Neurocomputing 164 (2015) 262–271

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Robust driveshaft torque observer design for stepped ratio transmission in electric vehicles

Xiaoyuan Zhu [a], Fei Meng [a], Hui Zhang [a,*], Yanmei Cui [b]

[a] Merchant Marine College, Shanghai Maritime University, Shanghai 201306, China
[b] School of Mechatronics Engineering, Zhengzhou Institute of Aeronautical Industry Management, Zhengzhou 450015, China

ARTICLE INFO

Article history:
Received 16 November 2014
Received in revised form
3 February 2015
Accepted 24 February 2015
Available online 4 March 2015

Keywords:
Robust shaft torque observer
Automated manual transmission
H_∞ performance
Linear matrix inequality
Electric vehicles

ABSTRACT

Knowledge of driveshaft torque is very important to powertrain oscillation damping control as well as gear shift quality improvement. However, the driveshaft torque cannot be easily measured by using affordable sensors. This paper provides a robust driveshaft torque observer design for electric vehicle equipped with stepped ratio transmission. The proposed observer is constructed using the measurable angular velocity signals and designed to be robust against modeling error, system uncertainties as well as external load disturbance. Torsion angle of the driveshaft is selected to be estimated instead of direct torque observation, which can be further used to calculate the driveshaft torsion based on driveshaft's spring–damper model. The H_∞ performance is adopted in the observer design to minimize the effect of the disturbance on the estimation error. Furthermore, the decay rate of the estimation error and transient response of the observer are also considered by using an eigenvalue placement technique. The observer gain is derived by solving the linear matrix inequality while simulation results are adopted to show the effectiveness of the proposed observer design.

1. Introduction

Electric vehicle equipped with stepped ratio transmission including automated manual transmission (AMT) and dual clutch transmission (DCT) has attracted considerable research efforts in recent years [1,2]. Despite wide operational speed range as well as relatively flatter efficacy map of the driving motor, a two speed or multi-speed gearbox still can be very helpful for the electric vehicle to achieve higher driving performance while lower energy consumption [3,4]. It is also good for size reduction of the driving motor as well as overload protection of the electrical components in powertrain system [5]. Some novel stepped ratio transmissions such as clutchless AMT, inverse AMT and eDCT have been especially developed for electric vehicles [6–8]. And the AMT has already been successfully applied to the powertrain system of pure electric bus [9,10]. To better use the stepped ratio transmission in the powertrain of electric vehicles, the gear shift quality must be ensured first. It is well known that knowledge of accurate drive shaft torque information is very helpful in the gear shift quality improvement, which can help to determine the most optimal time point to disengage the clutch or switch the working mode of the motor [11]. Furthermore, it will also benefit the active damping control of the transmission system a lot if accurate drive shaft torsion was available [12]. Despite the importance of accurate shaft torque information in the control of transmission system, the torque sensors are seldom used in the commercial vehicles due to the cost, durability and also the installation problem [13]. Based on the shaft's spring–damper model, driveshaft torque can be also calculated if the torsion angle measurement is available [11]. However, the torsion angles are also difficult to be obtained as high precision encoders are required. It is also not suggested to integrate the angular speed to get the torsion angle as the measurement noise is inevitable in engineering practice. Therefore, it will be better to estimate the driveshaft toque rather than measure it by using physical torque sensors or encoders. And the torsion angle estimation of the drive shaft can be adopted instead of direct torque observation to make full use of the angular velocities that can be easily measured.

In the past decades, considerable observer design methods have been applied to the powertrain system for driveshaft torque estimation. A virtual drive-shaft torsion sensor was constructed in [14] to estimate the driveshaft torque by using Kalman filter. The desired observer gain was obtained by solving Riccati equation where prior information on the noise is usually required. The Luenberger observer is also adopted to estimate the drive shaft

* Corresponding author. Tel.: +1 614 886 3583.
E-mail addresses: zhuxyc@gmail.com (X. Zhu), feimeng@shmtu.edu.cn (F. Meng), huizhang285@gmail.com (H. Zhang), cuiym03@aliyun.com (Y. Cui).

http://dx.doi.org/10.1016/j.neucom.2015.02.062
0925-2312/

Nomenclature

Abbreviations

AMT	automated manual transmission
DCT	dual clutch transmission
LMI	linear matrix inequality
MCU	motor control unit
TCU	transmission control unit
LQR	linear quadratic regulator

Notations

A_f	front area of the vehicle
C_d	air drag coefficient
C_r	rolling resistance coefficient
c_a	linear coefficient of air drag
c_f	driveshaft damping coefficient
c_m	motor damping coefficient
g	gravitational acceleration
i_0	final drive ratio
i_g	gear ratio
J_m	inertia of driving motor
J_g	inertia of gearbox
J_w	inertia of wheels
J_v	inertia of vehicle
k_f	driveshaft stiffness coefficient
m_v	vehicle mass
r_w	wheel radius
$T_{airdrag}$	aerodynamic drag torque
T_{grade}	T_{grade}
T_{load}	load torque
T_m	motor torque
T_{roll}	rolling torque
ω_m	rotating speed of driving motor
ω_g	rotating speed of gearbox output shaft
ω_v	wheel rotational speed
θ_g	gearbox output angle
θ_w	wheel angle
α	slope angle
ρ_{air}	air density

torque in [12]. As the disturbance is not considered in the observer design, the robustness of the drive shaft torque estimation cannot be guaranteed. Some nonlinear observers have also been adopted to estimate the driveshaft torque in the vehicle transmission system. The sliding mode observer has been designed to estimate the driveshaft torque in [13]. Though the sliding mode observer can be robust to bounded modelling errors and parameter uncertainties, the chattering problem cannot be easily attenuated. A reduced-order nonlinear driveshaft torque observer is designed in [11] where the input-to-state stability is adopted to ensure the robustness of the proposed observer. Compared with sliding mode observer, this novel observe cannot only achieve satisfying estimation performance but also eliminate chatters. However, the tuning parameters related to decay rate adjustment and offset reduction may are not easy to choose.

In order to better estimate the driveshaft torque, a robust observer design is proposed in this paper. The main contribution of this paper lies in the following aspects. First, H_∞ performance is selected for the proposed robust observer. Both the system uncertainty and the external disturbance are considered in the observer design for shaft torque estimation. Second, a pole placement method is adopted to further adjust the decay rate of the estimation error as well as transient response of the observer by adjusting the eigenvalues of the system matrix. In addition, the parameters for the observer are easy to tune, and the robust H_∞ observer gains can be obtained by solving the linear matrix inequality (LMI).

The rest of this paper is organized as follows. In Section 2, the uncertain powertrain dynamic model is derived. In Section 3, weighted H_∞ robust observer design is proposed. In Section 4, simulation studies using Simulink are conducted to validate the effectiveness of the proposed observer. Concluding remarks are summarized in Section 5.

2. Problem formulation

The powertrain system including the observer and control system is schematically shown in Fig. 1. The motor speed and wheel speed are directly measured by sensors while the driveshaft torque is estimated by the observer. These estimated signals will be sent to transmission control unit (TCU) to calculate the desired torque commands. Based on these torque commands, the motor control unit (MCU) will actuate the motors to generate corresponding torques which is finally applied to the vehicle powertrain dynamic system. As the driveshaft torque is required in the closed-loop shift control system, accurate torque estimation will be very critical in the gear shift improvement as well as active oscillation damping of the powertrain dynamic system.

When the transmission is running in a certain gear position, the powertrain dynamics can be simplified as follows [15]:

$$
\begin{aligned}
&J_{mg}\omega_m^2 = T_m - T_f/i_g i_0 - c_m\omega_m \\
&J_{mg} = (J_m + J_g/i_g^2 i_0^2) \\
&J_v\dot{\omega}_w = T_f - T_{load} \\
&J_v = J_w + m_v r_w^2 \\
&T_{load} = T_{roll} + T_{grade} + T_{airdrag} \\
&T_{roll} = C_r m_v g\ \cos(\alpha) r_w, T_{grade} = m_v g\ \sin(\alpha) r_w \\
&T_{airdrag} = \frac{1}{2}\rho_{air} A_f C_d V_v^2 r_w, V_v = r_w\omega_w
\end{aligned} \tag{1}
$$

where J_m is the inertia of the driving motor and J_g the gear box inertia, J_v is the vehicle inertia, J_w is the wheel inertia, m_v is the vehicle mass, T_m is the motor torque, ω_m is the motor rotation speed, ω_g and ω_w are the rotation speed of gearbox output shaft and wheel, while θ_g and θ_w are the output angles respectively. T_f is the torque in the flexible driveshaft. T_{load} is the external load torque including air drag $T_{airdrag}$, rolling torque T_{roll} and resistant torque T_{grad}. c_m is the damping coefficient of the motor. c_f is the driveshaft damping coefficient and k_f is the stiffness factor. C_r is the rolling resistance coefficient, α is the road grad, r_w is the wheel radius, ρ_{air} is the air density, A_f is the frontal area of the vehicle, C_d is the airdrag coefficient, V_v is the vehicle speed.

The driveshaft torque is modeled as a spring and damper system, which can be expressed as follows [16,17]:

$$T_f = k_f(\theta_m/i_g i_0 - \theta_w) + c_f(\omega_m/i_g i_0 - \omega_w) \tag{2}$$

As the motor speed and wheel speed can be measured by affordable sensor, the shaft torque estimation then can be reduced to estimate the torsion angle only. It should be noted that the torsion angle cannot be obtained by integration of these angular velocities due to the inevitable measurement noise.