Mechanical Systems and Signal Processing 44 (2014) 72–85

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Indicators for monitoring chatter in milling based on instantaneous angular speeds

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ARTICLE INFO

Article history:
Received 30 April 2012
Received in revised form
22 April 2013
Accepted 2 May 2013
Available online 15 June 2013

Keywords:
Chatter indicators
Milling
Angular cutting force
Instantaneous angular speed
Spindle encoder

ABSTRACT

The detection of chatter is crucial in the machining process and its monitoring is a key issue to ensure a better surface quality, to increase productivity and to protect both the machine and the workpiece. An investigation of chatter monitoring in the high speed machining process on the basis of the analysis of cutting forces and instantaneous angular speeds (IAS) in the angular domain is presented in this paper.

Experimental cutting tests were carried out on slot milling operation of aluminum alloy. Our experimental set-up allows for, on the one hand, the acquisition of the angular cutting force and, on the other hand, the measurement of IAS. The latter is computed from the signal delivered by the standard encoder mounted on the spindle motors. The same signal is used as a base for synchronous angular sampling.

The acquisition methodology is described and discussed in this paper. Data analysis confirms the relevance of cutting forces for chatter monitoring and the good correlation between cutting forces and IAS of the spindle. Two chatter indicators are developed in the angular domain from the periodic and residual parts of angular speed and cutting force signals. They are used successfully for the detection of the chatter phenomenon. The indicator based on IAS is very convenient because it does not require additional sensors and can be realized without increasing the cost of the manufacturing system.
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1. Introduction

In manufacturing, current evolution towards productivity improvement and cost effectiveness require monitoring of machining to survey spindle bearing wear, tool wear and self-excited vibrations that produce chatter. Unfortunately, the issue of downtime continues to plague the industry. Unscheduled downtime is costly, not only in terms of time lost, but also in terms of damage to tools, machines or workpieces. Estimates state that the amount of downtime due to cutter breakage on an average machine tool is around 7%, while others estimate it is closer to 20% [1–3]. Even if the tool does not break during machining, the use of damaged cutters can stress the machine–tool system and cause a loss of quality in the finished workpiece. In fully automated or lightly staffed machining environments, the timely detection of the wear (bearing or tool) or chatter state of cutting tools and the recognition of their damage is seen as essential to the improvement of productivity

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http://dx.doi.org/10.1016/j.ymssp.2013.05.002

and cost effectiveness. It has been predicted that an accurate and reliable tool condition monitoring system could result in a cutting speed increase of 10–15%, reduction in downtime by allowing maintenance to be scheduled in advance, and an overall increase in savings of 10–40% [4].

The detection of chatter and tool wear becomes crucial for maintaining efficient machining process. Chatter is a self-excited type of vibration that can arise in the machining process for specific combinations of cutting parameters, depth of cut and spindle speed. Various physical mechanisms can cause chatter; for example, the friction between the tool and workpiece, the thermodynamics of the process or mode coupling [5]. Chatter due to these physical mechanisms is often called primary chatter. Secondary chatter, which is considered to be one of the most important types of chatter, is due to the regeneration of waviness of the workpiece surface [6]. This type of chatter has been investigated in several studies since the late 1950s [7,8] and it will be considered in this paper.

Consequently, the online detection of these phenomena allows for determining suitable conditions to maintain a good part quality in production, but it also requires methods for monitoring the machining centers. In machining, an efficient monitoring system can maintain machine tools in stable condition without chatter and detect the occurrence of wear (tool or spindle bearings). Several sensors (dynamometer, accelerometers, acoustic emission and/or electrical power sensors) have been used for chatter detection in milling [9]. In many studies, researchers have investigated the application of the dynamometer sensor for chatter detection in machining operation. Dimla reviewed some methods that employed the static and dynamic cutting forces for tool wear monitoring [10]. Once the sensors have been chosen for monitoring and the signals have been acquired, the problem to be surmounted would be to extract suitable features that are well correlated with the anomaly in order to achieve a good detection of the defect [2]. Various methods have been developed in order to identify chatter. Scalar time descriptors and spectral analysis are often employed to extract information on the state of the cutting tools.

In the time domain, Nayfeh and Balachandran [11] analyzed the stability of milling operation by using a Poincaré section and a so called bifurcation diagram is shown to identify the transition from stable cutting to chatter. Insperger [12] analyzed system stability by modeling machine tool and developing differential equations. Bayly et al. [13] used the variance indicator in time domain to determine stability boundary, and Smith and Tlusty [14] proposed the peak-to-peak force method to identify the limits of stability. Advanced techniques have also been used, such as multilayer perceptrons or back propagation neural networks [15] and Information Theory [16].

However, the most common methods of analysis of force signals have been conducted in the frequency domain. Li et al. [17] proposed a frequency domain approach based on the cross-coherence of two perpendicular acceleration signals to detect wear and chatter. Zaghbani et al. [18] used frequency descriptors to analyze the stability in robotic high speed machining of aluminum alloys. Some of the earliest works used the Short Time Fourier Transform [19] or the wavelet transform [20,21] for chatter detection.

Unfortunately, most rotating machinery undergoes nonstationary operations, while most of the usual chatter detection methods are based on the assumption of stationarity. In fact, even under cutting conditions of pseudoconstant operations (speed, torque, temperature etc.), repetitive shocks and friction due to action of the tool and the workpiece (nonheterogeneity, etc.) during machining exhibit nonstationary phenomena during each cycle of the machine. The nonstationary nature of the signals, the sensitivity of the features being measured in the process to changes in cutting condition, and the nonlinear relationship of these features to the defect makes this a nontrivial task [22]. The study of cyclostationarity of the vibratory signals for rotating machinery allows for taking into account the random effects that can be produced during each tool revolution. The statistical properties of machine–tool vibratory signals are periodic with regard to the basic cycle. This periodicity is inferred by the cyclic operation of the machine. Angular sampling techniques have widely evolved to extract all relevant measurements information on several types of rotating machines (internal combustion engines, electric motors, power transmission by gears, machine tools). The angular approach allows for characterizing the periodic excitations of rotating machinery even for systems operating at variable speeds. The development of new formalisms based on angular description constitutes also a real opportunity for modeling tools to describe and control the vibratory behavior of rotating machines. Desbazeille et al. [23] used the crankshaft angular speed variation for diagnosis of large diesel engines. Stander [24] used the fluctuations in instantaneous angular speed (IAS) for monitoring a gear shaft and detecting deteriorating gear fault conditions, while introducing a distinction between cyclic stationary load modulation and noncyclic stationary load modulation. Remond and Mahfoudh [25] started from multiple IAS measurements to compute gear transmission errors and finally used specific and single angular sampling for detecting faults in a gear box transmission by using different cyclic means in the angular domain.

Cyclostationarity has also been used successfully for observing defects in machining. For example, Takata et al. [26] described a monitoring method of multiedge tools by means of fluctuation signals of spindle rotational speed. Girardin et al. [27] developed an original approach based on the IAS measured from an encoder for tooth breakage detection and wear monitoring in milling processes. New vectorial indicators based on the property of cyclostationarity for identifying the angular position where a specific phenomenon occurs have been developed [1,28,29]. These angular indicators were used for the detection of chatter and tool wear.

This paper aims to investigate the efficiency of Short Angular Fourier Transform (SAFT) methods in the angular-frequency domain and the development of chatter indicators for diagnosing chatter in high speed milling process. The method is based on the measurement of angular cutting force characteristics and IAS analysis. Since good correlation between cutting forces and IAS of the spindle has been shown, the future aim is to only use the IAS measurement for industrial applications.

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