

APPLICATION OF MORPHOLOGICAL ANALYSIS FOR GEAR FAULT DETECTION AND TRENDING

K. GRYLLIAS, C. YIAKOPOULOS, I. ANTONIADIS

National Technical University of Athens, School of Mechanical Engineering,
Machine Design and Control Systems Section Athens 15773, Greece
Tel: +30-210-7721524, Fax: +30-210-7721525, email: antogian@central.ntua.gr

Summary

Frequency domain based signal processing methods such as cepstrum analysis, Hilbert Transform based demodulation, cyclostationary analysis, etc have been shown to present a quite effective behaviour in the detection of defects, when applied to the analysis of vibration signals, resulting from gear pairs with one or more defective gears. However, these methods typically require some complex and sophisticated analysis, which renders their application cumbersome for applications requiring unskilled personnel or automated fault detection and trending. Alternatively to these methods, morphological analysis for processing vibration signals has been proposed, addressing the issues of how to quantify the shape and the size of the signals directly in the time domain. Morphological analysis and the resulting morphological index is applied in this paper to a set of twelve successive vibration measurements resulting from a gearbox prior to tooth breakage. As shown, the morphological index is able monitor the evolution of the potential fault, providing a clear warning prior to the breakage of the tooth.

Keywords: defective gears, morphological processing, fault trending, vibration analysis.

1. INTRODUCTION

Gearboxes are widely used in industrial applications. A sudden and unexpected failure of a gearbox may cause significant losses, not only from the economic but also from the human life point of view. Thus, it is very important to find early symptoms, which may indicate an approaching gearbox destruction. Typical faults of gears include pitting, chipping and more seriously, crack. The development of a local fault at a gear often introduces both amplitude and phase modulations at the vibration signals [1].

Since the increase of the number and of the amplitude of the sidebands often indicates faulty conditions, many frequency domain based signal processing methods have been proposed for gear fault detection, such as cepstrum analysis [2], envelope analysis [3], cyclostationary analysis [4], deconvolution filters [5] or combined time frequency analysis methods, such as wavelets [6, 7].

Although these methods have been shown to present a quite effective behavior in the detection of defects, they typically require some complex and sophisticated analysis, which renders their application cumbersome for applications requiring unskilled personnel or automated fault detection and trending.

Parallel, a number of traditional methods exist, requiring only a direct processing in the time domain, such as the root mean square of the signal, the crest factor, the kurtosis, the shape factor and the impulse factor, or the more recently introduced morphological analysis. Morphological signal processing comprises a broad collection of

theoretical concepts and mathematical tools for signal analysis, non-linear signal operators, design methodologies and application systems that are related to mathematical morphology [8, 9, 10]. Morphological signal processing was first used to analyze binary image data and was extended to grey level images. Since its launching, it has grown rapidly. This growth is a consequence of the great variety of applications which can be treated by mathematical morphology. The traditional tools of linear systems and Fourier analysis are of limited use for solving geometry-based problems because they do not directly address the issues of how to quantify the shape and the size of the signals. Contrarily, morphological signal processing is perfectly able to quantify all aspects, related to the geometrical structure of the signals. However, applications of morphological filters to one-dimensional time series have been quite limited, restricted practically to biomedical signals [11, 12, 13, 14].

Morphological signal processing of vibration signals resulting from defective rolling element bearings has been proposed in [15]. The basic concept of the proposed method is to modify the geometrical features of the signals in the time domain, in order to construct a kind of envelope, which accentuates information corresponding to the impulse series produced by the fault. As a result, a morphological index can be defined, able to monitor the evolution of the defects. As shown [16], this index presents a number of advantages over other traditional time indices, such as the root mean square of the signal, the crest factor, the kurtosis, the shape factor and the impulse factor, such as increased robustness to added noise, variations of the resonance frequency and damping ratio, rotation speed, etc.

This paper further proceeds to the application of this morphological index for the processing of vibration signals resulting from defective gears.

First, a revision of the basic concepts of morphological processing of signals is provided, resulting to the definition of the morphological index to be used. Then, morphological processing is applied to a series of twelve successive vibration signals, resulting from a gearbox under an evolving defect, just prior to a tooth breakage. The results indicate that the morphological index is able to monitor the evolution of the defect, being able to provide an early warning just prior to the breakage of the tooth.

2. BASIC CONCEPTS OF MORPHOLOGICAL PROCESSING OF SIGNALS

Morphological operators are indices that are sensitive to the geometric characteristics of the signals and they are a result of morphological signal processing. The fundamental concept of morphological signal processing [8, 9] is the modification of the shape of the signal through its interaction with another object, called the structuring element. The basic morphological operations of set erosion, dilation, opening and closing are related to Minkowski set operations and are used to construct morphological filters. Using the definitions for Minkowski addition and subtraction between functions, the four basic morphological operations are defined as:

$$dil(f, g) = (f \oplus g^r)(x) = f(x) \oplus g(-x) = \sup_{y \in D} \{f(y) + g(y-x)\} \quad (1)$$

$$er(f, g) = (f \ominus g)(x) = f(x) \ominus g(x) = \inf_{y \in D} \{f(y) - g(y-x)\} \quad (2)$$

$$cl(f, g) = (f \bullet g)(x) = [(f \oplus g^r) \ominus g](x) \quad (3)$$

$$op(f, g) = (f \circ g)(x) = [(f \ominus g^r) \oplus g](x) \quad (4)$$

where $g^r(x)$ denotes the reflected (symmetric) function $g(x)$ with respect to the origin of the x-axis.

Equations (1) - (4) can be significantly simplified, if $g(x)$ is an even function, i.e. $g(x)=g(-x)$, and if sampled functions are used. For a signal $f(k)$, defined over a domain D_f , and for a function $g(u)$, called the structuring element, which is of length L and defined over a domain D_g , the dilation and the erosion of the signal $f(k)$ by the element $g(u)$ are defined as:

$$dil(k) = (f \oplus g)(k) = \max_{u \in D_g} \{f(k+u) + g(u)\} \quad (5)$$

$$er(k) = (f \ominus g)(k) = \min_{u \in D_g} \{f(k+u) - g(u)\} \quad (6)$$

Similarly, based on erosion and dilation, the closing and the opening operations of the signal $f(k)$ by the element $g(u)$ are further defined as:

$$cl(k) = (f \bullet g)(k) = er(dil(k)) \quad (7)$$

$$op(k) = (f \circ g)(k) = dil(er(k)) \quad (8)$$

3. THE MORPHOLOGICAL INDEX

The Morphological Index results by the application of a closing process to a signal, using a flat structuring element [15].

The flat (zero) structuring elements are selected because they present the simplest structuring element with a straightforward application, since the only parameter which must be selected for their application, is their corresponding length L . Additionally, morphological operations using flat structuring elements seem to be quite appropriate for the detection of peaks of impulsive type vibration signals, resulting by faulty bearings or gears.

After the closing operation, a local maxima algorithm is further implemented, in order to evaluate the impulsive information contained in the closing. According to this algorithm, an impulse series $p(i)$ can be obtained by retaining only the local maxima of the closing $cl(i)$ of the signal $f(i)$, located at the time instants i which satisfy:

$$\begin{cases} p(i) = cl(i), & \text{if} \\ f(i) > f(i-1) \wedge f(i) > f(i+1) \wedge f(i) > tr \\ p(i) = 0, & \text{otherwise} \end{cases} \quad (9)$$

where tr is a threshold value, used to suppress low amplitude peaks, which are typically attributed to noise effects.

The morphological index MI is then expressed as the RMS value of the impulses $p(i)$ detected by the closing operation and characterizes the amount of energy involved in the pulse series caused exclusively by the bearing or the gear defect.

A detailed analysis on the effect of the length and the shape of the structuring element is performed in [15]. According to this analysis, a flat structuring element with a length in the range of 60%-70% of the impulse repetition period minimizes the noise effects. Thus a value of the structuring length equal to 60% of the impulse repetition period is further chosen in this paper. According to extensive analysis results, the optimal range for the threshold value is typically between 25 to 35% of the maximum impulse amplitude.

4. EXPERIMENTAL APPLICATION

The contact fatigue strength of gear steels and the performance of gear lubricants can only be determined by running gears at sufficiently high torque to cause contact fatigue or lubricant breakdown.

This often results in the need for high power and long test durations. For this reason, contact fatigue testing of gears can be carried out fast and more easily on back-to-back, or 'power recirculating' test rigs.

Thus, a series of twelve (12) measurements were performed on a back-to-back test rig (Figure 1) at the Vibroacoustic Laboratory of Warsaw University of Technology. The last one of them was obtained just prior to the breakage of the gear tooth. Two test gearboxes of identical gear ratio and centre distance are joined by torsionally compliant shafts (torsion bars), with an actuator in one shaft. This rotates the shafts to induce equal and opposite torques in the test gears at each end.

A small variable speed motor drives both gearboxes, the power required being only equal to the total mesh friction, windage and churning losses of the gears.

Each measurement consists of 8192 samples and the sampling rate is equal to 24 KHz. The shaft rotation frequency is approximately 21 Hz and the expected gear mesh frequency is approximately 670 Hz.

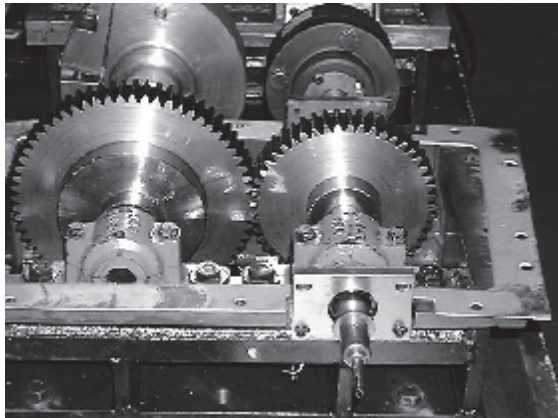


Fig. 1. Test rig used

Initially, the raw measured signals were processed using Fourier Transform. Their time waveforms and their corresponding spectra are presented respectively in Fig 2 and Fig. 3.

No significant changes of the measured signals related to the evolution of the defect can be observed, either in the time or in the frequency domain, with the slight exception of the last measurement.

Then, in order to apply morphological analysis, a soft-thresholding de-noising procedure is used at the first step, using wavelet analysis.

The purpose of this procedure is to remove as far as possible the random signal information and the amount of white noise, since morphological analysis is very sensitive to these effects. A soft thresholding procedure is performed using the db2 wavelet and level 2. The selected threshold settings are according to the minimax rule and the single level rescaling method.

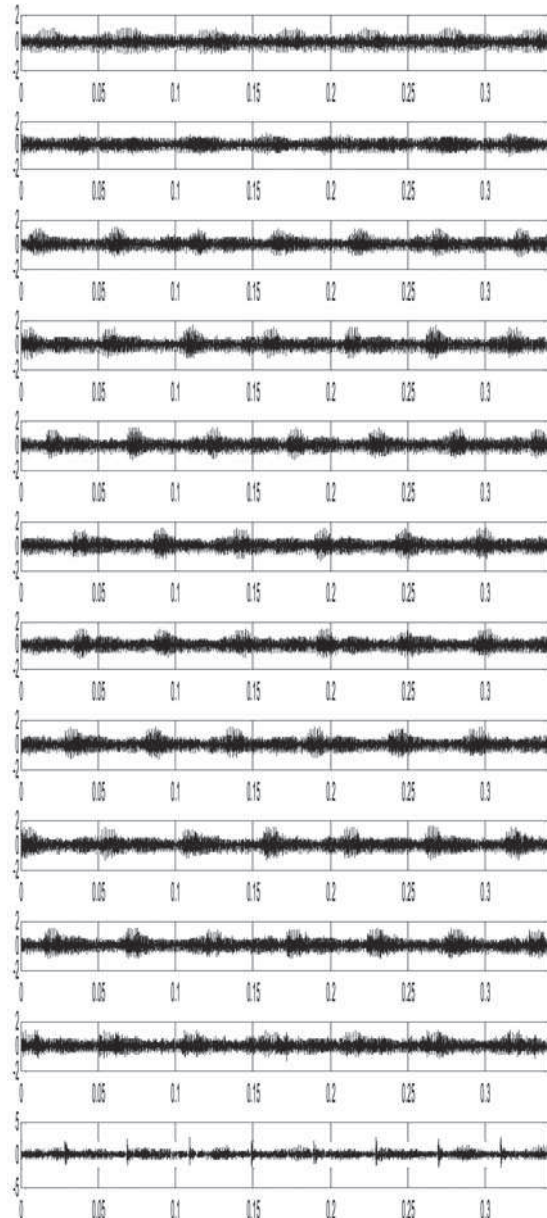


Fig. 2. Time waveforms of the raw signals.

The effect of denoising is minimal and the resulting signals keep almost the same periodic form as the original signals. However, the denoised signals appear more regular, as the presence of white noise and random components is limited, and they present a smaller amplitude and less noise. This can be observed in the spectral peaks of the frequency analysis of the signal from measurement 12 (Fig. 4), in the waveforms of the signals from measurement 12 (Fig. 5) and from measurement 2 (Fig. 6). The raw signals are presented with a solid black line and the de-noised ones with the dot gray.

Then, morphological closing was applied on all the original and de-noised signals, using a flat structuring element. The basic idea of the implementation of the morphological analysis on signals emitted by gears is to extract information from the time domain shape of the produced envelope.

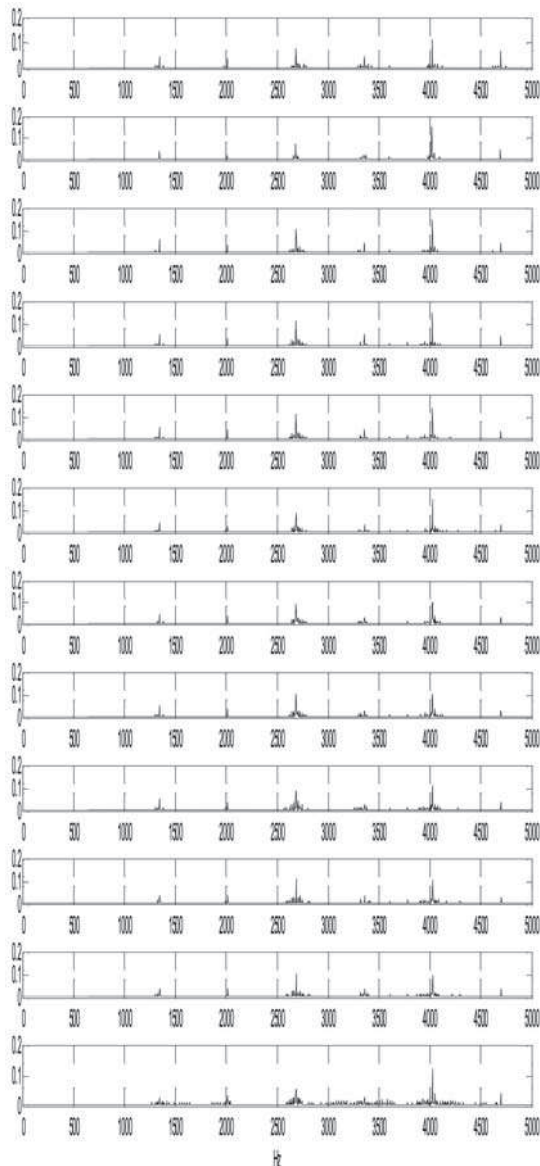


Fig. 3. Spectra of the raw signals.

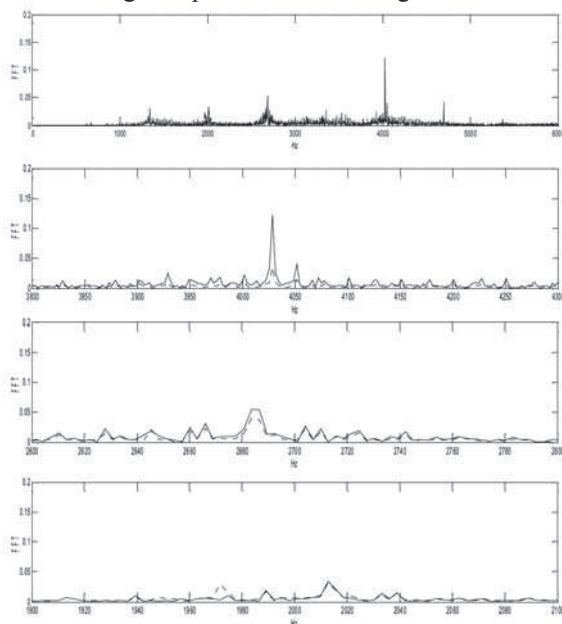


Fig. 4. Frequency regions of the spectrum analysis of the original and the de-noised signal 12.

Gear mesh frequencies are often very sensitive to load, but high GMF amplitudes do not necessarily indicate a problem if the side band frequencies remain at low level. Thus, the length of the structuring element was selected as 67% times the assumed repetition period, which corresponds to the inverse of the rotation frequency as the side bands around the GMFs spaced at this frequency.

The resulting signals after the closing operation are shown in Fig. 7, where the original and the denoised envelopes appear superimposed. Parallel, Figs 5 and 6 show detailed presentation of the resulting signals from the closing operation. As can be observed, a characteristic shape like an envelope appears above the original signals, presenting periodic lobes related to the rotation speed. The solid line envelopes which result from the implementation of the morphological analysis on the de-noised signals and the dot line envelopes result from the raw signals.

The difference between the envelopes from the raw and the denoised signals is minimal, due to the limited values of added noise.

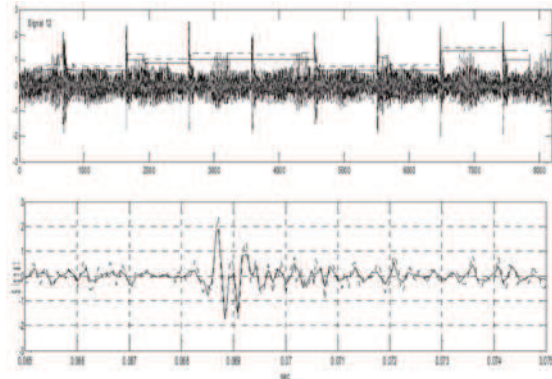


Fig. 5. Time waveform and closing of the raw and the de-noised signal 12.

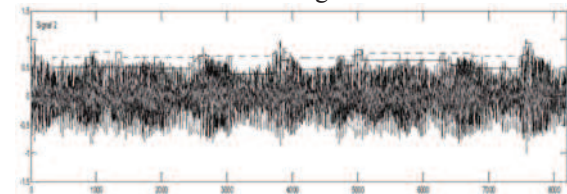


Fig. 6. Time waveform and closing of the raw and the de-noised signal 2.

After the closing operation, a local maxima algorithm is further implemented, in order to evaluate the impulsive information contained in the produced envelopes. According to this algorithm, an impulse series is obtained by retaining only the local maxima of a closing.

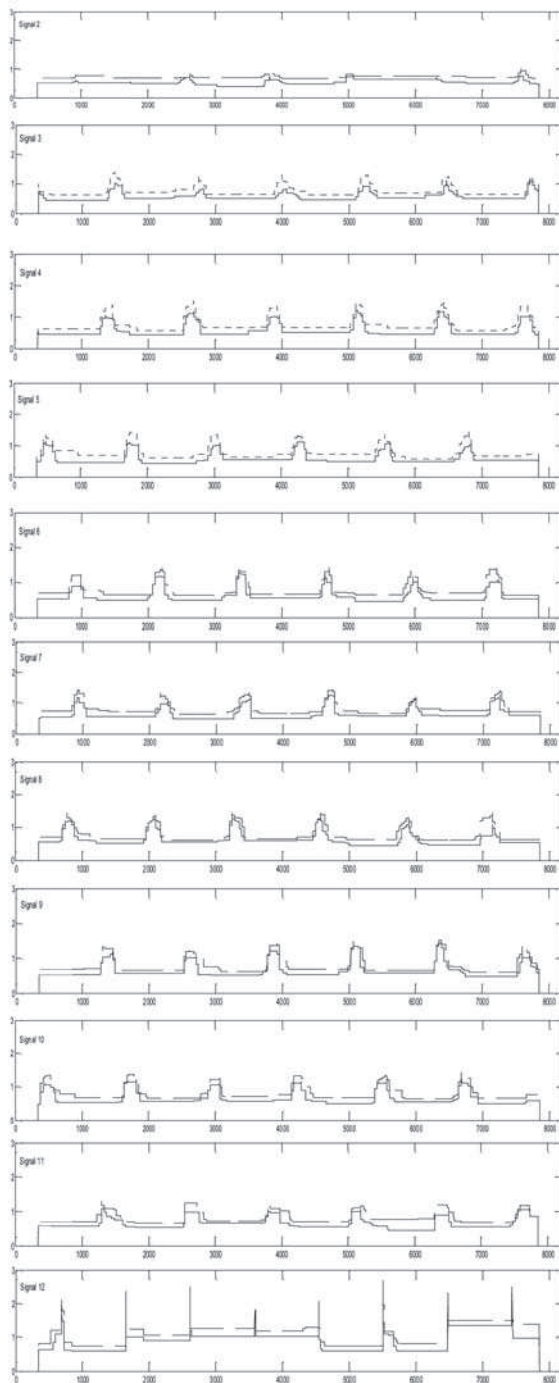


Fig. 7. Envelopes produced by morphological analysis of the raw and de-noised signals.

The morphological index MI is then calculated as the RMS value of the impulses detected by the closing operation. The MI characterizes the amount of energy involved in the pulse series caused exclusively by the gear defect. The resulting Morphological Index is presented in Fig. 8. As it can be observed, the MI follows monotonically the progress of the defect.

The closing of the signal exhibits an interesting property: it presents a kind of envelope, the shape of which is clearly related to an impulse sequence, which occurs periodically, with a frequency

determined by the geometry of the defective component and the rotation speed.

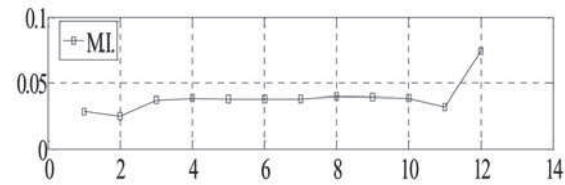


Fig. 8. Evolution of the Morphological Index with the progress of the fault

As observed in Fig. 7, the envelope produced by the closing operation is characterized by peaks. These peaks allow the detection of the time instants, at which the impulses occur. This periodic time duration is related to the inverse of the rotation frequency. As also observed in Fig. 7, the peaks tend to be sharper and their amplitude increases as the gear wear deteriorates.

Thus, according to the proposed procedure, the changes in the time domain shape of the signals obtained by the closing operation are shown at a first stage to be able to offer a visual inspection on the resulting envelope of the wear evolution. At a second stage, a quantitative indication of the evolution of the defect can be obtained by the evolution of the Morphological Index.

CONCLUSION

The morphological closing using a flat structuring element results to the extraction of a kind of envelope with a series of impulses corresponding to the impulses generated by a defective gear. This series can offer a better visual inspection of the impulsive nature of the signal. Parallel, they contain sufficient quantitative information about the repetition period and the intensity of the impacts.

Based on this envelope, the Morphological Index can be defined, providing a quantitative measure for the evolution of the defect.

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K. GRYLLIAS received his diploma in Mechanical Engineering from National Technical University of Athens in 2003. He is currently working towards his PhD degree with the Mechanical Engineering Department at the National Technical University of Athens (NTUA). His current research interests are in the area of signal processing, machine dynamics and condition monitoring of electromechanical systems. He is a member of the Technical Chamber of Greece (TEE).



C. YIAKOPOULOS is a Mechanical Engineer and member of the Lab of Dynamics and Structures at the Mechanical Engineering School, NTUA, Greece. He graduated the School of Mechanical Engineering, NTUA in 1996. He received his PHD degree from NTUA, Athens in February 2004. He has participated in 6 National research projects and he has 8 published over 21 papers in international journals and conferences in the areas of signal processing and condition monitoring of electromechanical systems.



Associate Professor
I. ANTONIADIS is the director of the Laboratory of Dynamics and Structures. His research interests include methods for the dynamic analysis and condition monitoring of structures and electromechanical systems. He has coordinated or participated as principal researcher in more than 14 International and National research projects, he is the author or co-author of 3 books and academic course notes and of more than 110 reviewed papers in international journals and conferences.