World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
Vol:8, No:7, 2014

Research on Control Strategy of Differential Drive Assisted Steering of Distributed Drive Electric Vehicle

J. Liu, Z. P. Yu, L. Xiong, Y. Feng, J. He

Abstract**—**According to the independence, accuracy and controllability of the driving/braking torque of the distributed drive electric vehicle, a control strategy of differential drive assisted steering was designed. Firstly, the assisted curve under different speed and steering wheel torque was developed and the differential torques were distributed to the right and left front wheels. Then the steering return ability assisted control algorithm was designed. At last, the joint simulation was conducted by CarSim/Simulink. The result indicated: the differential drive assisted steering algorithm could provide enough steering drive-assisted under low speed and improve the steering portability. Along with the increase of the speed, the provided steering drive-assisted decreased. With the control algorithm, the steering stiffness of the steering system increased along with the increase of the speed, which ensures the driver's road feeling. The control algorithm of differential drive assisted steering could avoid the understeer under low speed effectively.

Keywords**—**Differential assisted steering, control strategy, distributed drive electric vehicle.

I. Introduction

STEERING portability is one of the important factors which evaluated the handing quality of the vehicle [1]. In order to improve the steering portability and alleviate the handing burden of the driver under low speed or pivot steering, the electric power-assisted steering system is adopted in most traditional vehicles to provide steering power-assisted for the drivers. According to different speed, different effort is provided by the assisted motor to ensure the steering portability under low speed and enough road feeling under high speed. Meanwhile the driving safety was increased. However, assisted motor installation makes the system construction more complicated and increases the costs.

The distributed drive electric vehicle was driven by multiple motor independently and deemed as the development direction in the future [2], [3]. The output torque of each motor could be controlled independently and accurately and can be distributed at any proportion even driving on one side while braking on the other side within the range of the motor ability. The construction of the vehicle is tight and efficient in the driving [4], [5]. It is the unique dynamic control form that makes it possible to carry out the power-assisted for the differential distribution of right and left wheel driving torque.

This paper analyses the principle of the differential power-assisted steering. Based on the principle, the control strategy of differential drive assisted steering of distributed drive electric vehicle was designed. Firstly, assisted characteristic curves under different speed and steering torque were designed and the differential torques were distributed to the right and left steering wheels. Then the steering return ability assisted control algorithm was designed. At last, the joint simulation was conducted by the Carsim/Simulink.

J. Liu is with the School of Automotive Studies and Clean Energy Automotive Engineering Center of Tongji University, Shanghai, 201804China (phone: +86 13162503228; (e-mail: 2012tjqy_liujun@tongji.edu.cn).

Z. P. Yu, is with the School of Automotive Studies and Clean Energy Automotive Engineering Center of Tongji University, Shanghai, 201804 China (e-mail: yuzhuoping@tongji.edu.cn).

L. Xiong is with the School of Automotive Studies and Clean Energy Automotive Engineering Center of Tongji University, Shanghai 201804 China (Corresponding author: e-mail: xiong_lu@tongji.edu.cn).

II. The Principle of Differential Drive Assisted Steering

Because of the lateral offset of the king pin, the longitudinal force can create the torque of the king pin. Because of the differential mechanism, the torques of right and left driving wheels in the traditional vehicles were the same. Under average circumstances, the torques to the king pin caused by the longitudinal force of the two wheels were equal and reverse order. So they cancelled out which ensure the straight driving of the vehicles.

When comes to the distributed drive electric vehicle, the output of the electric machine can be controlled accurately so that, according to the needs, the machine controller enabled the right and left driving wheels to produce large difference value accurately, then the longitudinal force difference was produced. Because of the offset of the king pin, two different torques to the king pin was created. Together with the input steering torque, these driving steering torques overcomed the aligning torques and the steering system fiction torques helping the drivers to produce the anticipated steering angle.

Established T_1 and T_3 to be the left and right drive steering torques respectively. Established F_{t1} and F_{t3} to be the crosswise driving torque produced by the wheels and ground respectively.

$$T_{st1} = F_{t1} \cdot r_\sigma \tag{1}$$

$$T_{st3} = F_{t3} \cdot r_\sigma \tag{2}$$

So the steering torque of separated king pin produced by them were:

$$T_a = T_{st1} - T_{st3} = (F_{t1} - F_{t3}) \cdot r_\sigma \tag{3}$$

when the electric vehicle equipped with differential drive assisted steering system made a turn, it was supposed to ensure the longitudinal dynamics constant of the vehicle according to the driver. That was to say to ensure the stability of the longitudinal speed and accelerated speed. So when distributing the dive steering torques, (4), (5) should be satisfied:

$$T_1 = T_t \cdot d_f / 2 + T_a / 2 \quad (6)$$

$$T_3 = T_t \cdot d_f / 2 - T_a / 2 \quad (7)$$

Among them, the T_t was the total needed steering torque, the d_f was the proportion of the epipodium occupied in the total torque and the T_a was the difference value of the left and right wheels which produced the needed assisted steering. Through the analysis above, by controlling the needed left and right steering torque T_a, the needed steering torque handled by the driver was effected referenced to the control strategy of differential drive assisted steering, and the steering assistance can be realized through controlling the differential steering torque to the front wheels.

III. The Establishment of the Joint Simulation Model Based on the CarSim/Simulink

Recently, along with the development of the digital simulation technology, more and more dynamics software such as CarSim, veDYNA and ADAMS were used in the research of vehicle dynamics. In this paper, an electric finished vehicle dynamics model was established in CarSim, a differential assisted steering control model was established in Matlab/Simulink and the joint control block diagram was shown in Fig. 1.

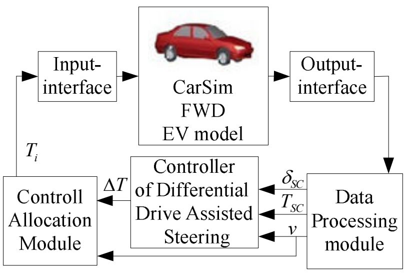

Fig. 1 Control structure of joint simulation of CarSim/Simulink

In the Carsim/Simulink joint simulation, the front-wheel drive electric vehicle model was presented as the S-function included the working condition information of the simulation. The vehicle state variables can be inspected and conducted afterwards. Among them, the signal of the steering wheel angle, the steering torque and the speed can be used as the controlled input and the front-wheel differential steering torque as the controlled module output. According to the speed and dive torque of the left and right front-wheel distributed by differential steering torque, the modules were distributed and reacted to the Carsim vehicle model through the model input interface.

IV. Control Strategy of Differential Drive Assisted Steering

The basic function of the differential drive assisted steering system was similar to the electric assisted steering system. And during the turning process, the amount of the steering wheel torque needed to weigh the steering portability and demands for the feedback to the drivers. Furthermore, the assisted steering control and the steering reversal control would not be aroused at the same time. So, separated modules should be established by control algorithm in two different control strategies. By steering, the present returning state can be estimated which contributed to the assisted control and turning reversal control under different circumstances. Fig. 2 was the block diagram of control strategy of the differential assisted steering.

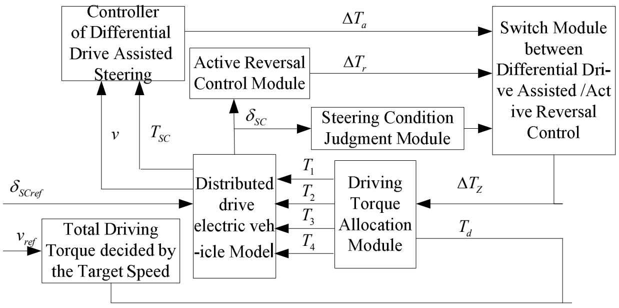

Fig. 2 Control strategy of the differential assisted steering

When putting the steering torque and speed signals into the assisted control module, the corresponding assisted differential value and the differential orient can be obtained according to the well-designed assisted differential characteristic curve which provided the assistance during the steering process. And the corresponding difference value of the target drive steering torque can be obtained by the active reversal control module according to the orient and amount of the steering-wheel angle. At last, the state of the steering system was estimated by the steering circumstances and the final output differential force torque was confirmed and the differential torque modules were distributed to the lefts and right drive machine averagely by the drive steering torque according to the difference value of the target drive steering torque. The steering assistances were realized while the drive force was ensured.

A. Design of the Differential Assisted Characteristic Curve

The differential assisted characteristic curve is the correlativity between assistant torque, steering wheel torque and vehicle speed. The more superior quadratic assistant curve was selected to be the form of the differential assisted characteristic curve taking example by the design method of electric power steering assisted characteristic curve. The specification should follow the principles [6]:

(1) If the steering wheel torque increases, the differential assisted torque increases; and if the velocity V increases, the differential assisted torque decreases.
(2) To avoid the steering of the mid-position was excessively sensitive, the steering wheel input torque was $|T_{SW0}| = 1N \cdot m$ when begin to assist.

(3) Subject to the limits of the driver's power, the steering wheel input torque is $|T_{SW0}| = 7N \cdot m$ when reach the maximum steering torque.

(4) The distribution of the left and right motors torque which provided the maximum power-assisted torque can be get by (6)

$$T_{PK} = \frac{f}{3}\sqrt{\frac{G_f^3}{P}}; \quad |\Delta T|_{\max}\frac{r_\sigma}{r_w} = T_{PK} - T_{SW}i \tag{8}$$

T_{PK} was the pivot steering drag torque, f was the tire-road friction coefficient, which is 0.8, G_f was steering shaft loads, P was the tire pressure, i was the transmission ratio of the steering system, r_σ was the kingpin spindle offset, r_w was the rolling radius.

(5) The other power-assisted torque under other vehicle speed can be obtained by linear interpolation. The accomplished differential assisted characteristic curve is as Fig. 3.

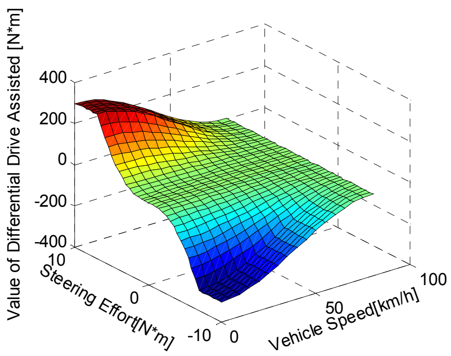

Fig. 3 The differential assisted characteristic curve

B. Returnability Control

In the handle property of the steering system, the reversal property was of significance. During the process of driving, the returning torque possessed the ability to return the steering-wheel to the middle when ended up the driving. According to the driving experience, the reversal ability was worse in low speed than higher speed. The main cause was the larger fiction torque under low speed which was smaller under high speed. Therefore, it was easier to return under high speed and harder under low speed. A simple PID controller was designed. The zero angle of the steering-wheel was its target and the proportional was used to return quickly. The integral terms were used to eliminate the constant error of the steering-wheel angle and the differential terms were used to control the damping. All these contributed to the accuracy of the returning sufficiently.

V. The Analysis of the Simulation Results

In order to analysis the effect of the assisted differential control, joint simulation analysis was conducted from three aspects: steering portability, analysis of the steering road feel and the analysis of the steering reversal property. The parameters of the steering system was shown as the Table I.

TABLE I
Parameters of Steering System

Parameters	Value
Lateral offset/mm	115
Kingpin inclination/deg	12
Caster angle/deg	3
Column inertia/kg·m^2	0.1
Column damping/N·m·s/deg	0.025
Column hysteresis/N·m	1.5

A. The Analysis of the Steering Portability

Lemniscate work condition was the steering portability test work condition in the national standard vehicle handle stability test which was mainly used to test the portability of the vehicle under low speed. This adopted the max steering torque and average steering torque to estimate the portability and the simulation was according to the GB/T 6323.5-94 standards. The result of the simulation was shown in Figs. 4~7.

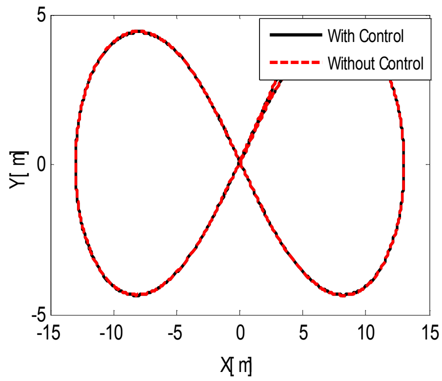

Fig. 4 X and Y Path

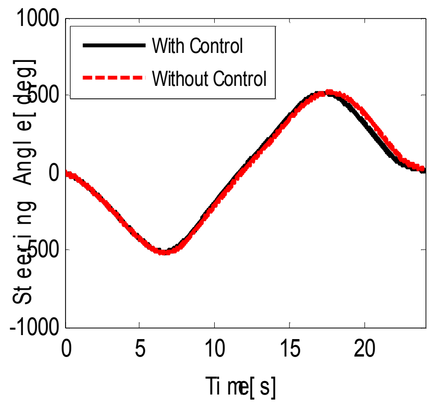

Fig. 5 Steering wheel angle

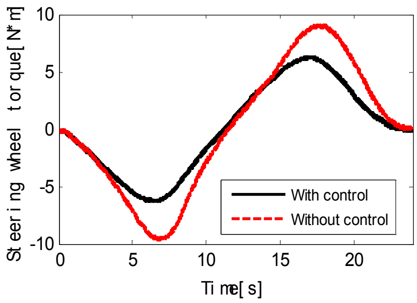

Fig. 6 Steering wheel torque

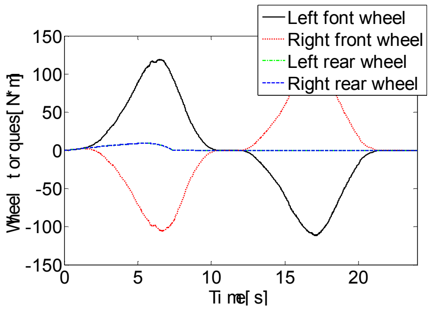

Fig. 7 Wheel torques

According to the pictures, under the control of assisted differential steering, the steering-wheel angle was diminished slightly and the phase position was brought forward, this was caused by the effects of the finished vehicle from differential assistance which increase the tilt angle gain of the finished vehicle to make the vehicle finish the work condition in advance (Fig. 5). As shown in Fig. 6, the steering-wheel torque was decreased sharply under control, the peak value was decreased from 9.8N·m to 6.2N·m, namely 36.7%, which can decrease the steering burden of the driver effectively by the assisted differential steering and improve the steering portability. From Fig. 7, in 2-10s, the orient of the vehicle differential steering torque was clockwise and the max differential steering torque was 220N·m same as the steering-wheel torque which can provided the steering assistance effectively. In 14-22s, the situation was similar.

B. The Analysis of the Steering Road Feel

In this paper, the steering stiffness, namely the proportion of the steering-wheel torque and steering-wheel angle, was used to be the indicator to estimate the steering road feel. The low speed (30km/h), middle speed (50km/h) and high speed (80km/h) were selected to conduct the steering test in the middle position and the steering stiffness was analyzed whether there was assisted differential steering control or not. The result was shown in Figs. 8~11.

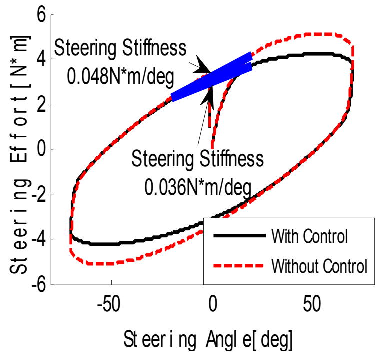

Fig. 8 Comparison of steering stiffness with/without control at 30km/h

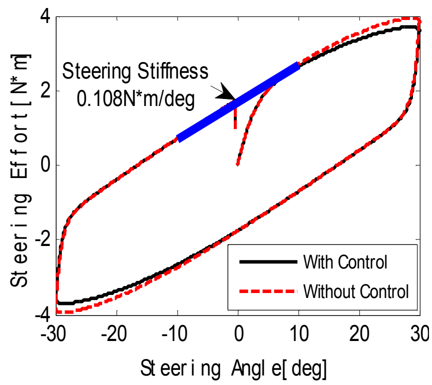

Fig. 9 Comparison of steering stiffness with/without control at 50km/h

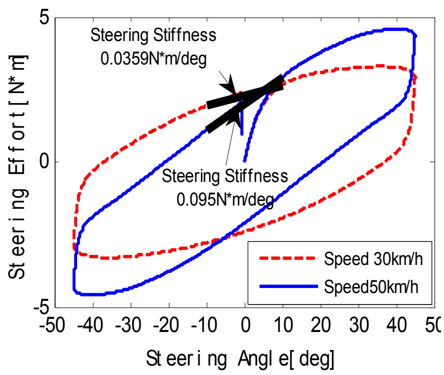

Fig. 10 Comparison of steering stiffness with/without control at 30 and 50km/h

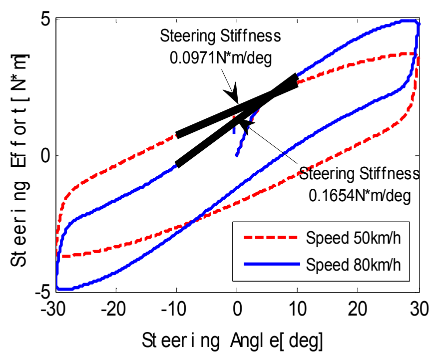

Fig. 11 Comparison of steering stiffness with/without control at 50 and 80km/h

From the assistance characteristic curve in Fig. 3, when the speed was above 80km/h, the assisted differential steering was not got involved so that there only analysis of steering stiffness whether there was control under the speed of 30km/h and 50km/h. According to Fig. 8, the differential assistance can decrease the steering-wheel torque effectively. However the steering stiffness would decrease after adding the assistance. That was to say that the road feel would be decreased by the dynamic steering to some degree which was the principle of the dynamic steering. According to Fig. 9, when the speed was added up to 50km/h, the assistance provided by the assisted differential steering decreased. And the steering stiffness under control or not were nearly the same which indicated that the assisted differential steering can provided variable steering assistance to keep the driving road feel under high speed.

The compared simulation results of the steering stiffness under the assisted differential steering control under low and medium speed and high speed were shown in the Figs. 10, 11. Along with the increase of the speed, the steering stiffness increased. It meant the needed steering-wheel torque was increased when the steering angle was the same which ensured the steering accuracy under high speed to ensure the straight driving of the vehicle and improve the road safety. From the results above, the interfere of assisted differential steering would not change the principle of the steering stiffness which would improve the steering portability meanwhile keep the road feel under medium and high speed.

C. The Analysis of the Returnability

Since the deficiency of the vehicle reversal property under low speed, in order to test the effectiveness of the reversal control algorithm, the vehicle reversal results whether there was reversal control algorithm or not were compared under 30km/h. At the beginning, kept the steering torque to be 6N·m and let it go in the 8th minute, namely the steering-wheel torque was from zero to the input value. Fig. 13 was the corresponding compared curves under two different circumstances whether there was active reversal control or not.

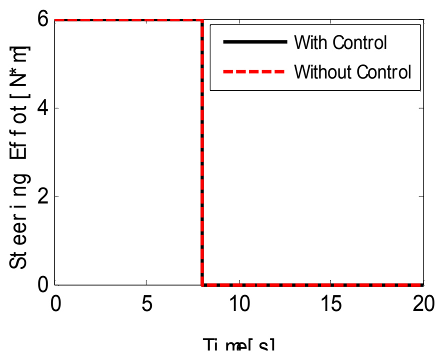

Fig. 12 Steering wheel torque input at 30km/h

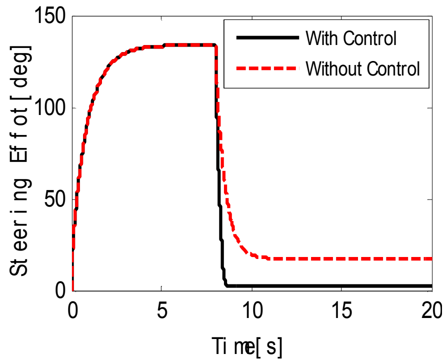

Fig. 13 Steering wheel angle at 30km/h

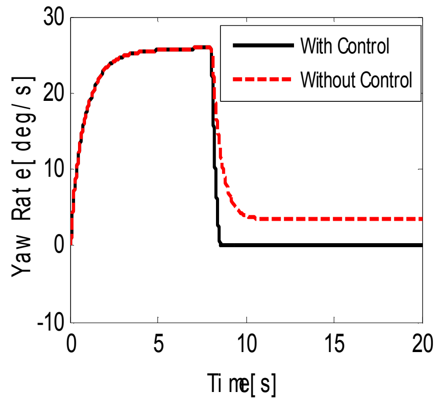

Fig. 14 Yaw rate at 30km/h

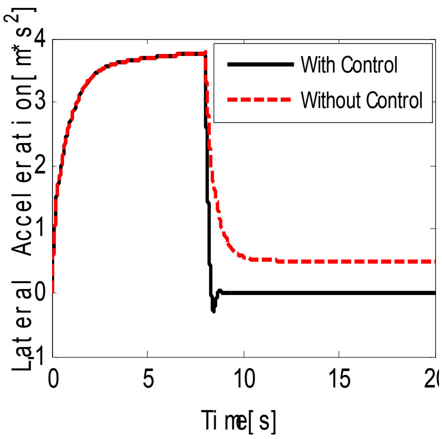

Fig. 15 Lateral acceleration at 30km/h

From Figs. 13~15, when the vehicle making a turn under low speed, since the effect of steering fiction resistance, the speed of the steering-wheel reversal was slow and it was hardly to return to the middle position accurately. There would be larger residual heading angle speed and lateral acceleration. Because of the introduction of the assisted differential reversal control, through controlling the left and right input differential steering torque, there would be effective and accurate steering reversal.

CONCLUSIONS

In this paper, control strategy of differential drive assisted steering of distributed drive electric vehicle was designed. And the conclusions conducted from the simulation were shown below.

(1) Same as the electric assisted steering, the assisted differential steering can provided the steering assistance varied with the speed. Under low speed, the steering assistance was provided to improve the steering portability. Along with the increase of the speed, the provided steering assistance decreased.

(2) When there was assisted differential control, the steering stiffness of the steering system increased along with the speed which ensured the road feel and improve the road safety.

(3) The control algorithm of assisted differential reversal can prevent the insufficiency of the vehicle reversal under low speed effectively.

ACKNOWLEDGMENT

This work was supported by National Basic Research Program of China (NO.2011CB711200).

REFERENCES

[1] Y. Q. Zhao, K. H. Guo. “A Research on Active Safety Evaluation of Vehicle”. *Automotive Engineering*, 2001, vol. 1, pp. 1-4.

[2] Y. Hori. “Future Vehicle Driven by Electricity and Control; Research on Four-Wheel-Motored ‘UOT Electric March II’ ”. *IEEE Transactions on Industrial Electronics*, vol. 51, pp. 954-962, 2004.

[3] A Youssef, C William. “Integrated chassis control system to enhance vehicle stability”. *International Journal of Vehicle Design,* 2006, vol 23,pp. 124-144.

[4] Z. P. Yu, Y. Feng, L. Xiong. “Review on Vehicle Dynamics Control of Distributed Drive Electric Vehicle”. *Chinese Journal of Mechanical Engineering,* vol. 8, pp. 105-114, 2013.

[5] S Gao, N. C. Cheung. “Skid Steering in 4-Wheel-Drive Electric Vehicle”. *In: Bangkok:* 2007, pp. 1548-1553

[6] J. N. Wang. “Study on Differential Drive Assist Steering Technology for Electric Vehicle with Independent-Motorized-Wheel-Drive”. Doctoral thesis, Jilin University. 2009.