Nonlinear Identification of Electronic Brake Pedal Behavior Using Hybrid GMDH and Genetic Algorithm in Brake-By-Wire System

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Abstract – In this paper, we represent a nonlinear identification of electronic brake pedal behavior in the brake-by-wire (BBW) system based on hybrid group method of data handling (GMDH) and genetic algorithm (GA). A GMDH is a kind of multi-layer network with a structure that is determined through training and which can express nonlinear dynamics as a mathematical model. The GA is used in the GMDH, enabling each neuron to search for its optimal set of connections with the preceding layer. The results obtained with this hybrid approach were compared with different nonlinear system identification methods. The experimental results showed that the hybrid approach performs better than the other methods in terms of root mean square error (RMSE) and correlation coefficients. The hybrid GMDH/GA approach was effective for modeling and predicting the brake pedal system under random braking conditions.

Keywords: Brake-by-wire, Group method of data handling, Genetic algorithm, System identification

1. Introduction

The X-by-wire system is a relatively new technology being increasingly implemented in modern automobiles. The X-by-wire system is an automotive system that interprets the driver's inputs and executes appropriate commands to produce desired vehicle behavior, typically via a microprocessor based control system. For fault tolerance, a typical X-by-wire system consists of redundant sensors, actuators, microprocessors, and communication channels. In the X-by-wire equipped vehicle, there are no mechanical or hydraulic connections between the driver's input interface (e.g., throttle, brake, steering) and the target vehicle system [1, 2].

The brake-by-wire (BBW) system, a type of X-by-wire, was first introduced in the Mercedes Benz SL series in 2001 [3]. However, that BBW system was decommissioned and removed from the vehicle a few years later due to a number of field problems. Work on the electro-mechanical brake (EMB) in the BBW was being pursued in the late 1990's by a number of automotive companies, including Bosch, Continental, and TRW [4]. However, issues related to reliability still remain and must be addressed before these systems can be used in an automobile [5-7].

To ensure the BBW system reliability, accurate modeling of the real system is an important step. Models can be used for the EMB analysis, to gain a better understanding of the

system. Models also allow us to predict and simulate the system's behaviors. Furthermore, models are necessary for designing new processes, analyzing existing processes, designing controllers, optimizations, supervision, and fault detection and diagnosis. For these purposes, various system identifications have been applied in many fields to model and predict the behavior of complex nonlinear systems based on given input/output data.

Many soft computing approaches for identifying and modeling the nonlinear systems have been proposed. Most of these methods require large amounts of data to estimate the parameters of the model in higher order systems [8]. For example, neural networks and fuzzy logics are used to identify and predict the nonlinear systems based on empirical raw data. Especially, the neural networks are one of the most powerful methods that have been widely employed in recent years in various fields [9, 10]. However, when using such methods, the nonlinear dynamics are not explicitly expressed as a mathematical model. Therefore, a group method of data handling (GMDH) was first developed by A. G. Ivakhnenko as a multivariate analysis method for complex systems modeling and identification [11]. The main idea in GMDH is to build an analytical function in a feed-forward network based on a quadratic node transfer function whose coefficients are obtained using regression technique. Note that once the analytical GMDH model has been found, application of this model is very quick and cheap. In addition, the GMDH identification is often "black boxes," and they are especially valuable when the underlying physics is complex or uncertain while there is plenty of data to develop a virtual sensor [12]. Consequently, GMDH provides an effective approach for the identification of higher order nonlinear

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systems [13]. However, the GMDH needs a suitable optimization method to find the best network architecture. For the best network architecture, the genetic algorithm (GA) is arranged in a new approach, to design the whole architecture of the GMDH. This provides the optimal number of neurons in each hidden layer and the connectivity configuration needed to find the optimal set of appropriate coefficients of quadratic expressions to model the system [14].

In this paper, first of all, the BBW system was developed. Based on that system, brake pedal sensor signals were measured. Secondly, a hybrid GMDH/GA was applied to identify the electronic brake pedal system for status monitoring. We then evaluated the performance of the hybrid GMDH/GA as a system identification tool.

This paper is organized as follows: Section 2 presents the developed BBW system; Section 3 describes the hybrid GMDH/GA algorithm; applications of the identification for predicting sensor output under random braking conditions are presented in Section 4; the results for identifying the pedal system using different methods are compared in Section 5. Finally, conclusions are presented in Section 6.

2. Configuration of Developed Brake-By-Wire System

The developed BBW system architecture is proposed and shown in Fig. 1. It consists of the EMB modules, the electronic brake pedal system, a communication network, main and local electronic control units (ECUs) and power supplies. The EMB actuators are based on the electric motors and a mechanism that applies force to friction pads. The detailed BBW systems are mainly comprised of four types of elements:

Fig. 1. Architecture of developed BBW system

Fig. 2. Block diagram of developed BBW system

1. Electronic Control Units (ECUs)
2. Sensors – pedal sensor, hall sensor and encoder
3. Actuator – electric motor, planetary gear, ball screw and caliper
4. Communication network – CAN or FlexRay

Fig. 2 illustrates the block diagram of the developed BBW system. Once the driver inputs a brake command to the system via the brake pedal, a command clamping force signal is generated by the main ECU. This command signal is sent to the EMB local ECU and display via a communication network. The controller uses the command clamping force as a reference input. The controller provides drive control commands for a motor drive module. This module controls three phase currents for the brake actuator which is a permanent magnet synchronous motor (PMSM), energized by a 42 [V] power source. In addition to tracking its reference, the controller also controls the current and position of the PMSM.

3. Application of Hybrid GMDH/GA to the Electronic Brake Pedal System

In this section, we describe for a hybrid GMDH/GA algorithm and propose the schematic of brake pedal system identification.

3.1 GMDH

The general connection between the inputs and output variables can be expressed by a complicated polynomial series in the form of the Volterra series, known as the Kolmogorov-Gabor polynomial [13]:

$$y = a_0 + \sum_{i=1}^m a_i x_i + \sum_{i=1}^m \sum_{j=1}^m a_{ij} x_i x_j + \sum_{i=1}^m \sum_{j=1}^m \sum_{k=1}^m a_{ijk} x_i x_j x_k + \dots \quad (1)$$

where x is the input to the system, m is the number of inputs and a are coefficients. For most applications the quadratic forms for only two variables, which are called partial descriptions, are used in the form to predict the output as follows.

$$y = a_0 + a_1 x_i + a_2 x_j + a_3 x_i x_j + a_4 x_i^2 + a_5 x_j^2 \quad (2)$$

To obtain the value of the coefficients a for each model, a system of Gauss normal equations is solved. The coefficient of nodes in each layer is expressed as follows.

$$A = (X^T X)^{-1} X^T Y \quad (3)$$

where

$$Y = [y_1, y_2, \dots, y_m]^T,$$

$$A = [a_0, a_1, a_2, a_3, a_4, a_5],$$

$$X = \begin{bmatrix} 1 & x_{1p} & x_{1q} & x_{1p}x_{1q} & x_{1p}^2 & x_{1q}^2 \\ 1 & x_{2p} & x_{2q} & x_{2p}x_{2q} & x_{2p}^2 & x_{2q}^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{mp} & x_{mq} & x_{mp}x_{mq} & x_{mp}^2 & x_{mq}^2 \end{bmatrix}.$$

The main function of GMDH is based on the forward propagation of a signal through nodes of the net similar to the principal used in classical neural nets. Every layer consists of simple nodes each of which performs its own polynomial transfer function and passes its output to nodes in the next layer. The basic steps involved in the GMDH modeling are as follows [15, 16]:

Step 1: Select input variables $X = \{x_1, x_2, \dots, x_m\}$. Divide the available data into training and checking data sets. Before applying the algorithm, the inputs and output are normalized.

Step 2: Construct $k = \binom{m}{2} = m(m-1)/2$ new variables $Z = \{z_1, z_2, \dots, z_k\}$ in the training data set and construct the regression polynomial for the first layer by forming the quadratic expression which approximates the output y .

Step 3: Identify the contributing nodes at each hidden layer according to the value of the root mean square error (RMSE). Eliminate the least effective variable by replacing the columns of X (old data) by the new columns of Z .

Step 4: The GMDH algorithm is carried out by repeating Steps 2 and 3 of the algorithm. When the errors of the checking data in each layer stop decreasing, the iterative computation is terminated.

The network constructed using the self-organizing GMDH algorithm is shown in Fig. 3 [17].

3.2 Genome representation

The GA is commonly used in the training of neural networks in terms of associated weights or coefficients, and has successfully performed better than traditional gradient-based techniques. In most GMDH algorithms, the neurons in each layer are only connected to neurons in the adjacent layer. Taking advantage of this feature, it is possible to present a simple encoding scheme for the genotype of each individual in the population [18, 19].

In Fig. 4, neurons in the first hidden layer are connected to the output layer by directly going through the second

Fig. 3. Self-organizing GMDH algorithm

Fig. 4. Genome representation

hidden layer. The genome or chromosome representation, which shows the topology of a GMDH, simply consists of a symbolic string composed of an alphabetic representation of the input variables [20]. In this encoding scheme, each input variable is assigned an alphabetic name, and a chromosome is a string of concatenated substrings of these alphabetic names of inputs. It should be noted that such repetition occurs whenever a neuron passes through some adjacent hidden layers and connects to another neurons in the next 2nd, 3rd, ... following hidden layer. In this encoding scheme, the number of repetitions of that neuron depends on the number of passed hidden layers l , and is calculated as 2^l .

3.3 Proposed scheme of electronic brake pedal system identification

In the BBW equipped vehicle, the brake pedal sensor is safety-critical component, and this failure will disrupt the vehicle's operation and endanger human lives [21]. The main ECU must always be informed of the driver's intentions to brake or to stop the vehicle, and fault data from the pedal sensor is a serious problem for vehicle control systems. For this reason, the design of a these vehicles need to include safeguards that prevent abnormal behavior. General solutions to this problem include providing hardware redundant sensors, and applying a fail-

Fig. 5. Proposed scheme of electronic brake pedal system identification using hybrid GMDH/GA

safe mechanism. In addition to the complete loss of sensor information, the ECU may also suffer from an intermittent data loss. This may result from an instantaneous short circuit or disconnection, a communication network fault, or a sudden increase in noise. To address these problems, we introduce a system identification approach based hybrid GMDH/GA as the virtual sensor. The following Fig. 5 shows the proposed scheme of the electronic pedal system identification. In order to model and identify the brake pedal system, the following sensory information is captured as inputs: pedal effort force [kgf], voltage signal AD1 [V], voltage signal AD2 [V] and pedal displacement [%]. The output is the clamping force command [N]. The residual analysis will conduct the fault diagnosis function; in other words, it will be used with the measured data given by the pedal behavior to compare with the results obtained using the estimated data generated by the hybrid GMDH/GA.

4. Experimental Results

4.1 Experimental setup

For the system identification, tests were made on a laboratory BBW system. Our BBW system is composed of brake pedal, pedal effort force sensor, ECUs, wheel speed sensors, and EMBs as Figs. 6 and 7. In the EMB system, the electric motor is of the PMSM type with ratings of 250 [W] and 11,000 [rpm] and ensures that the required clamping forces (up to 33 [kN]) can be achieved.

The parameters of interest in this four-input one-output system, which both affect the performance of the clamping force command are the pedal effort force [kgf], voltage signals(AD1[V] and AD2[V]) and pedal displacement [%]. Accordingly, there were a total of 100,000 experimental data considering four input parameters, as shown in Fig. 8. Out of which 70,000 data points are randomly selected for the training data set while the remaining 30,000 data points are selected for the checking data set. We choose the sampling interval of 0.2 [ms].

Fig. 6. Electronic brake pedal system

Fig. 7. EMB equipped wheel

In the hybrid GMDH/GA, a population size of 20 was employed together with a crossover probability of 0.9 and a mutation probability of 0.1 in a generation number of 6 and number of hidden layer of 4. The hybrid GMDH/GA was implemented in MATLAB on a PC with an Intel Core CPU 1.5 GHz and RAM 8 GHz. We can construct the structure of the network, which is shown in Fig. 9.

4.2 Comparison of results and discussions

The well-known criterion for comparing the different identification methods is the root mean square error (RMSE) and correlation coefficients R of the predicted

Fig. 8. Experimental data; pedal effort force [kgf] (first), voltage signal AD1 [V] (second), voltage signal AD2 [V] (third) and pedal displacement [%] (fourth)

Fig. 9. Network structure of the brake pedal behavior using hybrid GMDH/GA

Fig. 10. Neural network identification results

outputs from each model. The reason for using these criteria is that we need to measure the quality of the models and also the predictability of the models.

The neural network was trained for 1000 epochs using the Levenberg-Marquart back-propagation algorithm with a learning rate of 0.001 and an error goal of 0.01. Figs. 10-12 shows the results for the measured, estimated output

Table 1. Comparison of performance results for different identification methods

Identification	RMSE [N]	R
Neural Network	3211.8	0.95556
GMDH	1561.8	0.98949
Hybrid GMDH/GA	117.5	0.99223

Fig. 11. GMDH identification results

Fig. 12. Hybrid GMDH/GA identification results

data and residual errors for neural networks, GMDH and hybrid GMDH/GA identification, respectively. When a random stepwise and sinusoidal clamping force command is applied, the estimated values follow the target values, which show close agreement with the measured values. Especially, the figures show that proposed hybrid GMDH/GA identification offers good estimation performance.

Table 1 shows a numerical comparison of the RMSE and R results from different modeling methods applied to identification of the brake pedal behavior based on Figs. 10-12. As indicated in Table 1, considering the RMSE and R which are here regarded to be performance indicators, the experimental results clearly demonstrate that the hybrid GMDH/GA outperforms the other identification methods. In the case of the RMSE performance comparison, the hybrid GMDH/GA performed about 92% better than the GMDH and about 96% better than the neural network.

Considering the RMSE and R performance, the hybrid GMDH/GA identification may be the best choice because it had the smallest error compared with the other methods. In addition, the hybrid GMDH/GA identification shows good performance in correlation analysis.

5. Conclusions

In this paper, we have presented a hybrid GMDH/GA approach which was successfully used for the modeling and prediction of the brake pedal behavior. In conclusion, the results obtained using the hybrid GMDH/GA were better than those obtained using the other identification methods under random complex braking conditions. The accurate model obtained using the hybrid approach is expected to play an important role in the control and fault diagnosis of the BBW system in the future.

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