Design of low jerk automatic transmission for vehicle using fuzzy control to improve gear shifting quality and low fuel consumption

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Abstract. Vehicle driveline is the system used transfer engine traction to the wheels. An automatics transmission is the essential and has high role of the driveline. This research was designing a automatic transmission plant and gear shifting logic base on jerk sensing. Which exploit fuzzy mamdani controller. Input variable were throttle - Up and Down position and rate, desired vehicle speed and speed error and even Jerk sensor, while the output of the control was a eight gear shifting actuator. Shifting algorithm was implemented by state machine, which controlled by fuzzy. Based on discussion of simulation result, the proposed automatic transmission control system produce lower vehicle jerk response, smoother drive comfort and fuel consumption.

1. Introduction
Replacing the friction synchronization shifting of automated manual transmission (AMT) in HEVs, Combining the characteristics of motor with fast response speed with an electric drive automated mechanical transmission (EMT) is proposed. Result of experiment was shown it can reduce gear shifting jerk and power interruption time of HEV [1]. To achieve a power full trip time and lower fuel consumption a dynamic programming was used to control gear shifting in vehicle operation under several road cases [2]. The shift jerk and sliding friction were better by using combined clutch and the motor [3]. A research about gear shifting improvement process without Disengaging Clutch to approach gear shifting quality for AMT bus was also proposed [4]. A predictive control was used to control split transmission of hybrid electric vehicle to get fuel economy. An dynamic programming is used to solve and obtain the optimal control sequence within optimal problem in the prediction horizon [5]. A generalized load investigated and study which can comprehensively reflect driving condition information was considered to develop an adaptive shifting control strategy of auto transmission [6]. A research about using three-parameter shift schedule namely the random load standard deviation, alteration rate of both steady state values of the load and of the throttle position. For shifting control it was utilized a adaptive fuzzy to get higher traction efficiency [7]. A two-speed Dual clutch transmissions electric drivetrain is constructed from two gear pairs and a final drive gear in the two-speed gearbox was proposed and produced both in transient shifting control process and high shift efficiency [8]. A modeling, simulation of Shift oil pressure of stationary Combination valve and proportional solenoid valve were analyzed by dynamic simulation software in order to study the shift quality of heavy-duty vehicle automatic transmission. The result can be used for comparing within...
quality of gear shifting [9]. A research by modeling of automatic transmission and its shifting control by using matlab was introduced to investigate the shifting quality, fuel economy and driving comfort [10]. A dynamic transmission model, which can be used to develop the adaptive gear shift control systems and calibrate the engine was presented [11]. An review about the time line development of auto transmission was studied. Starting by a structural of specific constructions and control systems of automatic transmissions, with mechatronics implementation and next review is based on perspectives of development, by integrating soft computing, such as artificial intelligent to obtain a fuel economy, exhaust emission, comfort and vehicle performance [12]. A research about driver characteristic (TODS) adaptive vehicle control including transmission control by using artificial intelligent was also developed [13].

2. Engine, transmission and load modeling
The main objective of this paper is to develop a procedure that can correlate the functional requirements random operation engine torque and speed conditions and other limitations accordingly to the vehicle load and speed. The following contributions have been

- Investigation to engine characteristics (engine torque under engine working speed) related to Vehicle load (driven wheel traction and speed range) by developing engine model.

- Investigation to Vehicle as rigid body characteristics, by mean total mass, its desired maximum speed and acceleration aspect by developing drive line model.

- As a case study, the automotive gearbox is developed in 5 shifting gear. Design requirement of 5 shifting gear and its torque converter, that can deliver the engine torque through viscous joint

- Random operation conditions of the gearbox are included by using load spectrums, which are designed incorporating the results of the torque measurement, the users’ interview method and the assessment. Load spectrums and gearbox speed participation in the course of service life provide robustness to the approach.

- The computer program (Simulink of MatLab 2017) for controlling and optimizing the shifting gear in the best time line.

The torque, speed and power flow in a typical automotive drivetrain. Nonlinear ordinary differential equations model the engine, four-speed automatic transmission, and Vehicle. The model discussed in this demo directly implements the blocks from Figure 2 as modular Simulink subsystems. On the other hand, the logic and decisions made in the Transmission Control Unit (TCU) do not lend themselves to well-formulated equations. TCU is better suited for a State flow representation. State flow monitors the events which correspond to important relationships within the system and takes the appropriate action as they occur.

2.1. The engine model
The throttle opening and engine speed are the inputs to approximation function of engine torque shown in figure 3. The engine shaft is connected to the impeller of the traction represented by figure 1.
Simulation model of engine torque transferred to impeller can be seen as figure 2.

Then engine-impeller dynamic can be formulated as equation 1 and 2.

\[ J_{ei} \cdot \frac{dN_e}{dt} = T_e - T_i \]  \hspace{1cm} (1)

\[ T_e = f(N_e, Throttle) \]  \hspace{1cm} (2)

Where:

- \( J_{ei} \) = inertia of engine fixed mass
- \( N_e \) = engine or impeller speed
- \( T_e \) = engine torque driven by combustion
\( T_i = \text{load torque acted in impeler} \)

2.2. Transmission Model

2.2.1. Torque converter model. The input-output characteristics of the traction converter can be expressed as functions of the engine speed or impeller speed and the turbine speed. In this example, the direction of power flow is always assumed to be from the impeller to the turbine. It is constructed as figure 4

![Figure 4. Torque Converter Plant](image)

Dynamic of torque converter is described and simulated as figure 5, which it is developed with two function definition namely \( \varepsilon_1 \) and \( \varepsilon_2 \) as the function of capacitance and resistance.

![Figure 5. Torque Converter Model](image)

Dynamic of torque converter is developed as equation 3,4,5,6 and 7.

\[
T_t = \frac{\omega_{ei}^2}{K_{tc}} \quad (3)
\]

\[
K_{tc} = \varepsilon_1 \left( \frac{\omega_t}{\omega_{ei}} \right) \quad (4)
\]

\[
T_t = \frac{\omega_{ei}^2}{\left( \varepsilon_1 \left( \frac{\omega_t}{\omega_{ei}} \right) \right)^2} \quad (5)
\]

\[
T_t = R_{tc} \cdot T_i = R_{tc} \cdot \left( T_e - J_e \cdot \frac{d\omega_{ei}}{dt} \right) \quad (6)
\]

\[
R_{tc} = \varepsilon_2 \left( \frac{\omega_{ei}}{\omega_t} \right) \quad (7)
\]
Where:

\[ K_{tc} = \text{torque converter capacitance} \]
\[ R_{tc} = \text{torque converter resistance} \]
\[ \omega_t = \text{turbine speed} \]
\[ \omega_{ei} = \text{engine/impeller speed} \]
\[ \varepsilon_1 = \text{function capacitance} \]
\[ \varepsilon_2 = \text{function resistance} \]

2.2.2. **Gear Ratio Dynamic Model.** A varied eight gear ratio control as \( G_R \) and a constant gear ratio as final drive \( G_g \) are defined. \( G_R \) is varied follow the operating procedure of auto-rotary gear shifting of the level speed of mostly auto-transmission. All torque flow can be seen as figure 6.

![Figure 6. Drive line Plant](Image)

Torque from the turbine shaft \( T_t \) to \( k \)-gear can be simulated as figure 7.

![Figure 7. Turbine Shaft Dynamics Model](Image)

And Turbine Shaft Dynamics Model formulated as equation 8 below

\[
T_k = T_t - J_k \cdot \frac{\partial \omega_t}{\partial t}
\]  

(8)

Torque from the intermediate shaft \( T_{out} \) to sun-gear can be simulated as figure 8.

![Figure 8.](Image)
And Intermediate Shaft Dynamics Model formulated as equation 9 below

\[ T_{\text{sun}} = T_L - J_L \cdot \frac{\partial \omega_{\text{out}}}{\partial t} \]  

(9)

Dynamics of torque and speed in the final gear can be simulated as figure 9.

![Figure 9. Final Gear Dynamics Model](image)

And Final Gear Dynamics Model formulated as equation 10 and 11 below

\[ \omega_{\text{out}} = G_g \cdot \omega_v \]  

(10)

\[ T_{\text{sat}} = G_g \cdot T_{\text{sun}} \]  

(11)

Dynamic torque and speed changing during gear shifting process was simulated as figure 10 below.

![Figure 10. Shifting Gear Dynamics Model](image)

By the changing of gear ratio 1\textsuperscript{st} upto 8\textsuperscript{th} speed, input and output speed even torque continuously calculated as equation 12 and 13

\[ \omega_L = G_R \cdot \omega_{\text{out}} \]  

(12)

\[ T_L = G_R \cdot T_k \]  

(13)

Speed of final shaft of the driven wheel are depend on torque load and final drive and can be simulated as figure 11.
The vehicle drive and brake loads can be simulated as figure 13 below

And Vehicle Drive Load Model formulated as equation 16 below
\[ T_{load} = T_d + T_f + T_b + T_g \] (16)

Where:
\[ T_d = \omega_v \frac{\xi \cdot A \cdot v^2 \cdot R_v^2}{2} \]
\[ T_f = \omega_v \cdot R_v (R_o + R_t v^2) \]
\[ T_g = m \cdot g \cdot \cos(90 - \theta) \]

3. Fuzzy control design

3.1. Fuzzy Variable and Membership Design
Control fuzzy model use mamdani type with 5 input namely Throttle position-up, Throttle position-down, desired vehicle speed and error vehicle speed and current gear position. The outputs single is gear shifting actuation.

| Input Fuzzy Variable | Throttle_Up | Throttle_Down | Vehicle Speed | Error Vehicle Speed | Current Gear Speed |
|----------------------|-------------|---------------|---------------|---------------------|--------------------|
| Low_Acc              | Low_Decc    | Low_Sp        | Low_Er        | 1                   |                    |
| Midd_Acc             | Midd_Decc   | Midd_sp       | Mid_Er        | 3                   |                    |
| High_Acc             | High_Decc   | High_Sp       | High_Er       | 5                   |                    |

| Output Fuzzy Variable | Gear Up_Shift | Gear Down_Shift |
|-----------------------|---------------|-----------------|

The input – output were developed to the Simulink MatLab. It can be shown as figure 14.

**Figure 14. Fuzzy Variable setup**
By developing membership function for all input and output variable, then based on expert an 34 rules were designed like figure 15, 16 and 17 for examples.

![Figure 15. Rule Speed-error speed vs Gear](image1.png)

![Figure 16. Rule Throttle Up-error speed vs Gear](image2.png)

![Figure 17. Rule Throttle down-error speed vs Gear](image3.png)

3.2. **Shifting Logic Design Based Jerk Sensing**

To achieve better shifting dynamic such as low Jerk response and lower fuel consumption, the proposed transmission control was design with 8 gear speed. The logic shifting allows the desired vehicle speed associate and considerate to real time throttle position level and current gear position even the essential novelty design Jerk sensing. For engagement, a three dimension look up table was development as figure and the control state machine can be shown in figure 18.
3.3. Plant and Control Design

Finally, a complete transmission and its fuzzy control was successfully tailored and simulated by using Simulink Matlab. The proposed fuzzy based transmission control is shown in Figure 19.

Figure 18. State machine of Shifting Logic

Figure 19. Complete Plant & Control Design
4. **Result and discussion**

Result of soft computing simulation according varied acceleration excitation shown as figure 20 were showing the shifting dynamics in the form of positive jerk response lower shown as figure 21.

![Figure 20. Acceleration Excitation Setup](image)

Result of soft computing simulation according varied deceleration excitation shown as figure 22 were showing the shifting dynamics in the form of negative jerk response lower shown as figure 23.

![Figure 22. Acceleration Excitation Setup](image)
Otherwise Result of soft computing simulation of combining both acceleration and deceleration excitation shown as figure 24 were showing the shifting dynamics in the form of positive and negative jerk response lower shown as figure 25.

5. Conclusion
Base on discussion of the result a conclusion can be defined as follow:

- Proposed fuzzy based control design perform limited jerk response during shifting process
- Driving comfort during Acceleration and deceleration smoother.
- It produce a lower fuel consumption consequently
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