LabVIEW Based Adaptive Modeling of Piezo Actuators Used in Electro Pneumatic Positioner

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***Abstract*—Piezo actuators are widely use in positioning and control applications. Piezo actuators are nonlinear and possess time varying hysteresis nature. For controlling piezo actuators mostly inverse hysteresis model or adaptive inverse control model are utilize. To implement adaptive inverse control, adaptive model of piezo actuator is to be determined. There are various adaptive methods viz. Recursive Least Square (RLS), Kalman Filter (KF), Least Mean Square (LMS) and Normalized Least Mean Square (NLMS) by which the model can be determined. This paper discusses the system of piezo actuator and different methods of finding adaptive model for piezo actuator system. Further a comparative study of adaptive model identification is carried out and suitable model for this system is identified and discussed. A novel approach of identifying a suitable model is discussed in this paper. The experimentation is carried out using electro pneumatic positioner, which utilizes the piezo valve for positioning. LabVIEW 2014 is used along with data acquisition hardware for modeling of real time system. The results of experimentation shows that, RLS adaptive model is more suitable as compared to other adaptive algorithms.**

***Index Terms*—piezo actuator, nonlinear system, variable hysteresis, adaptive model, electro-pneumatic positioner, piezo valve.**

I. Introduction

Piezo electric actuator is a transducer that converts electrical signal to the physical displacement. When a voltage is applied to across the piezo, the atom in the crystal get displaced. A dipoles are get induced which results into change in the net polarization in the crystal. This results in physical deformation of the material. This deformation is used for the precise actuation. A reverse observation will occur when the piezo is loaded. This allows the same piezo to be used either or both as sensor or an actuator. This is the reason why the Piezo electric actuators have become popular for positioning application such as electro pneumatic positioner. These positioning elements are now a days replacing the traditional positioning system viz. electromagnetic based pneumatic positioner used for valve positoning. However the piezo actuator has a disadvantage of producing variable hysteresis and dead band. Furthermore slope of the hysteresis curve also changes with respect to time. To make matter more worse the valve stiction also introduces the dead zone. All this problems seriously limit system performance, to control such highly nonlinear and time varying systems inverse hysteresis model or adaptive inverse models are utilize. For implementing adaptive inverse control suitable adaptive system model is required to be identified. The focus of this paper is to identify suitable adaptive model for piezo valves used in electro pneumatic actuators.

II. Literature Survey

There are several studies and researches that describes the precise positioning and control of system having asymmetric, rate dependent and rate independent hysteresis viz. Piezo's. It is an important task to eliminate the hysteric behavior for the linear operation of the process. Ming-Jyi Jang[1] has developed the Control strategy consisting feed-forward controller and PD type feed-back controller are used for realization of highly precise positioning control of piezoelectric actuators driven stage in system. Lei Liu [2] implemented singular value decomposition (SVD) based identification and hysteresis adjustment of piezo actuators using Preisach Model. The Preisach based feed-forward controller helps significantly for improving the tracking performance and reduces the root mean square (RMS) tracking error of the controller. Some researchers used novel approach to model the hysteric behavior of piezoelectric actuators as set of hysteresis operator. Jonq-Jer Tzen [3] implemented the hysteresis mode with the help of identified parameter and dominant hysteresis operator. Inverse model proportional integral feed-forward controller improves the tracking performance of the system. Lien-Sheng Chen [4] said that model identification and digital controller design of piezo driven actuators and mechanical stages is the novel approach for the performance improvement of piezo actuators. Gorka Aguirre [5] said that treating the hysteresis as separate from other dynamical effects and formulating a simplified model that deals with a symmetric hysteresis based on linear operator also improves the accuracy of the systems. Ru Changhai and Hartmut Janocha [6, 7] talked about Simultaneous compensation of the hysteresis and creep in piezoelectric actuators using open loop inverse control operation which improves the open loop operation when compared with open loop control without any compensation. The inverse control model is formulated by using the simple hysteresis and creep operator. This operator based hysteresis and creep

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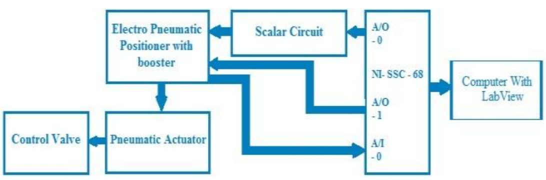
model results in the increasing the linearity effect of the piezo valve actuators. Mohammad Al Janaideh [8] has developed a rate dependent Prandtl Ishlinskii model. The model is developed for describing the hysteric behavior of the piezo actuators. The Integration of the rate dependent play operator and the density function developed using the rate of change of input and the observed behavior of the system is used to obtain the model. Using the model the behavior is examine under different frequency conditions. Changhai Ru [9] has worked on a mathematical model based on the hysteresis model which is used for precise hysteresis description. Main hystsresi loop is reduced bby using adaptive inverse control approach. Least Mean Square (LMS) is used for identification of the weights of the main hysteresis loop. The used of inverse feed-forward controller is advantageous for position prediction in open loop operation. J. Minase [10] has work on the unscented Kalman filter based adaptive identification algorithm is used for precise determination of non-linear dynamics such as hysteresis and creap effects of the piezo actuators and valves in open loop condition. U-Xuan Tan [11] has worked on rate dependent, rate independent and modified Prandtl Ishlinskii model to model the hysteresic behavior. The authors observed that it is possible to find the inverse of Prandtl Ishlinskii model analytically. He implemented the same for feed-forward controller.

It is observed that most of researchers uses model of physical systems for their research. Thus, to have complete and fool proof analysis as well as good control over physical system having rate dependent and rate independent hysteresis, behavioral characteristics of the system must be well known. Adaptive model such as RLS, KF, LMS, and NLMS uses the mathematical approach for computing the system behavior. This adaptive model is a complete representation of the physical system.

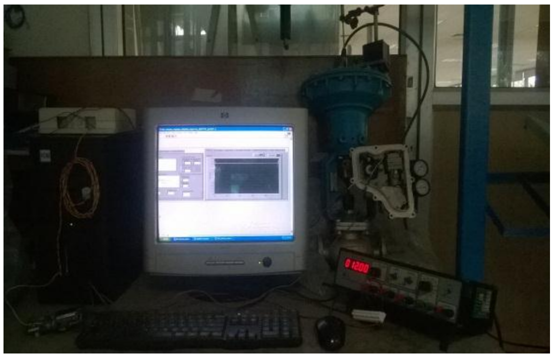
III. System Description

Fig. 1 shows block diagram description of physical system. Pneumatic actuator is placed on the control valve. The electro pneumatic positioner with booster serves as final element for controlling stroke of the pneumatic actuator. Stimulus signal to scalar circuit is given from analog output port zero of NI-SSC-68 block. The stimulus signal is generated from LabVIEW simulation environment.



System Description.

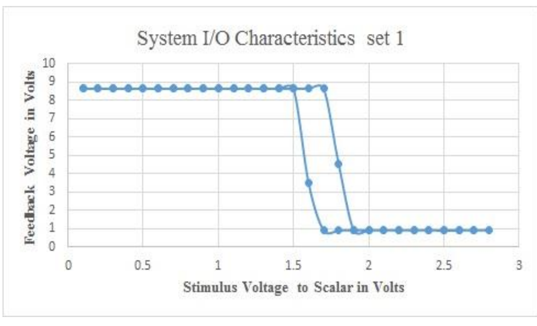
Fig. 2 shows that system consist of a pneumatic actuator on which electro pneumatic positioner. The electro pneumatic positioner consist of piezo valve which is coupled to pneumatic booster. A pneumatic booster boosts pneumatic pressure maximum up to 5 bar. This pressure is directly applied to diaphragm of the pneumatic actuator. Piezo valve is operated within the range of -21 to +21 volts. A scalar circuit is used to operate piezo valve which scales voltage from 0 to 3 volts in the range of -21 volts to +21 volts. A scalar circuit serves as interface between data acquisition card (NI-SSC-68) and piezo valve used in electro pneumatic positioner. There is a rotary type potentiometer, coupled with gear arrangement which serves as a feedback signal mechanism. This gear arrangement is used to convert linear displacement of stoke of cylinder into rotary motion which is further used to identify the position of the stroke of pneumatic valve. Rotary type potentiometer requires the reference signal of 10 volts so that to obtain the variable stoke position. Reference signal is generated on analog output port one in same way as of stimulus signal. Variable stroke position is obtain in terms of voltage because of rotary type potentiometer and gear arrangement.



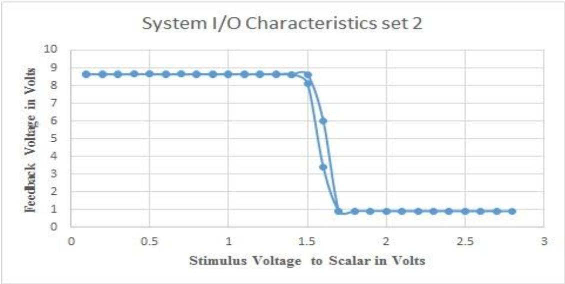
Experimental Setup.

IV. Experimentation

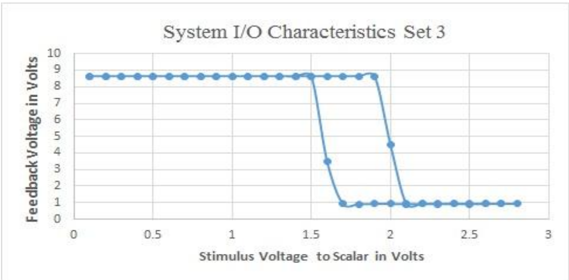
During experimentation different sets of readings with same operating conditions were taken. It is observed that system is time varying in nature. There is very small linear range of operation. Thus to analyze such system, buffer of suitable size to hold 5second of data is made using the LabVIEW measurement I/O tool kit. The sampling rate is made suitably high for better results viz. 20000 samples/sec. It is observed that because of variable nature of piezo used in electro pneumatic actuators all sets of readings have different values of dead band, saturation voltage or slope of the hysteresis curve. Fig. 3, 4 and 5 shows detail analysis of readings.



System I/O characteristics set 1



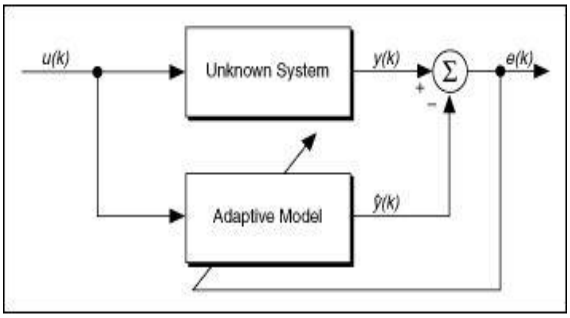
System I/O characteristics set 2



System I/O characteristics set 3

V. SYSTEM METHODOLOGY

In this paper we are using adaptive model estimation method. [13]Adaptive model estimation enables us to obtain a model of the physical system by using input output characteristics of unknown system. The adaptive model estimation processes input output data once it is available. This technique is helpful because we can obtain model of system in real time.



Adaptive model estimation

Fig. 6 represents an adaptive system identification application. System identification requires unknown physical system with stimulus and response signal. The stimulus signal *u(k)* is given as an input to both adaptive model and to unknown system. The response of the system *y(k)* and predicated response *ŷ(k)* are combine to determine error of systems.

$$e(k) = y(k) - \hat{y}(k+1) \tag{1}$$

The predicated response is generated by adaptive model is $\hat{y}(k+1)$ based on input *u(k+1)* after adjusting parametric $\vec{w}(k)$ based on the error *e(k)*. The recursive model estimation has four recursive method parameter that enables us to specify which recursive method to use. Proper use of adaptive method affects performance of recursive system identification application. The goal of each method is to adjust parametric vector until we get minimize cost function *J(k)*.

$$J(k) = E[e^2(k)] \tag{2}$$

Where *E* is expectation of enclosed terms. When cost function is sufficiently small, the parametric $\vec{w}(k)$ is considered to be optimum representation of system.

Recursive Least Square (RLS)

Recursive least square (RLS) technique of system identification uses following equation to obtain updated parameter matrix [12, 14].

$$p(k+1) = \gamma^{-1}[\, I - L(k+1)\, \Phi^T(k+1)\,]\, p(k) \tag{3}$$

Here, p(k+1) represents values to be updated into parameter matrix p(k). L(k+1), are gain values to be updated in gain matrix. $\Phi^T(k+1)$, represents data matrix. RLS algorithm uses previous error information for parameter estimation. It is observed for time varying processes that properties of system might vary with time, so to ensure proper tracking of algorithm forgetting factor γ must be adjusted properly. Typical range of forgetting factor is 0.98 to 1.

Kalman Filter (KF)

Kalman Filter [12, 15] is a linear optimum filter, that minimizes mean of the squared error recursively. The convergence rate of Kalman Filter is faster as compared to least mean square based algorithms. Kalman Filter uses following equation to obtain updated system parameter matrix.

$$p(k+1) = [\, I - L(k)\, \Phi^T(k)\,]\, p(k) + Q_p \tag{4}$$

Here, *p(k+1)* represents values to be updated into parameter matrix p(k). *L(k)*, are kalman filter gain matrix. $\Phi^T(k)$, represents the data matrix. Q_p is correlation matrix of process noise.

Least Mean Square (LMS) & Normalized Least Mean Square (NLMS)

Least mean square algorithm [16] is most widely understood adaptive system identification technique. Step size of test signal need to be properly adjusted for stability and convergence of this algorithm. In case of LMS algorithm, increase in step size increases convergence rate. However, It is observed that [17] LMS algorithm is unstable in nature as compared to NLMS. Thus, for betterment of results we have implemented the NLMS algorithm in this paper. Normalized least mean square uses self-adjusting mechanism for step size selection. Following equation is implemented to obtain updated parameter matrix.

$$\vec{p}(k+1) = \vec{p}(k) + \mu\, e(k)\Phi(k) \tag{5}$$

Here, p(k+1) represents values to be updated into parameter matrix p(k). μ, represents step size which is always a positive constant. Φ(k) represents data vector depends upon past input and output data.

VI. System Modeling And Comparison

In any control system design parameter estimation and system modeling has very high consideration. The reason is entire control loop is based on the mathematical model obtain on basis of this system modeling. There are various ways to obtain plant model, one way is to acquire input-output data and then to use system identification tools. System identification includes acquiring, formatting, processing and identifying mathematical models on the basis of stored data form the real world system. Validation of the obtained model means to fit model with observed system behavior.

LabVIEW offers readymade system identification pallet. In order to find model we require data based on real physical system. The stimulus and response signal are given as input to algorithm developed in LabVIEW. However, it is possible to store stimulus and response signal of physical system to LabVIEW measurement file and then apply it to algorithm. The results are drawn based on the real time or stored data.

Generating model based on stimulus and response signal is not sufficient. The model represents behavior of system for particular input, their validation and simulation is also an important task. Even more order of model is important for validity of the model. In this section we have compare ARX model of physical system using RLS, KF and NLMS techniques. The order of model is optimally selected for betterment of the results. Model equations obtain for I/O characteristics set no.1, 2, 3 as given in the analysis section are given in this section:

$$\frac{1.69466z^2 - 1.76827z}{z^2 - 1.24205z + 0.273977} \qquad (6)$$

Equ. (6) model for I/O characteristics set 1 using RLS method.

$$\frac{-0.875759z^2 + 0.934294z}{z^2 - 1.19012z + 0.221088} \qquad (7)$$

Equ. (7) model for I/O characteristics set 1 using KF method.

$$\frac{31.614z^2 - 10.2858z}{z^2 - 4.33575z + 3.7163} \qquad (8)$$

Equ. (8) model for I/O characteristics set 1 using NLMS method.

$$\frac{-1.66661z^2 + 1.73588z}{z^2 - 1.23806z + 0.26888} \qquad (9)$$

Equ. (9) model for I/O characteristics set 2 using RLS method.

$$\frac{-0.844z^2 + 0.85843z}{z^2 - 1.19416z + 0.22382} \qquad (10)$$

Equ. (10) model for I/O characteristics set 2 using KF method.

$$\frac{31.844z^2 - 10.1501z}{z^2 - 4.8461z + 4.2304} \qquad (11)$$

Equ. (11) model for I/O characteristics set 2 using NLMS method.

$$\frac{-1.62452z^2 + 1.68642z}{z^2 - 1.24125z + 0.270036} \qquad (12)$$

Equ. (12) model for I/O characteristics set 3 using RLS method.

$$\frac{-0.748629z^2 + 0.79357z}{z^2 - 1.1951z + 0.2216388} \qquad (13)$$

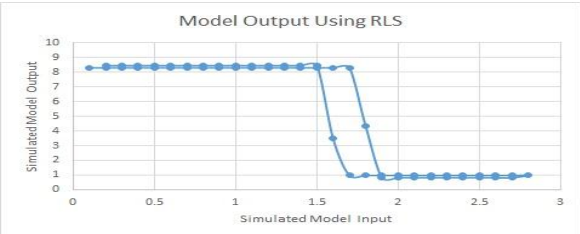
Equ. (13) model for I/O characteristics set 3 using KF method.

$$\frac{31.8451z^2 - 10.2226z}{z^2 - 4.90887z + 4.29232} \qquad (14)$$

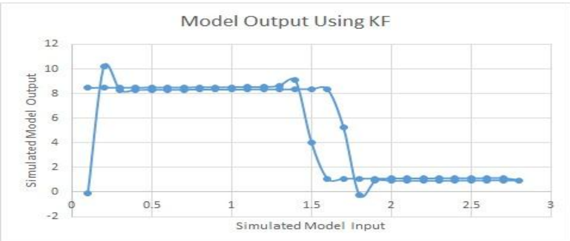
Equ. (14) model for I/O characteristics set 3 using NLMS method.

VII. Results & Discussion

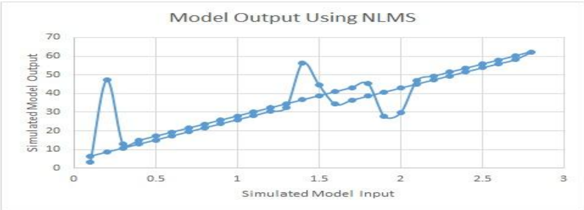
During experimentation a system of two poles and two zeros is considered for modeling. Equations 6, 9 and 12 shows the system function obtain by RLS method Equation 7, 10 and 13 shows the system functions obtain by KF method. Equation 8, 11 and 14 shows the system function by NLMS method. For different sets of readings the system function obtained are comparable. Utilizing these system functions, system analysis was carried out to find the input output characteristics of system. Fig no. 10 to 18 show input output characteristics of the system obtain by utilizing the respective adaptive models.



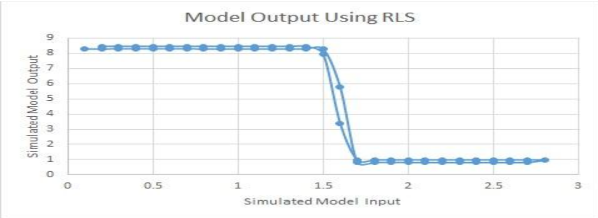
Adaptive ARX model (RLS technique) I/O characteristics set 1



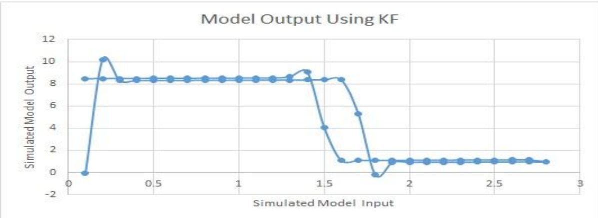
Adaptive ARX model (KF technique) I/O characteristics set 1



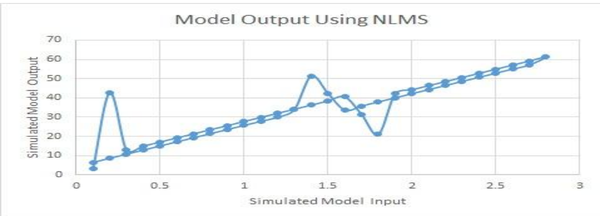
Adaptive ARX model (NLMS technique) I/O characteristics set 1



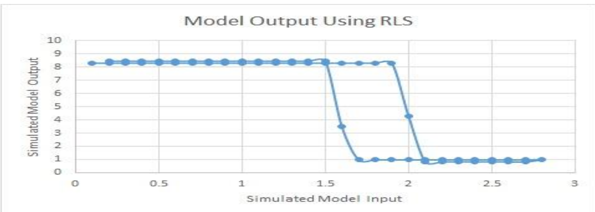
Adaptive ARX model (RLS technique) I/O characteristics set 2



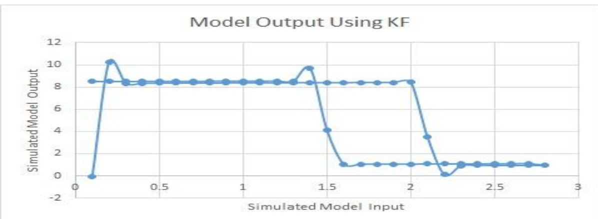
Adaptive ARX model (KF technique) I/O characteristics set 2



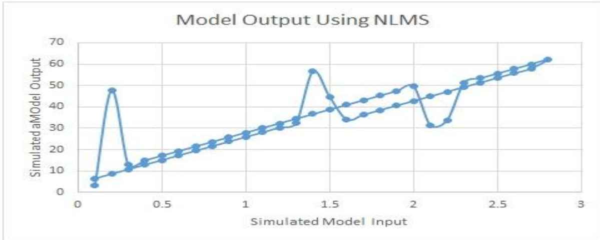
Adaptive ARX model (NLMS technique) I/O characteristics set 2



Adaptive ARX model (RLS technique) I/O characteristics set 3

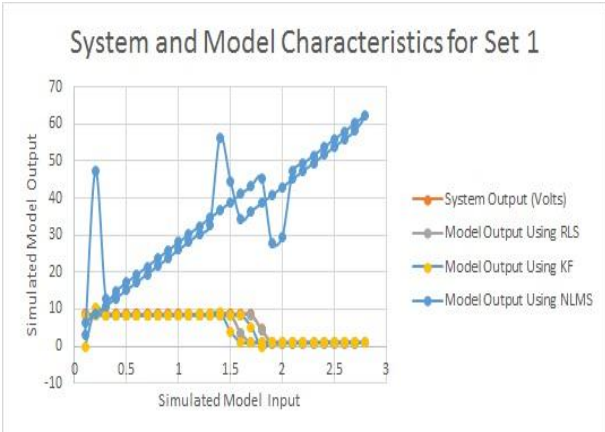


Adaptive ARX model (KF technique) I/O characteristics set 3

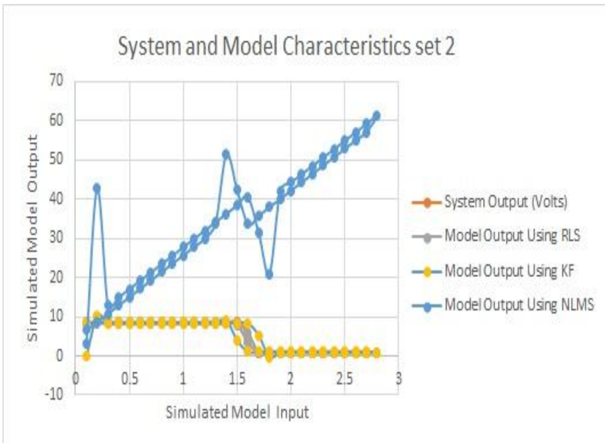


Adaptive ARX model (NLMS technique) I/O characteristics set 3

From fig. 19, 20 and 21 that ARX model with RLS technique gives most suitable results of modeling. Model output using KF technique also shows good results but model output overshoots at some point when simulated model is compared with the characteristics of physical system. It is observed that model output with RLS technique is almost a replica of the original system for all sets of input output characteristics. In the proposed LabVIEW-VI systems on-line as well as off-line analysis of system is taken into consideration. However one can go for on-line analysis only for further development.



Comparison of real time system model and ARX model by adaptive algorithms for reading set 1



Comparison of real time system model and ARX model by adaptive algorithms for reading set 2

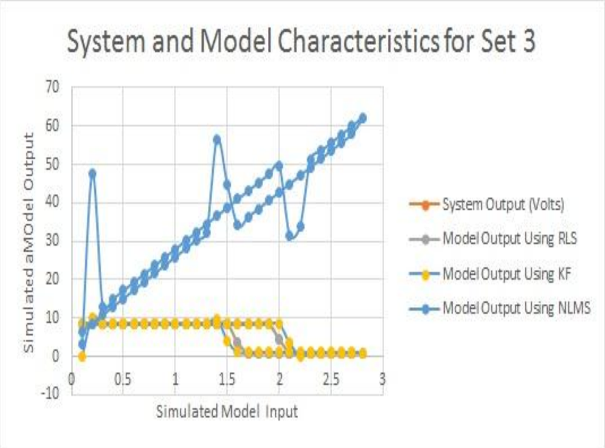


Fig. 18. Comparison of real time system model and ARX model by adaptive algorithms for reading set 2

VIII. CONCLUSION

This paper presents adaptive modeling using RLS, KF, NLMS adaptive algorithms. From the real time implementation it is observed that the physical system model and RLS adaptive model are similar. The model validation confirms the same. This simulation and experimental studies shows that adaptive model of piezo actuator gives mathematical representation of the piezo actuator system. This adaptive model can be further used to device inverse adaptive algorithms for controlling the nonlinear piezo actuator systems.

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