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An approach based on current and sound signals for in-process tool wear monitoring

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Abstract

This paper presents a tool condition monitoring system (TCMS) for on-line tool wear monitoring in turning. The proposed TCMS was developed taking into account the necessary trade-off between cost and performance to be applicable in practice, in addition to a high success rate. The monitoring signals were the feed motor current and the sound signal. The former was used to estimate the feed cutting force using the least squares version of support vector machines (LS-SVM). Singular spectrum analysis (SSA) was used to extract information correlated with tool wear from the sound signal. The estimated feed cutting force and the SSA decomposition of the sound signal alone with the cutting conditions constitute the input data to the TCMS. Again LS-SVM was used to estimate tool condition and its reliability for on-line implementation was validated by experiments using AISI 1040 steel. The results showed that the proposed TCMS is fast and reliable for tool condition monitoring.

Keywords: Tool wear; Flank wear; Motor current; Sound signal; LS-SVM

1. Introduction

Effective, efficient and on-line tool condition monitoring systems (TCMSs) have for more than a decade been gaining an importance in industry and manufacturing research. Researchers have therefore devoted much time and effort in developing TCMSs [1–24]. Nevertheless, only a few reliable TCMSs have as yet been established for industrial application [20]. This is mainly due to the nature of the monitoring signals, stochastic and non-stationary statistical, to the nonlinear relationship between the measured features and tool wear, and to economic reasons. For instance, many sophisticated methods proposed in the literature were designed to obtain a high success rate using multiple sensor signals, but their cost has made them economically non-viable for industrial applications. Other, more simplistic, methods are fast to use but are unfortunately often more sensitive to changes in cutting conditions and less sensitive to tool wear.

In this context, many researchers involved in the development of TCMSs have focused on the problem of extracting the most valuable information from the monitoring signals, so that several new signal processing techniques are currently being investigated [3–7,19], and on trying to achieve more efficient and accurate estimation methods [6,10,11,22,24] in order to achieve effective, efficient and on-line TCMS.

Nowadays, there is also recognition in the manufacturing research community of several needs in the development of a TCMS to be used in real applications, as can be:

- A trade-off between the number of sensors used and their cost, and the performance of the TCMS.
- A sufficiently reduced computing time that allows to change the tool before the wear exceeds the fixed threshold.
- The use of sensors that do not disturb the machining process.

This paper proposes a TCMS for turning based on the above considerations, i.e. trying to achieve a good trade-off

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Nomenclature

F_f	feed cutting force	λ_i	ith eigenvalue of the SSA decomposition
F_t	tangential cutting force	y_i	scalar output
I	total current of the feed motor	$\mathbf{w}$	weight vector
I_0	no-load current of the feed motor	$\varphi(\cdot)$	nonlinear transformation
ΔI	difference between I and I_0	b	bias term
f_r	feed rate	α_i	Lagrange multiplier
f	frequency of the current signal	$K(\mathbf{x}, \mathbf{x}_i)$	kernel function
v_c	cutting speed	e_i	random error
d	depth of cut	C	regularization parameter
$\mathbf{x}_i$	input vector	$\mathbf{\Omega}$	kernel matrix
		V_B	tool flank wear
		σ	kernel function parameter

between cost and performance, with a high reliability and a reduced computing time, and using sensors that do not disturb the machining process. Two monitoring signals, the feed motor current and the sound emitted during machining, are used in its development. Other monitoring signals were considered in the first step, but they were rejected for different reasons that are explained in Section 5. The feed motor current is used to estimate the feed cutting force (F_f), that alone with the features extracted from the singular spectrum analysis (SSA) decomposition of the sound signals are used as the input information to estimate tool condition. The least squares version of support vector machines (LS-SVM)—a modified version of support vector machines—is used as the estimation method in both cases, for the estimation of the feed cutting force and of the tool flank wear (V_B). Finally, the performance of this TCMS is validated against experiment, and the results are compared with previous works in this area.

2. Signal processing

Sensor systems are increasingly playing a pivotal role in advanced automated manufacturing systems. However, it is difficult to decide which are the best parameters to measure and which analytical methods to use for any given system. The cost of the sensor system is another important consideration, and has to be figured out when designing an industrial TCMS. In the present work, the monitoring signals are the feed motor current and the sound signal, for which the sensor costs are relatively low compared with other sensors. The following sections describe the proposed signal processing techniques.

2.1. Feed motor current processing

Monitoring cutting forces is a well-recognized technique to detect tool wear in turning [9,22–24]. The expense of force sensors, however, makes them non-viable for many real applications in which the cost of the TCMS is a priority criterion. Hence, various studies have investigated how to estimate cutting forces indirectly by measuring the motor current signals of machine tools [25–28]. Their findings demonstrate that it is possible to achieve a high correlation between cutting forces and current signals, with the resulting advantage of low cost and of not disturbing the machining process, both of which are important for any practical implementation of a TCMS.

In the present work, the feed motor current is used to estimate the feed cutting force (F_f), since the relative increase of this force with tool wear is greater than that of the tangential cutting force (F_c). The feed force can be expressed as [26–28]:

$$F_f = \Phi(\Delta I, f_r), \quad (1)$$

where ΔI is the difference between the measured value of the total current I (feed motor current) and the no-load current I_0, i.e. $\Delta I = I - I_0$. The value of ΔI can be calculated easily, since I can be measured during machining in the experiments and I_0 is a function of the feed rate (f_r). Indeed, we found that, at a 94.7% confidence level, I_0 (A) varies linearly with the feed rate (mm/min) according to

$$I_0 = -0.0007 f_r + 0.3378. \quad (2)$$

In the present work, we found that for different feed rates the no-load current changes according to Eq. (2), and, following different measurements on the turning center, that at a high confidence level (greater than 99%) the feed rate (mm/min) varies linearly with the frequency of the current signal (f in Hz) according to

$$f_r = 0.3488 f. \quad (3)$$

Therefore, the feed rate can be estimated from the frequency of the motor current signal. A more detailed explanation for an understanding of Eqs. (1)–(3) may be found in [26].

Based on the current measurements (ΔI) and the current frequency (f), the feed cutting force was estimated using LS-SVM to map the functional dependence. The structure of the estimation method is shown in Fig. 1 and in Section 5 the performance of this estimation method is described. In Fig. 2 comparison between I and I_0 is shown.