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Analysis of the structure of vibration signals for tool wear detection

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Abstract

The objective of this work is to develop a reliable tool condition monitoring system (TCMS) for industrial application. The proposed TCMS is based on the analysis of the structure of the tool vibration signals using singular spectrum analysis (SSA) and cluster analysis. SSA is a novel non-parametric technique of time series analysis that decomposes the acquired tool vibration signals into an additive set of time series. Cluster analysis is used to group the SSA decomposition in order to obtain several independent components in the frequency domain that are presented to a feedforward back-propagation (FFBP) neural network to determine the tool flank wear. The results show that this use of SSA and cluster analysis provides an efficient automatic signal processing method, and that the proposed TCMS based on this procedure, is fast and reliable for tool wear monitoring.

Keywords: Singular spectrum analysis; Turning; Flank wear; Tool wear

1. Introduction

Tool wear monitoring has aroused much interest among researchers [1–20]. The international research organization CIRP made an in-depth study of the situation considering the increase in demand for effective industrial tool condition monitoring systems (TCMSs) [21]. The following reasons summarize the interest in tool condition monitoring:

- Unmanned production is only possible if there is a method available for tool wear monitoring and tool breakage detection.
- Tool wear is an important factor directly affecting the surface quality of the machined products and one of the most undesirable characteristics affecting production optimization.
- Today tool changes are made based on conservative estimates of tool life. The consequence is that too many changes are made as the full lifetime of the tool is not taken into account, and hence valuable production time is lost.

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Nomenclature

$\mathbf{F}$	original time series
$\mathbf{F}^i$	principal component i
f_k^i	element k of principal component i
L	window length
N	time series length
$\mathbf{X}$	trajectory matrix
$\mathbf{E}_i$	elementary matrix i of the SVD
λ_i	eigenvalue i of the SVD
w_i	weight corresponding to element i of the inner product
ρ_{ij}^w	w-correlation of components i and j
c_j	center of cluster j
VB	tool flank wear
$\widehat{V}_B$	predicted tool flank wear
$x_x(t)$	longitudinal vibration
$x_z(t)$	transverse vibration
$x_x^i(t)$	Cluster-i component longitudinal vibration $i = 1, 2, 3$
$x_z^i(t)$	Cluster-i component transverse vibration $i = 1, 2, 3$

The result has been that effective and efficient, and on-line TCMSs have been gaining in importance in industry and in manufacturing research for more than a decade.

Tool wear monitoring methods can be classified into two categories: direct and indirect methods. Direct methods are based upon direct measurements of the tool wear using optical [1], radioactive, electrical resistance methods or vision systems [2–6], etc. These methods present the advantage of high accuracy but they have not yet proven to be very attractive either economically or technically. Indirect methods are based on the relationship between tool conditions and measurable signals from the cutting process. Different measurable signals have been used, including force [7–10], vibration [11–15], acoustic emission [16–18], cutting temperature [19,20], etc. for detecting tool wear. However, very few reliable indirect methods have been established for industrial applications. This is mainly because the monitoring signals can be considered stochastic and non-stationary in nature rather than deterministic, and because of the non-linear relationship between the measured features and tool wear.

The common goal of these research lines is to develop reliable and effective TCMS is to develop reliable and effective TCMSs [21]. The dilemma is, however, that the more sophisticated methods need multiple sensor signals and take time to perform the calculations. In addition, their cost makes them economically inviable, and consequently are not suitable for industrial application. On the other hand, simplistic methods, while fast to use, are often insensitive to changes in cutting conditions and unfortunately not very sensitive to tool wear either.

Given this situation, researchers have concurred that efforts in TCMS development should in the future center on trying to extract the most valuable information from the monitoring signals. Indeed, some new processing techniques have demonstrated promising results in the task of signal processing in this area. For example, previous work [22] by the present authors using SSA showed that vibration signals cannot be studied only over a reduced frequency range. Instead, while the information in the vibration signals is contained mostly in the high-frequency components, certain low-frequency components of these signals also contain information on the condition of the tool. This separation was possible since the SSA decomposition is not based on frequency, but on the principal component analysis of the time series.

The goal of the present work is to develop an on-line TMCS for turning, using SSA and cluster analysis to process vibration signals during a turning process. The objective can be summarized as to obtain a low cost and high average success rate TCMS using a small number of sensors to reduce the response time for optimizing the design of the TCMS.