International Journal of Machine Tools & Manufacture 89 (2015) 221–230

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

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

Spindle speed ramp-up test: A novel experimental approach for chatter stability detection

N. Grossi [a,*], A. Scippa [a], L. Sallese [a], R. Sato [b], G. Campatelli [a]

[a] Department of Industrial Engineering, University of Firenze, via di Santa Marta 3, 50139 Firenze, Italy
[b] Kobe University, 1-1, Rokko-dai, Nada, Kobe 657-8501, Japan

ARTICLE INFO

Article history:
Received 8 August 2014
Received in revised form
25 November 2014
Accepted 27 November 2014
Available online 4 December 2014

Keywords:
Chatter
Milling
Dynamics
Order analysis

ABSTRACT

Chatter is one of the most limiting factors in improving machining performances. Stability Lobe Diagram (SLD) is the most used tool to select optimal stable cutting parameters in order to avoid chatter occurrence. Its prediction is affected by reliability of input data such as machine tool dynamics or cutting coefficients that are difficult to be evaluated accurately, especially at high speed.

This paper presents a novel approach to experimentally evaluate SLD without requiring specific knowledge of the process; this approach is called here Spindle Speed Ramp-up (SSR) test. During this test spindle speed is ramped up, and chatter occurrence is detected by the Order Analysis technique. As result one single test ensures optimal spindle speed identification at one cutting condition, while if few tests are performed the entire SLD could be obtained. Results of the method applied to slotting operation on aluminum are provided and a comparison between different measurements devices is presented. This quick, easy-to-use and efficient test is suitable for industrial application: no knowledge of the process is required, different sensors can be used such as accelerometer, dynamometer or microphone.

1. Introduction

Milling has a central role in manufacturing industry thanks to its versatility and wide range of metal cutting capability. The increasing use of high-speed milling (HSM) has led to new challenges for the machine tool manufacturers and users. One of the main limitation to productivity increase of such technique is the occurrence of unstable regenerative phenomenon known as chatter that produces poor surface finish, tool wear and breakage [1]. In the last decades chatter has been widely studied [2]. Both predictive models and experimental approaches for identifying, monitoring and preventing chatter have been developed. The main output of predictive approaches is a chart, known as Stability Lobe Diagram (SLD), by means of which optimal machining parameters can be forecasted and hence selected [1–4].

These models are effective because they can predict chatter without performing cutting tests, avoiding time-consuming trial and error approach. However SLD accuracy is strongly affected by reliability of data entries: machine tool dynamics and cutting force coefficients. Extensive investigations on these inputs have been carried out highlighting the main issues related to their evaluation. Tool-tip dynamics is required and generally obtained by experimental impact tests. However machine tool dynamics varies changing tool: for each tool a new test has to be performed, increasing the number of tests required [5]. Additionally Tool-tip Frequency Response Functions (FRFs) are evaluated in stationary condition, but could change significantly increasing spindle speed due to thermal effect and ball bearing stiffness under load condition [6,7]. Moreover in some conditions (e.g. thin-wall machining) workpiece dynamics should be also taken into account [8,9], and the main drawback is that it changes during the machining process [10]. Besides cutting forces are influenced by tool geometry [11], type of operation [12], cutting parameters, e.g. cutting speed [13], and working conditions difficult to predict, e.g. vibration effect [14]. Taking these sources of variability into account, in general is not easy to have an accurate identification of FRFs and cutting forces and this could reflect in a wrong prediction of chatter conditions.

To overcome these limits, analytical approaches are hence replaced by chatter detection and prevention methods based on experimental tests [15–19], which use cutting tests to evaluate chatter onset. These approaches are more suitable for industrial application: they are easy-to-use, not directly requiring knowledge of the process and the phenomenon. Two main classes of approaches are presented in literature [2,15–23]: in-process methods and stability limit identification methods.

The first one aims at detecting chatter on-line and tries to avoid it, changing cutting parameters (e.g. spindle speed) during

* Corresponding author. Fax: +39 0554796400.
E-mail address: niccolo.grossi@unifi.it (N. Grossi).

http://dx.doi.org/10.1016/j.ijmachtools.2014.11.013
0890-6955/

machining operation. These methods generally analyze signals of sensors mounted on the machine: when chatter is detected, cutting parameters are adjusted to reach a stable condition. Different chatter indicators have been developed in order to reliably identify chatter occurrence. Despite the differences almost every indicator is based on the signal frequency spectrum: when chatter frequency amplitude exceeds a certain threshold value, chatter is detected. Different kinds of sensors have been tested: Liao et al. [15] presented an on-line method based on force transducer, Kuljanic et al. [16] a multi-sensors approach using two accelerometer and a dynamometer, but the most interesting sensor has revealed to be microphone because of its simplicity and low-cost: this sensor has shown good chatter identification capabilities [17]. Schmitz et al. [18,19] proposed a chatter detection approach by statistically evaluating milling sound variance. Bediaga et al. [20] developed an algorithm that uses sound signals to detect chatter and suggests alternative machining parameters.

The second class of methods aims at creating a stability experimental map to be exploited for selecting stable machining parameters. This approach is more reliable but more time-consuming than in-process ones. The most used consists in performing cutting tests for each single condition in order to detect the presence of chatter. Identification of chatter is carried out both on the surface finish (checking distinctive marks) and on sensors signals. A large number of tests are thus required to reconstruct SLDs, limiting its application to validation of predictive approaches. In order to extend this approach to industrial context more efficient tests have been proposed: Quintana et al. [21] proposed a new test in which axial depth of cut is increased gradually until chatter is identified: a single test can investigate chatter behavior at one spindle speed. Anyway if a wide range of spindle speed has to be analyzed, many tests should be performed. Ismail and Soliman [22] introduced a different method: in their test spindle speed is increased and chatter is detected thanks to a statistical indicator [23]. They performed a slow ramp of spindle speed in which feed per tooth is varying working out of the optimal cutting parameters: this leads to some drawbacks in chatter identification. Moreover the use of a statistical indicator instead of frequency analysis is less reliable: it is not possible to validate chatter occurrence on frequency content of signals and isolate it from other effect (e.g. forced vibrations). Method is not able to return chatter frequency values, useful to analyze and understand process behavior.

In this paper a novel experimental method to detect chatter and create an experimental stability map is presented. The proposed test has been called Spindle Speed Ramp-up (SSR). Spindle speed is increased continuously in the test, increasing simultaneously feed in order to keep feed per tooth constant, with fixed depth of cut for each test. Different sensors (accelerometer, dynamometer, and microphone) have been tested and analyzed using the Order Analysis (OA) technique to detect chatter frequencies. As a result a frequency map changing spindle speed has been obtained, and chatter detected checking chatter frequency onset. This very quick test, based on the OA technique, has revealed to be a very efficient way to identify process damping region, and stable and unstable zones for a single depth of cut. Moreover, repeating the test with different depths of cut, an accurate experimental stability map in the range of spindle speed can be efficiently obtained.

Compared to other experimental detection techniques, in which spindle speed is increased continuously [22], the proposed approach allows to ensure that feed per tooth is kept constant all over the test: this would allow to reduce influence of this parameter on the acquired data. In addition presented approach does not require any statistical indicator (e.g. [23]) to identify chatter onset and thus stability limits. The presented approach, in fact, is based on frequency analysis of measured signal: hence it allows to observe all the vibratory phenomena discerning from forced vibrations and instabilities, returning useful information to ensure accurate chatter identification in all engagement conditions.

2. Proposed test

SSR test aims at reducing number of tests required to experimentally identify stability limits of a machining operation. The idea is to compress large number of tests at different spindle speed in a single test in which spindle speed is increased in the entire range of interest. Therefore, compared to Quintana's test [21], depth of cut is not increased but is kept constant increasing spindle speed instead (Fig. 1). The main advantage of the proposed method is to obtain exploitable results with just one test: a single SSR test can extract stable cutting parameters for a working condition. This is relevant for industrial context in which could be enough to obtain the optimal spindle speed for a given depth of cut, because this would allow to improve process performances without changing the toolpath, which could be a time consuming issue that reduces the possibility to enable an on-line optimization.

Moreover, as exemplified in Fig. 1, with few tests it is possible to investigate the entirely SLD, drastically reducing the experimental effort usually required.

In order to obtain such result some shrewdness should be taken into account. First feed should be simultaneously increased with spindle speed in order to keep feed per tooth constant. In this way suggested cutting parameter for the tool are respected and cutting forces do not vary significantly. Then spindle speed should be increased linearly for mainly two reasons:

- Avoiding chatter growing uncontrollably: a continuous increase of spindle speed does not give time for chatter vibration to become dangerous for tool and machine because a new condition is reached immediately after;
- Easily and properly applying frequency analysis of the signals, as presented in the next section.

These features could be attained thanks to a proper definition of the NC code of the test, where the spindle speed and feed are changed linearly and accordingly.

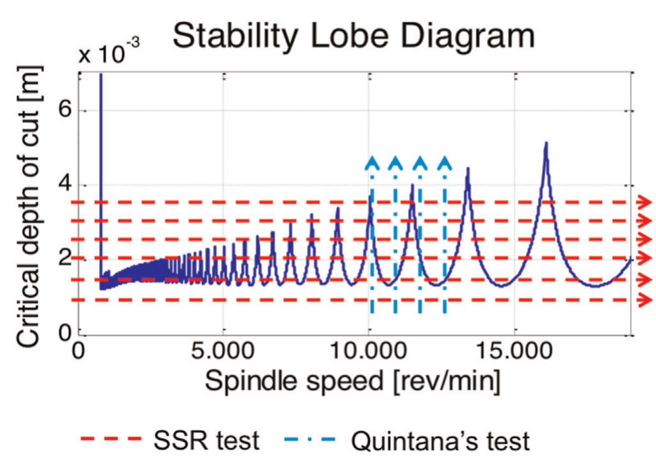

Fig. 1. SSR test compared to Quintana's approach [21] for SLD identification.