ROLE OF SIGNAL PREPROCESSING IN LOCAL DAMAGE DETECTION IN MINING MACHINES

Radosław ZIMROZ

Wroclaw University of Technology,
Diagnostics and Vibro-Acoustics Science Laboratory
Pl. Teatralny 2, Wroclaw, 50-051, Poland
Tel. (+48 71) 320 68 49, Telefax (+48 71) 344 45 12
E-mail: radoslaw.zimroz@pwr.wroc.pl

Summary

Local damage - a very important form of change of condition in gearboxes and bearings - is asociated with local change of stiffness/mass. In vibration signal it is manifested by appearance of periodic (at least cyclic) impulses and this properties of signal is used as a basis for damage detection. Unfortunately, especially at early stage, local damage "produces" weak signature that is completely masked by other sources of vibration. It means that one may not see any impulses in signal. A crucial problem in local damage detection is to eliminate non-informative parts of signal, improve *signal to noise ratio* or - in other words – to extract signal of interest (SOI). This paper shows results of application different pre-processing techniques to vibration signals captured from mining machines during normal operation.

Keywords: informative signal extraction, local damage, gearboxes, bearings, local damage.

ROLA WSTĘPNEGO PRZETWARZANIA SYGNAŁÓW W DETEKCJI USZKODZENIA LOKALNEGO W MASZYNACH GÓRNICZYCH

Streszczenie

Uszkodzenie lokalne jest bardzo ważną formą zmiany stanu w przekładniach i łożyskach. Zwykle wiąże się z lokalną zmianą sztywności i/lub ubytkiem masy. W sygnale drganiowym uszkodzenie lokalne powoduje chwilowe zaburzenie sygnału o impulsowym, cyklicznym charakterze. W praktyce sygnał informacyjny jest niskoenergetyczny i jest maskowany przez inne źródła drgań w maszynie, co oznacza brak możliwości wykrycia impulsów w sygnale zarejestrowanym na obiekcie. Fundamentalne znaczenie w detekcji uszkodzeń lokalnych ma odpowiednie wstępne przetworzenie sygnału eliminujące zakłócenia lub innymi słowy wyodrębniające sygnał informacyjny. W pracy pokazano wyniki zastosowania wybranych procedur przetwarzania sygnałów jako przetwarzanie wstępne mające na celu wyodrębnienie informacji o uszkodzeniu lokalnym. Wykorzystane sygnały zostały zarejestrowane na obudowie przekładni i łożyska w czasie normalnej eksploatacji w warunkach kopalni odkrywkowej.

Słowa kluczowe: ekstrakcja sygnału informacyjnego, przekładnie, łożyska, uszkodzenie lokalne.

1. INTRODUCTION

Local damage is a important form of change of condition in machines. This kind of damage in literature is mainly associated with gearboxes and bearings. Local change of stiffness/mass in mechanical system is manifested in vibration signal by appearance of periodic (at least cyclic) impulses. It is a basis for damage detection. Typical example of such change of condition is crack/breakage or spall/pitting on one tooth in gearbox and local damage of rolling element, outer/inner race – in bearing.

Unfortunately, especially at early stage, local damage "produces" weak signature that is completely masked by other sources of vibration. It means that one may not see any impulses in signal. That is crucial problem in local damage detection. A natural way is to eliminate non-informative parts of signal, improve signal to noise ratio or - in other words – to extract signal of interest (SOI).

For analysed objects – namely driving units used in mining machines - local damage seems to be very dangerous. Local damage (for example crack) may achieve final phase of degradation (i.e. breakage) quickly. A special feature for mining machines is non-stationary operating condition with frequent starts and stops of operation with fully loaded machine. It causes overloading of machine very often – especially if one consider bucket wheel excavator – that significantly accelerates degradation process.

Analysed machines (bucket wheel excavator, belt conveyor, stocking machine) work as production system connected in series. Breakage of one of them is critical and will stop whole system.

In this paper it will be showed that for mining machines with complex design, non-stationary operation, high level of random/deterministic interferences etc., detection of local damage is challenging task. Detection of local damage may be much easier if one will apply proper pre-processing technique. This paper shows results of application different pre-processing techniques (different form of classic filtering, adaptive filtering, wavelet based decomposition and cyclostationarity based tools) to vibration signals captured from mining machines during normal operation.

2. VIBRATION SIGNAL PREPROCESSING TECHNIQUES

For needs of local fault detection SOI is described as impulsive (due to local change of stiffness) and periodic signal (for example with period related to rotating shaft).

SOI generated by local damage may be interpreted as AM/PM modulated signal. Procedure of recovering modulating signal – for example amplitude demodulation (envelope analysis) becomes a standard in gearbox and bearing local damage detection [1].

During last decade an approach using cyclostationarity of signal was exploited extensively [2-6]. Cyclicity is a generalisation of periodicity. Assumption of periodicity may be not adequate if machine works under non-stationary speed – then one should consider cycles instead of periods.

Cyclostationarity of signal gives a chance to calculate 3D map of statistical relation between carriers frequencies and cyclic frequencies "*alpha*" interpreted as a modulating signal. An advantage of using spectral correlation density (SCD) is very clear during diagnosis of multi-faults that happens in mining machines.

A powerful application of cyclostationarity is usage of information about cyclic frequency and number of its harmonic for blind separation of cyclostationary sources. It gives a chance to extract any SOI with different frequency alpha from complex mixture of vibration signals [7-9].

Signals generated by gearboxes and bearing have a different properties from statistical signal processing point of view. Signal related to damaged bearing is stochastic and random in opposite to gearbox mesh/shaft signals that are deterministic. This difference gives opportunity for separation signals from damaged bearing masked by signal generated by mesh (cooperating geared wheel). It was introduced by Randall and other [10, 11] for bearings diagnostics in helicopters,

It was shown also by Lee and White [12] that this approach may be used for extraction of SOI associated with local damage from gearbox.

In previous work done by Zimroz it was found that it can be used in mining machines [12, 14].

As SOI is locally impulsive, non-stationary signal a natural direction is to use time-frequency methods. Application of wavelets analysis (especially Wavelets Packets) may be very useful for signal decomposition. It allows to decompose signal into SOI and non-informative signal.

3. APPLICATION TO INDUSTRIAL SIGNALS FROM MINING MACHINES

Results of application selected signal processing techniques to vibration signals are presented in this chapter.

3.1. Band-pass filtering – cut off frequencies selection

Band-pass filtering is a very simple and intuitive tool used as a pre-processor for example in envelope analysis. The purpose of band-pass filtering is to extract carrier and sidebands for demodulation of signal. Problem with centre frequency and bandwidth selection can be solved by optimisation of cut-off frequencies searching, fig. 1.

a) b)

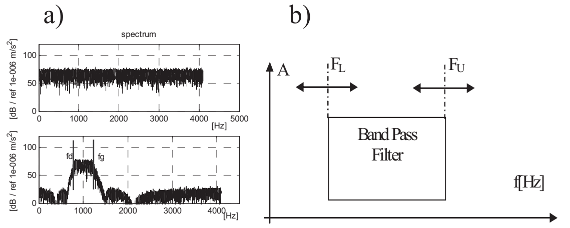


Fig. 1. a) Filter shape, b) idea of optimisation

a) b)

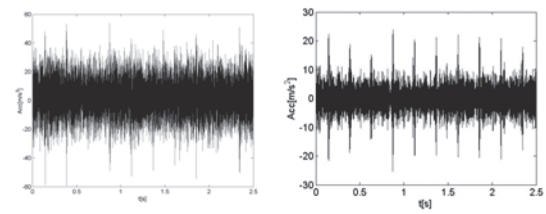


Fig. 2. Raw signal and extracted SOI

Optimisation is performed with kurtosis as a criterion, so pre-processed signal will be as much as possible spiky, fig. 2. [15]

$$FC(f_L, f_U) = \max\left(Kurtosis\left(F_{f_L}^{f_U}(S(t))\right)\right)$$

where

FC cost function

$S(t)$ raw signal

f_L, f_U cut off frequencies of band pass filter

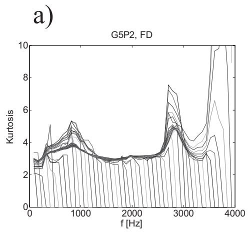
$F_{f_L}^{f_U}$ filtering operator at f_L, f_U

Kurtosis – $k = \frac{E\{(s-\mu)^4\}}{\sigma^2}$ where E-expected value, μ,σ - respectively mean and standard deviation of process s(t)

Result of optimisation is pair of cut off frequencies of band pass filter, Fig. 3.

On fig. 3 a distribution of kurtosis versus cut-off frequencies is presented. As it was shown in [16] due to random impulses (not related to fault) kurtosis may be not effective criterion. To avoid problems with non-cyclic impulses another criterion (normalised sum of components in envelope spectrum) was proposed in [17], fig. 3b.

a)



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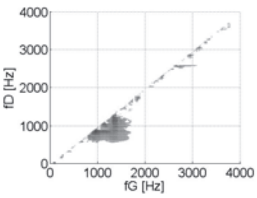


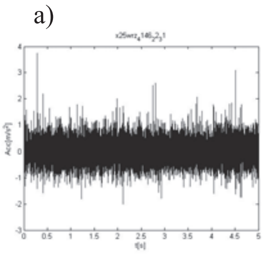
Fig. 3. Results of optimisation a) with kurtosis as a criterion(2D view) b) with NSofS as a criterion

3.2. Adaptive filtering

Assuming that vibration signal is a mixture of deterministic (with discrete components in spectrum – mainly related to geared wheels) and stochastic, random (related to wideband excitation caused by fault in bearing) signals it is possible to use adaptive filtering bases on prediction theory (deterministic signal may be predict, random not).

On Fig. 4 raw signal (no cyclic impulses) and filtered signal (clearly seen impulses) are presented

a)



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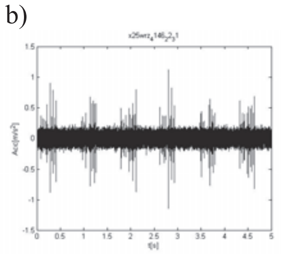


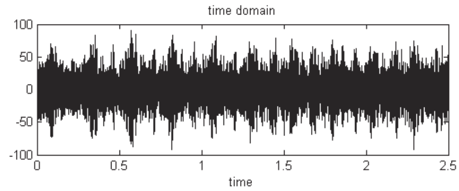
Fig. 4. Adaptive filtering for bearings signals: a) raw signals, b) extracted SOI

3.3. Wavelet based decomposition

Wavelets analysis seems to be very attractive tool for non-stationary signal analysis [18]. One of possible usage is signal decomposition.

The wavelet packet [19] method is a generalization of wavelet decomposition that offers a richer range of possibilities for signal analysis. In the wavelet packet decomposition (WPD), both the detail and approximation coefficients are decomposed. Fig. 5 shows original signal and SOI obtained by decomposition (Wavelet Packet, "dmey" wavelet, 5 levels of decomposition, node {5,10}). It is clear that in raw signal cyclic disturbance of signal has different period and nature (shape) than in SOI. It is example of multi-faults problem that appears in 2 stage gearbox.

a)



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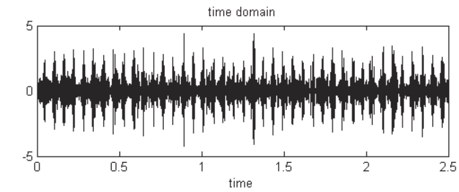


Fig. 5. Application of WPT: a) original signal, b) extracted impulsive signal

3.4. Cyclostationarity based tools

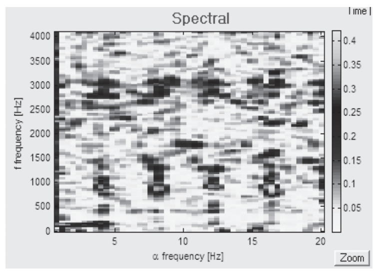
To take profit from cyclostationarity of signal one must estimate fundamental cyclic frequencies and number of their harmonics.

Cyclic sources in signal may be identified in the frequency domain through the double Fourier transform of auto-correlation function $R_x(t,\tau)$.

After selection of particular cyclic frequency one may extract source of vibration generating cyclic signal using reduced-rank cyclic regression method developed by Boustany and Antoni [7, 8].

Fig. 6a shows spectral Correlation density map as a base for separation. Fig. 6b presents raw and extracted signal

a)



b)

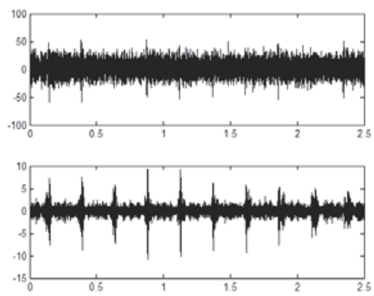


Fig. 6. Extraction of 2nd order cyclostationary SOI: a) Spectral Correlation Density map, b) original and extracted signal

4. CONCLUSION

Results of application of selected signal pre-processing methods for local damage detection oriented signal extraction have been presented.

It has been stated that for gearboxes and bearings used in mining machines local damage detection for raw signal is difficult. Using signal pre-processing it is possible to enhance signal significantly so one may use simple tool for detection and damage recognition

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Radosław ZIMROZ, PhD MSc from Faculty of Electronics (speciality -Acoustics) Wroclaw University of Technology, 1998, PhD (2002) at Mining Faculty, WUT (with honours). Until now with Machinery Systems Group at Institute of Mining Engineering, WUT. 9 months postdoc (2004) at Cranfield University (SOE/PASE/AMAC), UK.

Interest: modelling and diagnostics of gearboxes used in mining industry, vibration signal processing, application of AI methods, adaptive systems.