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Operational stability prediction in milling based on impact tests

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Chatter detection is usually based on the analysis of measured signals captured during cutting processes. These techniques, however, often give ambiguous results close to the stability boundaries, which is a major limitation in industrial applications. In this paper, an experimental chatter detection method is proposed based on the system's response for perturbations during the machining process, and no system parameter identification is required. The proposed method identifies the dominant characteristic multiplier of the periodic dynamical system that models the milling process. The variation of the modulus of the largest characteristic multiplier can also be monitored, the stability boundary can precisely be extrapolated, while the manufacturing parameters are still kept in the chatter-free region. The method is derived in details, and also verified experimentally in laboratory environment.

1. Introduction

There are many factors that influence the productivity of a cutting process in manufacturing. The material removal rate (MRR), which depends on the spindle speed, feed rate and axial/radial immersion of the machining operation, is one of those important quantities. The MRR, however, cannot be increased arbitrarily due to the undesired vibration that may arise during the cutting process. This undesired phenomenon is called chatter, which leads to unacceptable surface quality, extensive noise, toolwear and possible damage in the machine components. By limiting the technological parameters on an ad hoc basis, these vibrations can be avoided, but at the same time the industrial competitiveness also reduces. Therefore, the optimal tuning of the machining parameters is a highly important task for professional manufacturers, not only to increase productivity, but also to reduce financial costs.

Since the pioneering work of Tobias [1] and Tlusty [2] in the 1950s and 1960s, the so-called regenerative effect has become the most commonly accepted explanation for machine tool chatter. The vibrations of the tool are copied onto the surface of the workpiece, which modifies the chip thickness and induces variation in the cutting-force one revolution later. From dynamical systems' point of view, chatter is associated with the loss of stability of the stationary (chatter-free) machining process followed by a large amplitude self-excited vibration between the tool and the workpiece. The stability properties of machining processes are visualized usually by the so-called stability lobe diagrams on the plane of the depth of cut and spindle speed parameters. By evaluating these diagrams, the machinists can select optimal technological parameters in order to achieve maximum material removal rate without chatter.

There exist several mathematical methods to analyze the stability properties of milling operations governed by time-periodic delay-differential equations. Some of them apply the measured frequency response functions (FRFs) directly, such

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as the zero-order approximation (ZOA) [3], the multi-frequency solution (MFS) [4] or the extended multi-frequency solution (EMFS) [5]. Other techniques, such as the semi-discretization method [6], the full-discretization method [7], the integration method [8] and their extension by the implicit subspace iteration method [9], the Chebyshev collocation method [10,11], the spectral element method [12] and the temporal finite element analysis [13,14], require fitted modal parameters as input.

Although the most highly developed numerical methods construct the stability lobe diagrams within seconds, the practical applications still face many problems due to the deviation between the predictions and measurements. One of the most critical part in the calculation is the reliable identification of the system dynamics [15] and the correct modeling of cutting process mechanics [16]. Note that pure predictive approaches are not commonly applied in industry due to their enormous complexity, to the huge amount of required measurements (implying high additional times and costs), and also to the uncertainties affecting model coefficients causing unreliable and inaccurate predictions.

Uncertainties in the measurements, model simplifications and other assumptions lead to an impaired representation of the real dynamical system. This is the reason why experimental verifications often do not match the expected dynamic behavior.

In the recent decades, several numerical methods have been developed for experimental chatter identification, which often do not require stability lobe calculations (see, for instance, [17,18]). The detection method is usually based on some measured quantities that separate stable and unstable parameter domains [19]. The measurement processes from the sensing point of view might be classified as direct and indirect methods (see [20]). Since chatter corresponds to the variation of the cutting force, dynamometers, strain gauges or accelerometers are examples for direct instruments, while optical and sonic sensors are listed as indirect devices. Based on the evaluation process of the recorded signals, we can also distinguish off-line and on-line identification methods.

Off-line identification does not allow the machinists to prevent the occurrence of chatter. In most of the cases, the signals collected by dynamometers, accelerometers and industrial microphones [21,22] are evaluated, together with the observation of the surface quality [23], after the cutting process is finished.

On-line chatter detection techniques are essential elements of active chatter suppression methods, which are based on real-time signal processing. In the last decades, several techniques have been proposed to avoid unstable cutting operations. In most of the cases, the spectra of some signals are investigated which are typically obtained from industrial microphones and/or accelerometers (see [21,24–26]). Other techniques utilize directly the measured signals in time domain based on considerations of the periodic behavior of the system [22,27,28]. A more detailed study on chatter suppression methods is given by [29], and for a review on chatter detection, see [30] and all the reference therein.

In almost all of the cases mentioned above, the separation of stable and unstable operations is based on a so-called chatter indicator, which can be different for each method and the critical level of the indicator is usually empirically defined. These indicators are often not reliable close to the stability boundaries; this is while the accurate comparison between the predicted and measured stability lobe diagrams is a challenging task.

The aim of this research is not only to distinguish stable and unstable operations in a reliable way, but also to identify the transition between them and quantify the robustness of the applied cutting parameters [31]. In this paper, an experimental method is proposed, which can be used as an alternative chatter prediction technique. The main idea is to approximate only the largest Floquet multiplier of the periodic dynamical system based on operational impact tests [32,33]. This characterization of the dynamical behaviour makes unnecessary to identify any additional system parameter, and requires no exact stability lobe calculations. Like in case of autonomous systems, where the stability property is associated with the rightmost characteristic exponent, the fitted Floquet multiplier can give a measure for the "distance" from instability.

From engineering view-point, it is enough to decide whether the process is stable or not, that is the largest modulus of characteristic multipliers is greater or smaller than 1, respectively. The existing chatter detection techniques try to satisfy this 'yes/no' requirement.

However, the precise knowledge of the modulus of the critical multiplier makes it possible to identify the stability boundary by means of interpolation based on the stable and unstable measurement points. With the proposed method, it is also possible to predict the stability boundary by extrapolating the multipliers based on measurement points in the domain of stable machining parameters, only. In addition, by continuous the on-line monitoring of the Floquet multiplier, the cutting parameters can be adapted by 'smart machines' and a desired robustness can be guaranteed by keeping the modulus of the critical characteristic multiplier under a specific value.

The structure of the paper is as follows. First, the conventional stability calculation process is presented for a single-degree-of-freedom system (see Section 2). Then, the basic ideas of the semi-discretization method can be found, which is used to determine the stability lobe diagrams [6]. This section give the mathematical background for the identification of the largest modulus of Floquet multipliers. Then, the experimental method is introduced, which is the main contribution of the paper (see Section 3). The efficiency of the method is presented through a real case study, and the results are compared to those of the conventional chatter identification methods.

2. Dynamical model of milling

The reliable prediction of the stability limit of a milling process requires the accurate modeling of tool geometry, cutting force characteristics, precise measurement of the dynamics of the machine-tool-workpiece system and the cutter workpiece engagement [5]. The dynamical model presented in this section is based on the experimental setup to be discussed later in