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Design of control system for steel strip-rolling mill using NARMA-L2

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Abstract A Simulink and mathematical models have been proposed in this study in order to control the thickness in a rolling mill process. The simulation results show that the thickness oscillation can be manipulated with high accuracy by using NARMA-L2, since it can remove the non-linearity of servo system and other disturbances complexities. The proposed NARMA-L2 controller model has been compared with a more popular PID controller and demonstrated high efficiency. The model also demonstrated its ability to be resilient under any sudden changes in system dynamics. This efficacy continues to increase even in linear or nonlinear disturbances. For proving the efficiency of the model, it had been tested with different cases such as uniform or variable thickness, large thickness, small thickness... etc, and it had appeared acceptable robustness when subjected to sudden disturbances. Very small rise time and overshoot can be obtained. Also, with precision optimization of the main parameter of NARMA-L2 the steady-state error may be removed. Accurate profiles can be manufactured for the steel plates in a hot rolling mill by consideration of the presented strategy. More sources of nonlinearities of rolling systems are taken into account in this work. The results of the nonlinear case have been implemented for uniform and non-uniform thickness of the steel plate, where, it appeared very acceptable performance of the proposed model with high efficiency to avoid the sharp edges of the sheet profile. Recent manufacturing requirements need high precision of milling products, therefore, the present study explains the intelligent strategies that can be considered to reach this object. The result shows that fast control behavior with low uncertainties can be achieved. In some rolling mill applications, variable thickness products cannot be constructed with conventional approaches, theretofore, artificial intelligent with hard learning should be introduced.

1. Introduction

In the rolling mill field, the steel sheet thickness and the rolling speed represent a main important aim for the designers that work in this subject of manufacturing. Also; sheet surface quality is one of the great objects that many researchers have wanted to approach. Many strategies have been constructed and implemented in order to improve the control precision of sheet gauge such as hydraulic automatic gauge control (HAGC). Proportional -integral- derivative (PID) control scheme is widely used in the rolling production due to its simplicity and the acceptability of its cost. In addition to that PID can be tuned with many new methods and schemes especially intelligent techniques such as fuzzy logic (FL), artificial neural network (ANN) and genetic algorithm (GA). For magnesium plate rolling, hydraulic automatic gauge control (AGC) represents an important part of rolling procedures. However, the system of AGC usually has nonlinear behavior and high time delay. Also; it's a complex and multivariable system with a time – varying performance. Therefore, rolling is a fertile subject for researchers who still improve many schemes to increase the quality of the products. The speed of rolling process can reach great magnitudes therefore the controllers used in this application should be of a high-speed response. Also, the connection between the mechanical elements and actions with the required electronics circuits and processes is very complex and has multivariable and many affective factors which affect the performance of the control response.

In 2015, Jiangang [1] proposed a study for using adaptive PID control (APID) which depended on (ANN) in the adjusted of the main parameters of PID. This study showed an acceptable reduction in the settling time of the response and small percent overshoot has been reached. In this work, the step response test of HAGC is investigated, a test approach is implemented. By using MATLAB software, the transfer function model of the step response test is established and simulated. The experimental results show that the improved step response test model may reach the process requirements of HAGC and can produce a better stability as well as a faster response for steel sheet rolling. Fan et al. [2] in 2014 designed a sliding mode controller to adjust the position for the hydraulic automatic gauge control system (AGC). Comparing with general PID tuned with Ziegler-Nichols method this study shows a strong anti-interference ability and can produce a proper control action. In 2005, Zhang et al. [3] discussed the actuator and the process models of steel plate mill designed in this work. A quick and accurate control schemes and acceptable tuning of constants can be achieved with help of new software proposed in this paper. A theoretical model was established by Jie et al. [4] in 2015 for the hydraulic gap control (HGC). Offline identification was considered in the design of the important parts of the system. The improvement of the system robustness had led to reduce the overshoot and rise time with acceptable rate as compared with traditional controllers. Some nonlinearity has been considered in a mathematical model presented by Steiboeck et al. [5] in 2014 using Hamilton's principles simultaneously with Galerkin weighted residual procedure. In this model a hot strip tandem rolling mill is taken as a case study. Hot rolling is a significant process in which some manufacturing products can be finished. For this reason, a case study had been presented by Chauhan and Agrawel [6] in 2013 for reducing the defects in the leaf spring production which, intern, led to reduce the cost of product rejection and also the ganger of accidents can be safely controlled. Many researches have been focused on the strip behavior during the infeed in hot rolling such as Refs. [7, 8]. Many sources of nonlinearity in the rolling process have been analyzed with different control techniques [9-12]. Automated gauge control (AGC) system has taken a wide area of the recent studies that deals with hot and cold rolling mill. These studies had concentrated to improve the mill stretch design and the rolling speed control in order to accomplish fine thickness with respect to the compensation of the roll eccentricity and thickness oscillation due to speed reduction [13-15]. With the increasingly demand of the accurate tolerances in many manufacturing processes, the control of strip dimensions in rolling mill had been treated with some intelligent techniques such as fuzzy logic, neural network, etc. [16-18]. The main objects of these studies include the reduction of error that happened due to the movement of the strip. This undesirable movement of the strip may be occurred when random disturbances have been occurred.

The group, led by Rusnák [19] worked on the assessment the results about of investigating pointed at changing the rolling speed and the impact of outside particles within the steel strip, as well as the forces within the rolling prepare. It moreover compares the relationship of the lab results about, hypothetical desires, and real-life perceptions. The authentic databases created based on occurrences (strip breaks) since 2013 were utilized; the detailed position of each strip break was recorded, in conjunction with absconds found at the parcels of steel strips that broke or the data that no deformity was found.

Khosravi et al. [20] proposed a novel screen hydraulic automatic gauge control (HAGC) framework based on fuzzy feed-forward controller. This is often utilized within the advancement of cold rolling process mechanization framework to make strides the quality of the cold strips. In arrange to move forward the speed of the controller in dismissing unsettling influences presented by section strip thickness varieties, master information is included as a feed-forward term to the HAGC framework.

The team, led by Chen et al. [21] worked on the end of strip breaks amid rolling through progressed data analysis. They have overseen to set up twenty key parameters that influence strip breaks, but they did not succeed in deciding an express root cause of strip breaks. Their conclusion was the choice to carry out the investigation, centering on the information that gives more accurate details with information around the method.

In this work, an effective intelligent technique had been used in order to present a model for controlling the strip thickness in the rolling process. The proposed model will be tested with different case studies to reach a proper percentage of stability in the main factors of the response.

2. Mathematical model

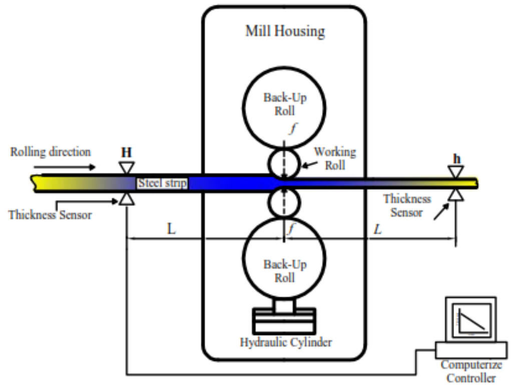
A mathematical model for the axial motion of rolling assembly is represented as shown in (Fig. 1(a)). Consider the linear equation of motion for forced dynamics:

$$M\ddot{X} + C\dot{X} + KX = F\left(t\right) \tag{1}$$

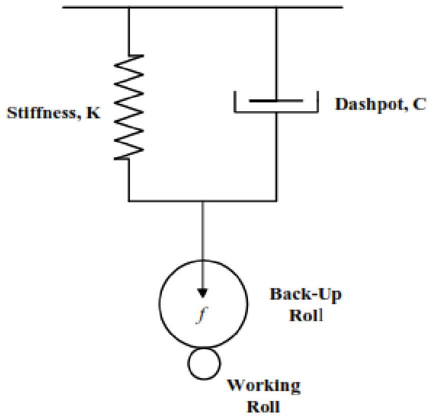
where M is the mass of rolling assembly (kg), C damping coefficient of system (N.s/m), K spring stiffness (N/m), X linear displacement of rolling assembly (m), $\dot{X}$ Linear velocity of rolling assembly (m/s), $\ddot{X}$ Linear acceleration of rolling assembly (m/s^2), F external force (N).

In practical, there are many sources that can produce a nonlinear terms in Eq. (1) such as damping system due to fluid dynamics and the spring assembly always works with some percentage of nonlinearity as shown in Fig. 1(b), then, Eq. (1) can be written as:

$$M\ddot{X} + C\ddot{X} \pm F_1\left(\dot{X}\right) + KX \pm \mu_1 X^2 \pm \mu_2 X^3 = F_2\left(t\right) \tag{2}$$



(a) Schematic representation for the rolling mill system model assembly



(b) Control system of displacement

Fig. 1. Mathematical model for rolling processing and control.

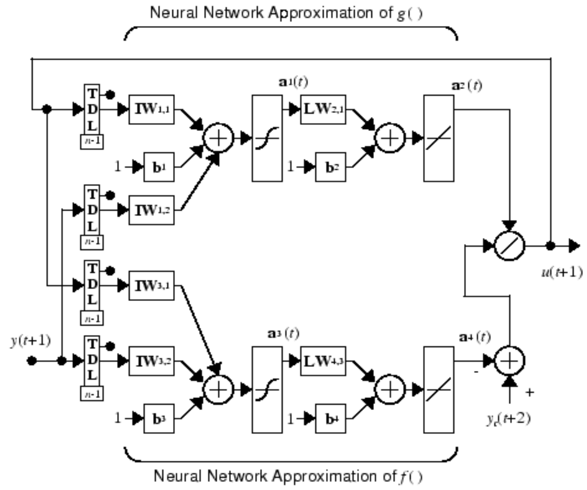


Fig. 2. NARMA-L2 structure with plant identification [22].

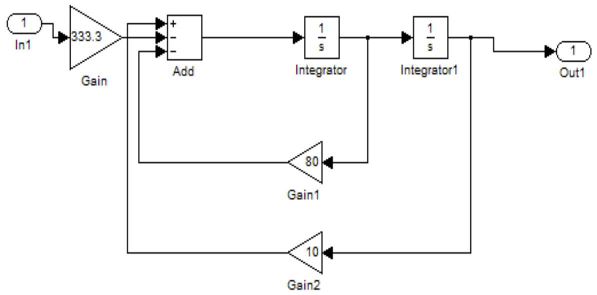


Fig. 3. Plant model.

where F1 Nonlinear function of velocity, F2 External force μ_1 and μ_2 coefficients of nonlinearity sources of displacement.

The above equation can be rearrangement to calculate the acceleration as:

$$\ddot{X} = (1/M)(F_2(t) - (C\dot{X} \pm F_1(\dot{X}) + KX \pm \mu_1 X^2 \pm \mu_2 X^3)). \quad (3)$$

In order to control the displacement (X), the variety of nonlinearity sources will make this object very difficult and need powerful schemes having high accuracy and an acceptable percentage of intelligence. For this reason, NARNA-L2 was considered in the proposed work which has an ability to linearize the feedback signal and can predict a complex cases of disturbances and sudden variation in the system parameters because its theory based on artificial neural networks (ANN).

3. NARMA-L2

The nonlinearities of the system dynamics can be approximated to linear behavior when using a powerful scheme depend on neural et work named NARMA-L2, Fig. 2. At the beginning, the system identification is applied with a proper sampling interval (0.05) and a proper minimum and maximum interval. The maximum and minimum plant input should be adjusted in order to cover the highest and lowest expected ranges. However, in this case the maximum adjusted at (10) and minimum at (-2). Also the maximum and minimum plant output have setting as (10 and 0), respectively. Then, 400 training sample will be trained using Levenberg- Marquardt training algorithm and 300 epochs. When the training is completed and the factor of correlation (R) and root mean square error (RMS) reach an acceptable values , then NAR MA-L2 is ready to be used in the main Simulink model as a controller.

4. Simulink model

The Simulink model of the plant that required to be tested is implemented in the Laplace form as shown in Fig. 3. The NARM-L2 controller receives the signal from the plan output and compare it with the reference signal, then, with the help of the system model that constructed from the identification process, the controller can produce an adequate signal to the actuator in order to manipulate the plant to the desired target, Fig. 4. The sources of nonlinearity of the axial displacement have been included in the Simulink model whole rolling assembly, Fig. 5. However, this model was tested for different aims with the help of the Simulink model shown in Fig. 6.

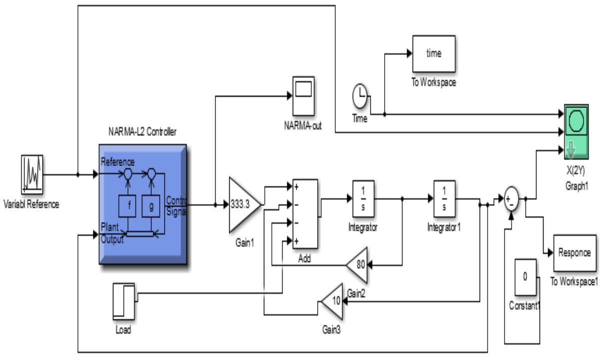


Fig. 4. Overall simulink model.

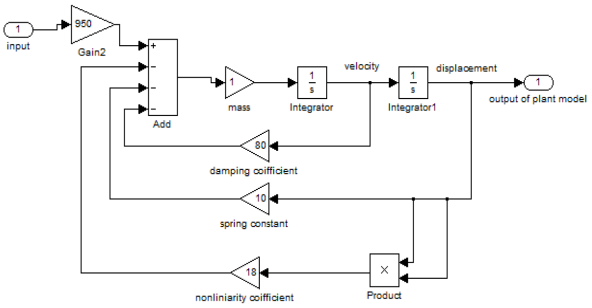


Fig. 5. Nonlinear simulink model of rolling assembly.

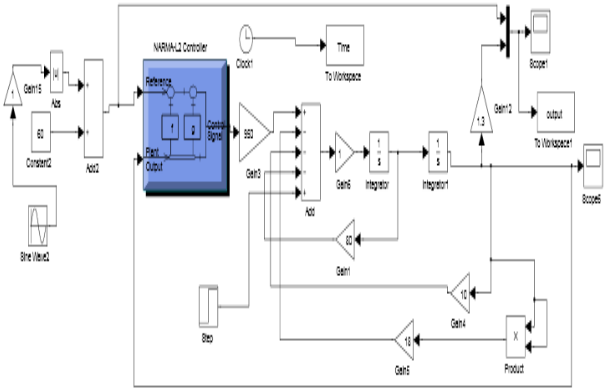


Fig. 6. Testing simulink model of nonlinear dynamics.

5. Results and discussion

The proposed model had been tested for short simulation time (10 sec) with uniform variation of strip, Fig. 7. In this case, as it clear noticed, the rise time that obtained with the NARMA-L2 model has very small value (about 0.2 sec). Also; the maximum overshoot of 1 % is acceptable for many application of rolling mill process. As compared with tuned PID there is great difference in the response curves. Due to high nonlinearities of the plant dynamics, PID cannot reach the desired behavior especially at the sudden variation of the set point.

In Fig. 7 also, a difference can be seen in the behavior of the two controllers, as the NARMA-L2 model controller follows the target function according to what is required and run along with it and has a capacity to adapt to the sudden changes that occur in the nature of the work of the plant dynamics, while the PID controller does not follow target function and behaves far from it and didn’t meets the plant dynamics requirements.

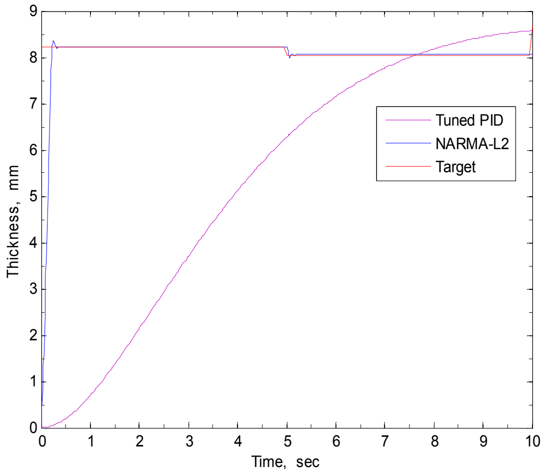


Fig. 7. Uniform random reference with short time.

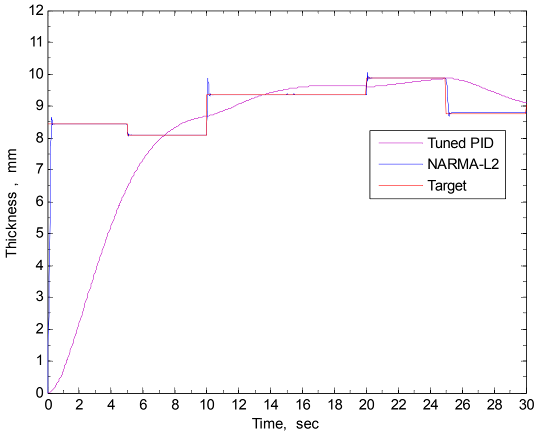


Fig. 8. Uniform random reference with long time.

Another test with a long time of simulation (30 sec) had been implemented as shown in Fig. 8. It can be clearly concluded that NARMA-L2 has appeared a powerful in the control of multi-change reference point. However, in this figure, the response at the time of (10 sec) has a such high amount because of the problem of sampling time adjustment. The presented model can reduce the effect of disturbances successfully while the conventional one had exhibited such difficulty in the return of system to the desired thickness, Fig. 9. In order to prove the robustness and effectiveness of the proposed scheme, the model was tested with number of special forms of set points such as sine wave and inclined line Figs. 10-12. Most requirements of steel sheets need a stable constant thickness with high accuracy and the uncertainties in the tolerances have to be reduced as possible. In Fig. 13, the propped model had been tested to produce a suitable performance to keep a thickness of 10 mm during the rolling process even at

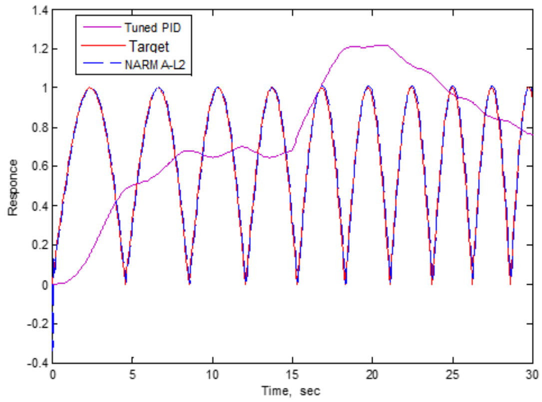


Fig. 9. Uniform random reference with disturbance at 15 sec of simulation time.

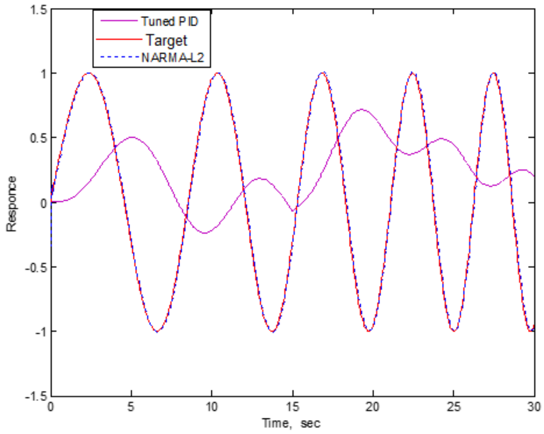


Fig. 10. Special wave form set-point.

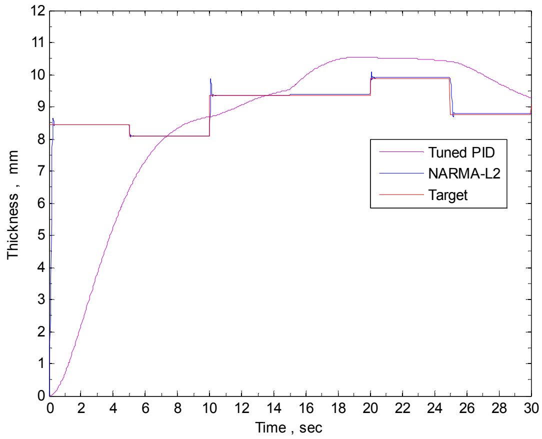


Fig. 11. Sine wave set point.

subjected a disturbance at the time 15 sec. In order to examine the proposed model at small target value, this value had been setting for several low magnitudes (Fig. 14) where the model had demonstrated its ability to be flexible under any sudden variations of system dynamics. This efficacy had still increasingly even when linear or nonlinear disturbance had been subjected to the system and at deferent times. In Fig. 14, a thickness of 1 mm and high erratic and complex disturbance had been applied. The conventional method had not reach acceptable value yet the time had recorded about 40 sec. however, Zeigler-Nichols was used in the tuning of PID controller but the result had shown that its weakness in prevention disturbance at the time of 20 sec.

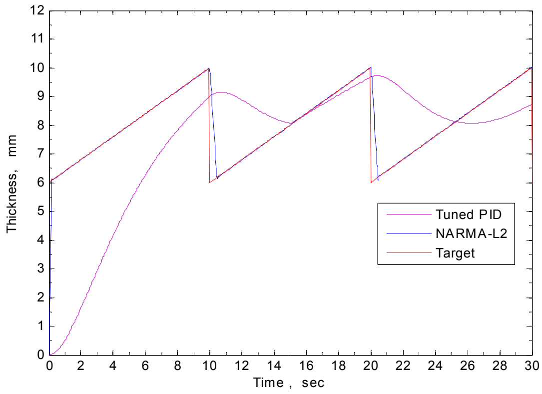


Fig. 12. Repeated inclined line form of set-point.

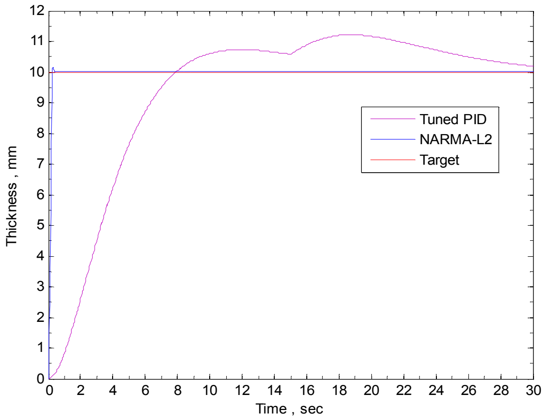


Fig. 13. High fixed target value and there is a disturbance at 15 sec.

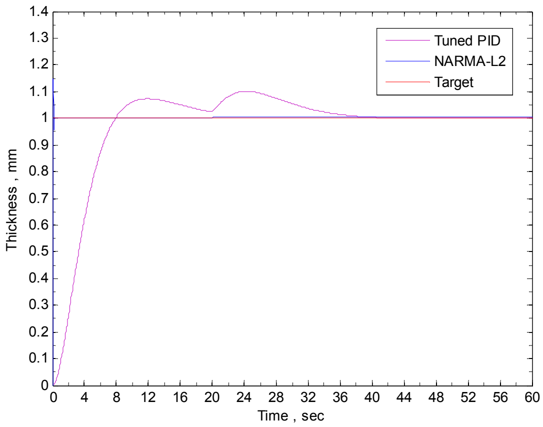


Fig. 14. Small target value and there is a disturbance at 20 sec.

For identify a proper NN model in order to study the effect of

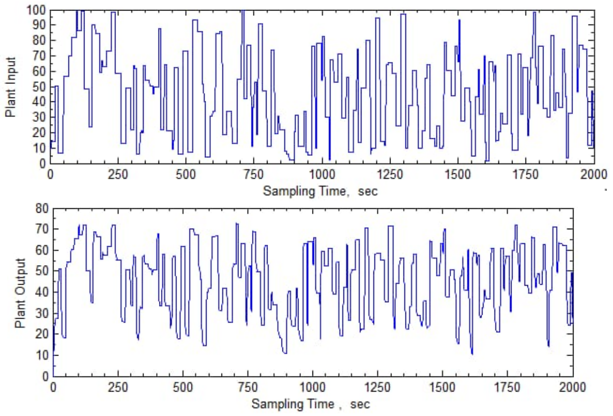


Fig. 15. Sampling of input –output plant.

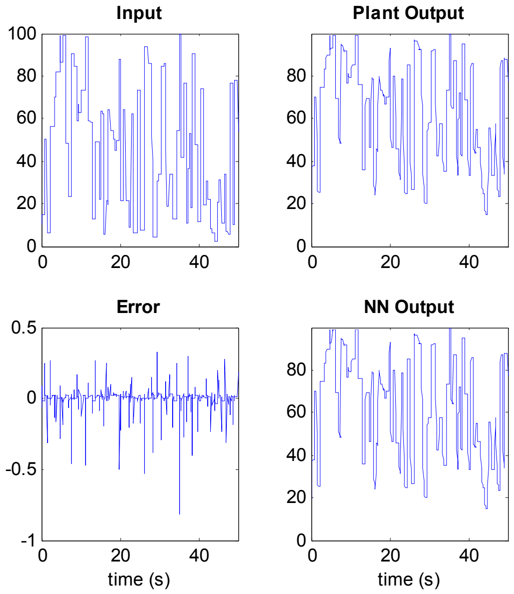


Fig. 16. Training of NN plant model.

nonliterary of rolling system parameter, a hidden layer size of (13) and sampling interval of (0.01 sec) have been selected as shown in Fig. 15. The number of samples was taken as (100) samples with maximum plant input of (100 mm) starting from zero. After generation of data produced in previous step, then, the network was trained with the using of testing and validation data as shown in Figs. 16-18. The plant and NN model have appeared very acceptable behavior with regression of (0.99999) for all of data types (test, train and validation), Fig. 19. Another indication can be noticed for the effectiveness of the model by the mean square error which may reach (2.6446×10-6), Fig. 20. NARMA-L2 using with Simulink model of Fig. 6 which implemented for nonlinear rolling system, is tested for variable sheet thickness, Fig. 21. The result is compared with tuned PID controller, where the proposed model appear high robustness although the complex variation of thickness. Also, the nonlinear model is tested for uniform sheet thickness, Fig. 22, in order to obtain (6-7 mm) sheet thickness. The result

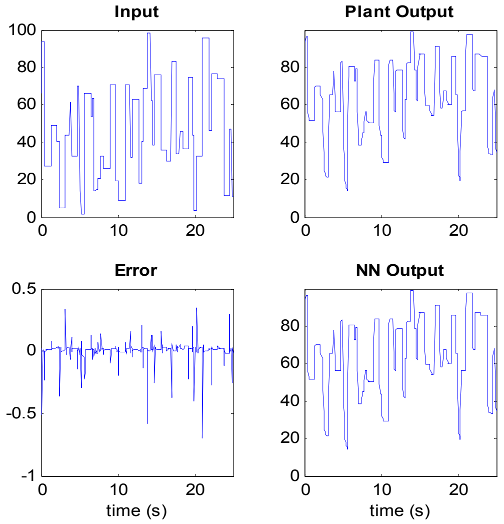


Fig. 17. Testing of NN plant model.

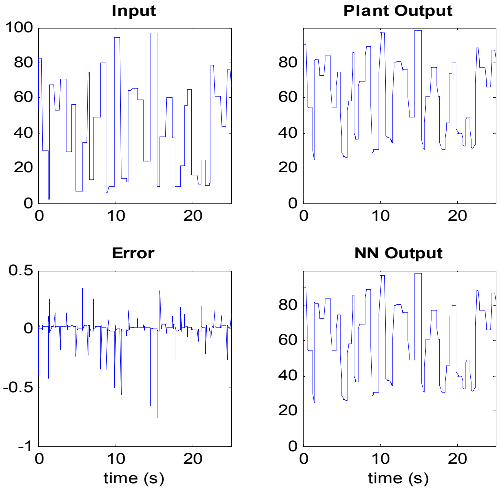


Fig. 18. Validation of NN plant model.

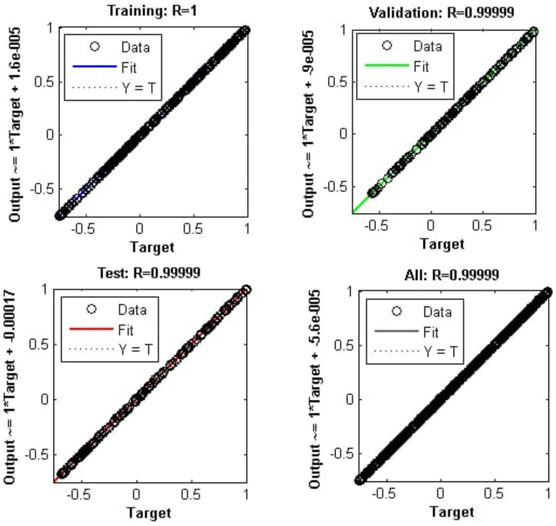


Fig. 19. Regression of training, testing and validation stages.

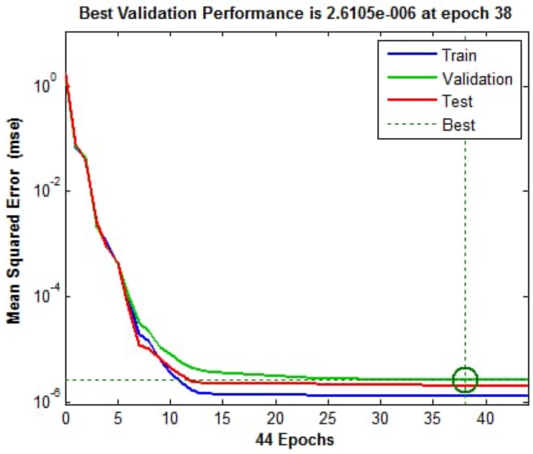


Fig. 20. Mean square error.

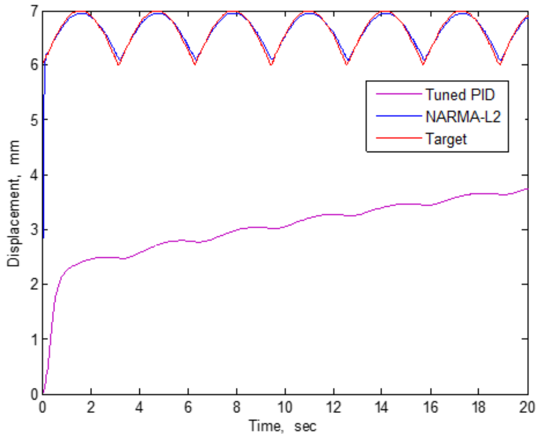


Fig. 21. Testing of NARMA-L2 in simulink model for variable sheet thickness with nonlinear behavior of rolling system.

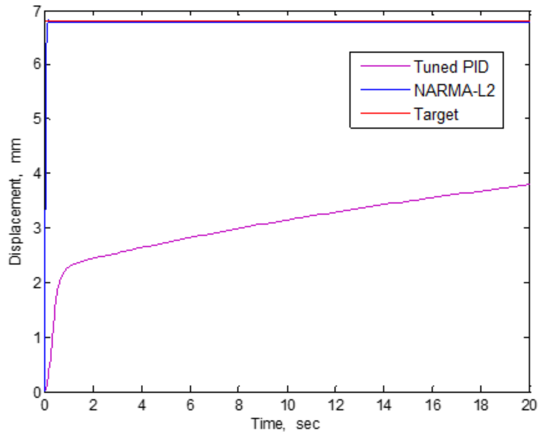


Fig. 22. Testing of NARMA-L2 in simulink model for uniform sheet thickness with nonlinear behavior of rolling system.

proves that the percentage error from the desired value is very small ranges of microns as compared with the other schemes.

6. Conclusion

A Simulink and mathematical models have been proposed in this study in order to control the thickness in a rolling mill process. The ability of NARMA-L2 for linearizing the sources of nonlinear dynamics makes it able to control these types of systems with high efficiency. Also, the fact that, the input- output data can be generated in this scheme with very flexible number of sampling, this, led the Artificial neural network to reach a best acceptable ranges of mean square error and regression. The identification of plant model will be efficient for treating different cases and complex input requirements in order to obtain precise plate profile. These advantages make the proposed scheme produce different ununiformed strip profile with best characteristic control response even though applied erratic sources of disturbances.

The simulation results show that the thickness oscillation can be manipulated with high accuracy by using NARMA-L2, since it can remove the non-linearity of servo system and other disturbances complexities.

For proving the efficiency of the model, it had been tested with different cases such as uniform or variable thickness, large thickness, small thickness... etc, and it had appeared acceptable robustness when subjected to sudden disturbances. Very small rise time and overshoot can be obtained. Also, with precision optimization of the main parameter of NARMA-L2 the steady-state error may be removed. Accurate profiles can be manufactured for the steel plates in a hot rolling mill by consideration of the presented strategy.

More sources of nonlinearities of rolling systems are taken into account in this work. The results of the nonlinear case have been implemented for uniform and non-uniform thickness of the steel plate, where, it appeared very acceptable performance of the proposed model with high efficiency to avoid the sharp edges of the sheet profile. Recent manufacturing requirements need high precision of milling products, therefore, the present study explains the intelligent strategies that can be considered to reach this object.

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