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Cyclostationarity approach for monitoring chatter and tool wear in high speed milling

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ABSTRACT

Detection of chatter and tool wear is crucial in the machining process and their monitoring is a key issue, for: (1) insuring better surface quality, (2) increasing productivity and (3) protecting both machines and safe workpiece. This paper presents an investigation of chatter and tool wear using the cyclostationary method to process the vibrations signals acquired from high speed milling. Experimental cutting tests were achieved on slot milling operation of aluminum alloy. The experimental set-up is designed for acquisition of accelerometer signals and encoding information picked up from an encoder. The encoder signal is used for re-sampling accelerometers signals in angular domain using a specific algorithm that was developed in LASPI laboratory. The use of cyclostationary on accelerometer signals has been applied for monitoring chatter and tool wear in high speed milling. The cyclostationarity appears on average properties (first order) of signals, on the energetic properties (second order) and it generates spectral lines at cyclic frequencies in spectral correlation. Angular power and kurtosis are used to analyze chatter phenomena. The formation of chatter is characterized by unstable, chaotic motion of the tool and strong anomalous fluctuations of cutting forces. Results show that stable machining generates only very few cyclostationary components of second order while chatter is strongly correlated to cyclostationary components of second order. By machining in the unstable region, chatter results in flat angular kurtosis and flat angular power, such as a pseudo (white) random signal with flat spectrum. Results reveal that spectral correlation and Wigner Ville spectrum or integrated Wigner Ville issued from second-order cyclostationary are an efficient parameter for the early diagnosis of faults in high speed machining, such as chatter, tool wear and bearings, compared to traditional stationary methods. Wigner Ville representation of the residual signal shows that the energy corresponding to the tooth passing decreases when chatter phenomenon occurs. The effect of the tool wear and the number of broken teeth on the excitation of structure resonances appears in Wigner Ville presentation.

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1. Introduction

1.1. Chatter

Chatter is a self-excited type vibration that can arise in the milling process at specific combination of cutting parameters, depth of cut and spindle speed. Various physical mechanisms can cause chatter such as the friction between the tool and the workpiece, the thermodynamics of the process or the mode coupling [1]. 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 regeneration of waviness of the workpiece surface [2]. This type of chatter has been investigated in several studies since the late 1950s [3,4]. An experienced machine–tool operator can often detect a chatter phenomenon due to the noise produced during cutting and the bad characteristics of surface finish.

Some factors like the need for automation of damage detection and the avoidance of human error have motivated research into more advanced detection methods. Consequently, different approaches have been developed. Sims [5] made some attempts to classify these various techniques. Techniques based on Fast Fourier Transform (FFT) are used to determine the information in frequency domain of the measurement signal such as the Power Spectral Density (PSD) with Welch's technique [6]. This technique can be applied to a variety of measurement signals, such as workpiece or tool acceleration/velocity/displacement, or force reading from a dynamometer. A microphone can also be used to detect and control the chatter phenomena [7]. Li et al. [8] have proposed a frequency domain approach based on the cross-coherence of two perpendicular acceleration signals to detect wear and chatter. Zaghbani et al. [9] used frequency descriptors to analyze the stability in robotic high speed machining of aluminum alloys. A major drawback of frequency domain techniques is that they offer no information in the time domain. Consequently, the time–frequency analysis comes to reconcile the advantages of both frequency and time analysis by characterizing the signal at time and frequency domain. This provides solution to separate near vibratory signatures that manifest themselves in frequency or in time domain and also compromise between the frequency resolution and the temporal resolution.

In time domain, Nayfeh and Balanchandran [10] analyzed the stability of milling operation using Poincaré section. They used bifurcation diagrams for identifying the transition from stable cutting to chatter. Insperger [11] analyzed the stability of systems by studying differential equations modeling tool dynamics. Bayly et al. [12] used a variance indicator in time domain to determine stability boundary. Smith and Tlusty [13] proposed a peak-to-peak force technique to identify the stability limits. Some of the earliest works use wavelets in solving chatter problem, this approach emphasizes the trade-off vs. frequency resolution [14]. Advanced techniques are also used, such as multi-layer perceptrons or back propagation neural network [15] and information theory [16].

1.2. Tool wear

Tool wear can occur progressively on the tool's face due to the contact with the chip or on the flank due to the friction between the tool and the workpiece material. Some authors [17] have presented an investigation of tool wear monitoring in the high speed machining process based on the analysis of different signals signatures in the time and frequency domain. Prickett and Johns [18] discussed the application of condition monitoring techniques to the detection of cutting tool wear and breakage during the milling process. Dimla [19] presented a review of some of the methods that have been employed in tool condition monitoring. A particular attention is paid to the manner in which sensor signals from the cutting process have been exploited and used in the development of tool condition monitoring systems. Altintas [20,21] developed many indicators for detecting tool breakage, such as differences of mean forces between successive teeth and relative variations of mean tooth forces between two consecutive revolutions. Other methods based on indirect estimation of cutting force have been developed such as the measurement of feed motor and spindle current [22] and power [23].

However these methods suffer from the available bandwidth of the sensors and the stationary nature of processes is generally supposed in signal processing. Because of the varying nature of physical phenomena, time-invariance and the notion of stationarity are often violated in practice. Therefore, the study of time-varying systems and non-stationarity processes is well motivated and the assumption of cyclostationary processes which are characterized by the periodicity they exhibit in their statistical properties is more suitable. An overview of cyclostationarity signal analysis and applications are presented in the next section.

1.3. Cyclostationarity

Cyclostationary signals occur in several physical problems leading phenomena and operations of periodic nature: communication [24], geophysical and atmospheric sciences [25,26], econometrics [27] and last few years in rotating machines [28,29]. Cyclostationarity is a property that characterizes stochastic processes whose statistical properties periodically vary with respect to some generic variables. In sixties, Gladysev introduced key representation of cyclostationary time series [30]. In 1969, Hurd's thesis introduced a continuous-time cyclostationary process [31]. Since 1975, Gardner and Franks have contributed to the theory of continuous-time cyclostationary signals, and especially their applications to communication engineering [32]. Gardner [33] has adopted a “non-probabilistic” viewpoint of cyclostationarity. Recently, the domain knew an increasing interest, mainly because of its applications in telecommunication. The cyclostationarity allowed improving the precision and the reliability of algorithms existing