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Practical application of wavelets in the engine's vibroacoustic analysis

JEL: L62 DOI: 10.24136/atest.2018.399
Data zgłoszenia: 19.11.2018 Data akceptacji: 15.12.2018

Vibrations are most often measured using ceramic piezoelectric sensors - accelerometers. The accelerometer uses a piezoelectric effect to measure the dynamic acceleration of its housing. They are mounted directly on the measuring system (moving or rotating, such as gearboxes, rotating blades, turbine engines or bearings). This is not their only use, because they can also be used in shock measurements, such as NCAP in the field of automotive safety or diagnostics (unfortunately they have lower accuracy than low-frequency LDV). The main advantage of using a piezoelectric accelerometer is its linearity in a wide range frequency and a huge range of work dynamics.
Engine vibration measurements are usually made at different points of the engine to be independent of each other. The engine block is a characteristic measuring point because it is best available. Accelerometers are assembled by glue, screwing or magnetic connection. The obtained vibroacoustic signal is most often analyzed using Fourier analysis. The following article presents another possibility of on-line analysis: short-term wavelet analysis "on-line".

Keywords: wavelet, engine, vibrations, vibroacustic

Introduction

Vibration is most commonly measured with use of ceramic piezoelectric sensors - accelerometers. Accelerometer use of piezoelectric effect to measure the dynamic acceleration of its casing. They are full-contact transducers that are typically mounted directly on elements that move or rotate with high frequency like gearboxes, spinning blades, turbine engines, or bearings. That's not their only application as they can also be used in shock measurements like automotive safety NCAP or failure test and much slower, low-frequency vibration measurements. The main benefit of using a piezoelectric accelerometer is its linearity over a wide frequency range and huge dynamic range of work.

Engine vibration measurements are typically taken at different points on the engine to make it independent of each other. Characteristic points to be measured on are the engine block, generator, and the base frame. Additionally auxiliary equipment like pumps, filters etc. are also measured to have the full picture of engine vibration.

Accelerometers that are used to pick up the vibrations from the object that can be simple hand-held accelerometers that only measure in one direction or more complicated accelerometers measuring in all three axes. The way of mounting the measuring device depends on the frequency of the object. Measurement device can be stud mounted, which can handle vibrations of up to 50 kHz. It can also be glued to the object and can then be used for vibrations of up to 2-5 kHz depending on the glue frequency. Magnetically mounted accelerometers can be accurately used up to 2-3 kHz [A]. The last way of mounting the accelerometer is by hand. This isn't very accurate and one can only measure frequencies of up to 1 kHz.

1. Wavelet

Measuring the accelerations or vibrations is a good start, but drawing conclusions from raw, unprocessed data is a completely different operation. To ease the act the signal processing transformations (like Fourier or Wavelet analysis) can be used to divide the redundant data from ones that can be useful.

Wavelet transformation is based on a linear combination of scalable and shifting functions. It can therefore be interpreted as the filtering of the signal analysed by the analysing function. The analysing function must be marked by an appropriate location in the time domain and by a limited band [2, 7].

It is impossible to use the continuous transform in engineering applications; this is why, a discrete representation of wavelets is employed. The discreet wavelet representation, re-scaled at the m-level, with the n-shift is recorded as [2]:

$$\Psi_{a,b}(t) \rightarrow \Psi_{m,n}(t)=(2)^{-m/2}\,\Psi(2^{-m}t-nT) \quad (1)$$

Starting from the analogue version of the transform [2, 7]:

$$W_x(a,b)=|a|^{-1/2}\int_{-\infty}^{\infty} x(t)\,\Psi\left(\frac{t-b}{a}\right)dt \quad (2)$$

where: Ψ – wavelet function, a – time scale, b – displacement.

The discrete wavelet transform can be written as a convolution function of the analysed signal x(t) and the wavelet function Ψ(t) [2]:

$$W_x(2^m,b)=2^{-m/2}\int_{-\infty}^{\infty} x(t)\,\Psi[2^{-m}(t-b)]dt \quad (3)$$

The discrete wavelet transform is reversible, which, however, is burdened with certain additions resulting from the discretization of the signal.

If the wavelet transform is treated as a function used to emphasize the changes occurring in the signal, then the usefulness of wavelets in diagnostics of non-stationary signals seems obvious. The value of such emphasis or 'highlight' is a derivative of superimposed (multiharmonic) vibration signals, which are produced by moving parts of the engine and the combustion process. The degree of 'emphasis' indicates the technical condition of the engine elements (moreover, it is possible to interpret those parts of the signal that will not be 'emphasized', but it is more difficult).

Currently, Discrete Wavelet Transform (DWT) in engineering applications is treated as a method of recursive filtering of the source diagnostic signal, in accordance with formula (3).

Wavelets are functions that, unlike the Fourier's analysis that rely mostly on scrutinizing the frequency of the signal, are suitable to analyze nonstationary, fast-changing signals with no or little recurrence. Mathematically it allows transition from time-value coordinate system to time-scale coordinate system, thus allowing the analysis of frequency change rate in the fixed amount of time.

Frequential localization of signal is far worse than in Fourier transformation, but in return wavelet analysis offers information about the rate of frequency change. Both of previously mentioned analysis methods lay their basis in scalar product s(t) and the remainder called transition kernel, which is the biggest difference between those two. Use of wavelets as transitions kernel allows to depict any continuous function with identifiable accuracy described with wavelet coefficients (a,b). Under the influence of coefficients a (scale parameter) and b (shift patameter) alteration Wavelet family is created, which is then use to decompose the signal s(t) on several levels of detail [2].

Even though wavelet analysis has many advantages it will never give precise information about for example frequencies that conclude the signal. It occurs owing to the fact that wavelet function, to be more precise it's transition kernel, does not represent one frequency, but most of the time period of frequency (pseudo frequency). But it gives information that is far more significant for the analysis like the time when the frequency change occurred, not about its precise value.Wavelet has many applications and another one that will be used in this overview is denoising the signal, that can be used to smooth the course of the function. To denoise the signal with use of wavelet "short" wavelets coefficients have to be deleted, thus neutralizing part of information. Example of such operation can be seen in figure 1, the result is smooth and free of peaks that were unusable for sake of examination.

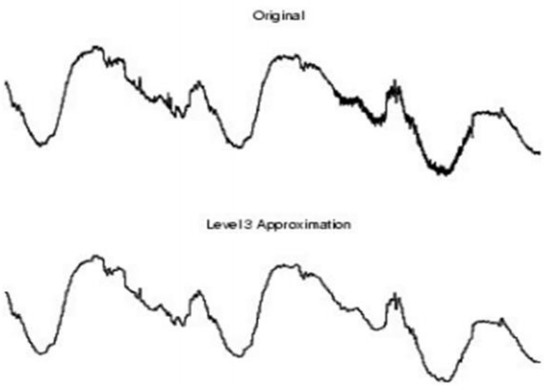


Fig. 1. *Signal denoised with use of wavelet analysis*

2. Researches

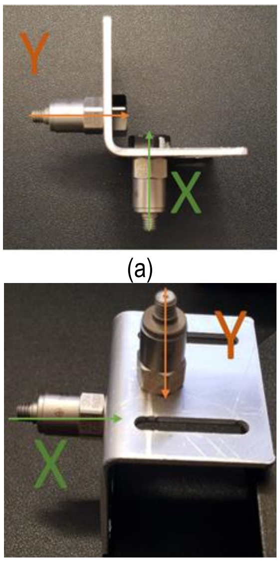
Vibroacustic displacement of spark ignition engine (1.4 dm^3) was used to take measurements of with the use of measurement devices (mutli-axe accelerometer [6], NI cDAQ-9171 chassis and NI 9215 C series measurement card [4]).

The NI cDAQ-9171 is a 1-slot NI CompactDAQ USB chassis designed for small, portable sensor measurement systems. The cDAQ-9171 chassis is designed for use with C Series modules. The cDAQ chassis is capable of measuring a broad range of analog and digital I/O signals using a USB 2.0 interface.

The NI 9215 module for use with NI CompactDAQ and chassis includes four simultaneously sampled analog input channels and successive approximation register (SAR) 16-bit analog-to-digital converters (ADC).

Each channel of the NI 9215 Series has a center pin to which the positive voltage signal AI+ can be connected, and a shield to which the negative voltage signal AI– can be connected.

To take measurements of the engine body vibration pair of PCB High-Resolution Piezoelectric Accelerometers and L shaped sheet of metal was used. Two holes for attach of the accelerometers were drilled in the same distance from the right angle. As it can be seen in fig. 2, four more holes were than milled. Their purpose is to hold the measuring case in the right place on the engine body with use of plastic bands. That solution allows to properly hold it in place and that the axis would not slip in any direction. Use of plastic bands does not harm the engine itself and can be easily detached.



(b)

Fig. 2. a, b *The method of attachment and the studied directions of accelerations during the experiment*

A program was developed for the measurement (LabView [5] language). Data acquisition in LabVIEW can be done using the DAQ.mx functions in LabVIEW libraries. At the beginning, *DAQmx Create Channel.vi* was used, to specify what kind of sensors will be attached to the measurement card, what kind of values are expected, its units and also the type of compensation.

Three user inputs were created, where sampling frequency, amount of samples and timeout of test can be chosen. When the measurement card would obtain the values, they should be displayed at the Front Panel, so that user can keep watch on them at the real time. Wavelet analysis of 2 axis vibration consists of 2 blocks that use wavelets (fig.3). First one is Wavelet Denoise which denoises the signal, which consists of many peaks with a low amplitude which is ambient vibrations. The measurement device was hard attached to the engine body to prevent any slip in any direction, what would cause the test to become wrong.

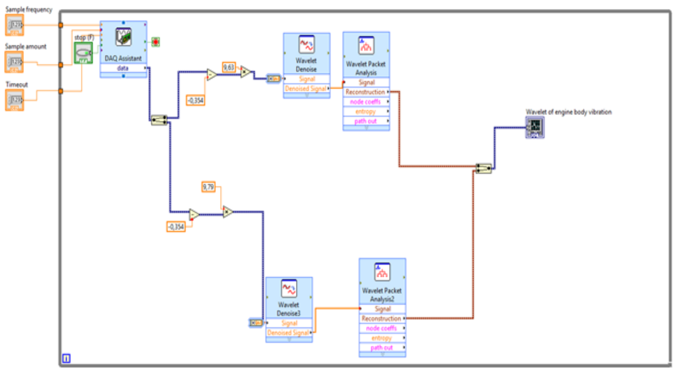


Fig. 3. *Block diagram of wavelet vibration analysis*

Denoising wavelet block removes all of the smalls peaks that ruined the graphs before. There is chosen UWT transform type with sym3 wavelet run as it was the most similar to what it had as ambient vibrations. Selection of Analysis wavelet was dependent on analysis necessities and shape of the rhythm that is sealable in the signal. Sym3 wavelet was chosen as it resembles the most the appearance which ambient vibrations, which were the object to get rid of.

Wavelet coefficients were automatically generated by the program, then the best tree of decompositions was chosen. After examination of several runs in the program, it has shown what kind of trajectory vibration would have, then the tree as the parameters were double checked. The amplitudes in the results section shown that generated tree with scaling functions was good enough for this kind of operation on the signal. The Entropy type was set to Threshold to ensure that the signal won't exceed a certain level. By neutralizing the coefficients part of the signal was omitted, however, as it will be shown in fig. 4 deletion of that part of data was crucial for the correctness of the research. The most important in vibration analysis is its magnitude and frequency change rate.

3.Results & conclusions

Fig. 4 presents the program results in work with continuous sampling. Two different vibration functions can be seen: vibration level in X-axis (blue), vibration level in Y-axis (red).

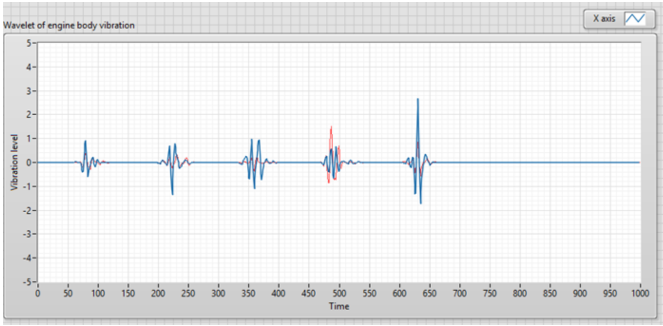


Fig. 4. *Results of continuous sampling of vibrating engine model*

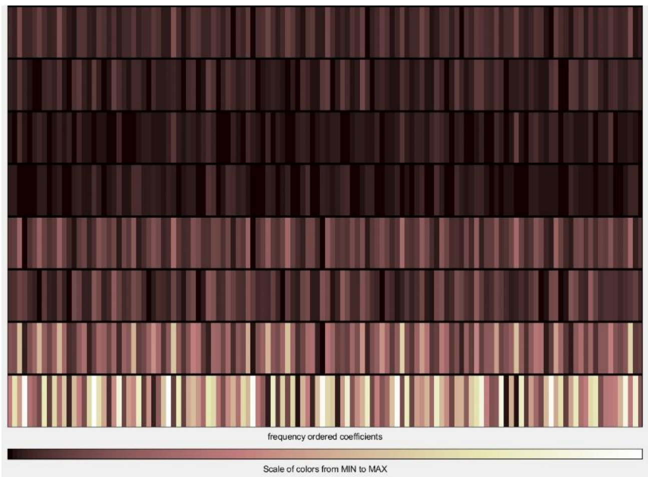


Fig. 5. Packet wavelet analysis of engine vibrations (2000 rpm, 50 Nm)

The results showed that the engine is at the very high level of vibrations that can easily damage the machine. Excessive aperiodic accelerations in any direction at a higher amount of time can and will make the engine wear faster. With the use of wavelet analysis of vibrations, several major problems with the engine as knocking combustion or other wrongly set injection parameters can be detected. The most damaging is the moment when the frequencies of vibrations in any axis impose on each other and with other parts – resonance. In this moment the engine is very unstable and it can damage the segments that are attached to it or itself. There have been many situations in motorsport or aerospace that the engine and circumfluent parts were in resonance and then the machine was destroyed. Engine vibration should be measured and if there are any suspicion of frequencies when the resonance may occur then precautions should be taken.

The results that we had achieved had shown that wavelet parameters were chosen correctly and the analysis was conducted with good accuracy.

Above engine vibration analysis shows the practical use of theoretical mathematics, but wavelets are not only used in technical aspects. They have also found application in image processing software, image compression, but likewise in far more life crucial areas like heart examination or coronary ostia detection. This technique has many purposes and no doubt the bank was not depleted.

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Praktyczne zastosowania falek w diagnostyce wibroakustycznej silnika

Wibracje są najczęściej mierzone za pomocą ceramicznych czujników piezoelektrycznych - akcelerometrów. Akcelerometr wykorzystuje efekt piezoelektryczny do pomiaru dynamicznego przyspieszenia jego obudowy. Są to przetworniki montowane bezpośrednio na układzie mierzonym (poruszającym się lub obracających, takich jak skrzynie biegów, wirujące łopaty, silniki turbinowe lub łożyska). To nie jest ich jedyne zastosowanie, ponieważ można je również stosować w pomiarach wstrząsów, takich jak NCAP w zakresie bezpieczeństwa w motoryzacji lub w diagnostyce (niestety mają mniejszą dokładność niż LDV w przypadku niskich częstotliwości) Główną zaletą zastosowania akcelerometru piezoelektrycznego jest jego liniowość w szerokim zakresie częstotliwości i ogromny zakres dynamiki pracy.

Pomiary wibracji silnika są zwykle wykonywane w różnych punktach silnika, aby były niezależne od siebie. Charakterystycznym punktem pomiarowym jest blok silnika, ponieważ jest najlepiej dostępny. Akcelerometry montuje się poprzez klej, przykręcenie bądź połączenie magnetyczne. Otrzymany sygnał wibroakustyczny jest najczęściej analizowany z wykorzystaniem analizy Fouriera. Poniższy artykuł przedstawia inną możliwość analizy „on – line": krótkoczasową analizę falkową „on-line".

Słowa kluczowe: falki, silnik, drgania, wibroakustyka

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