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Angular approach combined to mechanical model for tool breakage detection by eddy current sensors

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ABSTRACT

The paper presents a new complete approach for Tool Condition Monitoring (TCM) in milling. The aim is the early detection of small damages so that catastrophic tool failures are prevented. A versatile in-process monitoring system is introduced for reliability concerns. The tool condition is determined by estimates of the radial eccentricity of the teeth. An adequate criterion is proposed combining mechanical model of milling and angular approach.

Then, a new solution is proposed for the estimate of cutting force using eddy current sensors implemented close to spindle nose. Signals are analysed in the angular domain, notably by synchronous averaging technique. Phase shifts induced by changes of machining direction are compensated. Results are compared with cutting forces measured with a dynamometer table.

The proposed method is implemented in an industrial case of pocket machining operation. One of the cutting edges has been slightly damaged during the machining, as shown by a direct measurement of the tool. A control chart is established with the estimates of cutter eccentricity obtained during the machining from the eddy current sensors signals. Efficiency and reliability of the method is demonstrated by a successful detection of the damage.

1. Introduction

With High Speed Machining (HSM), cutting speeds and feedrates were significantly increased over the last decades. It results in higher productivity and better product quality. But, in the same time, risks of severe damages of workpieces or machine-tool components were also significantly increased. Indeed, if problems occur during machining, the operator reaction time has become insufficient and the significant speeds will cause serious damages. This is the reason why Tool Condition Monitoring (TCM) systems are needed. Commercial systems are proposed for mass production [1]. They are based on the teach-in method: a few workpieces need to be machined in order to set the thresholds of breakage detection. This is incompatible with flexible manufacturing systems.

Abundant literature is proposed. However, there is a lack of reliable TCM solutions for small batch and one-off productions in milling [2]. It is mainly due to misinterpretations between simple transient cuts and real incidents. Yet, reliability is the major issue according to the industrial end-users [3].

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Most of the methodologies are essentially based on signal processing techniques, such as statistical analysis in time or frequency domain, wavelet analysis, neural networks and fuzzy logic [3–5]. Other authors combine signal processing to mechanical model of the machining operation. Notably, the fact that a damage tooth removes less material leads to the monitoring of each tool tooth individually [6–8]. Few works deal with angular approach. It can be mentioned that Girardin et al. [9] studied the instantaneous angular speed from spindle encoder signal. Besides, Lamraoui et al. [10] introduced new criteria based on the cyclostationarity principles for the monitoring of chatter and tool wear.

TCM generally rely on the measurement of cutting force, vibration, spindle power, acoustic emission or tool temperature. Accuracy and bandwidth of forces issued from a dynamometer table are interesting but it is incompatible with industrial applications. Thus, alternatives for indirect estimate of cutting force are proposed: force ring at spindle housing [11] and capacitance [12] or eddy current [13–15] displacement sensor close to spindle nose. The latter requires signal processing because simple RMS (Root Mean Square) values are lowly sensible to cutting forces. The effects of thermal dilatation and centrifugal force can be removed implementing sensors on each side of the spindle in the two radial directions [15]. The bandwidth can be extended by disturbance Kalman filter technique so as to compensate distortions due to the three main eigenfrequencies of the tool-spindle system [12].

The paper proposes a new complete approach of TCM in milling. Firstly, a versatile in-process monitoring system is introduced for reliability concerns. A criterion is established combining mechanical model of milling and angular approach. It estimates the radial eccentricity of tool teeth. Secondly, a solution is presented for the estimate of cutting force using eddy current sensors implemented close to spindle nose. A signal processing methodology that analyse signals in the angular domain, notably by synchronous averaging technique, is proposed. Validity of the approach is investigated through a comparison with cutting forces issued from a dynamometer table. Lastly, the method is implemented in an industrial case of pocket machining operation in order to investigate the efficiency and the reliability of the method.

2. Monitoring of cutter eccentricity

Tool breakages are unpredictable and may lead severe consequences. This is the reason why the aim of the approach is to detect small damages as early as possible, in order to be able stop the machine-tool before a catastrophic failure.

2.1. Criterion principle

It is proposed to characterize the tool condition by an estimate of the radial eccentricity of teeth. Indeed, if a new endmill is considered, a radial eccentricity of a few hundredth millimetres can be measured for each cutting edge, once the tool clamped into the spindle. The radial eccentricity of teeth distributes the material to be removed unevenly between the teeth. Cutting forces are affected by the variations of chip thickness (Fig. 1a). This distribution is changed after the partial breakage of one of the cutter: the chipped tooth removes less material and the following one has to compensate, removing more material (Fig. 1b).

The estimate of cutter eccentricity seems interesting for cutter breakage detection, notably in the case of low defects. To do so, the contribution of each tooth to the cutting force is investigated. In order to know which tooth produced a given force peak, an angular approach is suitable.

2.2. Cutting force model

In presence of radial eccentricity of the teeth, Kline and DeVor [16] expressed that the chip thickness h_c removed by a given tooth j is given by:

$$h_{cj}(\varphi) = f_z \sin\varphi_j + \varepsilon_j - \varepsilon_{j-1} = f_z \sin\varphi_j + \Delta\varepsilon_j \tag{1}$$

$$\varphi_j = \varphi - \frac{2\pi}{Z} j \tag{2}$$

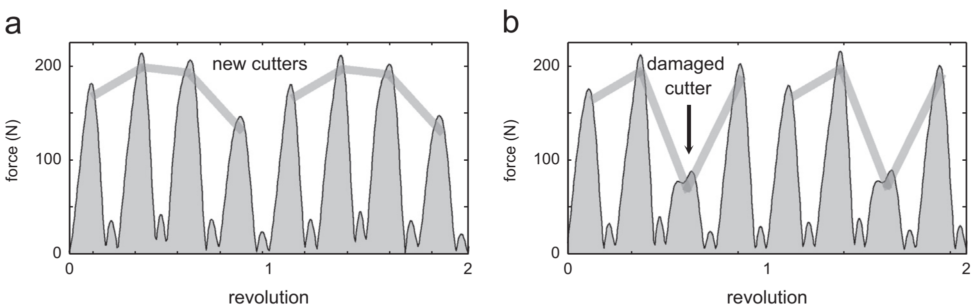

Fig. 1. Effect of the cutter eccentricity of tool teeth on cutting force.