RECOVERY OF IMPACT SIGNATURES IN DIESEL ENGINE USING WAVELET PACKET TRANSFORM (WPT)

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Summary

A fault diagnosis technique for internal combustion engines using time-scale representations of vibration signal is presented in this paper. Engine block vibration results as a sum of many excitations mainly connected with engine speed and their intensity increases with the appearance of a fault or in case of higher engine elements wearing. In this paper an application of acceleration signals for the estimation of the influence of piston skirt clearance on diesel engine block vibrations has been described. Engine body accelerations registered for three simulated cases representing piston skirt clearance variations were an object of preliminary analysis. The presented procedures were applied to vibration and pressure signals acquired for a 0.5 dm^3 Ruggerini, air cooled diesel engine. Reciprocating machines are difficult to diagnose using traditional frequency domain techniques because of generate transient vibration. In conducted experiments WPT has been chosen as the decomposition tool for feature extraction as a tool providing a flexible time-frequency resolution and a rich library of redundant wavelet bases.

Keywords: fault diagnosis, engine vibration, WPT.

WYKRYWANIE WYMUSZEŃ IMPULSOWYCH W SILNIKU ZS ZA POMOCĄ PAKIETÓW FALKOWYCH (WPT)

Streszczenie

W artykule przedstawiono wyniki badań diagnostycznych silnika ZS za pomocą analizy czasowo-częstotliwościowej. Drgania bloku i głowicy badanego silnika są spowodowane wieloma wymuszeniami związanymi z jego prędkością obrotową a ich intensywność wzrasta wraz z pojawianiem się uszkodzeń mechanicznych, zużycia eksploatacyjnego oraz występowania anomalii w procesie spalania. Sygnały przyspieszeń drgań wykorzystano do określenia wpływu stanu symulowanego luzu w złożeniu tłok cylinder.

W ramach badań silnika ZS, chłodzonego powietrzem o pojemności 0,5 dm^3 firmy Ruggerini zasymulowano trzy wartości luzu. Ze względu na fakt, że silniki spalinowe są złożonymi obiektami diagnozowania wykorzystanie tradycyjnych metod analizy częstotliwościowej nie zapewnia precyzyjnej identyfikacji charakterystycznych wymuszeń. W prowadzonych badaniach przeprowadzono dekompozycję sygnału drganiowego za pomocą pakietów falkowych (WPT).

Słowa kluczowe: diagnostyka uszkodzeń, silniki spalinowe, drgania, WPT.

1. INTRODUCTION

Identification of engine vibration sources is most important for making noise reduction strategies and engine diagnosis. An IC engine noise signal is composed of many components from different sources. To identify the requirement of noise signal analysis it is necessary to begin a discussion on the noise signal components. The combustion noise is produced by a rapid rate of in-cylinder pressure rise, which besides being a source of engine structural vibrations [3, 9, 17, 18]. The contribution of the combustion to the whole noise signal is some transient components. In a normal condition, the combustion noise is usually in a frequency range above a few 100 Hz as the combustion energy below this range is mostly transformed into useful work by pushing pistons forward. In the case of abnormal conditions, degradation in the combustion quality may produce some low frequency content in the combustion noise. A rise in the cylinder pressure pushes the piston from the top dead center – TDC, advancing to the bottom dead center - BDC. In this movement, the clearance between the piston and the cylinder or damage to piston rings can cause the piston to impact with the cylinder, the phenomenon of piston slap, which is another major source of engine noises. As the piston slap is caused by both the combustion and the clearance, the noise level reflects the combustion quality and changes in the clearance. The impacts will add transient components to the engine noise signal [15, 17, 18, 19]. As piston slap happens on the way from the TDC to the BDC, it can be identified by referring to the time axis. An important feature of IC engines is that they have both reciprocating and rotating parts. Different type of parts will produce different signal components. Rotating parts, such as the flywheel and front pulley, can excite harmonic components to the noise.

Decided by the engine speed, these harmonic components mainly distribute in the low-frequency range. An increase in the amplitude of the harmonic components indicates condition variations of these rotating parts. Contributions of different rotating parts to the noise can be identified with reference to their speeds. Injectors and valves are reciprocating moving parts. They produce impacts to the engine structure and hence contribute transient components to the noise. In an injector, the needle is held onto its seat by a high rate spring. This spring also serves to control the injection pressure and regulate the injection time. A decrease in the stiffness of the spring will bring forward the injection time. As a consequence, the combustion quality will be degraded. An engine has many inlet valves and exhaust valves. A valve is opened by a camshaft and pushed back to its seat by a valve spring. Any problems with valve seats, tappets, and mechanisms can cause a change to the transient vibrations produced during opening and closing, and thus the corresponding transient components of the noise signal. These valves open and close at different times, and so the contribution of different valves to the noise can be identified from the times of events. Fluid-induced noise, such as exhaust and inlet noise, is also an important part of the noise. Along with the sudden release of gas into the exhaust system or the rush of a sharp pulse of fresh air into the cylinder, oscillation of the air volume in the cylinder and the exhaust system is excited and hence noise is produced. When inlet and exhaust valves close, noises will also be generated for a change in the fluid field. The fluid-induced noise contributes transient components to the whole noise. Some early research shows that fluid-induced noise usually has high frequencies. With modern fluid passage designs, the level of fluid-induced noise is normally very low. Damage or problems with the exhaust and inlet system will increase the magnitude of the fluid-induced noise.

A noise signal can be mathematically described as:

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

where:

- A_i and $B_{ij}(t)$ denote amplitude of signal component,
- ω_i and ω_{ij} represent the frequency,
- $u(t)$ is the function step,
- t_j is the instant at which an event occurs,
- φ_i and φ_{ij} are phases of signal components.

The sample of engine noise signal is presented on figure 1.

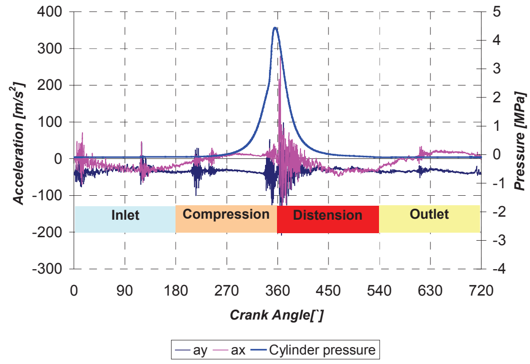

Fig. 1. Engine block vibration vs. crank angle for one cycle

2. SIGNAL PROCESSING PROCEDURE

2.1. Joint time frequency analysis

A basic requirement on a signal processing technique is that it should at least reveal information on the amplitude, the time, and the frequency content of an event. To satisfy the requirement, a signal processing technique should be two-dimensional, in the time-frequency domain [1, 6, 8, 11, 13, 14].

It is possible to get the information about main noise sources using JTFA (Joint time frequency analyses) based on few methods, i.e.:

- Gabor Spectrogram,
- Wigner Ville distribution,
- Choi-Williams distribution,
- Cone Shape distribution,
- Adaptative Spectrogram,
- STFT Spectrogram.

Each quadratic JTFA method has its own advantages and disadvantages. The STFT spectrogram is faster than all the other methods, but it has the worst joint time-frequency resolution. Based on the specific application a suitable JTFA method must be selected and a compromise must be chosen between the resolution, the cross-term interference and computation speed. Possibility to analyze a signal in the time-frequency domain simultaneously enables better process a particular signal. Especially this analysis allows observing how power spectrum of signal changes over time.

2.2. Wavelet decomposition of engine block vibration signals

The Wavelet Transform provides a more flexible way of time –frequency representation of a signal by allowing the use of variable sized windows. WT gives precise frequency information at low frequencies and precise time information at high frequencies. This makes the WT suitable for the analysis of irregular data pattern, such as impact signatures in IC engines. Wavelet function is composed of a family of basis functions that are capable of describing signal in a localized time and frequency (or scale) domain. The Continuous Wavelet Transform of a time varying signal *x(t)* consists of coefficient that are the convolution of the signal *x(t)* with a family of wavelets $\{\psi_{a,b}\} \in L^2(R)$ with finite duration in time and finite frequency:

$$W_x(a,b) = \int_{-\infty}^{+\infty} x(t)\psi^*_{a,b}(t)dt \qquad (2)$$

where:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{|a|}}\psi\left(\frac{t-b}{a}\right),\ a,b \in R, a \neq 0 \qquad (3)$$

where the (*) symbol denotes complex conjugation. The continuous wavelet transform (2) depends on the choice of the wavelet function. CWT creates redundant information. A discrete set of translation and dilation parameters are often sufficient for most tasks. The wavelet packet transform (WPT) is an extension of the WT which provides a complete level by level decomposition of signal /fig. 2/ Wavelet packets consist of a set of linearly combined usual wavelet function [2, 5].

The wavelet packet is a function where integers indices *i, j* and *k* are the modulation, scale and translation parameters:

$$\psi^i_{j,k}(t) = 2^{j/2}\psi^j\left(2^j t - k\right) \qquad (4)$$

The wavelet function can be obtained from the following recursive relationships:

$$\psi^{2j}(t) = \sqrt{2}\sum_{k=-\infty}^{\infty} h(k)\psi^i(2t-k) \qquad (5)$$

$$\psi^{2j+1}(t) = \sqrt{2}\sum_{k=-\infty}^{\infty} g(k)\psi^i(2t-k) \qquad (6)$$

The discrete filters *h(k)* and *g(k)* are the quadrature mirror filters associated with the scaling function and wavelet function. The WPT contains a complete decomposition at every level and hence can achieve a higher resolution in the high frequency bands The recursive relations between the *jth* and the *(j+1)th* level components are following:

$$x^i_j(t) = x^{2i-1}_{j+1}(t) + x^{2i}_{j+1}(t) \qquad (7)$$

$$x^{2i-1}_{j+1}(t) = Hx^i_j(t) \qquad (8)$$

$$x^{2i}_{j+1}(t) = Gx^i_j(t) \qquad (9)$$

where: *H* and *G* are the filtering decimation operators related to the discrete filters *h(k)* and *g(k)*.

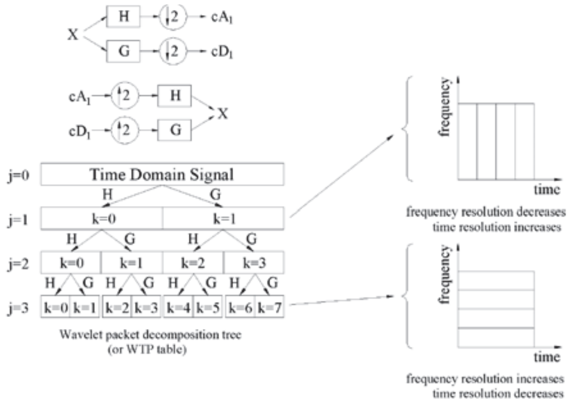

Fig. 2. Decomposition tree of time varying signal using wavelet packet transform

The basis step of a fast wavelet algorithm is presented in fig. 2 which can be implemented in two opposite directions, decomposition and reconstruction. In the decomposition step, the discrete signal *x* is convolved with a low-pass filter *H* and a high-pass filter *G*, resulting in two vectors cA_1 and cD_1 .The elements of the vector cA_1 are called approximation coefficients, and the elements of vector cD_1 are called detailed coefficients. The symbol ↓2 denotes down sampling.

3. EXPERIMENTAL SETUP

The experimental setup developed consisted of one cylinder, The procedures presented in this paper were applied to vibration and pressure signals from an 0,5 dm^3 Ruggerini, air cooled diesel engine (Fig. 3). Technical details describing the test object are listed in the table 1.

Table 1
Technical features of the engine

Parameters	Manufacturer data
Displacement [cm^3]	477
Stroke [mm]	75
Bore [mm]	90
Maximum power [kW]	6,0
rpm for max power [min^{-1}]	3000
Max torque [Nm]	21
rpm for max torque [min^{-1}]	2500

Test program provided sampling of the following data:

- in-cylinder pressure,
- vibration signal of engine head and wall, for two directions: x and y (Fig. 3),
- crankshaft revolution, together with TDC recognition,
- engine torque,
- manifold pressure.

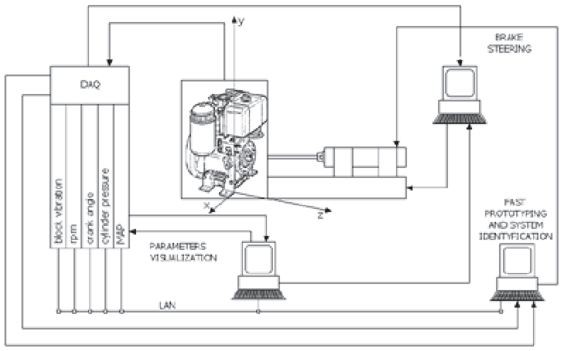

Fig. 3. Schematic diagram of experimental setup

In-cylinder pressure was measured with the use of piezoelectric pressure transducer type 6121 by KISTLER, coupled with charge amplifier model 5011. Crankshaft position and TDC recognition was done with the use of KISTLER 2613B transducer. Engine body vibrations were measured with ICP sensors by PCB interfacing with PA3000 signal conditioner manufactured by Roga Instruments.

Acceleration transducers were installed on engine body and engine head using thread connections. Signals were acquired with the use of eight channel data acquisition card NI PCI-6143, running under LabView 7.1 environment, where a dedicated program has been implemented. Sampling rate for all channels was set up to 50 kHz.

Research program was realized for engine running on idle, at higher rpm of 1500 min^{-1} without load and for rpm range from 1000 – 1500 min^{-1} with load not exceeding 10 Nm. Tests were carried on for three different setups of engine piston skirt clearances: nominal, 2 times bigger than nominal, 4 times bigger in respect to the nominal. For the purposes of simulation tests, at the selected clearance values the compression pressure was left at the same level. An example of in-cylinder pressure, and vibration signal traces is presented on figures 1 In-cylinder pressure and engine body vibration signals were registered for 18 engine operation points, each covering 150 engine cycles.

4. ANALYSIS RESULTS

Figures 4, 5, 6 present engine body acceleration traces and its time-frequency representation for three different simulated clearance values. Trace obtained for nominal clearance are presented on figure 4, meanwhile figure 5 presents results for 2 times bigger clearance and figure 6 for the 4 times bigger clearance. With the increase of clearance, an important raise of vibration signal level together with trace properties variations and increased engine body response time for excitation are observed. Changes in signal traces due to bigger clearance may also be noticed in time frequency plane. The distribution of vibration energy with scale is different for the normal clearance and 2xN and 4x N.

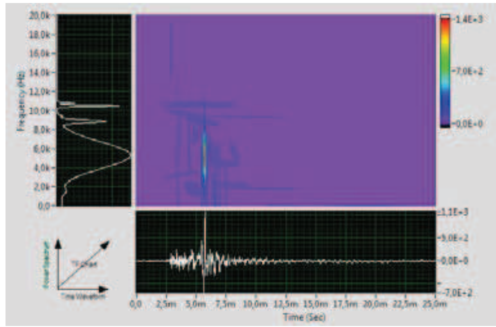

Fig. 4. Time-frequency representation of engine acceleration for nominal skirt piston clearance

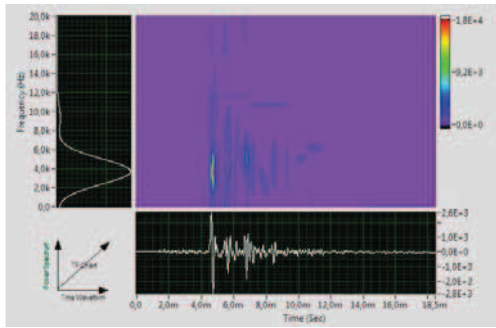

Fig. 5. Time-frequency representation of engine head acceleration for 2 times bigger skirt piston clearance

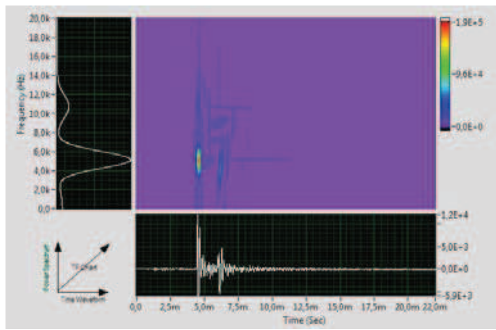

Fig. 6. Time-frequency representation of engine acceleration for 4 times bigger skirt piston clearance

Figures 7, 8 and 9 present results of vibration signal analysis using wavelet packet decomposition. The acceleration signal was decomposed into 4 levels for each transform. With the signal being decomposed into a number of sub-bands, features can be extracted from the wavelet packet coefficient in each sub –bands to provide information on the condition of IC engine being monitored. The energy content of acceleration signal can be calculated, based on the coefficient of the signals transform. Since the energy content of signal after decomposition /fig. 7, 8, 9/ is directly related to the simulated clearance it can be used as an effective indicator of the IC engine condition.

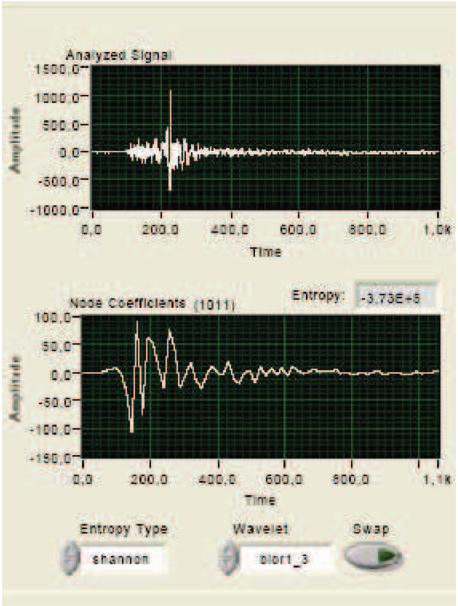

Fig. 7. WPT result of engine acceleration by nominal clearance for crankshaft angle range 372 – 420^{o}

Figures 7, 8 and 9 present results of vibration signal analysis using wavelet packet decomposition. The acceleration signal was decomposed into 4 levels for each transform. With the signal being decomposed into a number of sub-bands, features can be extracted from the wavelet packet coefficient in each sub –bands to provide information on the condition of IC engine being monitored. The energy content of acceleration signal can be calculated, based on the coefficient of the signals transform.

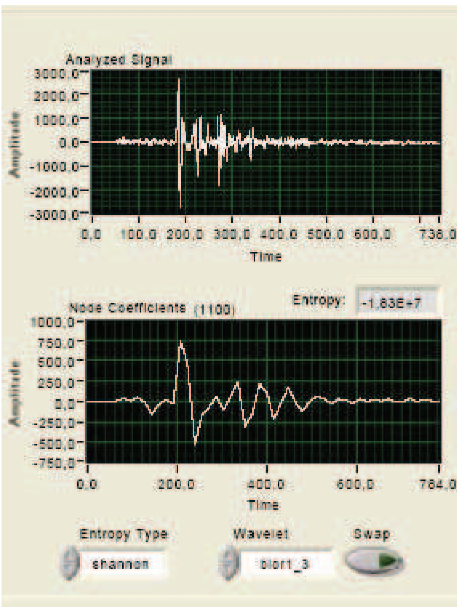

Fig. 8. WPT result of engine acceleration by 2 times bigger clearance for crankshaft angle range 372 – 420^{o}

Since the energy content of signal after decomposition /fig. 7, 8, 9/ is directly related to the simulated clearance it can be used as an effective indicator of the IC engine condition.

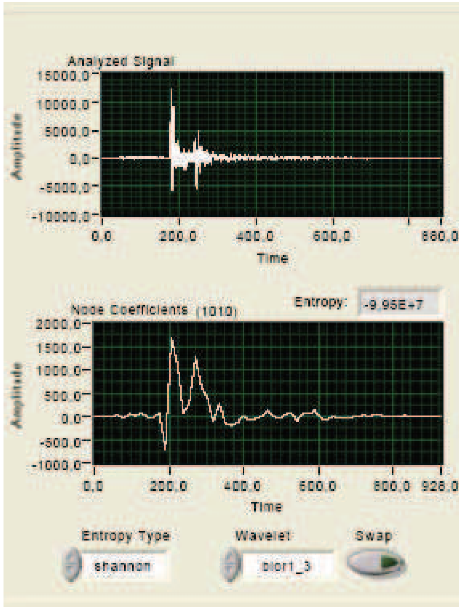

Fig. 9. WPT result of engine acceleration by 4 times bigger clearance for crankshaft angle range 372 – 420^{o}

5. CONCLUSION

The WPT is powerful tool for on-line monitoring and diagnostic of combustion process. The WPT decomposes a vibration signal into different components in different time windows and frequency bands.

It can recover important features of the vibration signal that are sensitive to the change of IC engine condition.

By using the WPT, accurate and reliable on-line monitoring decisions can be made.

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