Design of Estimators for the Output Shaft Torque of Automated Manual Transmission Systems

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***Abstract*— This study mainly focuses on the accurate estimation of the output shaft torque – and thus the clutch torque – of the automated manual transmissions as well as dual clutch transmissions, using the data available in the current production vehicles. The required information includes the nominal engine torque map and measurements of engine speed, clutch speed, and wheel speed. Utilizing the above-mentioned information, based on the design of four types of observers (unknown input observer, shaft compliance observer, synthesis of these two types of observers, and an adaptive observer), several methods to obtain the torque estimation without additional cost are developed to improve the feedback control performance of the clutch actuators and thus the vehicle launching and gear shift qualities. The stability of the proposed observers is investigated, and a set of assessments to confirm the performance of the observer system is arranged via simulation.**

Keywords*— automated manual transmission; clutch torque; output shaft torque; torque observer; estimation; adaptation

I. INTRODUCTION

The technological advancement of the automobile and its proliferation have brought convenience to modern society, but at the same time also have given rise to serious environmental and global energy issues. Researchers of various fields have attempted to alleviate the severity of such issues through numerous means including the development of more efficient engines, hybridization, weight reduction, etc. Among all of the topics related to energy efficiency, one of the most important relates to how effectively the generated power can be transmitted to the wheels of an automobile – the transmission technology.

Two of the most widely accepted transmission types are automatic transmission with a torque converter and traditional manual transmission. Both types involve distinct strengths and weaknesses. The advantage of manual transmission is that it is lightweight and transmits the energy produced from the engine effectively to the wheels by linking them mechanically through the clutch disks, although an evident weakness exists in that the driver must constantly manipulate the clutch pedal and gears. On the other hand, the automatic transmission is generally known for its smooth gear shifting and convenience since clutch pedal and gear shift inputs from the driver are not required. However, due to the use of a torque converter, energy loss is inevitable (despite the previous works to effectively control the lock-up clutch [1, 2]), and the unit cost is relatively higher than that of traditional manual transmission.

This complementary nature of the aforementioned transmissions inspired the researchers to develop a novel type of transmission called automated manual transmission (AMT) which can provide both energy efficiency and convenience [3, 4]. This type of transmission involves a clutch actuator and gear shifting mechanism so that such an automated system, instead of the driver, controls the clutch and shifts the gears. Using the actuators to control the transmission system implies that the vehicle launch and gear shift qualities vastly depend on the controller performance. Mere open-loop control of the actuators based on the experimentally-obtained actuation input to the clutch torque output relationship, which is stored as a map, is insufficient in eliminating the shift shock [5, 6], particularly in the case of launching the vehicle when the energy dissipated in the clutch is maximal. To properly manage the clutch actuation for launching and gear shifts, application of the feedback control tactics on top of the feed-forward control is crucial and can be realized with knowledge of clutch torque, or even the output shaft torque information [7–9]. Once an effective method to obtain this information is firmly established, it can also benefit the feedback control of dual clutch transmission (DCT) as well, for which a similar clutch actuation principle is applied when launching.

Unfortunately, however, simply using a torque measuring sensor does not provide a solution to obtain the torque information. This is firstly due to the spatial issue that there is no room to attach the sensor within the clutch. Although this issue can be resolved by indirectly estimating the clutch torque from the measured output torque information [7-9], the high cost of the torque sensors still hinders their application in the production cars.

Considering this background, the need for a clutch torque observer that estimates the torque information in real time with no additional sensor is indeed manifested. Previous works have designed Kalman filter-based observers [7–10], but the linearized models limit the estimation performances. Luenberger observer-based estimation schemes were also developed [11, 12], but the effects of the nominal engine torque error and varying vehicle inertia have been overlooked. Also, a sliding mode observer was designed to estimate the output shaft torque [13], but the chattering issue remains problematic. In addition, torque can be estimated in terms of an unknown input observer that was proposed in [14, 15]. Although it shows highly robust estimation performance, a phase lag issue exists in the estimated torque information.

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As an attempt to resolve the aforementioned shortcomings concerning the transmission torque estimation, two novel types of torque observers are proposed. The first is the combined unknown input observer (UIO) and the shaft compliance observer (SCO). This observer combines the strength of the UIO (robustness) and the strength of the SCO (transient state estimation accuracy) to obtain the output torque information. The second type of observer uses an adaptive scheme to take the nominal engine torque error into account, so that the output torque estimation can be robust against the effect of the engine torque uncertainty.

The organization of the paper is as follows. Section II A first describes the driveline model used throughout the paper. Section II B deals with the principle behind the conventional unknown input observer. Section II C briefly deals with the compliance model of the output shaft and the observer designed based on it. Section II D shows one of the major contributions of this study – the combined observer based on the unknown input observer and the shaft compliance observer. Section II E focuses on another core contribution of this study, which is the adaptive output torque observer. Section III displays the results of the simulation performed to validate the torque estimation performance.

II. OUTPUT SHAFT TORQUE OBSERVERS

A. Driveline Model

The driveline model used to describe the flow of the torque from the engine to the wheels can be basically shown as follows.

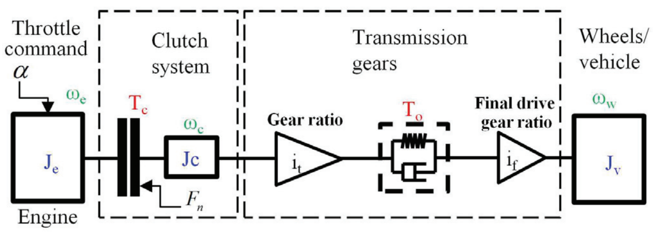

Fig. 1. Illustration of the driveline model of the automated manual transmission system (J: inertia, T: torque, ω : angular velocity)

Using the torque balance relationships, the above driveline model can be represented as shown next.

$$J_e\dot{\omega}_e = T_e - T_c \tag{1}$$

$$J_c\dot{\omega}_c = T_c - \frac{T_o}{i_t} \tag{2}$$

$$J_v\dot{\omega}_w = T_o i_f - T_v \tag{3}$$

where the torques are represented as follows.

$$T_e = f\left(\alpha_{th}, \omega_e\right) \tag{4}$$

$$T_c = F_n f_L\left(\omega_e, \omega_c\right) \tag{5}$$

$$T_o = k_o\left(\frac{\theta_c}{i_t} - i_f\theta_w\right) + b_o\left(\frac{\omega_c}{i_t} - i_f\omega_w\right) \tag{6}$$

$$T_v = r_w\left(\underbrace{m_v g\sin\left(\theta_{road}\right)}_{\text{road gradient}} + \underbrace{K_{rr} m_v g\cos\left(\theta_{road}\right)}_{\text{rolling resistance}} + \underbrace{\frac{1}{2}\rho v_x{}^2 C_d A}_{\text{aerodynamic drag}}\right) \tag{7}$$

Here, the engine torque is determined based on the empirically obtained relationship between the engine load conditions and produced net torque. However, as done in the actual production vehicles for the sake of shift quality improvement, the throttle input is reduced independently from the driver's intention in the cases of clutch engagement control. Also, the clutch torque is calculated based on the Lugre friction model [16] as a function of the engine and clutch speed. Here, the engine speed is assumed to be identical to the flywheel speed.

B. Torque Estimation by Unknown Input Observer

The unknown input observer (UIO) treats the estimation target as an unknown input, so that it can be estimated by making use of the difference between the measurable state and the observed state. Because this method of estimation does not require any model parameter but rather only depends on the feedback information, UIO tends to give robust estimation results under all conditions.

Recall equation (1). Solving for the engine angular acceleration gives the following result.

$$\dot{\omega}_e = \frac{T_e}{J_e} - \frac{T_c}{J_e} \tag{8}$$

Based on the above equation, formation of a PI-type unknown input observer leads to the following.

$$\dot{\hat{\omega}}_e = \frac{1}{J_e}T_e - \frac{1}{J_e}\hat{T}_c + l_1\left(\omega_e - \hat{\omega}_e\right) \tag{9}$$

$$\text{where } \dot{\hat{T}}_c = -l_2\left(\omega_e - \hat{\omega}_e\right) \tag{10}$$

Here, l_1 works as the gain for proportional error term, and l_2 works as the gain for integral error term.

As it can be seen, since this clutch torque observer solely depends on the feedback error between the measured and estimated engine speed, highly robust torque estimation performance can be anticipated. As long as the model described in (8) is considered accurate, the estimated clutch torque converges to the actual value.

However, the nominal engine torque information that is required in (8) may not always be equal to the actual engine torque, which implies that the model on which the UIO is based may be disturbed. Also, the observer structure that the estimated clutch torque is only the function of feedback state error inevitably induces phase lag problem.

C. Torque Estimation by Output Shaft Compliance Observer

The output torque can be also estimated based on the output shaft compliance model. This shaft compliance observer (SCO) bases on the principle that, whenever torque is applied to the shaft, the angles at the beginning and the end of the shaft differ by the amount of shaft compliance.

Recall equation (6). This expresses the output shaft torque in terms of the clutch and wheel angles and angular velocities, based on the fact that the torsional compliance exists with the equivalent torsional stiffness and damping constants of k_o and b_o. Based on this, (6) is differentiated with respect to time, and the damping term is neglected assuming that it is too small to be significant.

$$\dot{T}_o \approx k_o \left(\frac{\omega_c}{i_t} - i_f \omega_w \right) \tag{11}$$

Here, the wheel velocity is obtained as a function of the angular velocities of each individual wheel, so that it represents the vehicle speed as accurately as possible.

A Luenberger observer can be formed based on (11), by adding a reference feedback term as the following.

$$\dot{\hat{T}}_o = k_o \left(\frac{\omega_c}{i_t} - i_f \omega_w \right) + l_3 \left(T_{o,ref} - \hat{T}_o \right) \tag{12}$$

$$\text{where } T_{o,ref} = T_e i_t - J_e \dot{\omega}_e i_t - J_c \dot{\omega}_c i_t \tag{13}$$

Here, $T_{o,ref}$ is obtained by solving for the clutch torque in equation (1) and (2), and equating them.

Although SCO designed this way can give relatively accurate transient state estimation performance due to using the direct integration of the difference between the clutch and wheel angular velocities, it involves the drift issue without an accurate reference source. Additionally, noise in the sensor measurements and the compliance model parameter uncertainties can directly influence the integration, and thus the tactic to distinguish and eliminate such effect from the estimation result is essential.

D. Combined Unknown Input and Shaft Compliance Observer

As previously mentioned, the unknown input observer has the strength of robust estimation performance and simple structure with the weakness of estimation phase lag, whereas the shaft compliance observer has the strength of accurate transient state torque estimation with the weakness of sensitiveness to sensor noise and model parameter uncertainties. Thus we arrive at an idea of combining the UIO and SCO so that the advantages of each observer can be maximized.

Combining the two previously mentioned observers gives the following:

$$\begin{cases} \dot{\hat{\omega}}_e = \dfrac{1}{J_e} T_e - \dfrac{1}{J_e} \hat{T}_c + l_1 \left(\omega_e - \hat{\omega}_e \right) \\ \dot{\hat{T}}_c = -l_2 \left(\omega_e - \hat{\omega}_e \right) \\ \dot{\hat{T}}_o = k_o \left(\dfrac{\omega_c}{i_t} - i_f \omega_w \right) + l_3 \left(T_{o,ref} - \hat{T}_o \right) \end{cases} \tag{14}$$

where $T_{o,ref}$ can be expressed in terms of the UIO:

$$T_{o,ref} = \hat{T}_c i_t - J_c \dot{\omega}_c i_t \tag{15}$$

Now, knowing that the interim result obtained by UIO involves phase lag, it is possible to add a compensation term which is a function of engine torque, instead of the clutch torque obtained by the UIO. To do this, equation (1) and (2) are equated by solving for the clutch torque, which gives the following:

$$T_e - J_e \dot{\omega}_e = J_c \dot{\omega}_c + \frac{T_o}{i_t} \tag{16}$$

Rearranging the above gives

$$J_c \dot{\omega}_c i_t = T_e i_t - J_e \dot{\omega}_e i_t - T_o \tag{17}$$

that leads to the Luenberger-like observer shown next.

$$\begin{cases} \dot{\hat{\omega}}_e = \dfrac{1}{J_e} T_e - \dfrac{1}{J_e} \hat{T}_c + l_1 \left(\omega_e - \hat{\omega}_e \right) \\ \dot{\hat{T}}_c = -l_2 \left(\omega_e - \hat{\omega}_e \right) \\ \dot{\hat{T}}_o = k_o \left(\dfrac{\omega_c}{i_t} - i_f \omega_w \right) + l_3 \left(\hat{T}_c i_t - J_c \dot{\omega}_c i_t - \hat{T}_o \right) \\ \qquad + l_4 \left(J_c \dot{\omega}_c i_t - \left(T_e i_t - J_e \dot{\omega}_e i_t - \hat{T}_o \right) \right) \end{cases} \tag{18}$$

To check the stability of the above system described in (18), it is rearranged into the state-space form.

$$\dot{\hat{x}} = A\hat{x} + B \tag{19}$$

where $\hat{x} = \begin{bmatrix} \hat{\omega}_e \\ \hat{T}_c \\ \hat{T}_o \end{bmatrix}$, $A = \begin{bmatrix} -l_1 & -\dfrac{1}{J_e} & 0 \\ l_2 & 0 & 0 \\ 0 & l_3 i_t & -l_3 + l_4 \end{bmatrix}$, and

$$B = \begin{bmatrix} \dfrac{1}{J_e} T_e + l_1 \omega_e \\ -l_2 \omega_e \\ k_o \left(\dfrac{\omega_c}{i_t} - i_f \omega_w \right) - \left(l_3 - l_4 \right) J_c \dot{\omega}_c i_t + l_4 i_t \left(J_e \dot{\omega}_e - T_e \right) \end{bmatrix}.$$

The actual dynamics is expressed in terms of the state-space form as well.

$$\dot{x} = A^* x + B^* \tag{20}$$

where $x = \begin{bmatrix} \omega_e \\ T_c \\ T_o \end{bmatrix}$, $A = \begin{bmatrix} 0 & -\frac{1}{J_e} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$, and $B = \begin{bmatrix} \frac{1}{J_e} T_e \\ 0 \\ k_o \left(\frac{\omega_c}{i_t} - i_f \omega_w \right) \end{bmatrix}$.

Here, the clutch torque is assumed to be slowly varying.

Now calculating the error dynamics, $\dot{\tilde{x}} \equiv \dot{x} - \dot{\hat{x}}$, the following is obtained.

$$\dot{\tilde{x}} = A\tilde{x} \tag{21}$$

By investigating the state matrix A, it can be concluded that it is strictly Hurwitz, as long as $l_3 > l_4$, and $l_1, l_2, l_3, l_4 > 0$. Although the system is linear time-varying, asymptotic stability is shown using the above analysis with the frozen-time assumption that the parameters are sufficiently slowly-varying [17, 18].

Here, it must be noted that the combined observer designed in this section requires the angular acceleration information including $\dot{\omega}_e$ and $\dot{\omega}_c$. An issue concerning such requirement is that using these values as parameter may noticeably increase the level of noise in the estimation results, since differentiating the already-noisy sensor measurements of angular velocities cause increased level of noise. However, such issue can be majorly resolved by exploiting the unknown input observers to estimate the acceleration information itself.

E. Adaptive Output Torque Observer

As seen in the former sections, the observer structures are formed as a function of the nominal engine torque information, which inevitably causes the observer to be influenced by the engine torque uncertainty. In an attempt to resolve this issue, the adaptive output torque observer models the engine torque uncertainty as one of the states to be identified, so that the actual output shaft torque information can be less affected by the engine torque uncertainty.

First recall equation (17). It is rearranged so that the known terms are on the left and the unknown terms are on the right-hand side of the equation.

$$J_c \dot{\omega}_c i_t + J_e \dot{\omega}_e i_t = T_e i_t - T_o \tag{22}$$

Now the engine torque is separated into the nominal and the unknown part, and they are defined as $T_{e,n}$ and δ, respectively.

$$T_e = T_{e,n} + \delta \tag{23}$$

Substitution of (23) leads to the following relationship.

$$J_c \dot{\omega}_c i_t + J_e \dot{\omega}_e i_t = \left(T_{e,n} + \delta \right) i_t - T_o \tag{24}$$

Since, by now, $T_{e,n}$ is a known value, it is kept on the left-hand side of the equation, and the resulting equation is defined to be z.

$$z \equiv J_c \dot{\omega}_c i_t + J_e \dot{\omega}_e i_t - T_{e,n} i_t = \delta i_t - T_o \tag{25}$$

Then to ensure that the system is causal, a low pass filter is applied onto the actual and estimated systems as shown in the following.

$$\dot{z} = -\gamma \left(z - \delta i_t + T_o \right) \tag{26}$$

$$\dot{\hat{z}} = -\gamma \left(\hat{z} - \hat{\delta} i_t + \hat{T}_o \right) \tag{27}$$

where γ is the low pass filter gain.

Now, the adaptive variables $\hat{T}_o$ and $\hat{\delta}$ are redesigned so that they are functions of the engine speed and wheel angular acceleration.

$$\delta = \omega_e z_1,\ T_o = \dot{\omega}_w z_2 \tag{28}$$

$$\hat{\delta} = \omega_e \hat{z}_1,\ \hat{T}_o = \dot{\omega}_w \hat{z}_2 \tag{29}$$

The reason behind such maneuver is to satisfy the convergence criterion for the update laws to be designed. For a plant with parameter θ which as to be estimated by the update law $\dot{\hat{\theta}} = \Gamma \phi \varepsilon$ with order n, where $\Gamma = \Gamma^T > 0$, $\varepsilon = z - \hat{z}$, and $\phi = H(s) u$ with $H(j\omega_1), ..., H(j\omega_n)$ linearly independent on $\mathbb{C}^n$ for all $\omega_1,\ \omega_2,\ ...,\ \omega_n \in \Re$, the convergence criterion is met with PE (persistence of excitation) condition [19], if and only if u is sufficiently rich of order n. Here, a stationary signal u is sufficiently rich of order n, if the support of the spectral measures of u contains at least n points. More specifically, a signal u is sufficiently rich of order n, if it consists of at least n/2 distinct frequencies.

Thus, PE condition can be satisfied by including the engine speed and wheel acceleration variables in the adaptation targets as designed in (28) and (29), and by setting the update laws as shown next.

$$\dot{\hat{z}}_1 = \gamma_e i_t \omega_e \varepsilon \tag{30}$$

$$\dot{\hat{z}}_2 = \gamma_t \dot{\omega}_w \varepsilon \tag{31}$$

where γ_e and γ_t are the adaptation gains and $\varepsilon \equiv z - \hat{z}$.

For the stability analysis, simply choose a positive definite, decrescent, and radially unbounded Lyapunov candidate function as the following.

$$V = \frac{1}{2} \left(\varepsilon^2 + \frac{\gamma}{\gamma_e} \tilde{z}_1^{\,2} + \frac{\gamma}{\gamma_t} \tilde{z}_2^{\,2} \right) \tag{32}$$

This way, differentiation of the Lyapunov function with respect to time gives the following result.

$$\begin{aligned}\dot{V} &= \varepsilon\dot{\varepsilon} + \frac{\gamma}{\gamma_e}\tilde{z}_1\dot{\hat{z}}_1 + \frac{\gamma}{\gamma_t}\tilde{z}_2\dot{\hat{z}}_2 \\ &= \varepsilon\left\{-\gamma\left(z - \omega_e i_t z_1 + \dot{\omega}_w z_2\right) + \gamma\left(\hat{z} - \omega_e i_t \hat{z}_1 + \dot{\omega}_w \hat{z}_2\right)\right\} \\ &\quad - \frac{\gamma}{\gamma_e}\tilde{z}_1\dot{\hat{z}}_1 - \frac{\gamma}{\gamma_t}\tilde{z}_2\dot{\hat{z}}_2 \\ &= \varepsilon\left(-\gamma\varepsilon + \gamma\omega_e i_t \tilde{z}_1 - \gamma\dot{\omega}_w \tilde{z}_2\right) - \frac{\gamma}{\gamma_e}\tilde{z}_1\dot{\hat{z}}_1 - \frac{\gamma}{\gamma_t}\tilde{z}_2\dot{\hat{z}}_2 \\ &= -\gamma\varepsilon^2 + \gamma\omega_e i_t \tilde{z}_1\varepsilon - \gamma\dot{\omega}_w\tilde{z}_2\varepsilon - \frac{\gamma}{\gamma_e}\tilde{z}_1\dot{\hat{z}}_1 - \frac{\gamma}{\gamma_t}\tilde{z}_2\dot{\hat{z}}_2 \\ &= -\gamma\varepsilon^2 + \gamma\tilde{z}_1\left(i_t\omega_e\varepsilon - \frac{1}{\gamma_e}\dot{\hat{z}}_1\right) - \gamma\tilde{z}_2\left(\dot{\omega}_w\varepsilon + \frac{1}{\gamma_t}\dot{\hat{z}}_2\right) \\ &= -\gamma\varepsilon^2 \le 0 \end{aligned} \tag{33}$$

by substituting the adaptive laws obtained in (30) and (31).

Because the update law contains wheel acceleration information, it must be noted that the adaptive observer can be sensitive to the road gradient or uncertain vehicle inertia. To eliminate such limitation, road gradient estimator can be used to compensate the difference, or the idea of combining observers can be extended to merging the unknown input observer, which is robust against the road disturbance or model uncertainty, with the adaptive observer designed in this section. Also, concerning the noise issue, use of UIO to estimate the angular acceleration that is similar to what is done for the case of combined UIO and SCO can majorly reduce the noise level in the estimation result.

III. Simulation and Analysis

To show the estimation performances of the designed observers, launching simulations are done for the cases with no nominal engine torque error and with 50% increased engine torque information compared to the actual value. To simulate the real vehicle, noise is intentionally included in all sensor measurements. Simulation scenario is shown in fig. 2.

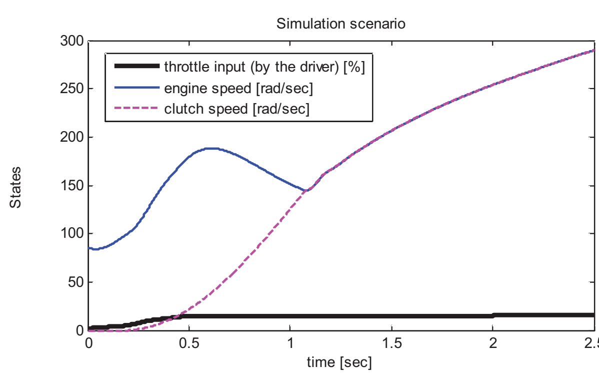

Fig. 2. Plot of the driver input, actual engine speed, and clutch speed

A. Estimation with no nominal engine torque error

In general, each aforementioned torque observers eventually converge to the actual output shaft torque. As expected, the estimation result obtained by UIO converges to the actual value with phase lag, and it is shown in fig. 3. Increasing the observer gain is not a desirable option, since doing so certainly reduces the amount of phase lag, but at the same time increases the amount of oscillation. The combined UIO and SCO, and the adaptive observer shows fast convergence to the actual value even during the transient states around 1.1 second, and the results can be seen in fig. 4.

B. Estimation with 50% increased nominal engine torque

While the estimation results obtained by all observers had shown decently accurate performances in the previous case, intentional 50% increase of the engine torque information that is available for the observers substantially decreases the estimation performance for the UIO, SCO, and the combined type. As it can be seen in fig. 5, the estimation results obtained by these three types of observers fail to converge to the actual torque. On the other hand, the estimation obtained by the adaptive observer shows robust performance.

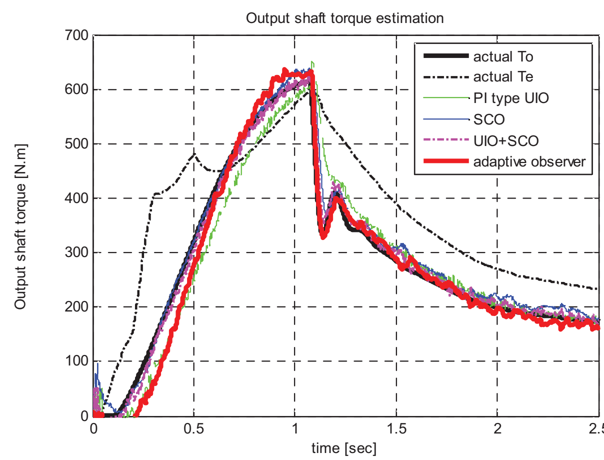

Fig. 3. Torque estimation results with no nominal engine torque error

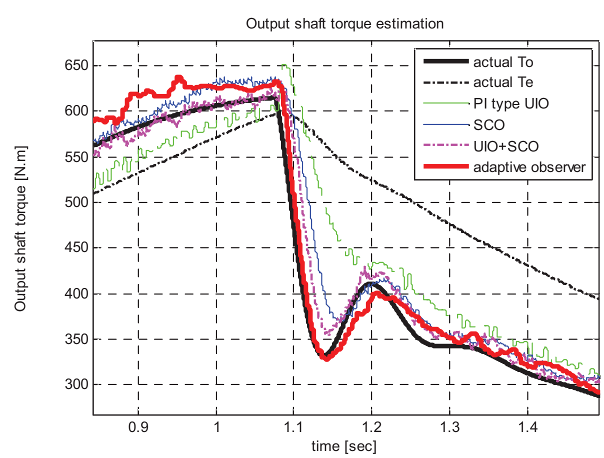

Fig. 4. Magnified torque estimation results with no nominal engine torque error

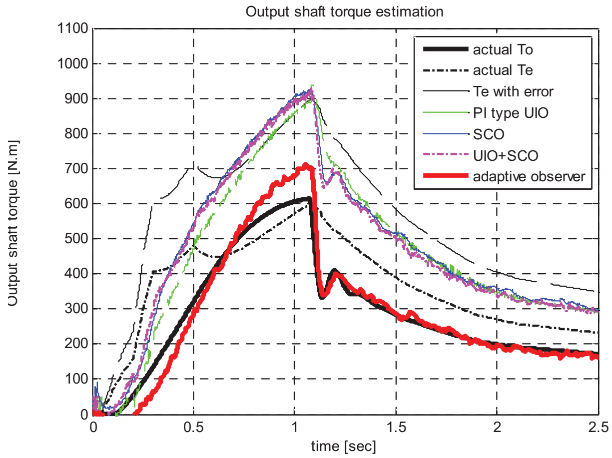

Fig. 5. Torque estimation results with 50% increased nominal engine torque

To compare the observer performances quantitatively, table 2 shows the RMS errors of the estimation results relative to the actual torque value.

TABLE I. QUANTITATIVE COMPARISON OF THE OBSERVER PERFORMANCES

Estimation Performance	**RMS error**		
	Without engine torque error	***With 50% engine torque error addition***	***Unit***
UIO	46.23	195.95	N·m
SCO	23.14	205.37	N·m
UIO+SCO	20.27	195.03	N·m
Adaptive Observer	28.35	38.44	N·m

IV. CONCLUSION

This study has proposed novel methods to effectively identify the output shaft torque of the automated manual transmissions and dual clutch transmissions during the launching phase. Making use of only the given set of data in the conventional production vehicles, the proposed observers with the structures of UIO, SCO, synthesis of UIO and SCO, and adaptive observer have presented accurate torque estimation performances that are shown via simulation. Summarizing the paper, two noteworthy contributions of the work are the following: improvement of the torque estimation accuracy without increasing the chattering or noise issue, and development of a method to estimate the output shaft torque that can be achieved even when the nominal engine torque information is inaccurate. The work shall be further extended to develop an observer which merges the last two types of observers so that estimation robustness can be even more increased.

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