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Multi-Dimensional Bisection Method in HIL Environment: Stability and Chatter Prediction in Turning

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Abstract

In turning operations, the harmful small-amplitude but high-frequency chatter vibrations are identified in hardware-in-the-loop (HIL) experimental environment by means of the application of a multi-dimensional bisection method. The dummy workpiece clamped to the real main spindle is excited by contactless electromagnetic actuators and the response of the workpiece is detected by laser-based sensors. According to the present and the stored previous positions of the rotating workpiece, the desired cutting force characteristic along with the surface regeneration effect can be emulated by means of a high-performance real target computer. While the conventional experimental results in the HIL environment identify the stability limits of the cutting operation accurately only in a high-resolution grid of the technological parameters, the embedded bisection method reduces significantly both the size of the required grid and the time duration of the measurement by path following the boundaries of the linear loss of stability. Based on this technique, the experimental stability boundary of the emulated turning process is presented in a wide range of spindle speeds.

Keywords

HIL, multi-dimensional bisection method, chatter, turning, stability

1 Introduction

In the manufacturing industry, there exists a continuous driving force to achieve high-speed and high-quality production at the same time. The need for reduced energy consumption complies with the environmentally friendly standards. While these measures are tried to be satisfied, they are still constrained by the arising critical thermal and vibration problems of the machine tool structure [1].

Due to the presence of the so-called surface regeneration effect, unexpected small-amplitude but high-frequency vibrations may arise, which are called chatter in machining processes. These harmful oscillations are originated in the compliance of the workpiece, the cutting tool or the whole machine tool itself. In case of turning processes, when the workpiece is assumingly more flexible than the cutting tool, chatter develops even for a small perturbation of the workpiece. This leads to the appearance of wavy sunflower-like patterns on the surface of the workpiece and the decrease of the life expectancy of the cutting tool.

The phenomenon of surface regeneration induces the variation of the chip thickness due to the relative vibrations between the workpiece and the cutting tool. This was first described mathematically by Tobias [2] and Tlusty and Polacek [3]. The tool cuts the surface of the workpiece that was machined in the previous revolution. That is, the instantaneous chip thickness can be defined by means of the difference of the present and the previous positions of the workpiece. This way of description of the material removal leads to delay differential equations where the time delay corresponds to the time period of one revolution of the workpiece.

For chatter avoidance, theoretical and/or experimental stability analysis of the underlying turning operation has to be carried out. This way, the linear loss of stability of the operation can be determined, which helps the machinist to achieve the highest possible material removal rate without facing the undesired vibrations. While the so-called stability lobe diagrams are approved in theory [1], they have low reliability in the industry due to their uncertain and costly identification via extensive laboratory tests [4–7].

To bypass these difficulties, there are available solutions for chatter prediction. A computational environment for virtual machining can be established where the prediction accuracy depends on the embedded mechanical models or

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cutting measurements of the machine tool structure [8, 9]. However, the determined stability lobes are very sensitive to the modal parameters that may reduce the accuracy of this digital twin technique.

Another possible way is to keep the real dynamic behavior of the machine tool structure and to observe the cutting operation in a computer controlled environment. In [10], the machine tool itself is preserved, however, the cutting tool/workpiece interaction is replaced by electromagnetic actuators and laser-based sensors. The actuation, that is, the emulated cutting force is calculated by a high-performance real target computer that makes the semi-virtual test-rig an experimental hardware-in-the-loop (HIL) environment. By using this setup, the stability of the material removal process can be identified precisely at high-resolution technological parameter grids [10, 11] in a fully automatic way.

The purpose of the current paper is to provide and effective way of chatter prediction in HIL environment where the stability limits of turning is detected by means of the multi-dimensional bisection method (MDBM) embedded in the host computer. Preserving the accuracy of convectional high-resolution measurements but highly reducing their time costs, fundamental parameter points of the stability boundary of the underlying turning process are determined through the experimental bisection of an initially defined coarse grid in parameter space. Based on these certain points, the loss of stability in the desired range of parameters is identified by means of an experimental neighbour search algorithm (based on [12]). The raison d'etre of this way of bisectioning in HIL environment is presented by experimental studies.

The paper consists of six main sections. As an outline, Section 2 presents the HIL experimental environment. In Section 3, the emulated cutting force is detailed that is used for operational stability analysis. Section 4 describes the operation of the embedded multi-dimensional bisection method in the high-performance host computer. Comparative chatter tests in distinct parameter spaces are provided in Section 5. Finally, the concluding Section 6 summarises the results and the achievable future goals.

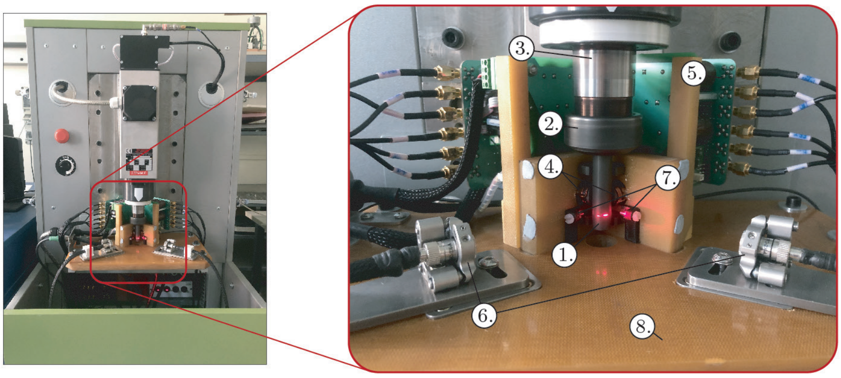
2 Experimental environment

The semi-virtual turning process in the HIL setup is shown in Fig. 1. While the machine tool structure is compliant resulting in the lateral deflection of the dummy workpiece, the cutting tool that is virtually substituted is assumingly rigid. The effect of the cutting tool and workpiece interaction is then produced through the substitution of the tool by contactless sensors and actuators.

The experimental test-rig consists of five main components: the dummy workpiece, the collet, the main spindle, laser-based sensors, and electromagnetic actuators that are crucial to emulate turning accurately.

The dummy workpiece of diameter 11 mm and of length 45 mm is clamped to the main spindle by means of an ER25 collet as shown in Fig. 1. To avoid the eddy currents arising due to the strong electromagnetic space, the workpiece and the actuator frame is made of ferrite material and non-conductive composite material, respectively. The main spindle is attached vertically to a solid steel block that is assumed to be satisfactorily rigid. The spindle is a 2 kW Series 3410 Teknomotor by which 18 krpm nominal and 24 krpm maximal speed can be reached. It is controlled by an OMRON variable frequency drive of type JZAB1P5BAA.

To emulate the cutting processes, the virtual cutting force is produced by electromagnetic actuators (see Fig. 1). The E-shaped cores of the magnets are manufactured from the same ferrite material as the workpiece and they are located 0.1 mm close to the workpiece. Since the cutting force varies fast for high spindle-speeds, the electromagnetic force is updated with the relatively high 100 kHz actuation frequency to meet the requirements. This actuation



1. dummy workpiece
2. collet
3. spindle
4. electromagnetic actuators
5. driving ECU
6. laser sources
7. fiber cables for photo diodes
8. actuator frame

Fig. 1 Experimental Hardware-In-the-Loop environment for turning process emulation speed is achieved by a National Instruments PXIe-8880 type real-time target that is installed with two NI7976R FPGA modules: an analog NI5751B digitizer input module and an analog NI5741 signal generator output module (with 1 MS/s at 16 bit and range of ± 2.5 V, see also [13]). Accordingly, the current test-rig is capable of emulating the variational component of the cutting forces appropriately at high frequency in the range of 10 N (see [14]).

To follow the virtual material removal in real time, the instantaneous chip thickness is observed, which depends on the angular and lateral positions of the dummy workpiece. The angular position is detected by means of an optical reflexive encoder (see [15]), by which the actual spindle speed can be accurately identified. The lateral displacement of the workpiece is measured by means of laser-based sensors (along with photo diodes) at 30 mm from its fixed end to the collet. As the laser beam grazes the surface of the workpiece, its intensity changes, which is proportional to the displacement of the workpiece. The measuring range and the sensitivity of the built-in photo diodes are 200 μm and 18 mV/μm, respectively, by which submicron resolution can be achieved. The calibration of these position sensors are carried out based on the run-out of the workpiece, which is 12 μm in the current arrangement.

Note that further details about the present HIL test-rig can be found in [10, 11, 13, 15].

3 Cutting force in feedback loop

To stay as close as possible to the real turning processes, the cutting tool/workpiece interaction has to be emulated accurately. There are many suggestions in the literature to estimate the cutting force characteristics (see [1, 16, 17]). The simplest linear estimation that is produced by the application of the corresponding electromagnet assumes the form (Eq. (1)):

$$F_c = F_{c0} + k_1\left(h(t) - h_0\right), \tag{1}$$

where F_{c0} is the mean value of the cutting force, $k_1 = K_c w$ is the virtual specific cutting force coefficient with cutting constant K_c and depth of cut w, and h is the instantaneous chip thickness varying around the theoretical chip thickness h_0 due to the surface regeneration effect. Accordingly, the chip thickness h can be formulated based on the present and the past positions of the rotating workpiece, which gives:

$$h(t) = h_0 + q(t-\tau) - q(t), \tag{2}$$

where the run-out of the dummy workpiece vanishes and the time delay τ corresponds to the time period of one workpiece revolution. Since the mean value F_{c0} does not affect the linear stability of the machine tool, it is emulated by a reduced magnetic force of the electromagnetic actuators [11].

Due to the high-frequency variation of the cutting force, it is calculated with 100 kHz sampling frequency based on the angular position and displacement signals of the workpiece produced by the angular position encoder and the laser-based sensors, respectively. While this means 333 available stored data for one workpiece revolution at the nominal spindle speed 18 krpm, only 256 samples, a power of two, are used to increase the calculation efficiency. This number of samples are satisfactory up to the low critical spindle speed $n_{cr} \approx 1.5$ krpm.

4 Bisectioning in HIL environment

The basic idea of the traditional bisection method is to find the zeros of real valued continuous functions by halving the corresponding intervals [18]. These functions assume the form $f(x) = 0$ with $f: \mathbb{R} \to \mathbb{R}$. The initial interval where the solution is sought is defined by the limit values x_s and x_e. Accordingly, when the signs of $f(x_s)$ and $f(x_e)$ are different, at least one zero of the function f is located in the prescribed interval. The iteration starts with the middle point $x_m = (x_s + x_e)/2$ of the interval by which $f(x_m)$ can be calculated. This way, the limit values are updated based on the sign of $f(x_m)$, that is, when it corresponds to the sign of $f(x_s)$, x_s is changed to x_m, otherwise, x_e modifies. If $f(x_m) = 0$ or $f(x_m) < 0$ fulfills, the iteration finishes.

The generalization of this procedure is used in the current HIL environment (see [12]). In higher dimensions, this multi-dimensional bisection method (MDBM) divides the initial interval into n-cubes (hypercubes) that are, for example, represented by a simple square in two dimensions. To identify the so-called bracketing cubes that involve a part of the solution, an initial mesh has to be defined for all the dimensions D by providing the limit values $x_{s,i}$ and $x_{e,i}$, $i = 1, 2, \ldots D$ along with the initial mesh resolution parameter N_i. Based on the initial data, the edge length of the n-cube is given by $\Delta x_i = (x_{e,i} - x_{s,i})/(N_i - 1)$. After evaluating the function f in all the mesh points, the bracketing cubes can be defined by means of any sign change in the corners of the n-cubes ("safe selection"), and the linear approximation of the solution can be based on a hyperplane fitting. The selected bracketing cubes are refined (halved along each dimension) creating 2^D new cubes and the process starts again.

If the iteration ends after a prescribed number of iterations, all the neighboring n-cubes must be analyzed to detect the possible missing parts of the solution. In higher dimensions (in case of multiple parameters), the loss of solutions is inevitable. This path following-like mechanism is repeated until all the neighboring n-cubes become non-bracketing ones or until the initial limit values are reached. As the last step of the method, zero order or first order interpolation is carried out to approximate the location of the root within the bracketing n-cubes.

This multi-dimensional bisectioning method is applied in the HIL experimental test rig to significantly reduce the number of measurement points, by which the dynamic behavior of the emulated turning process can be categorized as stable or unstable cutting and the stability lobe diagram can be constructed. The algorithm is based on the measured amplitude of the response signal of the dummy workpiece (see Fig. 1) that is used to identify the boundary of the stable domain of the cutting operation. Accordingly, two different implementations of the MDBM are investigated. While the first approach meets perfectly with the above description of the method, the second one does not use the resolution of the initial intervals, but it finds the stability boundary solution at a dedicated parameter point by a local bisection. After finding one solution point, the method traces the neighboring brackets only and thus it continues the solution. This second option is eligible to be used only when the stability boundary is closed, that is, it has no separate segments: multiple segments of the solution may not be discovered.

These two approaches for finding the stability boundary of emulated turning processes are investigated and they are compared via experimental case studies.

5 Experimental chatter tests

To identify the appearance of the harmful chatter vibrations, the spindle speed n and the virtual specific cutting coefficient k_1 are varied during the operation, and the response signal of the dummy workpiece is analyzed.

The measurement is automatized, and it is controlled by the host computer. In case of each pair of technological parameters, the set of the corresponding parameter point and the whole experiment last cca. 3 s (see [10]). The emulated turning process is said to be unstable when the amplitude of the arising oscillations, that is, the subtraction of the workpiece response signal and the run-out of the workpiece, reaches the level of 3 μm (see the upper panel of Fig. 2) at the chatter frequency, which is detected to be around the dominant natural frequency f_n = 3.05 kHz of the setup (see [11, 19]). This way, the effective experimental identification of the stability boundary of the cutting process is

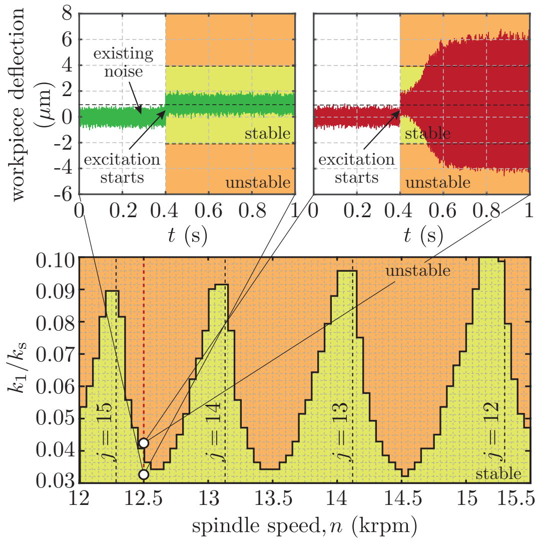


Fig. 2 Experimental chatter detection and stability chart when the brute force method for stability prediction is used. The stable parameter domain is indicated by green color and the unstable domain is shown by orange color

carried out according to two different techniques: the brute force method and the bisection method detailed in Section 4.

In case of the brute force method, a high-resolution parameter grid with 71 × 34 equidistant measurement points were defined (see the gray grid in the lower panel of Fig. 2). The real spindle speed was varied in the range n = 12.0 – 15.5 krpm and the virtual specific cutting coefficient was changed between k_1 = (0.03 – 0.10)k_s where k_s = 3.31 N/μm is the static stiffness in the current setup that was determined at 30 mm below the collet (see Fig. 1 and [20]). Accordingly, the experimental stability lobes are recognized with the black curves in the lower panel of Fig. 2. The dominant natural frequency corresponds well with the horizontal positioning j = 12, 13, 14, 15 of the stable pockets where $j = 60\,f_n/n$ is the sequential number of the stability lobes.

While this method of chatter identification provides orders of magnitude more accurate and faster prediction of the appearance of harmful vibrations than todays' standard laboratory tests, it still takes hours of experimental work (cca. 2 hours in the current narrow parameter range) to construct the stability lobe diagram. However, to analyze the influence of a larger set of parameters (e.g.: for cutting tool geometry optimization), even this time period is too long. For this reason, the MDBM was applied to detect the stability limits of turning precisely by reducing the total need of the time period of the whole measurement procedure.

The bisection method presented in Section 4 was initiated with the initial mesh resolution parameter $N_{1,2}$ = 5 for the underlying technological parameter domain. It iterated in 2 steps to find solution and then it sought the neighboring bracketing squares to follow the still unidentified solution segments until the lobe structure is completed in the given range of parameters or until the stability boundary reaches the borders of the pre-defined parameter domain. Due to the interval halving, the number of points where chatter tests were carried out reduced (see the red and green dots in Fig. 3 (a)), that means about 1-hour total measurement time period in the given range. This way, the identification of process stability was about the half time compared to the result of the brute force method. Note, that an even higher improvement could be achieved in the final resolutions, that corresponds to an increased number of iterations. In Fig. 3 (a), while red dots represent unstable parameter pairs, the green ones refer to the stable pairs. As the procedure is done, the stability boundary of the emulated turning process is determined by measurement results-based interpolation (indicated by the black curve in Fig. 3 (a)), which separates the stable and unstable domains.

This bisection technique can also be applied as a kind of continuation method when the solution is followed along the stability boundary of emulated turning. In this sense, a simple bisection was performed according to the introductory part of Section 4, that is, one parameter

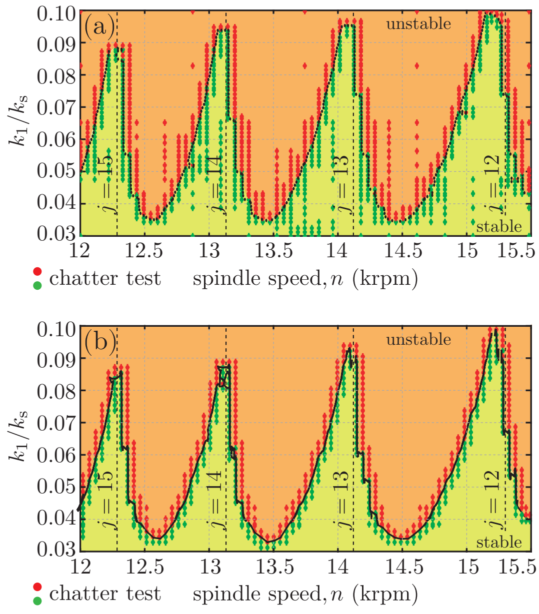


Fig. 3 Experimental chatter detection and stability chart when the bisection method is applied to predict stability. The stable region is colored with green, and the unstable region is illustrated by orange; (a) bisectioning and neighbor searching the entire parameter region that is in interest; (b) one-point bisectioning with continuation along the stability boundary of the emulated turning process

point along the stability boundary was identified at one single spindle speed n = 12.0 krpm. Based on this point, the neighboring bracketing squares were detected until the solution was not fully explored in the parameter domain (see Fig. 3 (b)). Since this technique checks the nearby squares only in contrast to the above version of MDBM, the number of chatter tests decreased again, which means that the total time period of the measurement was about 40 minutes. This reduction can also be seen in the number of experimental tests when Fig. 3 (a) and (b) are compared.

While the continuation-like version of the bisection method is a relatively fast way for constructing stability maps, it also has some disadvantages. If there is a split in the stability boundary, for example, due to the bounds of the given range of parameters, or multiple separated stability boundaries exist, only a segment of the solution will be detected. For these cases, the generalized version of the bisection method provides an effective and more robust way of chatter identification.

6 Conclusions

Since the manufacturing industry always faces with high precision standards related to cutting quality issues, the sources of possible harmful effects have to be explored. One of these is the arising self-excited chatter vibrations that can be avoided if accurate stability analysis of the underlying machining process is performed.

The present paper is dedicated to provide an efficient way of chatter identification in the Hardware-In-the-Loop (HIL) experimental environment where the turning process is emulated by contactless actuators and sensors while keeping the real machine tool structure. This way, the dynamic behavior and the stability properties of the material removal operation can be identified precisely in a computer-controlled setup. To reduce the time period of the whole measurement procedure, the stability boundary of turning is determined experimentally by means of the multi-dimensional bisection method. That is, the stability limit is detected by interval halving, which leads to a significant decrease in the number of measurement points. This method is applicable even in the presence of measurement noise because it does not rely on derivatives [19].

While todays' conventional laboratory tests are costly and time consuming, this efficient way of chatter prediction provides a fast and accurate alternative, which may also be easily extended to multiple technological parameter domains to find optimal parameter points for the cutting operation.

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