Mechanical Systems and Signal Processing 64-65 (2015) 29–45

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Multi-objective decoupling algorithm for active distance control of intelligent hybrid electric vehicle

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ARTICLE INFO

Article history:
Received 24 May 2013
Received in revised form
13 January 2015
Accepted 17 February 2015
Available online 20 April 2015

Keywords:
Hybrid electric vehicle
Intelligent vehicle
Active distance control
Tracking safety
Fuel economy

ABSTRACT

The paper presents a novel active distance control strategy for intelligent hybrid electric vehicles (IHEV) with the purpose of guaranteeing an optimal performance in view of the driving functions, optimum safety, fuel economy and ride comfort. Considering the complexity of driving situations, the objects of safety and ride comfort are decoupled from that of fuel economy, and a hierarchical control architecture is adopted to improve the real-time performance and the adaptability. The hierarchical control structure consists of four layers: active distance control object determination, comprehensive driving and braking torque calculation, comprehensive torque distribution and torque coordination. The safety distance control and the emergency stop algorithms are designed to achieve the safety and ride comfort goals. The optimal rule-based energy management algorithm of the hybrid electric system is developed to improve the fuel economy. The torque coordination control strategy is proposed to regulate engine torque, motor torque and hydraulic braking torque to improve the ride comfort. This strategy is verified by simulation and experiment using a forward simulation platform and a prototype vehicle. The results show that the novel control strategy can achieve the integrated and coordinated control of its multiple subsystems, which guarantees top performance of the driving functions and optimum safety, fuel economy and ride comfort.

1. Introduction

With increasing demands of driving safety, the greenhouse gas (GHG) emission and entertainment, automobile manufacturers are focusing on developing safer, more efficient, environmentally friendly and comfortable vehicles. To reduce fuel consumption and exhaust emission, a variety of clean energy vehicle technologies have been widely studied: pure electric vehicles [1], hybrid electric vehicles [2], plug-in hybrid vehicles [3], fuel cell vehicles [4] and alternative fuel vehicles [5]. In-depth study to improve safety performance of ICE vehicles has focused on active safety technology and intelligent safety technology, such as Anti-Brake System (ABS) [6], Electronic Stability Program (ESP) [7], Global Chassis Control (GCC) [8], Adaptive Cruise Control (ACC) [9], and Lane Keeping System (LKS) [10]. Integration of active safety technologies in clean energy vehicles have become increasingly important [11], as illustrated by the application of the ABS [12], TCS [13] and ESC [14] in pure electric or hybrid electric vehicles. Therefore, it is obvious that an advanced vehicle

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http://dx.doi.org/10.1016/j.ymssp.2015.02.025
0888-3270/

integrated with all the aforementioned vehicle technologies would be a more effective solution to vehicle safety, energy-saving, low emission and ride comfort issues. Considering all options for an advanced vehicle design, combining the advantages of clean energy vehicles and intelligent vehicles to create an intelligent clean energy vehicle is one reasonable solution. Intelligent hybrid electric vehicles are expected to have good prospects for promotion and application [15,16], according to the current market applications of clean energy vehicles.

In the field of the intelligent hybrid electric vehicle dynamics and control, many researchers have focused on optimizing the energy management strategy to improve fuel economy by using the vehicle parameters [17], road conditions statistics [18] or real-time traffic information [19]. For example, Hajimiri and Salmasi proposed an optimal energy management algorithm for HEV based on GPS communication [20]. The future path information of the vehicles based on GPS was taken into account to generate control signals. A fuzzy logic controller (FLC) was utilized for energy management based on the predicted vehicular status, while the energy management system was modified to optimize the state of the health (SOH) of the power battery. Simulation results demonstrated a 6.5% improvement in fuel economy. Yokoi et al. proposed a new energy management system which included a driving pattern prediction system based on driving conditions to improve the fuel consumption and emissions of hybrid electric vehicles [21]. In this paper, the future driving pattern could be predicted from the database of the past driving patterns constructed with the clustering method. The experimental result showed the effectiveness of the proposed system. Beck and Bollig introduced a global optimization strategy and a predictive optimal control strategy capable of achieving minimum fuel consumption, both relying on predictive information about the driving conditions within a limited future time horizon [22]. The simulation results showed that the global optimization strategy achieved better fuel economy than predictive optimal control strategy under the European driving cycle NEDC. Ripaccioli et al. introduced a hybrid MPC controller and a hybrid dynamical model. This model was developed through the use of linear and piecewise affine identification methods to reduce the fuel consumption and emission of the HEV and relies on GPS to predict the state of the vehicle [23].

The objective of intelligent hybrid electric vehicle's control is to integrate multiple objects, including safety, energy-saving, low emission and ride comfort. However, the current study just focused on multi-objective adaptive cruise control of the internal combustion engine vehicles. Kalabis et al. proposed an adaptive cruise control method coordinating the tracking safety and fuel consumption based on the model predictive control [24]. Based on the terminal constraints of the tracking time, the cost function of the fuel consumption was formulated to achieve the requirements of the driver to track the preceding vehicle. Simulation results showed that the fuel consumption decreased by 13.1% without reducing the travel time under the sine driving condition. Jonsson introduced a Stop-and-Go controller which led to the lowest fuel consumption and satisfactory following based on the model predictive control [25]. Simulations showed it was possible to follow the preceding vehicle in satisfactorily and at the same time reduce fuel consumption by approximately 3%. Li et al. focused on the servo-loop control design of a Pulse-and-Gliding (PnG) strategy to minimize fuel consumption in automated car following [26]. Simulations demonstrated that the PnG controller improved fuel economy by up to 20% when compared with a linear quadratic (LQ)-based benchmark controller. One shortcoming of abovementioned research is that these algorithms are still poor in real-time performance, and are difficult to implement in vehicle development.

In order to address the limitations of the above studies, a multi-objective decoupling algorithm for active distance control of intelligent hybrid electric vehicle is proposed in this paper. The objects of safety and ride comfort are decoupled from fuel consumption to improve real-time performance and adaptability to complex driving situations. In the top layer, the safety distance control and the emergency stop algorithms are designed to meet the safety and ride comfort goals. In the middle layer, the hybrid electric system energy management algorithm is developed to improve fuel economy. Simulation and experimental results demonstrate the proposed algorithm can achieve the integrated and coordinated control of the multiple subsystems, guaranteeing the optimal performance of the driving functions and optimal safety, fuel economy and driving performance. Comparing with the similar hybrid vehicles, the intelligent hybrid vehicle can achieve simultaneous optimization of tracking safety and fuel economy, as well as good real-time performance thanks to the hierarchical multi-objective decoupling control algorithm.

2. Intelligent hybrid electric vehicle configuration

The IHEV configuration is presented in Fig. 1.

The IHEV is composed of a traffic environment and vehicle states sensing subsystem, a hybrid electric propulsion subsystem, a driving assistance subsystem, a control subsystem and a communication network subsystem. The traffic environment and vehicle states sensing subsystem mainly comprises a Millimeter-wave radar sensor, a longitudinal acceleration sensor, an accelerator pedal position sensor, a brake pedal position sensor, a transmission gear sensor and an ignition switch position sensor. The hybrid electric propulsion sub-system mainly consists of a 1.5-l gasoline engine, a 20 kW driving motor, a 5 kW belt starter/generator (BSG), a 6 A h power battery and a 5 speed automatic transmission. The driving assistance sub-system mainly consists of a hydraulic brake assembly equipped with electric vacuum booster (EVB) and an electric power steering (EPS). The control sub-system mainly consists of a hybrid vehicle control unit (HCU), a radar control unit (RCU), an engine control unit (ECU), a transmission control unit (TCU), a motor control unit (MCU), a battery management system (BMS), an EVB control unit (VCU) and an EPS control unit (SCU). The communication network sub-system mainly consists of two high-speed CAN networks, namely power system CAN networks and driving assistance