# INTERNAL COMBUSTION ENGINE VIBRATION BASED FAULT DETECTION USING WAVELET PACKET TRANSFORM

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Summary
In this paper, the wavelet transforms of vibration acceleration signals which were acquired from the cylinder head and engine block for various faulty and healthy conditions of IC engine was used to fault detection. The engine which has been tested is 4-cylinder 4-stroke with eight valves fed with petrol and LPG. Many mechanical fault detection techniques based on vibration analysis have been developed over the last few decades. The analyssis of vibration signals associated with internal combustion engines is complicated due to the complexity of the engines and diffrent sources of vibration. The engine vibration signal is inherently a transient one even in engine steady operation. The time-frequency localization features of the wavelet transforms make them suitable for IC engine fault diagnosis and monitoring. In the present investigation, a fault diagnosis technique based on wavelet packet transform (WPT) i used to engine fault detection. The experimental results show that proposed method is useful for detection the faults in various engine working conditions.

Keywords: wavelet transform, IC engine, diagnostics.

PRZETWARZANIE SYGNAŁÓW ZA POMOCĄ TRANSFORMACJI FALKOWEJ W DIAGNOSTYCE WIBROAKUSTYCZNEJ SILNIKÓW SPALINOWYCH

Streszczenie
W artykule przedstawiono przykłady zastosowania analizy falkowej sygnałów przyspieszeń drgań zarejestrowanych na kadłubie i głowicy silnika ZI w celu wykrycia symulowanych uszkodzeń. Obiektem badań był 4-ro cylindrowy silnik spalinowy zasilany alternatywnie benzyną i LPG. W ostatnich latach opracowano i rozwinięto wiele metod diagnozowania opartych na pomiarach drgań. Analiza sygnałów drgań związanych z pracą silnika spalinowego jest utrudniona ze względu na złożony sygnał wywołany jednoczesnym działaniem wielu źródeł. Sygnał przyspieszeń drgań rejestrowany na kadłubie i głowicy silnika jest niestacjonarny i zawiera składowe impulsowe. Dlatego w diagnostyce drganiowej silników korzystne jest stosowanie metod czasowo-częstotliwościowych takich jak analiza falkowa, które umożliwiają tworzenie użytecznych cech diagnostycznych. W artykule przedstawiono przykłady zastosowania pakietu analizy falkowej (WPT) do wykrywania symulowanych uszkodzeń silnika. Z badań wynika, że zastosowana metoda może być użyteczna do diagnozowania różnych uszkodzeń silnika spalinowego.

Słowa kluczowe: analiza falkowa, silniki spalinowe, diagnostyka drganiowa.

## 1. INTRODUCTION

The diagnosing systems used in modern combustion engines aim at locating the element or system which, due to natural wear or damage, cannot further perform its function as specified by the manufacturer.

Increasing requirements concerning the durability and reliability of combustion engines and the minimisation of costs and disadvantageous influence upon the environment necessitate the acquiring of information on their condition during operation. Introduction of the obligation of manufacturing motor vehicles compliant with the OBDII standard resulted in the possibility of accessing data stored in the programmers of individual systems. Owing to this solution, new possibilities of diagnosing the technical condition of those systems arise [12].

The greatest efficiency of the on-board diagnostics system was assured in the area of monitoring the emission of toxic compounds. However, some types of damage, such as: growing wear of valve-seats and valve faces, a shift of the valve train phase, or wear of the cylinder bearing surface to a degree exceeding the dimensions allowable for a particular engine, in many cases in practice, do not result in a response of the diagnosing system. The most frequent reason for this are the used adaptive controlling algorithms for combustion engines. It is about controlling the processes with changeable dynamic properties and of changeable stochastic disturbance properties, during which estimation is carried out of the process model parameters and disturbance, so as to update the controlling algorithm [3, 7]. Adaptive control of an engine can lead to a situation where the appearing errors will be hidden or adapted. Mechanical defects and operational wear, in particular in the early phases of development, are compensated by adaptive adjustment systems as a result of permissible ranges of adjustment. Only after occurrence of a major failure, the course of the regulation process is so much disturbed, that finding the defect will be relatively easy, because the system will switch to an emergency mode.

In the modern engines, the detection algorithms of combustion knocking are a component of the engine controller system IC. A change of the ignition advance angle has a significant influence on the nature of the measured vibration signal. This poses a danger of masking the mechanical defects by control systems and can be the cause of more serious failure.

Therefore, changes of the technical condition of an engine, induced by early phases of its wear, are difficult to detect. An important issue in vibroacoustic examination of engines is a correct interpretation of complex measured signals by applying more and more proficient methods of their processing [1, 5, 9, 14, 16]. The main tasks in diagnostics include: separation of a useful vibroacoustic signal and selection of characteristic, damage-sensitive features of the processed signal.

## 2. DIAGNOSING OF COMBUSTION ENGINES WITH USE OF VIBROACOUSTIC METHODS

One of the methods of acquiring diagnostic information is to measure the vibration generated by the engine. A combustion engine is subject to the action of inner and outer forces. They encompass mainly:

- combustion pressure,
- movement of the crank-piston system,
- forces induced by the timing gear system,
- forces from the work of engine accessories, such as the alternator, compressor, and the like,
- forces transferred from the vehicle body and the power transmission system.

One of the significant forces appearing during the crank-piston system work are piston strokes while changing its movement direction. The value of the force depends significantly on the clearance between the piston and the cylinder wall [4, 5, 6], caused by wear and tear of the engine. The value of force is a function of combustion pressure and rotational speed of the engine.

The vibration signal recorded in any place on the engine block is a weighted sum of the engine block response to all elementary events (Fig. 1); convolutions with pulse functions of transfer from the place of generation to the reception place of the diagnostic signal are the weights here [2].

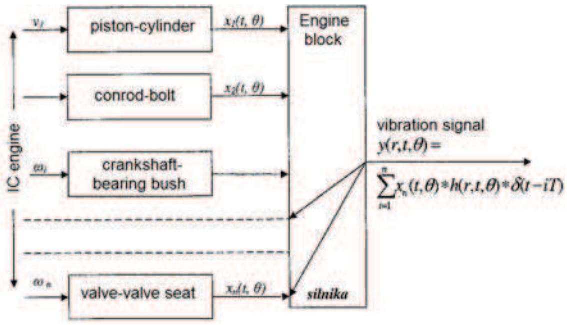


Fig. 1. Diagram of generating engine vibration signals

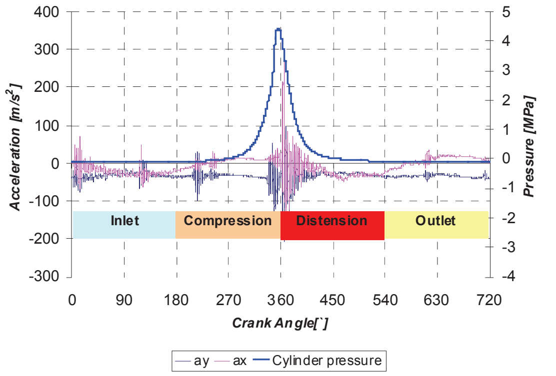


Fig. 2. An exemplary course of a working cycle of a single-cylinder combustion engine

All systems of the combustion engine work in a specific order (Fig. 2). The elementary events taking place in kinematic pairs are ordered, as well. In that case, the kinematic pair of an engine, which produced a percussive impulse, can be determined by the location of the impulse vis-à-vis the reference signal.

The vibroacoustic signal generated by the combustion engine can be presented in a simplified form:

$$x(t) = \sum A_i \cos(\omega_i t + \varphi_i) + \sum\sum B_{ij}(t) u(t - t_j) \cos(\omega_{ij} t + \varphi_{ij}) \quad (1)$$

where:
$A_i$ and $B_{ij}(t)$ - amplitudes of signal components,
$\omega_i$ and $\omega_{ij}$ - frequencies of vibration components,
$u(t)$ - pulse function,
$t_j$ - time determining the occurrence of pulsing phenomenon,
$\varphi_i$ and $\varphi_{ij}$ - signal component phases.

The first component of the equation reflects the main harmonic components, which are normally characterized by high amplitude values. After removing the low-frequency components, a residual signal containing high-frequency impulse components is obtained.

The above signal transformation facilitates isolating the summary signal of the investigated kinematic pair by means of time or angle selection. Vibroacoustic signals generated by individual kinematic pairs and combustion engine tooling are most frequently nonstationary due to the occurrence of nonlinear phenomena provoked, inter alia, by clearance, nonlinearity of elastic components' characteristics. Frequency characteristics of signals essentially depend on transmittance of the propagation route of component signals from their source to the measuring point. Vibration measured on a block is of a complex nature due to the overlapping signals which originate from various sources. For these reasons, diagnosing of combustion engine faults is a difficult process.

## 3. SIGNAL ANALYSIS IN THE TIME-SCALE DOMAIN

A simultaneous analysis of the time and frequency related properties of signals by means of a wavelet transform is more and more frequently used in diagnosing combustion engines [5, 10, 11, 14, 15, 16, 17].

The continuous wavelet transform of a finite energy function, $x(t) \in L^2(R)$, is defined as follows:

$$W_x(a,b) = \langle x(t), \psi_{a,b}(t) \rangle = |a|^{-\frac{1}{2}} \int_{-\infty}^{+\infty} x(t) \psi \frac{(t-b)}{a} dt \qquad (2)$$

$$a,\ b \in R,\ a \neq 0$$

An inverse transform of the transformation $W_x(a,b)$ takes the following form:

$$x(t) = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} W_x(a,b) \psi_{a,b}(t) \frac{da\,db}{a^2} \qquad (3)$$

Based on the definition, the function $\psi(t) \in L^2(R)$ is an acceptable elementary wavelet, if:

$$C_\psi = \int_0^\infty \frac{|\Psi(\omega)|^2}{\omega} d\omega < \infty \qquad (4)$$

where $\Psi(\omega)$ is the Fourier transform of the function $\psi(t)$.

Wavelet coefficients $W_x(a,b)$ are the function of scale $a$ and shift $b$. A change of the scale is tantamount to wavelet compression or stretch $\psi_{a,b}$. The coefficients $W_x(a,b)$ are the measure of signal's $x(t)$ correlation with the wavelet $\psi_{a,b}(t)$: for narrow wavelets, they represent the content of high-frequency components, and for wide wavelets, low-frequency components. The Continuous wavelet transform (CWT) is very excessive; after sampling its parameters, time $t$ and coefficient of scale $a$, the coefficients of a dyadic wavelet series are obtained. A discrete wavelet analysis of signal $x(t) \in L^2$ becomes reduced to determining its discrete wavelet transforms, which are the scalar products of signal $x$ and a sequence of function $\psi_{j,k}$. These products are called wavelet coefficients. The wavelet coefficients represent common characteristics of signal $x$ and wavelet $\psi_{j,k}$. Parameter $k$ localises the moment in which the analysis is being made, while parameter $j$ enables choosing the scale level (range of frequency), at which the signal spectrum is investigated.

The discrete wavelet transform finds broader and broader application the diagnosing of machines. Its expansion is reflected in the so-called wavelet packages, which enable multiple decomposition of signals. Wavelet packages consist of a linear combination of the wavelet function expansion:

$$\psi^i_{j,k}(t) = 2^{j/2} \psi^j \left(2^j t - k\right) \qquad (5)$$

$i = 1,2,3...$,
$j$ – scale parameter,
$k$ – shift parameter.

Function $\psi^i$ is defined by the following relations:

$$\psi^{2j}(t) = \sqrt{2} \sum_{k=-\infty}^{\infty} h(k) \psi^i (2t-k) \qquad (6)$$

$$\psi^{2j+1}(t) = \sqrt{2} \sum_{k=-\infty}^{\infty} g(k) \psi^i (2t-k) \qquad (7)$$

Discrete filters $h(k)$ and $g(k)$are mirror filters connected with the scaling functions and wavelet functions [1, 13]. The algorithm of multiple signal decomposition by means of wavelet packages (WPT) is presented in the block diagram (Fig. 3).

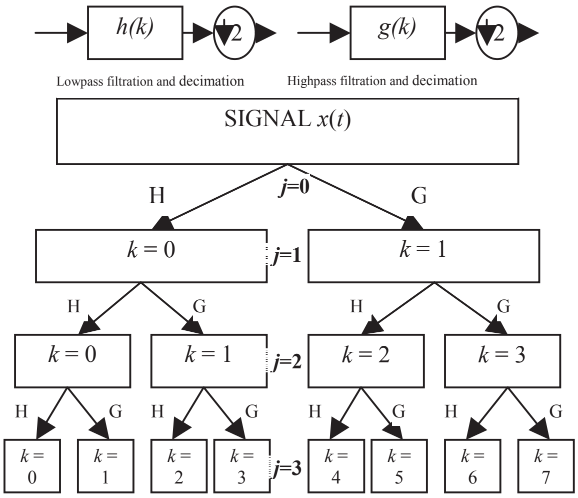


Fig. 3. Algorithm of decomposition by means of wavelet packages

The algorithm makes a frequency analysis of the signal through iteration of the double-channel set of filters consisting of low- and high-pass filters. Signal obtained as a result of filtration in the previous step undergoes further filtration. As a result of each iteration, a high-frequency component, called a detail, and a low-frequency component, called approximation, are obtained. The signal decomposition process is a multilevel iteration process, where further details and approximations are subject to further decomposition. The calculation algorithm (fig. 3) has the from of a set of filters with a binary tree structure, where the low- and high-pass branches are developed by means of a pair of the same filters. This type of analysis has been widely applied recently, because it enables creating standard sets of diagnostic characteristic used as input data of neuron classifiers[14, 16].

The above-mentioned properties of wavelet analysis make it more and more popular in diagnosing combustion engines, where non-stationary signals with impulse components are processed.

## 4. RESEARCH OBJECT AND TESTING PROCEDURE

Tests of vehicles equipped with 1.2 and 1.3 $dm^3$ spark ignition engines were conducted on a BOSCH chassis test bench, FLA203. During the tests, accelerations of the engine block and head vibration, rotational speed and location of the crankshaftwere recorded as a function of time. The signals were recorded with use of an eight-channel NI PCI-6143 data acquisition card, controlled with a programme developed in the Lab View 7.1 environment. A diagram of the measuring system is shown in Fig. 4.

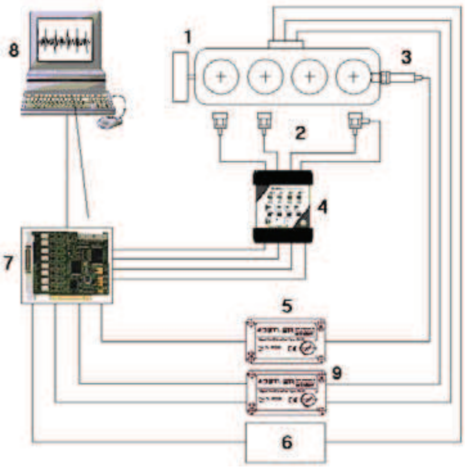


Fig. 4. Diagram of the measuring system l-combustion engine, 2-piezoelectric acceleration sensors, 3-piezoelectric pressure sensor, 4-charge amplifier, 5-signal amplifier, 6- signal converter of the subatmospheric pressure inlet system, 7-data acquisition card, 8-computer with LabView software, 9-amplifier of the rotational speed sensor signal and crankshaft position

The main purpose of the study was to determine the influence of the lack of the LPG fuel inflow into individual cylinders on the vibration signal characteristics. As part of the tests, 7 various states of engine operation were simulated (operational engine; cylinders 1, 2, 3 and 4 disengaged one by one; cylinders disengaged in pairs: 1-4 and 2-3).

In addition, the effect was examined of the simulated local fatigue crack of exhaust valve of the first cylinder in the 1.3 engine on the changes of the wavelet decomposition coefficients.

## 5. RESEARCH RESULTS

The time courses of vibration accelerations and their decomposition into low- and high-frequency constituents, performed with use of wavelet filtration for one working cycle of an engine during idle run, in the case of switching off the fuel inlet to cylinders 1 and 4, is shown in Fig. 5. In the signal filtered out by means of wavelet decomposition, it is possible to notice low-frequency interference induced by the simulated condition of the engine. Fig. 6 presents the results of approximation A5 and Fig. 7 shows details D4 for five simulated states of the engine operation. On the basis of the presented results of the wavelet analysis, the energy measures can be easily determined from the distributions at different levels of decomposition. The energy of wavelet decomposition coefficients for the selected decomposition level, $j$ and the band range, $k$, is determined as follows:

$$E_{j,k} = \sum_k \left| c_{j,k} \right|^2 \tag{8}$$

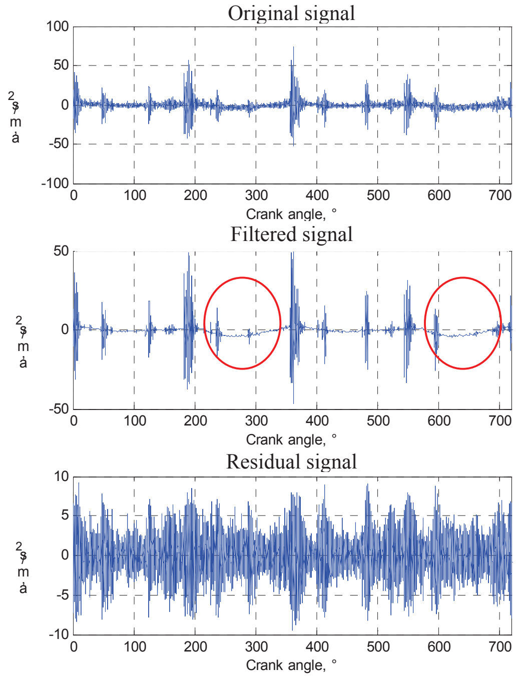


Fig. 5. Decomposition of vibration acceleration signal for an engine with cylinders 1 and 4 off, within one working cycle of the engine

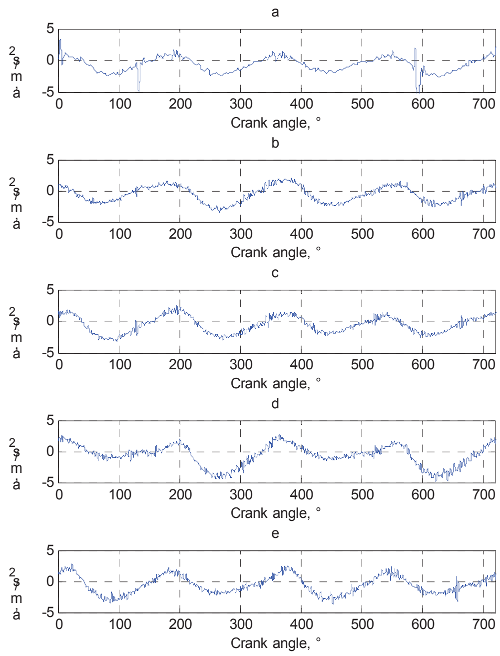


Fig. 6. Approximations at the A5 level, a-operational engine, b)1$^{st}$ cylinder off, c-2$^{nd}$ cylinder off, d- 1$^{st}$ and 4$^{th}$ cylinders off, e- 2$^{nd}$ and 3$^{rd}$ cylinders off

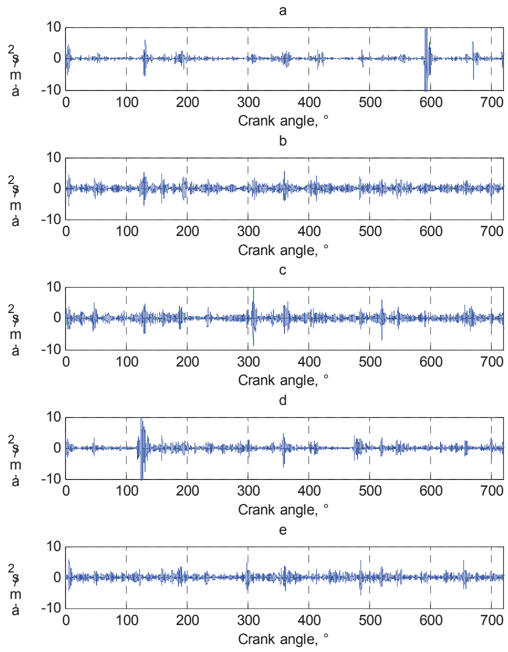


Fig. 7. Details at the D4 level, a-operational engine, b)1$^{st}$ cylinder off, c-2$^{nd}$ cylinder off, d- 1$^{st}$ and 4$^{th}$ cylinders off, e- 2$^{nd}$ and 3$^{rd}$ cylinders off

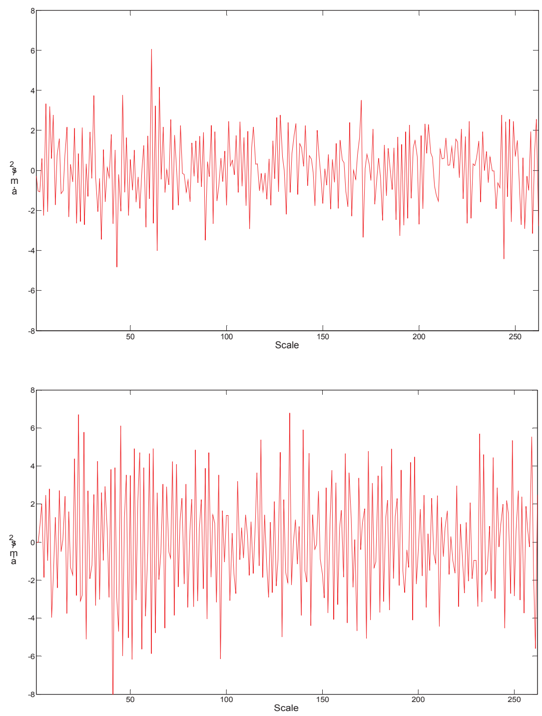


Fig. 8. Results of WPT decomposition for j=4 and k=1 for an operational engine (upper graph) and an engine with a simulated crack of the exhaust valve (lower graph)

Figure 8 shows the selected results of the decomposition by means of WPT for the engine with a simulated crack of the exhaust valve head in the first cylinder. The damage provoked a significant increase of $E_{j,k}$ wavelet coefficients' energy in the selected point of the decomposition tree. When compared to the fully operational engine, the simulated damage provoked a significant increase of energy of wavelet coefficients $E_{j,k\,uszk} / E_{j,k\,spr}$= 2.97.

## 6. CONCLUSIONS

On the basis of the examinations carried out and the papers published recently, it can be concluded that the multiple wavelet decomposition is a proper tool for the construction of a set of diagnostic characteristics. This type of analysis has been widely applied recently, because it enables creating standard sets of diagnostic features used as input data of neuron classifiers.

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