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Model based design of electronic throttle control

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Abstract: With the advent of torque based Engine Management Systems, the precise control and robust performance of the throttle body becomes a key factor in the overall performance of the vehicle. Electronic Throttle Control provides benefits such as improved air-fuel ratio for improving the vehicle performance and lower exhausts emissions to meet the stringent emission norms. Modern vehicles facilitate various features such as Cruise Control, Traction Control, Electronic Stability Program and Pre-crash systems. These systems require control over engine power without driver intervention, which is not possible with conventional mechanical throttle system. Thus these systems are integrated to function with the electronic throttle control. However, due to inherent non-linearities in the throttle body, the control becomes a difficult task. In order to eliminate the influence of this hysteresis at the initial operation of the butterfly valve, a control to compensate the shortage must be added to the duty required for starting throttle operation when the initial operation is detected. Therefore, a lot of work is being done in this field to incorporate the various nonlinearities to achieve robust control. In our present work, the ETB was tested to verify the working of the system. Calibration of the TPS sensors was carried out in order to acquire accurate throttle opening angle. The response of the calibrated system was then plotted against a step input signal. A linear model of the ETB was prepared using Simulink and its response was compared with the experimental data to find out the initial deviation of the model from the actual system. To reduce this deviation, non-linearities from existing literature were introduced to the system and a response analysis was performed to check the deviation from the actual system. Based on this investigation, an introduction of a new nonlinearity parameter can be used in future to reduce the deviation further making the control of the ETB more precise and accurate.

1. Introduction

Electronic Throttle Control is one of the ways of improving the performance of a vehicle along with reduced emissions [2]. Due to mass production of automotive parts and related relatively low technical quality, the dry friction is very significant in the throttle actuator. Even if the dry friction is fully known, the dry friction can be guessed with difficulty [3]. The control of the ETB can be perplexed due to the influence of the additional strong spring nonlinearities. Significant hysteresis is induced by dry friction which offers strong non-linear shape to the spring stiffness. An additional force is imposed by the return spring of butterfly valve against the motor torque in the opening direction and provides an extra force that helps the valve to respond faster in the closing direction. The summation of the motor torque, regulated by the motor drive controller, and the spring torque actually indicates the total torque acting on the valve plate [4]. Therefore, in order to improve the overall performance of the throttle body and to reduce the lag, the system should be designed in

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such a way that their nonlinearities are compensated. The design parameters, control variables will provide additional degrees of freedom to optimize the performance of the engine over its wide range of operation [1].

The coupling of the electric motor of ETB and TPS with a capable electronic controller for operation is required. Signal processing logics and some other components use the TPS signal of valve angle as feedback when trying to drive the valve to the desired angle [5]. This setup is actually the throttle controller which is basically made of purely electronic components such as operational amplifiers, capacitors, and resistors. The controller is a solely analog architecture and can also be used with a microcontroller, for attaining improved digital control architecture [6]. R. Pursifull et al. [7] have developed an ETB model in Simulink MATLAB which gave an input to the ETB's motor H driver and generated an output in terms of TPS signal. ETB was modeled with significant physical characteristics and was made to overcome numerical simulation issues. Finally, an HIL testing was carried out. Results were obtained avoiding difficult measuring characteristics which can affect the validity of the system. J. Ras et al. [8] have presented a paper on the problems of a Toyota Electronic throttle controller (ETC). Their work was divided into two parts, i.e. firstly considering the timing constraints in the ETC and secondly comparing the conventional throttle designs with ETC using classical control theory. Results showed that by considering timing constraints, safety requirements can be satisfied along with reduced errors in the design and lower debugging cost. Comparison of the conventional system with ETC also provided system assurance for all requirements of safety.

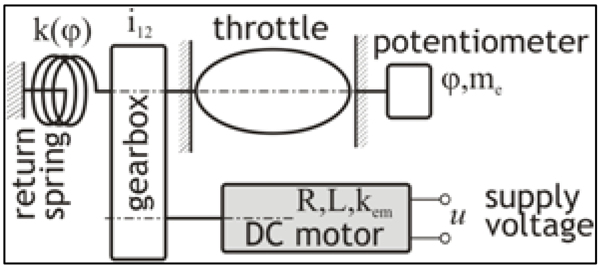

Figure 1. Schematic Diagram of an Electronic Throttle Control [17]

Jiao et al. [9] have used a feedback compensator and an adaptive nonlinear compensator with a PID controller to control the ETB. The nonlinear compensator was derived from values of friction, limp-home and backlash conditions. Comparing the enhanced ETB with theoretical values showed fast and accurate reference tracking. ETB results for test bench simulations demonstrated improved and faster reference tracking without compromising transient conditions like settling time and peak overshoot within the specified requirement. Several authors have highlighted that the comparison of the implementation and flexibility of each throttle design can be achieved by both analog and a digital throttle controller. Studies showed that the analog controller proved to be reliable and robust in many applications, an inexpensive microcontroller such as an Arduino greatly decreases implementation and setup time and effort, increases controller flexibility, all the while maintaining reasonable performance and reliability.

This paper depicts the improvements and advancements in electronic development platforms, such as the Arduino series, which have made programmable control of ETB as an excellent alternative to pure analog control. With ETB, several advantages like easier programmable development platform and reduced implementation time are obtained. The present study showed improvement of the simulation model of the throttle body by introducing different nonlinearities such as dead-zone and limp-home conditions. Thereafter designing of a nonlinear controller was carried out which provides the robust performance of the ETB. Finally, HIL testing and validation was performed on the hardware.

2. Design methodology

Firstly, the ETB was tested to verify the working of the system and the circuit used for the present experiment. Calibration of the TPS sensors was carried out in order to acquire faster and accurate throttle opening angle. The response of the calibrated system was then plotted against a step input. A linear model of the ETB was prepared using Simulink in commercially available MATLAB software. The model of the DC motor is illustrated in figure 3 followed by its governing equations 2.1 to 2.4 [16]. The input to the system is the voltage to the anchor side of the circuit denoted by u. As the input voltage u is varied, the shaft angle of the motor φ and as a result there is torque transfer to the spring set. The spring characteristics viz. spring constant K, dynamic damping D and the total inertia J which also includes the motor inertia. Equation 2.1 describes the Ohm's law for the anchor circuit. There is a counter-directed emf induced when the motor rotates, represented by equation 2.2. Equation 2.3 is the direct proportionality between the torque M_d to the anchor current I. Equation 4.4 is the mechanical torque equation acting on the springs. This model was used for System Identification in MATLAB to identify the unknown parameters like inertia of the butterfly valve and stiffness of the return spring. The Step Input response was plotted for the linear model of ETB. The obtained response was then compared with the experimental data to investigate the initial deviation of the model from the actual system. To reduce this deviation, nonlinearities were introduced from existing literature into the system after which a response analysis was performed to check the deviation from the actual system. Based on the investigation carried out with the research, an introduction of a new non-linearity parameter further reduced the previous obtained deviation.

Arduino Controller was used for designing the hardware circuit of the ETB because of its flexible and easy to use software and hardware. The Arduino controller was equipped with various digital and analog I/O pins which connected the ETB and other respective components. The Arduino program was written in C language and fed into the controller for operating the ETB. Figure 2 shows the entire ETB hardware setup along with Arduino Mega 2560 controller.

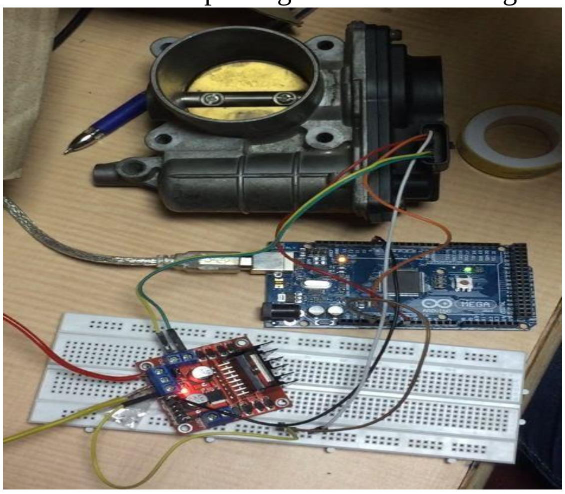

Figure 2. Experimental Setup for Electronic Throttle Control

MATLAB Simulink was selected for modeling the ETC system and its environment since it is widely used in the automotive industry. A Simulink model and its environment comprise of

IOP Conf. Series: Materials Science and Engineering **263** (2017) 062063 doi:10.1088/1757-899X/263/6/062063

successive levels or layers of blocks whose input and output functions are stipulated by wires drawn between blocks. The controller and the dynamics of the environment are part of the simulation block. The sensors and the drivers present in the system helps the controller communicates with the physical environment. They act as an interface of the controller software to the physical world. When the code is generated from the controller model, it requires the same interface to a set of sensors to measure plant states and drivers to run the actuators [10]. The focus of the ETC case study is on the modeling of the controller.

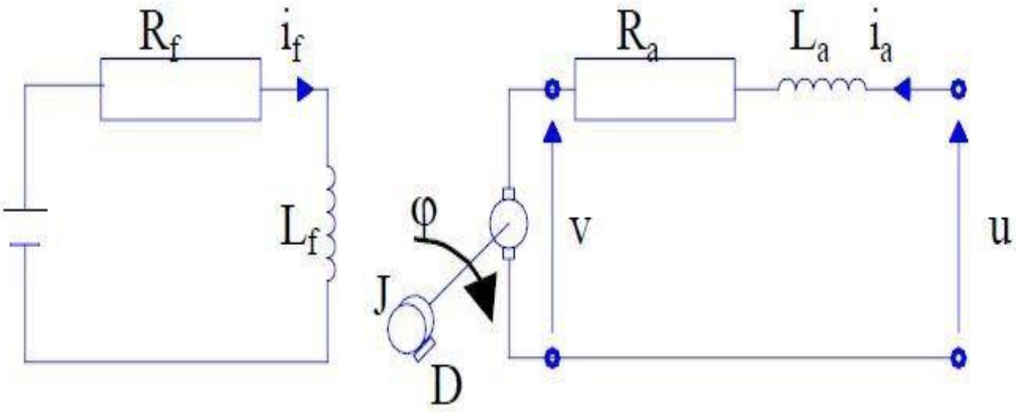

Figure 3. Linear Model for Electronic Throttle Control [16]

The equations for the linear model of ETB are given as [16]:

$$u(t) = Ri + L\frac{di}{dt} + v(t) \qquad (1)$$

$$v(t) = K_u.\frac{d\varphi(t)}{dt} \qquad (2)$$

$$M_d(s) = K_m\,.I(s) \qquad (3)$$

$$J.\ \frac{d^2\varphi(t)}{dt^2} = M_d(t) - D.\frac{d\varphi(t)}{dt} \qquad (4)$$

In order to find the various parameters of the Electronic throttle system, System identification was used using MATLAB. This methodology helps for building mathematical models of dynamic systems using measurements of the system's input and output signals [12]. In order to perform system identification of the throttle body, a response analysis was done. A unit step input was given to the throttle body in order to attain the Wide-Open Throttle (WOT) condition. The unit step input was given with a delay of 0.1 seconds for the duration of 0.5 seconds.

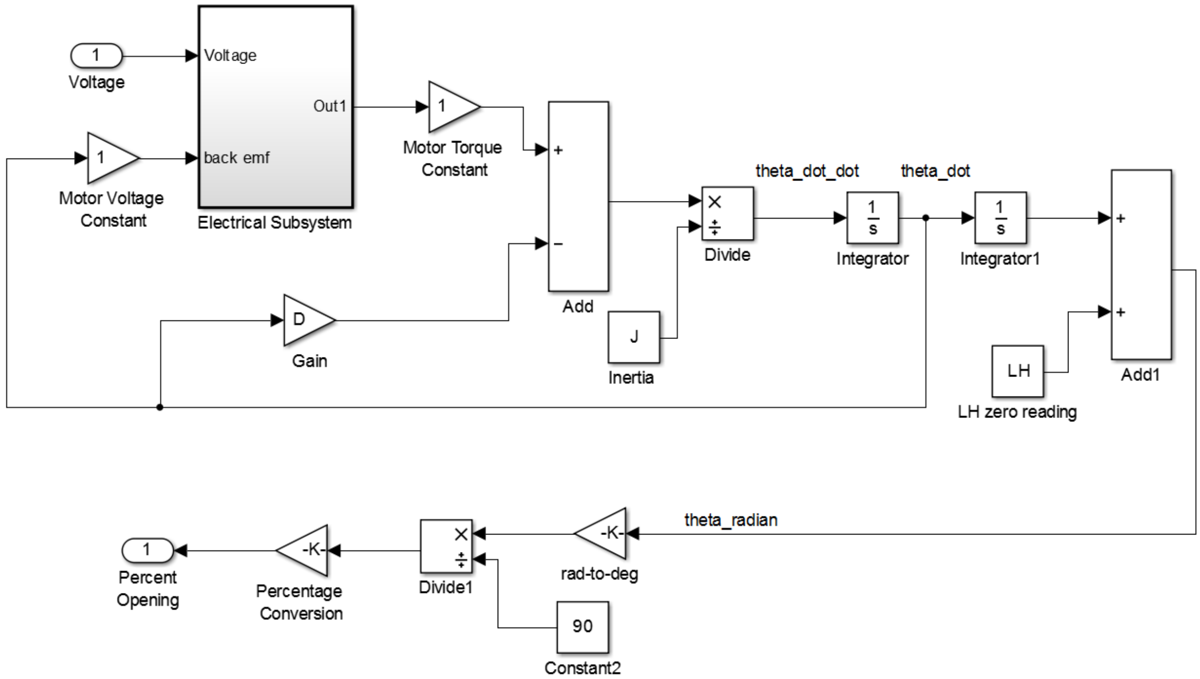

Figure 4. Simulink Block Diagram designed in MATLAB for ETB

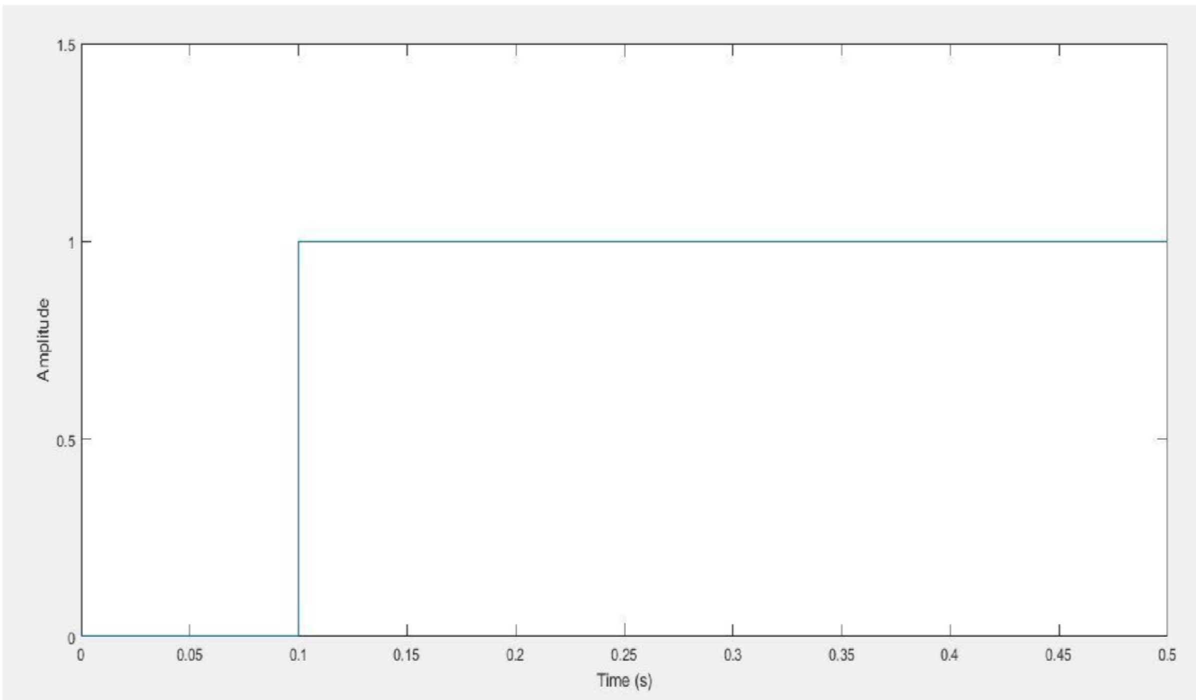

Figure 5. Step input plotted in MATLAB for ETB

The response was calibrated to get a percentage of throttle opening. The response does not follow the unit step input due to various nonlinearities present in the system. This data is required to perform the system identification in MATLAB.

IOP Conf. Series: Materials Science and Engineering **263** (2017) 062063 doi:10.1088/1757-899X/263/6/062063

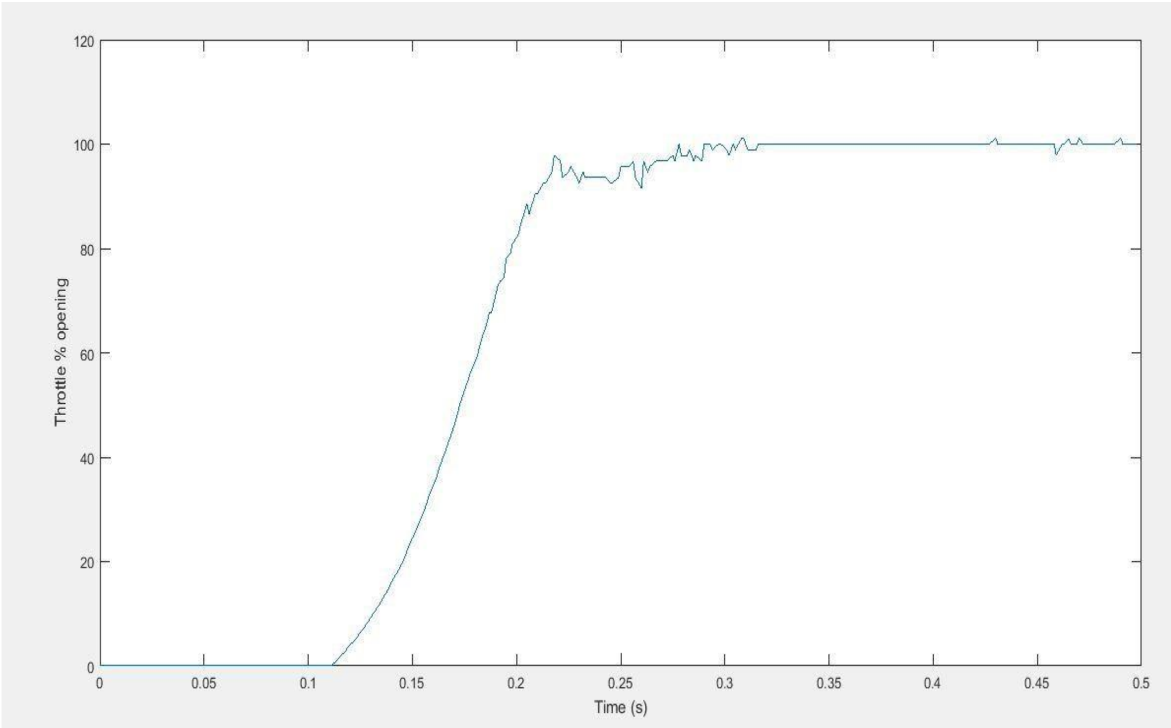

Figure 6. Percentage of Throttle Opening v/s Time plotted in MATLAB for ETB (Linear Condition)

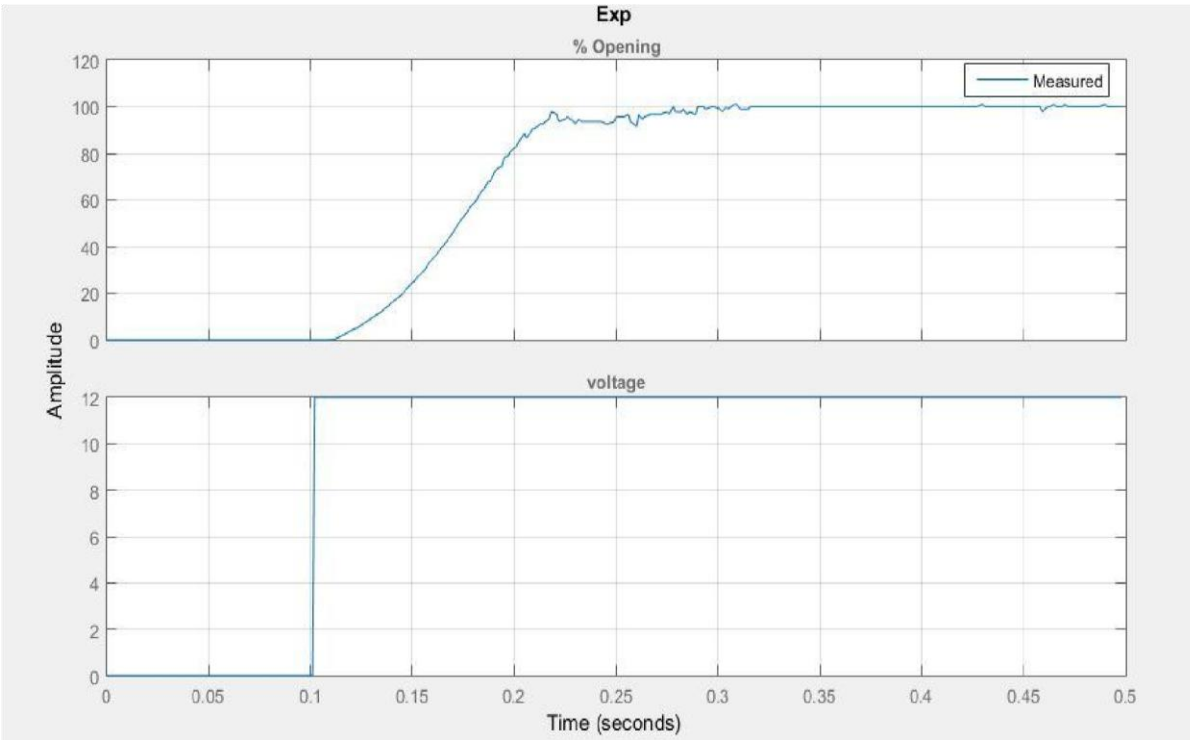

Figure 7. Percentage of Throttle Opening and Step input v/s Time plotted in MATLAB for ETB (Linear Condition)

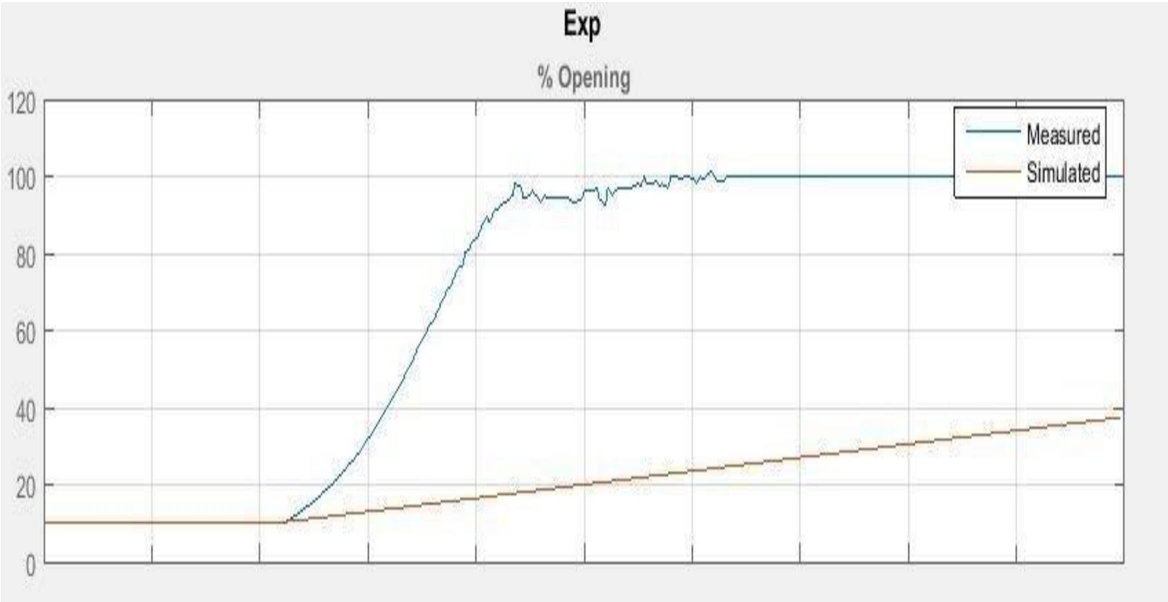

Figure 8. Percentage of Throttle Opening and Step input v/s Time plotted in MATLAB for ETB (Linear Model)

Figure 8 shows the percentage of throttle opening of ETB v/s step input after performing system identification using MATLAB. The measured curve differs from the linear signal due to various nonlinearities in the system which has to be investigated.

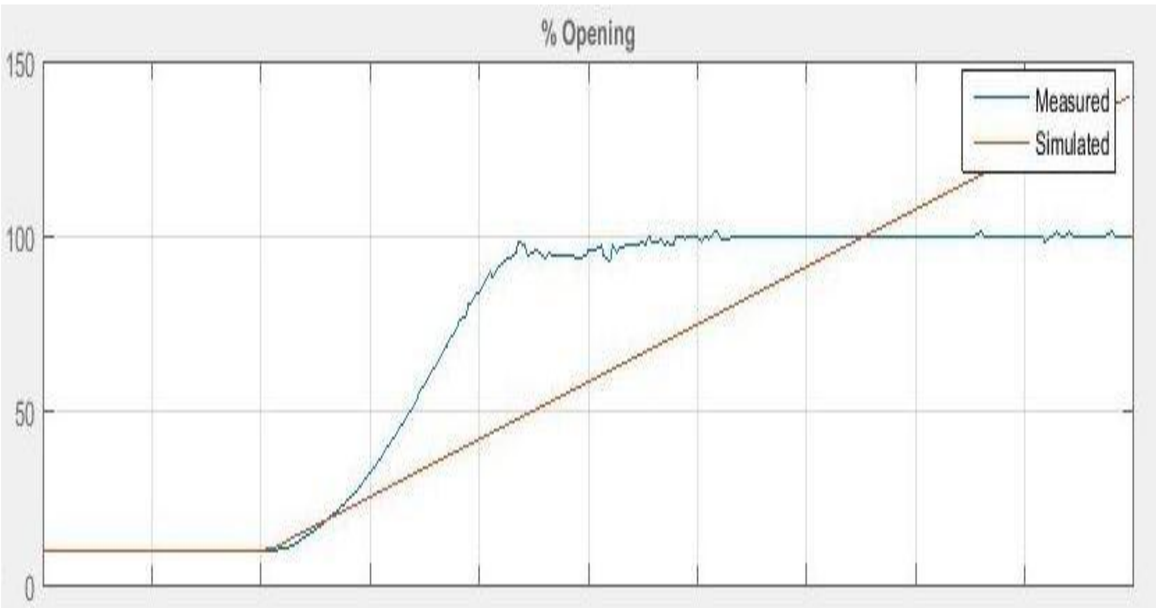

Figure 9. Percentage of Throttle Opening and Step input v/s Time plotted in MATLAB for ETB (Linear Model)

3. Results and discussions

After performing parameter estimation for the linear model, the nonlinearities were included. The first nonlinearity that arises is due to the torsional spring. In order to overcome that the motor has to apply extra torque which results in a delay in the response of the system as shown in Figure 9. With the new mathematical model of the system after including the nonlinearities, we obtained a closer approximation of the experimental data. Further, we included nonlinearity due to friction between the shaft of the butterfly valve and the needle roller bearing present in the housing of the throttle body. The improved mathematical model can then be used to design a linear PID controller using MATLAB. The gain parameters can then be tuned through software in loop techniques rather than hardware-in-loop [13]. Figure 10 shows the improved simulated curve v/s percentage of throttle opening after the addition of spring stiffness nonlinearity. It can be observed that the simulated curve is closer to the experimentally measured data with slight variations and overshoot.

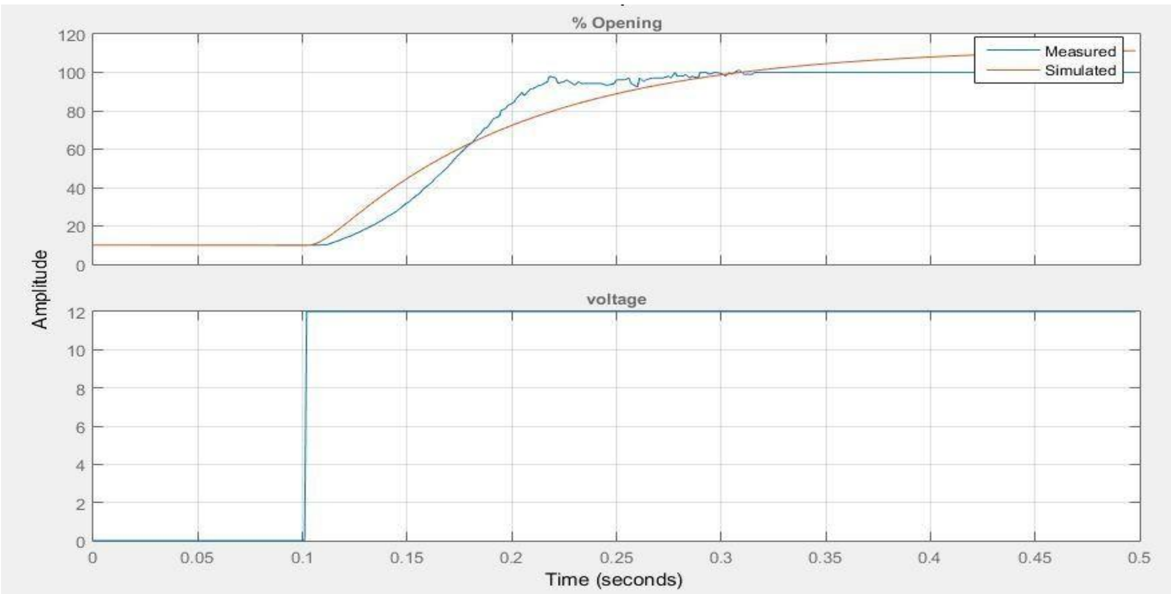

Figure 10. Percentage of Throttle Opening and Step input v/s Time plotted in MATLAB for ETB (Model using single nonlinearity)

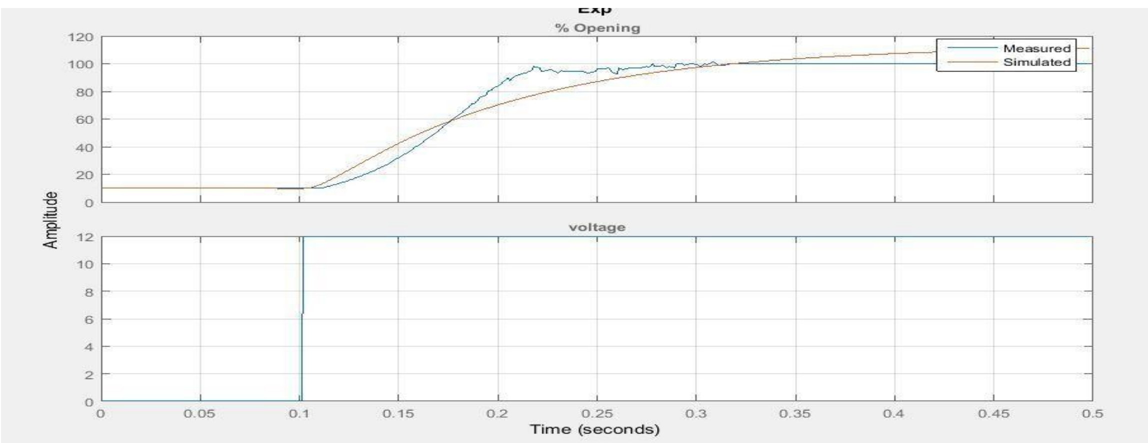

Figure 11. Throttle Opening and Step input v/s Time plotted in MATLAB for ETB (Model using two nonlinearity)

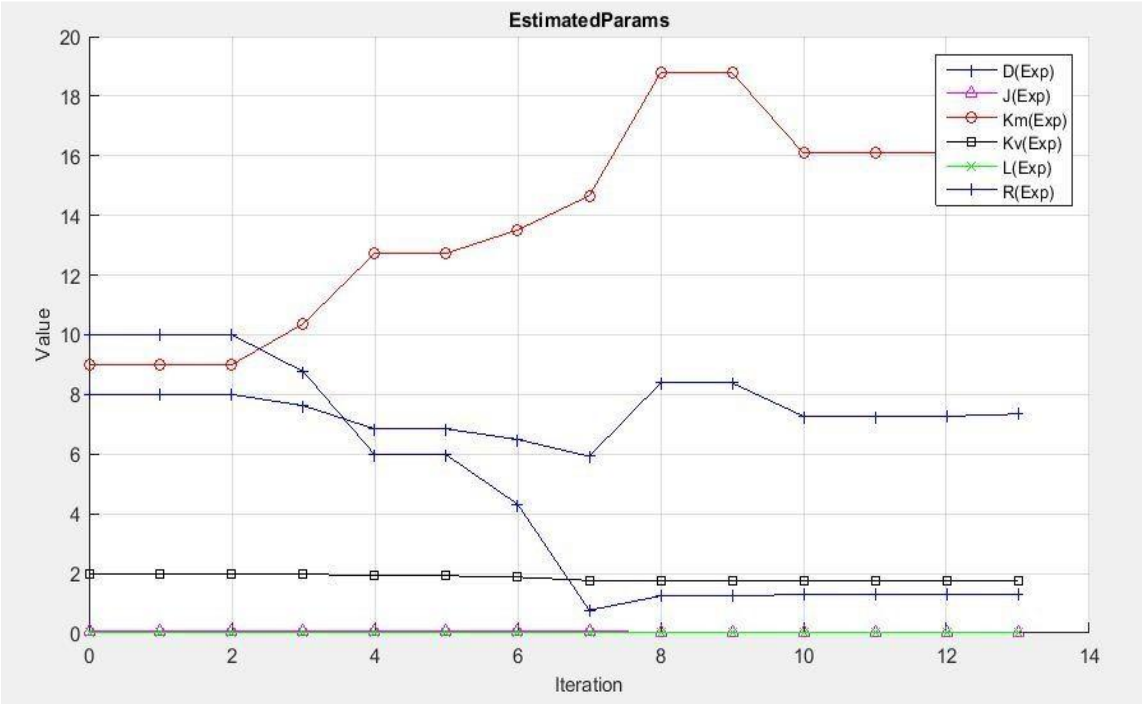

Figure 12. Convergence plot of the estimated parameters

By using the system identification tool in MATLAB, the unknown parameters of ETB mathematical model were obtained. Figure 12 shows the number of iterations required for convergence and the values of the unknown parameters as well.

4. Conclusions

The response of the throttle body was investigated successfully and the mathematical model was improved by introducing nonlinearities such as limp-home and dry friction. These results were found to be in concordance which previous studies. This mathematical model can be used to design an improved controller which can produce faster and precise throttle control. Further work can be achieved by considering the nonlinearity due to the break-away torque of the needle roller bearing present in the throttle body.

5. Acknowledgements

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