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Current distribution control of dual directly driven wheel motors for electric vehicles

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ABSTRACT

This paper proposes a current distribution control for dual directly driven wheel motors for electric vehicles. The objective is to maintain two driving wheels at a synchronous speed in order to keep the vehicle straight, or at differential speeds when cornering, even when they incur uneven load disturbance or parameter changes. The proposed control scheme employs a load disturbance observer, a model following controller, and a velocity command compensator to determine the proper amount of current supplied to each driving wheel. The vehicle dynamics and control strategy were modeled and the control performance was simulated numerically. Experiments were performed in a hardware-in-the-loop configuration with a dedicated wheel motor on a dynamometer and a virtual one on a field programmable gate array chip where the current distribution control was implemented. The resulting control performance verified the stability and robustness of the system in terms of its insensitivity to parameter variations and its rejection of external disturbances.

1. Introduction

Electric vehicles (EVs) are developing fast during this decade due to drastic issues on the protection of environment and the shortage of energy sources. While commercial hybrid cars have been rapidly exposed on the market, fuel-cell-powered vehicles are also announced to appear in 5–10 years. Researches on the power propulsion system of EVs have drawn significant attention in the automobile industry and among academics. EVs can be classified into various categories according to their configurations, functions or power sources. Pure EVs do not use petroleum, while hybrid cars take advantages of energy management between gas and electricity (Poursamad and Montazeri, 2007). Indirectly driven EVs are powered by electric motors through transmission and differential gears, while directly driven vehicles are propelled by in-wheel or, simply, wheel motors (Chen & Chau, 2001).

The basic vehicle configuration of this research has two directly driven wheel motors installed and operated inside the driving wheels on a pure EV. These wheel motors can be controlled independently and have so quick and accurate response to the command that the vehicle chassis control or motion control becomes more stable and robust, compared to indirectly driven EVs. Like most research on the torque distribution control of wheel motors, He, Hori, Kamachi, Walters, and Yoshida (2005) proposed a dynamic optimal tractive force distribution control for an EV driven by four wheel motors, thereby improving vehicle handling and stability. The researchers assumed that wheel motors were all identical with the same torque constant, neglecting motor dynamics—the output torque was simply proportional to the input current with a prescribed torque constant.

Under this assumption, Hori, Toyoda, and Tsuruoka (1998) proposed a model following control and an optimal slip ratio control to adjust tractive torque when the motor speed is suddenly increased by tire slip, under the assumption of equal torque and friction forces on the right and left tires. The model following control and the slip ratio control was effectively implemented on their experimental EV, the UOT March II, with four in-wheel motors (Hori, 2004). Mutoh and Higashikubo (2002) introduced a control structure to distribute torque to the front and rear wheels, which were driven independently and indirectly by a synchronous motor and an induction motor. A similar method known as direct yaw moment control was proposed by Sakai, Sado, and Hori (2002), where the vehicle's lateral motion was controlled by a yaw moment generated by the torque difference between wheel motors. Hallowell and Ray (2003) implemented an all-wheel-driven 1/8 scale vehicle model, with a wheel slip controller for each wheel and a central torque distribution controller to enhance lateral stability and follow the driver's intended trajectory. Pusca, Ait-Amirat, Berthon, and Kauffmann (2002) modeled and simulated a traction control

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algorithm for an EV with four separate drives to ensure lateral dynamic stability.

No previous researchers have taken into consideration the differences in motor dynamics among wheel motors, whose internal uncertainties, such as variation in motor parameters or fault motor components, may cause risky driving due to instability. When the dynamics of a wheel motor are considered, the input current produces output torque according to the variation of motor parameters, such as winding resistance, inductance, and viscous or dry friction, due to the change in temperature, manufacturing tolerance or aging effects. The same amount of current may produce different torque outputs from different wheel motors given the same road condition, thereby yielding different velocities and causing undesirable sideslip. It is therefore quite necessary to produce the desired torque for each wheel by properly distributing the current, subject to the variation of motor parameters as well as to external disturbances. In short, current distribution control is equivalent to torque distribution control when motor dynamics are incorporated in the control strategy.

This paper constructs an internal controller to distribute current to the driving wheels of EVs. Since wheel motors may be fabricated of different qualities, and age at different rates, the same current may not produce the same torque output. An uneven torque distribution to driving wheels will cause undesired sideslip in the cruising and cornering modes. The proposed internal controller serves to distribute the current, instead of torque, to the driving wheels, given different dynamics and uncertain loads from tires, thereby enhancing the robustness and stability of the system.

2. Wheel motor and its dynamics

The custom-designed wheel motor is a directly driven disc-type axial-flux brushless dc motor. The rotor is embedded with 18 fan-shaped magnets and sandwiched by two plates of stator. Each stator is toroidally wound with a strip of continuous steel to form 24 teeth. The coils are independently wired on stator poles and grouped into four phases, each of which is bound with six parallel-connected windings. The same phase on the left and right plates can be connected in two modes: serial and parallel for a single-phase model. The parallel mode is suitable for high-speed operation at higher phase voltage, while the serial mode for low-speed operation operates at a lower phase voltage. Its maximum torque is 64 N m, the maximum speed is 950 rpm, and the rated power is 1.85 kW at 340 rpm. The tire is mounted on the outer case that rotates with the rotor of the wheel motor. Its exploded graph and stator phase windings are drawn in Fig. 1, and its optimal design and control are addressed in Yang, Luh, and Cheung (2004) and in Yang, Wang, Wu, and Luh (2004). Fig. 2 illustrates the installation of two rear driving wheel motors on an EV.

The electrical and mechanical equations of the wheel motor are derived under the assumptions that (i) each wheel motor is an axial-flux dc brushless motor, (ii) the motor is operated in the linear range of the B–H curve of the magnetic material, and (iii) the flux flows straightly across the air-gaps between the stator and rotor, ignoring the fringing flux (Hanselman, 2003). The equations of motion of the vehicle driven by two rear wheels are written with other assumptions: (i) the tractive effort of two front tires is zero, (ii) the wheel mass is negligibly small compared with the vehicle mass, and (iii) the tire, yawing, pitching and rolling dynamics are not considered (Wong, 1978). Therefore, the dynamic equations of each rational wheel motor can be expressed as

$$T = 4k_t I, \tag{1}$$

$$V = IR + L\frac{dI}{dt} + K_e\omega, \tag{2}$$

$$T = J\dot{\omega} + D\omega + T_L, \tag{3}$$

where T is the produced torque, I is the input current, K_t is the torque constant as a function of motor parameters, the multiplier 4 accounts for four phases, V is the phase voltage, R is the phase resistance, L is the phase inductance, K_e is the back emf constant, ω is the rotational wheel speed, J and D are the wheel inertia and damping coefficient, respectively. The external load on tire T_L can simply account for the tractive torque $f_i r$ produced by the friction between ground and tire on each driving wheel i, where r is the tire radius. It is assumed that the wheels roll without slipping, thus $v_i = r\omega_i$; the friction f_i, which is less than the maximum static friction, becomes the tractive effort on the vehicle. When the phase inductance is neglected in the steady state, the combination of (1) through (3) yields

$$\dot{v}_i = -\left(\frac{D_i R_i + 4K_{ti}K_{ei}}{J_i R_i}\right)v_i + \left(\frac{4K_{ti}V_i - f_i r R_i}{J_i R_i}\right)r, \tag{4}$$

where $i = a$ and b, denoting rear wheels A and B.

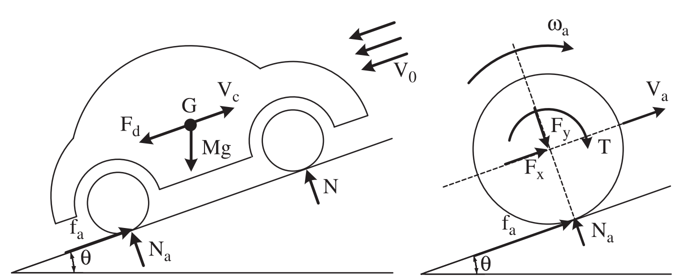

Fig. 2. (a) Free body diagram of driving wheel A and (b) longitudinal vehicle configuration.

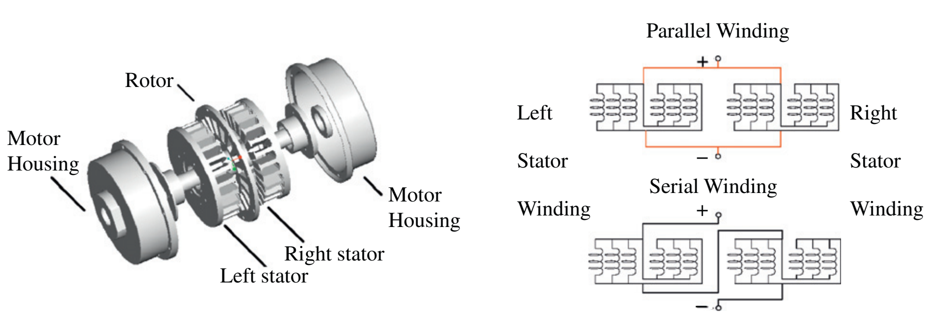

Fig. 1. Exploded graph of axial-flux dc brushless wheel motor and its stator phase windings.