Optimal Speed Tracking Control for Torque-Based Engine Management Systems

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Abstract—In this paper, speed tracking problem is investigated for spark ignition engines. A cost function which provides a trade-off between speed tracking performance and fuel consumption is introduced to evaluate engine control strategies. Based on this function, an optimal controller for torque-based engine management systems is proposed. For a given speed trajectory, the optimal engine torque is determined by dynamic programming. In succession, control algorithm based on torque observer is designed to track this torque demand. Torque observer applies mean value engine model to give a prior estimation and engine speed feedback to obtain better accuracy. Experimental results of the proposed optimal controller and a conventional controller are shown and compared finally.

Key Words: Speed tracking, Dynamic programming, Torque observer

1 Introduction

In engine speed control field, a great deal of literatures focused on idle operation and targeted the system nonlinearities and external torque disturbances [1, 2]. Also, various attempts have been made to tackle time-varying speed tracking problem [3, 4]. Generally, the objective of engine speed control is to find a control, which is often throttle angle, such that the engine speed can follow a given trajectory. Since the engine system from throttle input to speed response can be split into two subsystems, one is from throttle input to torque generation, the other is from torque input to speed response, the speed control approach can be solved in two stages: First, for a given speed trajectory, the torque demand is decided according to the crankshaft model. Then, engine torque is controlled to track this demand. The crankshaft can be simply treated as a rigid one for speed control problem. Thus the difficulty to reach the goal is the torque control.

Indeed, torque control is not a novel topic but has attracted a great deal of attentions in view of the increasing demand for improved driving ability and comfort. T. Nagata et al. employed a disturbance observer to control engine torque under the assumption that rotary torque sensor is available [5]. Y. Chamaillard et al. established a linear nominal model with uncertainty description and implemented the model on engine torque control [6]. In this literature, the IMEP (Indicative Mean Effective Pressure) is used as feedback data instead of effective torque. Unfortunately, both torque sensor and in-cylinder pressure sensor are too expensive and not technically available for mass production. Earlier publications developed various indirect methods to estimate engine torque and they can be sorted to several groups. The most common torque estimation method involves look-up tables where the signals used to generate the tables include mean engine speed, intake and exhaust pressures, spark advance and mass of fuel injected [7]. The second group pays attentions to modeling the dynamics from throttle input to torque generation. Y. Danno et al. proposed a linear model by introducing a new index, which is defined as the ratio of air mass flow into the cylinder and the engine speed [8]. As a progress of this model, T. Yi employed an intake pressure observer to estimate air mass flow into the cylinder [9]. The third group explores the relationship between engine torque and speed response. S.J. Citron et al.
used measured engine speed fluctuations to determine engine torque based upon an elastic model of the crankshaft \[^{[10]}\]. G. Rizzoni presented an electrical circuit model representing engine dynamics and estimated engine torque by measurement of crankshaft acceleration \[^{[11]}\]. Frequency analysis is also investigated in \[^{[9]}\] and \[^{[12]}\]. M. Kao et al. designed a PI input observer accounting for the differences between estimated and measured engine speed \[^{[13]}\]. The last group considers the whole system from throttle input to speed response. E. Hendricks employed an engine model to give a prior estimated torque and then used the difference between estimated and measured engine speed as the feedback to improve the accuracy by Kalman gains \[^{[14]}\].

In this paper, motivated by the torque demand-based control, we propose an optimal speed tracking approach via the torque control. For decision of the torque demand, a cost function is introduced which provides a trade-off between speed tracking performance and the fuel consumption, and an optimal torque demand for a given speed trajectory is provided by applying dynamic programming with the cost function. Then, a torque observer is present by employing a mean value engine model which gives a prior estimated torque and a crankshaft model which supplies the estimated speed. With the torque estimation provided by the observer, a feedback torque control is implemented utilizing PI gains. To obtain fast response, a look-up table where indicative torque is input while throttle angle is output is adopted. Finally, the proposed approach is validated by experiments.

The organization of this paper is as follows. In section 2, we define a cost function and calculate the torque demand for a given speed trajectory based on optimal control theory. In section 3, we present the torque control algorithm. Experimental results are shown in section 4. We draw some conclusions and suggest the future research direction in section 5.

2 Torque Demand Decision

In torque-based engine management system, the structure of torque demand-based speed control approach is shown in Fig.1.

For a given speed trajectory \(\omega_r(t)\), we consider the following cost function

\[
J = \int_{t_0}^{t_f} [(\omega(t) - \omega_r(t))^2 + \alpha_v T_e^2(t)]dt
\]  

(1)

where \(\omega\) denotes measured angular velocity, \(T_e\) denotes the actual effective engine torque output, \(\alpha_v\) denotes weight factor, \(t_0\) and \(t_f\) denote the starting and ending time, respectively.

Usually, the time constant of speed dynamics is several seconds, thus the crankshaft can be treated as a rigid one. The dynamic equation of the rotational movement of the crankshaft is represented as following

\[
\dot{\omega}(t) = \frac{1}{J_e}(T_e(t) - T_l(t))
\]  

(2)

where \(J_e\) denotes the equivalent inertial of the crankshaft including pistons and flywheel of the engine, \(T_l\) denotes the engine load. Exactly, the equivalent inertial varies as the crankshaft angular periodically. But this minor difference can be ignored especially the system time constant is much larger than an engine cycle. Therefore, the equivalent inertial is assumed constant and can be identified by engine tests. The discrete forms of cost function and equation (2) are as following

\[
J = \sum_{k=0}^{N} (\omega_k - \omega_{rk})^2 + \alpha_v T_{ek}^2 \cdot t_s
\]  

(3)

\[
\omega_{k+1} = \omega_k + \frac{t_s}{J_e} (T_{ek} - T_{lk})
\]  

(4)

where the subscript \(k\) is the index of discrete time, \(t_s\) signifies the sampling period.

The torque demand is decided by solving the optimization problem for \(T_e\) with the cost function (3) subject to (4), and the solution can be obtained by utilizing the dynamic programming \[^{[15]}\]. Since the torque demand is decided, the next step of the speed controller is to develop a torque control scheme.

3 Torque Control

For closed-loop torque control, the rotary torque sensor or in-cylinder pressure sensor is required to measure the torque output. Unfortunately, both of these sensors are too expensive and not technically available for mass production, as mentioned before. Thus, an observer is needed to estimate the torque.
3.1 Torque Observer

The architecture of torque observer is shown as Fig. 2, where ω represents intake pressure, ̂Te0 denotes pre-estimated effective mean torque, ΔTe denotes compensated torque by feedback of the difference between estimated and measured angular velocity, ̂Te denotes the estimated torque, Tl denotes the load torque and ̂ω denotes the estimated angular velocity.

Fig. 2: The architecture of torque observer

The torque generation model which supplies feedforward torque estimation implements a mean value engine model\[16, 17\]. Based on this model, the torque generation can be derived as\[18\]

\[
\hat{T}_e = \frac{H_u}{4\pi L_{th} R L_{man} T_{man}} \left( T_f + T_p \right) - \left( T_f + T_p \right) \tag{5}
\]

where \(L_{th}\) is the ideal air fuel ratio, \(T_f, T_p\) are the friction and pumping resistant torque, respectively. The dynamic equation of the rotational movement of the crankshaft used to estimate engine speed is the same with the one implemented for torque demand decision, which is rewritten as

\[
\hat{\omega} = \frac{1}{I_e} (\hat{T}_e - T_l) \tag{6}
\]

Finally, the estimated effective torque is

\[
\hat{T}_e = \frac{H_u}{4\pi L_{th} R L_{man} T_{man}} \left( T_f + T_p \right) + k_p (\omega - \hat{\omega}) + k_i \int (\omega - \hat{\omega}) dt \tag{7}
\]

where \(k_p, k_i\) are proportional and integral gain, respectively.

This approach is different from Hendricks’ work\[14\] by utilizing PI gains feedback instead of Kalman gains. With the additional integral gain, steady error will be eliminated. In \[13\], PI gains are also implemented as the feedback of the difference between estimated and measured engine speed. But it did not use a model to give feedforward torque estimation. That will lead to a phase delay between the estimated torque and the actual one. It is comprehensible that the speed response requires some time due to the system’s character.

3.2 Closed-Loop Controller

With the torque observer, a closed-loop torque controller can be arranged. As a primary attempt of utilizing the torque demand-based speed control, the most simplest feedback control namely PI control is implemented. To obtain fast response, we use a look-up table where indicative torque is input while throttle angle is output to give a nominal value of throttle angle. The table is accomplished by engine calibration tests. The structure of torque controller is shown in Fig. 3, where \(T_{cr}, T_{ir}\) are the desired effective torque and indicative torque, respectively, \(\hat{T}_i\) is the estimated indicative torque, \(\alpha_0\) is the nominal value of throttle angle and \(\Delta\alpha\) is the compensated amount by feedback of the difference between the desired torque and the estimated one.
4 Experimental Results

The engine is a direct-injected V6 SI engine, provided by Toyota Motor Corporation. It was installed in a test cell and connected to a dynamometer. Pressure sensors were installed in Cylinder 2, Cylinder 4 and Cylinder 6. The basic software of the engine control unit (ECU) was modified to allow the engine to run with the standard commercial controller, or to accept control commands from dSPACE, such as the throttle angle, spark advance, fuel injection, etc. Thus, we can control the throttle angle to regulate engine speed.

To validate the torque observer, the mean indicative torque is calculated from cylinder pressure, using the expression below.

$$\hat{T}_i = \frac{\int_0^{4\pi} p(\theta)V(\theta)d\theta}{4\pi} \times z$$  \hspace{1cm} (8)

where $p(\theta), V(\theta)$ denote cylinder pressure and volume, which are functions of crank angle $\theta$, $z$ is the cylinder number of the engine, $\hat{T}_i$ is the mean indicative torque in a cycle. In the following, all “measured” torque are obtained from the pressure sensors.

We first validate the torque observer and then compare the proposed optimal controller with a conventional speed controller, which is shown as Fig.5. To show the significance in the optimal controller of torque observer, we also give the results with an open-loop torque control approach (That means torque observer is not used for closed-loop control and only a look-up table is implemented). For the sake of simplicity, engine load is constant and remains at 30 N-m in all experiments. The speed trajectory for control is obtained by filtering a step signal. And the weight factor in the cost function (3) is taken as $\alpha_v = 0.01$.

For torque observer validation, we give a throttle step input and estimates the mean indicative torque generated. The results are shown in Fig.6. The maxim absolute error in transient process comes to 10 N-m but most are under 6 N-m. The maxim relative error is 10% and most are under 6%. It can be seen that the phase delay between estimated torque and actual one is eliminated by introducing the torque generation model as a prior estimation. Steady error is also reduced by utilizing an integral gain.

The comparisons of conventional speed controller and optimal controller are shown in Fig.7 and Fig.8. The results of optimal control without torque observer are also present. Fig.7 shows the speed tracking performance of these strategies. For controller without torque observer, speed error in steady state is existent. The torque generated is compared in Fig.8. It is noted that the curve for optimal controller is more close to the optimal one than the curve for conventional controller which has
a larger phase delay. For optimal controller with torque observer, we also give the estimated torque, which is similar with the measured one.

For the experimental engine, the ideal cost function for optimization control is given below.

\[ J^* = 0.1464\omega_0^2 - 49.8996\omega_0 + 4561.9204 \quad (9) \]

where \( \omega_0 \) is the initial angular velocity at time \( t_0 \). With \( \omega_0 = \frac{1600}{30} \times \pi = 167.55 \text{ rad/s} \), we can calculate the ideal cost value for optimization control is 311. For the conventional controller, the optimal controller with and without torque observer, the cost values are 2411, 352 and 1687, respectively, as shown in Table 1.

5 Conclusions

An optimal controller for torque-based engine management systems is developed. For a given speed trajectory, the optimal engine torque is determined by dynamic programming and then realized by torque control algorithm. An observer is employed to create closed loop torque controller. It is

<table>
<thead>
<tr>
<th>Controllers</th>
<th>Cost Value</th>
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<tbody>
<tr>
<td>Ideal</td>
<td>311</td>
</tr>
<tr>
<td>Conventional</td>
<td>2411</td>
</tr>
<tr>
<td>Optimal with observer</td>
<td>352</td>
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<tr>
<td>Optimal without observer</td>
<td>1687</td>
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verified that the observer has acceptable accuracy and is helpful to achieve good performance in optimal speed control. Developments such as on-line optimal control schemes have been expected for the future works.

References


