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METHOD FOR INCREASING THE CONTROL ROBUSTNESS OF THE PERMANENT MAGNET MACHINE TOOL FEED-DRIVE

Abstract: The article presents the results from the development of digital servodrive with permanent magnet synchronous motor within the CNC machine tool feed-drive. It 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. Presented here results takes into account the MIMO character of the process to be controlled.

1. Introduction

Within the framework of the research project “Development of the construction and experimental tests of a mechatronic machine tool feed-drive unit with a drive controlled by an intelligent modular actuator”, carried out by the Author’s team, a test stand for an intelligent digital servodrive is being constructed. 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 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.

The so-called 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 [12]. A robust DC motor speed control providing a basis for studying algorithms of robust control for other types motors has been described in [10].

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. 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 [13]. If the variations can be expressed mathematically, they are called perturbations.

In the literature several descriptions of perturbations may be found [14], however the multiplicative description using discrete transfer functions is commonly considered to be most appropriate to highlight the merits of robust control algorithms:

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

2.1. 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:

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

where $q \square z^{-1}$ is the unit delay operator.

Fig.1 shows the classic controller synthesis approach, takes into account (during analysis) perturbation of the model structure/parameter.

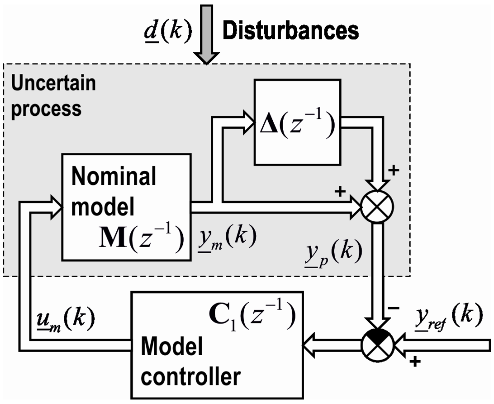


Fig. 1. Classic control system synthesized on the basis of identified model; introduction of the output multiplicative perturbation

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

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

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 $\mathbf{\Delta}(q)$. It is not possible to ensure these two goals at the same time with the use of classic single feedback control systems.

2.2. Two-degree of freedom control

Figure 2 presents a Model-Following Control (MFC) structure of two degrees of freedom that has been proposed in [11]. In [12, 13] the robustness of such a structure has been thoroughly analyzed and shown.

The reconstruction of the nominal model output is given by (for simplicity the q argument has been omitted in the following equations):

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

In [13] conditions are described to be met by controllers, $\mathbf{C}_1, \mathbf{C}_2$ if significantly better robustness is to be ensured. Approach from Fig. 2 is not efficient for highly non-linear processes, as the global linear model is poor approximation for this class of dynamical systems.

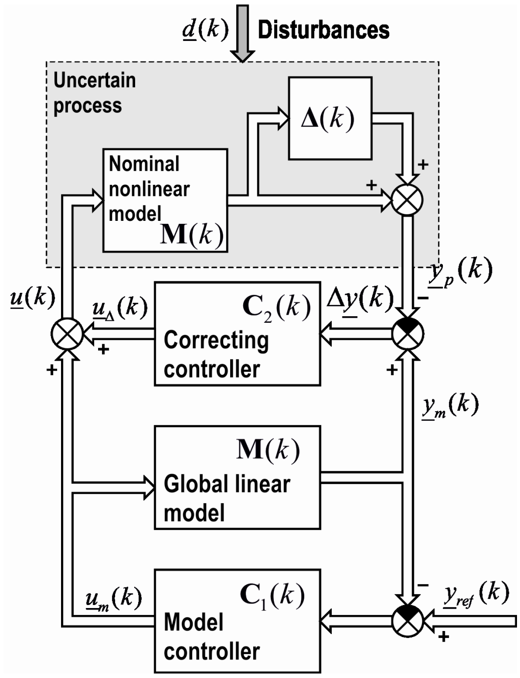


Fig. 2. Model-Following Control structure

2.3. Hybrid predictive controller

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

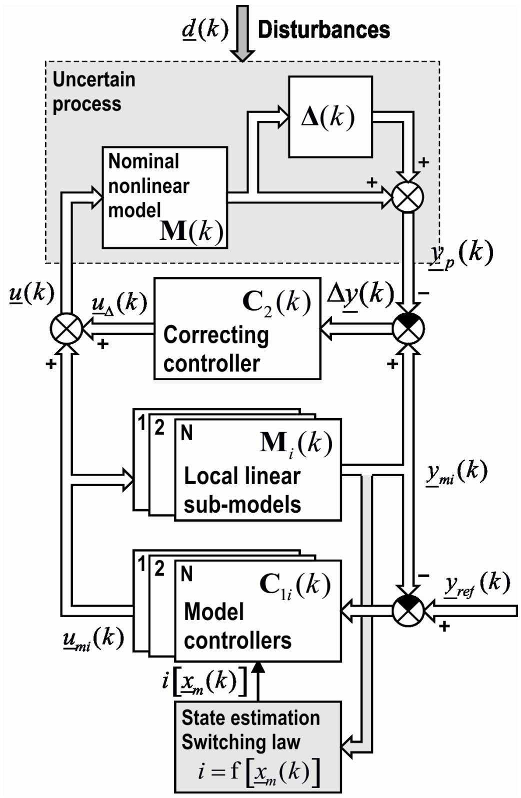


Fig. 3. Hybrid multi-degree of freedom Model-Following Control system

Robust properties exhibited by a two-degrees-of-freedom MFC system are 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 piecewise linear models of nonlinear dynamics exhibited by complex control processes into the control algorithm, and also to combine the continuous-time description of the dynamics with discrete switching between process plant states.

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

$$\begin{aligned} \underline{x}(k+1) &= \mathbf{A}_i \underline{x}(k) + \mathbf{B}_i \underline{u}(k) + \underline{f}_i \\ \underline{y}(k) &= \mathbf{C}_i \underline{x}(k) + \underline{g}_i \\ \underline{x}(k) &\in \mathrm{P}_i \quad \forall i = 1 \ldots N \\ \mathrm{G}_{X_i} \underline{x}(k) &\le \mathrm{G}_{C_i} \end{aligned} \tag{5}$$

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 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 P_i are defined by a finite number of linear inequalities called guard-lines G. The vars. $\underline{u}(k) \in \mathrm{R}^m, \underline{x}(k) \in \mathrm{R}^n, y(k) \in \mathrm{R}^l$ describe the input, state and output vectors respectively at sampling instants $k \in \mathrm{N}$. 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:

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

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:

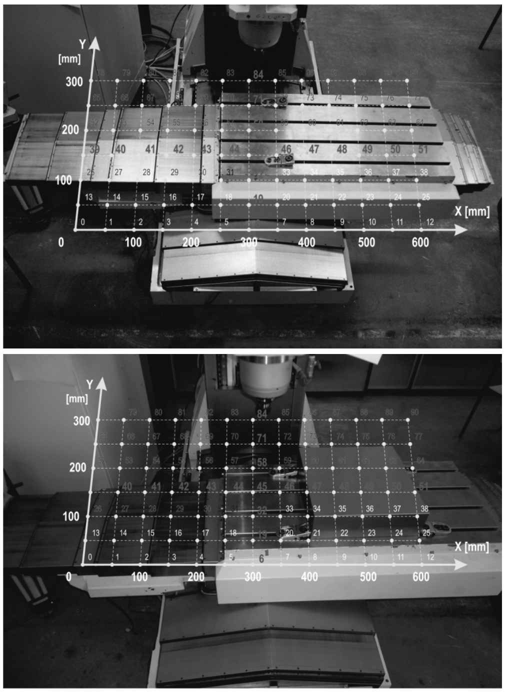
$$\min_{u(0)\ldots u(N-1)} \sum_{k=0}^{N-1} \left\{ \begin{aligned} &\left[\underline{y} - \underline{y}_{ref}\right]^T \mathbf{Q}_y \left[\underline{y} - \underline{y}_{ref}\right] + \\ &+ \underline{x}^T \mathbf{Q} \underline{x} + \underline{u}^T \mathbf{R} \underline{u} \end{aligned} \right\} \tag{7}$$

and with constraints (6) imposed on the signals. In [12, 13] 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.

3. Modeling the feed-drive dynamics

Many theoretical methods for modeling dynamics of machine tool feed axes drives both with a ball feed screw [15], 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 at Szczecin. The first stage of developing new control algorithms has been focused on identifi-

cation 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.
Fig.4 shows a measurement grid for the identification test, the algorithm of which has been developed and implemented in an open architecture CNC system.



a) b)

Fig. 4. Ball-screw driven X-Y table without load (a), and with about 90 kg mass (b)

The objective of the test was to determine a MIMO model for the X-Y table. 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 Fig. 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 $\mathbf{A},\mathbf{B},\mathbf{C}$ 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.
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 Berneck-er&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 $x_1(k)$ – position at the motion axis [mm] is that dividing the state space and the variable $x_2(k)$ 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),

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

$$\mathrm{Y}: \underline{x}_{Y1,i} = \left\{ \begin{array}{l} [-25\ldots25]_{6}, [25\ldots75]_{19}, \\ [75\ldots125]_{32}, [125\ldots175]_{45}, \\ [175\ldots225]_{58}, [225\ldots275]_{71}, \\ [275\ldots325]_{84} \end{array} \right\} \tag{8}$$

where $[-25\ldots25]_{39}$ in the case of X-axis denotes the range of variation $\underline{x}_{X1,39} \in [-25\ldots25]$ [mm] (position where the model is valid in the range between $-25[\text{mm}]$ and $+25[\text{mm}]$).

There have been determined piecewise linear discrete models of individual motion axes with sampling time 2.4 ms for both unloaded and loaded table (Fig. 4.b). 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 and loaded is defined by the following matrices:

$$\mathbf{A}_{X45} = \begin{bmatrix} 1 & 0.00237875 & 3.14552878\text{E}-5 \\ 0 & 0.98230847 & 0.02609009 \\ 0 & -0.00913818 & 0.98966759 \end{bmatrix}$$

$$\mathbf{B}_{X45} = \begin{bmatrix} 0.00072267 \\ 0.60110319 \\ 0.14844058 \end{bmatrix} \quad \mathbf{C}_{X45} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \tag{9}$$

and by constraints:

$$\mathrm{G}_{X_{X45}} = \begin{bmatrix} -1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \quad \mathrm{G}_{C_{X45}} = \begin{bmatrix} -275 \\ 325 \end{bmatrix} \tag{10}$$

$$\mathrm{G}_{X_{X45}} \underline{x}(k) \le \mathrm{G}_{C_{X45}}$$

Such models 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 Fig. 4, 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.

4. Selected results

Figs. 6 and 7 display results of the circular-type test with the use of a trapezoidal velocity profile shown in Fig. 5. Profiles of the reference axis position have followed from a single integration of the velocity profile.

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.

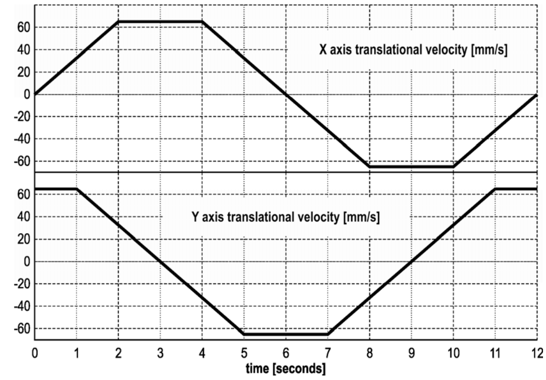
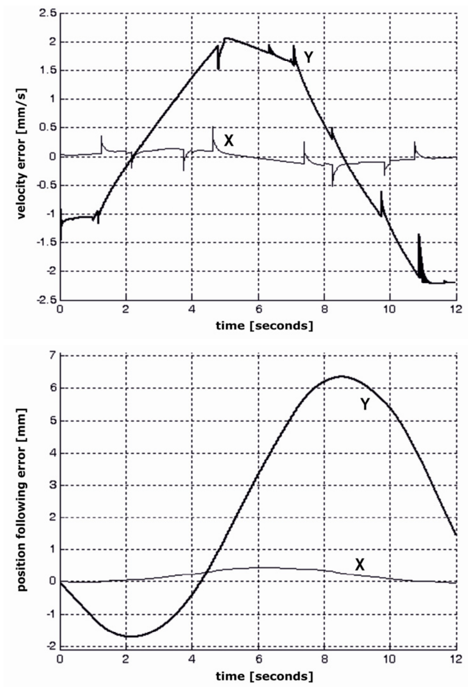


Fig. 5. Set velocity profiles in the circular-type test

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.



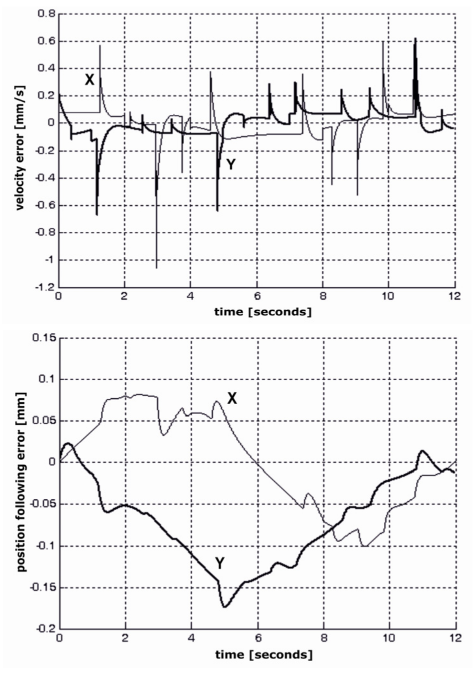
a)

b)

Fig. 6. Results from PID control simulation: velocity (a) and position following (b) errors

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 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:

$$\mathbf{Q} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{Q}_y = \begin{bmatrix} 100 & 0 \\ 0 & 100 \end{bmatrix} \mathbf{R} = \left[0.01\right] (11)$$



a)

b)

Fig. 7. Results from hybrid predictive MFC-type control simulation: velocity (a) and position following (b) errors

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 position/velocity control.

5. Conclusions

The paper presents the results that concern development of the concept of piecewise linear robust control based on hybrid algorithms of the model-based control family. 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.

6. Bibliography

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