

COMPARISON OF AMPLITUDE-BASED AND PHASE-BASED METHODS FOR SPEED TRACKING IN APPLICATION TO WIND TURBINES

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Abstract

Focus of the vibration expert community shifts more and more towards diagnosing machines subjected to varying rotational speeds and loads. Such machines require order analysis for proper fault detection and identification. In many cases phase markers (tachometers, encoders, etc) are used to help performing the resampling of the vibration signals to remove the speed fluctuations and smearing from the spectrum (order tracking). However, not all machines have the facility to install speed tracking sensors, due to design or cost reasons, and the signal itself has to then be used to extract this information. This paper is focused on the problem of speed tracking in wind turbines, which represent typical situations for speed and load variation. The basic design of a wind turbine is presented. Two main types of speed control i.e. stall and pitch control are presented. The authors have investigated two methods of speed tracking, using information from the signal (without relying on a speed signal). One method is based on extracting a reference signal to use as a tachometer, while the other is phase-based (phase demodulation). Both methods are presented and applied to the vibration data from real wind turbines. The results are compared with each other and with the actual speed data.

Keywords: speed tracking, speed estimation, instantaneous frequency, wind turbines.

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1. Introduction

The process of monitoring and diagnosis of rotating machinery has been steadily developing with a number of exciting additions in the last few years. Nevertheless, there is a range of machines (in particular where load and speed are not steady) to which the existing current state of the art techniques will not work properly to detect any emerging faults in the rotating components. Examples of such machines are wind turbines, mining equipment, some conveyors etc... The influence of load variation on the vibration signals have been the subject of a number of studies [1, 2]. The other, equally important factor is the variable rotational speed. Speed fluctuation and variation in the system causes “smearing” of the discrete frequencies (components) in the spectrum, meaning that these frequencies will no longer be seen and detected as discrete lines (sine/cosine signals with power concentrated in one line), but rather as a frequency band around the mean speed, where energy extends across a number of frequency bins. Such effect may cause significant disadvantages in the functionality of vibration-based condition monitoring systems. In particular the signal processing techniques developed to analyze signals at a constant speed in bearings and gears will fail. Such machines require order analysis (angular re-sampling) beforehand for proper fault detection and identification. Order analysis (tracking) is the process of re-sampling the vibration signal in the angular domain (constant phase intervals) rather than in the time domain. In many cases phase markers (tachometers, encoders, etc.) are used to help to perform the re-sampling of the vibration signals to remove the speed fluctuations and the smearing from the spectrum (order

tracking). In the case of wind turbines, order tracking is particularly useful for pitch-controlled units. Fig. 1 illustrates spectra of vibrations of a pitch-controlled wind turbine (a) and a stall-controlled (b) wind turbine. Due to speed fluctuations, the smearing effect is relatively strong in pitch-controlled turbines (Fig. 1.a). In stall-controlled machines (Fig. 1.b), the speed variation is limited and characteristic components are clearly recognizable.

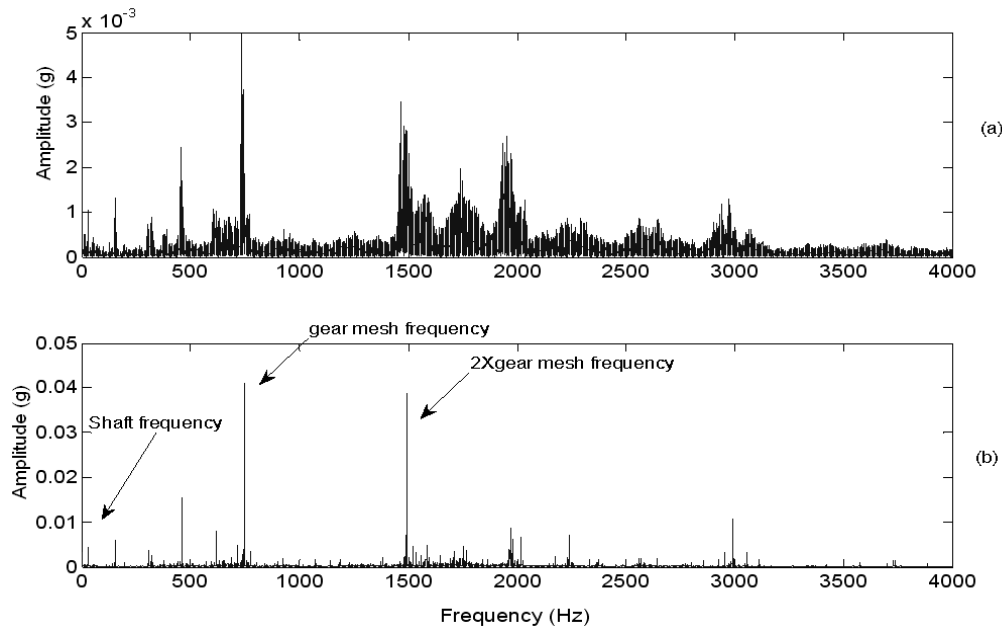


Fig. 1 Frequency spectrum of (a) pitch-controlled (b) stall-controlled wind turbine.

Order tracking can be performed using hardware (phase-locked frequency multiplier) [2, 3] or software methods [4], with very good accuracy. However, not all machines have the facility to install speed tracking sensors, due to design, cost reasons or other constraints. An interesting example may be the coal harvester, where the robust design makes the installation of speed sensors almost impossible. In other cases, there is often a need to analyze offline the data, which had been acquired without speed sensor information. In all such cases, the vibration signal itself can be used to extract the missing speed [4]. In principle, the process of using the vibration signal for order tracking can be achieved by selecting a suitable (narrow) band around one of the harmonics of the shaft speed and then phase demodulating this band. A variety of methods for phase reference estimation were described [5, 6] and applied to the subject of speed estimation [7, 8]. Also the comparison between a number of approaches (based on combining the use of tachometers and information from the signal itself) to achieve re-sampling in relation to performing the order tracking for one of the shafts of a jet engine has been done [9]. In a recent contribution to this area, a new algorithm to extract the instantaneous speed from the signal which is based on estimating an instantaneous time scaling factor was proposed [8]. This factor is determined, based on the gap between two segments of the signal (coined as the short time scale transform).

This paper is focused on the problem of speed tracking in wind turbines, which represents typical situations for speed and load variation. Two methods of extracting a speed tracking signal for a wind turbine are presented. The speed variation and the order-tracked signals obtained from the two methods are compared with those obtained from the tachometer signal installed to verify the robustness of the methods.

2. Wind turbine description

Fig. 2 presents a typical layout of a wind turbine. The main rotor with three blades is supported by the main bearing and transmits the torque to the planetary gear. The planetary gear has three planets. The planets transmit the torque to the sun gear. The sun shaft is the output of the planetary gear which drives a two-stage parallel gear. The parallel gear has three shafts: the slow shaft connected to the sun shaft, the intermediate shaft and the high speed shaft, which drives the generator. The generator produces AC current of slightly varying frequency. This current is converted first into DC power and then into AC power of frequency equal to the grid frequency. Electric transformations are performed by the controller at the base of the tower. The gearbox setup changes the rotational speed from about 25 rpm on the main rotor to about 1500 rpm at the generator.

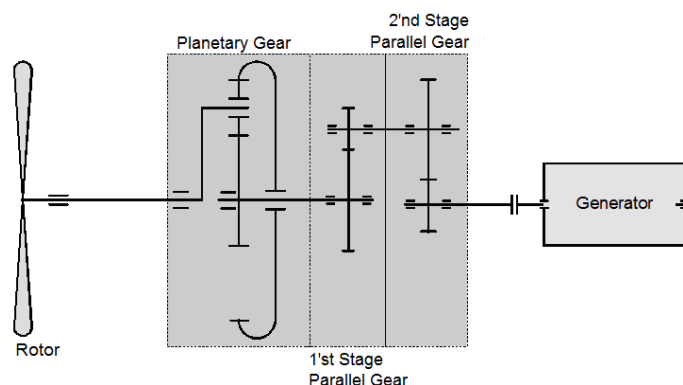


Fig. 2. Layout of a typical wind turbine

Wind turbines are generally designed for maximum efficiency at wind speed around 15 m/s. It is uneconomical to design turbines for stronger winds because of their rare occurrence. It is necessary to control the output power, so it matches the wind speed. Two different approaches are being commonly used for that task:

- Pitch control, where the blades of the main rotor are able to change the pitch. This mechanism is also used as an additional braking mechanism.
- Stall control, where the blades have fixed pitch and in stronger winds part of energy causes the stall, which in turn causes the power to decrease

Pitch-controlled turbines are the most popular nowadays. Their power control mechanism constantly changes the speed in order to maintain the highest efficiency possible. The variation of rotational speed can be significant, causing the smearing of lines in the vibration spectra. Such a phenomenon is much smaller in stall-controlled turbines (though it does exist), as they tend to maintain much more stable speed over relatively long periods of time. Vibration signals from the wind turbine contain mostly gear mesh components with additional shaft components (mostly the highest speed, i.e. generator shaft). As we are interested in reduction of the speed fluctuation, we will from now on focus on pitch-controlled turbines only.

3. Concept of narrowband speed estimation methods

This section presents two methods for speed reconstruction from the raw vibration signals. These methods will then be compared in the case study presented in the following section.

3.1. Phase-based method

The first method, proposed by Bonnardot et al. [4] is based on the phase demodulation concept. First, a proper shaft harmonic is selected - usually the one with the strongest energy. Next, the extent of speed fluctuation needs to be evaluated. It can be done using a typical Fourier spectrum, or for better clarity – spectrogram – the basic time-frequency representation of a signal, a 3D figure of square of STFT magnitude spectrum of the signal as a function of time and frequency.

Fig. 3 presents the spectrogram containing the first gear mesh component. The range of speed fluctuations can be clearly seen. After visual examination the most suitable frequency band can be used for filtration. The goal of the filtration step is extraction of the part of the signal representing the component related to the speed fluctuation. This result can be obtained with a number of filter types, the important constraint is to set the bandwidth so it contains the variability of the speed. In order to obtain the phase angle of the filtered signal it is crucial to represent it in its analytic form.

$$z(t, f, \Delta f) = x_r(t, f, \Delta f) + jx_u(t, f, \Delta f), \quad (1)$$

where Δf is the frequency band width selected for the filtration.

The mathematical instrument to obtain the imaginary part of the analytic signal is the so-called Hilbert transform:

$$x_u(t, f, \Delta f) = \frac{1}{\pi} \int_{-\infty}^{\infty} x_r(\tau, f, \Delta f) \frac{1}{t - \tau} d\tau, \quad (2)$$

Using the feature that the imaginary part of exponential representation of a complex number is its phase, the phase angle can now be obtained using the equation below:

$$\varphi(t, f, \Delta f) = \text{imag}(\log z(t, f, \Delta f)), \quad (3)$$

The obtained phase angle corresponds to the instantaneous signal frequency in the filtered frequency band and it is not yet directly related to the shaft rotational speed. For appropriate extraction of selected shaft phase angle increments, it is essential to normalize the results by dividing the frequency by m (m is the order of the harmonic component of the shaft from which the phase was estimated).

$$\varphi_n(t, f, \Delta f) = \frac{\varphi(t, f, \Delta f)}{m}, \quad (4)$$

The normalized phase angle corresponds to the angular position of the shaft. Phase markers necessary for application of order tracking algorithms can be acquired directly from the resulting signal.

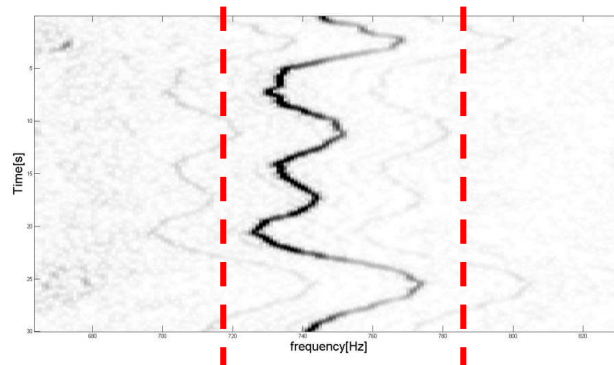


Fig. 3. Selected fragment of the spectrogram from the pitch-controlled turbine.

Fig. 4 shows the algorithm of the phase-based speed estimation method.

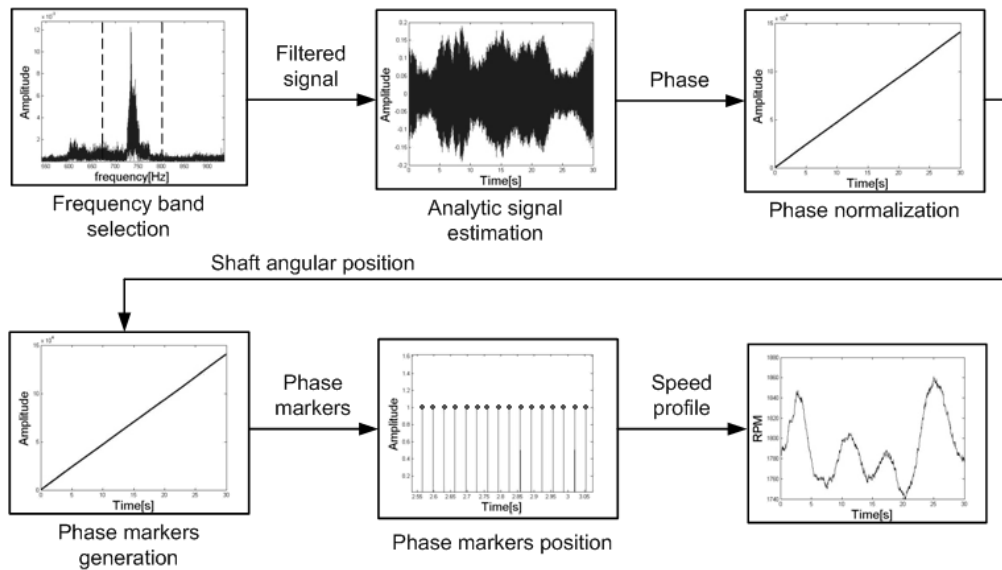


Fig. 4. Algorithm of the phase-based speed estimation method.

3.2. Period timing method

The process of extracting a reference speed signal is described schematically in Fig. 5 as applied to the turbine signals.

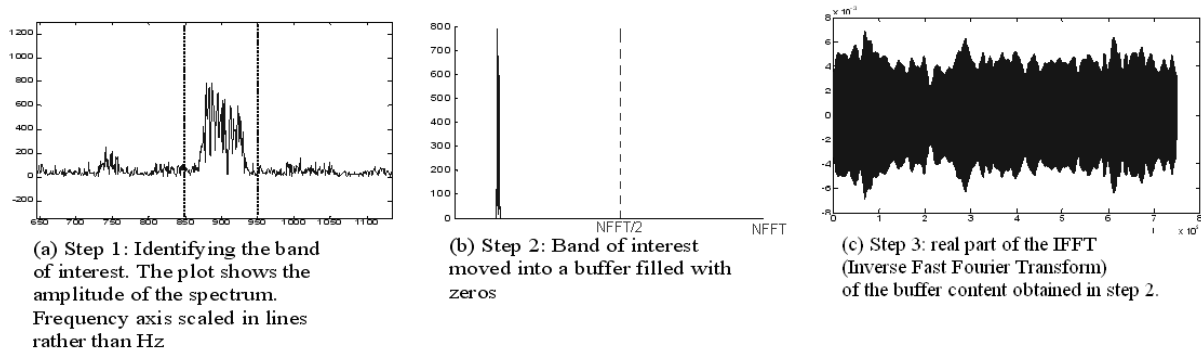


Fig. 5. Reference (speed) signal extraction stages (a) Identifying a separable band (b) Extracting the band into a new buffer (c) inverse transform signal b into the time domain.

In the first step (Fig 5.a), the spectrum of the signal under consideration is visually examined to identify a proper harmonic (and a suitable band around it) of the shaft to be tracked. Highest separable harmonics are preferable due to the clear effect of smearing and will give more accurate results. In the second step (Fig. 5.b), a buffer - filled with zeros- of a size equal to the FFT size is created. The complex spectrum of interest (band) is transferred to this buffer (filling in the same lines as in the original spectrum). Note that the presentation in Fig. 5.b only shows the amplitude of the spectrum, but it is the complex spectrum that has been transferred to this buffer and the phase information is thus preserved. Note also that only positive frequencies of interest were transferred leaving the negative part of spectrum filled with zeros. Finally the buffer is inverse transformed to the time domain to obtain the reference signal (Fig. 5.c). As the buffer is filled with zeros up to the sampling frequency- negative frequencies were set to zero- the inverse transform signal is analytic (complex) and it is the real part that will then represent the reference signal. The signal obtained in 5.c is a sinusoidal

signal whose periods represent the speed for each shaft rotation. The speed variation in this signal (a reflection of the speed variation of the shaft under investigation) can be traced using the zero crossing of the consecutive periods, which can be achieved by setting a trigger and identifying the crossings. This signal can also be used to order track the signal. Note however, that this process has to be repeated progressively to order track the signal to higher harmonics and achieve better results. This means that after each stage, a higher harmonic will be made available due to the removal of speed fluctuations and the analyst can select bands around the gear mesh harmonics to improve the quality of order tracking and gain more accuracy.

3.3. Spectrogram-based method

It may seem that since the proposed methods are based on visual examination of the spectrogram, it would be easier to estimate the instantaneous frequency simply by analyzing its local maxima. The position on the frequency axis of peaks of the highest energy on the spectrogram should correspond to the value of the instantaneous frequency at each moment in time. Fig. 6 shows the rotational speed of the signal presented in Fig. 3 estimated using such an approach.

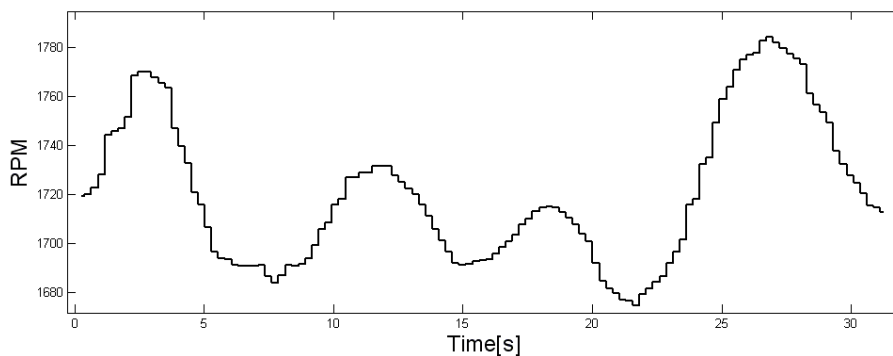


Fig. 6. Shaft rotational speed estimated by analysis of the spectrogram local maxima.

As shown in Fig. 6, the speed values were estimated with relatively good accuracy, however with poor time resolution. Such effect is caused by time resolution of STFT. In order to minimize it, more sophisticated methods of instantaneous frequency estimation could be applied. There is a variety of joint time – frequency based approaches [10], however it is not the subject of this article.

4. Case study

In this part of the analysis, order tracking was performed using a digital re-sampling technique, where both the vibration signal and the tachometer signal (extracted reference signal) were sampled simultaneously using a fixed time-based sampling frequency. Matlab® code was used for this purpose and included the use of a cubic spline interpolation of the vibration signal to calculate the values at the required sample points, based on the tachometer signal.

Fig. 6 compares the power spectrum densities (PSDs) for the raw vibration signal, the order tracked signal using the provided tachometer and the order tracked signal extracted with the period timing method. The comparisons are shown in the frequency range 0-900 Hz covering about 30 harmonics of the generator speed.

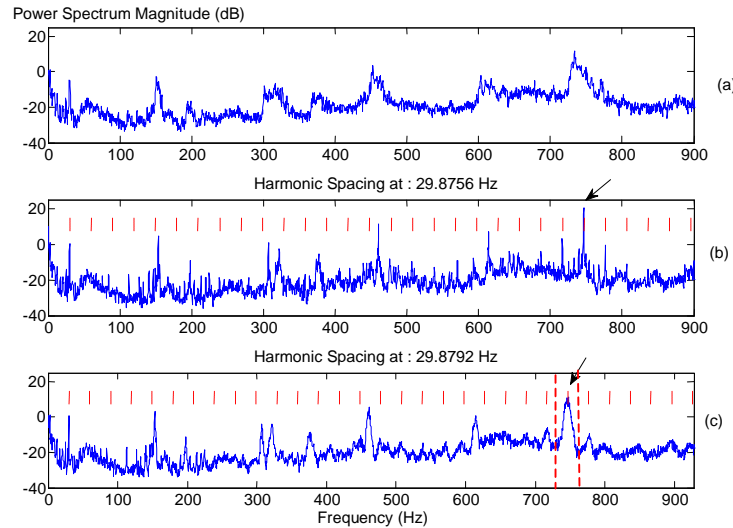


Fig. 7. (a) Power spectrum density (PSD) of the raw signal (b) PSD of the order tracked signal using the tachometer (c) the same as b), but using the extracted reference signal

The effect of order tracking is clear when comparing signal b (order tracked using the tachometer) with the original signal (signal a). The smearing effect has been removed and the gearmesh frequencies (25'th harmonic of the shaft characteristic component) along with the sidebands are very clear. In Fig. 6.c which represents the order tracked signal based on the extracted reference, the improvement is noticeable; however, the gearmesh frequency and its sidebands are still smeared, but separable. When a band around the gearmesh frequency (denoted by the two lines around it) has been extracted to form a second reference, the result has dramatically improved as can be seen in Fig. 7.b, which is well comparable with Fig. 6.b.

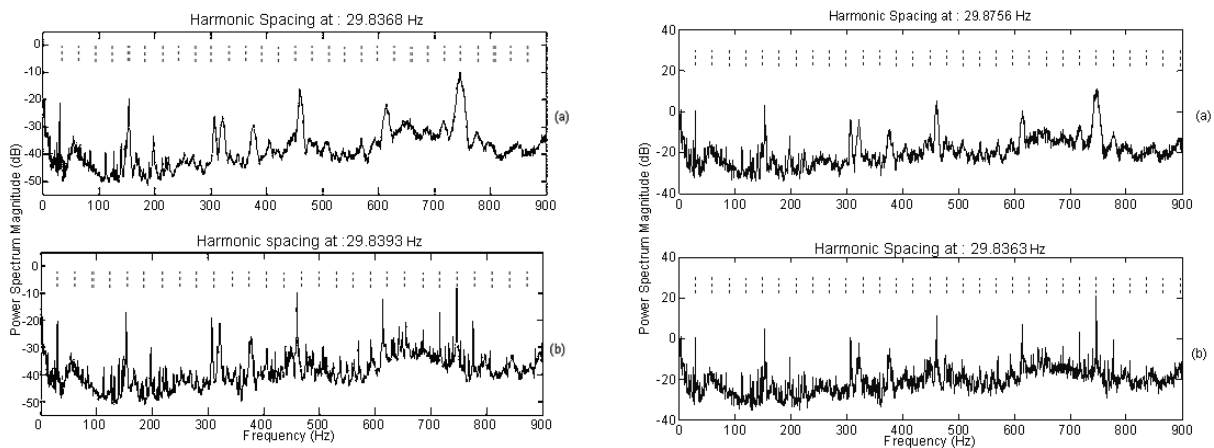


Fig. 8. Comparison of both presented methods: (a) PSD of the order tracked signals using the extracted reference signal based on the 1st harmonic (b) PSD of the second order tracked signals using the extracted reference signal based on the gearmesh frequency (25X shaft speed).

As shown in Fig. 8 very similar results can be obtained using both methods. The phase-based method is shown on the left, and the period timing method on the right.

5. Final remarks

Finally, to check the quality of the order tracking process, a simple measure similar to that in [9] has been employed. The separation index (SI) as defined in equation 5 measures the power of the synchronously averaged signal and compares it to the power of the residual signal (order tracked signal minus the synchronously averaged part). The better the order tracking process, the higher the SI index as the power of the synchronously averaged part will increase and the residual will decrease.

$$SI = \frac{\sum_{i=1}^{i=n} M(i)^2}{\sum_{i=1}^{i=n} R(i)^2} \cdot n, \quad (5)$$

where M is the synchronously averaged signal, R is the residual signal; n is the number of samples in the signal (M and R will have the same number of samples, so n in equation 5 is there for having a power estimate rather than energy). For the signals attempted in this section, the SI results are shown in Table 1.

Table 1 Separation index (SI) for different order tracking processes

Order tracking using	SI (Phase based)	SI (Pulse timing)
Tachometer	0.3791	
Reference signal based on first harmonic	0.0077	0.0043
Second reference signal based on the 25 th harmonic (gearmesh frequency)	0.3307	0.3293

The results show the necessity of carrying out more than one speed extraction process to enhance the order tracking results. The accuracy after 2 stages of processing is roughly 14% poorer than the results obtained from the original tachometer signal. However, a further third extraction process, perhaps for the 2nd gearmesh harmonic, will further improve the accuracy.

One has to say that it is hard to clearly state that one method is superior to the other. It can rather be concluded that each can be used for successful speed reconstruction with an accuracy comparable to that of the tachometer signal. Thus, both methods seem to be appropriate for wind turbines. The investigated signal was chosen as a typical one, with significant speed variation. In the future, the authors will be focused on determination of the applicability range of the proposed methods. Another interesting topic will be an attempt to apply the methods to machines with a different nature of speed variation, e.g. mining equipment.

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