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Experimental and simulation stability analysis in milling

Doświadczalne i symulacyjne badania stabilności frezowania

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Self-excited vibrations significantly reduce the milling productivity, deteriorate the quality of machined surface and tool life. One of the ways to avoid these vibrations is to modify the cutting parameters based on the stability analysis results. A method of numerical simulation of self-excited vibrations in the time domain can be used for this purpose. A comparison of numerical simulation results with those from experiments conducted using a milling machine is presented. The results confirm the correctness of applied modeling.

KEYWORDS: simulation numerical, vibration self-excited, milling

The presence of self-excited vibrations has a significant impact on the quality of the machined surface, the machining efficiency, tool life and the durability of machine tools. When starting up the production, the self-excited vibrations should be avoided.

Determining the stability limit consists in finding the axial depth of cut a_p, above which the system becomes unstable [1, 2]. It can be experimentally determined by subsequent flat milling with increasing depth of cut until self-excited vibration occurs, which is the most accurate, though awkward and time consuming. Milling with continuously increasing depth of cut is much more convenient and faster. Observation of the marks left on the surface enables easy identification of the stability limit. This method is often used, although it can lead to significant errors [3].

An alternative to experimental research is numerical simulation in the time domain to determine the stability limit [4, 5]. Numerical simulation allows to calculate waveforms of forces and vibrations during machining.

The purpose of the research presented in this paper is to verify the accuracy of numerical simulations by comparing results obtained by this method with those achieved in the course of actual milling. An important element in both simulation and experimental research is detection of self-excited vibrations, which allows to determine the moment, in which the increasing axial depth of milling exceeds the limit value.

Detecting the self-excited vibrations in the milling process

Stability analysis is aimed at recognizing the presence of self-excited vibrations during real-time machining and time - domain simulation. For this purpose, a force or vibration signal is used. However, in the course of time, there are forced oscillations associated with the frequency of spindles and rotation of spindles as well as their harmonics. At turning - where the vibration induced by the cutting process does not exist - the stability criterion can be taken to exceed the amplitude of the vibration of the specified threshold. This method cannot be used for milling, where the insertion of blades into the material causes the system to vibrate. The stability evaluation must therefore include the distinction between forced vibrations and self-excited vibrations.

The stability identification methodology used here consists of filtering out the frequency of forced vibrations determined by the frequency of the cutting edges and its higher harmonics [6] from the FFT spectrum. Actual spindle speed has some deviation from the setpoint, and hence the frequencies of the forced vibrations are also different from the theoretical ones for the given speed, and this will be of great importance for the correctness of the analysis results. It is therefore important to recognize the actual spindle speed.

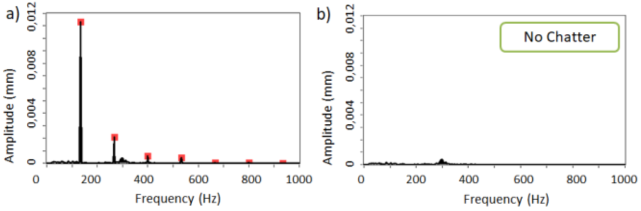

Fig. 1. Self-excited vibration detection - stable cutting

An example of the applied methodology is presented in fig. 1 and fig. 2. Fig. 1 shows the oscillation spectrum during stable processing. Fig. 1a identifies and determines the induction frequencies, eliminated in fig. 1b. The process has been rated as stable.

Fig. 2 shows the frequency spectrum obtained during unstable machining, where the frequencies of forced vibrations were detected. After their removal one form of vibration with significant amplitude remained and thus the state of the process was evaluated as unstable.

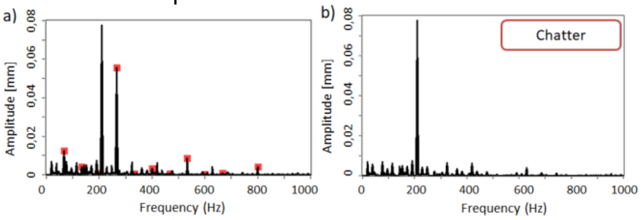

Fig. 2. Self-excited vibration detection – chatter occurrence.

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Experimental determination of machining stability

Experiments, the aim of which was the experimental determination of the critical depth of cut by milling with the continuously increasing depth, were carried out as described in [3]. Workpiece material was aluminum PA6. The rotational speed varied between 1000 and 6000 rpm at a feedrate of 0.03 mm/tooth. The 2-edge not coated cemented carbide cutter SILMAX 179100C of diameter ⌀10 mm was used. The inclination angle of the test surface was 3°28', which at the length of the workpiece 100 mm changed the depth of cut by 6 mm.

Recognition of self-excited vibrations in cutting trials was conducted in two ways. The first was the observation of the machining marks and the identification of the place where the marks of the vibrations reproduction on the machined surface appear. The second was the analysis of recorded vibrations as described by the self-excited vibration detection method. Obtained full compliance confirmed the usefulness of the method.

Fig. 3 shows the example of recorded vibration during milling at a speed of 3500 rpm, with the axial depth of cut a_p = 5.6 mm, including the site, where the self-excited vibration was detected.

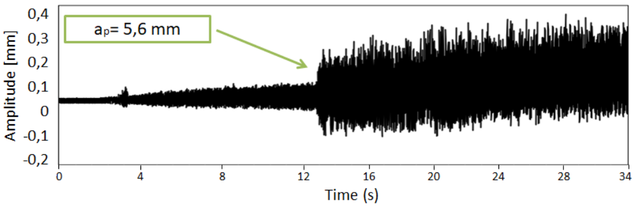

Fig. 3. Development of vibration during milling

Numerical simulation in the time domain

Numerical simulation allows to calculate the course of forces and vibrations during machining. In combination with the stability estimation methodology, it is possible to objectively compare experimental and simulated cutting depths. The basics of numerical simulations of self-excited vibrations are presented in [7, 8].

Authors' numerical simulations software based on the Tlusty and Ismail [9, 12] method, were used based on relationships describing the uniformly accelerated motion in the mass-damping-elastic system for one degree of freedom. Due to the superposition of single freedom degrees, it is possible to describe the real object as a system with many forms of vibrations with two freedom degrees [1, 2]. This allows for taking into account the main factors that determine the self-excited vibrations, i.e. coupling by displacement and vibration reproduction (fig. 4).

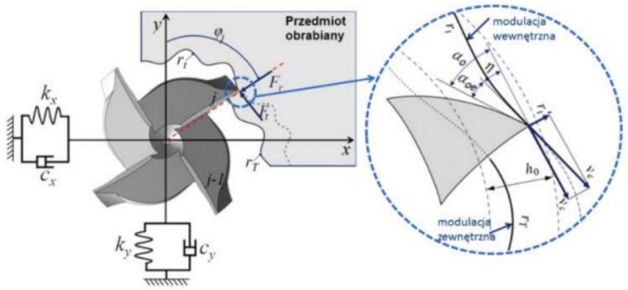

Fig. 4. Diagram of dynamic OUPN system during milling [8]

Input data for numerical simulation - which requires preliminary research, i.e. analysis of the simulated object - are dynamic cutting force coefficients describing the cutting forces and modal parameters describing the frequency response of the tool, the tool holder and the spindle.

Study of dynamic characteristics of the tool

Modal analysis used in the study is a single-input single output type [10, 11]. In modal tests, a modal hammer for vibration induction and an accelerometer for measuring, were used. These measurements were made for *X* and *Y* axes of the machine. This configuration is sufficient for the frequency response function, which is the basis for calculating the modal parameters. These parameters are the required input data for numerical simulation describing the dynamic characteristics of the spindle, the tool holder and the tool. Table I sets the modal parameters for *X* axis, and Table II - modal parameters for *Y* axis.

TABLE I. Modal parameters for X axis

Modal frequency, Hz	Modal mass kg	Modal damping Ns/m	Modal stiffness kN/m
937	1,376	505,50	47 765
597	9,273	2 106,4	130 868
528	24,70	5 134,1	272 827

TABLE II. Modal parameters for Y axis

Modal frequency, Hz	Modal mass kg	Modal damping Ns/m	Modal stiffness kN/m
908	2,279	396,62	74 247
616	5,750	2 028,7	86 468

Study of the characteristics of the cutting process

The dynamic cutting force coefficients are characteristic of the cutting process [1]. They rely on milling with a steady axial depth of cutting under stable conditions. The axial depth of cut must be such that no self-excited vibrations occur. Then the mean force values in each machine axis are determined and converted into dynamic cutting force coefficients. As a result, the dynamic coefficients were calculated according to the method described in [13,14]: K_{rc} = 685 N/mm^2, K_{re} = 26 N/mm^2, K_t = 380 N/mm^2, K_{te} = 13 N/mm^2, K_{ac} = 267 N/mm^2, K_{ae} = 14 N/mm^2. Calculated parameters are input data for numerical simulation.

Results of numerical simulation

The cutting forces and vibration waveforms in both axes calculated on the base of preliminary tests were evaluated for the detection of the presence of self-excited vibrations. An exemplary simulation result is presented in fig. 5 for a rotational speed of 3500 rpm, where self-excitation is detected at a milling depth a_p = 5.8 mm. Table III compares results obtained by numerical simulation with experimental studies.

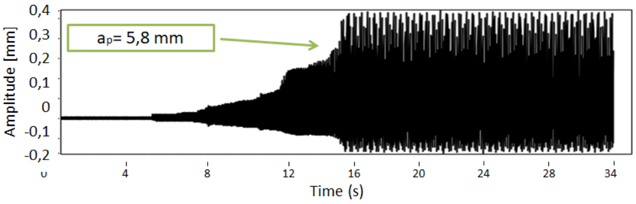

Fig. 5. Simulated development of vibration during milling

Results

Conducted stability experiments as well as force and vibration courses calculated using simulation allow for comparison of results – see Table III.

TABLE III. Comparison of results obtained by different methods

Spindle speed, rpm	Experimental stability limit, mm	Analytical stability limit, mm	Simulated stability limit, mm
1000	4,0	3,7	3,8
1500	4,2	4,0	4,1
2000	4,1	3,8	4,2
2500	4,0	3,6	4,1
3000	4,8	6,1	4,6
3500	5,8	6,0	5,6
4000	4,1	4,5	3,9
4500	4,8	4,3	5,2
5000	5,9	5,8	6,0
5500	6,9	7,1	7,0
6000	3,7	3,9	3,1

If Fig. 6 the stability limit calculated analytically, determined experimentally and by numerical simulation were compared.

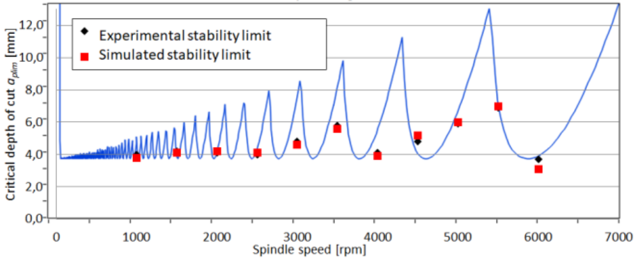

Fig. 6. Comparison the stability limit calculated analytically, determined experimentally and by numerical simulation

Conclusions

Experimental results were used as a basis for further analysis. The mean difference between results of the experimental stability limit and the numerical simulation is 0.2 mm, resulting in a 5% discrepancy. The mean difference between the stability and experimental results is 0.5 mm, which gives an average difference of 8%.

Based on the analysis, the difference between the results of numerical simulation and experimental results is less than difference between the results of analytical method and experimental results.

Comparison of the critical depth of cut determined experimentally and by numerical simulation in the time domain shows similar values, which confirms the correctness of the numerical simulation. Discrepancies may result from inaccurate preliminary tests.

The results of the analysis confirm that numerical simulation, in spite of the increased computational cost, is more accurate than the analytical methods of calculating the stability limit.

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