The Mechatronics System Control Quality Analysis Using Simulink and GUI in Matlab

M. Juhás, B. Juhásová, and P. Mydlo

***Abstract*—In this contribution is presented study of flexible mechatronics system control quality analysis. Control system is designed by various standard and advanced methods. The different criteria for quality evaluation are used. The Matlab – Simulink simulation model in conjunction with Matlab GUI is used for experiments realization.**

***Index Terms*—control quality, Matlab GUI, mechatronics system control, Simulink**

I. Introduction

THE contribution deals with flexible mechatronics system control quality analysis by the Simulink tool and with GUI utilization created in the Matlab. The impulse is ongoing necessity of further advancement of electric drives containing elements with different types of parasitic effects control methods, in this case flexible connection between an actuator and a load. There are different methods of mechatronics system control design analyzed in this article. The control quality is advised on base of local criterion as well as integral quality criterion.

II. Controlled system model

The permanent magnet synchronous motor (PMSM) with flexible coupling is chosen as analyzed mechatronics system. A special type of PMSM with the high torsion moment by the relatively low evolves – torque motor, was analyzed.

If the inertia of the transmission mechanisms is small compared to the motor and load, the flexible coupling between the motor and load can be treated as a two-mass motor/load system, as shown in Fig. 1. [2, 5, 6]

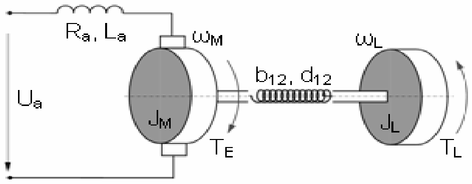


Fig. 1 PMSM with flexible join

TABLE I
Analyzed system parameters

Parameter	Unit	Description	Value
Ra	Ω	armature current	0.02
La	mH	resistance and inductance of armature winding	100
cΦ	Nm/A	torque constant	0.3
JM	kg/m2	inertia of the motor rotor	10
JL	kg/m2	inertia of the load	60
b12	Nms	damping of the transmission	0.1
d12	Nm	spring constant of the transmission	4
kTM	-	converter gain	1
TTM	-	converter time constant	2

The control system design was based on idealized condition where the infinitely rigid connection was considered instead of flexible connection between actuator and a load. This condition is described as

$$J = J_M + J_L \tag{1}$$

Oversimplified model of system as transfer function of this adjusted mechatronics system has a form

$$G_{PMSM}(s) = \frac{c\Phi}{(J_M + J_L)L_a s^2 + (J_M + J_L)R_a s + c\Phi^2} \tag{2}$$

A spurious effects caused by resonant frequency and antiresonant frequency occurrence in the flexible connection were eliminated by double notch filter [7, 9] in form

$$G_{filter}(s) = \frac{\left(\frac{1}{\omega_r}\right)^2 s^2 + \frac{2\xi_r}{\omega_r} s + 1}{\left(\frac{1}{\omega_a}\right)^2 s^2 + \frac{2\xi_a}{\omega_a} s + 1} \tag{3}$$

where

resonance: $$\omega_r = \sqrt{d_{12}\frac{J_M + J_L}{J_M J_L}} \tag{4}$$

resonance dumping: $$\xi_r = \frac{b_{12}}{2}\sqrt{\frac{J_M + J_L}{d_{12} J_{1M} J_L}} \tag{5}$$

antiresonance: $$\omega_a = \sqrt{\frac{d_{12}}{J_L}} \tag{6}$$

antiresonance dumping: $$\xi_a = \frac{b_{12}}{2\sqrt{d_{12} J_L}} \tag{7}$$

III. Control system design and control system model

For control system design was applied different methods. [1, 3, 4, 8] Classical feedback control has been designed by

--Naslin method

Manuscript received June 20, 2012; revised July 22, 2012.

M. Juhás is with the Institute of AIAM FMST SUT in Trnava, Hajdóczyho 1, 917 01 Trnava, Slovak Republic (phone: +421 918 646 021; e-mail: martin_juhas@stuba.sk).

B. Juhásová is with the Institute of AIAM FMST SUT in Trnava, Hajdóczyho 1, 917 01 Trnava, Slovak Republic (e-mail: bohuslava.juhasova@stuba.sk).

P. Mydlo is with the Institute of AIAM FMST SUT in Trnava, Hajdóczyho 1, 917 01 Trnava, Slovak Republic (e-mail: peter.mydlo@stuba.sk).

--Modulus Optimum Method
--Method of Inverse Dynamics

Next, the combination of classical feedback control and one of intelligent control methods has been applied

--Fuzzy controller

An advanced control method in form of cascade control with utilization

--2x Modulus Optimum Method
--Modulus Optimum Method and Symmetric Optimum Criterion

was also used.

A. Feedback control of angular velocity

The simulation was performed by simulation model (Fig. 2) [10] consists of

--controlled system – actuator electrical part (Fig. 3) and flexible join of actuator with load (Fig. 4)
--controller $G_R(s)$
--double notch filter

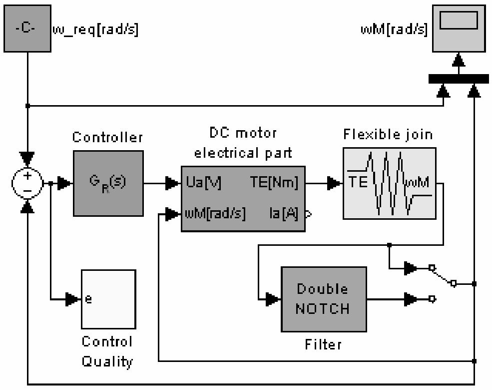


Fig. 2 Simulation model of angular velocity feedback control

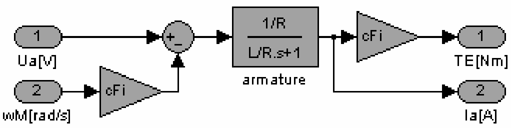


Fig. 3 Analyzed system simulation model of electrical part

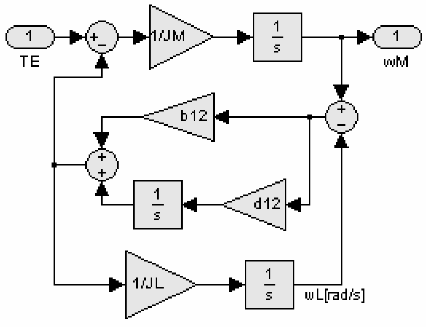


Fig. 4 Analyzed system simulation model of flexible join

PI controller – Naslin method

For controller of PI type in form

$$G_R(s) = r_0 + \frac{r_{-1}}{s} \tag{8}$$

is the closed control loop in form

$$Gc(s) = \frac{0.3r_0 s + 0.3r_{-1}}{7s^3 + 1.4s^2 + (0.09 + 0.3r_0)s + 0.3r_{-1}} \tag{9}$$

According this, for $\alpha = 2$ and maximum overshooting 5% following a Naslin method are valid inequalities

$$a_1^2 \ge \alpha a_0 a_2 : (0.09 + 0.3r_0)^2 = 2 * 0.3r_{-1} * 1.4 \tag{10}$$

$$a_2^2 \ge \alpha a_1 a_3 : 1.4^2 = 2 * (0.09 + 0.3r_0) * 7 \tag{11}$$

For PI controller coefficients calculation is used a boundary state – equality and the resulting values are

TABLE II
PI (NASLIN) CONTROLLER PARAMETERS

Parameter	Value
r_0	0.1667
r_{-1}	0.0233

PID controller – Modulus Optimum Method

For controller of PID type in form

$$G_R(s) = r_0 + \frac{r_{-1}}{s} + r_1 s \tag{12}$$

has an opened control loop form

$$Go(s) = \frac{0.3r_1 s^2 + 0.3r_0 s + 0.3r_{-1}}{7s^3 + 1.4s^2 + 0.09s} \tag{13}$$

Following an assumption that ideal closed control system transfer function has a value approaching to one, the equation involving real part of open control loop frequency response has form

$$Go(s) = \frac{\omega^4(0.42r_1 - 2.1r_0) + \omega^2(0.027r_0 - 0.42r_{-1})}{49\omega^6 + 0.7\omega^4 + 0.0081\omega^2}$$
$$Go(s) = -0.5 \tag{14}$$

The coefficients of PID controller are solved based on equations system in matrix form solution

$$\begin{bmatrix} -0.42 & 0.027 & 0 \\ 0 & -2.1 & 0.42 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} r_{-1} \\ r_0 \\ r_1 \end{bmatrix} = -0.5 \begin{bmatrix} 0.0081 \\ 0.7 \\ 49 \end{bmatrix} \tag{15}$$

The coefficients of PID controller designed by Modulus Optimum Method are

TABLE III
PID (MOM) CONTROLLER PARAMETERS

Parameter	Value
r_0	0.1602
r_{-1}	0.0199
r_1	–0.0323

PID controller – Method of Inverse Dynamics

For possibility to calculate controller coefficients by Method of Inverse Dynamics was transfer function of an actuator rigidly connected with a load modified to the form

$$G_{PMSM}(s) = \frac{0.3}{7s^2 + 1.4s + 0.09} = \frac{K}{T_0^2 s^2 + 2\xi T_0 s + 1} \tag{16}$$

where

$$K = 0.3 / 0.09 ; T_0 = \sqrt{7/0.09} ; \xi = \frac{1.4}{0.09 * 2 * T_0} \tag{17}$$

The coefficients of PID controller in form

$$G_R(s) = P(1 + \frac{T_i}{s} + T_d s) \tag{18}$$

are for defined time constant T_w=0.1 calculated according to equations

$$T_i = 2\xi T_0 ; T_d = \frac{T_0}{2\xi} ; P = \frac{T_i}{KT_w} \tag{19}$$

The coefficients of PID controller designed by Method of Inverse Dynamics are

TABLE IV
PID (MID) CONTROLLER PARAMETERS

Parameter	Value
P	46.6713
T_i	15.5556
T_d	5

Fuzzy control

The fuzzy controller was designed by experimental variation of k_e, k_{de} and k_{du} coefficients based on ITAE quality criteria tracking and evaluation. The simulation model of fuzzy controller, which was used in this simulation experiment, is shown in Fig. 5.

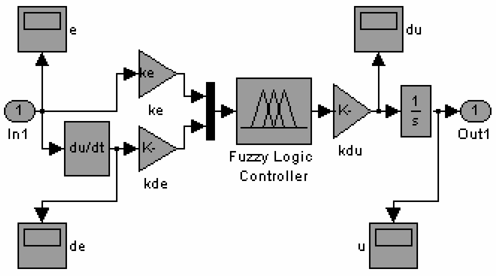


Fig. 5 Simulation model of fuzzy controller

The resultant values of fuzzy controller are

TABLE V
PD (FUZZY) CONTROLLER PARAMETERS

Parameter	Value
k_e	0.0016
k_{de}	0.0165
k_{du}	787.8

B. Cascade control

The most frequently used control structure in the controlled drives is the cascade control. In the case of speed control of PMSM are using two loops namely

--current (eventually torque) loop
--speed loop

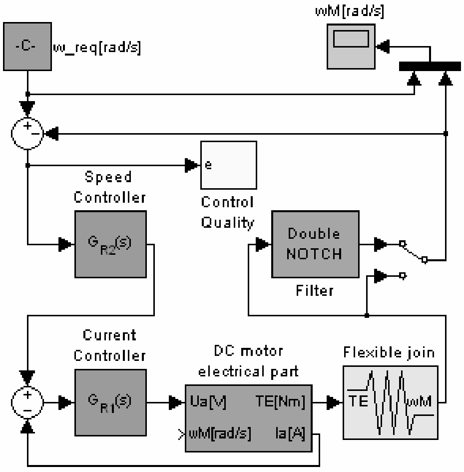


Fig. 6 Simulation model of PMSM cascade control

Current controller

The tuning method based on the Modulus Optimum optimization criterion was used for current controller design.

According to this criterion was specified PI controller in form

$$R_{PI} = k_{PI}\frac{Ti_{PI}s + 1}{Ti_{PI}s} \qquad (20)$$

with coefficients defined as

$$k_{PI} = \frac{Ti_{PI}}{2kT_{TM}}; Ti_{PI} = L_a / R_a; k = k_{TM} / R_a \qquad (21)$$

The coefficients of cascade control subordinate PI current controller designed by Modulus Optimum Method are

TABLE VI
PI (MOM) CURRENT CONTROLLER PARAMETERS

Parameter	Value
k_{PI}	0.025
Ti_{PI}	5

Speed controller I

The tuning method based on the Symmetric Optimum Criterion was used for first version of speed controller design.

According to the Symmetric Optimum Criterion was specified PID controller in form:

$$R_{PID} = k_{PID} + \frac{Ti_{PID}}{s} + Td_{PID}s \qquad (22)$$

with coefficients defined as

$$k_{PID} = \frac{J(4T_{TM} + J)}{8c\phi T_{TM}^{2}}; Ti_{PID} = \frac{J}{8c\phi T_{TM}^{2}}; \qquad (23)$$
$$Td_{PID} = \frac{J^2}{2c\phi T_{TM}}$$

The coefficients of cascade control master PID angular velocity controller designed by Symmetric Optimum Criterion are

TABLE VII
PID (SOC) CURRENT CONTROLLER PARAMETERS

Parameter	Value
k_{PID}	568.75
Ti_{PID}	7.2917
Td_{PID}	4083.3

Speed controller II

The tuning method based on the Modulus Optimum criterion was used for second version of speed controller design.

According to the Modulus Optimum criterion was specified PD controller in form:

$$R_{PD} = k_{PI}(1 + Td_{PI}s) \qquad (24)$$

with coefficients defined as

$$k_{PI} = \frac{1}{2\frac{c\phi}{J}T_{TM}}; Td_{PI} = 2T_{TM} \qquad (25)$$

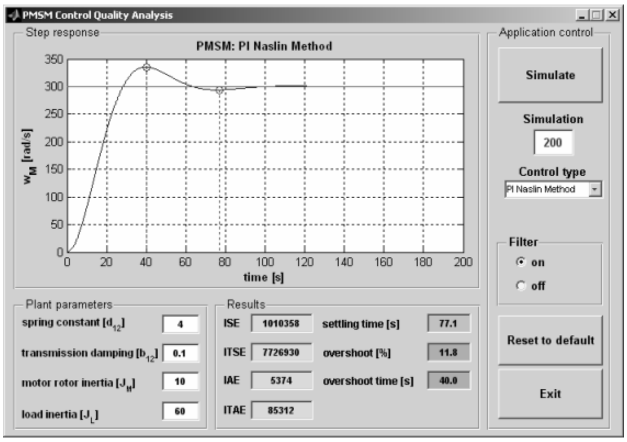
The coefficients of cascade control master PD angular velocity controller designed by Modulus Optimum Method are

TABLE VIII
PD (MOM) CURRENT CONTROLLER PARAMETERS

Parameter	Value
k_{PD}	58.3333
Td_{PD}	4

IV. GRAPHICAL USER INTERFACE FOR QUALITY ANALYSIS

For operation rejuvenation by the evaluation of analyzed system quality control the graphical user interface (GUI) was created (Fig. 7). [11] Designed application utilizes simulation and analysis of created simulation models to view various qualitative indicators. It also allows analyzing influence of elimination element – double notch filter application on control process quality increase.



Simulation: 200

Control type: PI Naslin Method

Filter: ● on ○ off

Plant parameters
spring constant [d_{12}] 4
transmission damping [b_{12}] 0.1
motor rotor inertia [J_M] 10
load inertia [J_L] 60

Results
ISE 1010358
ITSE 7726930
IAE 5374
ITAE 85312
settling time [s] 77.1
overshoot [%] 11.8
overshoot time [s] 40.0

Fig. 7 GUI for PMSM Control Quality Analysis

V. ANALYSIS RESULTS

The plots of angular velocity of particular simulation experiments are displayed extra for enabled (Fig. 8) and extra for disabled (Fig. 9) parasitic frequency filtration.

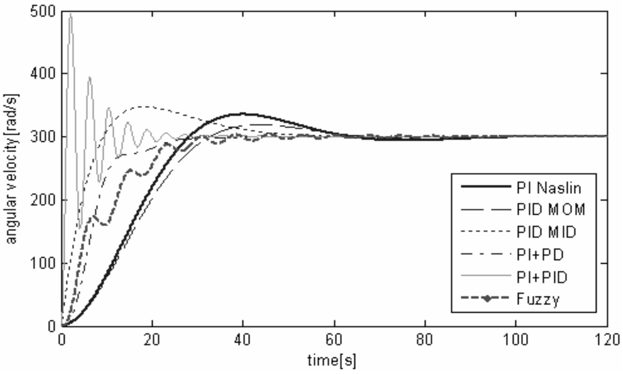


Fig. 8 Angular velocity with filtration

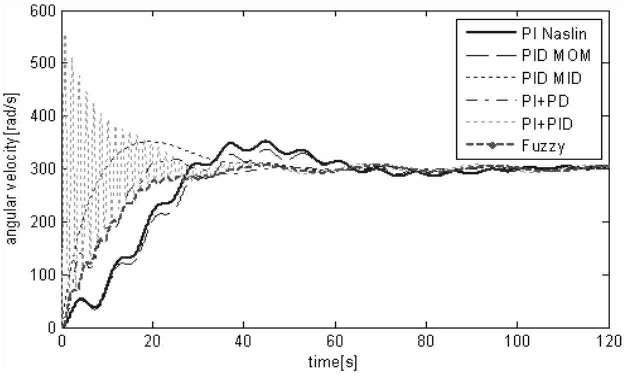


Fig. 9 Angular velocity without filtration

The quality of control process has been evaluated based on local criteria of quality

--Settling Time
--OverShoot
--OverShoot Time

as well as based on integral criteria of quality for control error space, acquired through the simulation subsystem [10] shown in Fig. 10.

--Integral Square Error (ISE)
--Integral Time Square Error (ITSE)
--Integral Absolute Error (IAE)
--Integral Time Absolute Error (ITAE)

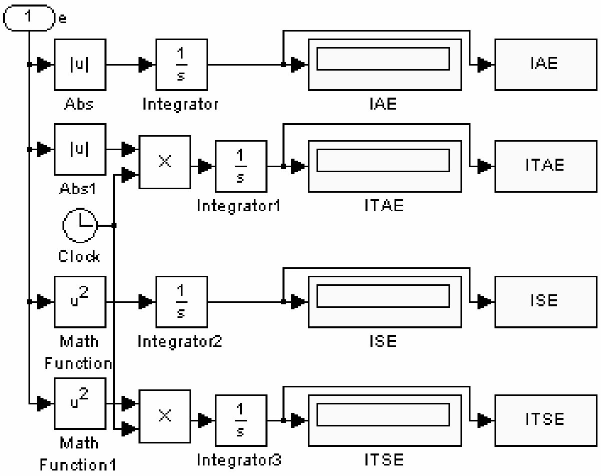


Fig. 10 Simulation subsystem for integral criteria measurement

The results of experiments, consisting of evaluating of different quality markers for different methods of flexible mechatronics system control design are shown in TABLE IX

TABLE IX
SIMULATION RESULTS

filter on	ISE	ITSE	IAE	ITAE	ST	OS	OST
PI Naslin	1010358	7726930	5374	85312	77.1	11.8	40
PID MOM	1056620	8103446	5306	72441	59.7	6.3	43.6
PID MID	233657	1147410	2147	29634	46	15.9	18.5
PI+PD	479922	1599638	2400	14409	24.9	0	0
PI+PID	130834	359755	1175	13332	23.3	64.8	2.1
Fuzzy	498810	2372726	3048	31162	42.7	1.2	46

filter off	ISE	ITSE	IAE	ITAE	ST	OS	OST
PI Naslin	1007834	9141781	5917	121337	92.2	17.2	44.9
PID MOM	1055588	9319508	5861	110914	99.1	12.5	45.1
PID MID	231924	1280192	2452	65804	50.7	17.2	19.7
PI+PD	443791	2041271	2719	24109	40.5	6.3	25.4
PI+PID	211086	1371905	2458	86346	191.9	85.5	0.8
Fuzzy	495243	2633827	3521	85453	184.4	2.6	42.7

Reached results were represented in graphical form (Fig. 11, Fig. 12, Fig. 13 and Fig. 14) because of analyses requirement. Graphical representation does not contain absolute numerical expression of results, but because of comparability they were transformed to percentage representation of specific part relative to entirety.

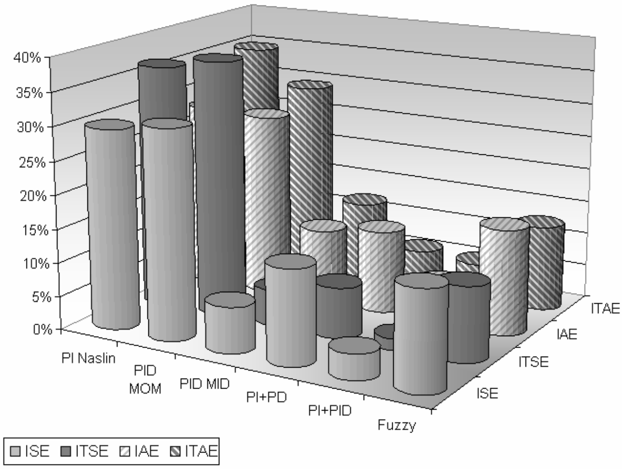


Fig. 11 Simulation results – Integral criteria of quality with filtration

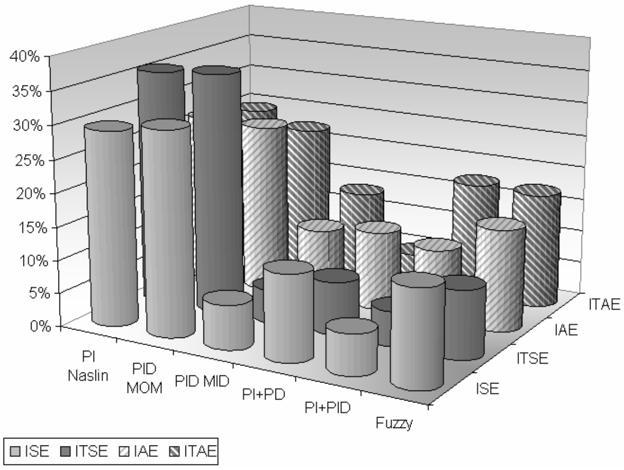


Fig. 12 Simulation results – Integral criteria of quality without filtration

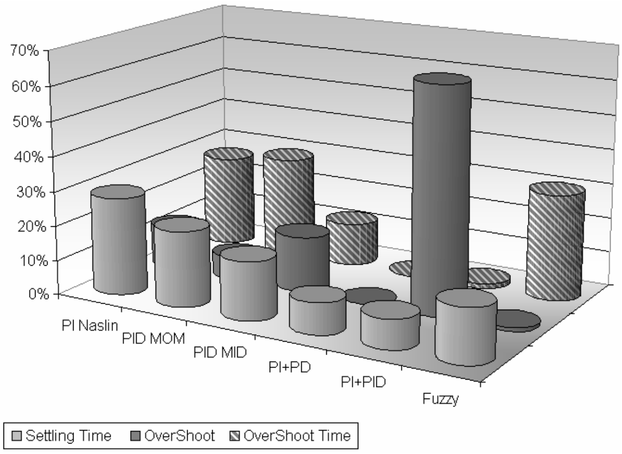


Fig. 13 Simulation results – Local criteria of quality with filtration

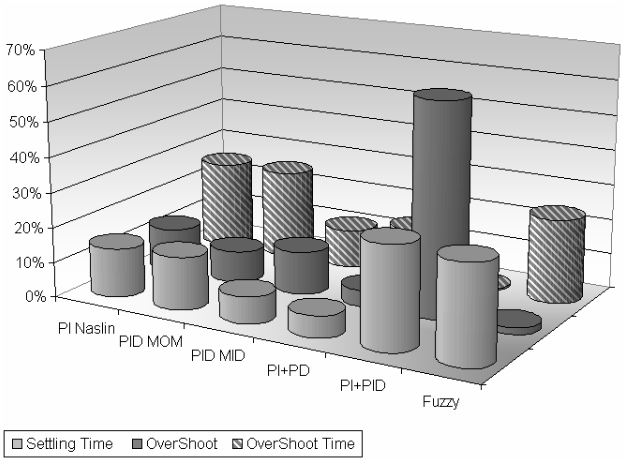


Fig. 14 Simulation results – Local criteria of quality without filtration

VI. CONCLUSION

The set of experiments, consist of simulation of flexible mechatronics system with control system designed by different methods, has been performed. The quality of control process was evaluated based on different markers. According to achieved results is possible to state, that:

--for control design necessity is possible to use a substitution of infinitely rigid join instead of flexible join in the concurrency with utilization of filter for flexible system antiresonant and resonant frequency;

--classical principles of control design (Naslin, MOM) are of advantage in term of local criterion especially by using them without filtering of parasitic elements, but according to quality integral criterion is their application markedly inept;

--according to integral criteria, as an optimal method for control design wears the cascade control with PI current controller and PID angular velocity controller, which is however at least advantageous in the term of maximal overshooting value;

--usage of advanced control methods, represented by fuzzy control in this case considering dynamics and system structure wears as disadvantageous;

--after evaluation of combination of all indicators is possible to assert, that the one of optimal methods of flexible mechatronics system control design is possible to consider the classical design method - method of inverse dynamics and advanced method - cascade control contains combination of PI current controller and PD angular velocity controller. These two methods show signs of robustness furthermore, in terms of unacceptable frequencies elimination without using of supplementary filter too.

REFERENCES

[1] J. Balátě, “Automatické řízení,” BEN – technická literatura, Praha, 2003

[2] D.A. Bradley, D. Dawson, N.C. Burd, A.J. Loader, “Mechatronics,” Chapman & Hall, London, 1991. ISBN 0-412-58290-2.

[3] I. Švarc, R. Matoušek, M. Šeda and M. Vítečková, “Automatické řízení,“ Akademické nakladatelství CERM, s.r.o. Brno, 2011

[4] M. Vítečková, A. Víteček, “Modulus optimum for digital controllers,” Acta Montanistica Slovaca, 2003, vol. 8, no. 4, pp. 214 – 216.

[5] S. Vukosavic, M. Stojic, “Suppression of Torsional Oscillations in a High-Performance Speed Servo Drive,” IEEE Trans. on Industrial Electronics, vol. 45, pp. 108-117, Jan. 1998.

[6] J. Vittek, P. Briš, P. Makyš, M. Štulrajter and V. Vavruš, “Control of Flexible Drive with PMSM employing Forced Dynamics,” 13th EPE-PEMC 2008, pp. 2219-2226. IEEE 978-1-4244-1742-1.

[7] J. Jovankovič, M. Žalman, “Mechatronické pohybové systémy (2),” AT&P journal, 2006, vol. XIII, no. 3, pp. 73 – 74. ISSN 1335-2237

[8] G. Ellis, “Control system design guide,” San Diego: Elsevier Academic Press, 2004. 464 pp. ISBN 0-12-237461-4

[9] J. Kalous, C. Kratochvíl and P. Heriban, “Dynamics of Rotary Electromechanical Drives,” ÚT AVČR – Centrum mechatroniky, Brno, 2007. ISBN: 80-214-3340-X.

[10] MathWorks. (2012, May 20). Simulink [Online]. Available: http://www.mathworks.com/products/simulink/

[11] MathWorks. (2012, May 20). Matlab GUI [Online]. Available: http://www.mathworks.com/discovery/matlab-gui.html