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Machine Tool Table Dynamics Tests when Starting and Braking during an Operation Test

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ABSTRACT

The main objective of the presented research is to analyze the dynamics of table motion of a CNC FV580A 3-axis milling machine during machining with fixed technological cutting parameters. The research includes the measurement of velocity, acceleration and deceleration, as well as distance and time parameters related to the movement of the machine's table during starting and braking during work tests. The results of the measurements were recorded using a Phantom v1610 high-speed video camera equipped with a Nikon ED AF NIKKOR 80:200 mm 1:2.8D lens, dedicated to the analysis of high-speed phenomena. The analysis presented in the publication includes a comparison of the results of the motion parameters obtained as a function of the feed motion speed v_f. The results of the obtained tests and their analysis are discussed and presented in graphs and tables.

Keywords: machine tools, machine dynamics, machining, acceleration, deceleration.

INTRODUCTION

Numerically controlled machine tools are one of the most commonly used machines operating in the metalworking industry (lathes, milling machines, drills, and others). However, milling machines and milling centres represent a very complex and multi-modular type of technological machine in modern industry. The authors of the study [7, 1, 10] analyse in detail the dynamics of machine tools. This work constitutes the basis for properly approaching the studying of modern technological machines. The authors of the paper [12, 15] analysed the dynamic state of a machine tool and its control [8, 19, 20].

The dynamics of modern numerically controlled machine tools are a very broad issue, covering several fields. These include issues in the field of machine mechanics and construction, electromechanics, pneumatics, thermodynamics, and machining of processed materials [5, 16, 21].

During the operation of a machine tool, an entire range of dynamic processes take place, regulated automatically by the machine's controls. The machine's dynamics arise directly from its design and the incorporated drive systems. It has a huge impact on the operation of the related to the machine tool, workpiece chuck and tool system, meaning the machine tool system, gripper, workpiece, and tool. This impact affects the quality of the workpiece and the dimensional tolerance of the workpieces [9, 24, 26].

Even the simplest numerical milling machine includes many modules, meaning individual assemblies and components that are responsible for individual tasks of a given machine. To carry out the machining of parts within a given dimension-shape tolerance, milling machines should meet the recommended requirements, which include high positioning accuracy and repeatability, both linear and angular movements, short drive reaction time at reversing points, small vibrations, axial and radial clearances as well as the machine's minimized geometric errors, etc. [2, 11, 13]. Only then we can be sure of the dimensional conformity of the workpieces and their repeatability, as well as a high efficiency allowing to achieve short production times, reliable performance of various machining procedures, and high reliability of operation [3, 6, 18]. That is why all assemblies and components of numerically controlled machines need to have the greatest possible structural accuracy, both geometric and kinematic, as well as very good dynamics [23].

A modular CNC (Computerized Numerical Control) machine includes, among others: bodies, drive units, or measurement and control systems. In the case of numerical milling machines, a complex CNC computer system is responsible for controlling individual modules. These movements are carried out by machine tool drives, which constitute highly complex and precise mechanisms, ensuring the greatest possible movement accuracy [27]. CNC milling machine drive units consist of a group of smaller components, such as: guides, drives, and rolling screws, as well as sensory elements responsible for the tool's proper positioning [4]. Due to the large number of motion systems used in machine tools, several errors, both linear and rotary, are possible. These errors arise as a result of wear, the machine's incorrect operation, or collision. A different group of errors can be exposed when starting and braking a machine table (or headstock), both when running in bulk and when working at reversing points. These errors have their basis in the dynamics of motion and the interaction of the inertia forces of the moving masses.

Literature [22, 28] shows that, unfortunately, during some machining cases (e.g. sockets with complex shapes) when changing the machining plane or at reversing points, such starting and braking cases are reflected in the accuracy of the workpiece. Therefore, we should avoid these phases (starting and braking) during the physical machining of parts when the tool is in contact with the workpiece, and use proper machine diagnostics, dynamic tests, and advanced numerical strategies [19, 25].

In order to do this, we have a number of tools at our disposal for analysing the accuracy of machine tools, for example, laser methods (interferometric systems), systems using kinematic ball rods, vision systems, multisensory induction systems, contact and non-contact methods, as well as methods for identifying dynamic parameters of machines [17]. The aim of dynamic tests of machine tools (measuring acceleration and velocity of movement, identifying vibrations, etc.) is primarily to assess or improve the dynamic properties that ultimately affect the accuracy of workpiece manufacturing. Machine tool dynamics tests also allow to assess the current technical condition of a given machine tool. By conducting a machine tool's dynamic tests, we are able to minimize production costs and increase the quality of products [10, 14, 29].

The article presents the results of preliminary tests of a numerically controlled milling machine table dynamics during an operation test, parameters of linear motion of drives, velocity, acceleration, and delays of the machine table as a function of the set feed velocity.

TEST DESCRIPTION

The conducted scientific tests aim to analyze the dynamics of an FV580A 3-axis numerically controlled milling machine table movement during an operation test. The research focuses on measuring velocity v_f [m/s], acceleration a [m/s^2], delay -a [m/s^2], as well as the distance s [m] and time t [s] - related to the movement of the machine table in a defined numerically controlled axis X - both during start and braking. The results of experimental tests were repeated 5 times on the numerically controlled X axis and for each defined feed velocity v_f. Comparative lists of motion parameters were developed as an arithmetic mean of the conducted repetitions, for the defined feed movement velocities v_f and the tested numerically controlled axis X. Measurements were made for the numerically controlled axis X with different feed velocities v_{fi}, where i = 1, 2,...,13. (v_{f1} = 100, v_{f2} = 250 v_{f3} = 500, v_{f4} = 750, v_{f5} = 1000, v_{f6} = 2000, v_{f7} = 3000, v_{f8} = 4000, v_{f9} = 5000, v_{f10} = 6000, v_{f11} = 7000, v_{f12} = 8000, v_{f13} = 9000 mm/min). The length of the measuring section was set at l = 0.1 m, which included run-up and braking of the working unit of the tested machine tool during operation tests.

Test model

The test model of analysing the start and braking dynamics of a working table of a three-axis vertical machining centre is presented in Figure 1. The model presents the fixed input quantity, and feed movement velocity, which assumed 13 different values. The interfering quantities that have an impact on the test object include quantities arising from the machining process and the machine tool: temperature fluctuations, voltage fluctuations, and movement resistance.

Fixed quantities are the machining depth a_p [mm] and the machining velocity v_c [m/min]. While the quantities analysed in the work were the movement s [m], the velocity v [m/min] and the acceleration a [m/s^2], and the delay $-a$ [m/s^2] of the machine table. A test model constructed in such a way allowed to implement the experiment in an orderly and systematized manner.

Test station

The test was carried out on a MOC Mechanicy FV580A three-axis machining centre with the Fanuc 0i-MC control system (Fig. 2). The FV580A vertical machining centre includes feed drives with servo motors from Fanuc in X, Y, and Z linear axes with rolling screws. The machine includes independent and direct drives for each axis. The subject of experimental tests was a table with T-slots with linear dimensions of 640×420 mm. The maximum feed of the machine tool table is: in the X axis = 580 mm, in the Y axis = 420 mm, in the Z axis = 510 mm. The power of the machine's spindle is 7.5 kW. The spindle is driven by a servo motor. The maximum spindle velocity is n = 8 000 rpm, while the maximum feed velocity during operation is v_f = 9 000 mm/min.

Recording the operation movements of the machine tool's table was possible thanks to using the phantom v1610 vision camera (Fig. 3.), which is characterized by high dynamics, good image quality, and high resolution. The basic parameters of the PHANTOM v1610 system are: bandwidth (16 Gpx/s), maximum resolution (1280×800 px), full resolution speed (16600 fps), maximum speed at 128×16 px (1,000,000 fps), ISO light sensitivity (38,000T mono, 3,500 T colour), bit depth (12 bit), pixel size (28 μm), sensor size (35.8×22.4 mm), minimum exposure time (1 μs). Apart from the PHANTOM v1610 camera and control unit (PC), the station has been additionally equipped with: HEDLER HF65 illuminating lamps, two DEDOCOOL lamps, and MANFROTTO 1178 tripods. During the conducted research work, the following camera measurement parameters have been used: an image with a resolution of 1280×800 pixels, and a frame rate of 16,000. It should be emphasized that such a resolution and

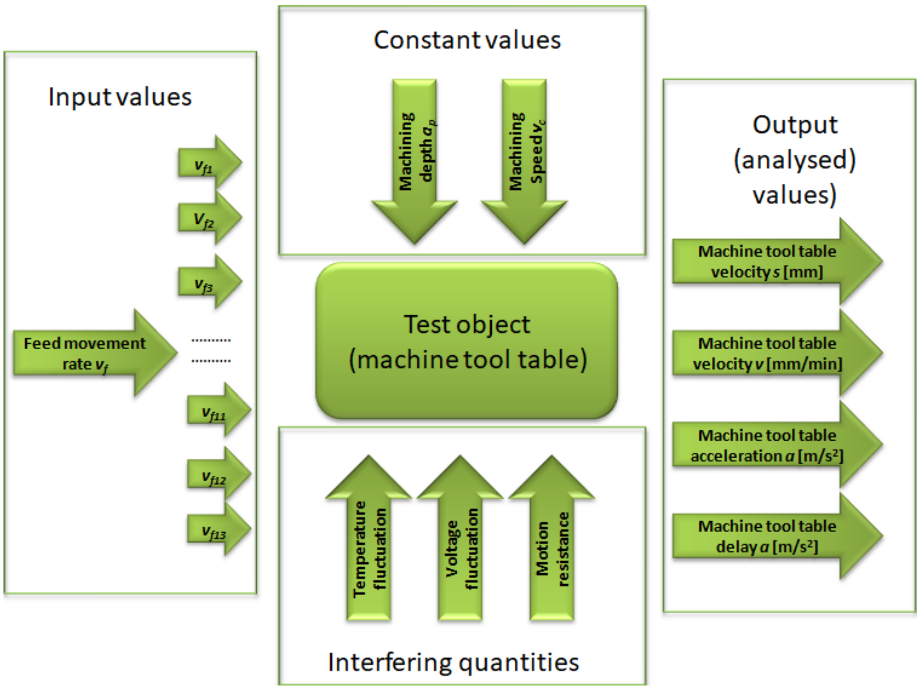

Fig. 1. Test model of analysing the dynamics of a machine tool table during an operation test

Fig. 2. MOC Mechanicy FV580A machining centre

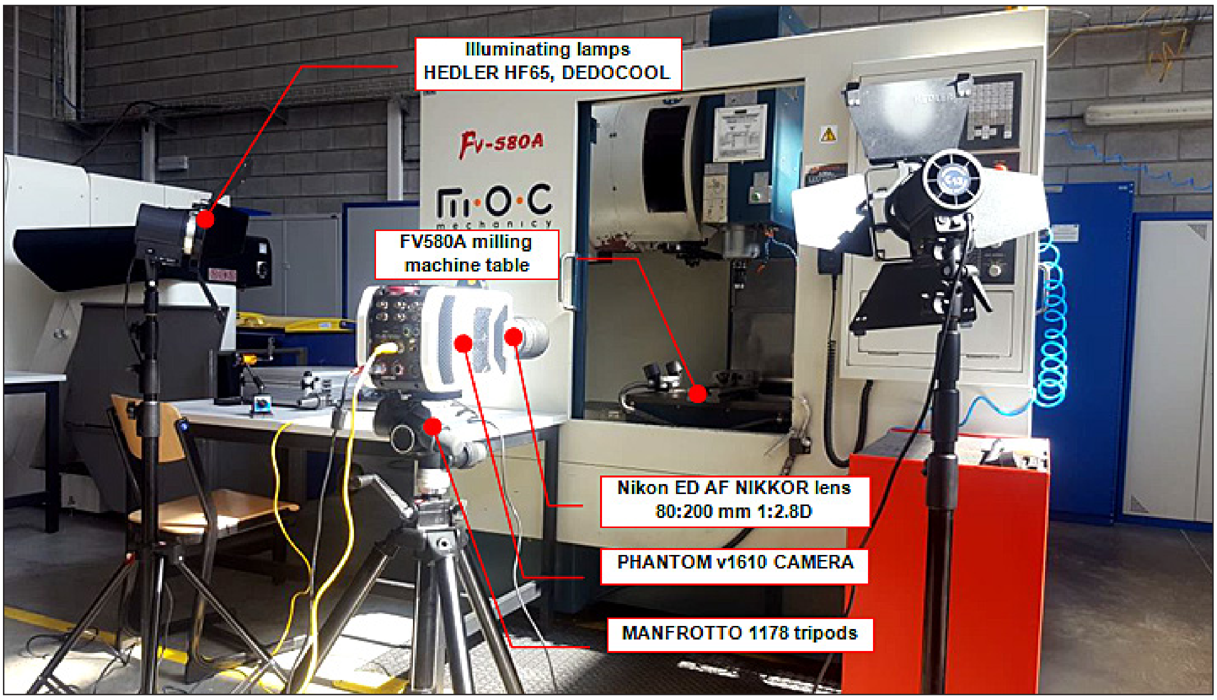

Fig. 3. Testing the dynamics of starting and braking the machine tool table with a camera for recording fast-changing phenomena with the Phantom v1610 vision camera

frame rate was enough to properly illustrate the course of the experiment. The camera has been equipped with a Nikon ED AF NIKKOR 80:200 mm 1:2.8D lens, dedicated to working in very intense light, which was directed at the object during experimental tests.

To carry out the experiment, reference points were placed in the machining zone (Fig. 4). Two static reference points marked in Figure 4 with the number (1) have been placed on a magnetic tripod. One of the dynamic points, sliding along with the machine tool table, was attached to the workpiece and marked with the number 2.

The entire machining area, including the determined markers, was included in the lens frame. The reference points constituted markers that were analysed in the environment of the Tema Motion computer program. The tests were carried out at room temperature (21 °C). During the tests, no significant changes in temperature were found. The thermal stabilization in the room was maintained at 0.5 °C.

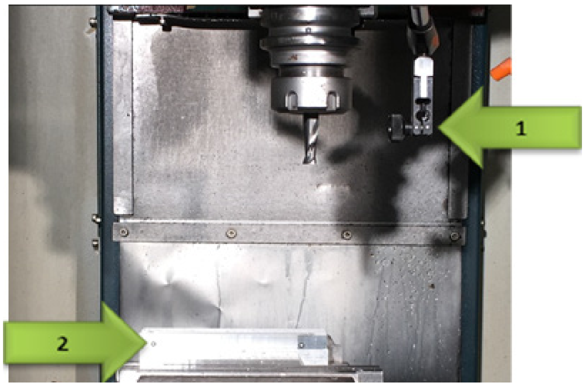

Fig. 4. Placing the reference points: 1– fixed reference points 6 mm apart, 2– moving point attached to the workpiece

Course of tests

The vision camera recorded the machine tool table's movement at a set feed rate. The obtained results were saved as video files. The recordings were later analysed in the Tema Motion program. The analysis was aimed at showing the start and braking of the machine's table when machining at a constant depth of cut as a function of time, for variable values of the set feed. The camera and special software allowed to obtain recordings which formed a basis for determining individual dynamic parameters of the milling machine table. Thanks to using camera image analysing software it was possible to achieve the observed values of movement s [m], velocity v [m/s] as well as acceleration/delays (a and $-a$ [m/s^2]) of the machine table during an operation test. The test experiment consisted in recording the movement of the milling machine table v [m/s] for thirteen different feed velocities v_{fi} [mm/min], while milling a workpiece. For each feed rate, v_{fi}, an image was recorded, and the values of movements s, velocity v and acceleration during start a and the delay during braking $-a$ were determined for the designated test point associated with the workpiece and at the same time the machine table as a function of time.

TEST RESULTS

Based on the tests conducted according to the model adopted, sets of values of linear movement of the milling table, velocity and acceleration when starting and delay during braking were obtained. The test results were averaged from individual test series (5 repetitions) for each set feed movement. Figures 5–8 present selected, exemplary time courses of changes in movement s [m] (Fig. 5), velocity v [m/s] (Fig. 6) as well as acceleration a [m/s^2] and delay $-a$ [m/s^2] (Fig. 7) as a function of time t [s], generated with the help of Tema Motion.

The diagram presented in Figure 5 shows the path corresponding to the machining distance s[mm] of 0.1 m, recorded at a set movement velocity of v_f= 3000 mm/min at t_p = 2.3 s. Figure 6 presents the nature of changes in the velocity of movement v[m/min] as a function of time t[s] during the movement of the CNC machine tool table in the X axis.

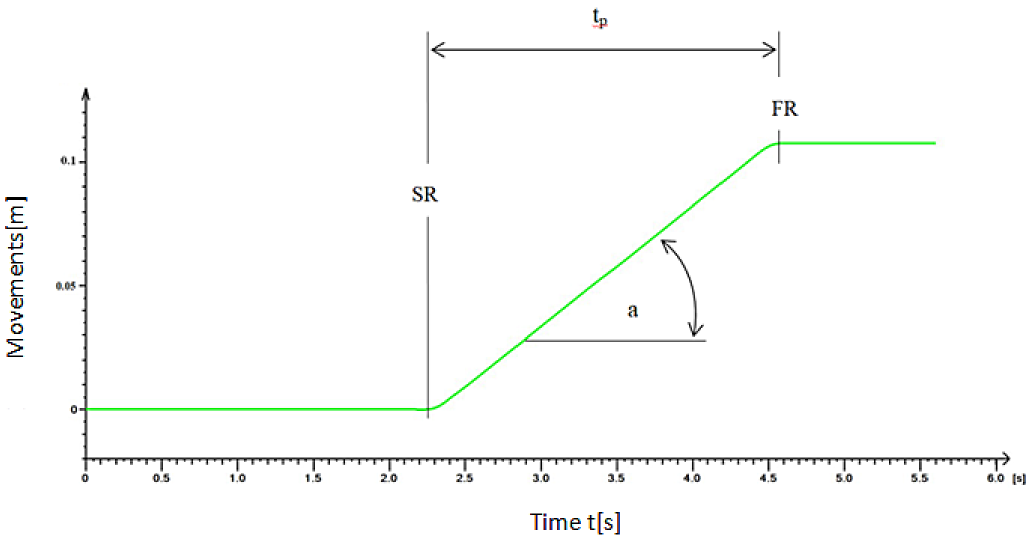

Fig. 5. Example of the course of changes of movement s [m] as a function of time t [s] during the CNC machines tool table movement in the X axis: t_p – movement time, a – angle of inclination of the travelled distance in time, SR-start of movement, FR-end of movement

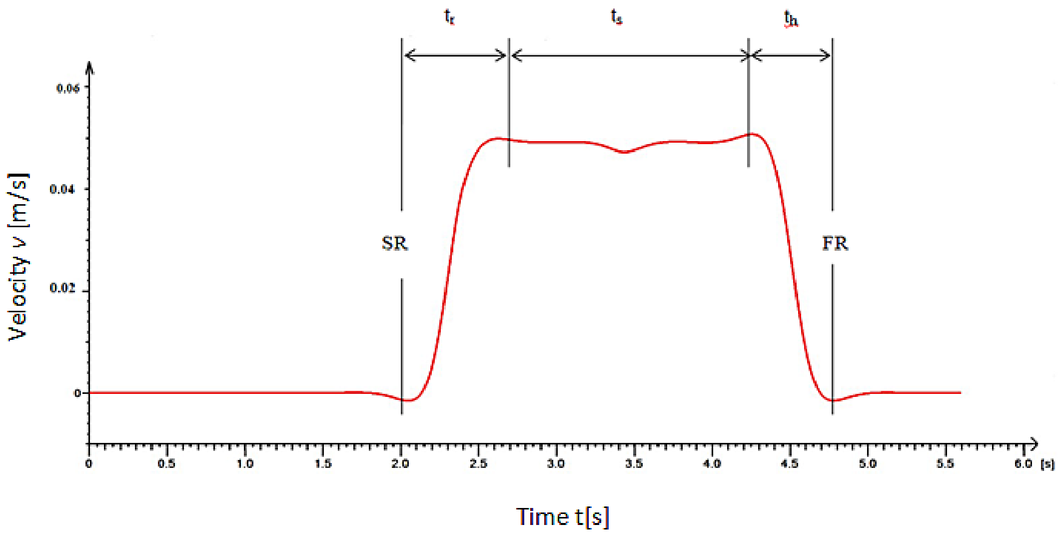

Fig. 6. Example curse of changes of velocity v[m/s] as a function of time t [s] during the CNC machine tool table movement in the X axis: SR– start of movement, FR– end of ovement, t_r– run-up movement time, t_h – movement braking time, t_s– stabilized operation time

Figure 6 represents the course of changes of velocity v [m/s] as a function of time t [s] during the movement of the CNC machine tool table in the X-axis, an increasing slope of the measured velocity v [m/s] in time t_r is clearly identifiable, during which a stable, constant level of the measured velocity value v [m/s] of the machine tool table movement in time t_s is achieved. When braking the linear movement of the machine table, a clear and repetitive falling slope of the recorded velocity of movement is outlined at time t_h. When the machine table reaches the velocity of motion v_f defined in the program, slight and repetitive fluctuations in the velocity of movement v occurring on the length of the measurement section s = 0.1 m are visible. The highest fluctuations in the movement velocity v were observed in the central part of the measuring segment corresponding to t_s.

Figure 7 presents the course of changes in acceleration a [m/s^2] as a function of time t [s] during the movement of the CNC machine table on the X-axis. Figure 7 shows a clear and dynamic nature of changes in the movement acceleration a when starting and delay -a when braking the milling machine table. These values represent two characteristic amplitudes: the amplitude of acceleration a at the start of the machine table movement and the amplitude of delay -a during braking. This shows that the working movement of the working unit of the machine is a uniformly accelerated (or delayed,

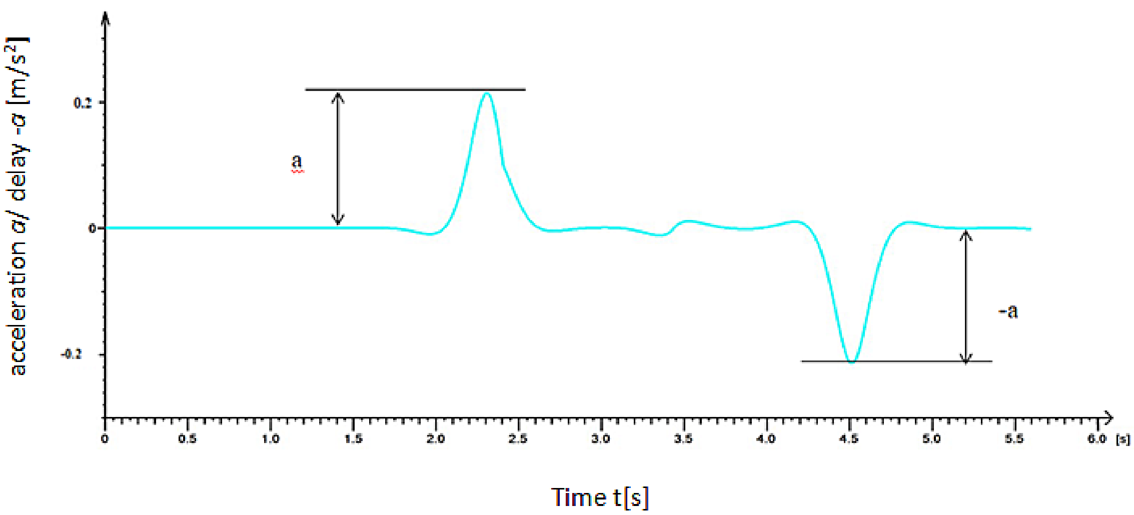

Fig. 7. Example of changes of acceleration a [m/s^2] as a function of time t [s] during the CNC machine tool table's movement in the X axis: a – acceleration amplitude, -a – delay amplitude

during braking) movement and changes dynamically during the movement of the machine table.

A distinguishing feature of the obtained time courses consists in the phenomenon of the occurrence of a characteristic peak on the velocity graph as a function of time *t* [s] for the set values of the table's feed velocities v_f [mm/min]. This peak occurs when the velocity increase value shifts towards a constant value. An analogous peak occurs when the velocity is reduced from constant to uniformly decreasing velocity until a complete halt of linear movement.

In the case of higher feed velocities, there was a reduction in rapid transition when starting and braking. To illustrate this relation, Figure 8 presents an example of the course of changes in the tested parameters as a function of time *t*. The graph shows the analysed parameters of velocity *v*, acceleration *a* / delay -*a* and distance *s* for a given velocity v_f=7000 mm/min. Red indicates velocity *v*, blue indicates acceleration *a* / delay -*a*, and green indicates movement *s*.

Based on the conducted analysis, tables of points characteristic of the machine tool table's

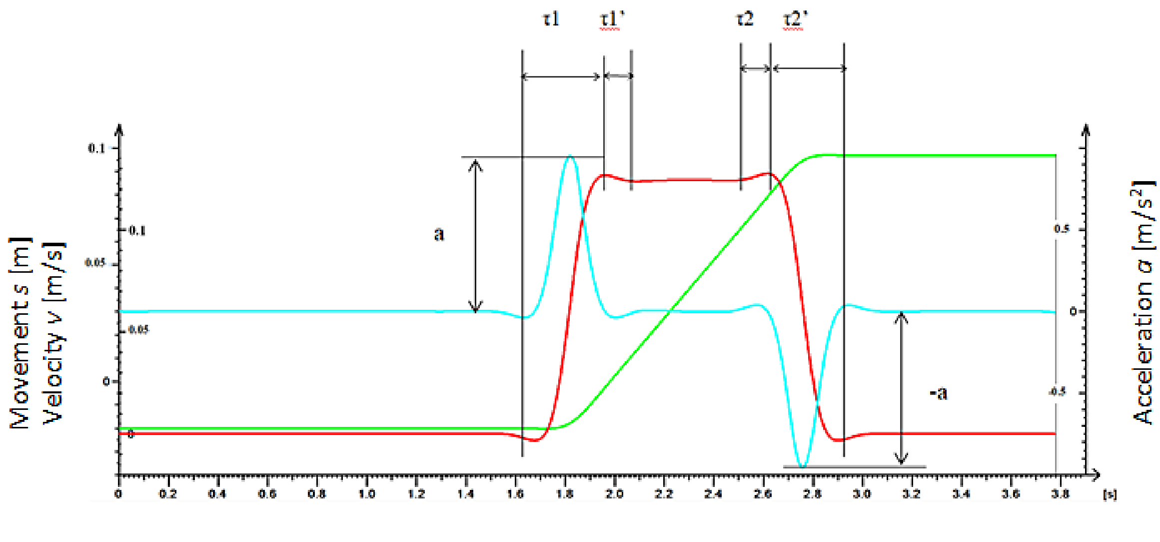

Fig. 8. The course of changes in movement, velocity, and acceleration as a function of time during movement of the CNC machine tool table in the X axis for a set feed rate v_f= 7000 mm/min, τ1 [s] – the time from start to reaching the maximum velocity value, τ1' [s] – time from reaching the maximum velocity value to obtaining a constant value, τ2 [s] time from constant value to reaching the maximum velocity, τ2'[s] - time from the maximum value to deceleration

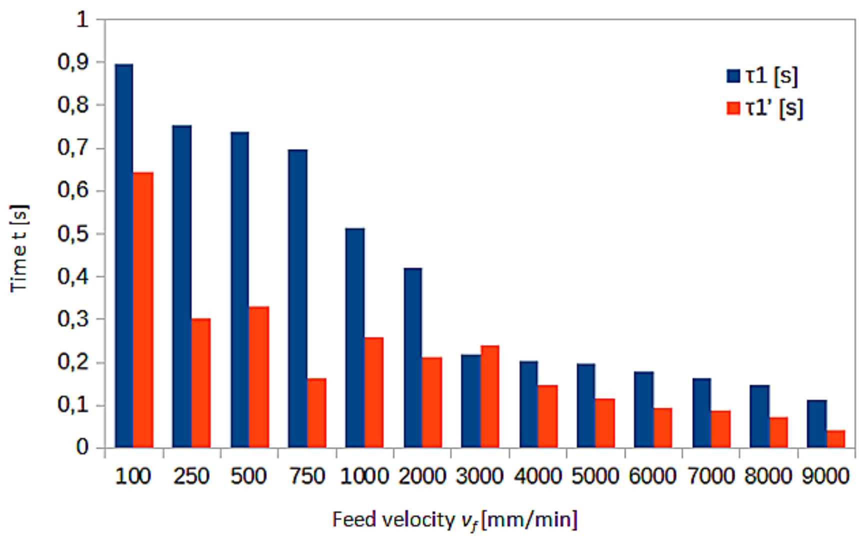

Fig. 9. A comparison of changes in time τ1 and τ1' as a function of the feed rate v_f of the machine tool table τ1 [s] – time from start to achieving maximum velocity, - τ1' [s] – time from reaching the maximum velocity value to achieving a constant value

different feed velocities were generated. A summary of the measurement results for the velocity of feed movement of the machine tool table is presented in the form of graphs in Figure 9, where - τ1 [s] is the time from start to achieving the maximum velocity value, - τ1’ [s] is the time from the maximum velocity to achieving a constant value.

Graphs in Figure 9 and Figure 10 present changes in the machine tool table’s movement *s* in the X-axis during the machining process at different feed velocities v_f. It is clear that in the case of times τ1, τ1’ the time τ1 for most velocities v_f is twice as large as time τ1’. Whereas, analysing the times τ2 and τ2’ it is possible to see that the time that has elapsed from starting braking to the complete loss of table velocity *v* is greater than time τ2.

The drive responsible for the machine tool table’s movement needed less time to minimize the velocity from the moment of braking to a complete stop than in the case of achieving the maximum velocity during the tool penetrating into the workpiece. This indicates the effect of occurring drive loads during the cutting process. The graphs

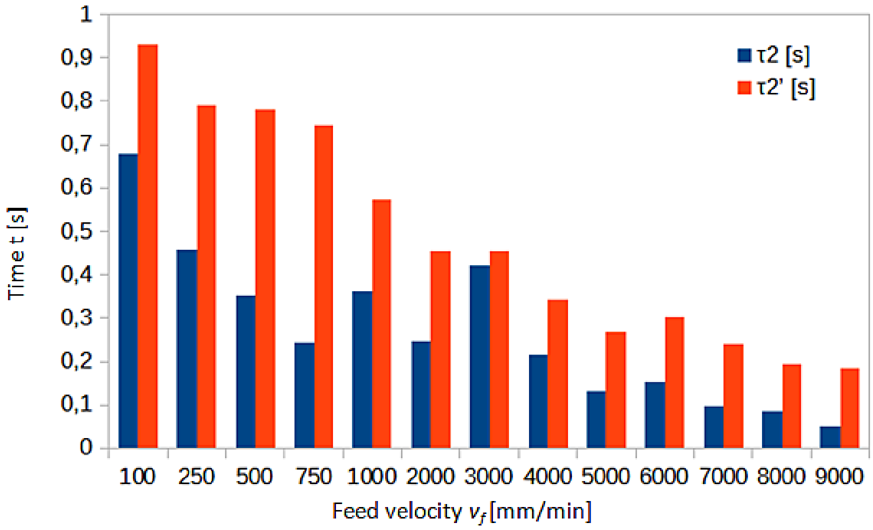

Fig. 10. A comparison of changes in time τ2 and τ2’ as a function of the feed rate *vf* of the machine table, τ2 [s] time from constant value to achieving maximum velocity, τ2’[s] - the time from the maximum value to braking

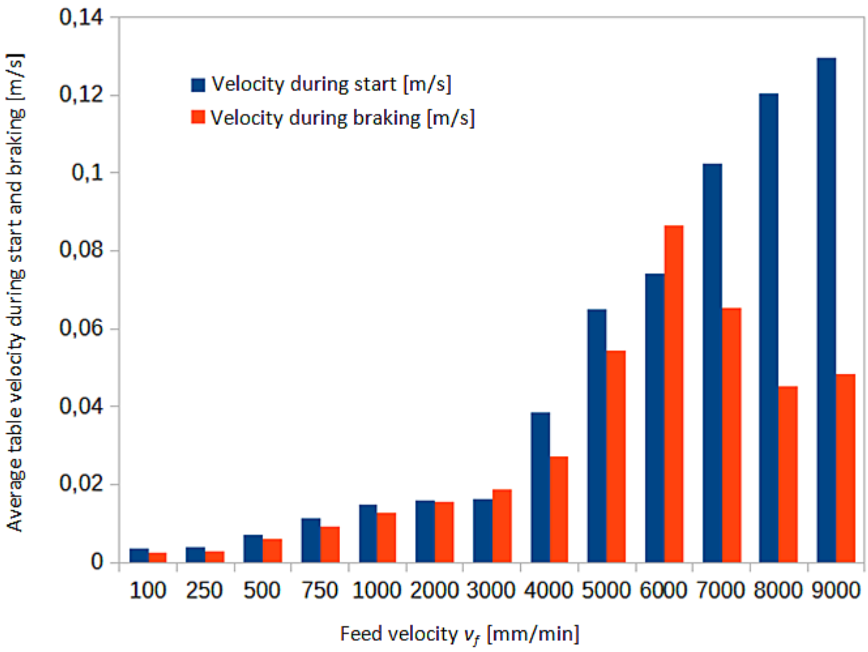

Fig. 11. A comparison of changes in average start and braking velocities as a function of feed rate v_f of the machine tool table

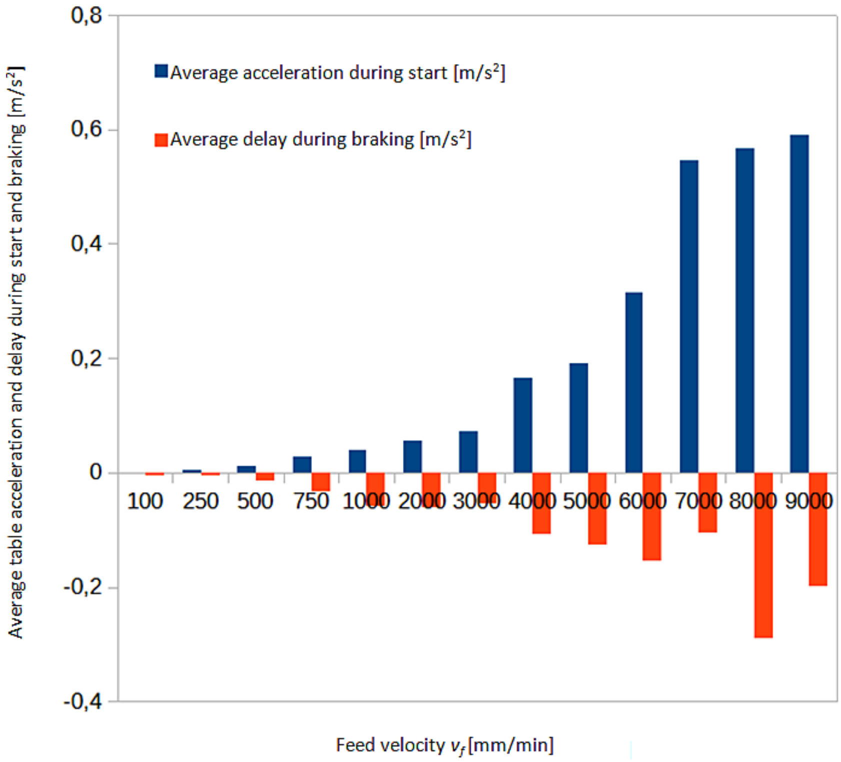

Fig. 12. A comparison of average acceleration and delay as a function of feed rate v_f of the machine tool table

also show that the drives allowing the machine tool table to move needed less time to reach the maximum velocity during the work test.

When analysing the results of changes in the average start and braking velocities of the machine tool table as a function of feed rate, it can be seen that as the velocity of feed movement increased, the table's average velocities of starting and braking increased. From the initial feed rate v_f= 100 mm/min to the velocity of v_{f7}=3000 mm/min, the differences between the table's average start and braking velocities were insignificant. From v_{f8}= 4000 mm/min, the differences between the average start and braking velocities were greater than compared to the initial feed velocities. In the velocity range from v_f=4000 mm/min to v_f=9000 mm/min, it can be seen that most of the values of the average start velocities were greater than the values of the average braking velocities.

When analysing changes in the average start and braking acceleration as a function of the feed rate v_f of the machine tool table, it can be seen that as the feed rate v_f increased, the average start acceleration and the average braking values of the table increased. The values of the average acceleration a during start were greater than the values of the average delay $-a$ during braking for all set values of the feed rate v_f.

CONCLUSIONS

Understanding the dynamic characteristics of a machining tool - changes in acceleration, velocity, vibration, and positioning time - is a key factor in terms of many applications. These characteristics have an impact on operating parameters such as positioning accuracy and repeatability. Machine tool drives are required to have high positioning accuracy, movement stability, especially at low velocities, as well as low resistance to movement resulting from minimizing the coefficient of friction in guides and propellers. This results, among other things, in lower energy consumption by the motors. At the same time, the drives are to provide a wide range of feed velocities, high spindle rotation velocities as well as high rigidity of the entire system, in order to ensure the stability of movements and proper machining conditions. Taking into consideration the conducted experimental tests, it can be concluded that:

- the movements are stable,
- the accuracy of movement, velocity, and acceleration is repeatable,
- starting and braking the machine table is associated with generating an increased amplitude of velocity and acceleration of movement,

- stabilizing velocity and acceleration (delay) parameters requires time strongly dependent on the defined velocity of movement,
- an increase in the set movement velocity implies a decrease in the amplitude of velocity fluctuations and acceleration (has a positive effect on the course of the tested parameters),
- the movement becomes more stable with an increase in the velocity of the machining tool's movement, the largest amplitude values are related to the low feed velocities of the milling machine.

Based on the conducted tests, it can be stated that the machine has very good dynamic parameters (stable velocities and accelerations).

Interpreting the test results, it can be observed that in terms of most feed velocities v_f during the machining process, the table delay values were less than the acceleration values.

Obtaining higher values of table velocity and acceleration during table start may have been associated with the stick-slip phenomenon, occurring at low feed velocities of elements between which friction is generated. When the machine operates at higher velocities, this phenomenon is reduced to zero, because the power of the machine drives is so high that it exceeds the resistance of the machining tool table as static friction. After analysing the values of the average velocities at starting and braking for the tested range of feed rate v_f of the table, it can be seen that the operation of the machine tool table is correct, and the occurring stick-slip phenomenon does not negatively impact the linear movement of the table during the operation test.

To sum up, the values of the start and braking velocities of the machining tool table, obtained in the experimental tests described in this article, are largely dependent on the general condition of the technological machine and the conditions in which the experiment is performed. Thanks to determining the characteristic dynamic parameters of the machining tool table movement, it is possible to easily determine its dynamics, which will affect the proper operation.

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