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The dynamic repeatability of a machine tool–holder–workpiece system

Powtarzalność wyznaczania właściwości dynamicznych układu obrabiarka–uchwyt–przedmiot obrabiany

Abstract

Knowledge of the dynamic properties of a machine tool–holder–workpiece system is crucial for the appropriate selection of machining parameters based on stability lobes. One of the most convenient methods allowing for the experimental identification of these properties is impact testing. However, the repeatability of such measurements may be different depending on the machine–workpiece setup and can lead to incorrect cutting parameter calculations. The article presents this issue on the example of a lathe-workpiece system. The experimental setup and obtained measurement results are presented and discussed.

Keywords: machining stability, turning, impact testing, dynamic repeatability

Streszczenie

Znajomość właściwości dynamicznych układu obrabiarka–uchwyt–przedmiot obrabiany jest kluczowa przy doborze odpowiednich parametrów technologicznych obróbki przy wykorzystaniu krzywych workowych. Jedną z podstawowych eksperymentalnych metod wyznaczania tych właściwości są testy impulsowe. Jednakże, w ramach rozpatrywanego układu obrabiarka–przedmiot wyniki uzyskane w ramach przeprowadzania takich pomiarów mogą się różnić, co jednocześnie prowadzić może do doboru niewłaściwych parametrów obróbki. W pracy przedstawiono niniejsze zagadnienie na przykładzie tokarki. Zaprezentowano badany układ, wyniki przeprowadzonych pomiarów oraz interpretację wyników.

Słowa kluczowe: stabilność obróbki, toczenie, testy impulsowe, powtarzalność

1. Introduction

In addition to ensuring appropriate dimensional accuracy and surface quality of machined parts, contemporary machining also needs to be highly efficient. The achievement of these requirements is possible only when the machining is carried out in stable cutting conditions i.e. where there are no chatter vibrations, leading to the surface damage on the workpiece (chatter marks), reduction of tool-life and faster wear of machine tool subassemblies [1–3]. Chatter vibrations may be avoided by proper selection of cutting parameters such as feed rate, cutting depth and rotational speed (of the workpiece for turning or the tool for milling). The selection of these parameters can be carried out using the so-called stability lobes presented as a border cutting depth at which chatter vibration develops as a function of rotational speed [2, 4]. In order to calculate the stability lobes, a model of the cutting process (determined by cutting force coefficients for specific machining operations) and the dynamic properties of the machine tool–holder–workpiece system need to be identified. These dynamic properties as a frequency response function (FRF) can be determined using a number of methods, these can be analytical, numerical (e.g. Finite Element Method models) or experimental (e.g. impact testing). It is the experimental methods that provide the most complete information about the dynamic properties of the real system; however, these are troublesome due to them typically being particularly laborious, requiring specialised equipment and the measurement uncertainty arising from the variability of the impact test results.

The problem of the repeatability of FRFs was raised by Medicus and Schmitz [5], where tool point dynamics for tool and holder changes were investigated. They proposed a number of methods of frequency based data presentation. A similar problem was examined in [6] by Lee and Donmez, where the authors presented tool point dynamic variability in milling and its influence on stability lobes. As a result, they highlighted the necessity for continuous updates to dynamic properties to minimalise uncertainty of stability lobes evaluation. In [7], the authors worked on the natural variability of the frequencies and mode shapes of the Alamosa Canyon bridge and proposed another approach for dynamic variability analysis. Kim and Schmitz in [8] widely discussed uncertainty contributors for FRF measurement obtained through

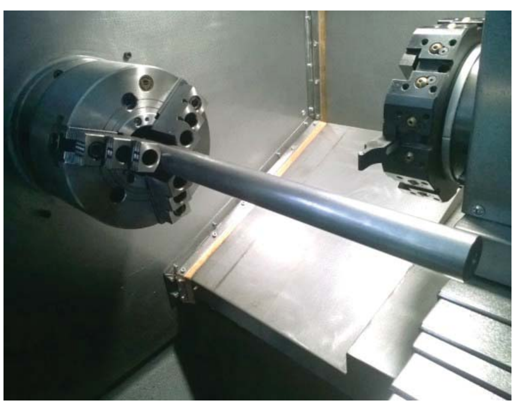

Fig. 1. Test setup: workpiece mounted in a 3-jaw lathe chuck

impact testing. They indicated four main contributors: statistical uncertainty, modal hammer and accelerometers' calibration coefficient uncertainty, cosine errors (due to misalignment between the hammer impact direction and the transducers axis) and accelerometer mass loading. As the authors pointed out, the cosine and mass loading uncertainty are negligible.

In this paper, the issues of repeatability of FRFs measurements for the machine-holder-workpiece system shown in Fig. 1, consisting of a rod-workpiece mounted in 3-jaw lathe chuck are presented. This setup is typical for rope thread machining.

In most cases relating to turning, to calculate the stability lobes, only the tool-tip impact test is preformed, assuming that the workpiece is a rigid body and that its dynamics are negligible. However, in the presented system, the workpiece is the source of significant dynamic compliance that cannot be disregarded.

For the considered system, variability in the experimentally determined FRF may be caused by a number of factors, such as:

- Machine tool issues – the degree of wear of bearings and chuck jaws, type of mounting, the rotational position of the spindle (arrangement of chuck jaws and rolling element of bearings)
- Workpiece issues – for objects of different geometrical and material properties, variability may be different
- Testing setup errors – e.g. variable length of the workpiece in the jaws of the holder, inaccuracies in the location of the accelerometers and the force impact points.

Knowledge of the variability of FRFs obtained experimentally appear to be important as it affects the location of stability lobes, which consequently, may indicate the selection of inappropriate cutting parameters.

The purpose of this study is to investigate the repeatability of the experimentally obtained FRFs of the machine-holder-workpiece system and the determination of their level of variability depending on the above factors and their influence on the calculated stability lobes.

2. Testing setups

The object of the research was the mid-size AFM TAE 35N 'Hanka' CNC lathe presented in Fig. 2 with a spindle equipped with a hydraulically clamped 3-jaw chuck Bison-Bial 2405-200-66K. The fact that the considered lathe was brand new enables the elimination of factors arising from wear of its assemblies (such as chuck jaws or spindle bearings), thus allowing the focus to be on factors independent of a particular machine.

In order to investigate the variability of the FRFs, a series of impact tests of the machine tool–holder–workpiece system presented in Fig. 3 was performed. Measurements on a workpiece of diameter *D* and length *L* are carried out at four equidistant points. Only the x-direction was considered for further analyses, since the other directions have a minor effect on the machining stability.

Fig. 2. Testing lathe – AFM TAE 35N

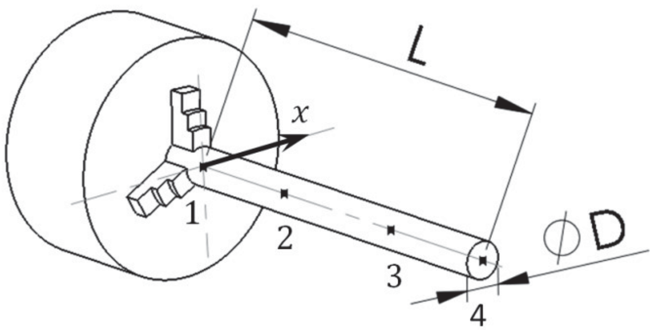

Fig. 3. Distribution of the measurement points on the workpiece

The measurements were carried out for four geometrical and material setups of the workpiece – these are presented in Table 1 below.

Used as workpiece material, A10X is a steel grade especially suitable for high-speed machining and thread cutting because the presence of a large number of non-metallic inclusions facilitates the breaking of the chip during cutting. C45 is a non-alloy quality steel for general engineering purposes.

Apart from workpiece issues, the experiment was designed to investigate the influence of spindle rotational position and testing setup errors (described in paragraph 1) on FRF

Table 3. Workpiece setups

No.	Diameter [mm]	Length [mm]	Material
1	35	350	A10X
2	31	300	C45
3	40	360	C45
4	35	200	C45

repeatability. Therefore, for each workpiece setup presented in Table 1, it was necessary to repeat the measurement cycle, which consisted of:

1) Adjusting the rotational position of the spindle (summary in Fig. 4)
2) Chucking the workpiece in the holder
3) Distribution of the measuring points
4) Impulse test at all four measuring points
5) Removal of the accelerometers
6) Unchucking the workpiece and removal from the holder

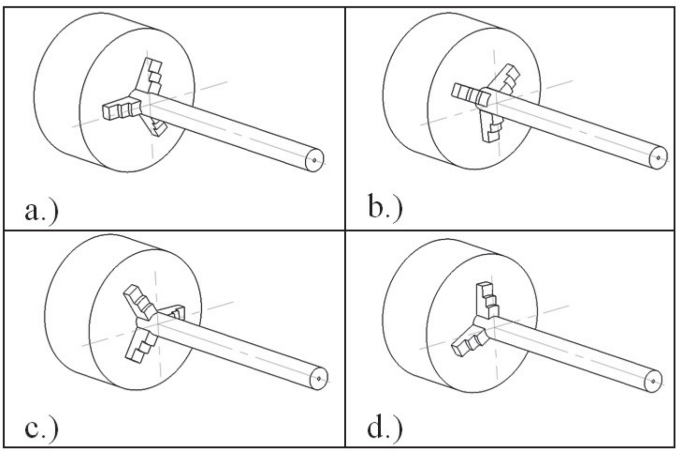

Fig. 4. Rotational positions of the spindle

The above measurement cycle was repeated 12 times for each workpiece configuration (three for each rotational position of the spindle presented in Fig. 4).

3. Experimental tests

In this section, the results of impact tests carried out according to the measurement cycle are presented. The impact tests were carried out using the LMS Scadas III data acquisition system, working with LMS Test Lab software (module Impact Testing). Vibration responses were measured using four PCB 356A01 3 – axial accelerometers, while the structure was excited with Kistler 9726A20000 modal hammer. A single measurement of FRF consisted of eleven averages (hits). The measurement frequency bandwidth was set at 2048 Hz.

The measurements were carried out at four points – this enabled the identification of the vibration mode shapes. However, the analyses of the repeatability are presented only in two characteristic points – the least compliant, at the spindle (point '1' – FRF H11), and the most flexible, at end of the workpiece (point '4' – FRF H44).

3.1. Mode Shapes analysis

In the considered frequency range, for setups 1-3, three major mode shapes are presented in Fig. 5. Due to it having the highest stiffness, the third mode shape of setup '4' occurred at a frequency above the bandwidth. The first and third modes are characteristic for lateral vibration *of fixed-free continuous beam* and the second, is associated with the vibration mode of the spindle.

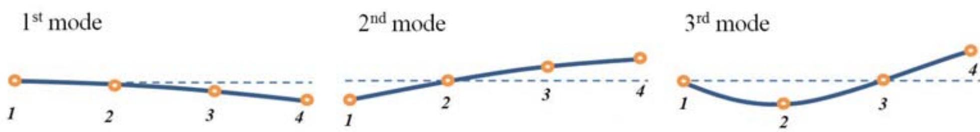

Fig. 5. Mode shapes

3.2. FRFs analysis

The experimentally obtained FRFs of all considered workpiece setups are presented as raw data, i.e. each Fig. contains twelve FRFs measured according to the cycle submitted in Section 2, without distinction between the rotational position of the spindle and other issues. The natural frequencies are summarised in Table 2.

Table 2. Measurement results – frequencies

Setup no.	Mode frequency range	Mean frequency	Standard deviation
1	139 – 149 Hz	144.2 Hz	3.13 Hz
	411 – 413 Hz	412.6 Hz	0.79 Hz
	988 – 1015 Hz	992.2 Hz	10.7 Hz
2	183 – 192 Hz	187.3 Hz	4.4 Hz
	419 – 420 Hz	419.6 Hz	0.51 Hz
	1184 – 1239 Hz	1216.8 Hz	22.3 Hz
3	119 – 142 Hz	131.1 Hz	9.44 Hz
	408 – 413 Hz	412.4 Hz	1.24 Hz
	930 – 1039 Hz	985.9 Hz	43.73 Hz
4	324 – 335 Hz	329.4 Hz	3.53 Hz
	464 – 488 Hz	473.77 Hz	9.66 Hz

The measured FRFs of setup '1' are presented below in Fig. 6.

For rotational spindle positions ‘a’ and ‘c’ (Fig. 4), the best repeatability for all three modes

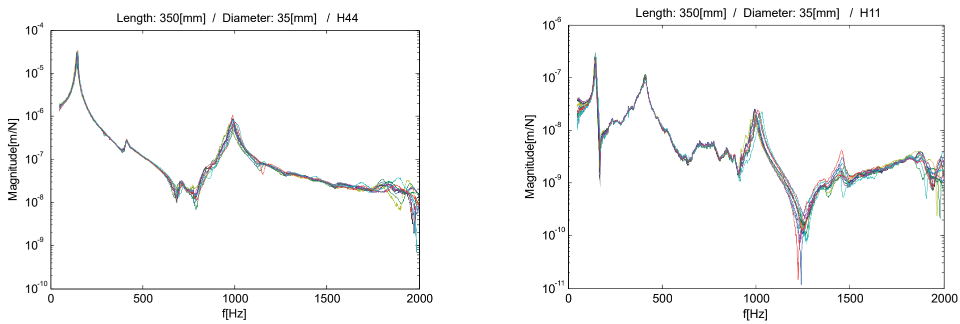

Fig. 6. Workpiece setup ‘1’ – FRFs in points ‘1’ and ‘4’

has been observed. Identified mode frequencies in these cases ranged 142–145 Hz for the first mode (first beam mode), 411–412 Hz for the second (spindle mode), and between 992–998 Hz for the third mode (second beam mode). For rotational positions ‘b’ and ‘d’, more divergence of the results has been observed, particularly for beam modes – the repeatability of the second mode (spindle) remained at a similar level. Apart from the type of rotational position presented in Fig. 4, the exact repetition of the position (one of the chuck jaws was marked) turned out to be significant.

The results of the impact tests for setup ‘2’ are presented below in Fig. 7.

Similarly to the setup ‘1’ three modes have been observed and the highest repeatability was

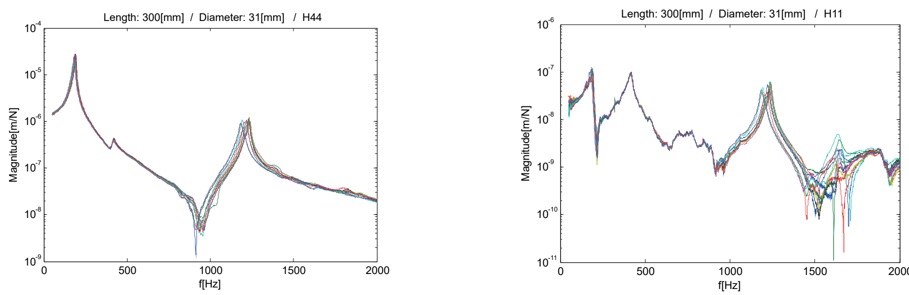

Fig. 7. Workpiece setup ‘2’ – FRFs in points ‘1’ and ‘4’

reached for the second mode (spindle mode) at 420 Hz which is a higher frequency than in other cases. For this setup, there was no noticeable influence of the rotational position of the spindle on the discrepancies of particular FRFs.

The repeatability of the experimental FRFs for setup ‘3’ presented above, taking into consideration all performed measurements, appears to be the lowest. However, out of all

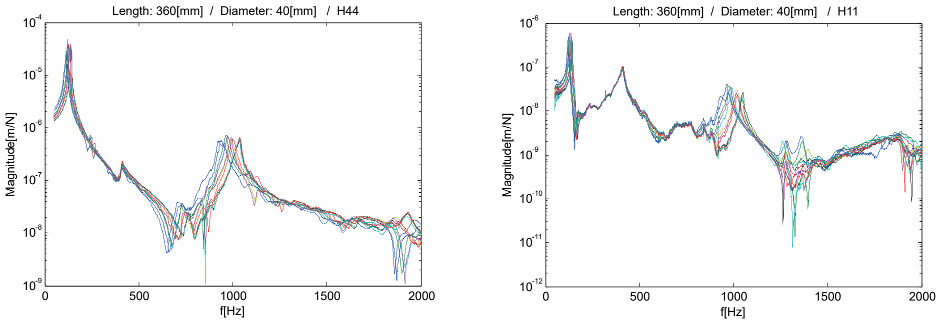

Fig. 8. Workpiece setup '3' – FRFs in points '1' and '4'

examined setups, it was for this case that the impact of the spindle rotational position turned out to be the most influential. The first mode ranged 136–137 Hz for the 'a' position, 119–121 Hz for the 'b' position, 126–129 Hz for 'c' and 139–142 Hz for position 'd'. In all cases, as with setups 1–2, the second mode has the highest repeatability, irrespective of rotational position. Discrepancies for the third mode were significant for all rotational positions.

The results of the impact tests for the last considered setup are presented in Fig. 9.

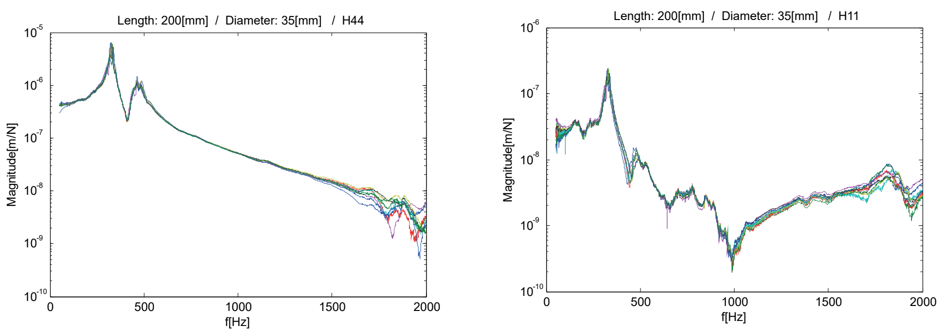

Fig. 9. Workpiece setup '4' - FRFs in points '1' and '4'

The structure of the FRFs of setup '4' is different from the other three setups due to observed dynamic absorber effect [5] that occurs when the natural frequency of the workpiece approaches the natural frequency of the spindle (410–420 Hz), splitting it into two resonant frequencies. Moreover, due to the highest stiffness, in the considered frequency range only two modes have been observed. There was also no effect of the rotational position of the spindle to the variability of the FRFs.

4. Conclusions

In this paper, the issues of repeatability of experimentally obtained FRFs of the machine tool–holder–workpiece for the turning operation are presented. The experimental tests were carried out for four configurations of the workpiece mounted in the 3-jaw chuck of the same, new lathe. For all considered configurations, the variability of results has been observed; however, this has been within different ranges. In setups 1 and 3, the angular position revealed its influence on the obtained FRFs, but not for all positions. Moreover, in configurations 2 and 4, this influence was not observed, and therefore this factor cannot be considered as the main cause of the discrepancies. The results may indicate the need for variability analysis of FRFs depending on the particular workpiece. Only such analysis would allow the reliable identification of the areas of stable machining by applying stability lobes uncertainties.

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