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Cutting tool wear classification and detection using multi-sensor signals and Mahalanobis-Taguchi System

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ABSTRACT

The detection of cutting tool wear during a machining process is one of the most important considerations in automated manufacturing systems. This study presents a new approach for classification and detection of tool wear in milling process using multi-sensor signals and Mahalanobis-Taguchi system (MTS). The MTS is one of the decision making and pattern recognition systems frequently used to solve a multidimensional system and integrating information to construct reference scales by creating individual measurement scales for each class. These measurement scales are based upon the Mahalanobis distance (MD) for each sample. Orthogonal arrays (OA) and signal-to-noise (SN) ratio are used to identify variables of importance, and these variables are used to construct a reduced model of the measurement scale. Mahalanobis distance (MD) values were calculated based upon the feature data set extracted from the six channels of machining signals under sharp cutting tool, medium wear and critical wear conditions. Experimental data of end milling AISI P20+Ni tool steel is used to construct Mahalanobis space, to optimize and validate the system. The results show that the medium wear and critical wear stages of cutting tool conditions can be successfully detected in real-time.

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1. Introduction

Tool wear is a normal phenomenon in the machining process, but is a detrimental factor that affects the quality and tolerance of machined parts. When the cutting process continues with a worn tool, it can cause a machine to breakdown; if the cutting tool suddenly fails. Therefore, tool wear should be measured periodically to avoid severe wear occurred in machining operation. Visual inspection of tool wear by using a tool maker's microscope or charged-couple-device (CCD) camera is a traditionally-based indirect method for tool wear measurement [1]. This has the advantage of capturing actual geometric changes arising from the edge of the cutting tool wear. However, direct measurement of tool wear is very difficult to obtain due to the continuous contact between the cutting tool and machined work part. It is made almost impossible by the presence of cutting fluid. In order to determine the tool wear state without disturbing the machining process, it can be performed using an indirect method of tool wear measurement by utilizing the sensor systems. In the indirect method, the tool wear is not measured directly, but detected and estimated from the measurable signal features which are obtained in real-time.

Recently, research on tool wear condition monitoring has gained increased interest and many researchers have studied tool wear monitoring during the milling process using various machining signals, such as cutting forces, vibrations, acoustic emissions, sound, torque, current, power of the spindle motor and temperature [2]. These signals correlate with the changes of tool wear, and can be used as a parameter to determine the state of the cutting tool. However, tool wear is a complex nonlinear phenomenon, and using a single sensor system for condition monitoring becomes less accurate for detecting wear changes at the edge of the tool. Tool wear changes are very small; thus making it difficult to determine whether a small change is a result of wear of the tool or a change in cutting condition parameters. Therefore, the use of a multi-sensor system is better at detecting the state of the cutting tool during the machining process [3].

A multi-sensor fusion system requires a pattern recognition algorithm to combine a variety of information from multiple sensors. Many previous researchers have used a tool monitoring system with multi-sensor fusion using Artificial Neural Network (ANN) [4], statistical methods or linear regression [5], fuzzy logic and Adaptive Network-based Fuzzy Inference System (ANFIS) [6] and other sensor fusion methods [7]. Although there are many methods proposed for tool wear detection, none of the Mahalanobis-Taguchi System (MTS) approach has been used as a

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Nomenclature

a_p	axial depth of cut, mm
a_e	radial depth of cut, mm
A_z	vibration in vertical direction, m/s^2
f_z	feed rate, mm/tooth
F_c	main cutting force, N
F_t	thrust force, N
F_{cN}	perpendicular cutting force, N
K	Kurtosis
MTS	Mahalanobis-Taguchi System
MD	Mahalanobis distance
MS	Mahalanobis space
MP	maximum peak
OA	orthogonal array
P	power spectral density peak
RMS	root mean square
RMSP	root mean square in power spectral density
SkP	skewness in power spectral density
Sk	skewness
STD	standard deviation
STDP	standard deviation in power spectral density
STP	sum of total power density
SN	signal to noise ratio
T_q	torque, Nm
T_m	tool tip temperature, °C
VB	flank wear land, mm
v_c	cutting speed, m/min
Z^∞	I-kaz coefficient

decision-making system in milling process. In the previous study, MTS was only used as a multi-sensor based decision-making prognostics tool to monitor pump failure [8], the condition monitoring of motor bearings [9], the damage detection of cooling fans [10] and the prediction of drill-bit breakage during the drilling process [11].

This study implements a Mahalanobis-Taguchi System (MTS) based approach in multi-sensor data fusion for the classification and prediction of cutting tool states in the milling process. Moreover, a wireless multi-sensor on a rotating tool is applied to collect six machining sensory data values as input variables for MTS. The signal comprises the cutting force in three directions, torque, vibration and tool tip temperature. Some of the features that can reveal the characteristics of the time and frequency domains of multi-sensor signals are extracted. By using experimental end milling data, Mahalanobis Space (MS) for normal index of cutting tool state as reference, is created using Mahalanobis distance (MD) values. The Taguchi method is employed to optimize the prediction system using Orthogonal Array (OA) and signal-to-noise ratio (SN). Then, a Mahalanobis space is reconstructed using only the useful features.

2. Experimental procedure

2.1. Milling process

In order to develop a real-time tool wear prediction system, linear end milling tests were performed on a CNC milling machine (DMC 635 V Ecoline) under dry cutting conditions. The cutting tool used was a coated carbide insert (AXMT170504PEER-G) with ACP200 grade. This grade of carbide tool is suitable for heavy duty cutting of steel and stainless steel. The machining signals, comprised of main cutting force (F_c), thrust force (F_t), perpendicular cutting force (F_{cN}), torque (T_q), vibration (A_z), and tool tip temperature (T_m), were collected by a wireless multi-sensor system. The force-torque strain gauge-based and wireless embedded sensors were developed by Rizal et al. [12,13]. The signals were recorded at a sampling rate of 5 kHz, and then analysed by a computer for the feature extraction process. A schematic of the wireless multi-sensor integrated rotating tool and experimental set-up is shown in Fig. 1.

End milling was performed on AISI P20+Ni tool steel with a hardness of 35 HRC and a composition of 0.37% C, 0.30% Si, 1.40% Mn, 0.01% S, 2.00% Cr, 0.20% Mo, and 1.00% Ni. This material is popularly used to make plastic injection moulds, extrusion dies, blow moulds, tooling designs, and other various components. The

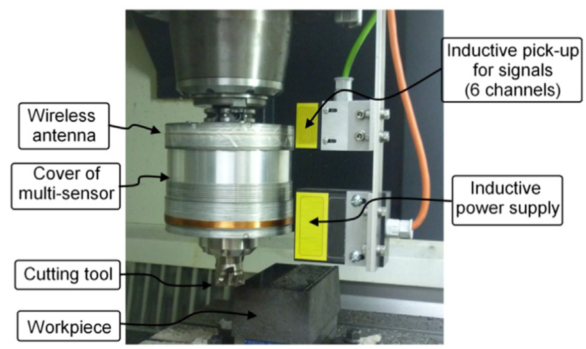

Fig. 1. Experimental and multi-sensor system set-up.

Table 1
Cutting conditions of the milling process.

Parameters	Low (1)	High (2)
Cutting speed v_c (m/min)	200	375
Feed per tooth, f_z (mm/tooth)	0.10	0.20
Radial depth of cut, a_e(mm)	0.4	0.6

dimensions of the material were 170 mm length, 100 mm width and 80 mm height so each length of cut was 170 mm. A (2^3) full factorial design was employed for each cutting tool used as shown in Table 1. A constant axial depth of cut (a_p) of 1.0 mm was used for all combinations of experiments.

During the milling process, a new tool insert was used for each set of combination parameters. For every 510 mm movement of the cutting tool in cutting the workpiece, the tool was removed periodically from the tool holder then the flank wear was measured using a Mitutoyo toolmaker's microscope equipped with a graduated scale in mm. The measured parameter to represent the progress of tool wear was flank wear width, *VB*. By using a standard recommended value in defining a tool life criterion based on ISO 3685:1993, the milling operation was stopped, and the cutting tool insert was discarded when *VB* reached 0.3 mm. The totals of the cutting tool insert used in this study were nine pieces. The ranges of flank wear values were divided into three classifications, normal wear (*VB* = 0 – 0.15 mm), medium wear (*VB*=0.15 – 0.25) and critical wear (*VB*=0.25 – 0.35 mm).

2.2. Feature extraction

The feature extraction aimed to reduce the dimensions of the raw machining signals, while maintaining the relevant

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