A brief overview on dynamics and control of electric vehicles

Atul Ray*, Rajkumar Sarangi

Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, West Bengal 721302, India

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Abstract

Electric vehicles are gaining ever-increasing popularity owing to their independence to crude oil, low-emission characteristics and performance, ride and stability of such vehicles. In-wheel-electric vehicles are modern electric drive systems that are able to accommodate in vehicle wheel assemblies while allowing packaging adaptability by removing the power transmission systems and components such as shafts, gear box, and universal joints. The importance of electric vehicles, its different types such as in-wheel electric motors, hybrid, plug-in hybrid and electric vehicles (HEVs, PHEVs, and EVs, e.g. P/H/EVs) are will be covered. Yaw-moment control of electric vehicle for improving handling and stability, fuzzy logic direct yaw-moment control system for all-wheel-drive electric vehicles and an optimal torque distribution approach for electric vehicle equipped with four independent wheel motors to improve vehicle handling and stability performance is discussed. Further discussions and explanations are presented during the context of paper.

Keywords: Electric vehicles; in-wheel motors; Control and dynamics

1. Introduction

The energy crisis and limitation of oil sources and the ever-increasing environmental concerns have promoted the necessity and application for research in alternative energy sources while electric vehicles have served as a strong candidate among all other choices [1] while also are eco-friendly means of transportation [2-3].

An electric vehicle is characterized by the adoption of one or more electric motors as energy provision system to create vehicle propulsion. The sources for vehicle powering can be sort of an external source, or alternatively through a self-contained system with a battery, solar panels or a generator to convert fuel to electricity. Electricity can be scavenged from different sources for instance, on-board rechargeable electricity storage system (RESS) and a direct continuous connection to land-based generation plants for purposes of on-highway recharging with unrestricted highway range, or on-board rechargeable electricity storage system and a fueled propulsion power source, so-called plug-in hybrid.

Electric vehicles also serve as a functional and robust solution to energy sustainability and air pollutant control (emission control). Electrified vehicles inherit the benefit of a considerable adaptability on account of active control of vehicle propulsion, and improving energy efficiency through energy regeneration from regenerative braking or energy harvesting sources from suspension system, tire, etc. All-wheel-drive EV where each wheel is driven separately by electric wheels is inventive configurations for electric vehicles are that electric motors can be housed in vehicle wheel assemblies usually known as in-wheel motors [4]. Improved safety, ride comfort and enhanced handling dynamics are the benefits of in-wheel motor adoption and controls. This is mainly because the torques can be controlled independently and direct yaw moment control and side slip control are extensively applied for vehicle lateral stability, traction efficiency and accident avoidance. Also it is possible to realize a more accurate control system by estimating the state of the tires while traveling on road or off road in on-line manner [5].

Hybrid, plug-in hybrid and electric vehicles (HEVs, PHEVs, and EVs, e.g. P/H/EVs) are developing vehicle engineering domains that have the ability to boost vehicle performance and fuel economy, and to decrease the environmental impacts such as vehicle emission. PHEV and EV fuel consumption is quantified on account of either fuel consumption (L (100 km)$^{-1}$), or energy consumption (ACW-h (km)$^{-1}$), or both [6].

It can be pointed out that studies documented in literature confirm the advantage of electric vehicles over internal combustion engines from its performance, emission to its energy saving nature. Therefore, electric vehicles are gaining ever-increasing popularity while precise and comprehensive studies are needed to cover the advantages and disadvantages of developing such vehicles.

2. Literature of in-wheel Motors

From the viewpoint of vehicle dynamics, electric vehicles can be designed to have different types of driving system, and
it is possible to place a built-in motor in each wheel for both driving and braking purposes [7]. A prototype of such in-wheel motor is illustrated in Fig. 1.

In Ref. [8], a vehicle motion control strategy was designed based on feedback linearization of a simple vehicle model and then adopted to distribute the generalized forces on the center of gravity of the vehicle to wheel forces. In Ref. [9], a direct yaw control DYC method for EVs with four independently in-wheel motors was proposed to solve the stability problem, a skid detection method as part of the traction control system was proposed to detect a skidding wheel without wheel velocity or vehicle velocity.

In Ref. [10], a new control approach for an in-wheel motored EV was proposed to follow the desired yaw rate while reducing the sideslip angle where the sequential quadratic programming method was used to obtain a dynamic traction force distribution to solve the actuator idleness difficulty. In Ref. [11], a variable torque distribution yaw control was suggested for an all-wheel drive hybrid vehicle by controlling the front-to-rear torque distribution and torque differential between the left and right rear wheels.

In Ref. [12] proposed a vehicle dynamic controller for an EV with four in-wheel motor using gain scheduling based on tire cornering stiffness estimation which was verified to stabilize the vehicle motion under critical driving conditions.

A top-view vehicle dynamics model is presented in Fig. 2 with three degrees of freedom regarding lateral motion, yaw motion, and longitudinal motion.

Lateral motion:

\[
F_{yfl} + F_{yfr} + F_{yrl} + F_{yrr} = ma_y
\]

\[a_y = v (\dot{\beta} + \gamma)\]

Yaw motion:

\[
I_z \dot{\gamma} = l_f (F_{yfl} + F_{yfr}) - l_r (F_{yrl} + F_{yrr}) + \frac{d}{2} (F_{sdl} + F_{sdr})
\]

Longitudinal motion:

\[
m \dot{v} = -(F_{yfl} + F_{yfr} + F_{sdl} + F_{sdr})
\]

where \(m\) is the vehicle mass, \(\beta\) is the side slippage, \(\gamma\) the yaw rate, \(F_i\) is the lateral forces, \(F_s\) is the longitudinal force, \(\delta_t\) the front wheel steering angle, \(v_i\) the vehicle velocity in \(X\) direction, \(v\) the vehicle velocity in \(Y\) direction, \(v\) the vehicle velocity, \(l_f\) and \(l_r\) the distances from the center of gravity to the front and rear wheel axle respectively, \(l\) the yaw moment of inertia of the vehicle, \(d\) the tread.

In the above model, the lateral velocity \(v_y\) and the yaw rate \(\gamma\) are the two state variables, while \(M_\gamma\) is the external yaw moment which must be determined by the control law. In this manner, the tire slip angle is another major index for the computation of tire lateral force. The following equations define the slip angles of the front and rear tires:

\[
\alpha_i = \delta_i - \tan^{-1} \left( \frac{v_{yf} + l_f \gamma}{v_s - 0.5 \gamma d} \right)
\]

\[
\alpha_i = \delta_i - \tan^{-1} \left( \frac{v_{yf} + l_f \gamma}{v_s + 0.5 \gamma d} \right)
\]

\[
\alpha_i = \tan^{-1} \left( \frac{l_r \gamma - v_f}{v_s - 0.5 \gamma d} \right)
\]

\[
\alpha_i = \tan^{-1} \left( \frac{l_r \gamma - v_f}{v_s + 0.5 \gamma d} \right)
\]

The adjustment of yaw rate response from second to first order model leads to the increment of the vehicle stability limit and avoids vibration regarding steering input. The formulation of the individual sideslips can be presented as following:

\[
\beta_i = \tan^{-1} \left( \frac{v_{yf} + l_f \gamma}{v_s - 0.5 \gamma d} \right)
\]

\[
\beta_i = \tan^{-1} \left( \frac{v_{yf} + l_f \gamma}{v_s + 0.5 \gamma d} \right)
\]

\[
\beta_i = \tan^{-1} \left( \frac{v_{yf} - l_f \gamma}{v_s - 0.5 \gamma d} \right)
\]

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\]

In linear tire model the lateral tire force is delivered by the tire cornering stiffness and the tire slip angle as following:

\[
F_{yi} = C_a \alpha_i \quad i = 1, 2, 3, 4
\]

\[
F_y = F_{y1} + F_{y2} + F_{y3} + F_{y4}
\]

Here we can present the lateral force based on Dugoff’s tire model that deals with the friction ellipse idea:

\[
F_h = C_a \frac{\tan \alpha}{1 - s} f(h)
\]

where

\[
f(h) = \begin{cases} 
  h(2-h) & \text{if } h < 1, \\
  1 & \text{if } h > 1,
\end{cases}
\]
and,

\[
h = \frac{\rho F_i (1 - \varepsilon x \sqrt{s^2 + \tan^2 \alpha})(1 - s)}{2\sqrt{C_i^2 s^2 + C_i^2 \tan^2 \alpha}} \tag{10}
\]

A simple non-linear tire model based on the Burckhardt method is incorporated can also be adopted, where the longitudinal force \(F_x\) and the lateral force \(F_y\) of the tires are described as functions of the longitudinal slip and the lateral slip respectively of the tires [13-14]:

\[
F_x = \frac{s_x F_z \mu_{res}}{s_{res}} \tag{11}
\]

\[
F_y = \frac{s_y F_z \mu_{res}}{s_{res}}
\]

where \(F_z\) is the vertical load of the tires, \(s_x, s_y\) and \(s_{res}\) are the longitudinal slip, lateral slip and the resultant slip respectively and \(\mu_{res}\) is the resultant friction coefficient, where the resultant slip can be described as:

\[
s_{res} = \sqrt{s_x^2 + s_y^2} \tag{12}
\]

The resultant friction coefficient \(\mu_{res}\) is obtained from the resultant tire slip \(s_{res}\) as following:

\[
\mu_{res} = c_1 \left(1 - e^{-c_2 s_{res}}\right) - c_3 s_{res} \tag{13}
\]

where \(c_1, c_2\) and \(c_3\) are the model constant derived from the experimental tests.

In Ref. [16], an optimal torque distribution approach was developed for electric vehicle with four in-wheel motors that run independently to improve vehicle handling and stability performance. The objective function was obtained through a novel method by considering the interference among different performance indices: forces and moment errors at the center of gravity of the vehicle, actuator control efforts and tire workload usage. The overall control structure for proposed torque control system, yaw rate and lateral acceleration response comparison, braking and driving torque have been shown in Figs. 3-5.

The EV investigated in this paper is equipped with four-wheel motors which can be controlled independently. The independent wheel motor is modeled as a first-order system as follows

\[
Q_{final} = \frac{1}{1 + \tau_m s} Q_{cal} \tag{14}
\]

where \(\tau_m\) is the time constant of the motor dynamics (\(\tau_m = 50 \text{ ms}\), \(Q_{cal}\) is the calculated torque and \(Q_{final}\) is the output torque to the vehicle.

Figure 1. A prototype small-scale electric vehicle “NOVEL” [7]

Figure 2. Top-view vehicle dynamics model
For a direct yaw-moment stabilization system, it is required to monitor the steering wheel angle input from driver, the yaw rate at the center of gravity, the driving wheel velocity, and the vehicle body velocity [17]. The steering wheel angle is measured by the installation of a rotary position coder while the yaw rate is obtained by a gyro sensor. Furthermore, the driving wheel velocity is measured directly by a rotary encoder, and the vehicle body velocity is measured ultimately from the non-driving wheel velocity (front wheel) by the rotary encoder. Such a system is further depicted in Fig. 7.

Fig. 8 represents the block diagram of the vehicle stability assist system. It is known that a fuzzy logic controller can be used to control the yaw rate. A fuzzy controller was adopted to avoid the tire forces being saturated due to the additional torque applied by the yaw controller [18]. The adoption of fuzzy logic is promptly increasing to mollify the following necessities: (1) to develop control systems with nonlinear characteristics and decision making systems for controllers, (2) to deal with a growing number of sensors and exploit the greater amount of information, (3) to decrease the running time, (4) to decrease the rates concerned with integrated technology into the product. Vehicle dynamics and braking systems is complex and perform strongly in non-linear manner which causes difficulties in developing a classical controller.
A novel rolling stability control (RSC) on in-wheel electric vehicle based on two-degree of freedom control was developed. Electric motors have several benefits over internal combustion engines or brake actuators. Differential torque by right and left motors can realize novel vehicle motion controls. Although RSC systems have been developed by automobile and several parts companies, the actuators are only brake actuator systems and cannot output positive torque rapidly and accurately. Electric motors can generate the output of torque accurately and rapidly at the desired direction. Along with the actuator advantage, two-degree of freedom control was applied for RSC [20]. The proposed method realizes following capability to command value and robustness to roll moment disturbance. Effectiveness of proposed roll stability control is verified with simulation and experimental results utilizing our two in-wheel electric motor on pure electric vehicle. With proposed RSC, peaks of roll rate and roll angle are suppressed for disturbance roll moment comparison to without control [20].
Fig. 8 shows the vehicle control system and shows simulation results of feedback control. The vehicle velocity was 4 (m/s) and steering input is 3 (Hz) sinusoidal wave. Roll rate was blocked by differential torque on two rear electric motors. Because the system has torque limitation and mechanical delay, perfect tracking is impossible, while, roll rate by sinusoidal steering input was effectively suppressed and controlled [20].

Fig. 11 shows simulation results of feedback control given that the vehicle velocity was adjusted at 4 (m/s) and steering input is 3 (Hz) sinusoidal wave. Roll rate was inhibited by differential torque on two rear electric motors. Meanwhile, the system has torque limitation and mechanical delay, perfect tracking is impossible, while, roll rate by sinusoidal steering input is effectively suppressed and controlled.

In another work [21], the intrinsic contribution of the yaw rate reference to the overall handling performance of an electric vehicle with torque vectoring control-in terms of minimum-time maneuvering was assessed. A range of yaw rate references are compared versus optimal control simulations incorporating closed-loop controller dynamics. The obtained results indicated that yaw rate reference has a significant effect on maneuver time.

A “time optimal” look-up table (Fig. 12 b) of yaw rate gain as a function of speed and longitudinal acceleration was developed [21]. The objective of this work is to evaluate the contribution of the yaw rate reference of a TV controller to vehicle performance in terms of time minimization. As a base-
line, an open-loop formulation is used with no TV controller, provided as an additional control input fed directly to the vehicle model, bypassing the TV controller (dashed line in Fig. 12a). Front and rear friction circles and steering rate limit constraints are enforced [21].

In another work was carried out regarding the development of a 4-Wheels vehicle model capable to reproduce the complete dynamical behavior [22]. The modeling task is firstly performed by the separated 3-D representation on the Dymola environment of the chassis, suspensions, tires and joints using the library for Multi-Bond Graphs in 3-D mechanics. Moreover, these parts are connected to form the complete vehicle model. The compactness and resemblance with a real vehicle assembling is shown. The main contribution of this paper is to provide a model applicable to electric or hybrid vehicles where the complete dynamics can be simulated. The simulation results obtained illustrate ordinary situations where the inclusion of traction control and ABS are essential for the vehicle safety and stability.

Figure 10. Simulation results of following capability of RSC [20]

Figure 11. Experimental results of following capability of RSC [20]

Figure 12. Optimal control framework to emulate ideal driver controlling a vehicle with TV controller, a) “Time-optimal” yaw rate reference look-up table [21]
A zigzag maneuver is performed at a constant speed of 43 Km/h. The steering follows the curve described in Fig. 13(a). Positive steering means turning to the left (negative z) and that is seen on the curves plotted in Fig. 13(b) and Fig. 13(c).
yaw response in Fig. 14 increases with positive steering and vice versa as expected. Fig. 15(a) evidences the load transferred towards the wheels external to the curve. The roll produced due to this load transfer is described in Fig. 15(b) [22].

3. Conclusions

Electric vehicles are gaining ever-increasing popularity owing to their independence to crude oil, low-emission characteristics and performance, ride and stability of such vehicles. In-wheel-electric vehicles are modern electric drive systems that are able to accommodate in vehicle wheel assemblies while allowing packaging adaptability by removing the power transmission systems and components such as shafts, gear box, and universal joints. The importance of electric vehicles, its different types such as in-wheel electric motors, hybrid, plug-in hybrid and electric vehicles (HEVs, PHEVs, and EVs, e.g. P/H/EVs) are will be covered.

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References


