Jurnal Teknologi

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# Application of Draw Wire Sensor in the Tracking Control of An Electro Hydraulic Actuator System

Sazilah Salleh[a], Mohd Fua'ad Rahmat[a*], Siti Marhainis Othman[b], Hafilah Zainal Abidin[c]

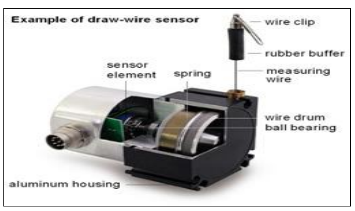
[a]Department of Control and Mechatronics Engineering, Faculty of Electrical Engineering, UniversitiTeknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]School of Mechatronic Engineering, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia
[c]Language Academy, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Malaysia

*Corresponding author: fuaad@fke.utm.my

**Article history**

Received : 15 August 2014
Received in revised form :
5 January 2015
Accepted : 10 February 2015

**Graphical abstract**




**Abstract**

A draw wire sensor is considered as a contact measurement method. It is normally used to measure the speed and position of a system. A draw wire sensor is convenient especially when a low cost solution and a small sensor dimension are desired. The objective of this paper is to describe the application of draw wire sensor in control tracking of electro hydraulic actuator system. This research started with the modelling of electro hydraulic actuator system by using system identification approach. During the data taking process, an experiment is conducted using electro hydraulic actuator test bed. A draw wire sensor is attached to the load of electro hydraulic actuator system to measure the output displacement when the system is injected with the desired input signal. Draw wire sensor is measuring the output displacement in millimeters and then the signal is converted to voltage reading regarding to the given input signal. The input and output signal is collected and is used in system identification technique to obtain the best mathematical model that can represent the electro hydraulic actuator system. Once a model is obtained, a Self Tuning Controller (STC) with Generalize Minimum Variance Control (GMVC) strategy is designed to control the tracking performance of the electro hydraulic actuator system. The designed controller is tested in simulation and experiment mode. Then, the output result from both modes is compared. The results show that the output performance from both modes are almost similar. Thus, this research had shown that a draw wire sensor has a significant role in capturing an accurate output data from electro hydraulic actuator system even with or without the controller.

*Keywords*: Electro hydraulic actuator system; draw wire sensor; self tuning controller; generalize minimum variance control



## ■1.0 INTRODUCTION

### 1.1 Draw Wire Sensor

A draw wire sensoris used to measure the displacement of a linear movement using a highly flexible steel wire. The wire that is attached to the sensor is used to measure the displacement and the sensor will provide the proportional output signal from the system. The basic components in a draw wire sensor are steel wire, mechanics element that consists of drum and spring motor and potentiometer to measure the generated signal. The design of the steel wire depends on the sensor design, where normally the wire is extremely thin and sheathed with polyamide. The thickness of the wire is around 0.8mm, however, it is depending on the types of the stress force involved. Figure 1 shows the illustration of the component in draw wire sensor [1].

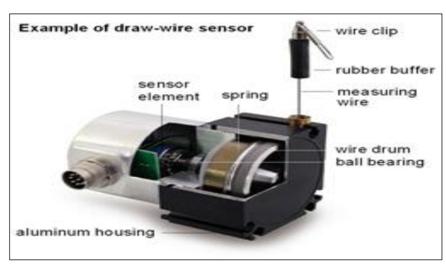



**Figure 1** Elements in draw wire sensor

The draw wire sensor is suitable for application that is large in measuring ranges, required a small sensory dimension and when a low cost solution is needed. The draw wire sensor is also convenient to use even in wet, dirty environment or even when the measuring range needs to travel over a harsh environment.

The draw wire sensor is operated when a linear movement is transformed into a rotation by draw-wire principle and then an electrical signal is generated by the rotary encoder. The spring motor that consists of a coil spring and torque load is used to provide a sufficient pre-tension to the wire, where the tensioning force is proportional to the displacement of the wire that is drawn out. The draw wire sensor can provide two types of interface signals which are analogue or digital outputs. Normally the analogue output is selected when it is operated in a high volume production application. Meanwhile,the digital output is chosen when relative position displacement needs to be measured.

One of the benefits of a draw wire sensor is its ability to measure a short range of measuring starting from the minimum of 100 mm to 5000 mm to a long range of measuring. The sensor is also widely used in industrial field because the sensor is rugged, robust and has a compact design. For medical engineering application, the draw wire sensor is commonly used in the position measurement in X-ray machine, SoloAssist, operating table, computer tomography and others. Meanwhile, in logistic application, a draw wire sensor is commonly used to measure the displacement of the slag transporter, catering trucks at Airbus and lift-height of fork-lift truck. Other than that, a draw wire sensor is also widely used in many other such as in automotive, aerospace and power plant.

### 1.2 Electro Hydraulic Actuator System

Electro hydraulic actuator system is a major driving tool that is commonly used nowadays, especially in industrial and automotive field. This situation happened due to the properties of an electro hydraulic actuator system itself, which can provide a high power density, good positioning capability and having a fast response characteristic [2-5]. However, despite the ability inherent in the system, electro hydraulic actuator system is still holding a drawback of having uncertainty behaviour together with the nonlinearities properties that makes modelling and controller design process for the electro hydraulic actuator system a challenging task [6-13]. Thus, in order to acquire the best performance of an electro hydraulic actuator system, a proper method should be used in modelling the system model and a suitable controller needs to be designed to control the system.

This research focuses on the use of a draw wire sensor in control tracking of electro hydraulic actuator system, though there are numbers of research that had been done on the control tracking of another system by using variety types of sensor. For example, In [14] researcher used utilize laser, cameras and image sensor to track the position of the patient on the treatment table during the radiation therapy session. In [15] the research shared a variety of modern technology approaches and improvement that had been done in the existing method to track the position of a system. Another research that is focusing on the use of sensors to track the position is in [16] where this research has encouraged the design of electronic devices to also considering on a new technology known as Hall-effect sensing that is widely used in certain areas. However, as a newly introduce technology, it is not yet widely accepted. In addition, Joerg Stephen wrote a paper [17] on how a low cost infrared sensor is used for contour tracking and the detection of the edge effects.

Gojko Nikolic and Goran Cubric wrote a paper [18] and described a different type of sensor that is suitable to use in positioning the edge accuracy of textile material, as the problem of position tracking in textile production is critical compared to other field of production and installation. Monica Schofield [19] has introduced the new position tracking system that is called PosEye to help solving the problem of higher investment in industrial robot by just improving its control tracking. An interesting research is done by Lee Danisch, Kevin Englehart and Andrew Trivett in [20] on how bent and the twist is sensed by using shape tape-a thin array of fiber optic curvature sensors that is laminated on a ribbon substrate. Moshe Shohamet [21] presented the work on how the real time optical sensor is integrated into a robot end effector. The sensor that is used consists of four elements of the position sensor spot detector that manage to control the robot position in two dimensions. In [22], the researcher investigated the application of batch oriented MAP estimation scheme to solve the problem regarding the control tracking of moving acoustic target at any uncertain position. Meanwhile, in [23] the author shared the basic principle of innovative position sensor and explained the advancement detail together with the example of an application that is suitable to use with the sensor.

## 2.0 EXPERIMENTAL SETUP

In this research, an experiment using a real electro hydraulic actuator system test bed, as in Figure 2, is conducted to take the data that will be used in the system identification technique process. The basic elements in an electro hydraulic actuator system are hydraulic pump, piston, draw wire sensor, servo valve and hydraulic motor.

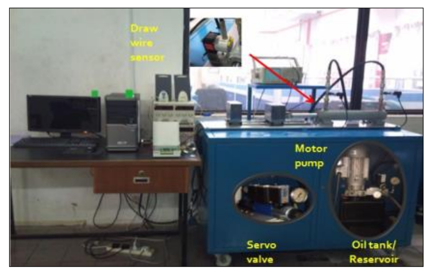



**Figure 2** Electro hydraulic actuator system test bed

A data acquisition (DAQ) card, NI PCI 6221 is used to interface between the real electro hydraulic actuator system test bed and MATLAB software in computer. A stimulus signal with three different frequencies (Figure 3), generated in MATLAB software is used to excite the interesting modes in electro hydraulic actuator system region. Equation (1) represents the stimulus signal that is used [24]:

$$y = 1.5cos2\pi(0.05)t + 1.5cos2\pi(0.2)t + 2.5cos2\pi(1)t \quad (1)$$

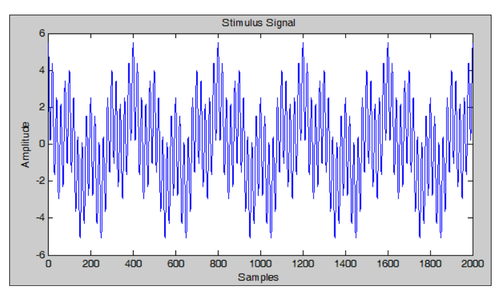



**Figure 3** Stimulus signal

When the stimulus signal is sent to the servo valve via DAQ card, the servo valve will control the flow of the hydraulic fluid which automatically will control the displacement of the piston. The displacement of the piston is captured by a draw wire sensor, WD 300 p60, that is connected to the load at the end of the piston. The maximum length of the draw wire sensor used coincides with the length of electro hydraulic actuator system which is 300 mm. Figures 4 and 5 show the draw wire sensor and how it is attached to the electro hydraulic actuator system in order to capture the displacement of the piston respectively.

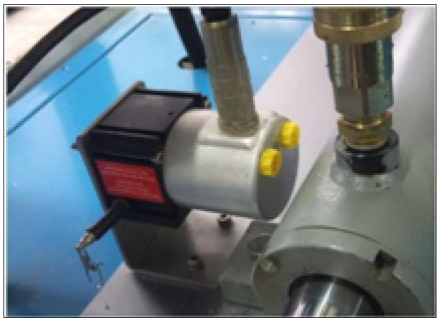


**Figure 4** Draw wire sensor

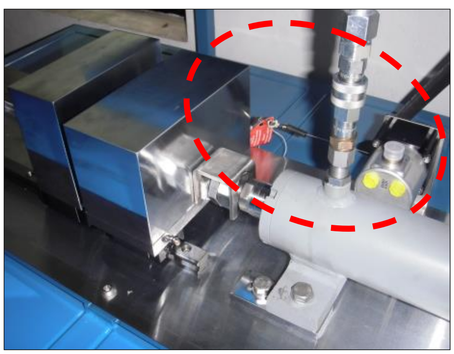


**Figure 5** Draw wire sensor is attached to the system

## ■3.0 MODELLING VIA SYSTEM IDENTIFICATION TECHNIQUE

The first step in designing a system controller is to obtain the mathematical model that can best represent the system understudy. In this research, system identification technique is used to obtain the electro hydraulic actuator system model. The system identification technique was first introduced by Zadeh. In this technique, only a stimulus set of response data is needed in order to obtain a mathematical model of a system [25]. This technique is different from system physical law technique, where in physical law an expert knowledge and full understanding about the studied system is compulsory. This is because all the necessary mathematical equation is related to all the components in the system itself. Due to the complexities of the step involved in system physical law, many researchers and academia avoid this method in developing a system model. Since the system identification technique only requires a set of stimulus response data without the need to explore an in-depth knowledge about the system in order to develop a system model, this technique becomes popular among researchers especially as this technique is much more convenient compared to system physical law.

A System Identification Toolbox that is available in MATLAB software is used in this research as an aid to obtain electro hydraulic actuator system model. The steps that are involved in the system identification process are data capture, model structure, model estimation and model validation.

### 3.1 Data Capture

Data capture is obtained from an experiment using electro hydraulic actuator system. During the experiment, the operating region of electro hydraulic actuator system is excited by a good stimulus signal; and the input output sets of response data is collected. A good stimulus signal that is used must be rich in frequency and amplitudes in order to excite all the operating region of electro hydraulic actuator system; and to ensure the best and accurate model that can represent an electro hydraulic actuator system is obtained. In this research, a multisine wave with different frequency is used. As electro hydraulic actuator system is highly nonlinear, a linearization process is done during the experiment by adding an offset to the given stimulus signal. The linearization process is done as the nonlinear estimation for the hydraulic actuator system is hard to achieve.

### 3.2 Model Structure

In the system identification toolbox, a variety of model selection is available to be used. The selection of model structure is based on the understanding and knowledge about system identification technique and the system understudy itself. In this research, an ARX model structure is chosen to represent the model structure for electro hydraulic actuator system. The ARX model structure is chosen because it is the simplest and a basic model structure to the other model structures such as ARMAX, BJ and others. An ARX model structure is also more efficient as it uses an analytical form to solve for linear regression equation. It also will give only one unique solution at the end of the calculation. Some of the research, as in [1, 26-27], also used the ARX model structure to represent electro hydraulic actuator system model and have proven that a linear ARX model structure can represent a nonlinear electro hydraulic actuator system with a good precision and accuracy.

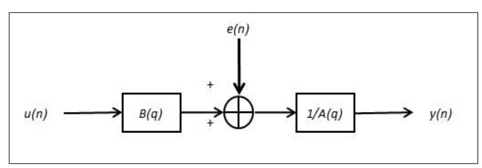



**Figure 6** General structure of ARX model structure

The general structure of ARX model structure is shown in Figure 6 and the general equation for ARX model structure can be written as:

$$y(t) = \frac{z^{-k}B}{A}u(t) \tag{2}$$

Where $u(t)$ and $y(t)$ represent a discrete input signal and discrete output signal respectively. Meanwhile polynomial $A$ and $B$ is given by:

$$A = 1 + a_1 z^{-1} + \ldots + a_{na} z^{-na} \tag{3}$$

$$B = 1 + b_1 z^{-1} + \ldots + b_{nb} z^{-nb} \tag{4}$$

Thus, Equation (2) can also be written as:

$$y(k) = -a_1 y(k-1) - \ldots - a_{na} y(k-n_a) + b_0 u(k-n_k-1) + \ldots + b_{nb} u(k-n_k-n_b) \quad (5)$$

However, in this research, below equation is derived and will be used:

$$y(k) = \frac{z^{-k}(b_0 + b_1 z^{-1} + b_2 z^{-2})}{1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}} \quad (6)$$

After deciding on a suitable model structure, the next step is to decide on the order of the model structure. For ARX model structure, the order can start with the lower degree as 2-2-1 or second order to the highest degree as 5-5-1 or fifth order. Normally, higher order will provide a better model estimation for the system, however, at the same time it will also result in a complex model structure that will cause the computation and the controller design process becomes complicated. Thus, to help in deciding the order of the model structure, Parsinomy Principle is applied. In Parsinomy Principle, it stated that the model in the simplest form will be chosen if there are more than one identifiable model structures that are available; where the simplest form indicates by having a lower order and less parameter that is involved in the structure.

### 3.3 Model Estimation and Validation

Model estimation is the process to estimate the coefficient of the system's transfer function or the process to estimate the coefficient value in the Equation (6). In system identification technique, estimation method that is used is the least square method, where in least square method Equation (6) is transformed into regression form as below:

$$y(k) = \varphi(k)'\theta(k) \quad (7)$$

where;

$$\varphi(k) = \begin{bmatrix} -y(k-1) \\ . \\ . \\ . \\ -y(k-n_a) \\ u(k-n_k-1) \\ . \\ . \\ . \\ u(k-n_k-n_b) \end{bmatrix} \quad (8)$$

$$\theta(k) = \begin{bmatrix} a_1 \\ . \\ . \\ . \\ a_{na} \\ b_0 \\ . \\ . \\ . \\ b_{nb} \end{bmatrix} \quad (9)$$

In least square method, the value of $\theta(k)$ needs to be calculated in order to minimize the sum of square residual *ε(k)*. The $\theta(k)$can be obtained by minimizing the Equation (10) or also known as the cost function equation and is represented as:

$$J = \frac{1}{2}\sum_{k=1}^{N}[\varepsilon(k)]^2 \quad (10)$$

In the system identification toolbox, the process of estimation and validation process is done by splitting the stimulus response data into two parts. The first part is used for model estimation and the second part is used for model validation. The model validation is done to ensure that the obtained model fits with the real electro hydraulic actuator system behavior. The process is done by comparing the performance result from the estimated model with the actual performance of an electro hydraulic actuator system. To standardize the validation result, best fitting percentage is used to indicate the more accurate estimated model that can best represent the actual system [26].

## 4.0 CONTROLLER DESIGN

The self-tuning controller (STC) was first introduced by Astrom and Wintermark in the year 1973. The general structure of STC is shown in Figure 7, where the general structure of STC consists of parameter estimation part and controller design algorithm part. The input output of the system is used in parameter estimation part to estimate the model parameter. Then the estimated parameters are used in controller design algorithm part to calculate the parameters for the controller.

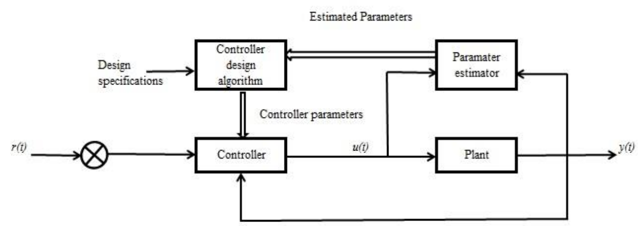



**Figure 7** General structure of STC

There are two types of STC- the indirect STC and direct STC. For indirect STC, the plant parameter is estimated first by using any estimation algorithm such as a least square method, maximum likelihood method and others. Then the estimated parameter is processed to obtain the parameters for the controller. Meanwhile, in direct STC, the estimator will directly estimate the controller's parameters. This makes direct STC simple and easy to use as the plant parameter does not need to be estimated. Examples of direct STC are Minimum Variance Control (MVC), Generalize Minimum Variance Control (GMVC), Detuned Minimum Variance Control (Detuned MVC) and others.

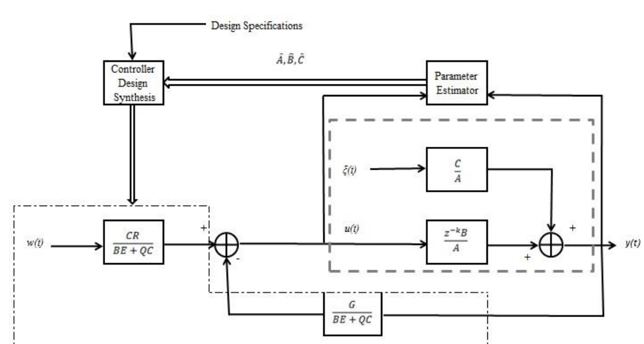



**Figure 8** General structure of GMVC

In this research, GMVC strategy is used to control electro hydraulic actuator system. The General structure of STC with GMVC strategy is shown in Figure 8. From the figure, system model can be represented as:

$$y(t+k) = \frac{B}{A}u(t) + \frac{C}{A}\zeta(t+k) \quad (11)$$

In STC with GMVC strategy, a pseudo-random output is introduced in the system. By assuming $p_0=q_0=r_0=1$, automatically the weighting factor is laid at the set point and the balanced control effort is penalized by $P$, $Q$ and $R$. The target of STC with GMVC strategy is to minimize the cost function as in Equation (12):

$$J = E[\emptyset^2(t+k)] \quad (12)$$

Then, the identity equation is used and is given as:

$$AE + z^{-k}G = PC \quad (13)$$

where;

$$E = 1 + e_1 z^{-1} + \cdots + e_{n_e} z^{-n_e}$$

$$G = g_0 + g_1 z^{-1} + \cdots + g_{n_g} z^{-n_g}$$

and

$$n_e = k - 1$$

$$n_g = \max(n_a - 1, n_p + n_c - k)$$

Finally, the control law for STC with GMVC strategy is obtained as:

$$u(t) = \frac{-G}{EB+QC}y(t) + \frac{RC}{EB+QC}w(t) \quad (14)$$

## ■5.0 RESULTS AND DISCUSSION

### 5.1 System Modelling

The sets of stimulus response data that consist of input and output data is collected and processed to obtain the electro hydraulic actuator system model. The process to obtain the system model is done through System Identification Toolbox in MATLAB software. By applying Parsinomy Principle, third order ARX model structure is selected to represent electro hydraulic actuator system model. And the model transfer function is obtained as:

$$G(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} = \frac{0.01253z^{-1} - 0.01373z^{-2} + 0.005231z^{-3}}{1 - 1.696z^{-1} + 0.7569z^{-2} 0.06054z^{-3}} \quad (15)$$

The next process is to validate the obtained model by simulating the response of the estimated model and compare it with the checking data. Figure 9 shows the validation result and from the result, it shows that the output response of the estimated model is almost similar to the actual system response with best fitting percentage of 94.88%.

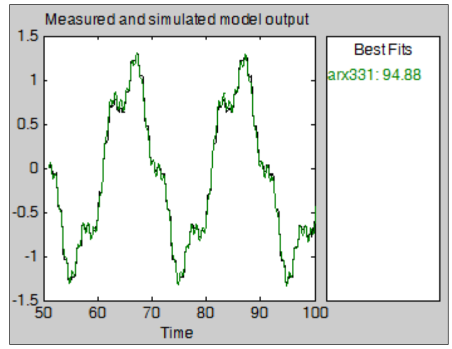



**Figure 9** Validation result

### 5.2 Controller Result

The process of designing an STC with GMVC strategy can start after obtaining the transfer function of electro hydraulic actuator system using system identification technique. The simulink block diagram of STC with GMVC strategy for both simulation and experiment is shown in Figure 10 and Figure 11.

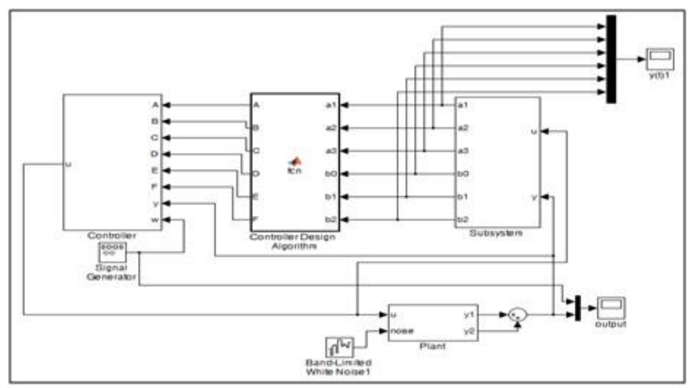



**Figure 10** Simulink block diagram for simulation

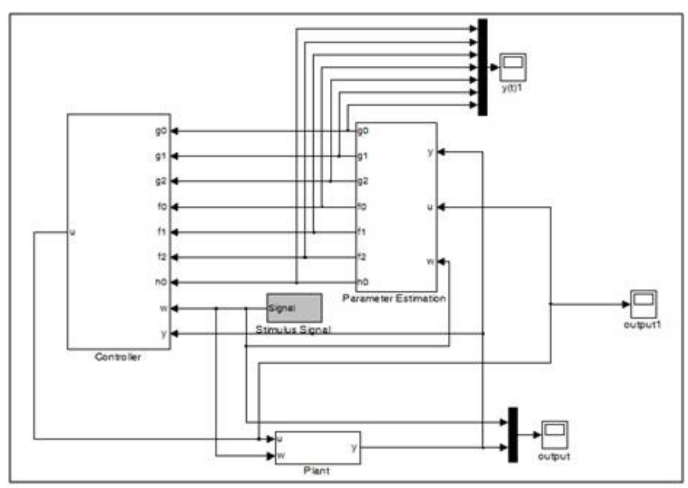



**Figure 11** Simulink block diagram for experiment

Figure 12 and Figure 13 Show the output response of the controlled system with square and sine input signals respectively.

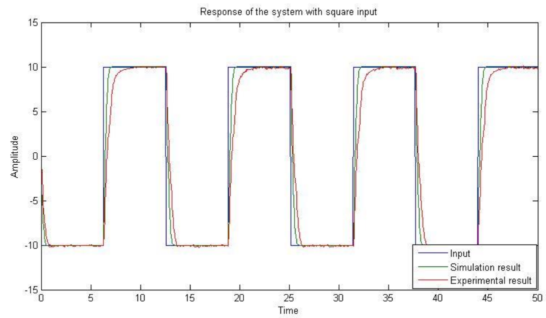



**Figure 12** Response of the system with square input

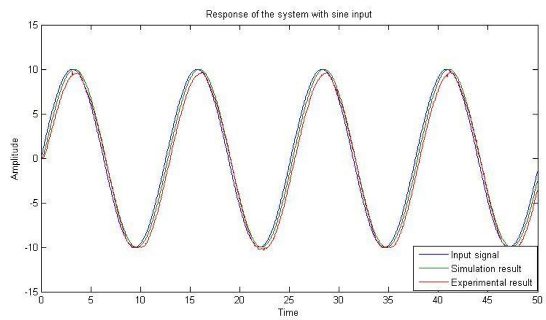



**Figure 13** Response of the system with sine input

Table 1 shows the summary of transient response performance for simulation and experiment output response.

**Table 1** Summary of transient response performance

| Transient response | Simulation | Experiment |
|---|---|---|
| Rise time (s) | 0.31 | 0.76 |
| Settling time (s) | 44.58 | 45.54 |
| Steady state error (s) | ± 0.02 | ± 0.05 |
| Phase lags error (°) | 6.25 | 6.25 |

From the above summary, it shows that the real time experiment response is almost the same with the output response from the simulation. The output response signal for both simulation and experiment also shown that it is tracking the given input signal with a small error of ±0.02s in simulation mode and ±0.05s in experimental mode. However, the output response seems to have a slight difference to the given input signal mainly due to the nonlinearity and uncertainty properties that is ignored during the system modelling process.

## 6.0 CONCLUSIONS

A proper system identification technique has been used to obtain the electro hydraulic actuator system model. An STC with GMVC strategy is designed to control the electro hydraulic actuator system and the controller has successfully been applied to the electro hydraulic actuator system in simulation mode and experimental mode. The output result from both modes shows that it successfully tracks the given input signal. Furthermore, the result obtained from real-time experiment is almost the same as the result from simulation modes. This research has shown the importance of a draw wire sensor in the overall process, especially in the experimental process to collect the output response from the electro hydraulic actuator system.

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