers a knock sensor signal component which must have other origins in a physical sense. Consider again eq. (9) the different decomposed signals are due to different powers of the polynomials. Since the even decomposed signal parts express odd polynomial powers, and since sinusoids can be expanded in a polynomial series containing only odd polynomial parts, the conclusion can be drawn that even the second signal is due to pure harmonics within the knock sensor signal, i.e., due to the torque M_x . This assumption is supported by the fact that the torque decreases when a misfire occurs and that the inertia evokes a delay of the decreasing as can be seen clearly in Fig. 5, whereas the third signal component reacts almost immediately. Hence this behaviour must be due to excitations of vibrations which are directly caused by the pressure distribution.

5 SUMMARY

In this paper a method for misfire detection with knock sensors was introduced. After considering the physical backgrounds of a SI-engine and working out the elementary parts which contribute to the knock sensor signal, a new polynomial based decomposition method was introduced which allows the separation of signal components which share the same frequency range. With an example for the second harmonic of the rotation frequency it was shown that the direct processing of the knock sensor signal doesn't lead to a homogenous behaviour of the calculated time frequency distribution. After applying the polynomial decomposition method, new signals could be extracted which are due different physical origins. These signal components can be examined separately and deliver different behaviours due to the presence of misfire occurrences. The big advantage of the decomposition method is the possibility to interpret the various signal components. An example was given for a knock sensor signal at 1200 rpm under full load for the second rotation frequency. Further examinations have proved that this method even delivers good results up to a speed of 4800 rpm under 50% of full load using additional speed harmonics such as the first, the third and so on.

REFERENCES

- [1] Malfunction and Diagnostic System Requirements – 1994 and Subsequent Model-Year Passenger Cars, Light Duty Trucks, and Medium Duty Vehicles with Feedback Fuel Control Systems. Proposed new regulations to Title 13, California Code of Regulations: 1968.1
- [2] Dai, W.; Flory, M.S.; Trigui, N. Prediction of Misfire Limits in Spark-Ignition Engines Using a Quasi-Dimensional Model, Proceedings of the 31st "ISATA Conference - Simulation, Virtual Reality and Supercomputing" (Düsseldorf, 2.-5. Juni 1998), p. 337-348.
- [3] Air Resources Board (1996), Modifications to Section 1968.1, Title 13, California Code of Regulation, Attachment II, California
- [4] Williams, J. (1996), An Overview of Misfire Cylinder Engine Diagnostic Techniques Based on Crankshaft Angular Velocity Measurement, SAE Paper 960039
- [5] Lindemann, M., Filbert, D., Methods for Misfire Detection with Knock Sensors, 3^{ème} Conférence Internationale, Méthodes de Surveillance et Techniques de Diagnostic Acoustiques et Vibratoires, (Senlis, France, 13.-15. Oktober 1998, p. 749-758
- [6] Urlaub, A., Verbrennungsmotoren, 2. Auflage Springer-Verlag, 1995
- [7] Mitschke, M., Dynamik der Kraftfahrzeuge, 3. Auflage, Springer-Verlag, 1997
- [8] Orfanidis, S.J., Introduction to Signal Processing. Englewood Cliffs, NJ: Prentice Hall, 1996.

AUTHORS: Dipl.-Ing. Michael LINDEMANN, Institut für Meß- und Automatisierungstechnik, Technische Universität Berlin, Einsteinufer 17, D-10775 Berlin, Germany, Phone +49 30 31425869, E-mail: Lindemann@ee.tu-berlin.de

Univ. Prof. Dr.-Ing. D. FILBERT, Institut für Meß- und Automatisierungstechnik, Technische Universität Berlin, Einsteinufer 17, D-10775 Berlin, Germany, Phone +49 30 31422541, E-mail: dieter.filbert@tu-berlin.de