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Robust control of integrated motor-transmission powertrain system over controller area network for automotive applications

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ABSTRACT

Integrated motor-transmission (IMT) powertrain system with directly coupled motor and gearbox is a good choice for electric commercial vehicles (e.g., pure electric buses) due to its potential in motor size reduction and energy efficiency improvement. However, the controller design for powertrain oscillation damping becomes challenging due to the elimination of damping components. On the other hand, as controller area network (CAN) is commonly adopted in modern vehicle system, the network-induced time-varying delays that caused by bandwidth limitation will further lead to powertrain vibration or even destabilize the powertrain control system. Therefore, in this paper, a robust energy-to-peak controller is proposed for the IMT powertrain system to address the oscillation damping problem and also attenuate the external disturbance. The control law adopted here is based on a multivariable PI control, which ensures the applicability and performance of the proposed controller in engineering practice. With the linearized delay uncertainties characterized by polytopic inclusions, a delay-free closed-loop augmented system is established for the IMT powertrain system under discrete-time framework. The proposed controller design problem is then converted to a static output feedback (SOF) controller design problem where the feedback control gains are obtained by solving a set of linear matrix inequalities (LMIs). The effectiveness as well as robustness of the proposed controller is demonstrated by comparing its performance against that of a conventional PI controller.

1. Introduction

Alternative powertrain solutions for ground vehicles have attracted increasing research efforts with the recent resurgence of electrified vehicles including both hybrid electric vehicle (HEV) and pure electric vehicle (PEV) [1–4]. HEV takes the advantages of energy management between gasoline and electricity while PEV only can be electrically propelled [5]. The powertrain structure of HEV can be generally classified into series hybrid, parallel hybrid, and power-split hybrid [6]. While for the PEV, it can be simply characterized by distributed motor-driven and centralized motor-driven [7]. The powertrain structure of distributed motor-driven PEV, e.g., four-wheel independently-actuated electric vehicle, is quite

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Nomenclature

Abbreviations

AMT	automated manual transmission
CAN	controller area network
ECU	electric control unit
HEV	hybrid electric vehicle
ICE	inter combustion engine
IMT	integrated motor-transmission
LPV	linear parameter-varying
MCU	motor control unit
NCS	networked control system
PEV	Pure electric vehicle
TCU	transmission control unit

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}	road grade torque
T_{load}	load torque
T_m	motor torque
T_{grade}	T_{roll}
T_{grade}	V_v
T_{grade}	ω_m
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

different from that of traditional vehicle. The mechanical transmission and differential are no long necessary in distributed motor-driven PEV while the vehicle is directly propelled by in-wheel motors [8,9]. Such an actuation flexibility has also attracted numerous research efforts in motion control, energy optimization and fault tolerant control, etc. for distributed motor-driven PEV [10–13]. For the centralized motor-driven PEV, some apparatus in the conventional vehicle's powertrain system can be still kept while the inter-combustion engine (ICE) will be replaced with electric machines. Though the distributed motor-driven PEV is more novel and flexible, the centralized motor-driven PEV still occupies mainstream status in current market due to its better inheritance with conventional vehicles [14]. Compared with ICE, electric motor generally owns much higher efficiency, better starting performance as well as flatter efficiency map. Therefore, signal speed drives with fixed gear ratio are commonly adopted in most present PEVs to simplify the transmission structure [15]. However, according to the studies in [16–19], two-speed or multi-speed transmission can still enable the PEVs to achieve higher performance and increased range. It can also reduce the motor size and help PEVs achieve better balance between performance and efficiency [20]. For the conventional multi-speed transmission, an electrically controlled clutch is usually required to ensure the smoothness of the shifting process [21]. However, with the electric motor's fast and precise response along with multiple working modes, i.e., speed mode, torque mode and free mode, the clutch is no longer necessary while the shifting process can be ensured by active control of the electric motors [22]. Actually, active control of the ICE has already been adopted in conventional vehicles for shifting without using the clutch [23]. Therefore, there will be no problem for the centralized motor-driven PEV to remove the clutch apparatus while better shifting performance can be even achieved with the active control of motors. Considering the weight, cost and especially the efficiency, the automated manual transmission is considered to be a suitable choice for centralized motor-driven PEV to further form an IMT powertrain system, e.g., clutchless automated manual transmission (AMT) system [24,25]. Actually, it has already been used in some pure electric buses where significant improvement in the drivability and energy efficiency can be achieved [26].

The vehicle powertrains are characterized by fast dynamics where driveline oscillation is easy to appear. While enjoying the benefit of motor control, the controller design for the driveline oscillation damping is becoming more challenging due the absence of the clutches [27]. Moreover, as the control signal from the controllers and measurements from the sensors are all exchanged by using area network (CAN) in present vehicles, the network-induced random delays are inevitable due to the bandwidth limitation in IMT powertrain system [28]. The random and time-varying delays can degrade the performance of the control system and even destabilized the closed-loop system [29], which bring up an additional challenge to the driveline oscillation damping control and haven't been fully addressed in the control of IMT powertrain system.

In the practical vehicle powertrain control system, the sensors are generally working under time-driven mode while the transmission control unit (TCU) and motor control unit (MCU) as well as motors are all in event-driven mode [30]. The time-driven sensors execute periodically with fixed sampling time. When the time-driven mode is assumed for all the nodes including the controller node and actuator node in the control system, the network-induced time-varying delays for the time-driven working mode would only be integral multiple number of default sampling period [31–33]. However, for the event-

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