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Multi-degree of freedom robust control of the CNC X-Y table PMSM-based feed-drive module[*]

KRZYSZTOF PIETRUSEWICZ

Faculty of Electrical Engineering
West Pomeranian University of Technology
Sikorskiego 37, 70-313 Szczecin
tel.: 48-505040910, 48-663398396
e-mail: krzysztof.pietrusewicz@zut.edu.pl

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Abstract: The paper presents results of studies on linear synchronous motors controlled in CNC feed axes through an intelligent digital servodrive. The research includes a conceptual design of an open servodrive control system and identification of dynamic models of a test stand with an open CNC system. Advantages of robust control over the classic one are discussed. A hybrid predictive approach to robust control of milling machine X-Y table velocity is proposed and results of simulation tests are presented. was prepared during the work for the Ministry of Science and Higher Education grant number N N502 336936, (acronym for this project is M.A.R.I.N.E. multivariable hybrid ModulAR motIon coNtrollEr), while its main purpose is the development of new robust position/velocity model-based control system, as well as to introduce the measurement of the actual state into the switching algorithm between the locally synthesized controllers. Such switching increases the overall robustness of the machine tool feed-drive module. The paper is the extended version of material proposed in [10].

Key words: robust control, hybrid control systems, machine tool feed-drive, PMSM

1. Introduction

A test stand for an intelligent digital servodrive is being constructed within the framework of the research project “Development of the construction and experimental tests of a mechatronic machine tool feed unit with a drive controlled by an intelligent modular actuator” (MNiSW Project No. N 502 336936, code-name *M.A.R.I.N.E.* (*multivariable hybrid ModulAR motIon coNtrollEr*), carried out by the Author. One of the objectives the project has to attain is development of a servodrive, the control algorithm of which takes into account not only the current position, but also other quantities. These can be quantities available to be measured during the machining process like accelerations and sound. Determining the main component

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[*] This is extended version of a paper which was presented at the 47th International Symposium on Electrical Machines SME 2011, Szczecin, Poland.

of the manipulated variable involves development of a robust model-based velocity control algorithm.

Modeling the CNC machine tool feed axis is not a trivial task due to its strongly nonlinear character brought about by complex physical phenomena associated with, among others, friction and restrictions imposed on motion parameters.

Model-based control [2, 3] has gained recognition for many years [6] owing to explicit use of the process model, unlike the majority of known control algorithms. Although they do not employ the process model explicitly, its knowledge is required in order to optimize the control system structure and its settings.

A control algorithm is called robust if the control performance depends only to a small extent on variations in process parameters or on possible additional disturbances acting on the control system. The merits of a two-degrees-of-freedom robust control algorithm have been described, among others, in [13]. A robust DC motor speed control providing a basis for studying algorithms of robust control for other types motors has been described in [11].

In this paper an extension of the robust model-based algorithm by a hybrid predictive mechanism [1] is proposed. The purpose of the mechanism is to ensure robustness to process nonlinearities brought about by varying X-Y table position on the working plane.

The control loop has been supplemented by a corrective block, the purpose of which is to compensate the effect caused by variations in table load that are associated with the loss in mass of the workpiece during the machining process.

2. Robust control of the metalworking machine tool

The control law in the synthesis of adaptive systems is determined on the basis of observations of changes occurring in properties of the controlled process [17]. These changes, if appropriately taken into account with a designed safety margin, enable a robust control algorithm to be created. The robustness of the control system for machine tool feed axes drives is required unquestionably not only for reasons of machining quality, but also for reasons of safety.

To achieve a constant high machining quality the feed drives control systems should exhibit insensitivity to the following factors:

- variations in environmental conditions (vibrations, changes of temperature),
- variations in machining parameters (rate of travel composed of rates for individual axes, accelerations, travel profiles, etc.),
- nonlinearities of selected machine modules (friction, backlash),
- geometrical errors of the machine.

A feed drive control system insensitive to the above factors is a robust system. If a CNC machine tool control system corrects for those factors on the basis of their models, then the system is called adaptive one. Employing an adaptive control system is a means for improving the general robustness of a control system, however the system is not robust by definition. Development of a robust or adaptive drive control algorithm is difficult to accomplish in the classic approach to machine design, according to which the machine construction is designed first, and the machine control system is designed afterwards. The matter is additionally complicated in the case of machines directly driven by linear motors. An effective implementation of "intelligent" control functions becomes possible due to the mechatronic approach, where the machine tool drive system is designed simultaneously on many levels, both on the side of the construction and that of the control system itself.

The following specifications should be determined when designing a machine tool drive system:

- machine kinematics (horizontal or vertical axes, dimensions of the machine),
- types of motors applied to feed drives (rotary or linear),
- machining parameters, hence, motion parameters for individual axes (typical machining, high-speed machining, high-precision machining).

The above-mentioned specifications determine requirements for hardware and software components of the drive control platform. These are the following:

- the way the position/velocity is to be measured, as well as the measurement resolution and the desired accuracy;
- communication protocols between the CNC processing unit and drive modules (for 'typical' machines it can be the CAN network, the MODBUS network, the nondeterministic Ethernet TCP/IP protocol to exchange data with the company office layer, or in the case of high-precision multi-axial applications it can be only the real-time industrial Ethernet: EtherCAT, Ethernet Powerlink, SERCOS, Ethernet/IP, ProfiNet or MODBUS-IDA),
- software architecture as to: sampling times, real-time operation including the way computations are to be allocated between many processor cores or processors themselves operating sometimes in the network, degree of advancement of control algorithms to be used in view of the designed precision level, the degree the machine tool operation monitoring and active supporting are to be integrated, hardware/software fusion concerning information from additional sensors.

Determining all of the above specifications is necessary to make decision about the choice of the drive control platform. Here a solution already available on the market can be chosen, or in case of necessity, due to a specific application, a tailor-made solution can be found. The decision about the construction and the machine tool control system is also dependent on economic factors and manufacturer's strategy, however these issues are outside the scope of the study.

In the next section a concept of robust control algorithm with more than two degrees of freedom is presented. The algorithm makes use of the nominal process plant model represented here by the machine tool feed axes model identified on the basis of tests carried out.

3. Model-based control

A robust control system features high control performance in the presence of external disturbances/load variations, but also in the presence of unknown yet bound variations in parameters of the controlled process [14]. If the variations can be expressed mathematically, they are called perturbations.

In the literature several descriptions of perturbations may be found [15], however the multiplicative description using discrete transfer functions is commonly considered to be most appropriate to highlight the merits of robust control algorithms:

$$\mathbf{P}(z^{-1}) = \left[\mathbf{I} + \boldsymbol{\Delta}(z^{-1})\right]\mathbf{M}(z^{-1}). \tag{1}$$

3.1. Classic single feedback control

In the classic single-loop control system (Fig. 1) the model controller $\mathbf{C}_1(z^{-1})$ governs the accurately known (perturbations equal zero) nominal model $\mathbf{M}(z^{-1})$ of the process $\mathbf{P}(z^{-1})$, the output of which is given by:

$$\underline{y}_p(k) \overset{\Delta}{=} \underline{y}_m(k) = y_m(k)\Big|_{\substack{\Delta=0\\ d(k)=0}} = [\mathbf{I} + \mathbf{M}(q)\,\mathbf{C}_1(q)]^{-1}\,\mathbf{M}(q)\,\mathbf{C}_1(q)\,\underline{u}_m(k), \tag{2}$$

where is the unit delay operator. Figure 1 shows the classic controller synthesis approach, takes into account (during analysis) perturbation of the model structure/parameter.

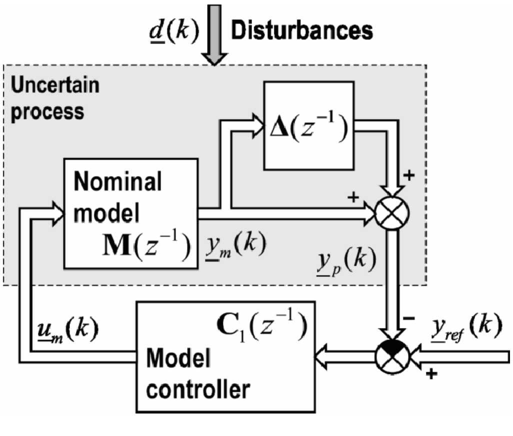

Fig. 1. Classic control system synthesized on the basis of identified model; introduction of the output multiplicative perturbation

If the process is subject to perturbations, then the system output may be defined in a modified form:

$$\underline{y}_p(k) = [\mathbf{I} + \mathbf{P}(q)\,\mathbf{C}_1(q)]^{-1}\,[\mathbf{I} + \boldsymbol{\Delta}(q)]\,[\mathbf{I} + \mathbf{M}(q)\,\mathbf{C}_1(q)\,\underline{y}_m(k)], \tag{3}$$

As it can be seen from (3) controller $\mathbf{C}_1(q)$ has to ensure a good reference tracking $\underline{y}_m(k)$ as well as to minimize the influence of model mismatch $\boldsymbol{\Delta}(q)$. It is not possible to ensure these two goals at the same time with the use of classic single feedback control systems. At least two-degrees of freedom structure has to be adopted.

3.2. Two-degree of freedom control

Figure 2 presents a Model-Following Control (MFC) structure of two degrees of freedom that has been proposed in [12]. In [13, 14] the robustness of such a structure has been thoroughly analyzed and shown. The reconstruction of the nominal model output is given by:

$$\underline{y}_p(k)=\left[\mathbf{M}(q)\left(\mathbf{I}+\mathbf{P}(q)\mathbf{C}_2(q)\right)\right]^{-1}\mathbf{P}(q)\left[\mathbf{I}+\mathbf{M}(q)\mathbf{C}_2(q)\right]\underline{y}_m(k)\,. \tag{4}$$

In [14] conditions are described to be met by controllers, if significantly better robustness is to be ensured. Approach from Figure 2 is not efficient for highly non-linear processes, as the global linear model is poor approximation for this class of dynamical systems.

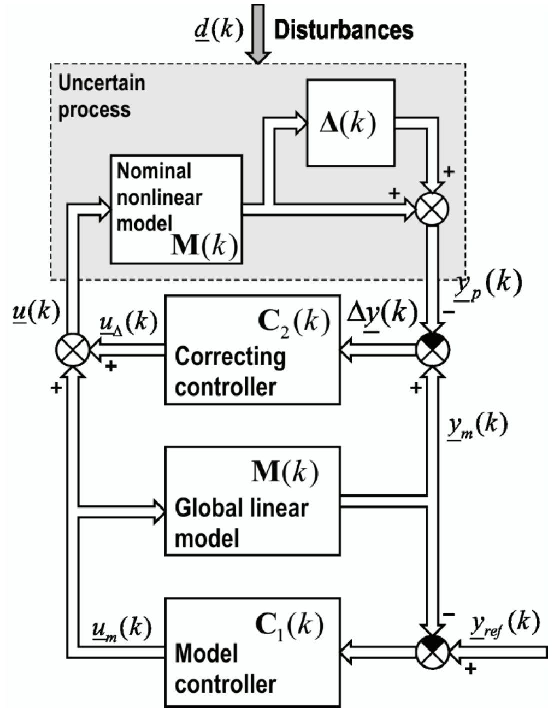

Fig. 2. Model-following control structure

3.3. Hybrid predictive control and piecewise affine approximation of nonlinear systems

Figure 3 displays a novel concept of a control system for nonlinear processes developed as a result of experience gained in employing the system of Figure 2 for that class of processes.

Robustness property exhibited by a two-degrees-of-freedom MFC system is excellent if it is applied to linear or weakly nonlinear processes. However, if severe constraints are imposed on manipulated variables and nonlinearities are strong, other solutions should be sought for. Predictive control [4, 5] is one of a few commonly used in industry solutions that enable one to design a control system with due regard for constraints imposed on manipulated variables, process plant outputs and state variables [9]. A hybrid approach to predictive control is a relatively young research area, which makes it possible to include piece-wise linear models of nonlinear dynamics exhibited by complex control processes into the control algo-rithm, and also to combine the continuous-time description of the dynamics with discrete switching between process plant states.

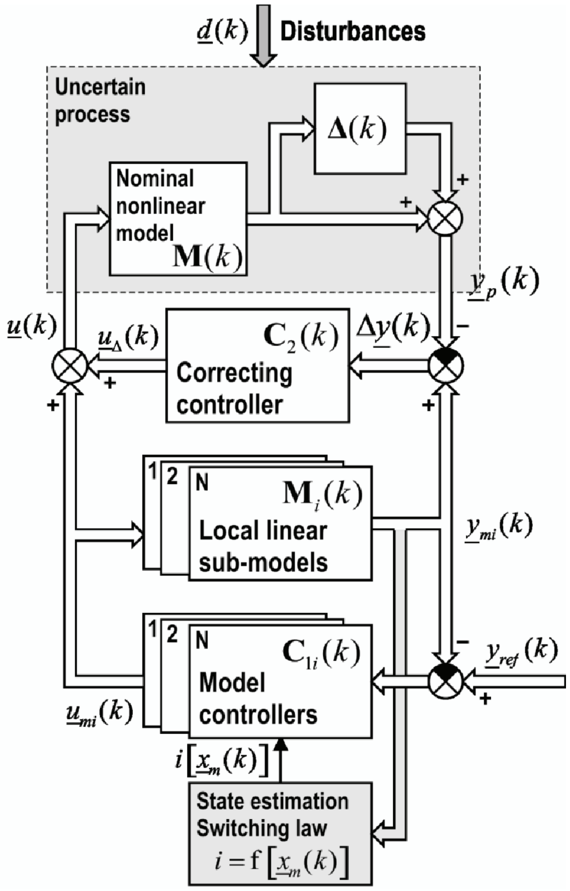

Fig. 3. Hybrid multi-degree of freedom model-following control system

Piecewise affine systems (PWA) are one of the simplest extensions of linear systems, which make it possible to model complex dynamics of nonlinear systems:

$$\begin{gathered}\underline{x}(k+1) = \mathbf{A}_i\,\underline{x}(k) + \mathbf{B}_i\,\underline{u}(k) + \underline{f}_i \\ \underline{y}(k) = \mathbf{C}_i\,\underline{x}(k) + \underline{g}_i \\ \underline{x}(k) \in \forall\, i = 1 \ldots N \\ \mathcal{G}_{X_i}\,\underline{x}(k) \le \mathcal{G}_{C_i}\,. \end{gathered} \tag{5}$$

Equations (5) show simplified version of the PWA model, where the polyhedral constraints depend only on the partial state vector of the model (autonomous state jumps version of the hybrid dynamical system [1]). Constraint $\mathcal{P}_i$ is a convex polyhedron in the space of state (and input) variables, which defines their range, where a given linear dynamic sub-model is sufficiently accurate to describe the behavior of the modeled nonlinear process. The range of state and input variables is called region of activation of the i-th dynamics of a piecewise linear model of a nonlinear process. The sides of the polyhedron $\mathcal{P}_i$ are defined by a finite number of linear inequalities called guard-lines $\mathcal{G}$. The vars. $\underline{u}(k) \in \mathbb{R}^m$, $\underline{x}(k) \in \mathbb{R}^n$, $y(k) \in \mathbb{R}^l$ describe the input, state and output vectors respectively at sampling instants $k \in \mathbb{N}$. Indexes m, n, l are the dimensions of the input, model, and the output, respectively. If the conditions $\underline{f}_i = \mathbf{0}, \underline{g}_i = \mathbf{0}$, are met, then Eqs. (5) represent a piecewise linear dynamic model. Such a description of a nonlinear process has been chosen in this study in view of the future implementation of designed algorithms in real-time digital control systems. Eqs. (5) are the subject of set of input-output constraints given by:

$$\begin{aligned} \underline{y}_{\min} &\le \underline{y}(k) \le \underline{y}_{\max} \\ \underline{u}_{\min} &\le \underline{u}(k) \le \underline{u}_{\max} \\ \Delta \underline{u}_{\min} &\le [\underline{u}(k) - \underline{u}(k-1)] \le \Delta \underline{u}_{\max}. \end{aligned} \tag{6}$$

The necessity of ensuring the appropriate position/velocity control performance in the entire space of motions to be made by the milling machine X-Y table (model loop) and necessity of minimizing the effect of table load variations (corrective loop) has called for the hybrid MFC structure (Fig. 3) instead of simple MFC (Fig. 2) to be used. In such a case the model loop is based on the piecewise linear model governed by the hybrid predictive controller, while the corrective controller is based on the conventional linear approximation of the entire space.

The problem of designing the main model controller in MFC has been formulated for a finite horizon of prediction N and control N_c with the quadratic performance index to be minimized:

$$\min_{u(0)\ldots u(N-1)} \sum_{k=0}^{N-1} \left\{ \underline{u}(k)^T \mathbf{R} \underline{u}(k) + \underline{x}(k)^T \mathbf{Q} \underline{x}(k) + \left[\underline{y}(k) - \underline{y}_{ref}(k)\right]^T \mathbf{Q}_y \left[\underline{y}(k) - \underline{y}_{ref}(k)\right] \right\} \tag{7}$$

and with constraints (6) imposed on the signals. In [13, 14] conditions have been presented to be met in order for MFC to track better the control system nominal loop. These conditions are to be fulfilled for each combination of the i-th model and the local model controller.

4. Programming of modern digital servodrives

Programming of digital servodrives is made possible more and more often in a standardized way by means of function blocks described in the PLCopen Motion Control standard. A hybrid automaton given by the standard is depicted below. The basic motions accomplished by machines include: discrete motion to a specified position given in an absolute or relative way, continuous motion in a positive or negative direction with a specified velocity, synchronized motion (one axis of motion follows up the other). The state diagram for digital control (without synchronized motion state) of a servodrive as in the mentioned standard is displayed in Figure 4.

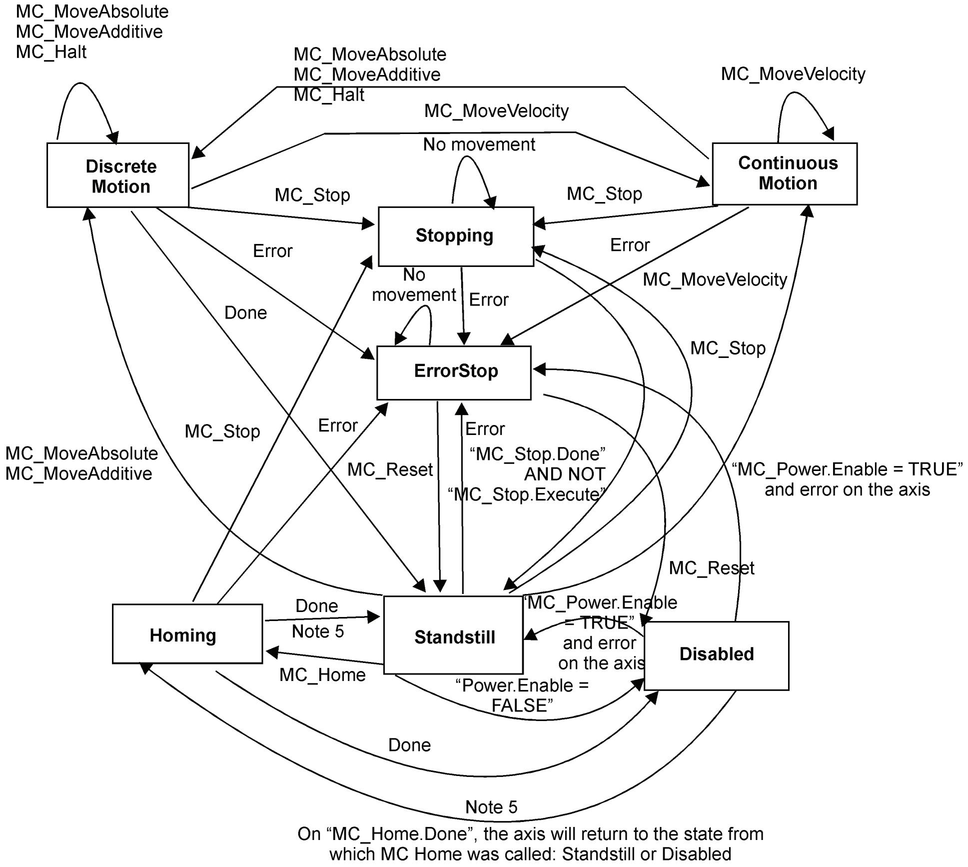

Fig. 4. PLCopen motion control concept

The individual states reflect the situation in which the given motion axis is:

- *Disabled* – the drive controller is switched off,
- *Standstill* – the drive is at standstill – awaits action, the motor axis is held in current position,
- *Homing* – in case of absolute encoders the motion procedure in direction to the nearest limit switch is not triggered off, however homing is necessary for initialization of numerical axes,
- *ErrorStop* – a stop after an error has occurred, all errors should be acknowledged,
- *Stopping* – stopping of the currently carried out motion,
- *Discrete Motion* – motion to a specified location, motion with a defined terminal point,
- *Continuous Motion* – motion without a specified location, motion without a terminal point.

A transition between states is accomplished by calling appropriate functions like MC_Move Absolute (absolute motion) or MC_MoveAdditive (relative motion in a specified direction).

In order to ensure a constant quality of positioning in each of the possible motion modes it is necessary to optimize the drive control system operation. This is a complex problem, since it necessitates analyzing all drive operation modes, requirements placed upon drives in operation and working out optimization procedures for drive control systems parameters.

The outlined hybrid predictive control associated with the Model-Following Control approach improved in the scope of robustness is a very promising and applicable solution for this problem.

5. Modeling the milling machine X-Y table feed-drive dynamics

Many theoretical methods for modeling dynamics of machine tool feed axes drives both with a ball feed screw [16], and also those directly driven by a linear motor [7, 8] may be found in literature.

Identification of the process for research on new position/velocity control algorithms have been conducted by the Author on real objects, i.e. X-Y tables with PMSM and PMLM motor. The tables have been constructed within the framework of the project aimed, amongst others, at developing a prototype test stand with an open architecture control system for a CNC machine tool. The project was carried out by the Mechatronics Center of the West Pomeranian University of Technology, Szczecin. The first stage of developing new control algorithms has been focused on identification of dynamic models that describe the operation of feed axes not as a result of a theoretical analysis, but as a result of a practical experiment described below.

Figure 5 shows a measurement grid for the identification test, the algorithm of which has been developed and implemented in an open architecture CNC system.

The objective of the test was to determine a SIMO model for the X-Y table (position/ velocity outputs as a consequence of current input). In this paper only models of axes feed drive dynamics in the middle of their ranges of operation have been presented, namely at Y = 150 [mm] for the X-axis, and at X = 300 [mm] for the Y-axis as far as the test stand of Figure 4 is concerned. To create the model measuring points from No. 39 to No. 51 for the X-axis, and Nos. 6, 19, 32, 45, 58, 71 and 84 for the Y-axis from among the total of 91 points have been chosen for the purposes of this work.

The tests were carried out for cases when the machine-tool table was unloaded, and when it was loaded by a steel block of almost 90 kg in mass, which represented a workpiece. The additional mass increased significantly the inertia of individual axes; therefore this factor should be taken into consideration by the velocity control algorithm.

The identified linear models are of the *grey-box* type with a specified structure of matrices **A, B, C** in the "set value of quadrature component of current – actual velocity" path, which is the most appropriate way, from the viewpoint of further control, to reflect the properties of the controlled process, i.e. the axes of miller table motion. As a result of identification piecewise linear dynamic models for X and Y axes of the form (5) have been obtained.

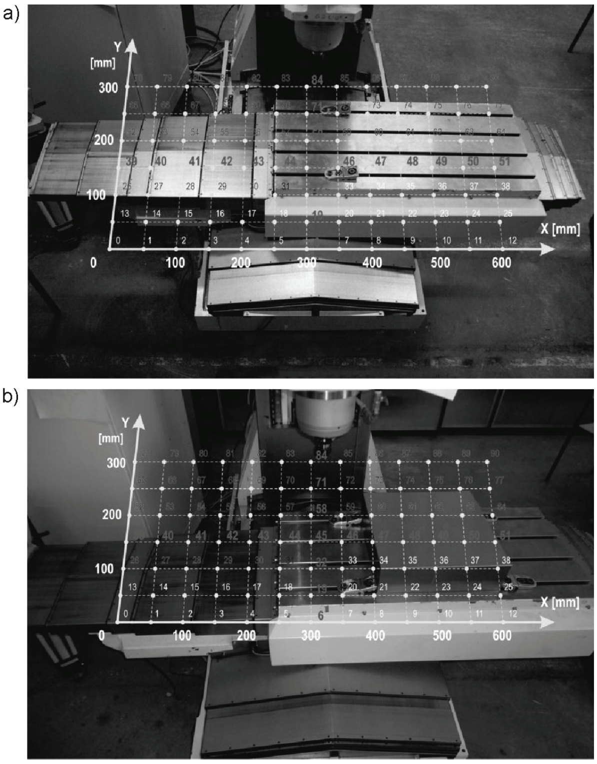

Fig. 5. Ball-screw driven X-Y table without load (a), and with about 90 kg mass (b)

Such approach arises from the fact that in typical servodrive users cannot influence the signals within the current controller, so the only way is to evaluate additional set torque value. It is sufficient to increase the overall stiffness of the machine – tool. Parameters of the motors are as follows (8LSA55.E3030D000-0 from Bernecker&Rainer): voltage constant 98.43 [mVmin], rated speed 3000 [1/min], rated torque 10.5 [Nm], torque constant 1.63 [Nm/A], rated current 6.441718 [A], stator resistance 1.6 [Ω], stator inductance 1.401 [mH], motor inertia 0.0008 [kgm^2]. Rated switching frequency of the servodrive is equal to 10 [kHz].

In the identified model the variable – position at the motion axis [mm] is that dividing the state space and the variable denotes the linear velocity of the motion axis determined from the rotational speed of the motor shaft [mm/s] and the lead of the drive ball-screw mechanism.

Models in individual axes are switched over depending upon the $x_1(k)$ variable in the manner, shown by (8),

$$X : \underline{x}_{X1,i} = \left\{ \begin{array}{l} [-25\ldots25]_{39}, [25\ldots75]_{40}, [75\ldots125]_{41}, [125\ldots175]_{42}, [175\ldots225]_{43} \\ [225\ldots275]_{44}, [275\ldots325]_{45}, [325\ldots375]_{46}, [375\ldots425]_{47}, [425\ldots475]_{48} \\ [475\ldots525]_{49}, [525\ldots575]_{50}, [575\ldots625]_{51} \end{array} \right\} \qquad (8)$$

$$Y : \underline{x}_{Y1,i} = \left\{ \begin{array}{l} [-25\ldots25]_{6}, [25\ldots75]_{19}, [75\ldots125]_{32}, [125\ldots175]_{45} \\ [175\ldots225]_{58}, [225\ldots275]_{71}, [275\ldots325]_{84} \end{array} \right\}$$

where $[-25\ ...\ 25]_{39}$ in the case of X-axis denotes the range of variation $\underline{x}_{X1.39} \in$ $\in [-25 \ldots 25][\mathrm{mm}]$ (position where the model is valid in the range between and).

There have been determined piecewise linear discrete models of individual motion axes with sampling time 2.4 [ms] for both unloaded (Fig. 5a) and loaded table (Fig. 5b). Subscripts from 0 to 90 mean that 91 local model have been determined for each of the axes (X and Y) with and without load. The resultant model composed of local models will provide a basis for developing a MIMO robust two-axes position/velocity controller at the next stages of the project.

For example, the model at the measuring point No. 45 with the table unloaded:

$$\mathbf{A}_{X45} = \begin{bmatrix} 1 & 0.002378755808256 & 3.1455287813\mathrm{E}-5 \\ 0 & 0.982308479314894 & 0.026090092764928 \\ 0 & -0.009138185537298 & 0.989667595503954 \end{bmatrix}$$

$$\mathbf{B}_{X45} = \begin{bmatrix} 0.000722669483042 \\ 0.601103192907749 \\ 0.148440583401762 \end{bmatrix} \qquad \mathbf{C}_{X45} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \tag{9a}$$

and loaded is defined by the following matrices:

$$\mathbf{A}_{X45} = \begin{bmatrix} 1 & 0.002385124849225 & 2.7293796263\mathrm{E}-5 \\ 0 & 0.987592928606562 & 0.022625523520929 \\ 0 & -0.009814483024065 & 0.98103349139358 \end{bmatrix}$$

$$\mathbf{B}_{X45} = \begin{bmatrix} 0.000659505255125 \\ 0.548539719002824 \\ 0.021677551221911 \end{bmatrix} \qquad \mathbf{C}_{X45} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \tag{9b}$$

and by the constraints:

$$\mathcal{G}_{X_{X45}} = \begin{bmatrix} -1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \quad \mathcal{G}_{C_{X45}} = \begin{bmatrix} -275 \\ 325 \end{bmatrix}$$

$$\mathcal{G}_{X_{X45}} \underline{x}(k) \leq \mathcal{G}_{C_{X45}}\,. \tag{10}$$

Models in the form (9a, b) have been identified for all ranges from (8). To be certain that identification has been carried out correctly each recording has been repeated three times at each point of the grid shown in Figure 5, and for each recording a linear discrete model with an adopted form of the **C** matrix and sampling time of 2.4 [ms] (*zero order hold* method) has been determined. It has been adopted that the number of models for the entire range of operation would be 91, i.e. as many ones as the number of measuring points. The concept of robust hybrid control provides for optimization of the number of local models; however this issue is outside the scope of the paper.

6. Selected simulation results

The following Figures 7-11 display results of the circular-type test with the use of a trapezoidal velocity profile shown in Figure 6. Profiles of the reference axis position have followed from a single integration of the velocity profile shown.

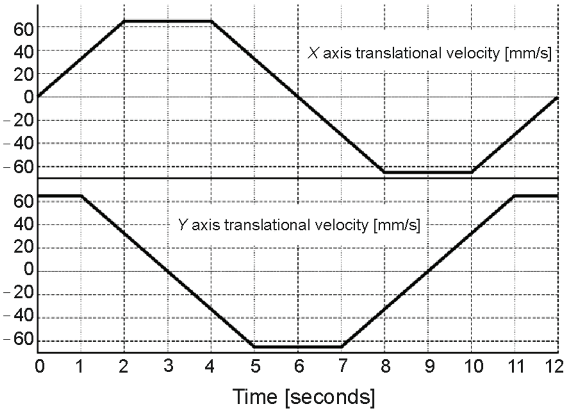

Fig. 6. Set velocity profiles in the circular-type test

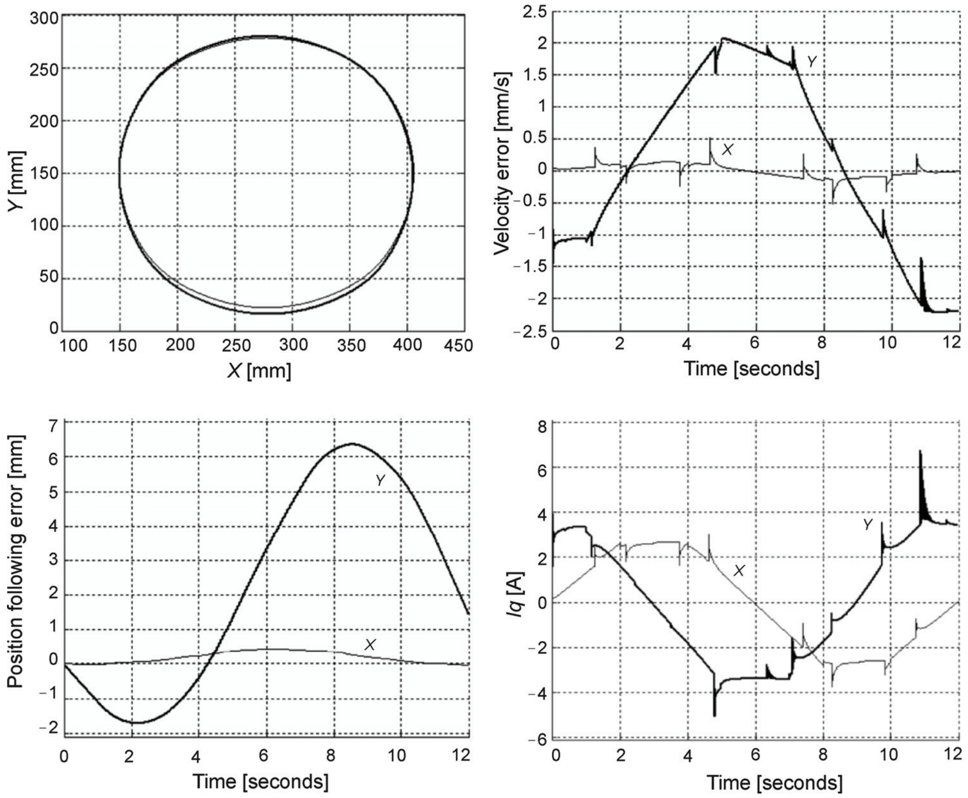

Fig. 7. PID control of the loaded X-Y table

Below a comparison between the classic single-loop PID control structure and the novel control structure of robust hybrid predictive multi-degree of freedom controller proposed in this paper has been made. The robustness of each of the mentioned control algorithms has been tested in the following way: settings of each controller have been tuned to the model of an unloaded X-Y table, while the controllers had to govern the model of a loaded table. Controller settings in the classic structure have been tuned by experiment after tentative tuning according to tuning methodology had been carried out.

Since PID controllers (Fig. 1) in the single-loop control system for individual motion axes have been tuned on the basis of linear models approximating the feed drive dynamics in motion axes, it is obvious that an appropriately high control performance cannot be ensured.

Figure 8 depicts results of the test performed for the MFC structure. Here in the model loops (Fig. 2) linear models of the entire range of motion are employed, which brings about tracking the linear approximation by the nonlinear process, according to MFC concept.

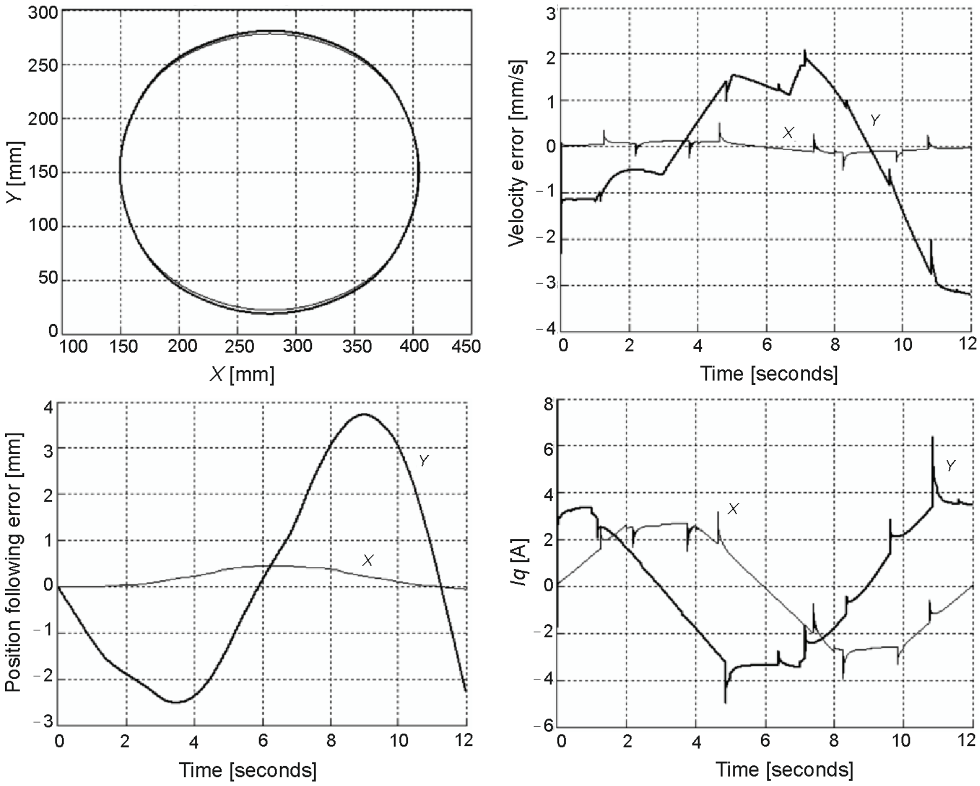

Fig. 8. MFC control of the loaded X-Y table

The next two figures depict results of using the hybrid predictive controller to control the X-Y table. The predictive hybrid controller has been designed for piecewise linear models of motion axes. The whole range of operation of the X axis has been described by 13 models, and that of the Y axis by 7 models. Short identical horizons for prediction and control $N = N_c = 2$

have been adopted. The weight matrices have been chosen in such a way as to minimize the error in the position and velocity paths. Due to the control margin of the modeled process, violent manipulated variables have been allowed for in the performance index (7) to be minimized:

$$\mathbf{Q} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{Q}_y = \begin{bmatrix} 100 & 0 \\ 0 & 100 \end{bmatrix} \mathbf{R} = [0.01]. \tag{11}$$

Figure 9 shows results of the circularity test for the unloaded X-Y table, while Figure 10 presents the situation where the loaded plant is controlled by the hybrid predictive controller designed for an unloaded plant.

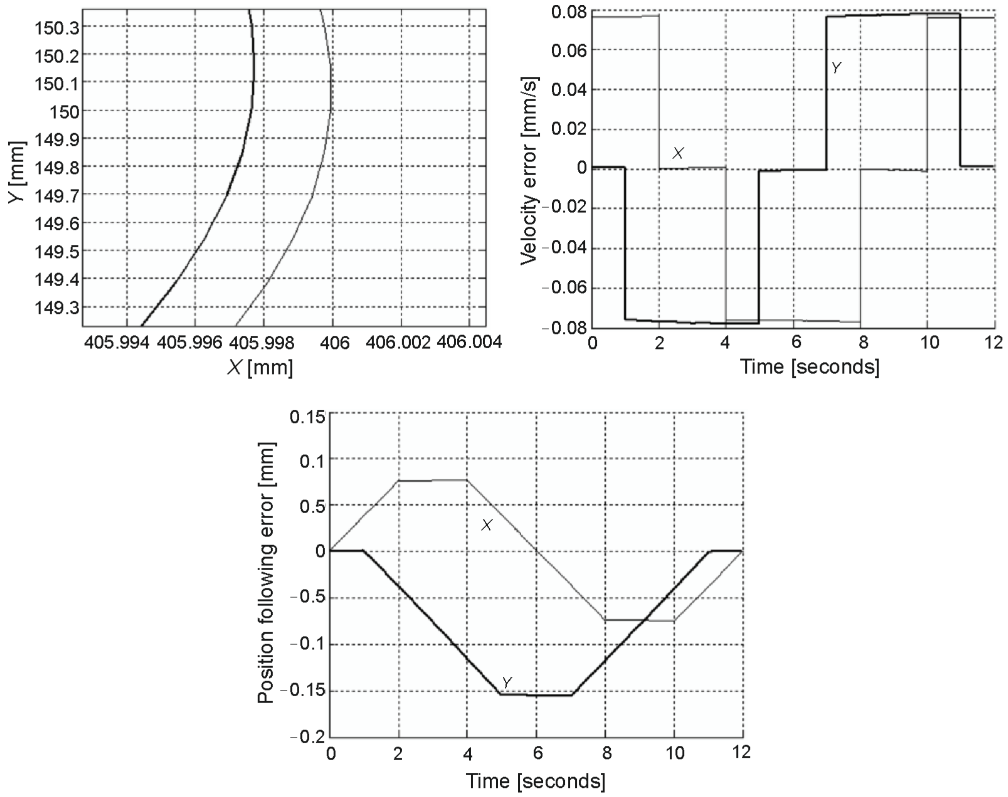

Fig. 9. Hybrid predictive control of the nominal unloaded X-Y table

The static friction taken into account in the motion axes model introduces an additional nonlinearity at low velocities. As a result the control performance provided by the hybrid predictive controller designed for a friction-free model is impaired. An additional corrective controller suggested in Fig. 3 remedies the situation by computing an additional value of the control current, which makes the operation similar to that carried out for the friction-free model.

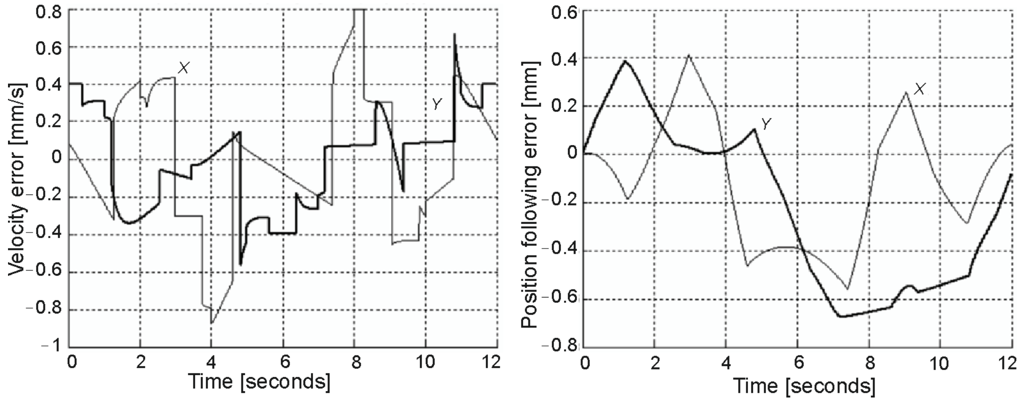

Fig. 10. Hybrid predictive control of the loaded X-Y table

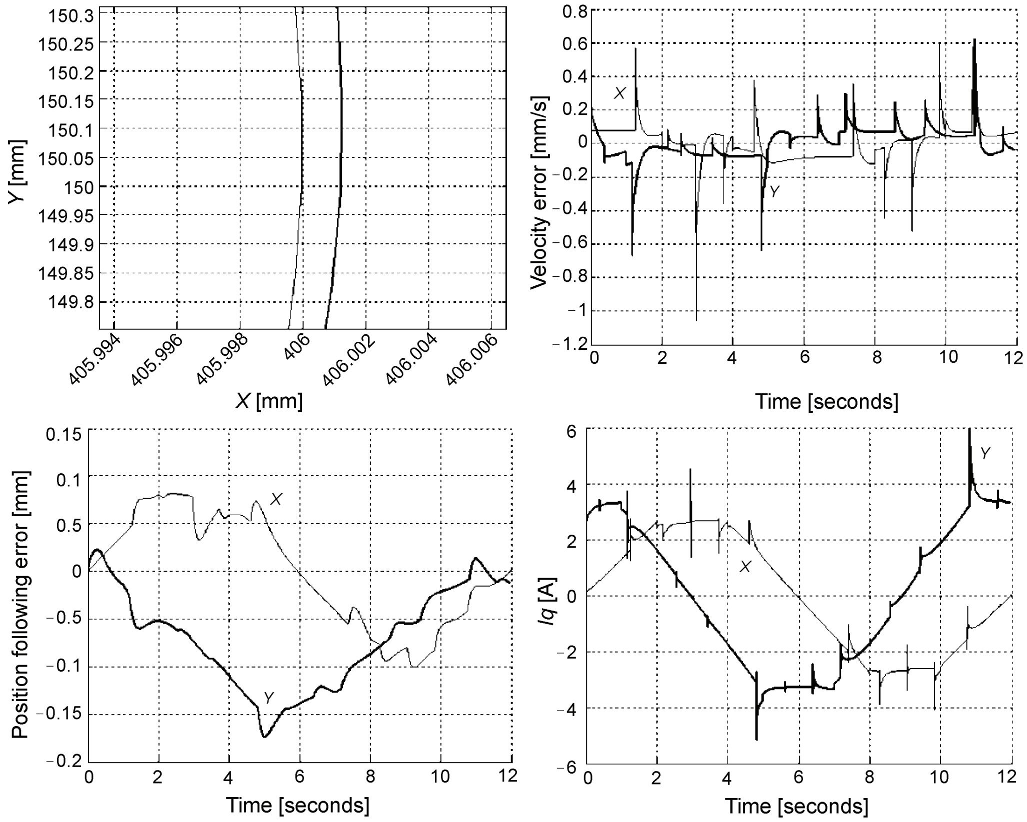

Fig. 11. Hybrid predictive control of the MFC-type (control of the loaded X-Y table)

An algorithm for designing the corrective controller is currently in its final development stage. The position accuracy values obtained by using the hybrid predictive controller in the circularity test are still not satisfying and do not reflect the amount of effort needed to identify local models of machine tool axes. Therefore, an additional degree of freedom in the velocity/position control path should be employed in the next stage of study. The presented results of control with the use of MFC corroborate the idea of applying such structures to control of nonlinear processes.

The next figure depicts results of using the hybrid predictive system of the MFC type (where the designed main controller governs the model defined for an unloaded X-Y table, while the process plant is represented by a loaded table).

The obtained test results show that the effect produced by perturbations of this type, i.e. the varying mass of the workpiece, can be eliminated by robust hybrid predictive multi-degree of freedom model-following position/velocity control.

7. Concluding remarks

The paper presents results of the research work currently carried out within the framework of the project “Development of the construction and experimental tests of a mechatronic machine tool feed unit with a drive controlled by an intelligent modular effector” (MNiSW Project No. N 502 336936). The results concern development of the concept of piecewise linear robust control based on hybrid algorithms of the model-based control family. There are strong grounds to hope that these methods will turn out to be effective in improving control robustness of complex mechatronic processes exemplified by feed axes of modern CNC machine tools. Ensuring a constant high quality of feed velocity control for machine tool motion axes during the machining process is a real challenge nowadays when requirements on feed motion (working motion) velocity are growing, and rotary drives are gradually supplanted by linear drives with permanent magnets. The next stages of research work will concern implementation of developed algorithms as a part of “intelligent” architecture of a digital servodrive and will involve integration with an open architecture CNC system the acronym of which is *O.C.E.A.N.*

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Research has been done within the framework of the project “Development of the construction and experimental tests of a mechatronic machine tool feed unit with a drive controlled by an intelligent modular actuator” (MNiSW Project No. N 502 336936, code-name M.A.R.I.N.E. (multivariable hybrid ModulAR motIon coNtrollEr)

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