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Detecting catastrophic failure events in large-scale milling machines ☆

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ABSTRACT

Catastrophic failure in milling machines is a major concern for manufacturers employing these processes in the production of vital parts. Tool chipping or breakage can lead to machine breakdown, which is a costly consequence in today's highly demanding industry. This paper introduces a novel and practical concept for the detection of failure events in milling. Using the historic data of the machining process (a collection of average spindle power signals) the detection algorithm computes discrete probability distributions representing the power consumption profile along finite synchronous process segments. These distributions play a central role in identifying failure; an unexpected occurrence in the process. Using a combination of real data collected from a powerful industrial milling machine and failure disturbance simulations, concept testing results illustrate that the proposed algorithm is capable of promptly detecting catastrophic faults while keeping unnecessary interruptions to the machine operation to a minimum.

1. Introduction

The effective management of the risk of failure in high-speed milling processes is becoming increasingly critical in today's highly competitive industry. Risk mitigation is the most common technique in the management of risk in machining. Starting with the highest impact events, potential causes of failure are considered, analysed and maintained in order to reduce the probability of occurrence. Mitigation measures require the installation of a comprehensive management process to ensure a well-maintained machine and a reliable machining process. All constituents of the machining process—the machine, the spindle, tooling and setup—are measured, analysed and maintained. Hidden dangers exist in adopting mitigation as the sole approach to risk management. This is increasingly so in powerful large-scale machines where it is impossible to mitigate for all the sources of failure. Here, the term 'large-scale' refers to the size of the machine and its operation: time consuming processes involving a powerful high-speed spindle, large tools and workpieces. The Ingersoll profiler is an example of a large-scale milling machine. The machine is employed in the production of Aircraft wing spars for a number of Airbus aircraft models. High-power (up to 80 kW), high-speed (up to 40,000 rpm) spindles provide high material removal rates. A typical machining process run on the Ingersoll may last for more than 4 h. In such a powerful machine, the impact of failure is catastrophic, and a contingency detection system is required as an additional risk management measure. Such systems halt the machining process once a failure event is detected, preventing damage to any part of the machine tool.

In large-scale machines, a contingency protection system must cope with the special challenges associated with long machining processes. Huge amounts of data are processed and stored in these processes. As a result, the choice of the sampling rate of the monitoring system and the complexity of the detection rules must be considered carefully. Additionally, phase synchronisation of the condition monitoring signals is harder to achieve in long processes. A mechanism is required to ensure that the detection process is in phase with the monitoring signal at all stages throughout several hours of continuous machining. Furthermore, high levels of variation in the acquired condition monitoring signals are a consequence of the wide range of dynamic forces exerted in large-scale machining. The variation in data due to the transitional effects of moving from one type of cut to another presents a particular challenge in the design of a successful fault detection strategy. In its extreme form, a transient phase takes the tool from a cut in air, as illustrated in Fig. 1, into a steady-state material cut, where the exerted forces and the power consumed are particularly high.

For example, in making the transition described in Fig. 1, the Ingersoll spindle is moved from free rotation in air to consuming more than 50 kW, typically. At transient points, the condition monitoring signal may take a wide range of values depending on the setup of the monitoring system. Furthermore, a phenomenon known as 'shock loading' produces a signal burst as a direct

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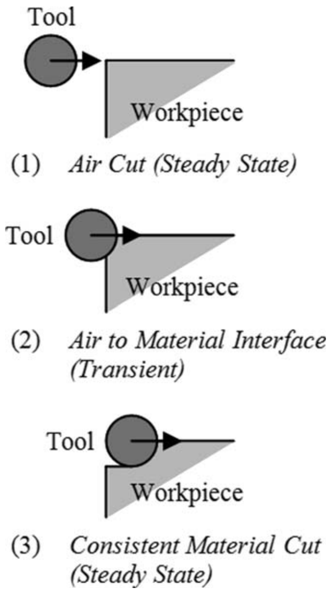

Fig. 1. The Position of the tool in relation to the workpiece during transient blocks at the start of a machining cut.

reaction to the slope of change [1,2]. These signal burst are a feature in transients in general milling operations. In large-scale processes, it is difficult to distinguish between transient power spikes and those generated as a result of failure occurrences.

1.1. *Milling machine protection in the literature and industry*

Tool monitoring techniques for detecting failure events in the milling processes have been widely researched. Yesilyurt [3] and Groekar et al. [4] utilise vibrations and acoustic emission signals, respectively in the identification of faults in small-scale milling operations. The high noise sensitivity of these signals limits their use in cutting processes [5], especially large-scale milling applications. Cutting force and torque measurements are more widely used in failure detection in milling. The works of Lee et al. [6], Huang et al. [7], Romero-Troncoso et al. [8] and Ritou et al. [9] demonstrated notable successes. Being readily accessible by measuring the spindle motor current, the spindle power signal seems a more convenient alternative and a popular choice in the literature and industry. Many authors, such as Jantunen [5] and Bassiuny et al. [2], complain that the spindle power signals tend to mask gradual deterioration in condition of the cutting tool (e.g. wear). However, events such as tool chipping or breakage which are largely associated with catastrophic failure are readily detected [10]. Investigations in drilling [11] and turning [12] have been reported for the use of a spindle power sensory signal for detecting these events.

In the literature, many applications of the power signal in failure detection are reported for milling. Axinte et al. [12] showed that a power signal can be employed to detect chipping and breakage per cutting tooth providing a reasonably high acquisition sampling rate. Due to the intermittent characteristics in milling, the power signal showed low sensitivity on the detection of small events such as light chipping of the cutting edge. Although their experiments have limited success in milling, better results are achieved in turning operations. In 1996, Jones and Wu [13] filed a patent describing a system which uses the spindle power signal for active detection of failure events. Their system requires a learning cycle and high sampling rate. The mathematical operations of a wavelet packet transform is utilised to restructure the power consumption signal and calculate a cut-off power threshold. In its monitoring mode, the system counts the number of threshold crossings before offering a delayed response. Li et al. [14] attempt to improve on earlier efforts in failure detection in milling using wavelet analysis. However, by his later work with Bassiuny [2], Li highlights three major drawbacks: shift sensitivity, poor directionality and the absence of phase information. These make it unsuitable for large-scale operations as the length of the processes requires accurate signal phasing and a fairly speedy decision-making process. Bassiuny et al. [2] offer an alternative system which employs the Hilbert–Huang transform and smoothed non-linear energy operator. Using a reasonable high sampling rate, the technique employed decomposes the signal into small segments of 0.064 s long, within which independent detection decisions are made. Their results demonstrated an efficient detection performance in identifying failure pulses in a milling power signal. Nonetheless, their simulation and experimental results are limited to low-power, short and consistent milling up-cuts. They offer no indication of how the phase synchronisation of the detection increments can be preserved in a long machining process. Furthermore, a large-scale process consists of a long series of different types of milling cuts. Using their proposal, these would require a significant computational effort and analysis to address. Table 1 compares some of the more recent attempts where power signals are used for detecting failure events in milling processes as presented by Jones et al. [13], Axinte et al. [12] and Bassiuny et al. [2].

1.1.1. *Commercial failure detection systems*

In 2005, Omative Systems [15], a machining solutions company, developed a piece of software for detecting unexpected events in machining processes. The software uses a load band monitoring technique in which an upper permissible power boundary is calculated during a learning cycle. The software can only operate for machining processes, which run for a total of 10 min or less [15]. It is the authors' opinion that the short operating time of the Omative system is a result of the use of machining time as the primary synchronisation mechanism between the detection band and the live power signal. The detection strategy employed in the Omative System, as well as its inability to address the needs of large-scale operations, is typical of commercially available failure detection systems. The latest review of practical condition monitoring systems is conducted by Jemielniak [16]. He considers a range of commercially available systems provided by the industry leading suppliers of condition monitoring sensors and systems, namely Brankamp, Kistler, Montronix, Nordmann and Prometec. Different detection strategies are employed in systems developed by each supplier:

- A *simple fixed limits* strategy uses a rigid threshold and would only work for a continuous cutting process where parameters such as the depth of cut remain constant [10].

Table 1
Advantages and disadvantages of some of the systems using the spindle power signal for fault detection.

System	Advantage(s)	Disadvantage(s)
1996: Jones et al. [13]	**Suited for milling**	**Complicated computational analysis**
	Sensitive to failure	**Long response window**
2004: Axinte et al. [12]	Simple experimental setup	Limited success in milling
	Independent of NC Programme	Very high sampling rate (>2 kHz)
2007: Bassiuny et al. [2]	**Ideal for milling**	**Difficult to synchronise in long processes**
	High sensitivity to failure	**Requires sig. computational effort**
	Short response times	**High sampling rate (>1 kHz)**