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THE CNC SYSTEM WITH STEPPER MOTOR DRIVES

ABSTRACT *In the paper the conception of CNC system with stepper motor drives is presented. The system consists of a PC computer and a stand-alone CNC controller based on FPGA (Field Programmable Gate Array). In order to eliminate geometric discontinuities of motion trajectory in "G" and "M" codes, special conversion to NURBS (Non Uniform Rational B-Spline) curves on the PC is realized. Additionally, optimization of the motion trajectory feedrate is achieved by using the Look-Ahead algorithm. In the stand-alone CNC controller the software processor and CLK pulses generator are implemented. CLK pulses with high resolution and varying time period are sent to each of drives independently. An appropriate test to verify the correctness of CNC system was realized.*

Keywords: *stepper motor drives, CNC controller*

1. INTRODUCTION

Most of CNC systems with stepper motor drives are open loop systems. Motor drives with microstepping mode affects to minimize torque pulsation and simultaneously increasing stepper motors angular resolution.

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The motion trajectories for multiaxial machines are most commonly described by "G" and "M" codes. The curvature fragments of motion trajectory in many cases are described by a G1 code (linear interpolation). This description produces geometrical discontinuities in the points of connection of various sections of the trajectory. This implicates abrupt feedrate changes during motion trajectory realization. In many cases this may cause vibration and loss of synchronism[5]. Eliminating the geometrically discontinuous of motion trajectory improves the quality of its realization. There are many ways of describing geometrically continuous motion trajectory [2, 3, 4, 6, 9]. In the paper, the description of motion trajectory is realized by means of NURBS curves.

One of the more well-known ways to implement velocity profiling of movement is Look-Ahead algorithm [1, 8, 11, 13]. The proposed algorithm is based on an analysis of motion trajectory described by NURBS curves. The trajectory is realized with variable feedrate. The speed is adjusted in regard to individual characteristics of each mechanical axle dynamics and the curvature realization of current motion trajectory part. Particular attention should be paid to not exceeding the maximum value of acceleration feeds of each axle. The maximum acceleration values are derived from the multiaxial machine specification supplied by the manufacturer or calculated from mathematical models of axles and anticipated load. Calculations related to the analysis of motion trajectory are computed on-line.

2. THE ARCHITECTURE OF CNC SYSTEM

The block diagram of the proposed CNC system is shown in Figure 1. The system can run with stepper motor drives and servo drives.

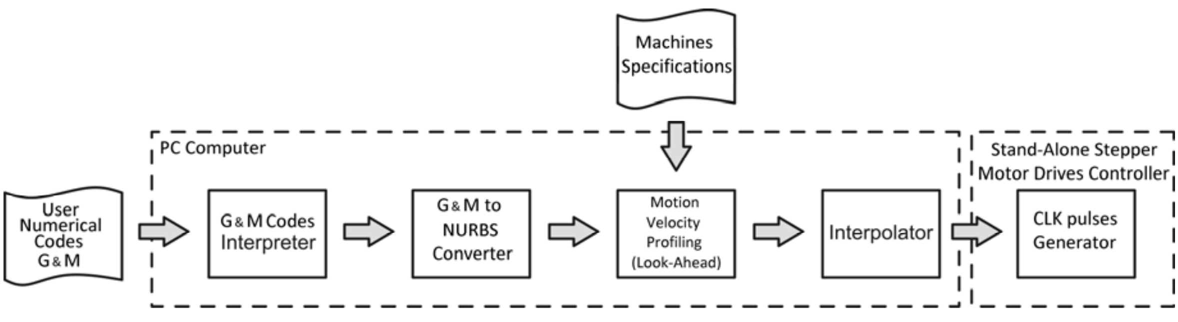

Fig. 1. The conception of CNC system

In the system, the motion trajectory is described by "G" and "M" codes. The interpreter block transforms numerical codes to NURBS curves form. Motion optimization is conducted by the feedrate profiling block using Look-Ahead algorithm. The interpolation block generates the next position of the axle.

Modern multiaxial machine control systems with stepper motor drives can run with high velocity (about 5-30 m/min). When designing control system, the dynamic development of stepper motor drives must be taken into account.
For the exampled parameters of the mechanical axle:

- linear velocity of slides – 15 m/min;
- lead of rolling screw gear – 5 mm/turn;

and a resolution of the stepper motor drive – $2\pi/51200$ (200 steps per turn, driver in 256 microstepping mode), the frequency pulse CLK (to drives) is 2.56 MHz. The jitter of CLK pulse ought to be as small as possible. The CLK pulses generation at high resolution and trajectory analysis described by NURBS curves using Look-Ahead algorithm, requires large resources and computing power of machine control system.

The proposed CNC control system is based on a PC and the stand-alone CNC controller (Fig. 2).

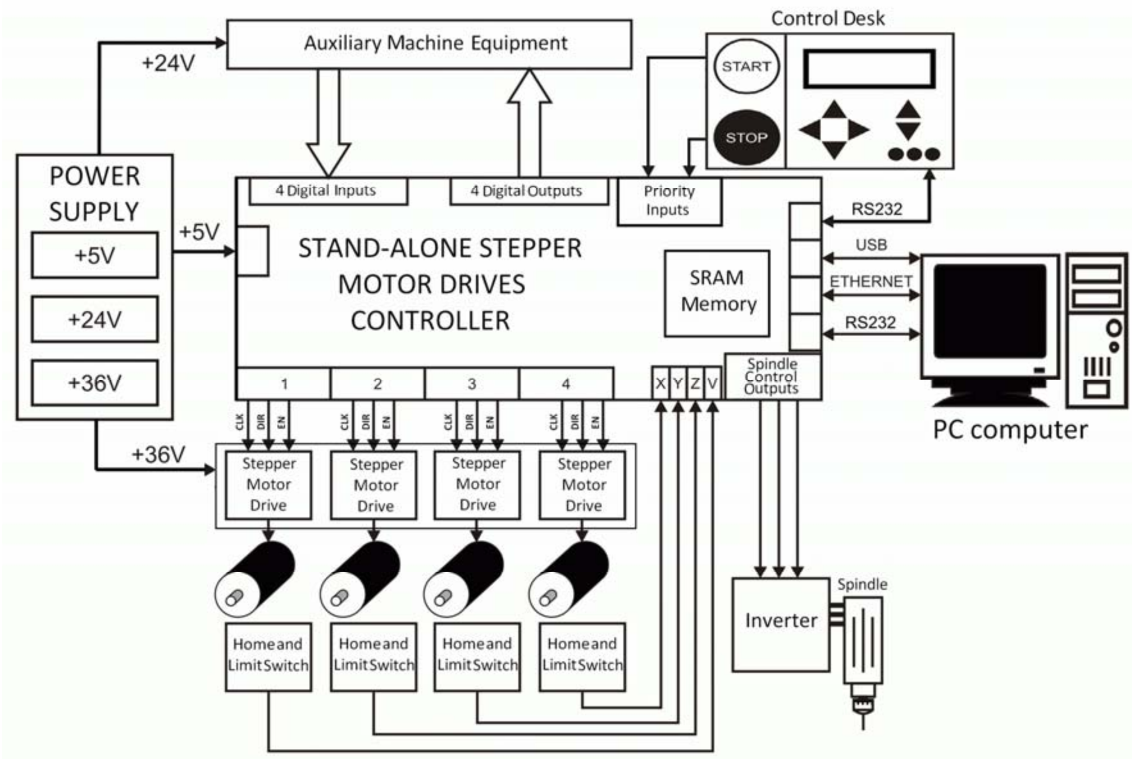

Fig. 2. The architecture of CNC control system

Calculations performed on the PC include: conversion of motion trajectory in the "G" and "M" codes to the NURBS curves form, feedrate profiling using Look-Ahead algorithm and interpolation. The data from the PC computer are sent to the stand-alone CNC system controller via Ethernet, USB (Universal Serial Bus) or RS232. The stand-alone CNC controller is based on a FPGA device. The controller calculates data from PC to form of pulses with variable time period and generates the CLK pulses at high resolution to stepper motor drives.

3. TRAJECTORY CONVERSION FROM “G AND M” CODES TO THE NURBS CURVES

The CAD/CAM systems usually generate motion trajectory in G1 codes. A motion trajectory represented in G1 codes, is geometrically discontinuous and a large amount of resources for its description are needed. Other form of description include parametric curves [3, 12] or different varieties of Bézier curves [1, 6, 8, 11]. In the CNC system the proposed representation are NURBS curves. The example of motion trajectory described by NURBS curves is presented in Figure 3.

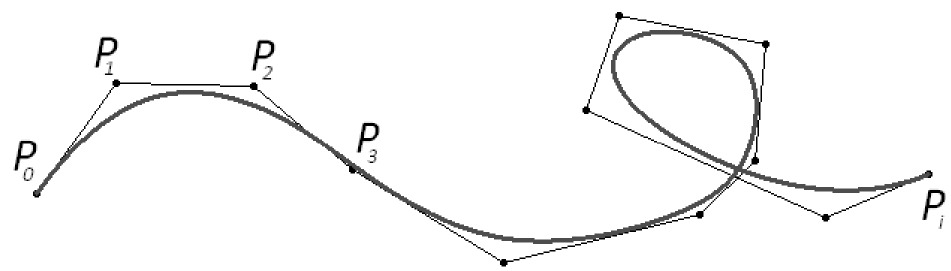

Fig. 3. The example of motion trajectory described using NURBS curves

The parametric representation of NURBS curves is [10]:

$$C(u) = \sum_{i=0}^{n-1} \frac{N_{i,k}(u) \cdot w_i}{\sum_{j=0}^{n-1} N_{j,k}(u) \cdot w_j} \cdot P_i \qquad \text{where:} \qquad P_i = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} \tag{1}$$

where:

- $C(u)$ – the point coordinates on the curve for the specific value u,
- P_i – control points,
- w – weights,
- n – the number of control points,
- k – curve degree,
- $N_{i,k}(u)$ – the k-th-degree basis function,
- u – parameter accepting the value of (0,1), identifying location on the curve.

Basic functions are defined using a recurrent formula:

$$N_{i,k}(u)=\frac{(u-u_i)\cdot N_{i,k-1}(u)}{u_{i+k}-u_i}+\frac{(u_{i+k+1}-u)\cdot N_{i+1,k-1}(u)}{u_{i+k+1}-u_{i+k}} \quad \text{where:} \quad N_{i,0}(u)=\begin{cases}1 & u\in[u_i,u \\ 0 & u\notin[u_i,u\end{cases} \qquad (2)$$

Equation (1), can describe a straight line and a conic section. The motion trajectory conversion algorithm from the "G" and "M" codes to NURBS curves is described in [7]. That work focuses mainly on the line segment elimination described by G1 codes. The revised description still contains geometrical discontinuous points.

In many cases, there is a possibility of motion trajectory realization with a specific contour error tolerance. In such cases the motion trajectory can be modified to form which eliminates all the geometrical discontinuities. The proposed modification includes circular motion trajectory interpolation in part where geometrical discontinuities occur. The motion trajectory conversion algorithm from "G" and "M" codes to NURBS curves is implemented in application on a PC computer.

4. MOTION TRAJECTORY VELOCITY PROFILING

In most cases motion trajectory is realized with constant motion velocity. One of many ways of velocity profiling is the Adaptive Feedrate algorithm [12]. The motion velocity is calculated according to the following formula:

$$V=\begin{cases}F & V_{af}>F \\ \frac{2}{T}\sqrt{\rho^2-(\rho-\delta_{\max})^2} & V_{\min}<V_{af}<F \\ V_{\min} & V_{af}<V_{\min}\end{cases} \quad \text{where:} \quad \rho=\frac{1}{\kappa}, \quad V_{af}(\rho)=\frac{2}{T}\sqrt{\rho^2-(\rho-\delta_{\max})^2}\ , \qquad (3)$$

where:

- V – calculated feedrate,
- F – desired feedrate,
- $V_{\min}$ – minimum feedrate,
- V_{af} – federate with constrained chord error,
- $\delta_{\max}$ – chord error tolerance,
- ρ – radius of curvature,
- κ – curvature, calculated from the formula:

$$\kappa(u) = \frac{\left|C'(u) \times C''(u)\right|}{\left|C'(u)\right|^3}, \tag{4}$$

The disadvantage of Adaptive Feedrate algorithm is discontinuous motion velocity, which causes sudden changes of acceleration. To avoid this shortcoming, the feedrate profile should be generated as an "S" profile with simultaneous forward motion trajectory analysis – Look-Ahead algorithm.

Look-Ahead algorithm implemented in CNC control system realizes both motion trajectories described in the “G” and “M” and NURBS curves.

5. STAND-ALONE STEPPER MOTOR DRIVES CONTROLLER

Stand-alone stepper motor drives controller is based on Spartan 3E 1600 FPGA device. In its structure the software 32-bit Harvard RISC MicroBlaze processor, the interpolator block and the generator of CLK pulses for stepper motor drives are implemented. The MicroBlaze processor converts the data obtained from the PC computer in form of displacement in constant time period to a form of constant displacement in variable time period. Additionally, the processor configures CNC control system, sets digital inputs and outputs, communicates with the PC computer and controls auxiliary machine equipment. The generator block implemented in FPGA structure generates CLK pulses for stepper motor drives in real time. The blocks implemented in FPGA structure and calculations done by the processor run parallel. The schematic diagram of stand-alone stepper motor drives controller is presented in Figure 4.

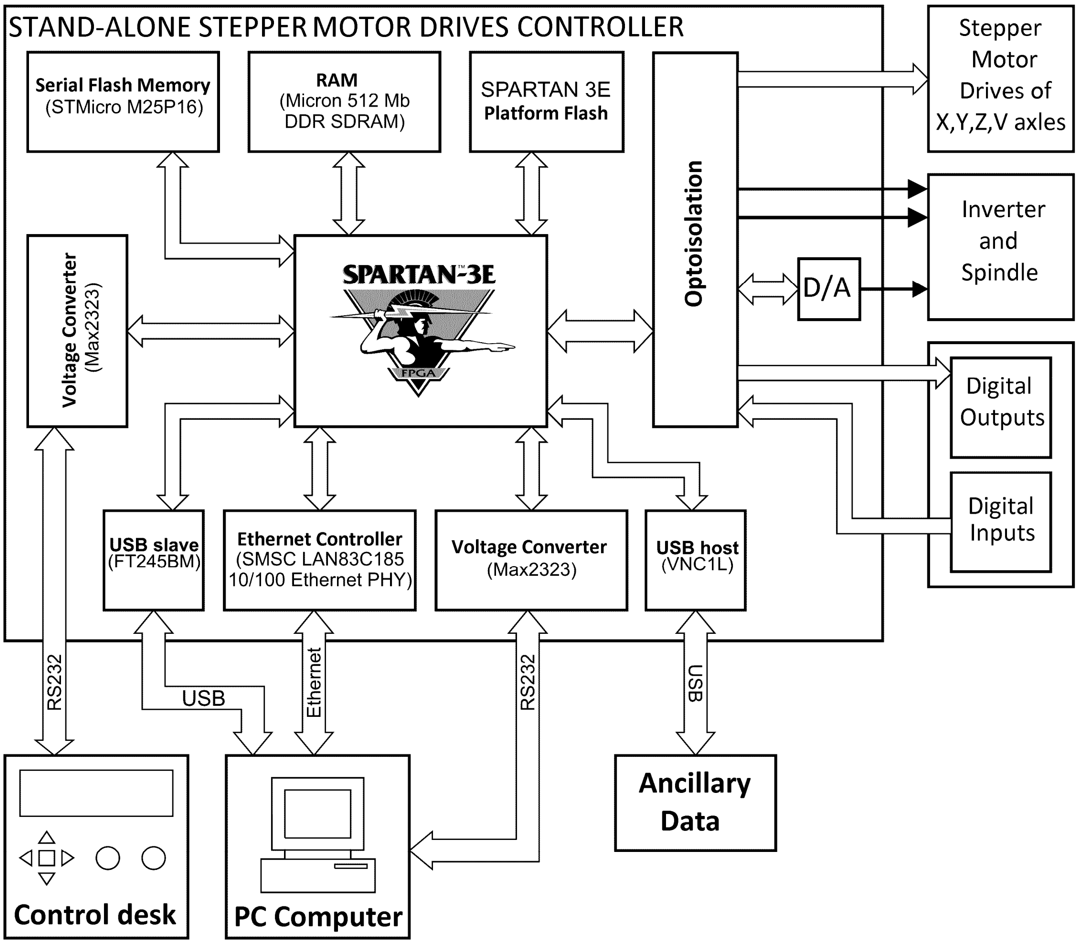

Fig. 4. Stand-alone stepper motor drives controller

6. EXPERIMENTAL RESULTS

The presented CNC control system with two step motor drives run correctly. Tests of the PC-based part of the CNC control system were aimed at verifying the correctness of the running application on the PC and communication with stand-alone CNC controller via USB bus. It was verified that the Look-Ahead algorithm and trajectory conversion of "G" and "M" codes to the NURBS curves are running correctly.

In stand-alone CNC controller tests verified the processing accuracy of the data received from the PC. The MicroBlaze processor software was tested to investigate the correctness of the CLK pulses generation algorithm in varying time period. CLK pulses generation in stand-alone CNC controller was checked as a result of the trajectory realization on multiaxial machine (cross-XY table).

Examples of motion trajectory of circle and broken line described in G1 code are presented in Fig. 5. Figure 6 shows CLK pulses sent from the controller to stepper motor drives. There is visible continuous change in the time period of CLK pulses in case of trajectory in form of circle and stable period time for broken line trajectory.

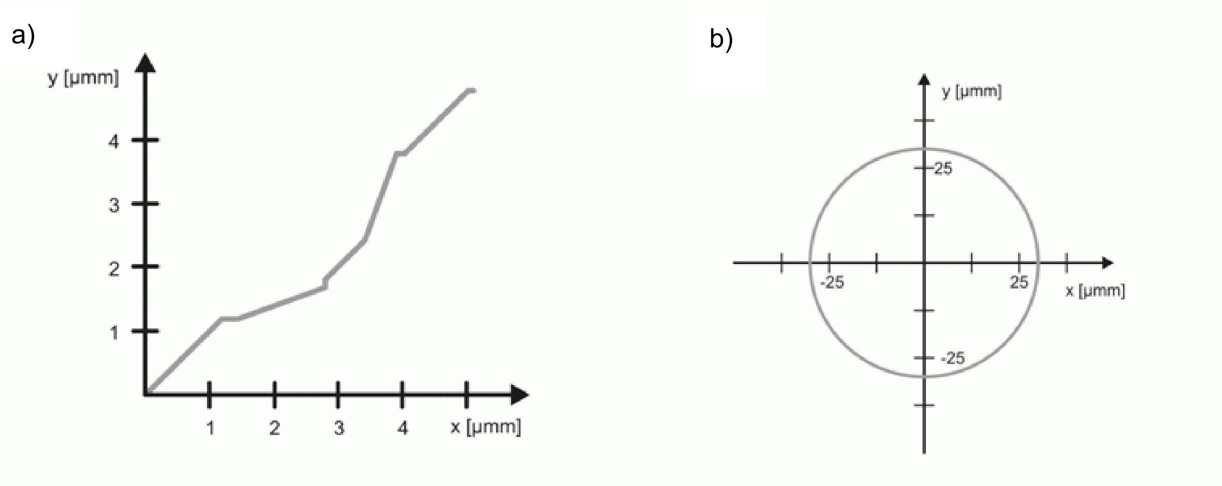

Fig. 5. Motion trajectory realizes by multiaxial machine:
a) broken line, b) circle

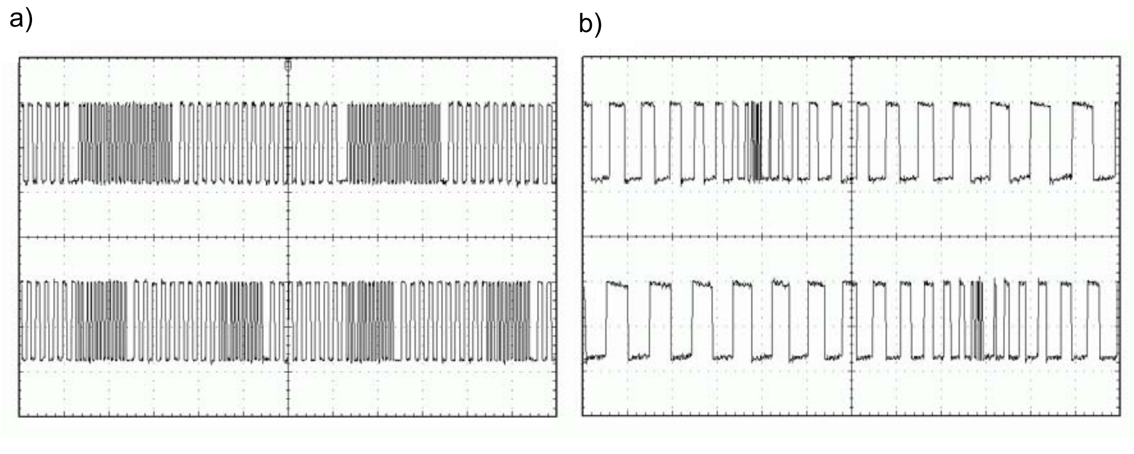

Fig. 6. Oscillogram of CLK pulses sent to X and Y stepper motor drives of multiaxial machine axles for motion trajectory presented in a) figure 5a, b) figure 5b

7. REMARKS AND CONCLUSION

The presented CNC system with stepper motor drives consists of a PC computer and stand-alone CNC controller. Implementation of "G" and "M" codes to the NURBS curves trajectory converter and the Look-Ahead algorithm in the PC application, remove geometrical discontinuities from the motion trajectory and determines the optimum feedrate of its realization. The stand-alone CNC controller generates high resolution and high precision CLK pulses with varying time period for the stepper motor drives. The presented system provides more smoothness of operation and is more resistant to vibration and falling out of steps.

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UKŁAD STEROWANIA CNC Z NAPĘDAMI SKOKOWYMI

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STRESZCZENIE *Na rysunku 1 przedstawiono schemat blokowy proponowanego układu sterowania CNC. Układ może być użyty do sterowania napędami skokowymi jak i serwonapędami. Złożony jest z komputera PC oraz autonomicznego sterownika CNC (rys. 2). Na komputerze PC wykonywane są obliczenia związane z realizacją funkcji interpretera kodu numerycznego, konwertera opisu trajektorii ruchu z kodów „G" i „M" na opis z wykorzystaniem krzywych NURBS (ang. Non Uniform Rational B-Spline) oraz profilowania prędkości parametrycznej z wykorzystaniem algorytmu Look-Ahead. Autonomiczny układ sterownika CNC realizuje zadania związane z generacją sygnałów sterujących CLK z dużą rozdzielczością dla poszczególnych napędów skokowych osi mechanicznych.*

Opis trajektorii ruchu w kodach G1, charakteryzuje się występowaniem nieciągłości geometrycznych. Proponowanym opisem trajektorii ruchu jest opis z wykorzystaniem krzywych NURBS. Opis za pomocą krzywych NURBS umożliwia minimalizację występowania nieciągłości geometrycznych. Na rysunku 3 przedstawiono przykład trajektorii ruchu, opisanej z wykorzystaniem krzywych NURBS.

W celu optymalnego dostosowania prędkości realizacji trajektorii ruchu zastosowano profilowanie prędkości po krzywej „S" z jednoczesną analizą zadanej trajektorii ruchu w przód – algorytm Look-Ahead.

Na rysunku 4 przedstawiono budowę autonomicznego sterownika CNC. Sterownik zbudowany jest na układzie FPGA (ang. Field Programmable Gate Array). W układzie FPGA zaimplementowano procesor MicroBlaze oraz układ generacji sygnałów sterujących CLK dla napędów skokowych. Generator impulsów z dużą rozdzielczością oblicza okresy impulsów CLK dla każdej z osi i niezależnie wysyła je do napędów skokowych.

Badania układu CNC miały na celu sprawdzenie poprawności działania aplikacji uruchomionej na komputerze PC (algorytmu Look-Ahead i konwersji z kodów „G" i „M" na opis z wykorzystaniem NURBS) oraz komunikacji poprzez port USB. W autonomicznym sterowniku CNC przeprowadzono badania związane z poprawnością przetwarzania otrzymywanych danych z komputera PC poprze port USB. Przykłady trajektorii ruchu w postaci okręgu i linii łamanej opisanej w kodzie G1 przedstawiono na rysunku. 5. Na rysunku 6 przedstawiono oscylogramy impulsów CLK wysyłanych do napędów skokowych.