Scientific Journals
Maritime University of Szczecin

Zeszyty Naukowe
Akademia Morska w Szczecinie

2014, 39(111) pp. 161–168
ISSN 1733-8670

2014, 39(111) s. 161–168

CNC milling machine feed drive laboratory stand for purposes of velocity control algorithms prototyping

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Key words: feed drive control system, control algorithms rapid prototyping, servodrive control, MFC/IMC, CNC

Abstract
Article describes extended concept of digital servodrive velocity control algorithms rapid prototyping, which is crucial component of milling machine feed drive equipped with ball screw. Approach presented here describes the case where the user has no access to the internal control structure the servodrive (design wide-spread in commercially applied CNC solutions), and can only use an additional signal (additive value of torque/current), calculated on the basis of a comparison of the real object and its nominal dynamic model.

Introduction

Nowadays servodrives are exploited in many technical applications which makes them one of the most important group in terms of industrial automation. Due to the extended feedback possibilities servodrives provide a very high-precision, ensuring a high dynamic motion, positioning, but also the stable operation of the system at low speeds. Because of their parameters servodrives have been used as motor drives and a part of ball-screw feed drive of CNC machines.

Modern control systems of CNC machines are designed to ensure stability, good control and robustness to disturbances and changing conditions during machining operations. The servodrive efficiency control in such applications is difficult, because of their sensitivity to changes in the additional load and the control system parameters. Manufacturers are constantly developing their products and offer more and more features improving the milling process quality.

Newly developed, robust servo control algorithms, that improve the properties of numerically controlled machine feed units, in terms of the control quality and resistance to disturbances, increase the performance of milling. From this point of view an interesting group of control algorithms are methods based on the plant model (Model-Based Control). Publications [1, 2] shows exploitation of the MFC concept (Model Following Control) in the control of electric drives. Automatic systems utilizing the plant model can achieve very good quality control, in cases, where the plant exhibits strong non-linear properties, whereas crucial for the control system additional parameters vary in time.

CNC milling machine control systems

One of the key functional element of each CNC machine is control system which determines the utility of the device. The simplest CNC systems offer basic functionalities, such as reading the tool path from file or start of the machining process. More sophisticated systems allow, for example, to carry out simulation before machining, change tools parameters and its route settings, tool diameter compensation and visualization of the work progress in real time.

The vast majority of modern control systems used in milling machines have closed architecture and does not allow the user to any intervention on their part, such as servodrive digital control algorithms. The operator is forced to use pre-defined by the manufacturer functions and do not have access to the devices lower levels functionalities. Some

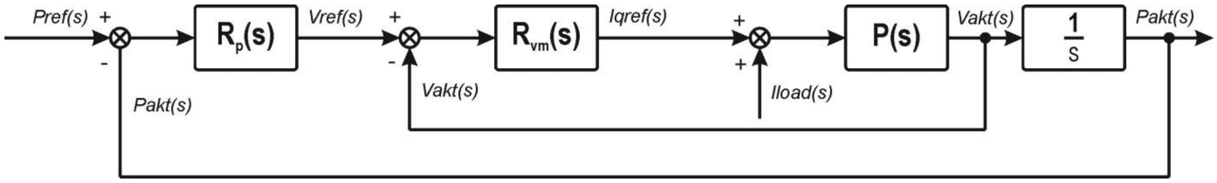

Fig. 1. Cascade position control exploited in CNC machines; $P_{\text{ref}}(s)$ – reference position value, $R_P(s)$ – position controller, $V_{\text{ref}}(s)$ – reference velocity value, $R_{vm}(s)$ – velocity controller, $I_{q\text{ref}}(s)$ – current reference value, $P(s)$ – plant, $I_{\text{load}}(s)$ – external load, $V_{\text{akt}}(s)$ – actual velocity value, $P_{\text{akt}}(s)$ – actual position value

manufacturers of CNC machines give you the ability to modify their software and hardware solutions for the CNC kernel level but it is very expensive and very few people are able to afford it.

Development trends bring to the front CNC systems with open architecture, that allows to add new dynamic states supervising functions of the machine in the time of the milling process. The studies and projects (Osaka, OSEC, OMAC, Hoam – CNC) in order to create a solution architecture that allows the user to modify the algorithms in order to obtain a flexible control system, and thereby adjust the functionality of CNC machines for their own needs. This topic is also goal of the research projects carried out on West Pomeranian University of Technology, Szczecin [3, 4].

Methods of improving geometrical and motional quality in CNC control systems

The requirements set for modern CNC machine control systems is steadily increasing due to the growing expectations of users. New control systems should provide possibilities of: ease of operation and programming, openness and flexibility of the structure, modularity construction and ensure high process dynamics and precision control, safety and robustness as well as durability and maintain special concern for the natural environment.

Manufacturers of hardware and software solutions for the CNC systems, in order to meet the generally prevailing trends are constantly developing their products and extend them with new features. Novel functionalities are supposed to improve the machining parameters, increase stability and extend the life of the tool. These solutions include, for example: nano-interpolation (GE Fanuc), active vibration control (Mazak), an intelligent thermal control (GF AgieCharmillesMikron), adaptive Feed Rate Control (Heidenhain), position control of machine tools (Sinumerik).

Servo drive control system structures in CNC feed drives

In a series of servo systems it is essential to ensure precise movement trajectory interpolation between the start and the end point. In commonly exploited numerically controlled machines market solutions of the servo control system, several types of position control structures are used [5]. The most common variant is the position control based on a cascade of PI controllers. Such a system consists of three feedback loops: current/torque control, velocity control $R_{vm}(s)$ and position control $R_p(s)$. Schematic architecture of the cascade controller current / torque, velocity and position is shown in figure 1.

Position and velocity control with fixed controllers settings in the structure shown in figure 1 gives good performance in limited range of machine operation, however, does not work for the entire length of the feed axis [6]. Significant movement parameters changes caused, for example, by such phenomena as an alternating screw stiffness as a function of the position, state a challenge for the currently used control systems which entail a prototyping need of new algorithms and implementing new solutions improving the quality and enhancing the stability of the milling process.

Rapid prototyping of servodrive velocity control algorithms

Rapid prototyping can be divided into several stages:

- Software-in-the-loop simulations – are sets of specially prepared tests which main purpose is to reduce the necessary time for implementing a new solutions. Usually, every algorithm is first tested in this way. Nowadays, one of the most popular simulation environment is Matlab / Simulink. As there are a few of tools available on the market vendors provide possibility of conducting numerical co-simulations. One of the possibility enables the usage of LMS. AmeSim (for physical modeling of complex mechatronic structures) in connection with Matlab / Simulink (for implementing and testing control part of the system);
- Virtual prototyping – is a technique, allowing software validation of created algorithms before implementation on real plant. Its exploits hardware resources of a PC for simulating behavior

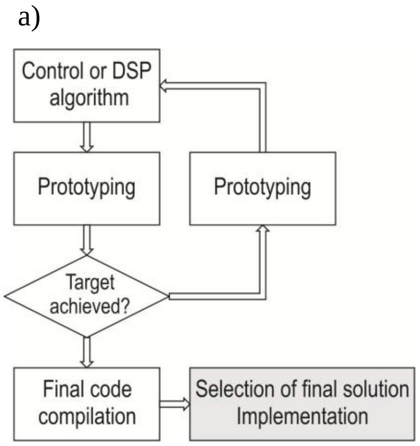

Fig. 2. Rapid prototyping common approaches: a) scientific b) industrial c) proposed in the article

of algorithms in various conditions. It allows also consider undesirable functional states and eliminate them before executed in the physical process. Integrating a software simulation environment on a PC with Real-time control system gives additional opportunity to imitate the work conditions and test algorithms and equipment.

- Hardware-in-the-loop simulations – the purpose of this stage of prototyping is to try out different, sophisticated concepts of control system algorithms without the risk of damaging any of the real plant's elements. The hardware-in-the-loop simulation provides an effective platform by adding the complexity of the plant under control to the test platform. Implementation of this stage of the prototype requires preparation process and controller to be executable in real –time conditions.

There are several rapid prototyping platforms available on the market. Most of them are solutions derived from the world of science (Fig. 2a) which task is to facilitate and expedite research progress. Those platforms require the user to additional burden for the implementation of the algorithms on target object.

Systems, shown in figure 2b are free from this inconvenience and thanks to automatic code generation functionality e.g. Matlab / Simulink allows to prepare a control tasks (compilation and programming) for target industrial control systems.

In case, when an industrial control system of mechatronic device cannot be easily modified but allows to automatic code generation, then it is reasonable to apply the approach outlined in figure 2c, where correction algorithms are prototyped in relation to the basic algorithm. The approach presented in figure 2c, is a unique approach developed in the grant: "Development of construction and experimental research work on mechatronic machine tool feed drive with the intelligent modular actuator", research project, N N502 336936, West Pomeranian University of Technology, Szczecin, 6/25/2009 – 6/24/2012, project manager: Krzysztof Pietrusewicz.

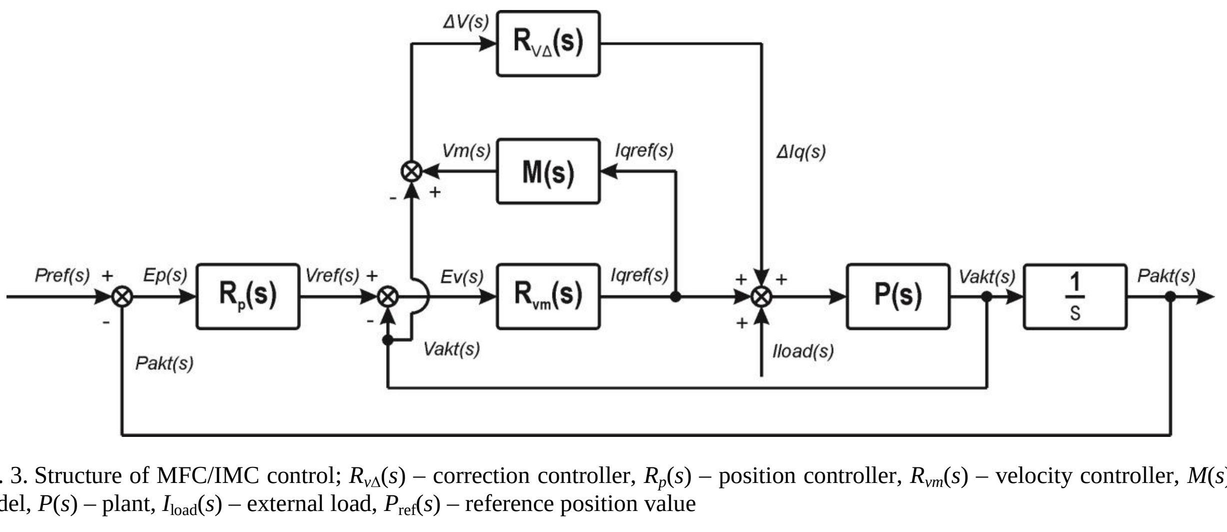

Fig. 3. Structure of MFC/IMC control; $R_{v\Delta}(s)$ – correction controller, $R_p(s)$ – position controller, $R_{vm}(s)$ – velocity controller, $M(s)$ – model, $P(s)$ – plant, $I_{load}(s)$ – external load, $P_{ref}(s)$ – reference position value

Reference signal dynamic correction based on plant's model

Nonlinearities occurring in numerically controlled machines due to their construction and operation are from the control point of view a process disruption. Perturbations are caused by both: external factors (e.g. load change), and internal arising from the inner structure of the plant.

In the case of CNC machines an important element for their proper operation is suitable tuning of digital servodrive's individual controllers, which is the part of axis feed drive. Nowadays, commonly used servo-control systems do not allow the realization of the disturbance free process which results in lower performance. One way of raising the level of parameters precision adjustment and plant control, could be a presented here algorithm called Model Following Control [7, 8, 9].

If thedynamic model has been identified using values of: reference current / torque and actual velocity, it is possible to introduce additional correction element which task is to calculate additional current quantity used for plant control $\Delta I_q(s) = \Theta[I_{qref}(s), v_{akt}(s)]$. Plant output $P(s)$ will track nominal model output which equal internal correction block signal $v_m(s) = M(s)I_{qref}(s)$. In presented correction element the signal is generated by the additional controller $\Delta I_q(s) = R_{v\Delta}(s)[v_m(s) - v_{akt}(s)]$ basing on difference between model output and actual velocity of controlled feed drive.

Approach introduced in this article should be considered as current feed-forward. Most of similar solutions exploited in industrial applications has been developed to increase control quality of known machine operation conditions, therefore, they tend to high sensitivity to parameters changes in relation to nominal model.

Presented in figure 3 control structure using dynamic current correction of velocity control level, based on MFC/IMC (Internal Model Control) algorithm is significantly better in mentioned areas due to the additional control degree, consisting of internal nominal model $M(s)$ and correction controller $R_{v\Delta}(s)$ which ensure: tracking quality improvement of velocity setpoint value, decreased influence of plant $P(s)$ parameter changes in relation to known nominal model $M(s)$, reduced impact of load changes $I_{load}(s)$ on the plant's input. Features mentioned here will be demonstrated in the next section of this article.

Sensitivity functions of analyzed plant

Sensitivity of control system is defined as its susceptibility to external disturbances. It is desired to obtain possibly low system sensitivity simultaneously maintaining proper performance. Sensitivity functions are exploited to describe relations between the plant's model and the external disturbances affecting its operation.

In this article the author presents comparison of CNC axis feed drive velocity control system sensitivity functions [10, 11]: conventional – cascade and introduced here MFC/IMC. To compare both structures transfer functions were defined (1) and (2).

Nominal input sensitivity $S_{x0}(s)$ (Fig. 4) reflects, basing on calculated frequency response, tracking quality of reference velocity value $v_{ref}(s)$. The equations (1) and (2) show that the proposed system (MFC / IMC) improves quality of reference velocity value tracking – absolute nominal input sensitivity function value equal to one denotes perfect tracking of setpoint value on the output. Calculations which the results are shown in the figures 4 and 5, were conducted for sensitivity functions described with equations (1) and (2).

Nominal system sensitivity $S_{load}(s)$ in function of input load $I_{load}(s)$ (Fig. 5) determined in the frequency domain defines load dumping effect, reduced to the controlled plant's input. Absolute value of function $S_{load}(s)$ in velocity control system is also called dynamic stiffness of axis feed drive.

Presented results shows that introduced MFC / IMC control system of CNC axis ball screw feed drive is an interesting alternative for conventional cascade control architectures. By the cost of little complexity increasing, user gets possibility of flexible dynamic properties changing of axis feed drive in the field of reference value tracking accuracy as well as dynamic stiffness.

$$v_{\mathrm{akt}_{\mathrm{clas}}}(s) = \frac{P(s)R_{vm}(s)}{1+P(s)R_{vm}(s)} v_{\mathrm{ref}}(s) + \frac{P(s)}{1+P(s)R_{vm}(s)} I_{\mathrm{load}}(s) \tag{1}$$

$$v_{\mathrm{akt}_{\mathrm{MFC/IMC}}}(s) = \frac{P(s)R_{vm}(s)[1+R_{v\Delta}(s)M(s)]}{1+P(s)R_{vm}(s)+P(s)R_{v\Delta}(s)M(s)R_{vm}(s)+P(s)R_{v\Delta}(s)} v_{\mathrm{ref}}(s) + \\ + \frac{P(s)}{1+P(s)R_{vm}(s)+P(s)R_{v\Delta}(s)M(s)R_{vm}(s)+P(s)R_{v\Delta}(s)} I_{\mathrm{load}}(s) \tag{2}$$

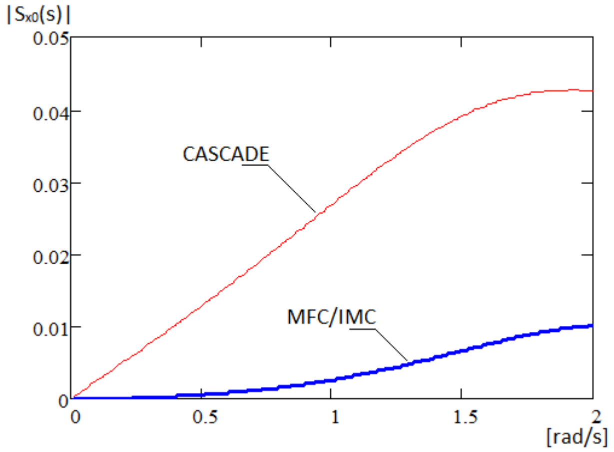

Fig. 4. Nominal input sensitivity (calculated for parameters values used in simulation experiment)

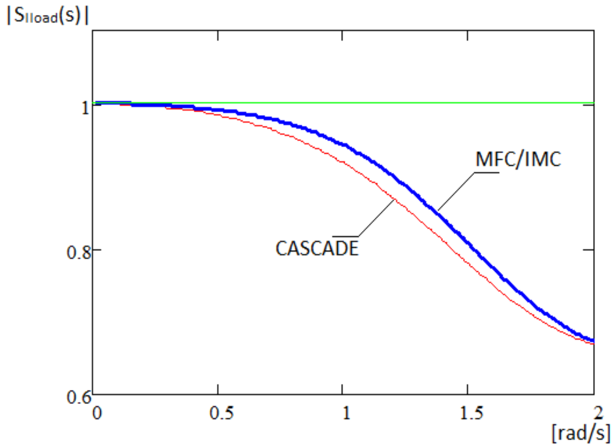

Fig. 5. System susceptibility for additional input load I_{load} (s) (calculated for parameters values used in simulation experiment)

Laboratory stand

Laboratory stand presented here, developed for purposes of CNC axis feed drives modeling experiments and rapid velocity algorithms prototyping, gives possibility of conducting novel tests in field of increasing control quality of feed drives. Prepared, experimental identification models can be compared with analytical ones. Architecture of the laboratory stand gives opportunity to test and prototype every, even the most sophisticated position / velocity control algorithm. To create a new control solutions, dSpace 1104 platform is exploited, because of facility of algorithms prototyping and validation. It is connected directly with dedicated frequency inverter which control CNC axis motors. Additionally in experiments was used industrial computer of National Instruments to measure tool table vibrations.

Model preparation and identification

In order to conduct simulations, laboratory stand's nonlinear model was developer in AMESim environment. It consisted the following elements: rotary load – motor shaft (1), spring dumper – clutch (2), rotary load – screw shaft (3), screw/nut mechanism (4), mass – nut (5), spring dumper – guide rails (6), mass – tool table (7). Known parameters of the feed axis, such as rotary load moment of inertia, screw diameter or pitch were used in model, the rest of factors were estimated in identification process conducted in cosimulation mode Matlab / Simulink – AMESim (Fig. 7). Exploited model parameters are presented in table 1.

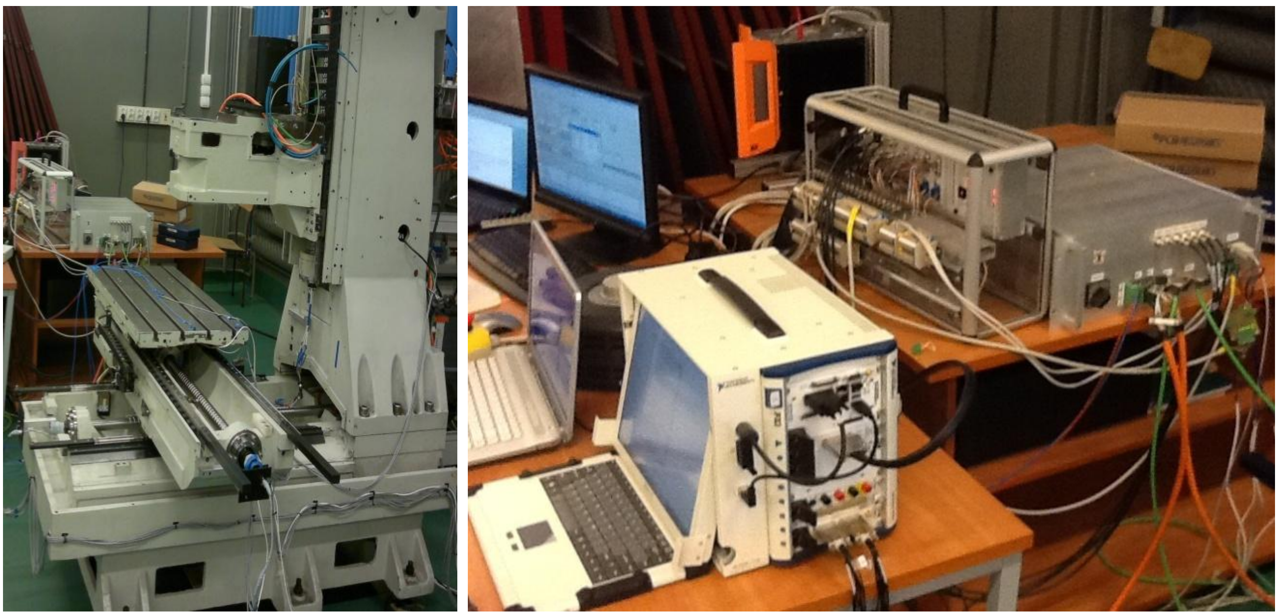

Fig. 6. Photos of laboratory stand

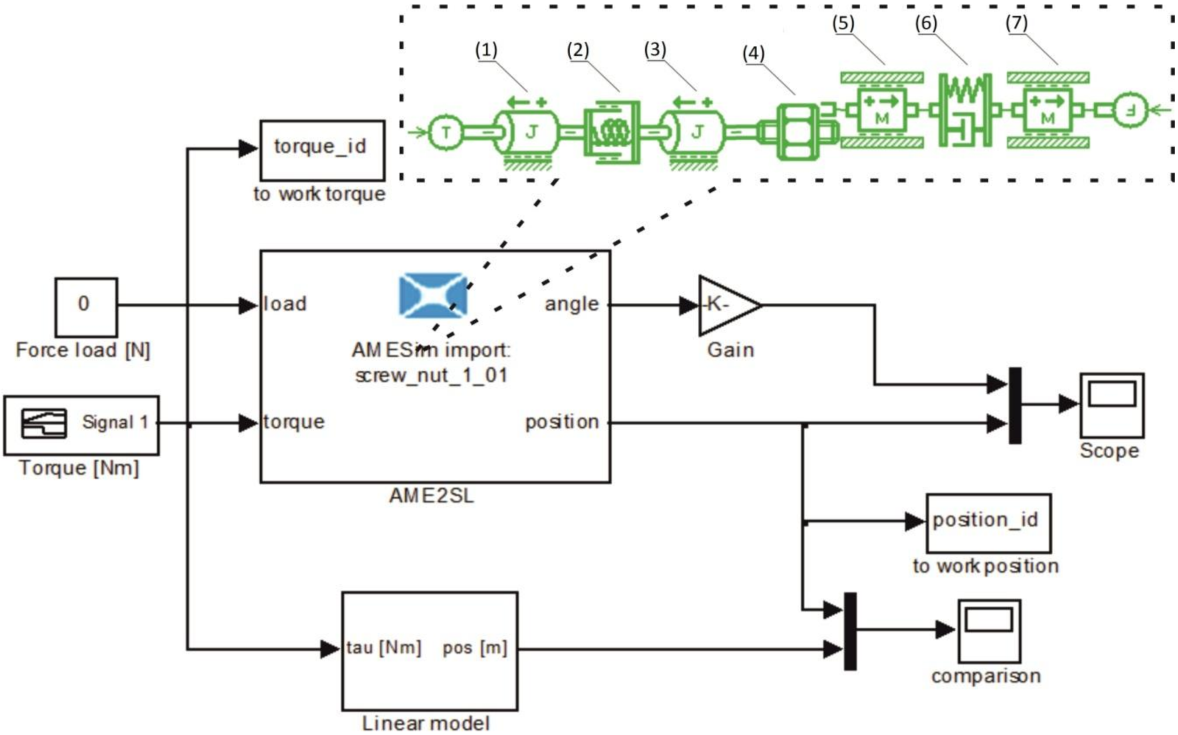

Fig. 7. Cosimulation mode Matlab/Simulink – AMESim

Table 1. Model parameters

	Parameter	Value	Unit
(1)	Moment of inertia	0.0017	kgm^2
	Coefficient of viscous friction	0.001	Nm/(rev/min)
	Coulomb friction torque	0.2	Nm
	Stiction torque	0.22	Nm
(2)	Stiffness	360	Nm/rev
	Damper rating	0.95493	Nm/(rad/s)
(3)	Moment of inertia	0.0032	kgm^2
	Coefficient of viscous friction	0.0004	Nm/(rev/min)
(4)	Diameter	40	mm
	Pitch	20	mm
	Contact stiffness	1e9	N/m
	Contact damping	1e6	N/(m/s)
	Stiction coefficient	0.12	–
	Coulomb friction coefficient	0.1	–
	Stick displacement threshold	0.001	mm
(5)	Mass	5	kg
	Stiction friction force	0	N
	Coulomb friction force	0	N
	Coefficient of viscous friction	0	N/(m/s)
(6)	Spring rate	100,000	N/m
	Damper rating	1,000	N/(m/s)
(7)	Mass	250	kg
	Stiction friction force	90	N
	Coulomb friction force	80	N
	Coefficient of viscous friction	0.003	N/(m/s)

Figure 8 presents step responses of model with estimated parameters and process from reference velocity measurements. Because of plant nonlinearity it was hard to select ideal factors that would resemble its behavior. One of the best results is shown below.

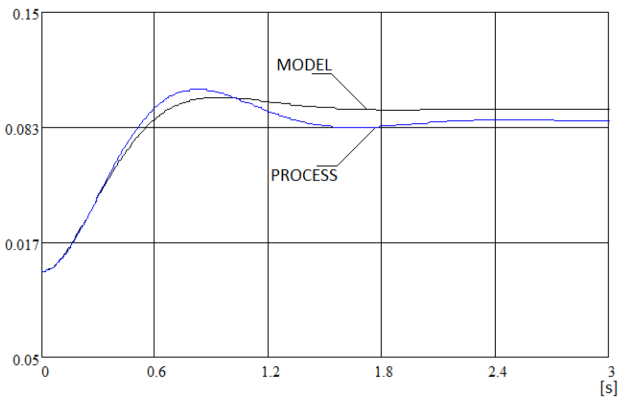

Fig. 8. Model and process step response comparison

Comparative simulation of MFC/IMC and cascade structures

Comparative simulation experiments of MFC/IMC and typical cascade control structures were made to show correctness of employed assumptions. Exploited plant's model is a base for prototyping developed algorithms. Below, in figure 9 comparison of both responses – simulated plant's and its model for reference velocity is presented.

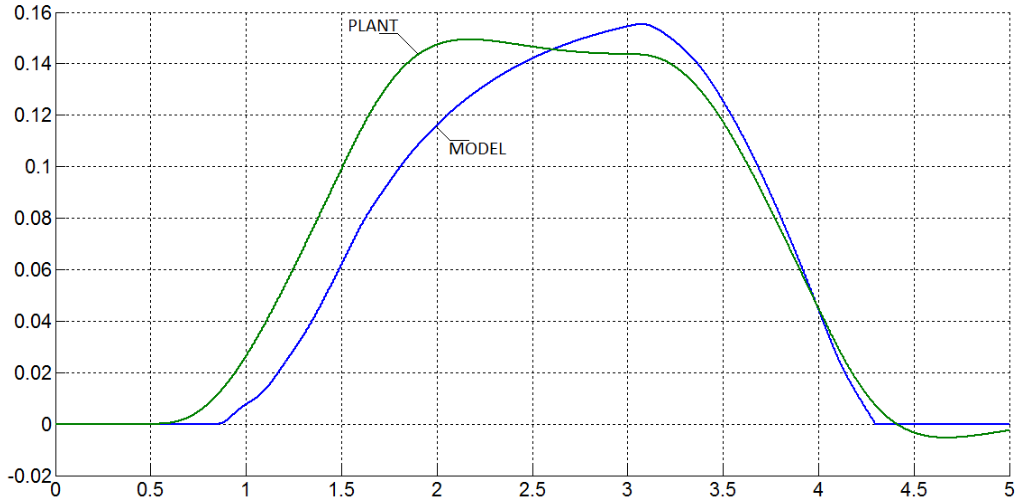

Fig. 9. Response of plant and model for reference velocity

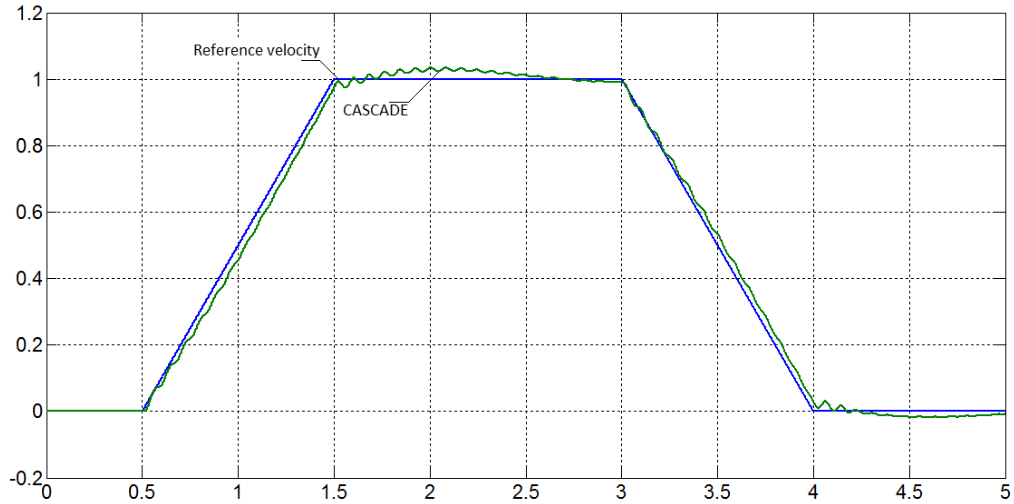

Fig. 10. Response of typical cascade structure for reference velocity value

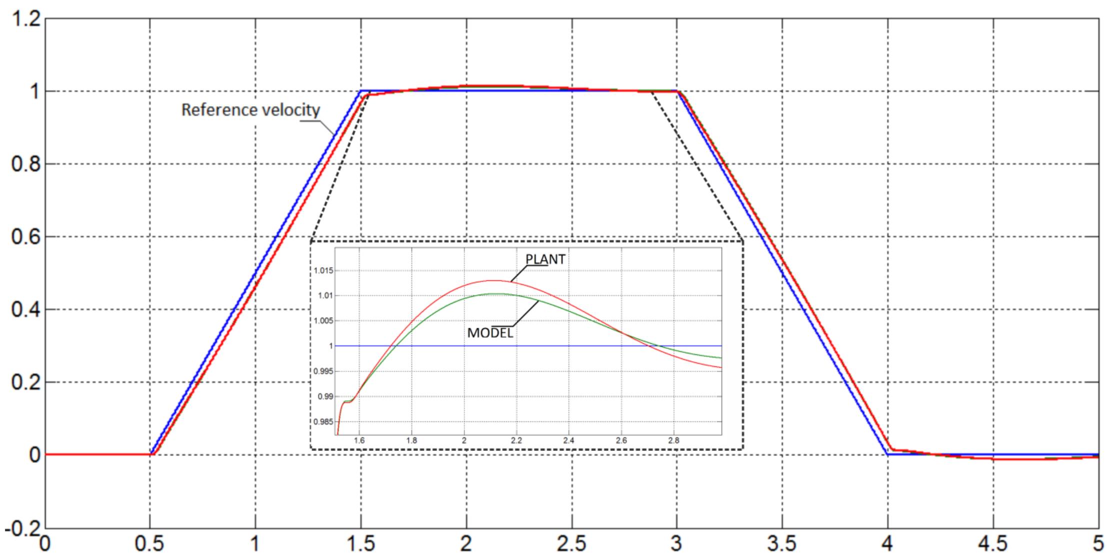

Fig. 11. Response of MFC/IMC structure for reference velocity value

Response for reference velocity value of typical cascade control structure was simulated using nonlinearplant model and PID controller. Tunes of the controller were selected experimentally: Proportional (P) = 40, Integral (I) = 6, Derivative (D) = 0.5. Figure 10 presents tracking of the reference velocity by the plant's PID output.

Assumption of the MFC/IMC architecture is exploiting the same PID controller with identical tunes as introduced in the cascade structure case. Extra, linear model of the plant (P = 100, I = 20, D = 2) is used to improve control quality. It calculates the additional correction signal which has an impact on the main control value. Obtained simulation results stands that presented in this article structure gives positive outcomes in terms of improving the tracking reference velocity value by plant's output. Figure 11 shows, how plant's output was forced to resemble model's output in order to adopt its behavior.

Conclusions

Presented in this article approach basing on plant's model ensures control quality improvement of CNC axis feed drive. It is a result of noticeable deviation reduction between reference and actual velocity and may be considered as alternative for commonly exploited cascade control architecture. An undoubted advantage of the presented here solution is the possibility of implementation in a digital servo drive system without interference with its constituent algorithms. It can be introduced in every system which allows user implementation of his own correction/control algorithms using signals of: actual velocity, reference current (from measurements) and entering additional signal (additive reference current) which affect the main control value.

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