Electronic Clutch Design for Torque Converter in Automotive Applications

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Abstract - This paper presents a novel model design of a torque converter clutch. Present market in automotive industry prefers automatic transmission which is not as efficient in terms of fuel as manual transmission. The loss in efficiency is due to the Impeller connected to the engine rotates with greater angular velocity than the Turbine, connected to the Transaxle at high vehicle speeds. To counter this problem a clutch mechanism has been designed to connect the engine to the automatic transaxle, which reduces engine speed for a cruising vehicle speeds and helps in improving fuel efficiency and reduce losses. We develop the clutch operation pattern to be fed into an ECU which will help control the mechanism.

Index terms - Torque converter, Simulink, clutch, Friction

I. INTRODUCTION

In automatic transmission, a torque converter is employed unlike manual transmission which uses a clutch [1]. Torque converters use the principle of fluid coupling to connect the engine and transmission. It has a disc connected to the engine called the Impeller and another disc connected to the transmission shaft input called the turbine. The vehicle moves because of the motion of the turbine unless it is in neutral gear or in parking mode. Torque converters use transmission fluid, the impeller while spinning pushes the fluid against the turbine making it spin [2]. When the driver presses the accelerator, the impeller spins faster thus pushing transmission fluid against the blades of the turbine and making it spin faster too, when the brakes are applied the turbine stops spinning. To get the transmission fluid back from the turbine to the impeller a small finned freewheel called a stator is used. The stator is kept still by a one-way clutch. In the torque converter, there is no direct connection, as a result the impeller spins a lot faster than the turbine, this is known as Slippage. The slippage needs to be controlled otherwise the vehicle will not move, and by then the vehicle will reach the stall speed and stop. The most important factor to control the torque converter is stall speed as it is used to determine the power delivered to the transmission. When the vehicle is accelerating the torque converter slippage is important but once the vehicle reaches a cruising speed, i.e high engine rpm (Revolutions per minute), it causes the turbine to rotate with more angular velocity than the impeller thus leading to reduced fuel efficiency and heat losses [3]. Thus, a torque converter clutch is necessary to avoid such losses. In this paper, we shall develop the mechanism of such a clutch and design it on Simulink.

II. MECHANISM AND DESIGN

The use of the lock up clutch in a torque converter is to directly connect the engine and transmission when the slippage condition is exceeded. When the lock up clutch is activated into operation it makes the turbine and impeller rotate together thus making the linkup complete between the engine and transmission. By the linkage of the engine and transmission the engine speed is reduced for a given vehicle speed thus making the vehicle for fuel efficient[4].

Figure 1: Schematic of the clutch system

Figure 1 shows the schematic of a clutch system, the white disc being the impeller connected to the engine and the black disc schematically depicts the turbine connected to the transmission. The variables used in the design are given in table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{IP}$</td>
<td>Input Torque by Engine</td>
</tr>
<tr>
<td>$T_c$</td>
<td>Torque due to clutch</td>
</tr>
<tr>
<td>$F$</td>
<td>Force between the friction discs</td>
</tr>
<tr>
<td>R</td>
<td>Equivalent net radius</td>
</tr>
<tr>
<td>$r_1, r_2$</td>
<td>inner and outer radii of discs</td>
</tr>
</tbody>
</table>

Table 1
Angular speed of engine $\omega_T$

Moment of inertia of engine $I_E$

Moment of inertia of transmission $I_T$

Damping rate at engine side $b_E$

Damping rate at transmission side $b_T$

Kinetic coefficient of friction $\mu_k$

Static coefficient of friction $\mu_s$

Friction torque needed for lockup $T_f$

The state equations for the system. Considering the engine and transmission parts of the mechanism

$$I_E \cdot \frac{d \omega_E}{dt} + T_f = I_T \cdot \omega_T - T_C \quad (1)$$

$$I_T \cdot \frac{d \omega_T}{dt} = T_C - b_T \cdot \omega_T \quad (2)$$

The general equation for maximum torque capacity for a clutch mechanism can be derived as follows

$$T_{F_{\text{max}}} = \int_{\omega = a}^{\omega = b} \left[ \frac{r \cdot F_r}{\mu} \right] / A$$

$$= \frac{F_r}{\pi r^2} \int_{0}^{2\pi} r^2 dr d\theta = \frac{2}{3} R F_r \mu$$

$$R = \frac{\frac{b}{2} - \frac{a}{2}}{\frac{b}{2} + \frac{a}{2}}$$

As mentioned in Eq(3) when the vehicle is at slow speeds, yet to approach cruising speeds the impeller is slipping, thus we will try to model the equations during the slipping condition as torque converter slippage is essential during vehicle acceleration. When the converter is in slipping condition, the clutch model shall use the kinetic coefficient of friction

$$T_{F_{\text{max}}}/K = \frac{2}{3} R F_r \mu K$$

$$T_C = \text{sgn} (\omega_E - \omega_T) \cdot T_{F_{\text{max}}}/K$$

Where sgn signifies the signum function only when $(\omega_E - \omega_T)$ is greater than zero will this equation be valid.

When the vehicle reaches high speeds or cruising speeds, the clutch locks thus the angular velocities of impeller and the turbine become the same and they rotate together, thus making the engine and transmission shaft rotate in unison.

$\omega_E = \omega_T = \omega_T'$

(6)

Combining this with the state space equation (1) we generate the torque equation for the locking mode as,

$$I_E \cdot \frac{d \omega_E}{dt} + T_f = I_T \cdot \omega_T - (b_E + b_T) \cdot \omega_T \quad (7)$$

The maximum torque equation will have the coefficient of static friction as,

$$T_{F_{\text{max}}}/S = \frac{2}{3} R F_r \mu S$$

The clutch stays in lock up mode until the magnitude of the coefficient of friction does not exceed the static friction capacity, thus using equations (1) and (6) we have derived the clutch torque

$$T_C = \frac{\pi T_f \cdot \left| \text{sgn} (\omega_E - \omega_T') \right|}{I_E + I_T}$$

$$I_T \cdot \omega_T$$

The models for slipping and lock up modes have been mathematically defined, the torque converter will remain in the slipping mode if it fulfills the following condition [5],

$$|T_f| > T_{F_{\text{max}}}/S \quad (9)$$

And the torque converter will shift to the lock up mode if

$$|T_f| < T_{F_{\text{max}}}/S \quad (10)$$

And $\omega_E = \omega_T'$

3. SIMULINK MODELING

In this section, we do the electronics realization of the mathematical model in Simulink [7], [8], from which we can generate the code and the code can be fed into a ECU which can further be used for industrial purposes. In this model we have done parallel operations to calculate the vales of torque and determine which subsystem should function by the use of enable block.

Initially we begin with the clutch pedal input and determine the values of $T_{F_{\text{max}}}/S$ and $T_{F_{\text{max}}}/K$.

![Friction calculation model](Figure 2)

![lock up mode](Figure 3)

![slipping mode](Figure 4)
Figure 5: Logic model to determine which mode to select

In Figure 3 we have modeled Eq(7) which is model representation of the lock up mode and in Figure 4 we have the model for the slipping condition.

In Figure 5 we first model Eq(7) and then check with the value of \( T_{F\text{max}} \) to determine which mode shall be enabled and depending on the output flag the torque converter functions in slipping or lockup mode.

IV. SIMULATION AND EXPERIMENTAL RESULTS

Figure 6: Comparison between vehicle inputs, engine speed, shaft speed, and lockup condition

In Figure 6 we can see the input from the clutch pedal and engine torque, subsequently they generate the engine rpm and the transmission in the shaft axle. As soon as the engine speed becomes comparable to the shaft speed, the torque converter changes to the lockup mode of operation. When the lockup flag is high we notice that the engine rpm and the shaft speed are same, which means that both of them are rotating together.

Figure 7: Slippage condition and lockup condition flags

From the above graph, we can observe the transition between slippage and lockup in the torque converter system. Once the flag changes from 0 to 1 or vice versa that enables the subsequent subsystem in the design to operate [9]. Thus, as per the desired design we have got the simulated values, as per the clutch friction calculation logic the mode, slippage or lockup, the subsystem is enabled and operated as a part of the torque converter for the automatic transmission system.

CONCLUSION

The torque converter clutch has been mathematically designed and successfully simulated on Simulink. As the torque converter, will function on two different modes as per the engine rpm and shaft speed. When the converter shifts from slippage mode to lockup mode we have successfully been able to demonstrate that the engine and shaft are connected together and rotate in unison. This lockup mode helps in improving the fuel efficiency and avoid heat losses [10]. The advantages of the proposed model design are parallel operations, as soon as the change in engine speed and torque is detected the lockup subsystem is enabled and vice versa for the slippage subsystem. There is continuous checking for the conditions specified in Eq (9), (10) and (11), thus a smooth transition from one mode to another is possible. In the future, the proposed design can be included in industrial process as a part of the model design for an ECU (Electronic controller unit) to operate the vehicle.

REFERENCES