A Wavelet Approach to Estimate The Quality of Ground Parts

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ABSTRACT

The manufacturing process of metal parts is subjected to machining instabilities that can degrade the surface finish quality and the reliability of products. Some instabilities are of transient nature and traditional inspection systems are unable to adequately estimate the grade of affectation in the finished parts. Time-frequency analyses are techniques that overcome these limitations and have recently been incorporated in special industry inspection equipment to improve the quality of the manufactured parts. Grinding is a process used to get high precision and very smooth surface in flat or cylindrical parts because of the target applications such as the automotive industry where the highest standards can be found. This paper reports a technique to estimate the quality of ground parts based on time-frequency transforms that are used to enhance the defects. This makes it easier to implement the technique for surface characterization in online pass/no-pass inspection machines. The fundamentals of the methodology are revised and the technique is applied to the identification of vibration marks in cylindrical ground rods. Results show that this approach identifies adequately imperfections of transient nature and it is able to estimate the extension and amplitude of the defects on the surface of the manufactured parts.

Keywords: grinding, time-frequency, wavelets, surface quality.

RESUMEN

Los procesos de manufactura de partes metálicas se encuentran sujetos a inestabilidades en la maquinaria que pueden degradar la calidad superficial de los productos y su confiabilidad. Algunas inestabilidades son de naturaleza transitoria por lo que los sistemas de inspección tradicionales no son capaces de estimar adecuadamente el grado de afectación del acabado superficial. Los análisis de información en el dominio tiempo-frecuencia son técnicas que superan estas limitaciones y se han incorporado gradualmente en equipos especiales en la industria para mejorar la calidad de las partes manufacturadas. El rectificado es un proceso utilizado para obtener una superficie de gran precisión y calidad en piezas planas o cilíndricas, en aplicaciones tales como la automotriz, en donde se tienen las más altas exigencias de calidad. En este trabajo se reporta una técnica para estimar la calidad del acabado en piezas rectificadas, basada en una transformada tiempo-frecuencia, la cual es utilizada para destacar los defectos producidos durante el maquinado. Esto facilita la implementación de técnicas para caracterización superficial en sistemas de inspección en línea pasa/no-pasa. Se revisan los fundamentos de la metodología y se aplica el método en la identificación de defectos en piezas cilíndricas rectificadas. Los resultados muestran que la técnica es capaz de identificar defectos de naturaleza transitoria así como la extensión y amplitud de los defectos sobre la pieza inspeccionada.

1. Introduction

Grinding is an abrasive machining process for removing material in the form of small chips by mechanical action. It uses abrasive particles as the cutting medium. This process is relevant when the material is too hard for conventional machining and for demanding applications where high accuracy and surface quality of the workpiece are required. Grinding is applied mainly in metalworking because of the use of abrasive grains that are harder than any metal. It is a final machining process in the production of components requiring smooth surfaces and fine tolerances. Figure 1 shows the basic elements of the process.

The process uses a grinding wheel that consists of a large number of particles called grains held together by a bond material. Cutting grains, irregularly shaped and randomly distributed, are situated at the surface of the wheel and perform the cutting action. The grinding swarf is the material
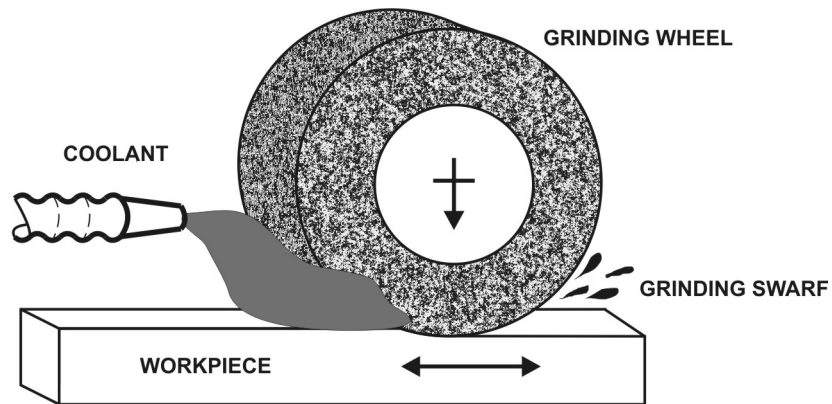
Figure 1. Elements of the grinding process.

removed derived from the high speed tool cutting process. The coolant fluid lowers the temperature of the workpiece, washes away the swarf and provides lubrication at the contact zone.

To get higher productivity, it is necessary to increase the grinding speed throughput. This may induce vibrations caused by improper setup, worn equipment or poor wheel performance. As a result, a series of marks appear on manufactured parts. This is called chatter and it prevents assembled components from operating quietly. Research on methodologies that can be used for minimizing the grinding cycle time, while meeting the requirements for the ground part quality, is under development [1].

Engineering surfaces are known to be comprised of a range of spatial wavelengths and filtering techniques are commonly used to separate the different components. Among these are spline, morphological, wavelets, regression and robust regression filters. Filtering is necessary prior to characterization for extracting information needed to provide process feedback [2]. New optical techniques are being developed to extract the roughness of moving surfaces under high rotational speeds for in-process measurement. By projecting a coherent light onto a rough surface, a reflected image is formed due to the combined effects of interference and light scattering. An image pattern, which depends on the surface quality, is projected onto a screen for posterior analysis [3].

Work has been done to identify the grinding process variables that affect the quality of manufactured parts. A statistical quality control is proposed after analyzing different techniques such as chi squared, Shapiro-Wilks, symmetry, Kurtosis, Cochran, Hartlett, and Hartley and Krushal-Wallis. The existence of predictive variables that are sensible to the processes setup and the quality of the products obtained is demonstrated [4].

Surface quality monitoring is a major concern in machining processes. This information is needed for enhanced process control. Industrial real-time methods based on B-spline wavelets have been used because of their excellent time-frequency localization. In this technique the change of the amplitude in the selective frequency bands and the root sum square of wavelet power spectrum are good indications of the quality of surface finish [5]. Continuous wavelet transform and normalized fractal dimension Dn are capable of the detection of local self-similarity in the surface profile of longitudinal turning operations of steel [6].

New on-line monitoring methods for feature extraction of machining processes to obtain criteria to detect changes of the process conditions are effective. Techniques based on wavelet packet transforms can be used to implement automatic procedures for process control decisions [7].

The influence of machining operations on surface topography has also been investigated. Wavelet reconstruction has been used for profile filtering in

hard turning to relate workpiece surface characteristics and the dynamic behavior of the machine tool. It has been found that machine vibration remarkably affects the surface topography at small feed rates, but has negligible effect at high feed rates [8]. Characterization has been done through the fractal dimension and it has been demonstrated that the wavelet transform method is the most precise in the calculation of the fractal dimensions of the curves. This technique obtained more accurate results than other methods like Box Counting, Yardstick, Co-variation, Structure Function, Variation, Power Spectrum and Rescaled Range analysis. It is established that a precise calculation of the fractal dimensions of the curves is the first step in characterizing machined surface topography [9].

Techniques to predict machinery conditions that affect the surface roughness have been tested. Methods based on wavelet and support vector machine are applied as an amplification of defect premonition, where the standard deviation of the wavelet transform and the wavelet packet energy ratio are used [10]. Wavelet analysis has been used to study the surface structures and decompose and reconstruct the sampled surface profile signals in cutting processes. Results are used to obtain predictive models to modify finishing of manufactured parts [11].

2. Wavelet approach

Signals are time-amplitude representations that commonly need to be transformed to other domains such as frequency or time-frequency for their analysis. These transformations make it possible to identify hidden content and additional information. Fourier transform is the most used tool for frequency content analysis. The technique decomposes a waveform into a sum of sinusoids of different frequencies. This is a transformation of a signal from time-domain to the frequency-domain. However, the procedure is applied only to stationary signals. This is, the frequency content does not change with time. Therefore, signals of transient nature are not discovered because of their short duration.

The problem of analyzing non-stationary signals was overcome with the development of the short-time Fourier transform. In this technique the signal is divided into sections and each section is analyzed for frequency content. Each segment can be considered a sample of a stationary process. A single window size is used for all frequencies and the resolution of the analysis is the same at all locations of the time-frequency domain.

The continuous wavelet transform was developed to analyze transient signals with a variable windows size. Large windows are used to describe the gross features of the signal, while small windows will describe small discontinuities. It has the ability to identify frequency components simultaneously with their location in time. In contrast to the Fourier transform, that uses sines and cosines to approximate a signal, the wavelet approach adopts a prototype function called "mother wavelet" which correlates better with sharp discontinuities.

According to [7], an energy limited signal can be decomposed by its Fourier transform as

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} F(\omega)e^{i\omega t}d\omega \tag{1}$$

and

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)e^{-i\omega t}dt \tag{2}$$

Equation(2) is the Fourier transform of $f(t)$ where the function is decomposed into a family of harmonics $e^{i\omega t}$ and the weighting coefficients $F(\omega)$ represent the amplitudes of the harmonics in $f(t)$ and Equation (1) is the inverse of the Fourier transform.

The wavelet transform is defined in a similar manner. Instead of using the harmonics $e^{i\omega t}$, a mother wavelet is used

$$\psi_{s\tau}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right) \tag{3}$$

Where s represents the frequency, τ represents the time shift or location, and ψ is the mother wavelet function. The parameter τ operates on the location of the wavelet function as it is shifted over the signal giving time information in the wavelet transform. The scale parameter s dilates (expand) or compress the signal. Large scales provide low frequency information while small scales provide high frequency information.

As in Fourier, a function $f(t)$ can be decomposed into a family of wavelet bases:

$$f(t) = \frac{1}{c_\psi} \int_{-\infty}^{+\infty} \int_0^{+\infty} W_s[f(\tau)] \frac{1}{s} \psi \left(\frac{t-\tau}{s} \right) ds \, d\tau \qquad (4)$$

Where c_ψ is a constant which depends on the base function, and $W_s[f(\tau)]$ is the wavelet transform defined as

$$W_s[f(\tau)] = \frac{1}{\sqrt{s}} \int_{-\infty}^{+\infty} f(t) \Psi \left(\frac{t-\tau}{s} \right) dt \qquad (5)$$

The continuous wavelet transform is defined in Equation 4 and Equation 5 is the inverse or the reconstruction wavelet transform. This time-frequency approach describes the information of $f(t)$ in various time windows and frequency bands.

There are a number of basis functions that can be used as the mother wavelet. Daubechies wavelets are the most popular and are used in numerous applications. Figure 2 shows the wavelet and scaling functions.

The application of the continuous wavelet transform is impractical because its implementation consumes a significant amount of time and resources. The discrete wavelet transform (DWT) was developed to overcome this situation. It is based on a sub-band coding which can be implemented with a high computational efficiency.

The DWT applies successive low-pass and high-pass filters to the discrete time-domain signal as shown in Figure 3. This procedure is known as the Mallat algorithm.
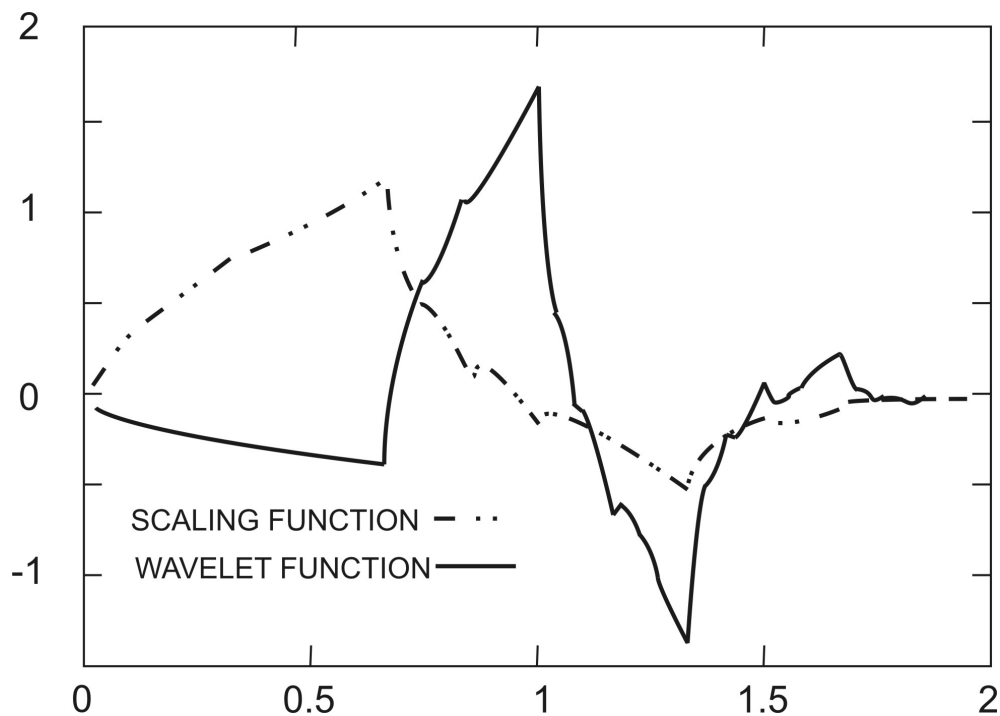

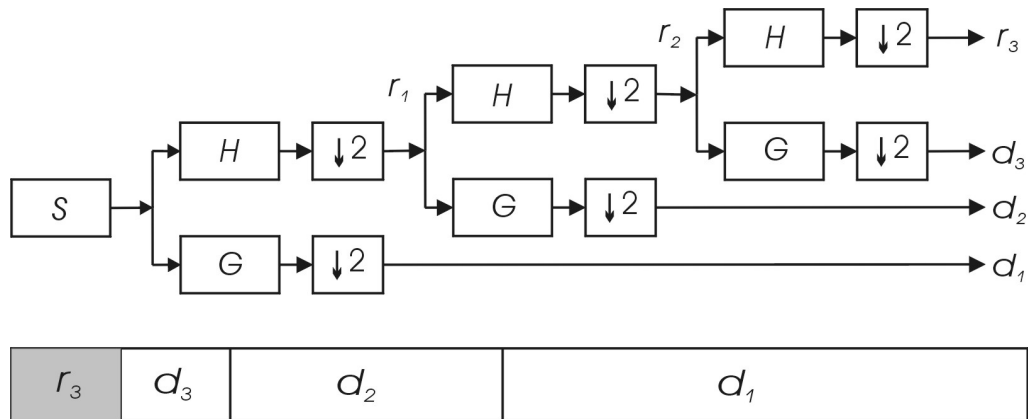Figure 2. Daubechies wavelet and scaling functions.

Figure 3. Discrete wavelet transform algorithm.

The algorithm uses a cascade of filters to decompose the signal. Each resolution has its own pair of filters. A low-pass filter is associated with the scaling function, giving the overall picture of the signal or low frequency content, and the high-pass filter is associated with the wavelet function, extracting the high frequency components or details. In Figure 3, the low-pass filter is denoted by H and the high-pass filter is denoted by G. Each end raw is a level of decomposition. A sub-sampling stage is added to modify the resolution by two at each step of the procedure. As a result of this process, the time resolution is good at high frequencies, while the frequency resolution is good at low frequencies.

3. Results and discussion

Experimental work was carried out in a cylindrical grinding machine. This machine showed instabilities that produced vibration marks on steel rods when ground. The defect was characterized by a variable extension and intensity, varying from one mark to a series of waves on the surface of the piece. A sketch of the surface profile observed is given in Figure 4.
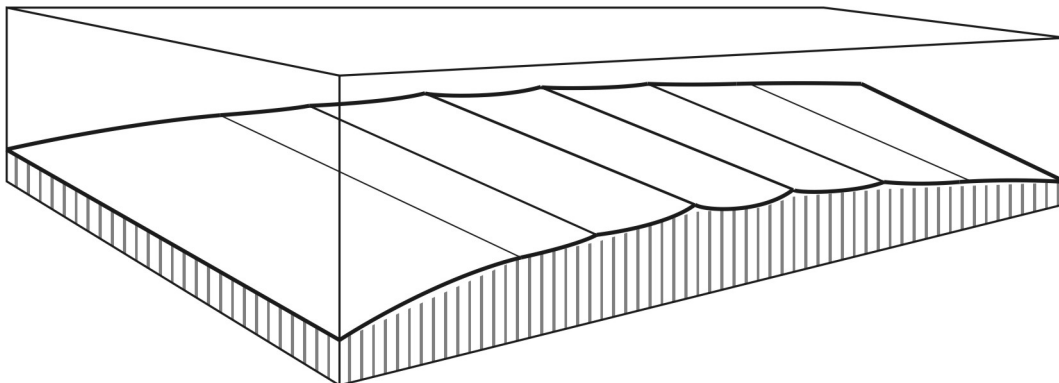

Figure 4. Surface profile of a rod with defects.

The periphery of the rods at the ground region was analyzed to get a signal which corresponds to the surface topography. A profiler sensor and an acquisition data system were used. The signal obtained showed two components: a low frequency oscillation derived from the total run-out and high frequency ripples mounted on the run-out signal. The high frequency contains the surface roughness and grinding defects. Figure 5 shows a representative signal of a rod which presents a section with strong vibration marks.

Daubechies wavelet transform was applied to the signals according to the description given in the last section to enhance the defects and facilitate the analysis of the surface. Figure 6 shows the signal transformed to the time-frequency domain. The wavelet procedure results in a vector that has the same number of elements as the digitized time-domain signal. The index represents each one of these elements. The sub-bands with the frequency content of the signal have been coded in this vector in such a way that the upper half portion contains the high-frequency band information. This

is the first level of decomposition. The next half of the remaining vector, or second level of decomposition, contains the halved high-frequency band information, and so on until there are only two elements at the corresponding level of processing.

A zoom can be observed in Figure 6. This embedded image contains a section where coefficients grow gradually and then disappear in two time locations. This is the sub-band where the algorithm enhances the rod defects shown in Figure 5 through the good correlation between the wavelet function and the signal produced by the surface of the rod. With the wavelet transform, it is possible to obtain the values of the frequencies which correspond to this band.

After the defects have been enhanced for easy identification, it is possible to apply filtering and statistical techniques, such as the RMS value, to get an estimation of the amplitude and extension of the imperfections. Figure 7 shows the results obtained after processing the signal.
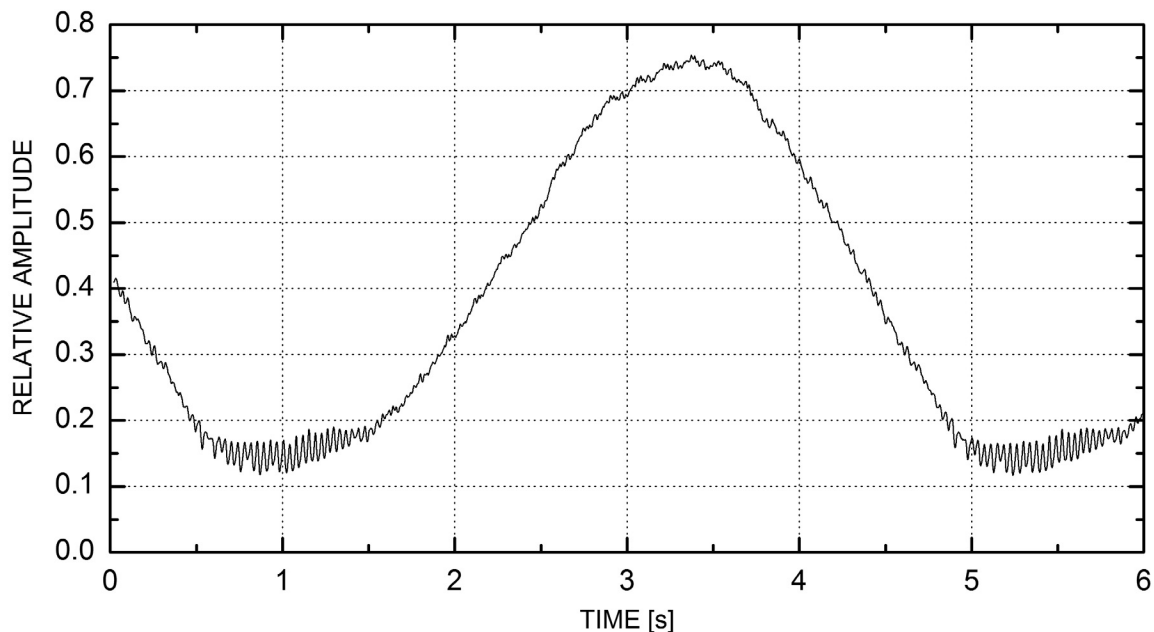

Figure 5. Steel rod with strong defects produced by vibration of the grinder system.
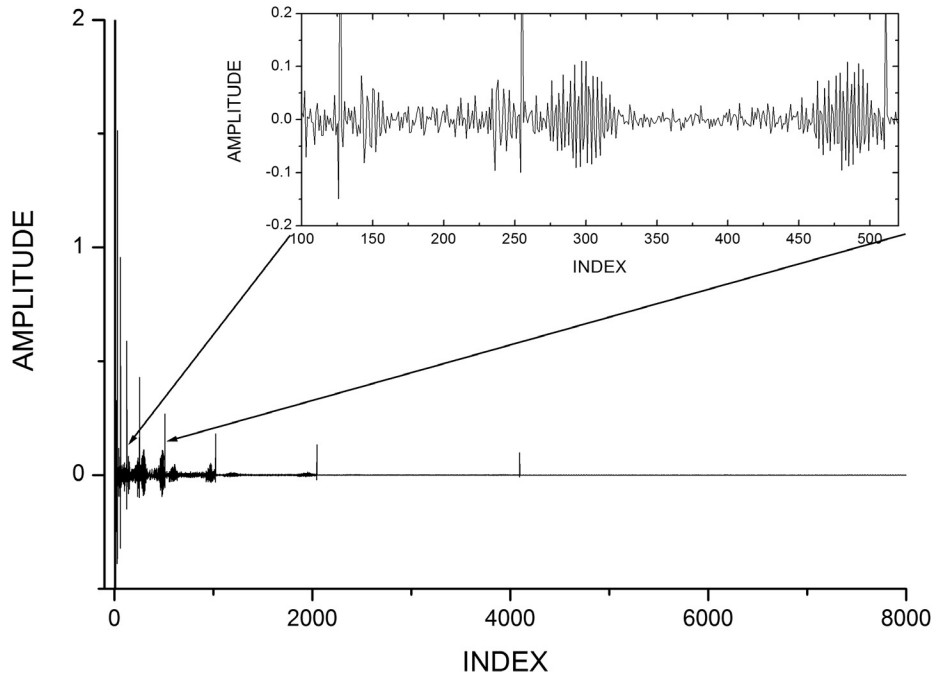
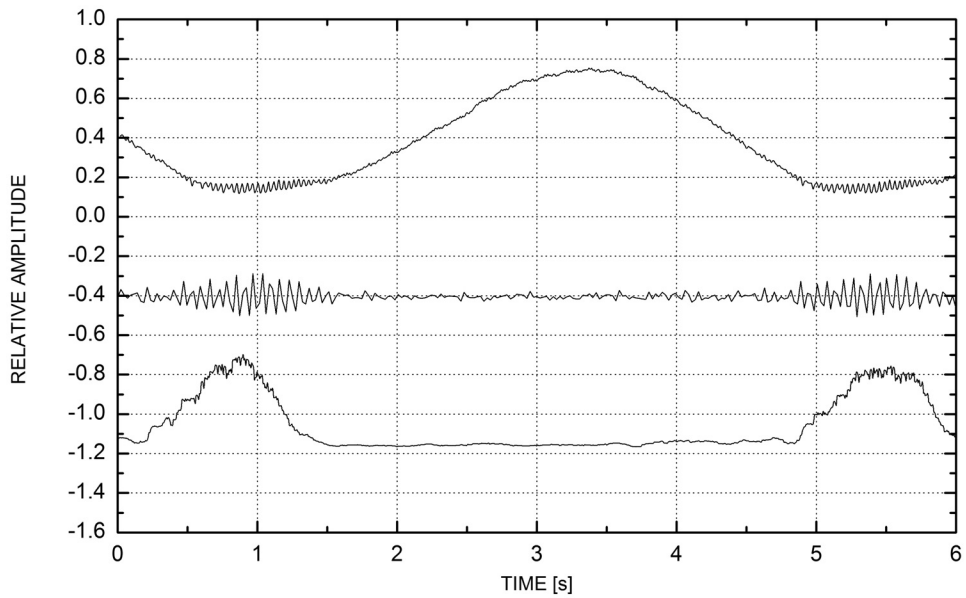Figure 6. Signal transformed to time-frequency domain.

Figure 7. Signal processing results.

As time is preserved by the algorithm, the position of marks can be located on the periphery of the rods. A value can be assigned to their extension and amplitude for the surface quality estimation and for automatic testing of parts with pass/no-pass equipment for production lines.

The wavelet transform is able to detect signals of transient nature. Grinding machine instabilities may give rise to isolated marks during the process as shown in Figure 8. This figure shows a ground rod with a defect characterized by a single mark or singularity. The nature of the algorithm, which performs a correlation between the signal and a mother wavelet, makes it possible to detect a single defect like this. The bottom graph shows the coefficients of the transform that grow when the analysis process reaches the location of the singularity. With an adequate system, the defect can be localized over the periphery of the part.

The cascade algorithm of the wavelet transform can be implemented in a straightforward manner and with a high computational efficiency. This makes the development of systems for grinding machines possible that measure on-site the quality of the parts manufactured. A machine concept of a system like this is shown in Figure 9.

This machine has a grinding mechanism and an electronic system which includes a wavelet processor. This processor can be an industrial PC or microcontroller based implementation. The process can be measured in real time to take the corrective actions to keep parts quality within manufacturer specifications.
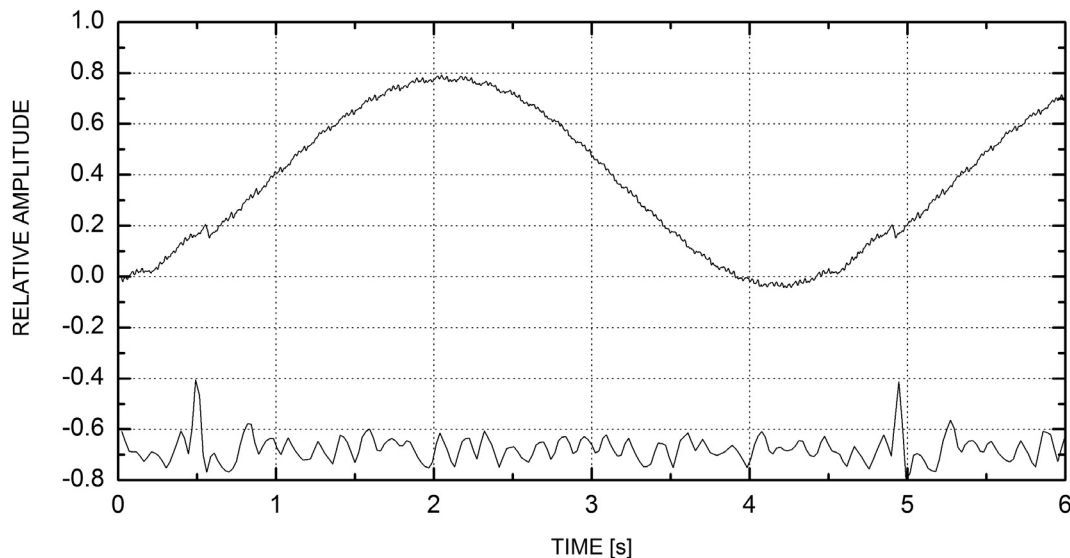

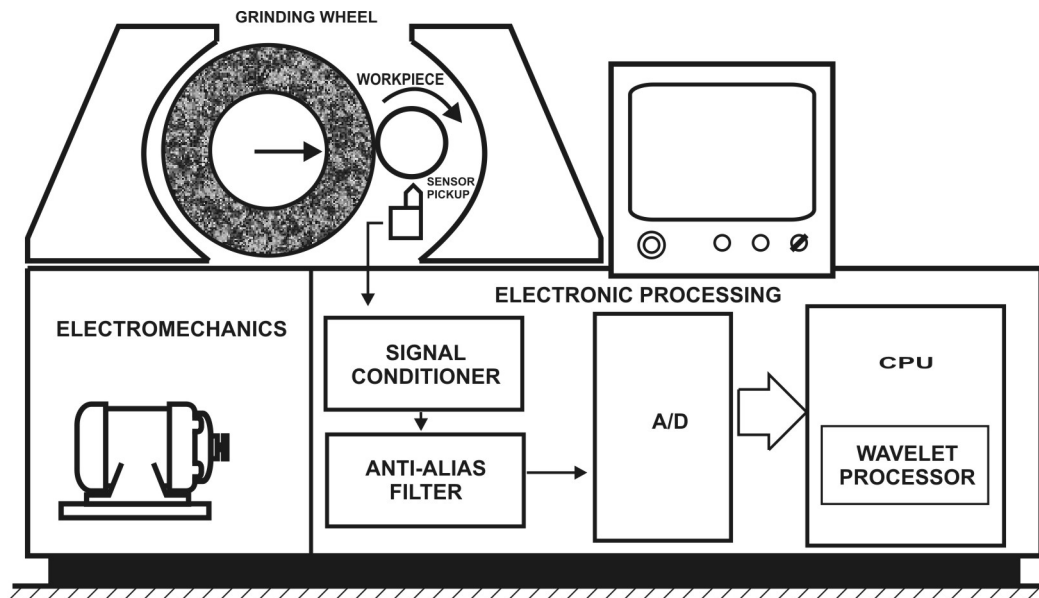Figure 8. Detection of singularities with wavelets.

Figure 9. System with real-time surface-quality measurement through wavelets.

4. Conclusions

Instabilities in grinding processes may affect the quality of manufactured parts. Electronic systems are necessary to detect and control the process to avoid manufacturing of elements out of specifications, especially in volume manufacturing where in-line testing is essential. A methodology for vibration marks detection that uses recently developed techniques based on wavelet transforms was presented. This technique is able to detect non-stationary phenomena, as the vibration defects described can be considered. The method has various advantages, among which its capability to identify not only the amplitude of the defects, but also the extension and location over the periphery of the parts can be mentioned. Isolated defects are adequately identified too. The algorithm can be implemented with a high computational efficiency which makes it an ideal candidate for real-time on-line testing systems for high volume manufacturing.

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Acknowledgments