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Development of an intelligent multisensor chatter detection system in milling

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ABSTRACT

The development of a chatter detection system based on multiple sensors and suitable for application in industrial conditions was investigated in this paper. The signals obtained from a monitoring system composed of accelerometers mounted on the machine head and an axial force sensor were processed by using advanced signal analysis techniques such as wavelet decomposition. The statistical parameters obtained from wavelet decomposition were used to detect chatter by using an artificial intelligence classification system based on neural networks. The outputs of the neural networks for each sensor signal were further combined by using different strategies in order to obtain a multisensor chatter indicator. The performances of different strategies were evaluated by using experimental data, evidencing that it is possible to obtain an efficient chatter detection system both in terms of accuracy and of robustness against malfunctions and compatible with modern machine tool operation and automation.

1. Introduction

Nowadays, the need of increasing the productivity and reducing the production costs is pushing towards fully automatic, unmanned machining centers or intelligent machining systems. In the new conditions, machine tool should be able to perform automatically the following activities: collision detection and prevention, tool condition monitoring, optimization of cutting parameters, detection and suppression of chatter vibrations. Specifically, the integration of chatter detection systems into control unit of machine tool would be a great improvement in precision machining.

Chatter is a vibrational phenomenon which arises in machining processes for specific combinations of cutting parameters. It consists of unstable, chaotic motions of the tool or of the workpiece and by strong, anomalous fluctuations of cutting forces. The onset of chatter may cause abnormal tool wear or tool breakage, damage of both the tooling structure and the spindle bearings, poor surface roughness and poor dimensional accuracy of the workpiece. Chatter is mainly caused by the regenerative effect, which is an unstable behaviour of the uncut chip thickness due to combination of the vibrations with the waviness produced by the previous tooth passage [1,2].

Many researchers focused on the development of analytical and numerical methods for the prediction of chatter [3,4]. However, the applicability of these methods in industrial conditions is limited, since they require accurate modeling of machining system dynamics and of cutting forces.

As proposed in literature, alternative solutions to the problem of chatter are based on passive and active chatter suppression strategies.

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The most common passive strategies for chatter suppression rely on the principle of increasing the damping and the stiffness of the machining system elements (workpiece fixture, tooling system, spindle bearings). Other approaches are variable pitch cutters and spindle speed modulation. In general, the reliability of passive chatter suppression strategies is not very high.

Higher damping of the machining system can be either achieved by using mechanical parts made of high-damping alloys—for instance Densimet tungsten alloys, or by applying special high-damping kinematic couplings, as reported by Weck et al. in 2006 [5].

Variable pitch cutters—VPC are special tools for milling whose teeth are not equally spaced. The uneven angular teeth distribution of VPCs disturbs the regenerative effect, therefore it slightly improves the process stability as evidenced by Budak in 2003 [6].

Alternatively, the spindle speed modulation approach can be applied, as proposed by Soliman et al. [7] and Saastry et al. [8]. In this approach the spindle speed is perturbed by a low-frequency sinusoidal fluctuation around the nominal value. This method is quite effective, however it can be applied only on machine tools provided with a special spindle drive.

Better results can be obtained by applying active chatter suppression strategies based on the feedback principle: the state of the machining system is identified by a set of sensors and controlled in order to keep the amplitude of vibrations small. For this purpose, real time actuators, such as electromagnetic bearings or electrostrictive actuators, as proposed by Dohner et al. in [9], could be applied. Otherwise, spindle speed and feed speed may be varied until a stable machining condition is reached, as proposed by Liao et al. [10], by Tarng et al. [11] and by Ismail et al. [12].

It has to be pointed out that all these chatter suppression strategies are based on the application of reliable systems for chatter detection. In this work, the development of a multisensor chatter identification system composed of three sensors – two accelerometers and an axial force sensor – and suitable for industrial application is discussed. The proposed system is tested with experimental data, in order to determine its accuracy and its robustness against malfunctions when applied to very different experimental conditions.

2. Chatter identification systems

Table 1 illustrates some research works focused on chatter identification systems. The table is organized to indicate the machining process, measured physical quantities, sensors' setup, signal processing techniques, chatter classification criteria and the authors' reference.

For successful chatter identification both the frequency bandwidth and the positioning of sensors are crucial, as evidenced by Delio et al. in 1992 [13]. Specifically, the frequency bandwidth of the sensor must cover the frequency range of chatter vibrations, typically from 100 to 5000 Hz. The general rule for sensor location is that the sensor should be located as close as possible to the source in order to acquire a good signal.

Several contributions investigated the development of chatter identification systems in milling. The sensors which are mostly applied are displacement and acceleration sensors, plate dynamometers and microphones.

Also, displacement probes – for instance, eddy current or laser – can be effectively used to identify chatter in milling, but their positioning is often not compatible to the tool changer and the working space is reduced.

According to Delio et al. [13], the applicability of dynamometers for chatter detection in milling is reduced by their limited bandwidth, which is approximately 1 kHz. Therefore, dynamometers can be successfully applied in face milling, whereas they may be inadequate for application in end milling and finishing. According to the same author, microphones are very suitable for chatter detection in milling, being their sensitivity to chatter onset comparable to that of expensive sensors such as plate dynamometers, displacement probes and accelerometers. Nevertheless, microphones are affected by some limitations such as directional considerations, low-frequency response and environmental sensitivity. Particularly, the suppression of environmental noise is mandatory for a successful application of microphones.

In relation to the signal processing, the following analysis techniques were mainly applied:

- time domain analysis (once per revolution sampling—OPRS, poincarè sections—PS);
- frequency domain analysis (fast Fourier transform—FFT, power spectral density—PSD);
- time–frequency domain analysis (wavelet transform—WT); and
- other (entropy, coarse-grained entropy rate—CER, normalized coarse-grained information rate—NCIR).

When the signal is strongly related to tool tip vibrations, such as in the case of non-contact displacement sensors pointing at the rotating tool, chatter can be easily identified by qualitative analysis of signals in time. In other cases, the most common approach is to define quantitative chatter indicators and threshold levels for automatic chatter recognition.

For instance, the OPRS method is based on the analysis of signal values sampled once per spindle revolution, and the dispersion of data is used as chatter indicator. In the frequency domain methods, the machining condition is classified as unstable when some spectral peaks exceed a predefined threshold (in turning and grinding) or when anomalous chatter peaks emerge between the tooth pass excitation peaks (in milling).

All the proposed systems were mainly applied in laboratory conditions and there is a lack of commercial systems for chatter detection to be applied in production. Specifically, a chatter identification system to be applied in industrial