Extracting periodically repeating shocks in a gearbox from simultaneously occurring random vibration

Konsta Karioja

Mechatronics and machine diagnostics, Faculty of technology,
P.O. Box 4200, FI-90014 University of Oulu, Finland
E-mail: konsta.karioja@oulu.fi

Sulo Lahdelma

Tirriäisentie 11, Oulu, Finland
E-mail: sulo.lahdelma@gmail.com

Grzegorz Litak, Bartłomiej Ambrożkiewicz

Lublin University of Technology, Faculty of Mechanical Engineering,
Nadbystrzycka 36, 20-618 Lublin, Poland
E-mail: g.litak@pollub.pl

Abstract

Periodically repeating shocks are a quite common indication of certain defect in machinery. Detecting these shocks in early stage, before the defect is severe enough to cause failure, can provide a huge advantage in maintenance planning. The earliest possible warning of a defect may be highly important, especially in targets where failure can lead to a vast loss of production or a safety risk. Shock-like vibrations are, however, usually rather faint when the defect is a minor one. This simply means that the shocks may often be too low in magnitude to be easily detected. In this paper, we use different techniques based on real order derivative to detect gear defects. Higher real order derivative, discrete Fourier transform, and Hilbert transform are discussed.

Keywords: condition monitoring, envelope spectrum, feature extraction, fractional derivative, Hilbert transform, real order derivative

1. Introduction

The example case here is a gearbox with an induced fault in a single gear tooth of the secondary gear. The gearbox was coupled to a water pump. The pump was run in a normal state, and in a state where the intake valve of the pump was closed, and this induced cavitation in the pump. In this study, we experiment some techniques to extract the periodically repetitive shocks out of the random vibrations due to cavitation. Enveloping is commonly utilised in this type of cases. In our study we point out that the frequency band used to obtain the envelope may have a drastic effect to the result. In addition, we show that using an envelope of some other signal than acceleration or velocity may be useful.

Previous research on different methods to apply on gear fault cases also exists. Techniques applied include e.g. acoustic emission[1,2] and spectral kurtosis of vibration[3,4]. Faults of rotating elements such as gears, bearings or shafts can be also detected by application of Hilbert transform to obtain envelope signal[5,6] in a different way than usually in condition monitoring[7,8].

2. Signal processing

Signal processing methods utilised here include Hilbert transform, real order derivative and ideal filtering. The two latter ones can be achieved by discrete Fourier transform (DFT).

2.1 Real order derivative and ideal filtering

Several signal processing methods, e.g. the real order derivatives applied here are widely discussed in[9,10]. In fact these papers discuss the methodology more extensively and thoroughly than applied in this paper.

Here we apply the definition in[11] for an α order derivative of an exponential function where $\alpha \in \mathbb{R}$. If we consider displacement $x(t)$, which is usually represented by discrete series $\{x_r\}$ in computer applications[12], the α order derivative of displacement can be calculated in three following steps[13]:

1. Compute the DFT of $\{x_r\}$, to obtain $\{X_k\}, k = 0, 1, 2, ..., (N-1)$, which is a sequence of complex numbers.
2. Multiply each term of $\{X_k\}$ by factor $(i\omega_k)^\alpha$, where ω_k is the k^{th} angular frequency and i is the imaginary unit.
3. Compute the sequence $\{x_r^{(\alpha)}\}$ representing the α order time derivative of displacement $x^{(\alpha)}(t)$ by utilising the inverse DFT.

The so called ideal filter is applied in this study as well. It is a simple operation, where the DFT is performed first and frequency components in the stop band of the filter are replaced with zeros, and the inverse DFT is applied after. The techniques presented above have been applied before for example in[14,15,16].

2.2 Hilbert transform

The Hilbert transform (HT) of the signal $x(t)$, denoted by $\hat{x}(t)$ is defined by an integral transform[17,5]:

$$\hat{x}(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t - \tau} d\tau. \tag{1}$$

The Hilbert transform can be utilised in order to obtain the envelope signal $A(t)$. This is done by calculating the absolute value or modulus of a so called analytic signal $z(t)$ defined by:

$$z(t) = x(t) + i\,\hat{x}(t). \tag{2}$$

The envelope signal results from the modulus of Equation (2). This is to say the envelope signal obtained via Hilbert transform can be written: $A(t) = |z(t)|$.[5,6,18]

3. Testing arrangement

The test rig used here, and which is shown in Figure 1, was originally manufactured by G.U.N.T. Gerätebau GmbH, and was later modified in the Otto von Guericke University, Magdeburg. The tests in study were conducted when a single tooth of the secondary gear of the gearbox was intentionally damaged.

The test equipment consisted of:

- Bodywork of G.U.N.T. PT 500 test rig
- 1.1 kW electric motor manufactured by EMK
- Nordac 700E frequency converter
- Mädler 41200102 bevel gearbox with transmission ratio 1:2 ($z_1 = 54, z_2 = 27$)
- Centrifugal pump with 3 blades (i.e. $B = 3$) on impeller for cavitation testing, manufactured by G.U.N.T.
- 2 KTR claw clutches, with 4 claws on flexible elements

On these tests the motor was run at 2000 rpm. This is to say the rotational speed of the pump was 4000 rpm. The respective frequencies are $n_1 = 33.33$ Hz and $n_2 = 66.67$ Hz. The blade pass frequency (BPF) is $B \cdot n_2 = 200$ Hz.

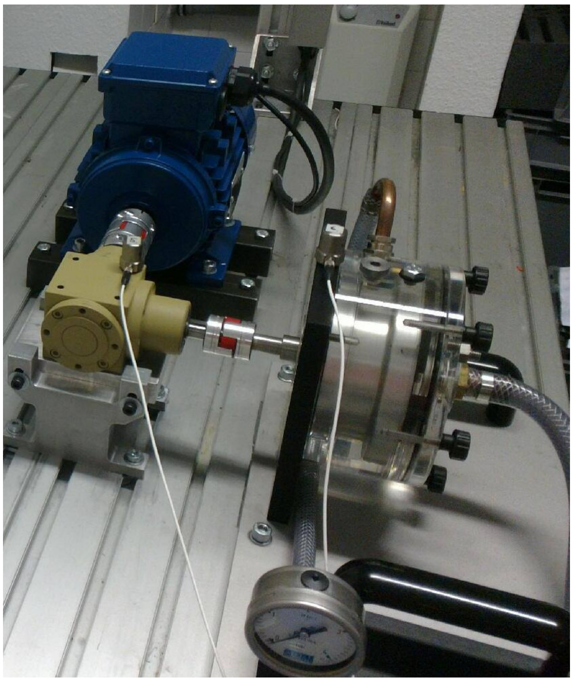

Figure 1. The testing equipment consisting of electric motor, bevel gear and pump

4. Analysis

The measurements were conducted by using accelerometers of type IMI 621B51 and the signals were sampled using data acquisition card NI 9233. The sampling rate was set to 50 kHz.

4.1 Acceleration signals

The signals presented in Figures 2 and 3 show the signals with no cavitation on the left (blue) and the signal with cavitation on the right (black). The frequency range of the signals is from 1 Hz to 19530 Hz. It can be stated that the difference between the situation with cavitation to the one with no cavitation is clear when considering the measurement from the pump, but no clear difference can be seen in the signals from the gearbox.

4.2 Enveloping by rectifying

Envelope techniques[8] are often utilised when aiming to detect periodically repeating shocks from vibration measurements. The envelope signal is quite commonly created by first band pass filtering the signal, then rectifying it, and finally low pass filtering the resulting signal.

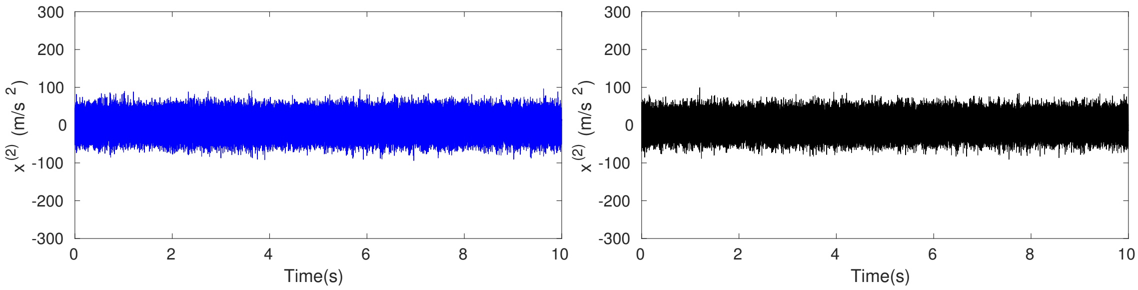

Figure 2. Acceleration signals from the gearbox, the signal on the left is measured when there is no cavitation and the signal on the right is from the situation when cavitation occurs

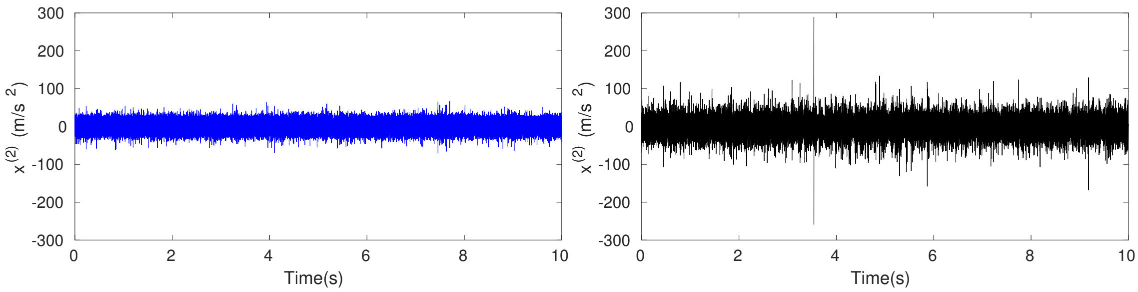

Figure 3. Acceleration signals from the pump, the signal on the left is measured when there is no cavitation and the signal on the right is from the situation when cavitation occurs

Enveloping is a common method in condition monitoring. However, it is rarely applied to any other signals than acceleration or velocity. These signals might sometimes be adequate, but e.g. derivatives of fractional order where order of derivative is any real number, can be used.

Here the envelope signals are generated utilising the ideal band bass filter (see Section 2) and taking absolute values of the resulting signal. Here we do not utilise a separate low pass filter.

It is a generally accepted fact that a cracked tooth in a gear causes shocks in a time interval, equal to time of revolution of the gear. In this case it means the shocks are expected to occur in time interval which correspond to frequency $n_2 = 66.67$ Hz. Distinguishable peaks in envelope spectrum at that frequency and its multiples are considered a sign of this type of fault.

In Figure 4 are the envelope spectra up to 400 Hz from the gearbox. The envelope spectra of acceleration and snap ($x^{(4)}$) show that in this case, the both signals seem to be adequate detect the fault. However, when comparing the peaks near the rotational frequency (66.67 Hz) of the second stage of the gearbox, the envelope spectrum of snap Figure 4 has a more distinctive peak than the envelope spectrum of acceleration, this is to say the snap signal seems to be more sensitive in this case.

In Figures 5 and 6 are the envelope spectra from the pump. It can be stated here as well that utilising fractional derivatives $x^{(2.67)}$, $x^{(3.33)}$ and the snap signal instead

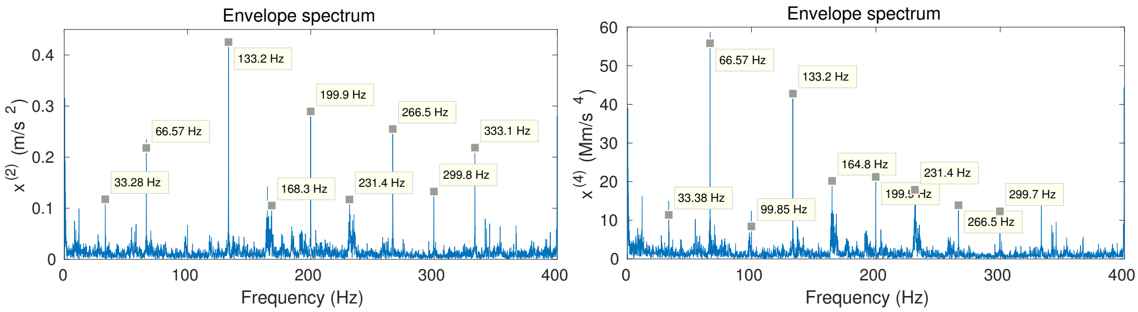

Figure 4. Envelope spectra of acceleration and snap from the gearbox when cavitation occurs, band pass filtering from 1000 Hz to 2000 Hz

of the acceleration, the indication of the fault seems to be more distinguishable. In addition Figures 5 and 6 show a peak at 54.65 Hz. This suggests that there is some mechanical phenomenon on this frequency, but this has no obvious explanation. A bearing fault in the pump could be one possible explanation, but seems unlikely as this can not be seen in the envelope spectrum when pump operates normally without cavitation. This can be seen in Figure 7 where the envelope spectra of acceleration and snap are presented from the situation when no cavitation occurs.

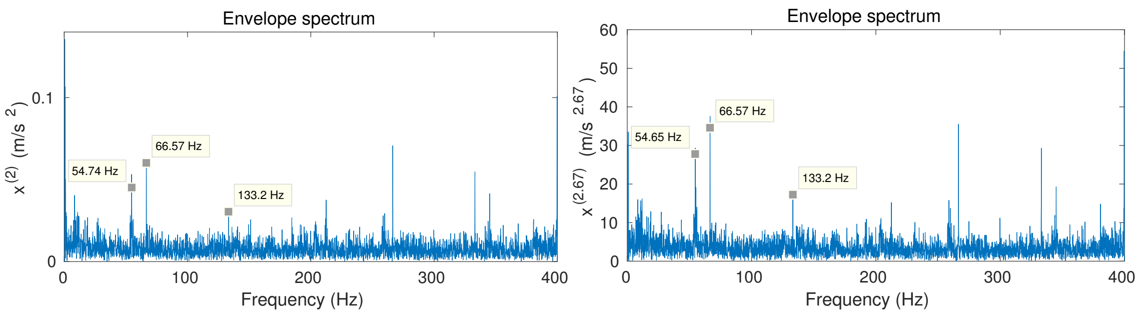

Figure 5. Envelope spectra of acceleration and $x^{(2.67)}$ from the pump when cavitation occurs, band pass filtering from 1000 Hz to 2000 Hz

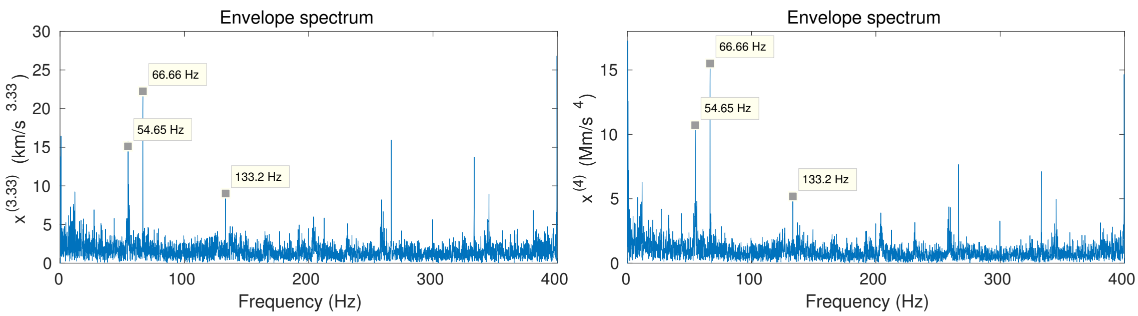

Figure 6. Envelope spectra of $x^{(3.33)}$ and snap from the pump when cavitation occurs, band pass filtering from 1000 Hz to 2000 Hz

Moreover, comparing Figures 5, 6 and 7 shows that enveloping as a technique is, as expected, rather insensitive to random vibrations. The peaks in the envelope spectra indicate the periodically repeating shocks, are clearly distinguishable even when the random vibration occurs.

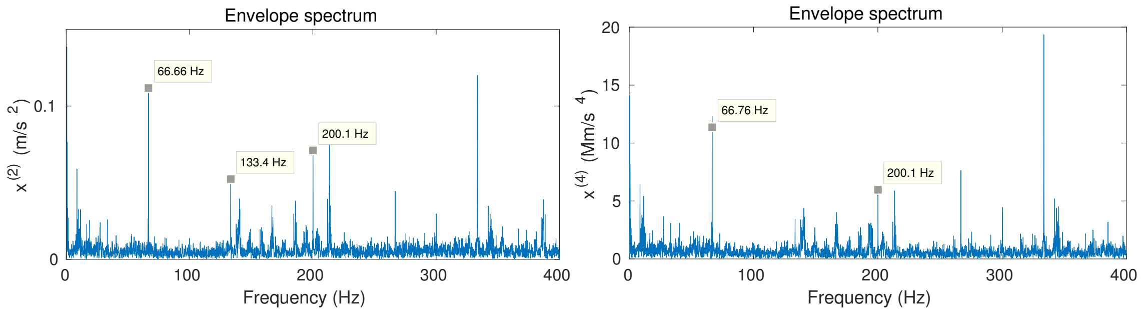

Figure 7. Envelope spectra of acceleration and snap from the pump without cavitation, band pass filtering from 1000 Hz to 2000 Hz

4.3 Enveloping by Hilbert transform

The envelope spectra in Figure 8 are obtained as discussed in Section 2.2. In this case the envelope spectra obtained through HT the peaks indicating the fault seem to be a bit more clear than in envelope spectra obtained through rectifying. Nonetheless, all the other components seem to be higher as well, so it is at least debatable whether or not the HT produces better indications of the shocks than the enveloping by rectifying technique.

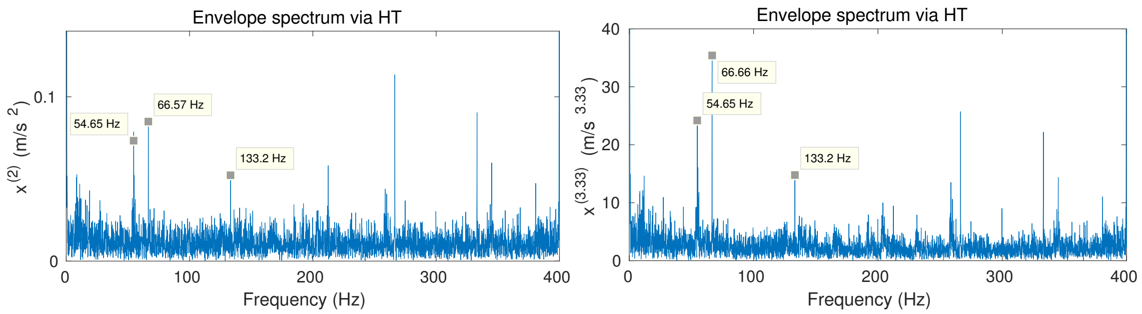

Figure 8. Envelope spectra of acceleration and $x^{(3.33)}$ obtained via Hilbert transform from the pump when cavitation occurs, band pass filtering from 1000 Hz to 2000 Hz

5. Conclusions

Results show, that envelope spectrum of fractional derivatives and snap signal have potential to detect shocks when random vibration occurs simultaneously. In this case, it seems to provide better results than using the envelope of acceleration. Because the indication of the fault is greater in the envelope spectrum of the snap signal here, it seems probable that a less severe fault of this type, which cannot be detected using mere acceleration, can be detected when using the snap signal.

The snap signal was the most sensitive one studied here, but some other real order derivative might produce better results, and even higher order of derivative than snap could be the optimal choice[10]. Creating a signal of any order of derivative is effortless with modern technology, so it would be quite simple to implement in several condition monitoring systems.

For future work, the differences between the two enveloping techniques discussed here might be worth some study, because in this study we have concluded that these two techniques produce slightly different results.

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