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Application of the wavelet packet transform to vibration signals for surface roughness monitoring in CNC turning operations

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ABSTRACT

The wavelet packet transform method decomposes a time signal into several independent time-frequency signals called packets. This enables the temporary location of transient events occurring during the monitoring of the cutting processes, which is advantageous in monitoring condition and fault diagnosis. This paper proposes the monitoring of surface roughness using a single low cost sensor that is easily implemented in numerical control machine tools in order to make on-line decisions on workpiece surface finish quality. Packet feature extraction in vibration signals was applied to correlate the sensor signals to measured surface roughness. For the successful application of the WPT method, mother wavelets, packet decomposition level, and appropriate packet selection methods should be considered, but are poorly understood aspects in the literature. In this novel contribution, forty mother wavelets, optimal decomposition level, and packet reduction methods were analysed, as well as identifying the effective frequency range providing the best packet feature extraction for monitoring surface finish. The results show that mother wavelet *biorthogonal* 4.4 in decomposition level *L*3 with the fusion of the orthogonal vibration components ($a_x + a_y + a_z$) were the best option in the vibration signal and surface roughness correlation. The best packets were found in the medium-high frequency *DDA* (6250–9375 Hz) and high frequency *ADA* (9375–12500 Hz) ranges, and the feed acceleration component a_y was the primary source of information. The packet reduction methods forfeited packets with relevant features to the signal, leading to poor results for the prediction of surface roughness. WPT is a robust vibration signal processing method for the monitoring of surface roughness using a single sensor without other information sources, satisfactory results were obtained in comparison to other processing methods with a low computational cost.

1. Introduction

Techniques for the monitoring of machining processes use sensors to supervise machining conditions and aspects such as: dimensional deviation, surface finish and roughness, surface malfunctions, residual stress, chip formation, tool condition, chatter, faults in spindle positioning, among others [1,2]. In recent decades, numerous studies designed to improve and optimize machining processes using on-line monitoring techniques have underscored that satisfactory results are only obtained

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with the correct selection and location of sensors, and the application of adequate signal processing techniques for extracting signal information correlated to the monitored parameter. Numerous studies have been published on the monitoring techniques of a broad spectrum of signals e.g., cutting forces, vibration, acoustic emission, power consumption and sound signals, etc. [1,2]. Research on signal processing methods has tended to focus on three main lines: analysis in the time domain, analysis in the frequency domain, and simultaneous analysis of both time and frequency. The most widely used method in the time domain is time direct analysis (TDA) due to its simplicity and low analytical-computational cost [3,4]. Under certain circumstances, this method is not sufficiently effective for obtaining signal data, and more advanced methods are required such as singular spectrum analysis (SSA) [5,6], or principal component analysis (PCA) [7]. In the frequency domain the fast Fourier transform (FFT) [8] and power spectral density (PSD) methods [9] have been extensively used. However, neither of these methods enable the temporary location of transient events, which imposes considerable limitations to the monitoring of several technological parameters in machining processes. In order to overcome this drawback, time-frequency analysis was applied, where signals in both the time and frequency domains are simultaneously analysed. In time-frequency analysis, the most commonly used methods are the short time Fourier transform (STFT) [10,11] and wavelet transform (WT) [12].

Of the above mentioned signal processing methods, the WT technique decomposes a signal into a shifted and scaled version of a prototype function called the mother wavelet, characterized on a time-frequency scale [13]. In the last two decades, WT has been extensively implemented in the monitoring of machining processes. In its continuous form (CWT), the information obtained is excessive and often redundant, entailing a high computational cost that restricts its use to off-line applications [14], and explains why the technique is not extensively used for the monitoring of machining processes. However, in its discrete form (DWT), the WT has a much lower computational cost, making it apt for on-line applications. DWT has been used to monitor mainly technological aspects related to tool conditions in machining processes [15–18]. However, DWT presents substantial limitations in providing an in-depth analysis of high frequency signal components. To improve the analysis of high frequencies, a generalization of the DWT was used i.e., the wavelet packet transform (WPT), generating more frequency bands and enhancing the extraction of relevant information from the original signal. Similar to the DWT, the WPT has been primarily employed for the monitoring of tool condition [19–24], whereas other technological aspects such as chip formation [25–27], chatter [28], residual stress [29], and surface roughness [30,31] have received little attention in the literature.

The effective application of the WPT requires the optimization of four fundamental aspects: (1) the selection of an appropriate mother wavelet for adequate filtering of the signal; (2) the selection of the decomposition levels that provide the best packet feature extraction; (3) the selection of parameters for statistical feature extraction that are correlated to the technological factors under analysis; (4) and an optimum packet selection method.

The correct selection of the mother wavelet is crucial for obtaining optimum results, and is conditioned by the signal behaviour under analysis. The review of Zhu et al. [12] of the WT method applied to the monitoring of machining processes underscored the shortcomings in the random selection of mother wavelets without any prior analysis or justification. Recently published studies have mainly used mother wavelets from the Daubechies family i.e., db08 [19], db04 [23,27], db06 [23], db04 [25], db03 [29–31], but the behaviour of a wide range of other mother wavelets have not been assessed and are the aim of the present study.

The decomposition level applied to the WPT determines the frequency intervals for decomposing the original signal, and accordingly the number of approximation and detail components (packets). This parameter mainly depends on the signal typology, the machining process, and the technological aspect under evaluation. A more controversial aspect is the packet selection methods that should be analysed. In some cases, all of the packets are analysed e.g., Segreto et al. [29–31] and Naiki [23] analysed independently each packet without grouping. Whereas in other instances the volume of information and the computational cost are reduced, and criteria such as maximum energy or maximum entropy are applied. Wu and Du [21] applied the WPT method to vibration signals by selecting for analysis only the maximum energy components and disregarding all other signals. Similarly, Kamarthi et al. [18] used the maximum energy criterion of acoustic emission signals, whereas Sheffer and Heyns [22] used Shannon's entropy. Zhu et al. [19], Xu et al. [24], and Danesh and Khalili [32] analysed packets form the last decomposition level and rejected all the other levels without any prior justification. Karam and Teti [25] selected packets with the highest ranked wavelet feature vectors. These criteria allow for reducing the number of components under analysis and thus lower the computational cost, but may entail the loss of crucial information.

Moreover, surface finish in machining operations is a crucial aspect used as an indicator of correct machine-tool behaviour and correct selection of cutting conditions. Its value depends on several aspects directly related to: tool geometry, cutting parameters, cutting fluids, chatter, workpiece material, among others [1,2]. The most widely used parameter for characterizing surface finish is the *arithmetic mean deviation of the assessed profile Ra* [33], as measured by a profilometer.

In the monitoring of machining processes, little attention has been paid to surface finish as compared to other technical aspects such as tool condition or chatter. Until recently, most of the literature has evaluated the simple signal processing methods of TDA and FFT. In the time domain, Hessainia et al. [3], Kirby and Chen [34], Upadhay et al. [4], and Risbood et al. [35] used TDA with vibration signals to monitor the parameter *Ra* by also incorporating other cutting parameters as a process data source. Azouzi and Guillot [36] employed TDA to monitor surface finish by fusing cutting forces, vibration, and acoustic emission sensors, and incorporating cutting parameters as a process data source. Özel et al. [37] applied the TDA method to calculate the parameter *Ra* using cutting forces and power sensors, as well as cutting parameters, cutting time, cutting power, and specific force. Beggan et al. [38], Pittner et al. [39], and Pawade and Joshi [40] monitored surface finish with EA signals. The SSA method has been employed to monitor machining processes. Salgado et al. [5] used vibration