Int J Adv Manuf Technol (2015) 80:1363–1368
DOI 10.1007/s00170-015-7110-6

ORIGINAL ARTICLE

Identification of structural damage in the turning process of a disk based on the analysis of cutting force signals

M. Khechana [1] · M. C. Djamaa [1] · A. Djebala [1] · Z. Boumazza [2]

Received: 18 December 2014 / Accepted: 31 March 2015 / Published online: 19 April 2015

Abstract During the machining of mechanical parts, structural damages such as cracks can appear on the finished surface, consequently, the measured cutting forces being perturbed. It is difficult to detect directly such damages starting from the measured signals because they are always mixed with the measuring noise. In this paper, a method based on the wavelet multiresolution analysis is applied to extract the required information relating to the existence of structural damages in a disk using the cutting force signals measured by a Kistler dynamometer during the disk machining. In order to simulate the structural damage, a longitudinal crack is voluntarily created on the cylindrical surface of the disk. Since periodic impacts are produced each time the cutting tool comes into contact with the structural damage, an optimized wavelet multiresolution analysis is used as a filtering and a denoising tool. The experimental results show the validity of this method within the detection of single and multiple defects created on the disk surface during the machining processes.

Keywords Structural damage · Turning process · Turbine disk · Wavelet multiresolution analysis

1 Introduction

The presence of structural damage in the mechanical pieces is a current observation of manufacturers. During machining, the workpiece can contain invisible damages like cracks or hard inclusions, masked in the structure of the piece and which can appear during the machining process. Also, rotating disks and beams with imperfections can affect the dynamic behavior of rotating machines by the presence of unbalances. Because of the high rotation speeds, the presence of a small defect in gas and nuclear turbine bladed disks can involve very important magnitudes which are very dangerous for the system making it instable [1].

The detection of structural damage can be achieved by various techniques of non-destructive control which require special equipments. In this case, the machine must stop working to carry out this type of control which presents a main inconvenience for the production. Recently, other techniques were applied using the analysis of vibration and cutting force signals in the case of machining operations.

In order to know the magnitude and the fluctuation of the cutting forces, the measurement is the unique way giving some important information on the stability of the machining process. In this way, we can mention the work of Francisco Mata [2], Kaymakci et al. [3], and Akyildiz and Livatyali [4]. Because the cutting forces are obtained by measurement, the noise that disturbs results requires the use of advanced signal processing techniques usually used for detecting bearing and gear defects. In this context, Magnevall et al. [5] present a method to keep the information related to the cutting forces at high frequencies independently to the dynamic effects of the measurement system while using an inverse filtering. The proposed approach is illustrated by a comparison between the filtered forces by two different filters and the unfiltered forces under different cutting conditions. The results show that a more reliable evaluation of the cutting forces can be obtained according to the proposed method in relation to traditional low-pass filtering, particularly in transient cutting conditions and high cutting speeds.

✉ M. C. Djamaa
mc_djamaa@yahoo.fr

[1] Laboratory of Mechanics and Structures, University 8 may 1945, Po. Box 401, 24000 Guelma, Algeria

[2] Algerian Atomic Energy Commission, 2 Boulevard Frantz Fanon, Po. Box 399, 16000 Algiers, Algeria

The revolution in the field of defect detection in rotating machinery (namely bearing and gear defects) is certainly the founding of time-frequency methods since the defect signature is generally transient. The time-frequency approach is well adapted because it gives a local visualization of the signal instead of the global visualization obtained from the classical fast Fourier transform. Since the 1980s, many researches applied the wavelets for fault diagnosis of rotary machines and a good review with applications is proposed in [6]. The continuous wavelet version has been successfully applied for bearing and gear fault detection [7–9]. It has been also compared to other time-frequency methods such as the short-time Fourier transform used by Boltezard et al. [10] and with bi-spectral analysis proposed by Yang et al. [11]. A discrete version of the wavelet also exists, and it has been widely used since the establishment of the waterfall algorithm proposed by Mallat in 1989 [12] which is named wavelet multiresolution analysis. This technique has been applied by Brabakhar et al. [13] for bearing fault detection using vibratory signals and by Chinmaya et al. [14] for the detection of gear defects using the motor current signals. An optimized version of the wavelet multiresolution analysis, especially adapted to shock signals, has been proposed by Djebala et al. [15] using the kurtosis as optimization criterion. It has been successfully applied for bearing fault detection allowing the filtering and the denoising of the signal at the same time. Clear frequency-domain visualization of the defect by the envelope spectrum of the wavelet coefficients is obtained. This approach has been also combined with Hilbert transform in the work of Djebala et al. [16] for the detection of gear defects giving good results with the advantage to isolate the defect frequency even for small or combined defects.

The main objective of the proposed work is the detection of structural damages of a disk using wavelet multiresolution analysis which is applied on cutting force signals measured directly during the cutting process.

2 Formulation of wavelet transform and proposed approach

In wavelet transform, the sinusoids of the Fourier transform are replaced by a family of translations and dilations of a same function called wavelet which can be defined by the following:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{1}$$

With a as the scaling parameter and b the translation parameter.

If ψ^* is the conjugate of the wavelet ψ, the continuous wavelet transform of a signal $s(t)$ is defined by the following:

$$\mathrm{CWT} = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} s(t)\psi^*\left(\frac{t-b}{a}\right)dt \tag{2}$$

Contrary to the Fourier transform, the wavelet analysis makes the projection of the function $s(t)$ on a family of functions (wavelets) deduced from an elementary function, named mother wavelet, by translations and dilations. At high frequencies, this process permits to have a precision in increased time corresponding to the short phenomenon for which the apparition instant and the time are important characteristics. However, at low frequencies, the frequency precision improves the expense of the temporal aspect since the phenomenon has a lot of longer times.

The discrete wavelet transform (DWT) is a discretization of the continuous wavelet transform (CWT). By replacing a and b by $2m$ and n^{2m}, respectively, where m and n are integers, we obtain the following expression:

$$\mathrm{DWT}(m,n) = 2^{\frac{-m}{2}}\int_{-\infty}^{+\infty} s(t)\psi^*\left(2^{-m}t-n\right)dt \tag{3}$$

A convenient version of this transform, called wavelet multiresolution analysis (WMRA), consists of introducing the signal in low-pass and high-pass filters. As a result, two vectors are created; the elements of the first one are called approximation coefficients corresponding to the lowest frequencies of the signal, while elements of the second one are called detail coefficients corresponding to the highest frequencies. The decomposition process can be repeated n times, where n is the maximal number of decomposition levels.

During the decomposition, the signal $s(t)$ and the resulting vectors incur an under sampling. It is the reason why the approximation and detail coefficients pass all again through two reconstruction filters. The two resulting vectors A_k called approximations and D_k called details are related by the following relationship:

$$\begin{aligned} A_{k-1} &= A_k + D_k \\ s &= A_k + \sum_{i\le k} D_i \end{aligned} \tag{4}$$

Consequently, every wavelet has its own bank of filters that allow proceeding to the multiresolution analysis.

If F_{max} is the maximal frequency of the measured signal, the frequency band of each level i is $\left[0-\frac{F_{max}}{2^i}\right]$ for approximations and $\left[\frac{F_{max}}{2^i}-\frac{F_{max}}{2^{i-1}}\right]$ for details.

Let us note that for all treated signals in this work, the Daubechies 5 (db5) is used as a mother wavelet because this kind of wavelets is well adapted to the shock signal analysis as those presented subsequently.

The wavelet multiresolution analysis of the treated signal being made, thereafter, the proposed approach consists of keeping the characteristic detail (as a filtered signal) of a periodic shock caused by every contact between the cutting tool and the created defect. A statistical parameter called kurtosis has been used because it is a very sensitive shock parameter. If its value is up to three, the presence of a shock is confirmed. Its formula is given by the following:

$$\text{Kurtosis} = \frac{\frac{1}{N}\sum_{k=1}^{k=N}\left(s_k-\widetilde{s}\right)^4}{\left[\frac{1}{N}\sum_{k=1}^{k=N}\left(s_k-\widetilde{s}\right)^2\right]^2} \quad (5)$$

Where s is the treated signal, $\widetilde{s}$ is its average value, and N is the number of points.

3 Experimental investigations

3.1 Experimental set-up

To pilot the experiment part of the work, some defects are voluntarily created on the cylindrical surface of ordinary steel disk as a fit of 2 mm of depth and 0.5 mm of width. The experimental set-up (Fig. 1) is composed of a universal lathe model SN40, a tool with carbide insert GC415 and a Kistler dynamometer which permits to record in real time the intensity of cutting forces in three directions.

The cutting conditions are fixed according to the variation of one parameter. Three rotating speeds are chosen: 1400, 710, and 355 rev/min, but the feed and the cutting depth are maintained constant equal to 0.08 mm/rev and 0.5 mm, respectively. The measurement of all cutting force components is automatically performed by the Kistler dynamometer. We are mainly interested in the results of the tangential cutting force (Fz) measured during the turning operation according to cutting conditions already mentioned because the tangential cutting force is, in general, the dominate component measured in the rotating direction of the work-piece and then the contact between the tool and the existing defect can happen one time for each rotation period of the disk.

3.2 Measured cutting force signals

Figures 2, 3, and 4 show, respectively, the tangential cutting force (Fz) measured during the turning of a disk without defect at 1400 rev/min (23.33 Hz) of a disk with only one defect at 710 rev/min (11.83 Hz) and of a disk with two defects spaced by 90° at 355 rev/min (5.91Hz).

No particular information can be extracted from the signal presented in Fig. 2. The corresponding kurtosis is equal to 2.16 which indicates the absence of a shock. The same observation is valid for the signal of Fig. 3 which does not give any information on the existence of the defect created on the disk. The corresponding kurtosis is equal to 1.75. The measured signal presented in Fig. 4, once again, does not give any significant information.

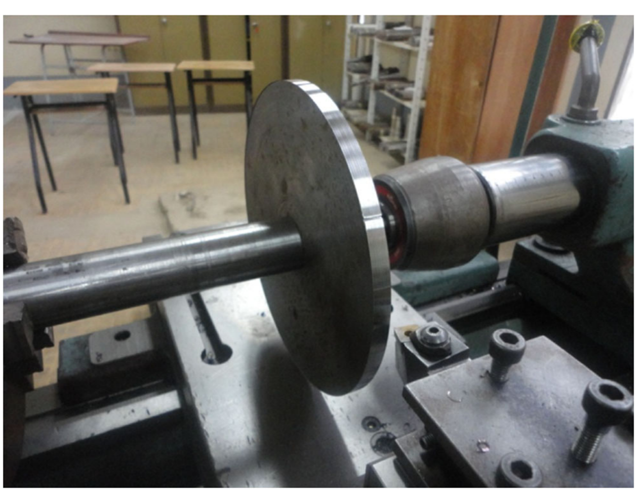

Fig. 1 Experimental set-up

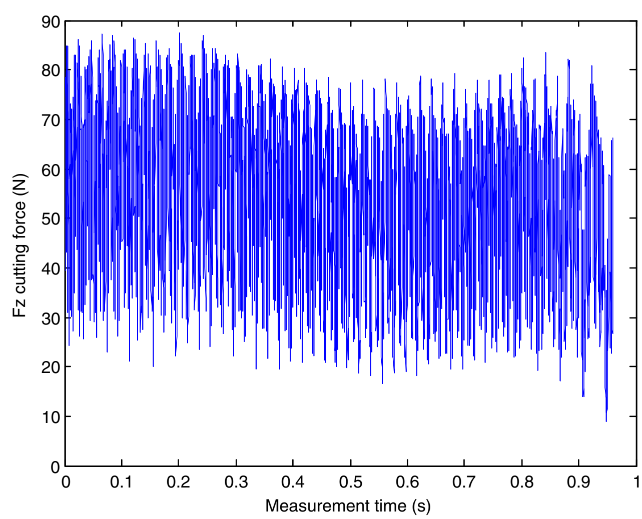

Fig. 2 Fz cutting force measured on a disk without defect at 1400 rev/min

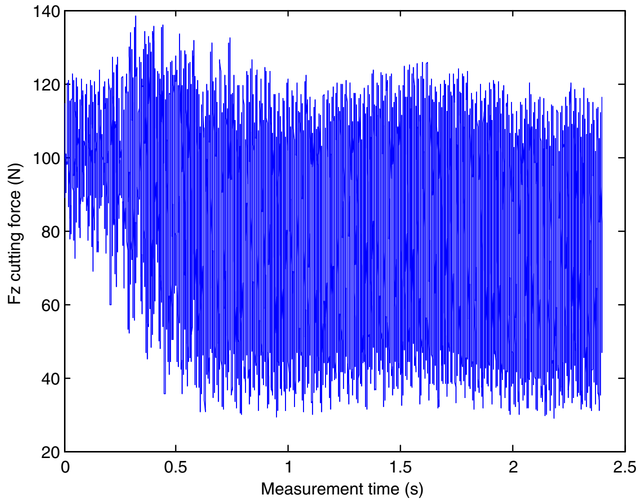

Fig. 3 Fz cutting force measured on a disk with one defect at 710 rev/min

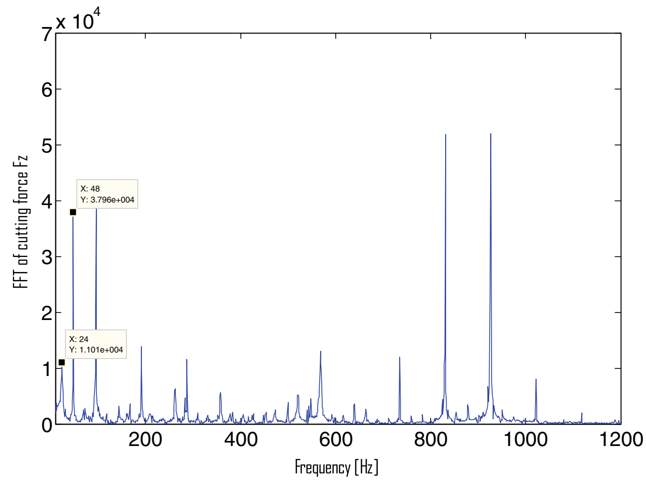

Fig. 5 Spectrum of the signal plotted on Fig. 2

Consequently, it is impossible to detect the structural damage created on the disk directly from the measured cutting force since the signals are mixed with the measurement noise.

4 Results analysis

The measured cutting force signals are previously treated by the classic fast Fourier transform. The spectrum of Fig. 5, corresponding to the signal of Fig. 2, shows the rotation frequency (about 24 Hz) and several of its harmonics. This result shows that the disk does not include any imperfection. However, the analysis of the spectrum of Fig. 6, corresponding to the signal of Fig. 3, shows the presence of a peak at the resonance frequency of the disk at 588 Hz modulated by two sidebands spaced by the rotation frequency (about 12 Hz). The peak, appearing at 48 Hz, corresponds to the frequency of electric network which is confirmed by other measurement using the pulse instrument working with the battery. The same remarks are observed on the spectrum of Fig. 7 corresponding to the signal of Fig. 4 which is similar to those of the previous case but with higher amplitudes. The spectrum well confirms the existence of a modulation by the rotation frequency (about 6 Hz) of the resonance frequency of the disk but does not specify the number of existing defects.

Since the FFT analysis does not give any concrete information of the defect, an optimized wavelet multiresolution analysis, especially adapted to the shock signals, is applied. Figure 8 shows the result obtained after the application of the proposed method on the signal of Fig. 2 in which there is no defect. The signal of the detail 5, as presented by Fig. 8, shows that there is no significant

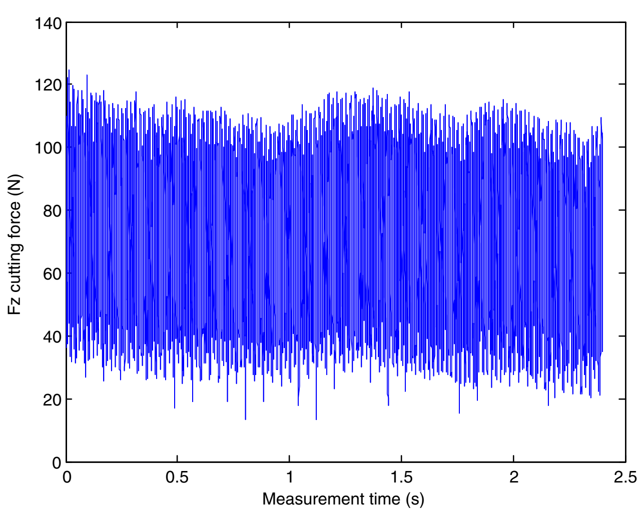

Fig. 4 Fz cutting force measured on a disk with two defects at 355 rev/min

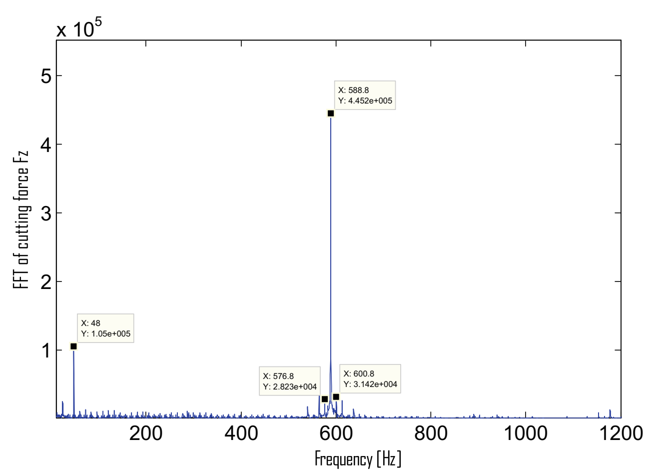

Fig. 6 Spectrum of the signal plotted on Fig. 3

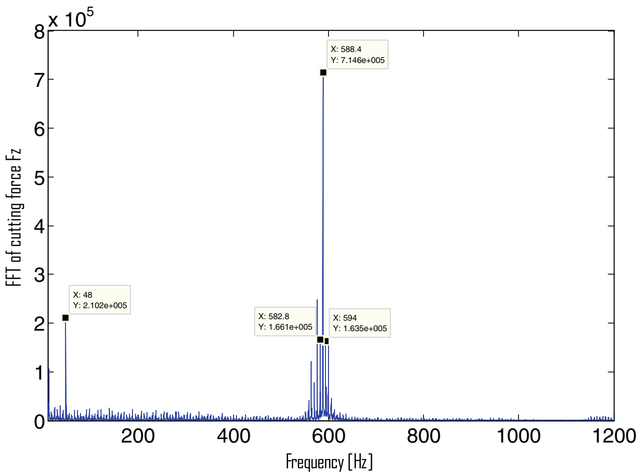

Fig. 7 Spectrum of the signal plotted on Fig. 4

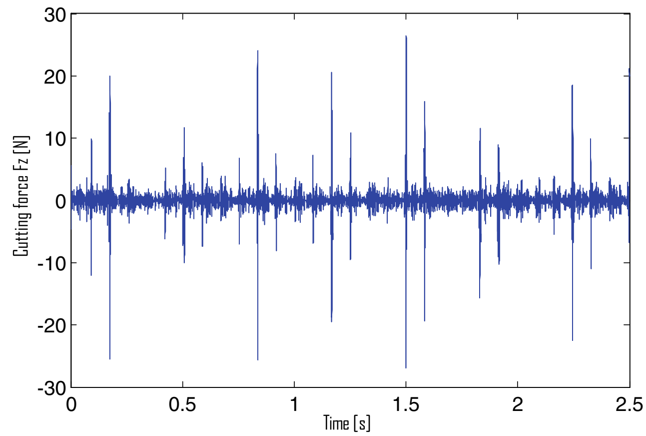

Fig. 9 Filtered signal obtained from wavelet decomposition of the original signal of Fig. 3

signature of the existence of the defect since no shocks are observed. On the other hand, Fig. 9 presents the signal of the detail 5 obtained from the wavelet decomposition of the signal of Fig. 3. There is a set of shock whose period is equal to 0.084 s, corresponding to the disk rotational frequency (11.83 Hz) which does not make any confusion on the existence of a defect. These impacts are undoubtedly created each time the cutting tool comes into contact with the created defect. In addition, the kurtosis in this case is equal to 44, which is a very significant value of the presence of the shock.

In the same way, Fig. 10 presents the signal of the detail 5 obtained from the wavelet decomposition of the signal of Fig. 4 where two defects were created. It shows the existence of two sets of shock with the same period equal to 0.162 s corresponding to the rotation frequency of the disk (5.91 Hz). This result confirms the presence of two defects temporally spaced by 0.044 s corresponding to an approximate separation angle of 90°.

5 Conclusion

In this work, a method based on the wavelet multiresolution analysis is exposed to treat the cutting force signals measured during the turning process of a disk including structural defects. First, the classical FFT analysis is performed on the signals of single and multiple defects created on the disk surface. It has been shown that in the absence of the defect, the spectrum does not show any information. However, in the presence of a defect, the natural frequency of the disk is modulated by the rotation frequency. The spectrum does not indicate the number of defects, and moreover, the modulation phenomenon may correspond to another defect. The application of the wavelet multiresolution analysis permitted the detection of simple and multiple defects as a consequence of the filtering process of the original signals. The impacts corresponding to the passage of the tool on the created defects are clearly identified. We note that the proposed method is easy to implement in any programming language, such as Matlab, and need only a reduced computing time as for a simple FFT.

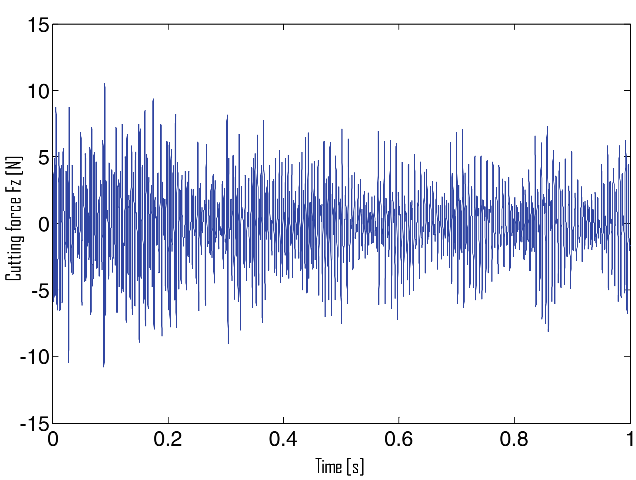

Fig. 8 Filtered signal obtained from wavelet decomposition of the original signal of Fig. 2

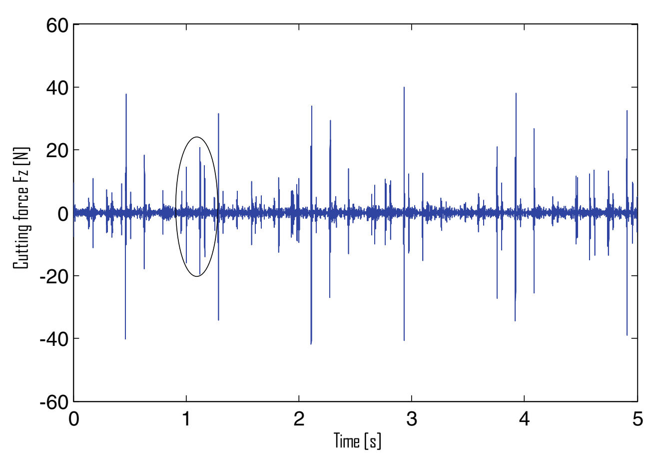

Fig. 10 Filtered signal obtained from wavelet decomposition of the original signal of Fig. 4

References

1. Salio M, Berruti T, De Poli G (2006) Prediction of residual stress distribution after turning in turbine disks. Int J Mech Sci 48:976–984
2. Mata F, Beamud E, Hanafi I, Khamlichi A, Jabbouri A, Bezzazi M (2010) Multiple regression prediction model for cutting forces in turning carbon-reinforced PEEK CF30. Adv Mater Sci Eng 2010:1–7
3. Kaymakci M, Kilic ZM, Altintas Y (2012) Unified cutting force model for turning, boring, drilling and milling operations. Int J Mach Tools Manuf 54–55:34–45
4. Akyildiz HK, Livatyali H (2011) Prediction and experimental analysis of cutting forces during machining of precision external threads. Mach Sci Technol 15:485–506
5. Magnevall M, Lundblad M, Ahlin K, Broman G (2011) High frequency measurements of cutting forces in milling by inverse filtering. Mach Sci Technol 15:147–166
6. Yan R, Gao RX, Chen X (2014) Wavelets for faults diagnosis of rotary machines: a review with applications. Sig Proc 96:1–15
7. Sun Q, Tang Y (2002) Singularity analysis using continuous wavelet transform for bearing fault diagnosis. Mech Syst Signal Process 16–6:1025–1041
8. Nikolaou NG, Antoniadis IA (2002) Demodulation of vibration signals generated by defects in rolling element bearings using complex shifted Morlet wavelets. Mech Syst Signal Process 16–4:677–694
9. Peter W (2000) Wavelets analysis. A flexible and efficient fault diagnostic method for rolling element bearing. 7th Int Cong Sound and Vib 507-514, Germany 4-7 July 2000
10. Boltežar M, Simonovski I, Furlan M (2003) Fault detection in DC electro motors using the continuous wavelet transform. Meccanica 38:251–264
11. Yang DM, Stronach AF, Mac Connell P (2003) The application of advanced signal processing techniques to induction motor bearing condition diagnosis. Meccanica 38:297–308
12. Mallat S (1989) A theory for multiresolution signal decomposition: the wavelet representation. IEEE Trans Anal Mach Intel 11–7:674–693
13. Brabhakar S, Mohanty AR, Sekhar AS (2002) Application of discrete wavelet transform for detection of ball bearings race faults. Tribol Int 35:793–800
14. Chinmaya K, Mohanty AR (2006) Monitoring gear vibrations through motor current signature analysis and wavelet transform. Mech Syst Signal Process 20–1:158–187
15. Djebala A, Ouelaa N, Hamzaoui N (2008) Detection of rolling bearing defects using discrete wavelet analysis. Meccanica 43–3:339–348
16. Djebala A, Ouelaa N, Benchaabane C, Laefer DF (2012) Application of the wavelet multiresolution analysis and Hilbert transform for the prediction of gear tooth defects. Meccanica 47–7:1601–16121