

Nonlinear Model-Free Control and ARX Modeling of Industrial Motor

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Abstract

System identification is one of the main challenges in real time control. To design the best controller for linear or nonlinear systems, mathematical modeling is the main challenge. To solve this challenge conventional and intelligent identification are recommended. The second important challenge in the field of control theory is, design high-performance controller. To improve the performance of controller, two factors are very important: 1) high performance mathematical or intelligent modeling, 2) chose the best controller for the system. This paper has two main objectives: after data collection from position motor from industry the first objective is modeling and system identification based on Auto-Regressive with eXternal model input (ARX) and defined Z-function and S-function and the second objective is; design the high-performance controller to have the minimum rise time and error.

Keywords: *System identification, highly nonlinear dynamic equations, Auto Regressive with eXternal model input, control methodology*

1. System Modeling

Motors are very important instruments in any industries. The applications of motors are wide such as, pumping fluids, compressors, and position movement. Servos motor and stepper motors are two important motors for position control. To detect the position servo motors are used. In this types of motors, two parameters can control angular position and velocity. In this type of motor, the output's position is controlled by the potentiometer. This potentiometer is used to detect the required voltage and send to motor's output to select the desired position with the minimum error [1-5].

To modeling this system the sample frequency is 10 ms. The data collection extract from real motor. Figure 1 shows the position, velocity and input data collection by 1001 sampled.

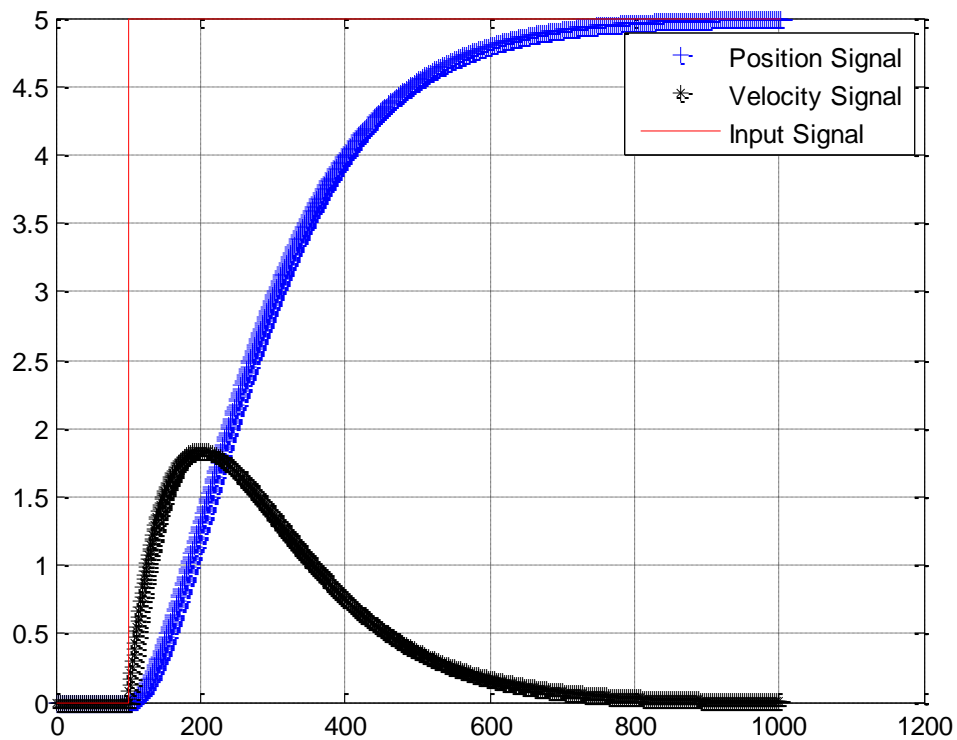


Figure 1. Position, Velocity and Input of Motor Data Collection

To modeling the position system based on ARX theory, the general input-output form is:

$$A(q)y(t) = \frac{B(q)}{F(q)} u(t - nk) + \frac{C(q)}{D(q)} e(t) \quad (1)$$

the five polynomials $A(q)$, $B(q)$, $C(q)$, $D(q)$ and $F(q)$ are introduced and the state A is:

$$A(q) = [1 \ a_1 \ a_2 \ a_3 \ \dots \ a_n] \quad (2)$$

The most used model structure is the simple linear difference equation:

$$y(t) + a_1y(t - 1) + a_2y(t - 2) + \dots + a_ny(t - na) = b_1u(t - 1) + b_2u(t - 2) + \dots + b_nb u(t - nk - nb + 1) \quad (3)$$

which relates the current output $y(t)$ to a finite number of past outputs $y(t-k)$ and inputs $u(t-k)$. To ARX modeling we have:

$$A(q)y(t) = B(q) u(t - nk) + e(t) \quad (4)$$

To ARX modeling three factors are important: inputs, noise and output. Assuming the signals are related by a linear system, the relationship can be written

$$y(t) = G(q)U(t) + e(t) \tag{5}$$

where q is the shift operator and $G(q).U(t)$ is short for:

$$G(q)U(t) = \sum g(k).U(t - k) \tag{6}$$

and

$$G(q) = \sum g(k)q^{-k}, q^{-1}u(t) = u(t - 1) \tag{7}$$

There are two problems concerning to system identification modeling 1) highly nonlinear system and 2) the techniques of parameter identification. The parameters of the ARX model structure is:

$$A(q)y(t) = B(q) u(t) + e(t) \tag{8}$$

The order in ARX modeling is:

$$nn = [na \ nb \ nk] \tag{9}$$

Where na is output order in ARX, nb is input order in ARX and nc is delay order.

In this system if $nn = [2, 1, 1]$ the system identification is as Figure 2.

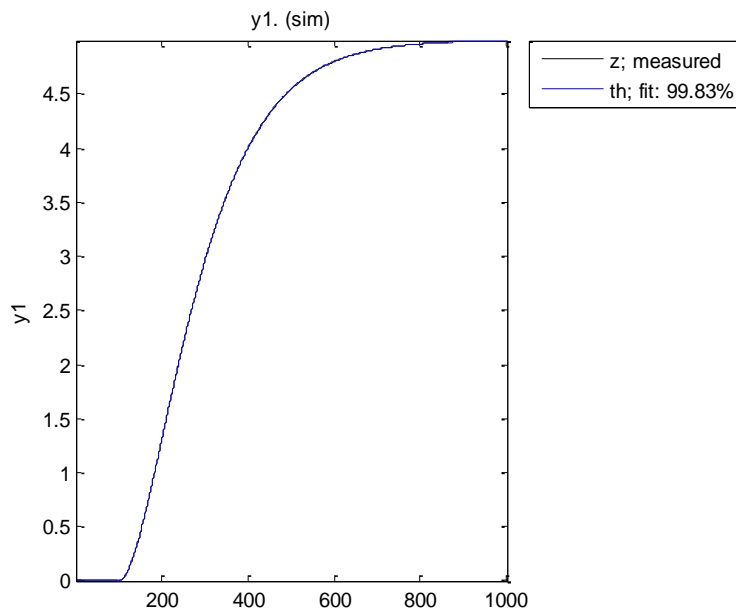


Figure 2. Fitting Test Compare between ARX Identification and Output, 99.83% Fitting Test

Figure 3 shows the error between real system and system identification.

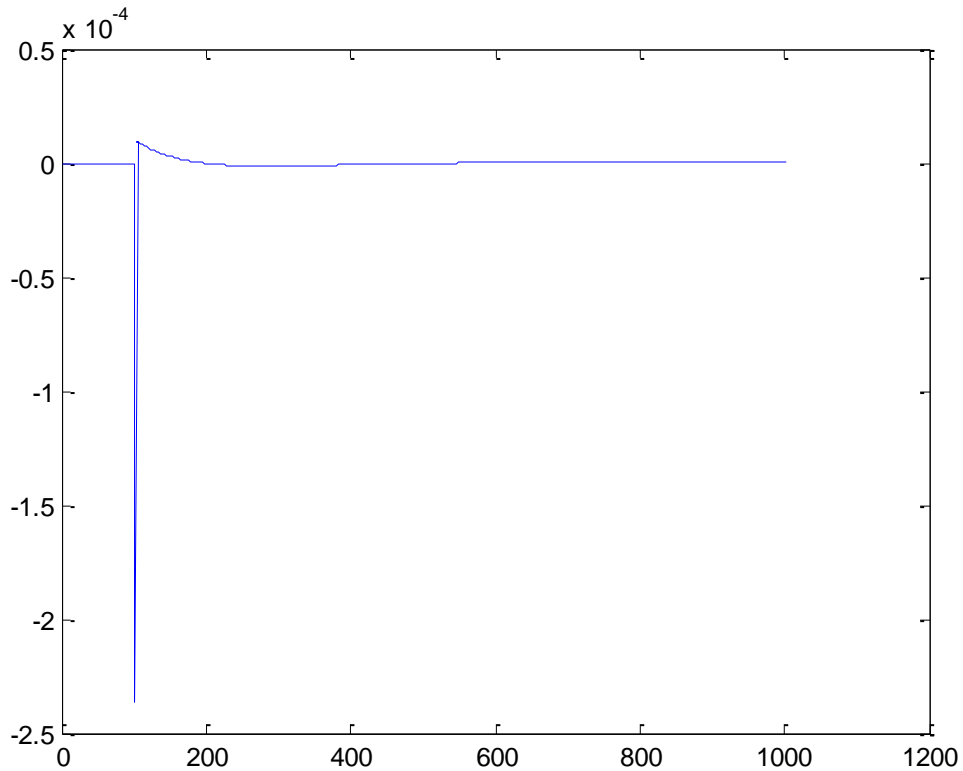


Figure 3. Error Test Compare between ARX Identification and Real System

Regarding to Figure 2, the Discrete-time IDPOLY model is:

$$A(q)y(t) = B(q)u(t) + e(t)$$

$$A(q) = 1 - 1.81 (\pm 0.002154) q^{-1} + 0.8187 (\pm 0.00207) q^{-2}$$

$$B(q) = 0.009056 (\pm 9.416e^{-5}) q^{-2}$$

Based on the system identification the loss function is $2.18697e^{-8}$ and final predictive error is $2.20008e^{-8}$. The continuous time IDPOLY model is:

$$A(s)y(t) = B(s)u(t) + C(s)e(t)$$

$$A(s) = s^2 + 0.2s + 0.01$$

$$B(s) = 0.004837s + 0.01$$

$$C(s) = s^2 + 1.634s + 1.104$$

The Z-transform of this system is:

$$H(Z) = \frac{0.0091}{Z^2 - 1.8097Z + 0.8187}$$

The S-transform of this system is:

$$H(S) = \frac{(0.0048 S + 0.01)}{S^2 + 0.2 S + 0.01}$$

Regarding to above Z-transform and S-transform, we can find the mathematical function to design controller.

2. Desihn Model-free Nonlinear Controller

The second challenge in this research is design a controller for highly nonlinear plant. The main idea to design this type of nonlinear model-free controller is based on the following formulation;

$$\tau_{(q,t)} = \begin{cases} \tau_i^+(q, t) & \text{if } S_i > 0 \\ \tau_i^-(q, t) & \text{if } S_i < 0 \end{cases} \quad (10)$$

A time-varying $s(x, t)$ in the state space R^n is given by the following formulation:

$$s(x, t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} \tilde{x} = \mathbf{0} \quad (11)$$

The $s(x, t)$ can be defined as Proportional-Derivative (PD), Proportional-Integral (PI) and the Proportional-Integral-Derivative (PID). The following formulations represented the three groups are [6-7]:

$$S_{PD} = \lambda e + \dot{e} \quad (12)$$

$$s(x, t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} \left(\int_0^t \tilde{x} dt\right) = \mathbf{0} \quad (13)$$

$$S_{PI} = \lambda e + \left(\frac{\lambda}{2}\right)^2 \sum e \quad (14)$$

$$S_{PID} = \lambda e + \dot{e} + \left(\frac{\lambda}{2}\right)^2 \sum e \quad (15)$$

According to above formulation the formulation of controller is:

$$U_{dis} = K(\vec{x}, t) \cdot \text{sgn}(s) \quad (16)$$

and

$$\text{sgn}(s) = \begin{cases} \mathbf{1} & s > 0 \\ -\mathbf{1} & s < 0 \\ \mathbf{0} & s = 0 \end{cases} \quad (17)$$

$$U_{dis-PD} = K \cdot \text{sgn}(\lambda e + \dot{e}) \quad (18)$$

$$\tau_{dis-PI} = K \cdot \text{sgn} \left(\lambda e + \left(\frac{\lambda}{2}\right)^2 \sum e \right) \quad (19)$$

$$\tau_{dis-PID} = K \cdot \text{sgn} \left(\lambda e + \dot{e} + \left(\frac{\lambda}{2}\right)^2 \sum e \right) \quad (20)$$

Discontinues part is used to design suitable tracking performance based on very fast switching. This part of the controller is work based on the linear type methodology; therefore it can be PD, PI, and PID. Fast switching or discontinuous part have the essential role to achieve to good trajectory following, but it is caused system instability and chattering phenomenon. Chattering phenomenon is one of the main challenges in this controller and it can cause some important mechanical problems such as saturation and heats. Figure 4 shows the chattering phenomenon [8-9].

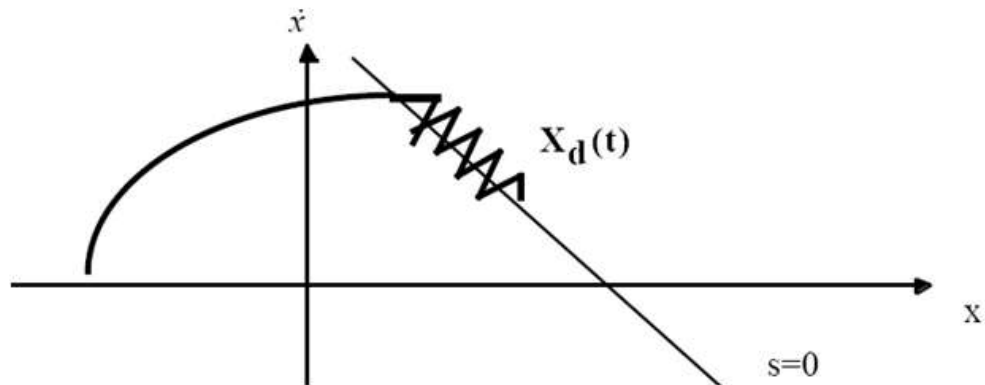


Figure 4 . Chattering Phenomenon

To reduce the chattering linear boundary layer method is introduced. The saturation (linear) method with small neighborhood of the switching surface is calculated as

$$B(t) = \{x, |S(t)| \leq \phi\}; \phi > 0 \quad (21)$$

where ϕ is the boundary layer thickness. The controller formulation is written by:

$$U = K(\bar{x}, t) \cdot \text{Sat} \left(\frac{S}{\phi} \right) \quad (22)$$

While saturation function formulation ($\text{Sat} \left(\frac{S}{\phi} \right)$) is as follows

$$\text{sat} \left(\frac{S}{\phi} \right) = \begin{cases} 1 & (S/\phi > 1) \\ -1 & (S/\phi < -1) \\ S/\phi & (-1 < S/\phi < 1) \end{cases} \quad (23)$$

However, this method can reduce or eliminate the chattering but it has three new challenges: increase the error, increase the rise time and reduce the stability and robustness. To reduce the chattering in presence of switching functions; the linear

controller is added to discontinuous part of sliding mode controller. The linear controller is the type of stable controller as well as conventional sliding mode controller. In proposed methodology PD, PI or PID linear controller is used in parallel with the discontinuous part to reduce the role of sliding surface slope as the main coefficient. The formulation of new method control technique is:

$$U_{dis-new} = K_a \cdot \text{sgn}(S) + K_b \cdot S \quad (24)$$

$$U_{dis-PD-new} = K_a \cdot \text{sgn}(\lambda e + \dot{e}) + K_b \cdot (\lambda e + \dot{e}) \quad (25)$$

$$U_{dis-PI-new} = K_a \cdot \text{sgn}\left(\lambda e + \left(\frac{\lambda}{2}\right)^2 \sum e\right) + K_b \cdot \left(\lambda e + \left(\frac{\lambda}{2}\right)^2 \sum e\right) \quad (26)$$

$$U_{dis-PID-new} = K_a \cdot \text{sgn}\left(\lambda e + \dot{e} + \left(\frac{\lambda}{2}\right)^2 \sum e\right) + K_b \cdot \left(\lambda e + \dot{e} + \left(\frac{\lambda}{2}\right)^2 \sum e\right) \quad (27)$$

In rise time point of view (Figure 1), our system (motor) has about 9 seconds rise time. Therefore, one of the main objectives to design controller for our system is, reduce the rise time. To test it, nonlinear model free switching controller, nonlinear model free saturation controller and new methodology are compared. Figure 5 shows the trajectory following in these three types of controllers.

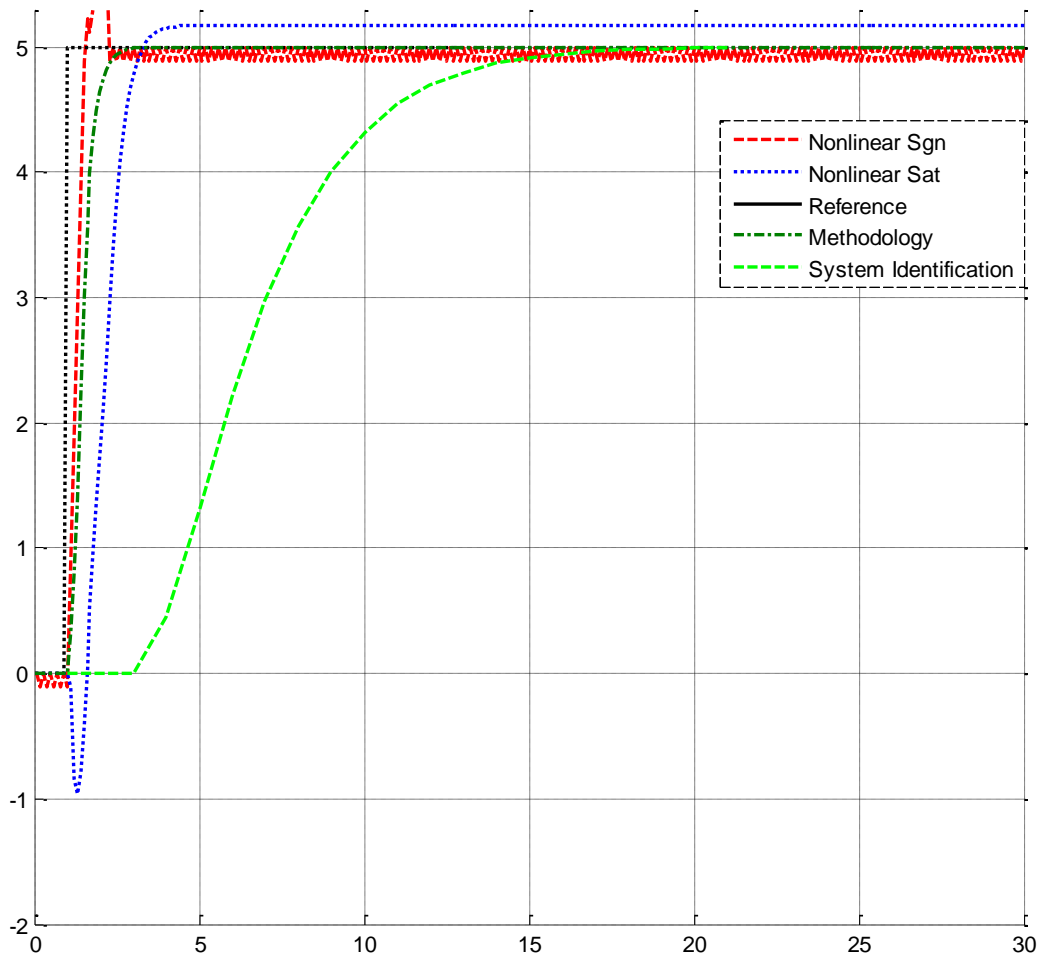


Figure 5. Trajectory Following: Nonlinear Model Free sgn Controller, Nonlinear Model Free Sat Controller, New Methodology

Regarding Figure 5, the rise time in these three types' controllers is reduced from 9 seconds to less than two seconds. In oscillation point of view, the nonlinear model free switching controller has oscillation in comparison to nonlinear model free saturation controller and new methodology controller. In error point of view, nonlinear model free saturation controller's error is about 0.02, but new methodology controller's error is about near to the zero.

Figure 6 shows the S-factors. To have the best response in these types of controllers S-factor is one of the main factors. Zero is the best value for S and the rate of s-factor in new methodology controller is better than the nonlinear model free saturation controller.

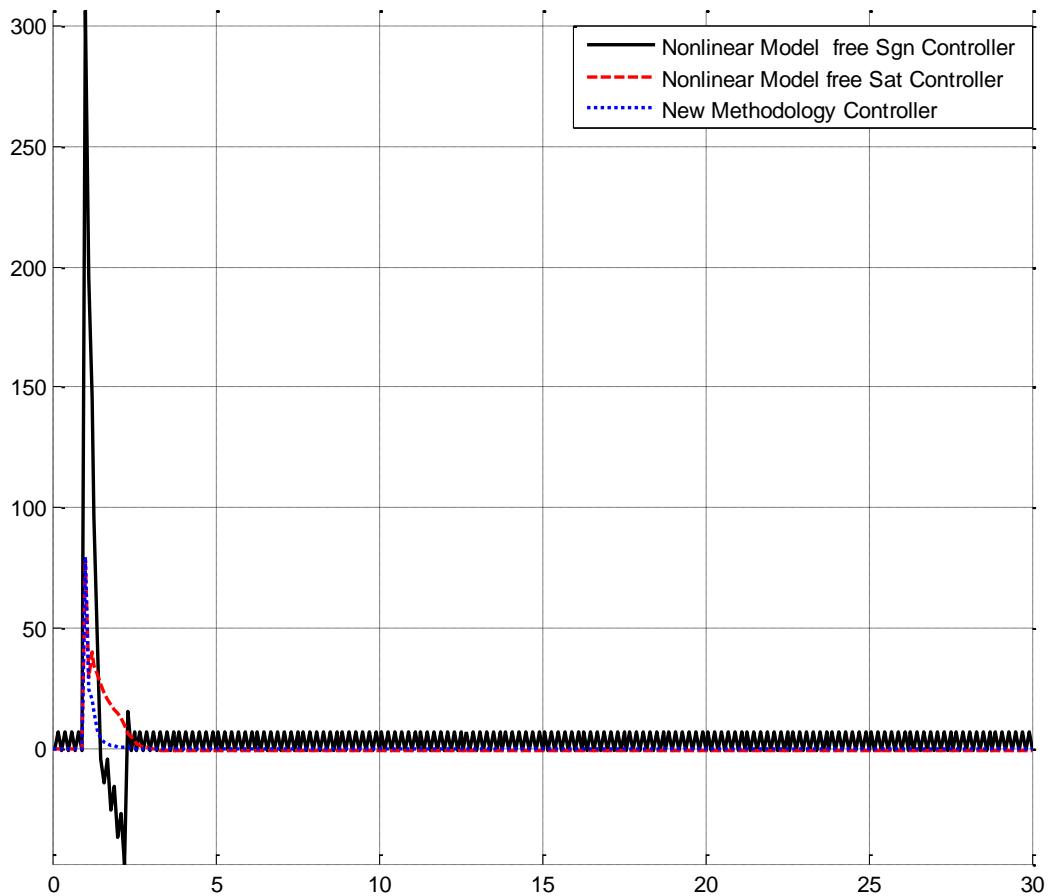


Figure 6. S-Factors: Nonlinear Model Free sgn Controller, Nonlinear Model Free Sat Controller, New Methodology

To robust and stability checking, controllers are tested under uncertainty conditions. In these situations, band-limited white noise is applied to these types of controllers. In open-loop systems in presence of uncertainty, the rise-time increase from about 9 seconds to about 34 seconds. Regarding Figure 7, the rate of rising time is increased about 400% in open loop system in presence of uncertainty. In this state, the role of controllers is improved the rise time as well as reduces the oscillations and errors. According to Figure 7, nonlinear model-free with saturation controller has moderate fluctuations. In this situation, the rate of oscillation in the nonlinear model free switching controller is about the same as certain condition and it has oscillation. Based on Figure 7, new methodology's fluctuations is about zero.

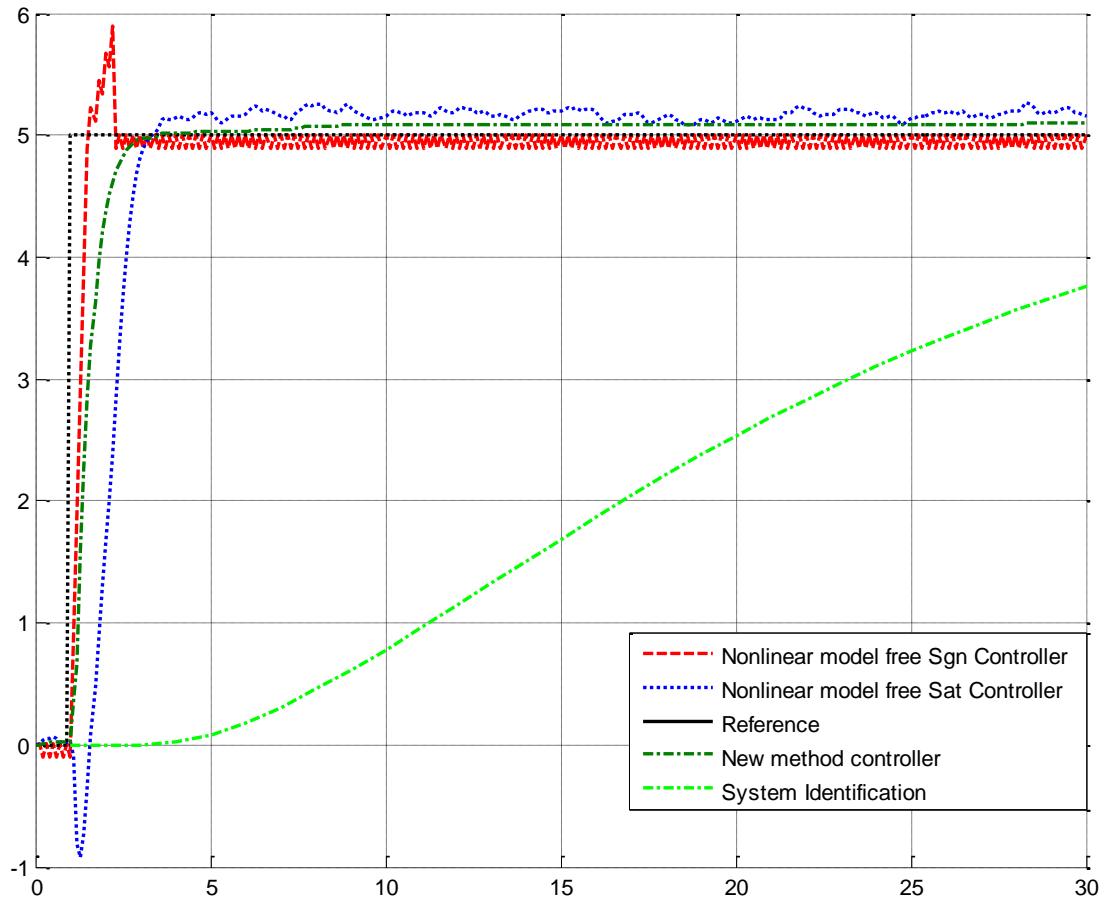


Figure 7. Disturbance Rejection: Nonlinear Model Free sgn Controller, Nonlinear Model Free Sat Controller, New Methodology

3. Conclusion

This research has two main objectives: system identification and control. In the first part of this research paper, the ARX system identification is used system identification and modeling. We modeling this system with 99.83% fit and find second order laplas function. The rise-time in this system in the certain condition is about 9 seconds and in uncertainty is about 34 seconds. To improve the response of this system three types of the controller is applied: nonlinear model free switching controller, nonlinear model free saturation controller and new method controller. According to above discussion, the nonlinear model free switching function is stable and robust but it has oscillation which caused to challenge in our system (motor). To improve nonlinear model free switching controller, nonlinear model free saturation controller is introduced. However, this controller eliminates the oscillation and improves the rise-time in certain and uncertain condition but it has two important negative points: increase the error and reduce the stability and robustness. To improve these challenges new method is used in this research. After applied this controller to our identify system, the oscillation in certain and uncertain condition is eliminated, the rise-time is reduced from 9 seconds to about 1 seconds in certain and 34 seconds to 1.2 seconds in uncertain condition, the error is reduced compare to nonlinear model free saturation controller, improve the stability and robustness

compare with nonlinear model free saturation controller. Regarding above discussion for identification, ARX methodology and for control, the high speed robust nonlinear model-free controller is recommended.

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Maryam Sarostad is currently working as a research assistant in Control and Robotic Lab at the institute of advanced science and technology, IRAN SSP research and development Center. Her current research interest is in the area of system identification.



Farzin Piltan is an outstanding scientist in the field of Electronics and Control engineering with expertise in the areas of nonlinear systems, robotics, and microelectronic control. Mr. Piltan is an advanced degree holder in his field. Currently, Mr. Piltan is the Head of Mechatronics, Intelligent System, and Robotics Laboratory at the Iranian Institute of Advanced Science and Technology (IRAN SSP). Mr. Piltan led several high impact projects involving more than 150 researchers from countries around the world including Iran, Finland, Italy, Germany, South Korea, Australia, and the United States. Mr. Piltan has authored or co-authored more than 140 papers in academic journals, conference papers and book chapters. His papers have been cited at least 3900 times by independent and dependent researchers from around the world including Iran, Algeria, Pakistan, India, China, Malaysia, Egypt, Columbia, Canada, United Kingdom, Turkey, Taiwan, Japan, South Korea, Italy, France, Thailand, Brazil and more. Moreover, Mr. Piltan has peer-reviewed at least 23 manuscripts for respected international journals in his field. Mr. Piltan will also serve as a technical committee member of the upcoming EECSI 2015

Conference in Indonesia. Mr. Piltan has served as an editorial board member or journal reviewer of several international journals in his field as follows: International Journal Of Control And Automation (IJCA), Australia, ISSN: 2005-4297, International Journal of Intelligent System and Applications (IJISA), Hong Kong, ISSN:2074-9058, IAES International Journal Of Robotics And Automation, Malaysia, ISSN:2089-4856, International Journal of Reconfigurable and Embedded Systems, Malaysia, ISSN:2089-4864.

Mr. Piltan has acquired a formidable repertoire of knowledge and skills and established himself as one of the leading young scientists in his field. Specifically, he has accrued expertise in the design and implementation of intelligent controls in nonlinear systems. Mr. Piltan has employed his remarkable expertise in these areas to make outstanding contributions as detailed follows: Nonlinear control for industrial robot manipulator (2010-IRAN SSP), Intelligent Tuning The Rate Of Fuel Ratio In Internal Combustion Engine (2011-IRANSSP), Design High Precision and Fast Dynamic Controller For Multi-Degrees Of Freedom Actuator (2013-IRANSSP), Research on Full Digital Control for Nonlinear Systems (2011-IRANSSP), Micro-Electronic Based Intelligent Nonlinear Controller (2015-IRANSSP), Active Robot Controller for Dental Automation (2015-IRANSSP), Design a Micro-Electronic Based Nonlinear Controller for First Order Delay System (2015-IRANSSP).

The above original accomplishments clearly demonstrate that Mr. Piltan has performed original research and that he has gained a distinguished reputation as an outstanding scientist in the field of electronics and control engineering. Mr. Piltan has a tremendous and unique set of skills, knowledge and background for his current and future work. He possesses a rare combination of academic knowledge and practical skills that are highly valuable for his work. In 2011, he published 28 first author papers, which constitute about 30% of papers published by the Department of Electrical and Electronic Engineering at University Putra Malaysia. Additionally, his 28 papers represent about 6.25% and 4.13% of all control and system papers published in Malaysia and Iran, respectively, in 2011.



Fatemeh Dehghan Ashkezari is currently working as a research assistant in Control and Robotic Lab at the institute of advanced science and technology, IRAN SSP research and development Center. Her current research interest is in the area of system identification.



Nasri Sulaiman is advisor and supervisor of several high impact projects involving more than 150 researchers from countries around the world including Iran, Malaysia, Finland, Italy, Germany, South Korea, Australia, and the United States. Dr. Nasri Sulaiman has authored or co-authored more than 80 papers in academic journals, conference papers and book chapters. His papers have been cited at least 3000 times by independent and dependent researchers from around the world including Iran, Algeria, Pakistan, India, China,

Malaysia, Egypt, Columbia, Canada, United Kingdom, Turkey, Taiwan, Japan, South Korea, Italy, France, Thailand, Brazil and more. Dr. Nasri Sulaiman has employed his remarkable expertise in these areas to make outstanding contributions as detailed below:

- Design of a reconfigurable Fast Fourier Transform (FFT) Processor using multi-objective Genetic Algorithms (2008-UPM)
- Power consumption investigation in reconfigurable Fast Fourier Transform (FFT) processor (2010-UPM)
- Crest factor reduction And digital predistortion Implementation in Orthogonal frequency Division multiplexing (ofdm) systems (2011-UPM)
- High Performance Hardware Implementation of a Multi-Objective Genetic Algorithm, (RUGS), Grant amount RM42,000.00, September (2012-UPM)
- Nonlinear control for industrial robot manipulator (2010-IRAN SSP)
- Intelligent Tuning The Rate Of Fuel Ratio In Internal Combustion Engine (2011-IRANSSP)
- Design High Precision and Fast Dynamic Controller For Multi-Degrees Of Freedom Actuator (2013-IRANSSP)
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- Design a Micro-Electronic Based Nonlinear Controller for First Order Delay System (2015-IRANSSP)

