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MEASURING STABILITY OF MILLING PROCESS

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1. Introduction

This work presents a case study about measuring milling process vibrations. The presented study concentrates on determining linear stability boundaries by keeping in mind the possible involvement of nonlinear effects. The paper includes measurement of the dynamic structure of the machine tool, force measurement of the workpiece material and prediction of stability boundaries. The measurement shown here is a preliminary work of proving so-called unsafe zone [1] exists in milling.

Nowadays, the virtual design of machines pretty much replaced with traditional designing techniques. Engineers can assemble machines in 3D environment routinely. Physical calculations like volume, mass, moment of inertia's and elastic static stress and strain fields are easily calculated in virtual environment. However, vibrations in general, requires specific modelling of part connections and nonlinear effects, which behaves differently in different frequency ranges, and extremely difficult to measure and simulate. Machine tools are subjected to these phenomena, that makes modelling of these important manufacturing processes demanding. Therefore, hybrid semi-analytical models still play important role in predicting machining behavior.

The basic modelling of regenerative vibrations appearing in e.g. turning, milling, boring was first explained in the Pioneering works of Tlusty and Tobias. The mathematical modelling of the governing delayed differential (DDE) was widely discussed in [4]. The stationary cutting is the required vibratory state of a given machining process. In the case of autonomous (time independent) turning process this is only a simple deflection, while in case of non-autonomous milling that is an unavoidable time periodic vibration. The industrial requirement is to have stable stationary cutting solution, which requires of calculating the stability properties of the corresponding DDE model.

There are plenty of methods dealing with the stability of the resulting linearized DDE. In the industry dynamics usually described by frequency response functions (FRF's) that can be easily included in D-subdivision and Hill's representation for autonomous and time periodic DDE's, respectively. This gave the rise of the zeroth order solution (ZOA) [2] and multi-frequency solutions (MF) [2]. Among many time domain based methods, the one, which is easy to use is the semi-discretization (SDM) [3] fully satisfies industrial demands in terms of precision and efficiency.

2. Machine Dynamics

The reflected dynamics on the tip of the milling cutter was measured by a micro accelerometer and excited by modal impulse hammer (Fig. 1). We assumed the tiny accelerometer and its cord do not affect the measurement significantly. The measurement showed that using different force levels the reflected FRF's differ in frequency and flexibility (Fig. 2).

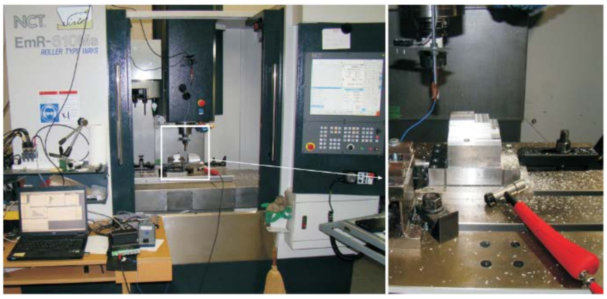

Fig. 1. Measurement arrangement

Regardless of the level of changing, it is important to emphasize that the peak level force for the impulse excitation distributes in the active frequency range. This results in tiny roughly a Newton level of excitation, which is far from the realistic excitation level of the cutting force. That is, even small changes in flexibility and natural frequencies can be a sign of more dramatic change in-operation dynamics.

In calculation-wise, we performed fitting on FRF's using traditional RFP fitting algorithm. Since we have no access for in-operation measurement, then, we performed stability predictions using all available FRF's assuming linear dynamics for the tool-spindle assembly.

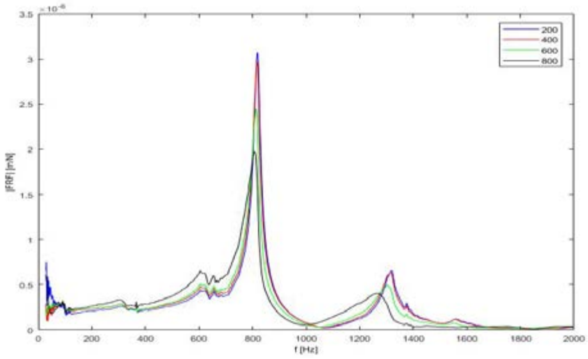

Fig. 2. FRF for different force peak levels representing the slightly changing dynamics.

3. Force Modell

The empirical force model [1] was determined performing stable ¼ down-milling shoots cutting a workpiece fixed on a dynamometer plate. The empirical force characteristics was calculated from the averaged cutting forces by the method presented in [2] for cylindrical milling cutters.

$$\mathbf{f}(h)=\begin{bmatrix} f_t(h) \\ f_r(h) \\ f_a(h) \end{bmatrix}=\begin{bmatrix} K_{t,c}h+K_{t,e}(1-e^{-E_t h}) \\ K_{r,c}h+K_{r,e}(1-e^{-E_r h}) \\ K_{a,c}h+K_{a,e}(1-e^{-E_a h}) \end{bmatrix}. \qquad (1)$$

After performing force measurements for different cutting speeds a set of averaged parameters are determined (see Tab. 1.) for the Al 2024 T351 workpiece material.

$K_{t,c}$ (MPa)	$K_{t,e}$ (kN/m)	E_t (10^3/m)
1015	30	1/0.009
$K_{r,c}$ (MPa)	$K_{r,e}$ (kN/m)	E_r (10^3/m)
185	40	1/0.012

Tab. 1. The fit parameters of the force model (1).

4. Stability of Milling Process

After having fitting on the presented FRF's the linear stability boundaries of the milling process are calculated. Remark that, since the machine is nonlinear neither the fitting nor the linear stability prediction of the stationary solution are mathematically correct. The real motivation here was to show what errors can be made only by fitting wrong data on not carefully measured dynamics of the machine.

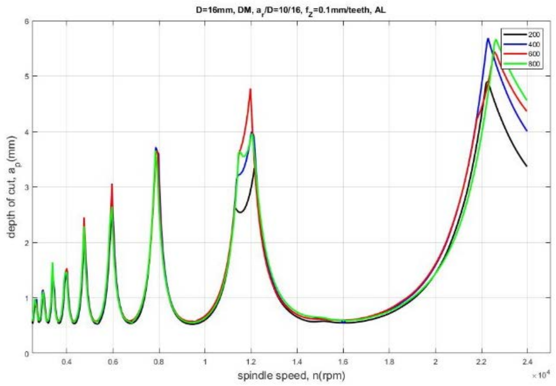

Fig. 3. Stability diagram

The stability boundaries were calculated by semi-discretization [3], in which cutting coefficients were calculated using (1) "around" the stationary solution.

Conclusion

Machines tools (spindle) often show nonlinear stiffening characteristics. Impact test excitation level is not comparable with in-operation excitation level. The stability boundaries are determined by correct linearization, although the dynamics was considered linear for one specific force level due to the lack of correct nonlinear structural model of the machine tool.

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