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Cutting force-based real-time estimation of tool wear in face milling using a combination of signal processing techniques

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Abstract

In this paper, combinations of signal processing techniques for real-time estimation of tool wear in face milling using cutting force signals are presented. Three different strategies based on linear filtering, time-domain averaging and wavelet transformation techniques are adopted for extracting relevant features from the measured signals. Sensor fusion at feature level is used in search of an improved and robust tool wear model. Isotonic regression and exponential smoothing techniques are introduced to enforce monotonicity and smoothness of the extracted features. At the first stage, multiple linear regression models are developed for specific cutting conditions using the extracted features. The best features are identified on the basis of a statistical model selection criterion. At the second stage, the first-stage models are combined, in accordance with proven theory, into a single tool wear model, including the effect of cutting parameters. The three chosen strategies show improvements over those reported in the literature, in the case of training data as well as test data used for validation—for both laboratory and industrial experiments. A method for calculating the probabilistic worst-case prediction of tool wear is also developed for the final tool wear model.

Keywords: Tool condition monitoring; Exponential smoothing; Multiple linear regression; Isotonic regression; Discrete wavelet transformation

1. Introduction

Cutting tool failures (wear and breakage) typically represent about 20% of the downtime of a machine tool (Karuda and Bradley [1]). Tool wear is found to have a direct impact on the quality of surface finish, dimensional precision and ultimately cost of the finished product (Sick [2]). Moreover, the criteria for tool life vary significantly in terms of the machining requirements (Bukkapatnam [3]). Over-estimation of tool life results in degraded product quality and damaged part (in case of early breakage of the tool), while under-estimation leads to frequent stoppage of the machining process and increased cost of production. So, real-time

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tool wear estimation in machining processes is a key research topic in automated manufacturing. Under the process of gradual wear, wear on the main cutting flank is the deciding criterion for failure of the tool [4].

Direct methods of wear estimation such as by visual inspection, by measurements of volumetric changes and those based on surface textures are not cost effective and reliable. Research for finding an efficient and effective *TCM* method, thus, mainly focuses on indirect methods of estimating wear, which are *online* and use process signals, such as cutting forces, current and power for various drives, vibration and acoustic emission (*AE*), that are known to be significantly affected by the wear phenomenon [5]. The basic approach is that the acquired signals, after necessary signal processing, are summarized into signal *features*, which are then related to the observed values of wear by a suitable wear *model*. The model should form the basis of predicting the state of the tool accurately and reliably during real-time applications.

Forces are widely known as the most reliable and robust indicators for on-line tool condition monitoring (*OLTCM*). Scheffer and Heyns [6] reported that most *TCM* systems employ forces, *AE* and vibration or a combination of these signals. This fact is also corroborated in Datta et al. [7], Balazinski et al. [8] and the review articles of [2] and Byrne et al. [9]. Only a few of the reported methods rely on vibration, *AE* or electrical signals alone. These signals are mostly used along with the force signals for improving performance of the estimator.

Tansel and McLaughlin [10] adopted a time-series analysis of the forces for wear estimation. Altintas et al. [11] and Altintas and Yellowley [12] developed methods for detection of tool breakage in milling using force signals. Tarng and Lee [13] used the average and the median per tooth with a threshold method to judge the tool condition. Szecsi [14] estimated wear using offline measurement of the axial force and a linear regression model. Datta et al. [7,15] proposed *TCM* strategies for face milling using tri-axes forces along with speed, feed and depth of cut, using an artificial neural network (*ANN*) model. Gong et al. [16] used the coefficients resulting from wavelet transform of the force signals as the recognition parameters for wear states. A new method of feature extraction and assessment using wavelet techniques is introduced in Wu et al. [17] for cutting process monitoring. Zhou et al. [18] proposed *ANN* and wavelet transform-based techniques for *TCM*. Kasashima et al. [19] used discrete wavelet transform (*DWT*) to detect tool failure in face milling operations. Tansel et al. [20,21] applied wavelet transform to compress and encode thrust force signals of micro-drilling operations for detection of severe tool damage just before complete tip breakage occurs. Saglam and Unuvar [22] proposed *ANN*-based *TCM* for face milling using the cutting forces. Ghosh et al. [23] used *ANN*-based sensor fusion approach for estimating wear in face milling. In [3], a combination of tri-axis forces, vibration and *AE* signals are used for effective tool condition estimation. *ANNs* were employed in majority of such works for developing the wear model.

In this paper, we propose an *OLTCM* method that relies on simple time-domain features and multiple linear regression (*MLR*) models using the cutting force signals, yet producing improved performance over earlier methods that use complex models like *ANNs*. This is achieved by:

- adopting new combinations of signal preprocessing strategies to extract simple and robust time-domain features,
- introducing postprocessing techniques to enforce smooth and monotonically increasing nature of the extracted features,
- using sensor fusion in the feature domain to enhance robustness and performance of the estimator,
- developing an estimator of tool wear for specific cutting conditions using the force signals and *MLR* models,
- introducing a statistical model selection criterion for choosing the best model for a given combination of signal processing methods,
- combining the individual models for specific cutting conditions into a unified model, in accordance with proven theory, including the effect of the cutting process variables,
- developing a method for calculation of the probabilistic upper bounds for model errors,
- using laboratory data as well as industrial data to show wide applicability of the proposed methods.

Block diagram of various modules of the proposed method is shown in Fig. 1. The measured force signals are fed in parallel to the three signal *preprocessing units*, employing Strategies I, II and III, respectively. In the