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Research paper

An optimized observer for estimating torque converter characteristics for vehicles with automatic transmission

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Abstract

The trending technology in the automobile power train system is the automatic transmission which allows the driver to drive the vehicle without pressing the clutch and can make gear shifting decisions themselves and thus frees the driver from shifting the gears manually. The system consists of torque convertor which replaces clutch and an alternate transmission system which consisting of planetary gears and actuators as drivetrain. In spite of the advantages of the automatic transmission system, there is a problem developing a controller for the system. That is because of the fact that the parameters characterizing the performance of the power train are not measurable because of sensor cost and reliability considerations. There is a need to provide real time information about the un-measurable parameters especially the internal state parameters of the torque converter. Thus, this paves the way for the development of model-based estimation for automatic transmission system to improve the fuel economy during the whole driving profile. The state space analysis can aid in the process. Several outputs from the system can be measured and can be used as a model for observing the internal states of the torque converter system. For this analysis MATLAB/Simulink can be used to model the plant and tools available in MATLAB can aid in developing a specific "state observer" which is the means in which the states can be studied.

Keywords: *Automatic Transmission; Gear Shift Schedule; State Space Observer; State Space Analysis; Torque Converter.*

1. Introduction

To provide the driver more comfort and ease of access, the automatic transmission system in a vehicle is developed which can make gear shifting decisions themselves and relieves driver from pressing the clutch during every gear shift. This system can change gear ratios automatically as the vehicle runs, and thus frees the driver from shifting the gears manually. The advantages of automatic transmission system are the simple mechanical design which will reduce the size and also the weight of the transmission system. This will be influential in the vehicle's fuel economy. This will also reduce the cost of production of the transmission system. To increase the vehicle's fuel economy, the number of speeds in the automatic transmission system can be increased. This can increase the fuel economy even while maintaining drivability and performance goals. The gear shift schedule of the automatic transmission can directly affect the fuel economy, riding comfort, emissions and safety during a gear shift of the vehicle. In spite of its advantages, the major problem in automatic transmission system is the design of controllers for this type of transmission system in vehicles. It is a problem because the parameters characterizing the performance of the power train are not measurable because of sensor cost and reliability considerations. Hence, there is a need to provide real time information about the un-measurable parameters. Thus, this paves the way for the development of model-based estimation for automatic transmission. In this paper, we have focused to develop the torque converter observer model to study the internal states of the torque converter. The maximum forces allowed, effects of different inputs on the internal systems of torque converter can be studied using the simulation model. The simulation examines the primary modifications to the system and provides suggestions for optimization. The model based real time estimation of output pressure and turbine speed for the torque converter during the driving conditions are developed and validated. To simulate the behavior of the transmission system, the detailed model of every concerned component of the powertrain is developed in MATLAB/SIMULINK. [2] A spark ignition engine is chosen for our study. The Engine produces power as per the driver demand. The power form the engine is fed to the automatic transmission system. The power output from the transmission system then propels the vehicle.

The modeling of the drive train enables us to develop a state space analysis of the system. In state space analysis, the entire system can be studied like a black box and all the outputs and inputs of the system are related with internal states of the system. Our objective here is to study the internal states of the system using available outputs from the system. [9] A state observer model is to be developed based on the state space analysis of the system.

2. Modeling of the vehicle drive train

The vehicle drive train is modeled in MATLAB/SIMULINK for high modularization of each subsystem. [1] Configuration of the vehicle drive train is given in Figure 1, which represents the mechanical connections between the components. The modeled vehicle drive train includes engine, automatic transmission system,

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planetary gearbox and gear shift controller. Apart from that, the drive shafts and the differential gearbox also constitute the drive train of the vehicle. [12] The modeling of vehicle drive train should also include the vehicle model to represent the vehicle velocity and tire slip during different driving conditions.

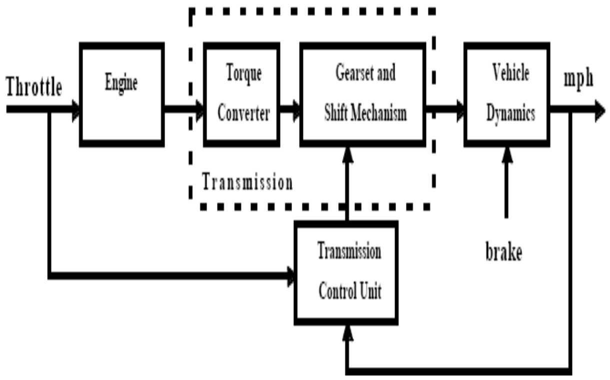

Fig. 1: Simulation of the Modeled Vehicle Drivetrain.

2.1. Engine

The engine is the power production plant which produces the necessary power to drive the vehicles and transmits it through the transmission system. Hence, the first and primary component in the drive train, the engine is modeled.
The engine chosen for our modeling is a petrol engine designed with the peak speed for 7000rpm. It produces the peak power of 1.5kW at about 4500rpm. The engine idles at 800rpm and stalls at 500rpm. The engine throttle is supplied with variable driver demand. The driver initially accelerates rapidly and then he slowly reduces the speed and maintains a steady speed in the end.

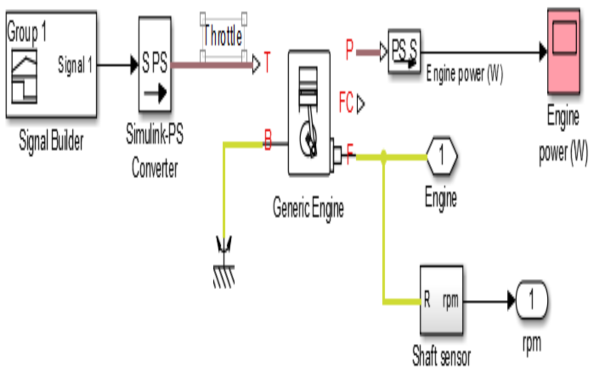

Fig. 2: Modeled Engine Block.

The demand profile is modeled using the signal builder block in Simulink. The engine is initialized with a speed higher than the stall speed for continuous operation.

2.2 Modeling of automatic transmission

The automatic transmission of the vehicle consists of many components namely torque converter, planetary gearbox and gear shifting controller. Each of the above components must be modeled individually.

2.3. Torque converter

The torque converter is a type of fluid coupling between the engine and the transmission system. The torque converter consists of an impeller and a turbine. [7] The impeller is driven by the engine and the turbine drives the transmission system. The two are enclosed in a sealed box which is filled with incompressible fluid. The key characteristic of the torque converter is the ability to multiply the torque when the output rotational speed is low. [6] A torque converter has three stages of operation. They are stall, acceleration and coupling. During the stall phase, the engine is applying power to the impeller but the turbine cannot rotate. During the acceleration phase, the load is accelerating but there is still a relatively large difference between impeller and turbine speed. During the coupling phase, the turbine has reached about 90% of the speed of the impeller.
The torque converter is modeled with the following parameters [10]:
Speed ratio R_ω:
The speed ratio is the ratio of the turbine angular speed to the impeller angular speed.

$$R_\omega = \omega_T/\omega_I \quad (1)$$

Where ω_T is the turbine angular speed and ω_I is the impeller angular speed.
Torque ratio R_τ:
The torque ratio is the ratio of the output (turbine) torque to the input (impeller) torque

$$R_\tau = \tau_T/\tau_I \quad (2)$$

The torque converter is modeled with the torque converter block available in Simulink library.

2.4. Planetary gearbox

The planetary gearbox system consists of a sun gear and set of small gears surrounding it. The gearbox consists of several clutches which can be actuated individually. [11] The actuation of the different clutches enables different gear ratios. The following table depicts the different combination of actuations for different gears.

Gear	A	B	C	D
1	X			X
2	X		X	
3	X	X		
4		X	X	

Fig. 3: Clutch Actuation Combination for Different Gears.

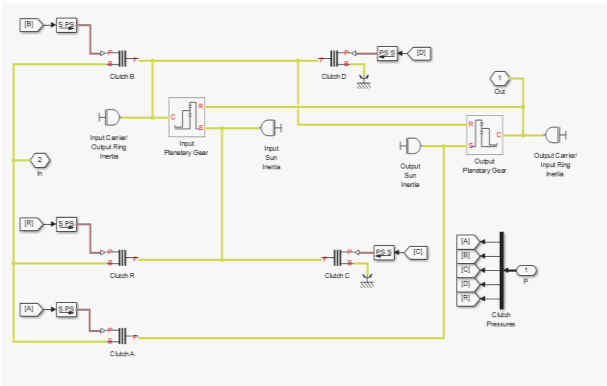

Fig. 4: Planetary Gear Box Modeled in Simulink.

The planetary gear system in the above model can provide both underdrive and overdrive with corresponding torque conversion. The clutches are activated by signals from the transmission control unit (TCU).

2.5. Gear shifting controller

The gear shift controller takes decision for shifting the gears forward and backward based on the velocity of the vehicle and the driver's input. The gear shift also takes into account the engine speed to prevent the engine stalling and over speeding. The gear shift logic is modeled as state machine with each gear being a state.

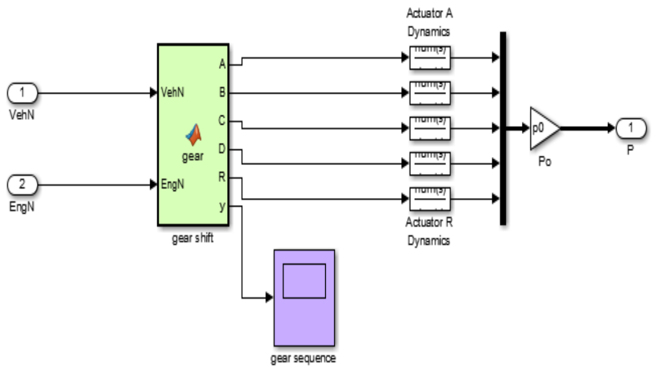

Fig. 5: Transmission Control Model.

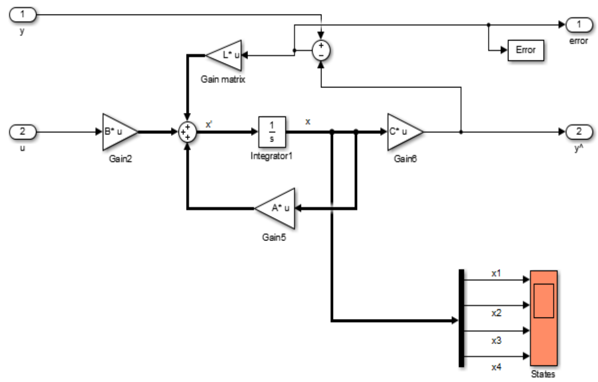

Fig. 7: State Observer Model.

2.6. Vehicle model

The vehicle model serves the following purposes:

- Load for the engine
- Variation of load due to aerodynamic drag
- Variation of load due to inclination
- Tire slip
- Braking

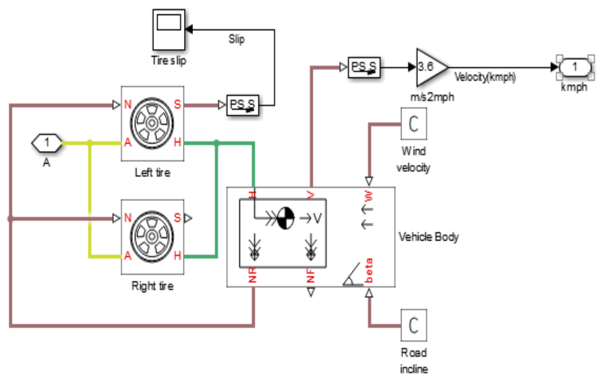

Fig. 6: Vehicle Model.

The vehicle is modeled with kerb weight of 1.2 tones using MATLAB blocks. The vehicle is modeled with two tires per axle. With this vehicle model, it is possible to obtain necessary information about the vehicle velocity and tire slip. The vehicle velocity is the feedback to the transmission controller to take decisions for gear shifts.

2.7. Modeling of state observer

For our modelled automatic transmission system of the vehicle, we follow the non linear approach.[9] The state observer is modelled with the above matrices and the observer type we have chosen is a simple Leuhenberg Observer.[12] An observer can be defined in the form:

$$\dot{\hat{x}}(t) = f(\hat{x}(t), u(t)) + L(y(t) - \hat{y}(t))$$
$$\hat{y}(t) = g(\hat{x}(t), u(t))$$

Where y is the actual measured output and y^ is its approximation by the observer and L is the observer gain matrix, n*1 dimension matrix.

3. Linearization

It takes a long time to solve this function by analysis or numerical method directly, because the powertrain is a continuous nonlinear system. The general approach to solve the optimization problem is to make the state space discrete of the respective non linear system. Based on the principle of Linearization, the problem is presented as follows: In our case, n=4,
X 1 is the output pressure in bars,
X 2 is the piston velocity in m/s,
X 3 is the piston displacement in m,
X 4 is the turbine rotational speed in rpm
E = Bulk Modulus (1.7335e^{8} kg/m^{2})
A = Piston Area (0.006542 m^{2})
V_o = Trapped Air (0.09 m^{3})
Q_{in} = Flow Rate into Clutch
C = Flow coefficient=0.7
ρ = Fluid Density (800 kg/m^3)
Psolenoid = Solenoid Pressure (next page)
Ao = Orifice Area = pi * (Orifice Diameter ^{2})/4
m = Piston Mass (1kg)
Fspring = Return Spring Force
Fax = Axial Force
T24=Torque N/M
K24 = 0.000490792567 cubic meters

$$Qin = C * Ao * \sqrt{\frac{2\,|Psolenoid - x1|}{\rho}} \tag{3}$$

$$Qin = 0.7 * Ao * \sqrt{\frac{2\,|Psolenoid - x1|}{800}}$$

$$Qin = 0.7 * Ao * \sqrt{\frac{|Psolenoid - x1|}{400}}$$

$$Qin = 0.035 * Ao * \sqrt{|Psolenoid - x1|}$$

$$Qin = 0.035 * Ao * (Psolenoid - x1)\wedge(\tfrac{1}{2}) \tag{4}$$

Using Binomial Theorem and neglecting higher powers,

$$Qin = 0.0175 * Ao * \left(\frac{Psolenoid\wedge 1/2}{x1^{1}/2} + \frac{x1^{1}/2}{Psolenoid\wedge 1/2}\right) \tag{5}$$

And

$$\dot{x1} = \frac{E}{V - Ax3}(Qin - Ax2) \tag{6}$$

substituting Qin

$$\dot{x1} = \frac{E}{V - Ax3}\left(0.0175 * Ao * \left(\frac{Psolenoid\wedge 1/2}{x1^{1}/2} + \frac{x1^{1}/2}{Psolenoid\wedge 1/2}\right) - Ax2\right)$$

$$\dot{x1} = \frac{1.7335*10^\wedge 8}{V-Ax3}\left(0.0175*Ao*\left(\frac{Psolenoid^{\wedge 1}/2}{x1^{1}/2}+\frac{x1^{1}/2}{Psolenoid^{\wedge 1}/2}\right)-0.006542x2\right)$$

$$\dot{x1} = \frac{1.7335*10^\wedge 8}{V-Ax3}\left(0.0175*Ao*\left(\frac{Psolenoid^{\wedge 1}/2}{x1^{1}/2}+\frac{x1^{1}/2}{Psolenoid^{\wedge 1}/2}\right)-0.006542x2\right)$$

$$\dot{x1} = \frac{1.7335*10^\wedge 8}{V-Ax3}\left(0.0175*Ao*\left(\frac{Psolenoid+x1}{x1^{\wedge 1}/2*Psolenoid^{\wedge 1}/2}\right)-0.006542x2\right) \quad (7)$$

$$\dot{x1} = \frac{1.7335*10^\wedge 3}{V-Ax3}(0.0175*Ao*(Psolenoid+x1)-0.006542x2)$$

Psolenoid is independent of states and 'u' of the plant

Assuming the value is greater than 1

$$\dot{x1} = \frac{1.7335*10^\wedge 3}{V-Ax3}(0.0175*Ao*x1-0.006542x2)\ +1$$

$$\dot{x1} = \frac{1.7335*10^3}{V-Ax3}(0.0175*Ao*x1-0.006542x2+\ V-Ax3)$$

And $V \gg A$

$$\dot{x1} = \frac{1.7335*10^\wedge 3}{V}(0.0175*Ao*x1-0.006542x2+\mathrm{V}-\mathrm{Ax3})$$

Ignoring the constant V as it is independent of u and x

$$\dot{x1} = \frac{1.7335*10^\wedge 3}{V}(0.0175*0.01*x1-0.006542x2-0.09x3)$$

$$\dot{x1} = 5.7783*10^\wedge 3(0.0175*0.01*x1-0.006542x2-0.009x3)$$

$$\dot{x1} = 1.01*x1-3.7x2-1.55x3 \quad (8)$$

$$\dot{x}_2 = \frac{1}{m}(A(x1)\text{-}F_{spring}\text{-}F_{ax}$$

$$\dot{x}_2 = \frac{1}{m}(A(x1) - F_{spring} - F_{ax}$$

$$\dot{x}_2 = \frac{1}{1}(0.006542(x1) - 100 - 1000$$

$$\dot{x}_2 = 0.006542x1 - 1100$$

$$\dot{x}_3 = x2$$

$\dot{x}_4$= Fn (Tt, T24, TLR, IT, Levers)

=y

y is the turbine speed

y=ωT = R_ωωI

Where ωT is the turbine speed and ωI is the impeller speed. $R_\omega$is the speed factor.
But ωI =u
Therefore, y= Rω u
Rω has value between 0 and 1 depending on engine speed
Substituting mean value for Rω i.e. 0.5

y=0.5u

$$\dot{x} = Ax + Bu \quad (9)$$

$y = Cx$

we get

A= [1.01 -3.7 -1.55 0

0.006542 0 0 0

0 1 0 0

1 0 0 1]

B= 0.5

C= [0 0 0 1]

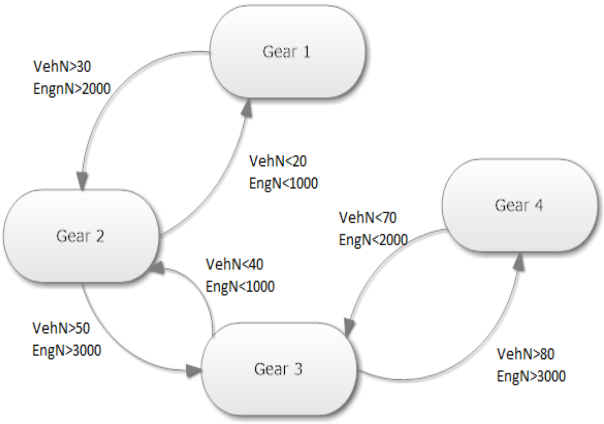

Fig. 8: State Machine Logic for Gear Shift.

4. Result

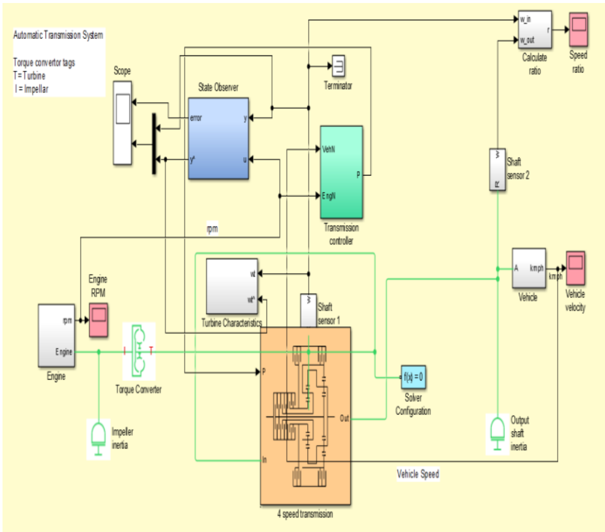

Fig. 9: Entire Model.

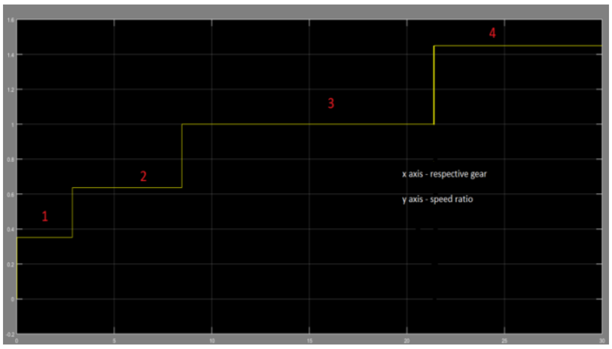

Fig. 10: Gear Ratios for Different Gears with Planetary Gear System.

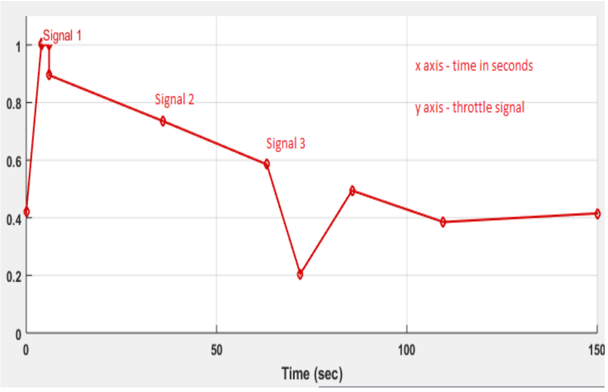

Fig. 11: Driver Demand (Throttle).

Thus, the automatic transmission system is modeled by modeling each of its components in Simulink and the state observer is developed and the real time model based estimation of internal states of the torque converter is done using the state space analysis. The error was calculated to check its accuracy with respect to the original measured values and it is found to be as small as it is enough to be used for practical laboratory and other applications.

5. Conclusions

In this paper, a vehicle's entire drivetrain model is developed in MATLAB/SIMULINK to study the internal states of the torque converter. Using the models developed and state space analysis, the real time model based estimation of the internal parameters of the torque converter is designed to provide suggestions for optimization of the system and to aid the proper and smooth gear shift process in the automatic transmission systems. The error obtained proves that the developed observer is appropriate and eligible for practical applications for the study in automatic transmission systems. This optimized observer for the torque converter characteristics in the automatic transmission system will help to improve the design to get better fuel economy and the gear shift quality during the entire driving profile of the vehicles.

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