System Identification of Electromechanical Dual Acting Pulley Continuously Variable Transmission (EMDAP CVT)

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Abstract: This research investigates the performance of dynamic modeling using identification techniques of an Electromechanical Dual Acting Pulley Continuously Variable Transmission (EMDAP CVT) system for development of intelligent control. In this paper, the implementation details are described and the experimental studies conducted in this research are analyzed. The input and output speed data of the system were first acquired through the experimental studies using Integrated Measurement and Controls (IMC) data acquisition system. In this study, we applied engine speed to the EMDAP CVT and investigated the dynamic response of the system. The modeling of the system was developed using the Genetic Algorithm (GA). The validation and verification of the obtained model was evaluated using mean squared error (MSE) and correlation test. The performance of the nonlinear approach was compared and discussed based on MSE value. The prediction ability of the model was further observed with unseen data. The result shows that, Nonlinear ARX (NARX) model converges to an optimum solution faster with increasing of model order and the obtained dynamic model also described the EMDAP CVT system well. The models of the EMDAP CVT thus developed and validated will be used as the representation of the transfer function of the system.

Key-Words: System identification, Nonlinear identification, Continuous Variable Transmission

1 Introduction

The Electro-Mechanical Dual Acting Pulley Continuously Variable Transmission (EMDAP CVT) was developed by Universiti Teknologi Malaysia Drive-train Research Group (DRG) [1,2,3,4]. EMDAP CVT uses V-belt as its ratio variator and electro-mechanical actuation system (EM actuation system) to actuate the movement of the dual pulley sheaves simultaneously during the event of changing ratio. The EM actuation system in EMDAP CVT uses 2 DC electric motors for shifting ratio and clamping. During the event of changing ratio, primary DC electric motor actuates the axial movement of the primary pulley and secondary DC electric motor actuates the axial movement of the secondary pulley. These movements change the radius of the V-belt on the primary and secondary pulleys, hence changing the ratio accordingly. After that, secondary DC electric motor changes the length of the disk spring on secondary pulley accordingly in order to provide sufficient clamping force on the V-belt to avoid slipping or overstress.

Fig. 1 shows the existing EM actuation system in EMDAP CVT.

The first work related with the EMDAP-CVT was done by Sugeng Ariyono [3]. In his research, Ariyono want to control the engine speed for the vehicle with EMDAP-CVT system. His work focused on developing an intelligent control system using adaptive artificial neural network (AANN) method that provide appropriate CVT ratio. The research then continued by Bambang Supriyo [1,2]. His research focused on designing and developing EMDAP CVT ratio controllers in time domain analysis based on several algorithms. The problems with the current EMDAP CVT is, it is nonlinear and a complex system. Using system identification method, it is possible to obtain the transfer function of the EMDAP CVT system.

Nowadays, system identification techniques have become potential candidates for control application. The major aim of the system identification is to locate approximate or accurate models of dynamics systems based on the observed input and output.
A number of researchers have applied techniques to solve the problem related to system identification [5,7,10,13].

D.C. Foley et al. (2001) have reported a model identification and backstepping control of a continuously variable transmission system. The research introduced separate notions of geometric ratio and speed ratio and their relation to each other through the output power efficiency of the CVT. A simulation incorporating the entire drive train and vehicle dynamics demonstrates good closed loop behavior of the control system.

Terek A. Tutunji et al. (2005) have reported dc motor identification using impulse data. In this research, an Auto Regressive Moving Average (ARMA) model with steepest descent algorithm was used to minimize the error between the original and modeled velocities. Simulated results show that the model was able to predict the angular speed of the original motor system for several input signals with excellent accuracy.

Tolgay Kara et al. (2003) have reported nonlinear modeling and identification of a DC motor for bidirectional operation with real time experiments. The research uses Hammerstein nonlinear system approach for the identification purposes. The major nonlinearities in the system, such as Coulomb friction and dead zone were discussed in the research. Simulations indicate the advantages of the nonlinear identification approach compared to the linear identification.

The purpose of this study is to develop a model characterizing the EMDAP CVT system using system identification techniques. A dynamic model for the EMDAP CVT based on laboratory experiments has been developed by Universiti Teknologi Malaysia Drive-train Research Group (DRG). Finally, the validity of the obtained model was investigated using mean squared error (MSE) and correlation tests. The procedure for the system identification is shown in Fig. 2.

\[ \text{Experimental data} \rightarrow \text{Model structure determination} \rightarrow \text{Model estimation} \rightarrow \text{Model verification} \rightarrow \text{Acceptable} \]

Fig. 1 The existing EM actuation system in EMDAP CVT (Drivetrain Research Group of UTM, 2011).

\[ \text{Experimental data} \rightarrow \text{Model structure determination} \rightarrow \text{Model estimation} \rightarrow \text{Model verification} \rightarrow \text{Acceptable} \]

Fig. 2 System identification procedure

2 Experimental setup

In this research, the input-output data of the system were first acquired through experimental studies using Integrated Measurement and Controls (IMC) data acquisition system. To provide the experimental data, a variety of engine speed is applied to the EMDAP CVT system and the dynamic response was then investigated. The experimental arrangement developed for this study was established as shown in Fig. 3.

\[ \text{To sense the primary and secondary shaft speed, incremental encoder which gives 500 pulses per revolution (ppr) to represent the angular speed of the shaft were used. The signal from the rotational encoder then acquired through an IMC data acquisition unit as shown in Fig. 4. The acquired signal was then shown and analyzed on PC based using IMC software. Fig. 5 shows the separated EMDAP CVT test rig that comprises of CAMPRO engine 1.6 litres as a power source, electro-} \]

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mechanical friction clutch (EMFC) to engage and disengage the power from the engine to reverse forward mechanism (RFM), EMDAP CVT and eddy current dynamometer. RFM is used to reverse, neutral and forward the rotation from the engine to the EMDAP CVT sub-system and dynamometer.

3 Model structure

There are a lot of model structures that available to assist in modeling of a system. Non-linear autoregressive moving average model with exogenous input (NARMAX) is the most renowned for non-linear models (Ljung L., 1999). It is obvious from the literature that if the plant’s input and output data are obtainable, the NARMAX model is an appropriate option with standard back-propagation learning algorithms for modeling non-linear systems. Mathematically the model is given by equation (1) [16].

\[
\hat{y} = f(u(t-1), \ldots, u(t-n_u), y(t-1), \ldots, y(t-n_y), e(t-1), \ldots, e(t-n_e))
\]  

where, \(\hat{y}\) represents the output vector determined by the past values of the system input vector, output vector and noise. \(n_u, n_y\) and \(n_e\) represent model orders. \(f()\) represents the system mapping, which can be constructed through non-parametric method with a suitable learning algorithm. If the model is acceptable to identify the system without noise term incorporated or the noise is considered as additive term at output, the model can be represented in the NARX form (Ljung L. 1999). The NARX model is used as a model structure for this research. Mathematically the model in (1) can be written in discrete form as in equation (2) [8];

\[
y = f(u(k-1), \ldots, u(k-n_u), y(k-1), \ldots, y(k-n_y)) + e(t)
\]  

4 Model validation

It is necessary to validate whether the model is sufficient to represent the system or not after obtaining the model for the system. The procedures that considered for sensing the sufficiency or fitted model are called Model validity tests. The principles of model validation are:

- Compare model simulation or prediction with real data in time domain.
- Compare estimated model’s frequency response and spectral analysis result in frequency domain.
- Perform statistical test prediction errors.

There are a lot of validation tests that are existing in the literature, some of which are mean squared error, correlation test, model predicted output and one step-ahead prediction [8]. The mean squared error and correlation test are used to validate the model in this research.

4.1 Mean Squared Error (MSE)

MSE is one of the most common methods used for validations purposes. The MSE is different between the real output \(y(n)\) of the system and the predicted output \(\hat{y}(n)\) produced from the input to the system and the optimised parameters as shown in equation (3).

\[
\text{mse} = \frac{1}{N} \sum_{t}^{N} (y(t) - \hat{y}(n))^2
\]  

4.2 Correlation test

Correlation test is the usual statistical method to validating identified non-linear models that is more convincing for model validation [8]. It has been shown that a suitable prediction through different data sets is produced only if the model is unbiased. The prediction error sequence \(e(t)\) should be uncorrelated with all linear and non-linear computations.
combinations of past inputs and outputs (unbiased) when the model structure and the estimated parameters are correct. This will hold if and only if the following equations; which are described by Billings and Voon, (1986), are satisfied:

\[ \phi_{ee}(\tau) = E[e(t-\tau)e(t)] = \delta(t) \]  \hspace{2cm} (4)

\[ \phi_{ue}(\tau) = E[u(t-\tau)e(t)] = 0, \quad \forall \tau \]  \hspace{2cm} (5)

\[ \phi_{ue}(\tau) = E[(u^2(t-\tau) - u^2(t))e(t)] = 0, \quad \forall \tau \]  \hspace{2cm} (6)

\[ \phi_{ee}(\tau) = E[e(t)e(t-\tau)u(t-1-\tau)] = 0, \quad \tau \geq 0 \]  \hspace{2cm} (8)

where, \( \phi_{ue}(\tau) \) indicates the cross-correlation function between \( u(t) \) and \( e(t) \), \( e(t) = e(t+1) \), \( \delta(t) \) is an impulse function.

The model is considered as satisfactory if the correlation test lay within 95% confidence limits, which is defined as \( 1.96/\sqrt{N} \), where \( N \) is the data length. Autocorrelation of the error also will never be as an ideal delta function but will be considered as sufficient if the autocorrelation plot enters the 95% confidence limits before lag one [8].

5 Implementation and results

Results of the nonlinear ARX (NARX) model have been validated with a range of test including input/output mapping, mean-squared error and correlation tests. It is observed that the modeling method have performed very well in approximating the system response.

The models of the EMDAP CVT system thus developed and validated will be used as the transfer function of the system in subsequent investigations for the development of the control strategies in the future. Fig. 6 shows the input/output data obtained from the experimental test. The data has been plotted in terms of CVT ratio based on the speed.

5.1 Nonlinear identification

For the nonlinear identification, Nonlinear ARX (NARX) model has been used as the model structure. The model was tested with several different orders. The data set, comprising 1800 data points was divided into two sets of 900 data points. The model was trained using the first data set, and validated using the whole set. The best result for the nonlinear identification was achieved with an order 3. The models reached the MSE value of 0.000009. Fig. 7 and 8 show the result for the nonlinear identification with different orders.

![Fig.7 Real system response (yt) and identified model response (yhat) for nonlinear identification with 2nd order](image1)

![Fig.8 Real system response (yt) and identified model response (yhat) for nonlinear identification with 3rd order](image2)

Fig. 9 shows the error between the real system response and identified model response. The result clearly indicates the good output tracking performance of the nonlinear identification process with respect to the linear approach. To determine the model effectiveness, correlation tests were carried out. Fig. 10 (a) to (e) shows the result for the correlation tests. The results were found out to be within 95% confidence level thus confirmed the accuracy of the obtained results.
6 Discussion

The Mean Square Error (MSE) values for the linear and nonlinear identification experiment were calculated for different model orders and summarized in Table 1.

<table>
<thead>
<tr>
<th>Model order</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear</td>
<td>0.00096</td>
<td>0.00001</td>
<td>0.000009</td>
<td>-</td>
</tr>
</tbody>
</table>

From the validation tests, it is observed that different modeling methods considered in this study have performed sufficiently well. Comparing the MSE value in Table 1, it is showed that the nonlinear identification method have performed better with the increasing of model order. From the result, it is noted that by having more (nonlinear) flexibility can improve the model fidelity.

The results are numerically and graphically demonstrated. For nonlinear identification, nonlinear ARX model with 3rd order shows the best fit with MSE value 0.000009. The identification error and the convergence properties of the estimates also seemed to improve with introduction of the nonlinear approach. The outlined
identification method assumes the system to be linear. However, the system obtained is nonlinear. The nonlinearities of the system are caused by the actuators and CVT geometry [13].

7 Conclusion

Results of various modeling methods have been validated with a range of test including input/output mapping, mean-squared error and correlation tests. The modeling method that used is observed to be performed very well in approximating the system response.

The models of the EMDAP CVT system thus developed and validated will be used as the transfer function of the system in subsequent investigations for the development of the control strategies in the future.

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