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Energy Optimization of Brushless DC Motor in Electric Power-Assisted Steering

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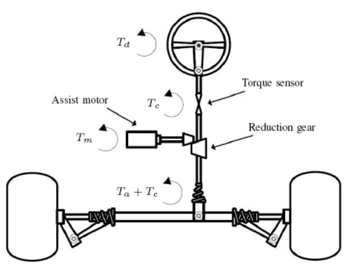
Graphical abstract



Abstract

In an electric power-assisted steering (EPS) an electric motor is controlled to provide assistance in vehicle steering and to enable various steering feels. To optimize energy consumed by a column-type EPS equipped with a brushless dc (BLDC) motor the author designs two controllers as needed. Firstly a controller to generate driver torque is developed based on nonlinear adaptive regulation method using the mathematical model of EPS. The second controller is a PID motor controller that is applied to produce assistance torque for desired energy saving. The trade-off between driver's comfort and energy consumption is demonstrated using Matlab simulation results. In electric vehicles (EVs) where electrical energy is limited the control scheme introduced here is expected to fit perfectly.

Keywords: Energy optimization; electric power-assisted steering; brushless DC motor; nonlinear adaptive regulation; PID control

Abstrak

Dalam sistem bantuan stereng elektrik (BSE) motor elektrik dikawal untuk memberikan kemudahan kepada pemandu dalam pengawalan stereng dan untuk membolehkan pelbagai tahap keselesaan. Untuk mengoptimumkan tenaga yang digunakan oleh BSE jenis lajur yang dilengkapi dengan motor dc tanpa berus, penulis mereka bentuk dua pengawal. Pengawal pertama adalah untuk menjana tork pemandu yang dibangunkan berdasarkan kaedah kawalan adaptif menggunakan model matematik BSE. Pengawal kedua pula ialah pengawal motor PID yang digunakan untuk menghasilkan tork bantuan untuk merealisasikan penjimatan tenaga yang diingini. Perbezaan yang terhasil antara tahap keselesaan pemandu dan penggunaan tenaga elektrik ditunjukkan menggunakan keputusan simulasi Matlab. Dalam kenderaan elektrik di mana tenaga elektrik adalah terhad, skim kawalan yang diperkenalkan di sini adalah amat sesuai.

Kata kunci: Penjimatan tenaga; sistem bantuan stereng elektrik; kawalan adaptif; kawalan PID

1.0 INTRODUCTION

In a vehicle EPS assists a human driver by measuring torque exerted by the driver and providing additional torque by means of an electric motor. Conventionally an EPS system consists of a dc motor and relies on vehicle velocity and driver torque measurements to determine target motor current levels from assist characteristic [1] or boost [2] curve.

The assist characteristic curve is a set of graphs of motor current versus driver torque and vehicle velocity that is generated experimentally to produce desired assistance torque and thus predetermined steering comfort [3]. An implication of this is that for a fixed driver torque and vehicle velocity a fixed amount of electrical energy is consumed by an EPS. While in internal combustion engine vehicles provision of maximum steering comfort to drivers is possible careful considerations are needed to be made in EVs. Given a limited power supply in an EV higher torque assistance would result in a faster battery drain. Therefore the use of the assist characteristic curve to obtain reference assistance torque levels is not applicable in EVs and a better approach enabling energy optimization is justified.

While the use of a traditional brushed dc motor in an EPS requires a low cost and a simple control some disadvantages include high maintenance of the brushes, low overall power density and electromagnetic interference (EMI) problems associated with commutator arcing [4]. These drawbacks motivate the author to apply a BLDC in an EPS system in this paper.

Some previous works on EPS will now be reviewed. In [3] a modified Linear Quadratic Gaussian controller is shown to be able to track the characteristic curve and attenuate external disturbances for a column-type EPS system. From the simulation results the controller performs well despite the inclusion of nonlinear rotational friction terms even though explicit expressions of the friction are not provided. Chitu *et al*. applied a Linear Quadratic Regulator to derive an optimal controller for an EPS system in [2]. Both simulation and dSPACE ControlDesk real-time application utilizing the assist characteristic curve show stability in frequency, robustness and closed-loop stable step responses during parameter variation. In [5] a Fuzzy PID control strategy is simulated for assist motor current tracking. The simulation model that includes a simple road surface disturbance demonstrates the effectiveness of the proposed controller. While brushed dc motors are considered in the above works an EPS with a BLDC actuator is studied in [6]. Zhu *et al*. propose an adaptive control method to achieve torque control by approximating motor electrical dynamics with back EMF compensation error correction. In another related work Hu *et al*. constructed a test bed and developed a controller for a BLDC EPS system and reported an acceptable system performance in [7].

Out of the four control objectives of an EPS system (cf. [8]) the basic function of an EPS i.e. assistance torque control is considered here. To achieve energy optimization the authors develop a mathematical model of a column-type EPS with a BLDC assist motor. Nonlinear rotational friction and LuGre dynamic tire friction are included in the mathematical model for accurate EPS representation. The model is then used to design a controller based on nonlinear adaptive regulation for driver torque generation to track a reference wheel angle trajectory. To enable an option to select torque assist level and consequently amount of energy saving desired eco factor *E* is introduced in later sections of this paper. Target assistance torque is then achieved using PID control of motor current with Pulse Width Modulation (PWM) implementation.

The paper is organized as follows; in Section 2.0 the EPS mathematical model is discussed. A brief explanation on controller designs is provided in Section 3.0 after which simulation results and conclusion are given in Sections 4.0 and 5.0 respectively.

■2.0 MATHEMATICAL MODEL

The following is the mathematical model of a column-type EPS (see Figure 1).

Torque sensor model:

$$T_c = K_s(\theta_s - \frac{x_r}{R_s}) \tag{1}$$

Steering column model:

$$J_s\ddot{\theta}_s = T_d - T_c - B_s\dot{\theta}_s - T_f^s \tag{2}$$

Assist motor model:

Rack and pinion model:

$$\begin{aligned}
T_m &= \frac{n_p}{\dot{\theta}_m}(E_a i_a + E_b i_b + E_c i_c) \\
V_n &= \frac{1}{3}(V_a + V_b + V_c) - \frac{1}{3}(E_a + E_b + E_c) \\
L\dot{i}_a &= V_a - V_n - Ri_a - E_a \\
L\dot{i}_b &= V_b - V_n - Ri_b - E_b \\
L\dot{i}_c &= V_c - V_n - Ri_c - E_c \\
(J_m + \frac{J_G}{G^2})\ddot{\theta}_m &= T_m + \frac{T_c}{G} - (B_m + \frac{B_G}{G^2})\dot{\theta}_m - T_f^m \\
T_a &= GT_m \\
M_r\ddot{x}_r &= \frac{T_a + T_c}{R_s} - F_{TR} - B_r\dot{x}_r - K_r x_r
\end{aligned} \tag{3}$$

where

θ_s	-	steering wheel angle
θ_m	-	assist motor armature shaft angle
T_d	-	driver torque
T_c	-	steering column torque sensor measurement
T_m	-	assist motor torque
T_a	-	assistance torque
T_f^s	-	steering column friction
T_f^m	-	assist motor and reduction gear friction
B_s	-	steering column viscous damping coefficient
B_m	-	assist motor viscous damping coefficient
B_G	-	reduction gear viscous damping coefficient
B_r	-	pinion and rack viscous damping coefficient
J_s	-	steering column moment of inertia
J_m	-	assist motor moment of inertia
J_G	-	reduction gear moment of inertia
K_s	-	steering column stiffness
K_a	-	assist motor torque coefficient
K_b	-	assist motor back emf coefficient
K_r	-	rack equivalent spring constant
$V_{a,b,c}$	-	BLDC motor three-phase voltage
$i_{a,b,c}$	-	BLDC motor three-phase current
$E_{a,b,c}$	-	BLDC motor three-phase trapezoidal back EMF
V_n	-	BLDC motor neutral voltage
n_p	-	BLDC motor number of poles
R	-	BLDC motor resistance
L	-	BLDC motor inductance
G	-	reduction gear ratio
x_r	-	horizontal rack displacement
R_s	-	pinion radius
F_{TR}	-	pinion, rack and wheel equivalent mass
M_r	-	dynamic tire friction

The nonlinear rotational friction is given by

$$T_f^i = (\alpha_0^i + \alpha_1^i e^{-\alpha_2^i|\dot{\theta}_i|})\,\mathrm{sgn}_1(\dot{\theta}_i) + (\alpha_3^i + \alpha_4^i e^{-\alpha_5^i|\dot{\theta}_i|})\,\mathrm{sgn}_2(\dot{\theta}_i), \qquad i = s, m$$

where

$$\mathrm{sgn}_1(\dot{\theta}_i) = \begin{cases} 1 & \dot{\theta}_i \geq 0 \\ 0 & \dot{\theta}_i < 0 \end{cases}$$

$$\mathrm{sgn}_2(\dot{\theta}_i) = \begin{cases} 0 & \dot{\theta}_i \geq 0 \\ -1 & \dot{\theta}_i < 0 \end{cases}, \qquad i = s, m$$

and

$$\alpha_0^i \neq \alpha_3^i, \alpha_1^i \neq \alpha_4^i, \alpha_2^i \neq \alpha_5^i, i = s, m$$

and

$$\alpha_j^i \in \Re, \alpha_j^i > 0, j = 0, \ldots, 5$$

in general [12].

The LuGre dynamic tire friction can be expressed as

$$\tau_a = M_s + M_{sa}$$

$$F_{TR} = \frac{\tau_a}{r}$$

where is r the steering arm length and M_s, M_{sa} are sticking and self-alignment torques respectively. For complete expressions of M_s, M_{sa} please refer to [13] and [14].

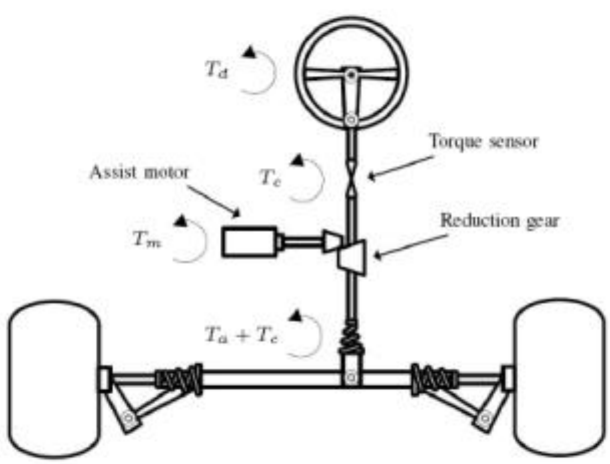


Figure 1 A column-type EPS

■3.0 CONTROLLER DESIGN

The main objective of this work is to demonstrate the option made available to choose a desired steering comfort. Since a better steering feel is provided by a higher torque assist higher energy consumption would result and the reverse is also true. The amount of assistance torque T_a to be produced is determined by the *eco factor* E and driver torque T_d. Therefore in this section the controller design is done in two stages. In the first part a controller based on nonlinear adaptive regulation is developed to generate driver torque T_d to track a reference wheel angle trajectory. Next a reference assistance torque T_a^* is obtained using the generated T_d and E. In the second stage BLDC motor control is carried out using PID and PWM application to track T_a^*

3.1 Driver Torque Generation

Consider (3) with $T_a = 0$,

$$M_r \ddot{x}_r = \frac{T_c}{R_s} - F_{TR} - B_r \dot{x}_r - K_r x_r \tag{4}$$

and a reference wheel angle trajectory θ_w^* given by

$$x_r^* = \sum_{i=1}^{N} A_i \cos(\Omega_i t + \varphi_i) \tag{5}$$

$$\theta_w^* = \frac{x_r^*}{r},$$

with a fixed N, unknown amplitudes A_i, phases φ_i and frequencies Ω_i. Then from (4) and (5) a steady state steering column torque T_c^* needed to track θ_w^* is given by

$$T_c^* = (F_{TR} + B_r \dot{x}_r + K_r x_r + M_r \ddot{x}_r^*) R_s \tag{6}$$

From (5) and (6) a reference steering wheel angle is obtained as follows.

$$\theta_s^* = \frac{T_c^*}{K_s} + \frac{x_r}{R_s} \tag{7}$$

By solving for a steady state driver torque T_d^* from (2) using (7) we have

$$T_d^* = T_c + B_s \dot{\theta}_s + T_f^s + J_s \ddot{\theta}_s^*. \tag{8}$$

Note that in steady state T_d^* will produce θ_s^*, T_c^* and consequently x_r^*.

Using the nonlinear adaptive regulation method expressions (7) and (8) yield controllers of the forms

$$\begin{aligned} e_1 &= x_r^* - x_r \\ u_{st}^1 &= k_2^1(\dot{e}_1 + k_1^1 e_1) \\ g_{st}^1 &= G u_{st}^1 \\ \dot{\xi}_1 &= (F + G\hat{\Psi}_1)\xi_1 + g_{st}^1 \\ T_c^u &= \hat{\Psi}_1 \xi_1 + u_{st}^1, \qquad k_1^1, k_2^1 > 0 \end{aligned} \tag{9}$$

and

$$\theta_s^u = \frac{T_c^u}{K_s} + \frac{x_r}{R_s}$$
$$e_2 = \theta_s^u - \theta_s$$
$$u_{st}^2 = k_2^2(\dot{e}_2 + k_1^2 e_2)$$
$$g_{st}^2 = G u_{st}^2$$
$$\dot{\xi}_2 = (F + G\hat{\Psi}_2)\xi_2 + g_{st}^2$$
$$T_d = \hat{\Psi}_2 \xi_2 + u_{st}^2, \qquad k_1^2, k_2^2 > 0 \qquad (10)$$

whose performances are subject to the tuning of $k_1^1, k_2^1, k_1^2, k_2^2$. For definitions of the control parameters and detailed explanation of control designs (9) and (10) readers are advised to refer to [10] and [11]. The above controllers can be shown to be able to track x_r^* in a globally asymptotically and locally exponentially stable manner.

3.2 Assist Motor Control

The controller designed in the previous section will generate driver torque T_d for reference wheel angle θ_w^* tracking. From the steering column torque measurement T_c desired assist motor torque T_m^* is obtained as follows.

$$T_a^* = ET_c$$
$$T_m^* = \frac{T_a^*}{G} \qquad (11)$$

Given the value in (11) reference assist motor current $i_a^* = T_m^* / K_a$ is then computed for BLDC motor control as depicted in Figure 2. A PID controller is tuned to achieve desired accuracy in i_a^* tracking of the assist motor that is powered by PWM.

Note that $E = 1$ would mean that equivalent steering effort has to be put by both a human driver and the assist motor. Even though that results in a comfortable steering it leads to higher battery usage as compared to setting $E = 0.1$.

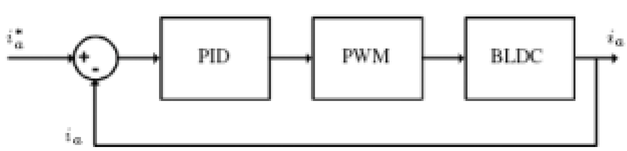


Figure 2 Assist motor control

4.0 SIMULATION RESULTS

The mathematical model of a column-type EPS system given in Section 2.0 together with the control designs in Section 3.0 is simulated using Matlab. Parameters of the EPS model are adopted from [7], [6] and [9].

Recall that in Section 3.A a controller is designed to generate driver torque T_d for reference wheel angle θ_w^* tracking. From Figure 3 it could be seen that controllers (9) and (10) performs well since a very close tracking is achieved.

In Figure 4 steering column torque T_c and assistance torque T_a are plotted for $E = 0.6$. As the values of T_a are always approximately 60% of T_c as desired the effectiveness of the PID controller with PWM from Section 3.B is demonstrated.

Figures 5 and 6 show steering column torque T_c and assist motor torque T_m respectively for different values of E. Note the inverse relationship between T_c and T_m. As a higher T_m is desired (by setting a higher value of E) a lower T_c is required for steering.

As expected assist motor phase A (as well as two other phases) current i_a varies accordingly to changes in E settings in Figure 7. From Figures 5 and 7 it is clearly shown that a lighter steering feel (a higher E) requires a higher current draw from a car battery. However if users are given the option to choose E as desired a better management between steering comfort and power usage could be achieved for energy optimization.

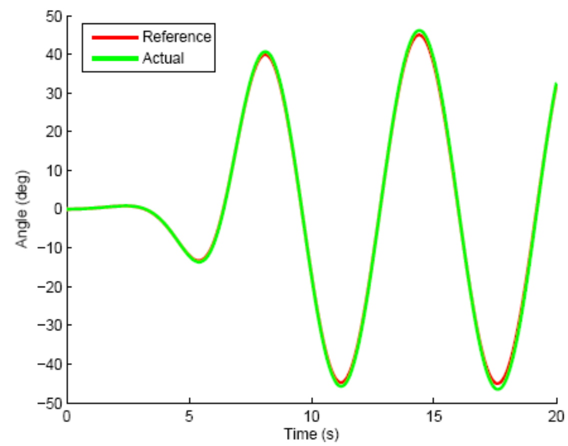


Fig. 3. Reference wheel angle θ_w^* and actual wheel angle θ_w

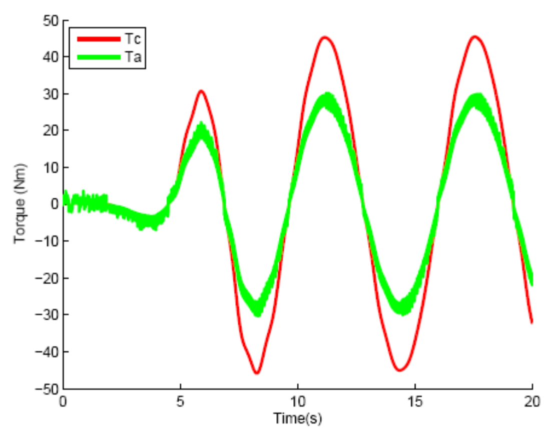


Fig. 4. Steering column torque T_c and assistance torque T_a for E = 0.6

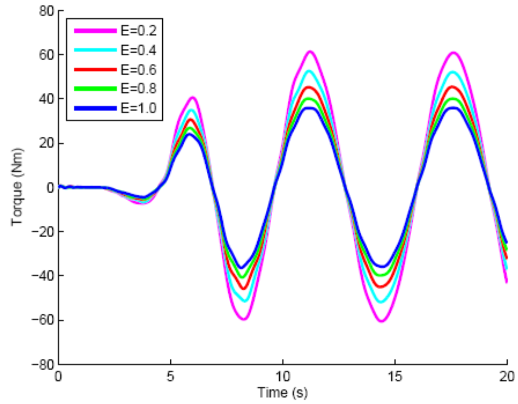


Fig. 5. Steering column torque T_c

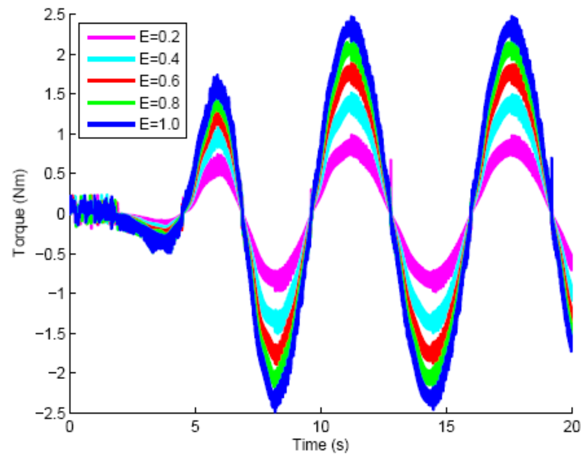


Fig. 6. Assist motor torque T_m

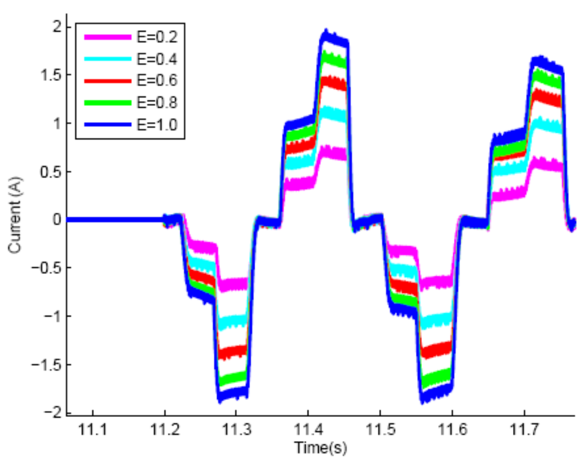


Fig. 7. Assist motor current i_a

5.0 CONCLUSION

Conventionally target assist motor current is obtained from a lookup table that is obtained experimentally given vehicle speed and steering column torque. Since the approach generates fixed values of reference assist motor current to generate required assistance torque energy saving of battery is almost impossible. In this work given the motivation to optimize the energy consumed by EPS in EVs the author introduced the *eco factor E* as an option to set the level of steering comfort as desired. Consequently drivers could choose to save battery energy given the inverse relationship between steering comfort and power consumed by the assist motor. Based on the simulation results produced using Matlab feasibility of the proposed control methods in achieving energy optimization in EPS is verified.

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