Analysis of the Table Motion of a 3-Axis CNC Milling Machine Tool at Start-up and Braking

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Abstract. The main goal of the paper was to analyze the table motion of a 3-axis CNC milling machine tool. The analysis involved measuring the velocity, acceleration and delay as well as the distance and time associated with the machine motion during idling. The measurements were made with a laser interferometer and an ultrahigh-speed digital camera. A comparative analysis of the motion parameters results obtained by various measuring methods is made. The accuracies of displacement, velocity and acceleration differ depending on the employed measuring system. The stabilization of velocity and acceleration (delay) parameters requires time depending on the defined feed rate. An increase in the set feed rate leads to a decrease in the amplitude of velocity and acceleration (it has a positive effect on the values of the tested parameters). The knowledge of machine tool dynamic characteristics, i.e. acceleration, velocity, vibration, positioning time, resonance and damping, is of vital practical importance in many applications. The experiments are described, and obtained results are discussed and presented in the form of plots and tables.

Keywords: Measurement · Displacement · Velocity · Acceleration · Delay

1 Introduction

Milling machines and machining centers are examples of very complex, multi-module machine tools used in the industry [1–3]. Kinematics of CNC machine tools determines their technological possibilities [4–6] while dynamic and static parameters determine their accuracy and stability [7–16]. Even the simplest numerical milling machine consists of many modules, i.e. special assemblies that are responsible for particular tasks of a given machine. A standard modular CNC machine consists of a body, drive unit as well as measuring and control systems. These issues are discussed in the works [7–16]. CNC milling machines are equipped with a complex computer system controlling the motion of individual modules [3, 6]. This is implemented by the machine tool drive units that are very complex and precise mechanisms ensuring the highest possible motion accuracy [4–6].

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2 Literature Review

The drive units of a CNC milling machine consist of a group of smaller drive components such as guides, drives, ball screws and sensory elements ensuring proper tool position [1]. Due to the fact that machine tools are equipped with the large number of motion-related systems, there may occur linear and rotational errors. In the papers [4, 5, 14] an integrated approach based upon simulation and experimental work for reducing the positioning errors of a small to medium size CNC machine-tools were analyzed. These errors arise as a result of wear, improper machine operation or collision. Another group of errors is associated with the start-up and braking of the machine table (or headstock) at idle run and during operation at reversal points [4–6]. These errors result from the dynamics of motion and the impact of inertia forces exerted by moving masses. In the papers [7–13] investigation of the dynamic characteristics and machining stability were analyzed. A survey of literature [1–6] has demonstrated that in some cases of machining (e.g. with complex-shape seats), when the machining plane is changed or at reversal points, the above motion errors occur in the work-piece at start-up and braking. Therefore, they should be avoided in machining, and more advanced numerical strategies should be employed [16–18]. The applications of measurement of different parameters of CNC machine tools and their methodology especial using for moto-drives (high-frequency electromagnetic fields, noise, friction, kinematic, etc.) and CAx systems modeling used in manufacturing and CNC branch are outlined in many scientific papers [16–30].

3 Research Methodology

The main goal of the study is to analyze the kinematics of a 3-axis CNC milling machine during idling. The analysis involves measuring the velocity, acceleration and delay as well as displacement and time associated with the machine tool motion in the numerically–controlled axes X, Y, Z, at start–up and breaking. Experiments are run 5 times per every numerically controlled axis and every tested velocity. Results of the motion parameters are compared and presented as the arithmetic mean of the test runs for the investigated velocities and individual numerically–controlled axes. The measurements are made for the 3 axes (X, Y, Z) at five different feed rates v_{fi}, where i = 1, 2, 3, 4, 5 (v_{f1} = 0.033 m/s, v_{f2} = 0.067 m/s, v_{f3} = 0.1 m/s, v_{f4} = 0.133 m/s, v_{f5} = 0.167 m/s). The experiments consist in measuring and analyzing all motion–related parameters of the machine tool such as feed rate v_{fi} [m/s], acceleration a[m/s^2] and displacement s [m]. The measuring length is set equal to L = 200 mm, and contains both the start–up and braking of the machine working unit tool under study.

3.1 Test Stands

The object of the study is a 5 – axis machining center, DMU 65 MonoBLOCK, provided with Sinumerik CNC controls (Fig. 1a). The working unit of the machine tool under study is a headstock moving along 3 numerically–controlled axes, X, Y, Z, mounted in the rolling guides (Fig. 1b). Based on a survey of literature and experimental plan, the kinematics of the 5–axis CNC milling machine is investigated using two measuring systems: Ametek's ultrahigh–speed digital camera Phantom v2511 (Fig. 2a) provided with the Carl Zeiss Planar 1,4/50 ZF2 lens and the Renishaw XL – 80 laser interferometer (Fig. 2b).

a) b)

Fig. 1. Test object: (a) 5 – axis milling center DMU 65 MonoBLOCK, (b) headstock work unit.

a) b)

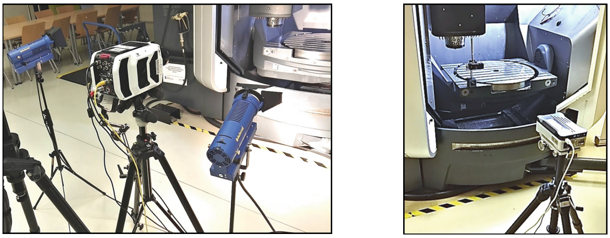

Fig. 2. Test stand and methods: (a) stand with the Phantom v2511 ultrahigh–speed digital camera, (b) Renishaw XL – 80 laser interferometer.

The Phantom v2511 has the following specifications: throughput speed: 25 [Gpx/s]; full resolution: 1280 × 800 [px]; maximum frame rate at full resolution: 25600 [fpse, 10,000T color; bit depth: 12 [bit]; pixel size: 28 [µm]; maximum frame rate at 128 × 32 [px]: 1000000 [fps]; ISO: 100,000T monochrom 35.8 × 22.4 [mm]; minimum exposure: 1 [µs]. The Renishaw XL–80 laser interferometer is primarily used to measure errors of CNC machine tools (positional accuracy and repeatability). Owing to advanced algorithms, it also enables measurement of displacement, velocity and acceleration. Interferometry is used to measure relative displacement (initial position measurement), and not absolute displacement (measurement of a specified position). The XL–80 laser system enables continuous data capture at up to 50 kHz. The experiment was performed at room temperature (21 °C). No significant changes in the temperature were observed during the tests. The room thermal stability was maintained at 0.5 °C. According to the experimental plan, 5 measurements were made for each of the 5 tested feed rates v_{fi} *(i-1,2, 3, 4, 5)* and 3 numerically–controlled axes, X, Y, Z. The results obtained with the Phantom v2511 camera were analyzed using the specialist

Tema Motion software, while those obtained with the XL – 80 laser interferometer were analyzed with the use of the QuickViewXL software package. These systems are designed for real–time data capture and review of dynamic data from the system.

4 Results

Figures 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12 present the results of displacement s, velocity v and acceleration a in the axes X, Y and Z, obtained for 5 different feed rates v_f. Figure 3 shows the plot illustrating the displacement *s* of the CNC machine tool headstock unit versus time *t* in the X-axis. The results were obtained with the use of the Ametek Phantom v2511 ultrahigh–speed digital camera.

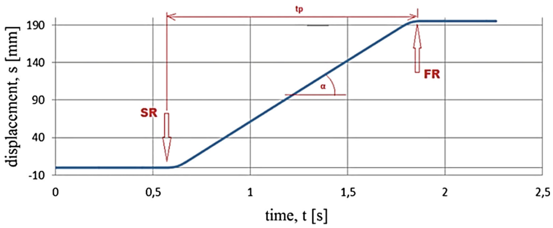

Fig. 3. Displacement s versus time t in the X – axis, obtained with the Ametek Phantom v2511: SR – start of motion, FR – end of motion, *tp* – time of motion, *s* – displacement vs time slope *t*.

The plot shows the displacement of 200 mm at the set velocity versus the time t = 1.2 s. Figure 4 shows the variations in the velocity v versus time t in the X–axis during the motion of the CNC machine tool headstock, obtained with the use of the Ametek Phantom v2511. Figure 4 clearly shows the presence of an increasing velocity slope at tr, when the machine tool working unit achieves the full set velocity. A similar situation can be observed at the breaking time th when the machine tool achieves the preset velocity. In addition to that, one can clearly observe some interference in the machine velocity over the measuring length set at L = 200 mm. The highest feed rate variations can be observed in the middle of the measuring length.

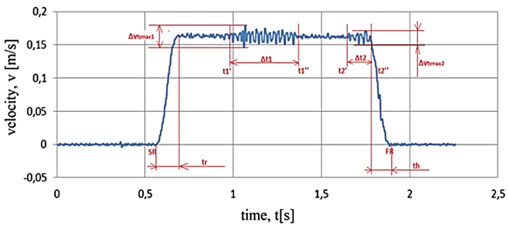

Fig. 4. Velocity *v* versus time *t* in the X – axis, obtained with the Ametek Phantom v2511: SR – start of motion, FR – end of motion, t_r – start–up time, t_h – breaking time, Δv_{fmaxi} – maximum feed rate variation, $t_{1(2)}^{'('')}$ – time of the beginning and end of the maximum feed rate variation Δv_{fmaxi}.

Figure 5 shows the plot of acceleration a versus time t in the X–axis, obtained with the Ametek Phantom v2511. Figure 5 points to a clearly dynamic nature of the acceleration variations, which is manifested as an increasing acceleration amplitude at the start–up of the machine tool working unit. A similar delay of motion can be observed at breaking. The acceleration dynamically changes in the middle of the measuring length, and the amplitude amounts to 10 m/s^2. This means that the idle run of the machine tool working unit is uniformly accelerated motion (or delayed at breaking), and it changes dynamically with displacement of the machine tool working units.

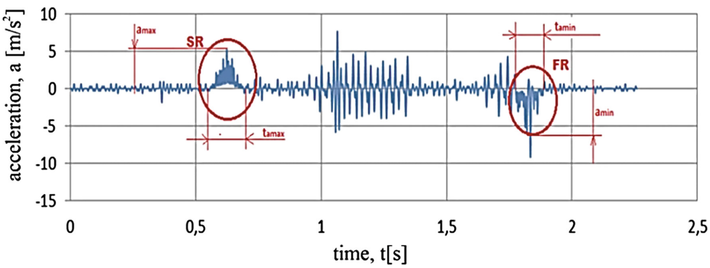

Fig. 5. Acceleration a versus time t in the X – axis, obtained with the Ametek Phantom v2511: SR – start of motion, FR – end of motion, $t_{a(max,\ min)}$ – time of variations in motion acceleration (delay), $a_{(max,\ min)}$ – amplitude of acceleration (delay).

Similar results were obtained with the use of the Renishaw XL–80 laser interferometer. Figure 6 shows variations in the displacement of the CNC machine tool headstock unit versus time t in the X–axis, obtained with the Renishaw XL–80. Figure 7 illustrates the variations in the velocity v, while Fig. 8 shows acceleration a versus time t.

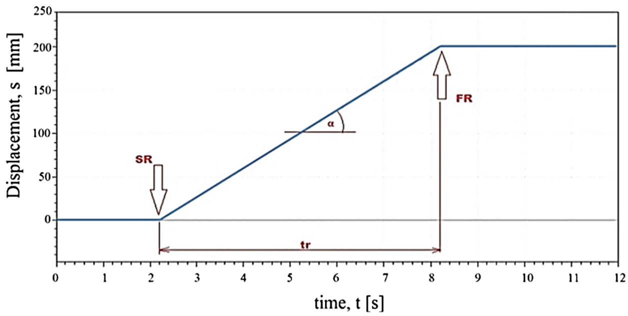

Fig. 6. Displacement s versus time t in the X – axis, obtained with the laser interferometer, SR – start of motion, FR – end of motion, t_p – time of motion, s – displacement vs time slope t.

Figures 6, 7, 8 show the results obtained with the XL – 80 laser interferometer. It can be observed that they are similar to those obtained with the ultrahigh–speed digital camera (Figs. 3, 4, 5).

The maximum displacements s_{max} versus the tested feed rates v_{ft} are compared in Figure 9. The displacements measured with the high–speed camera are lower by approx. 5 mm than the measuring length $L = 200$ mm, which leads to significant errors in their identification. The displacements measured with the laser interferometer are more accurate, as the measuring accuracy is approx. 0.01 mm.

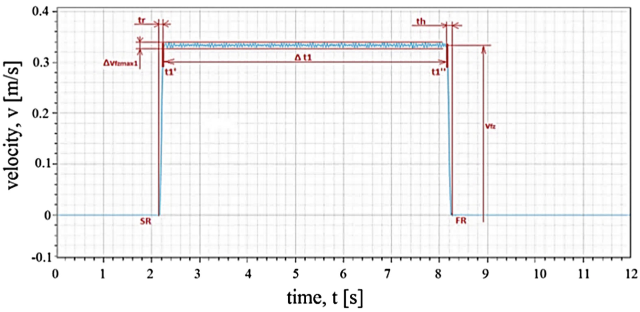

Fig. 7. Velocity v versus time t in the X – axis, obtained with the Renishaw XL – 80: SR – start of motion, FR – end of motion, t_r – start-up time, t_h – braking time, $\Delta v_{fmax\ i}$ – maximum feed rate variation, $t_1^{'(")}$ – time of the beginning and end of the maximum feed rate variation $\Delta v_{fmax\ i}$.

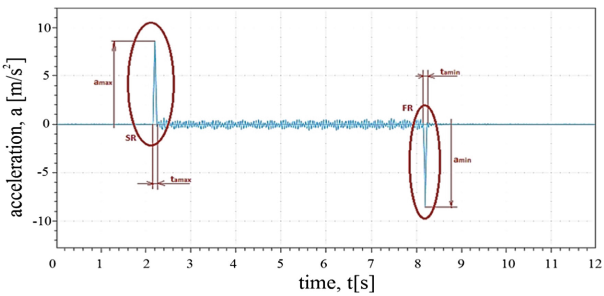

Fig. 8. Acceleration a versus time t in the X – axis, obtained with XL – 80 laser interferometer: SR – start of motion, FR – end of motion, $t_{a(max,\ min)}$ – time of variation in motion acceleration (delay), $a_{(max,\ min)}$ – amplitude of acceleration (delay).

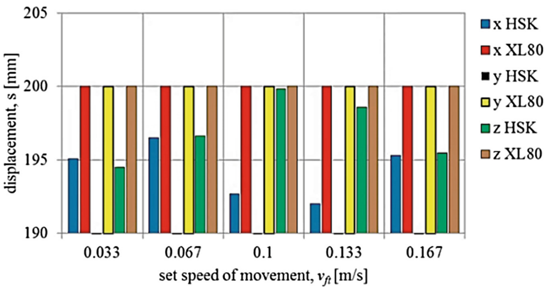

Fig. 9. Displacement s versus set feed rate $v_{ft,}$ depending on the axis and measuring system.

Figure 10 compares the velocity v_{fm} and the set feed rates v_{ft}, depending on the axis and the employed measuring system.

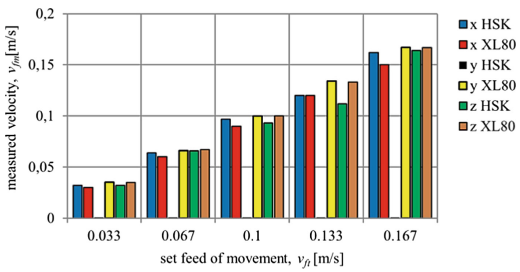

Fig. 10. Measured velocity v_{fm} versus set feed rate v_{ft}, depending on the axis and measuring system.

Figure 11 compares the accelerations a_{max} and the feed rates $v_{ft,}$ obtained for individual axes with the use of two measuring systems. The lowest acceleration a_{max} was obtained at v_{ft} = 0.033 m/s. With increasing the feed rate v_{ft}, the acceleration begins to increase linearly. The results obtained for individual systems are similar.

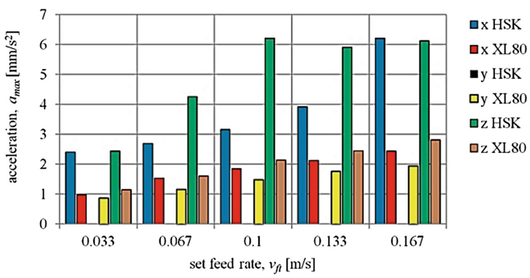

Fig. 11. Acceleration a_{max} versus feed rate v_{ft}, depending on the axis and measuring system.

Figure 12 compares the results of the delay of motion a_{min} as a function of the set feed rate v_{ft}.

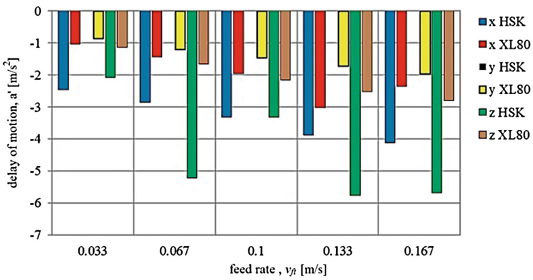

Fig. 12. Delay of motion a_{min} versus feed rate v_{ft}, depending on the axis and measuring system.

The negative acceleration values shown in Fig. 12 indicate a motion delay resulting from the deceleration of the CNC machine tool headstock. One can observe differences between the results, depending on the employed measuring system.

5 Conclusions

The knowledge of machine tool dynamic characteristics, i.e. acceleration, velocity, vibration, positioning time, resonance and damping, is of vital importance in many applications. These characteristics affect operating parameters such as positioning accuracy and repeatability, as well as the quality of machine system mating surfaces and their wear. The machine tool drive must ensure high positioning accuracy, displacement stability – especially at low velocities – and low resistance to motion by minimizing the friction factor value in the guides and power screws. This leads, among others, to lower energy consumption by the engines. At the same time, the drive must provide a wide range of feed rates, high spindle rotational speeds as well as high rigidity of the entire system to ensure displacement stability and adequate machining conditions. Taking into account the experimental results, one can draw the following conclusions:

– the displacements are stable,
– the accuracies of displacement, velocity and acceleration differ, depending on the employed measuring system,
– the start-up and braking stages of the machine tool working units are associated with higher amplitudes of velocity and acceleration,
– the stabilization of velocity and acceleration (delay) parameters requires time depending on the defined feed rate,
– an increase in the set feed rate leads to a decrease in the amplitude of velocity and acceleration (it has a positive effect on the values of the tested parameters),
– the headstock unit motion becomes more stable with increasing the machine tool velocity, while the highest amplitude values are related to low feed rates of the milling machine,

Thanks to above-mentioned systems, it is now possible to determine not only the machining tool positioning accuracy, but, first and foremost, to identify the machine's dynamic characteristics, i.e. acceleration, velocity, vibration, positioning time, resonance and damping. Based on the experimental findings, it can be claimed that the machine tool has very good dynamic parameters (velocity and acceleration). In a future research authors plan modeling and prognosis of the dynamical parameters and their errors with the help of artificial neural network. Also, we plan to examine the dynamic characteristics during work of CNC Machines Tools (during cutting) with different loading and feed rate in all numerical axis. This study confirms the possibility of using specified measuring systems to examine the kinematics of machine tools and other devices such as industrial robots. Considering the complexity of experiments and data processing, the use of laser interferometry can be regarded as the easiest method for identifying the dynamic characteristics of a machine tool.

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