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Research Article

Research on Steering Stability Control of Electric Vehicle Driven by Dual In-Wheel Motor

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Abstract
The dual in-wheel motor electric vehicle has the advantages of fast response and high flexibility, while its stability and safety are more difficult to control. To study the stability control of the dual in-wheel electric vehicle when turning, firstly, the paper establishes the Ackerman model of the dual in-wheel electric vehicle, and controls the wheel speed and slip rate by the method of logical threshold value; then establishes the linear two degree of freedom model of the double hub electric vehicle, obtains the vehicle yaw moment and ideal yaw rate by using the mathematical formula, and controls the wheel speed and slip rate by the sliding mode control. The moment is distributed so that the actual yaw rate keeps tracking the ideal value. The electronic differential control strategy of wheel slip rate and wheel yaw rate is established. Finally, the control strategy is simulated by MATLAB. The simulation results show that the proposed control strategy of slip rate and yaw rate can make the vehicle drive stably when turning.

Keywords: In-Wheel Motor, Steering Stability, Slip Rate, Yaw Rate, Sliding Mode Control, Electronic Differential

Introduction

The continuous expansion of car ownership has not only brought tremendous convenience to people's production activities and daily life, but also caused the consumption of energy and environmental pollution. Vigorously developing pure electric vehicles is an effective measure to solve the environmental pollution caused by exhaust from fossil-fueled car, which is significant to alleviate the energy crisis, improve the energy structure and construct a green transportation system.

The traditional electric vehicle drive system includes reducer, differential gear, drive shaft and other parts. A downside to hub motors being direct drive is that it wastes a certain amount of energy when drive wheels are rotated. Therefore, it can be inferred that the energy waste will be very low when we utilize hub motors drive without reducer and other parts [1, 2].

Aiming at the features of the independently controllable and quick response of torque of wheels in a hub motor-driven EV, the electronic differential control strategy is proposed with driving wheel torque as control variable and slip rate equilibrium of two driving wheels as control objective [3]. In order to solve the problem of traditional yaw moment control, for example, profound calculation and poor adaptability, several solutions have been proposed, including an adaptive lateral stability control system based on Fuzzy Neural Network FNN, a distributed estimation algorithm based on cooperation, and an adaptive sliding mode control method based on feedback linearization [4-6]. Qu Shuai contended that the driving torque can be controlled by the sliding mode, and he studied the rollover situation and put forward the corresponding anti-rollover strategy in his master degree dissertation [7]. Wang Chen argued in his master's degree paper that, with the actual tyre-road friction and wheel slip ratio as the input of fuzzy control, the torque output of each driving wheel is controlled by the sliding mode variable structure control theory, so that the slip ratio is always kept near the desired slip ratio [8]. The stability of all-wheel hub motor-driven EV is controlled by the direct-yaw-moment-control system (DYCS) based on Unscented Kalman Filter Method [9]. The total desired longitudinal force and yaw torque from the sliding mode vehicle controller are distributed to each wheel by the corresponding advanced allocation mode. In this way, the desired sliding ratio can be tracked [10].

Admittedly, the hub motor-driven EVs build compact electric motor into each wheel. Compared with traditional vehicles' stability controlled by mechanical differential braking, the hub motor works independently and responds quickly. With the increase of vehicle flexibility and freedom, it's also harder to control vehicle, which means a higher requirement for the stability and safety of the vehicle, as a result, a new control strategy should be put forward [11, 12]. Generally, the stability is well during straight line driving. However, it is a big difference when hub motor-driven EV turns, which thereby is worth studying the vehicle steering stability. Currently, most hub motor-driven EVs adopt direct-yaw-moment control (DYC) to accomplish vehicle stability manipulation. This paper aims to put forward a new strategy of vehicle stability during turning with slipping ratio and yaw ratio as control variable.

Dynamic Model of Dual In-Wheel Hub Motor-Driven EV

Model of Dual In-Wheel Hub Motor-Driven EV Based on Ackermann Steering Model

Assumption: 1) A vehicle is a rigid body; 2) The yawing force in driving is zero; 3) Drive wheel is for pure rolling motion.

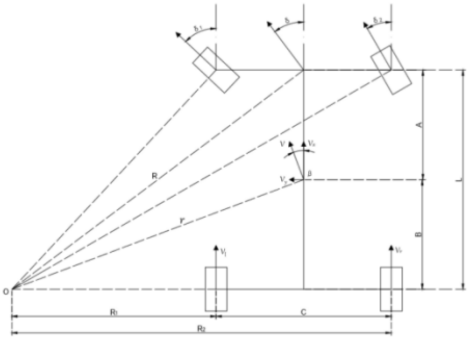

Figure 1: Ackermann Steering Model

Supposing that the vehicle turn left, V is the actual vehicle speed when turning, δ Ackermann steering Angle (vehicle steering Angle), δ_1 the left front wheel steering Angle, δ_2 the right front wheel steering Angle, and $\delta_1 > \delta_2$. O is vehicle steering center where the centerline of the four wheels meet, with L for wheelbase, C for wheel tread and A wheelbase centroid distance. And r is the radius of the vehicle mass center around the steering center O while R is the radius of front axle center around the steering center O; R_1 is the radius of the steering circle of the left rear wheel; R_2 is the radius of the steering circle of the right rear wheel; Vl the speed of the left rear wheel, and V_r the speed of the right rear wheel, see Fig. 1.

$$\begin{cases} \tan\delta = \dfrac{L}{R_1} \\ \tan\delta_1 = \dfrac{L}{R_1 + \dfrac{C}{2}} \\ \tan\delta_2 = \dfrac{L}{R_2} \\ r = \sqrt{B^2 + \left(R_1 + \dfrac{C}{2}\right)^2} \end{cases} \tag{1}$$

From Instantaneous Center Theorem, we can get:

$$\frac{V}{r} = \frac{V_l}{R_1} = \frac{V_r}{R_2} \tag{2}$$

Substituting (1) into (2) yields

$$\begin{cases} V_l = \dfrac{V\left(\dfrac{L}{\tan\delta} - \dfrac{C}{2}\right)}{\sqrt{B^2 + \left(\dfrac{L}{\tan\delta}\right)^2}} \\ V_r = \dfrac{V\left(\dfrac{L}{\tan\delta} + \dfrac{C}{2}\right)}{\sqrt{B^2 + \left(\dfrac{L}{\tan\delta}\right)^2}} \end{cases} \tag{3}$$

And the slip rate S can be given by

$$s = \begin{cases} \dfrac{W*R}{V} - 1\left(V > W*R, V \neq 0\right) \\ 1 - \dfrac{V}{W*R}\left(V < W*R, W \neq 0\right) \end{cases} \tag{4}$$

The equation (3) and (4) can be solved to yield the desired V1(left rear wheel), Vr(right rear wheel) and slip rate. Then, the actual speed of the vehicle is compared with the desired speed. The wheel speed is appropriately increased or decreased to ensure that the slip rate of the vehicle remains at a stable level.

Model for Hub Motor-Driven Electric Car Based on 2 DOFs Linear Model

In order to achieve 2 DOFs Linear Model as shown in Fig. 2, only lateral and yaw motion are considered with front wheel angle and vehicle speed forward unchanged. The model ignores the role of steering and suspension system. The vehicle is fixed in the plane of parallel ground. Tire sideslip property is always within the linear range with a small side-slip Angle.

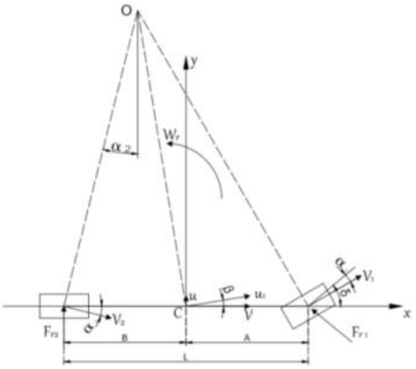

Figure 2: 2 DOFs Linear Model

The motion differential equations of 2 DOFs linear model is

$$\begin{cases} K_1\left(\beta + \dfrac{AW_r}{V} - \delta\right) + K_2\left(\beta - \dfrac{BW_r}{V}\right) = M\left(V\dot{\beta} + VW_r\right) \\ AK_1\left(\beta + \dfrac{AW_r}{V} - \delta\right) - BK_2\left(\beta - \dfrac{BW_r}{V}\right) = I_Z\dot{W}_r \end{cases} \tag{5}$$

The ideal yaw rate Wrd is generated with $\dot{\beta} = 0, \dot{W}_r = 0$, in (5),

$$W_{rd} = \frac{V}{(A+B)\left(1 + KV^2\right)}\delta \tag{6}$$

where K is stability coefficient determined by the parameters of vehicle itself. The equation of K is

$$K = \frac{M}{(A+B)^2}\left(\frac{A}{K_1} - \frac{B}{K_2}\right) \tag{7}$$

The calculation of slipping rate and yaw rate is achieved on the basis of the Ackermann Steering Model and 2 DOFs linear model.

Stability Strategy for Vehicle Steering

In this section, stability control strategy for vehicle differential steering is presented based on sliding mode control.

When the vehicle is on the road, the braking effect is best when the slip rate is around 20%, while the slip rate turns 0%, the vehicle has the strongest resistance to sideslip and the best stability. So, the optimal range of slip rate is from 0% to 20%, where the stability of vehicle can be guaranteed [13]. Because the yaw rate is affected by vehicle parameters, speed and steering angle, the vehicle lateral stability is better when the actual yaw angular speed are as close as the ideal speed [14].

Method

Based on Ackermann steering model and 2 DOFs linear model, the ideal vehicle speed and yaw rate have been calculated. The slip rate is manipulated through the logic threshold control method and the actual yaw rate is designed to track ideal rate by sliding mode control. Finally, in doing so, the stability control strategy for vehicle differential steering is achieved.

Procedure

Electrical differential control system is activated when vehicle turns. The ideal speed of left rear wheel and right rear wheel are worked out based on the Ackermann steering model with δ and V put into controller. The motor is controlled to track the reference speed, with the speed of the inner wheel down and the speed of the outer wheel up, which may lead to wheel slip. Therefore, the controller should calculate the slip rate in real time. When the wheel speed is detected, the outer speed decelerates and the inner speed accelerates with the slip rate within 0 ~ 20%. In order to keep the yaw rate within a proper range, the actual yaw moment $\mathbf{M_V}$ is calculated to track ideal yaw rate $\mathbf{W_{rd}}$. To achieve $\mathbf{M_V}$, we use sliding mode control method to define the sliding surface by the equation $s = \dot{E}+E$ where E is equal to $\mathbf{W_r}$-$\mathbf{W_{rd}}$ and based on constant reaching law $(\dot{s})$ is equal to $\mathbf{-k_r\,sgn(s)}$. And $\mathbf{W_{rd}}$ can be calculated by 2 DOFs linear model. By doing this, the vehicle steady differential steering is realized.

The electronic differential model is established as shown in Fig. 3. In this model, we put into the steering angle δ and speed V, on the basis of relevant mathematical equations, yielding the yaw rate and yaw moment of rear wheel in the control and un-control situations.

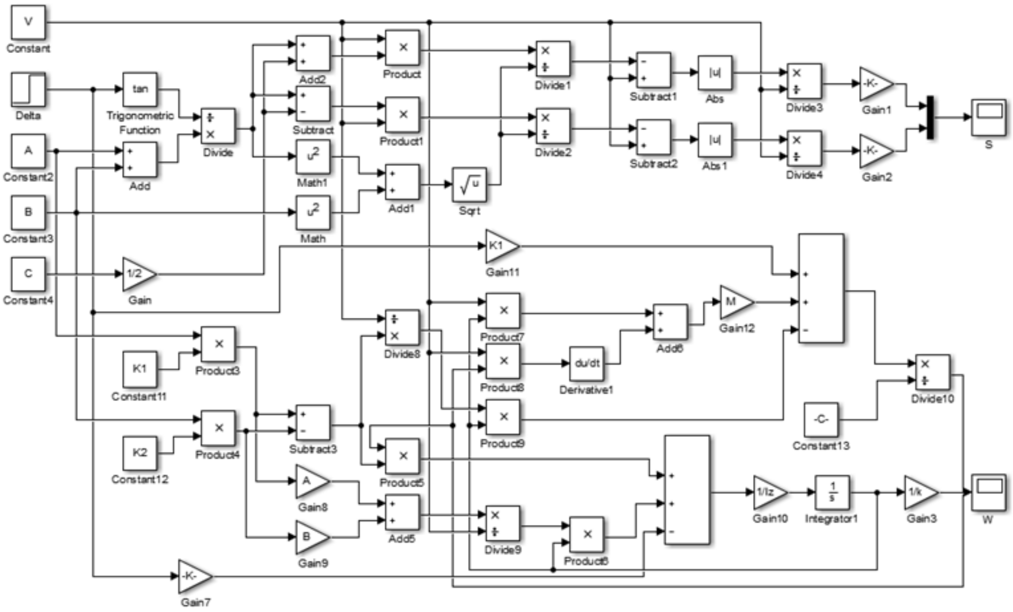

Figure 3: Electronic Differential Model

Experiment and Results

We simulated the proposed model in MATLAB/Simulink to prove its effectiveness. In the experiment, the vehicle parameters are listed as the following: A=1.22m, B=1.44m, C=1.80m, Iz=1808.8kg/m^2, K1=49342N·m / rad, K2=63176N·m / rad, M=1482.7kg.

The experiment is demonstrated as follows.

The simulation result, when front-wheel turning angle is equal to 5° or 20° at a velocity of 30 km/h in 3 seconds, are depicted in Fig. 4 and Fig. 5 respectively. It can be seen that under controlled conditions, the wheel slip rate is kept below 20%. When the steering angle is 5°, the controlled slip rate tends to be a stable range of 6%~7%, but the uncontrolled slip rate is up to 12%. When the steering angle is 20°, the controlled slip rate tends to be stable value of 8%~9%, while the uncontrolled slip rate obviously exceeds 20%, and the maximum can be 16%. Due to the low speed, the uncontrolled slip rate within 15 seconds does not exceed 20%, while the uncontrolled slip rate was significantly higher than the controlled one, indicating that under this condition, the control strategy can effectively improve the wheel slip rate.

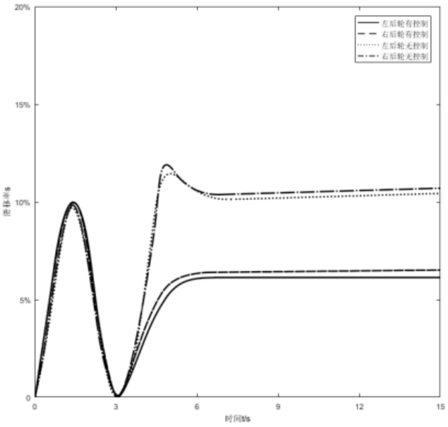

Figure 4: Front-Wheel Turning Angle=5°

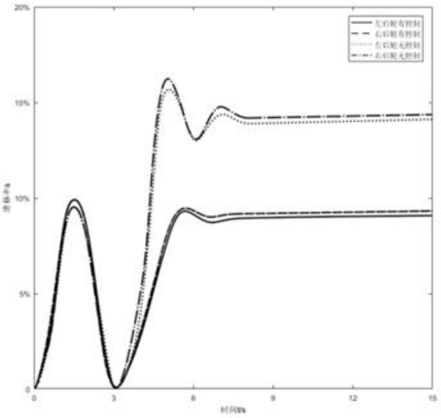

Figure 5: Front-Wheel Turning Angle=20°

The simulation result, when front-wheel turning angle is equal to 5° or 20° at a velocity of 70 km/h in 3 seconds, are depicted in Fig. 6 and Fig. 7 respectively. It can be seen that the slip rate of the left and right wheels fluctuated under the control, but remained below 20%. But the slip rate of the uncontrolled wheels significantly exceeded 20% and fluctuated obviously, showing an upward trend. When the steering angle is 5°, the controlled slip rate tends to be 13%-14%, while the uncontrolled slip rate is up to 34%. When the steering angle is 20°, the controlled slip rate tends to be a stable scope of 16%~17%, but the uncontrolled slip rate obviously exceeds 20% and the maximum can be 37%. It can be predicted that as the simulation continues, the uncontrolled wheel slip rate will increase rapidly and exceed 20%, leading to the instability caused by the yaw motion. The simulation results show that this control strategy can effectively improve the instability of vehicle slip rate when turning.

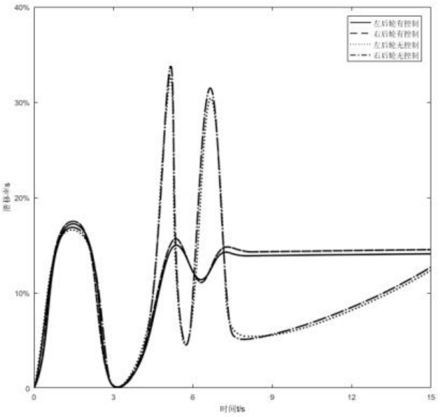

Figure 6: Front-Wheel Turning Angle 5°

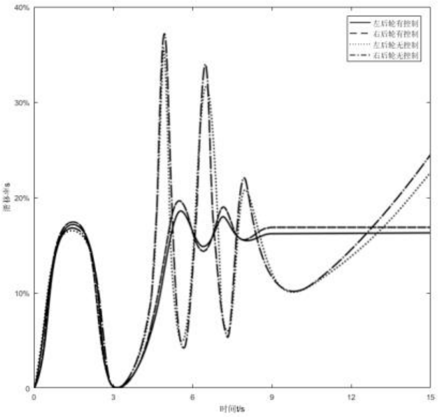

Figure 7: Front-Wheel Turning Angle 20°

Table 1: Wheel Slip Rate Data

		30km/h		70km/h	
		5°	**20°**	**5°**	**20°**
LW	Control	4%~7%	4.6%~7.5%	12%~15%	14.9%~19%
	Uncontrol	10%~12%	13.5%~16%	5%~32%	5%~35%
RW	Control	5%~7.5%	4.8%~7.7%	11.5%~16%	15.2%~20%
	Uncontrol	10%~13%	13%~16.5%	5.5%~34%	5%~37%
SS	Control	6%~7%	9%~10%	13%~14%	16%~17%
	Uncontrol	10%~11%	14%~15%	exponential growth	exponential growth

Simulation experiments were carried out at speeds of 30km/h and 70km/h. When the simulation time is 3s, the front wheel input step steering angle is 5°, and the comparison curves about the simulation results and ideal yaw rate under sliding mode control and yaw rate without control are obtained, as shown in Fig. 8 and Fig. 9. According to the simulation results, when no control is applied, the stable time is 13s and 10s at the speed of 30km/h and 70km/h respectively. In contrast, when the control is applied in 9s and 8s, the uncontrolled yaw velocity is significantly longer than the control rate in response. And the controlled yaw rate is closer to the ideal rate.

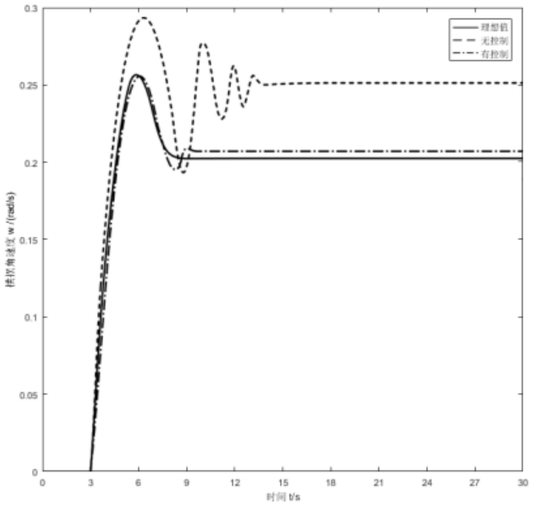

Figure 8: v=30km/h

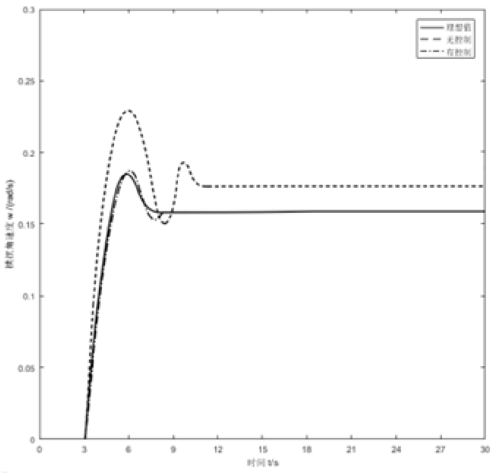

Figure 9: V=70km/h

The input of the front wheel step steering angle is 20° at speeds of 30km/h and 70km/h in 3 seconds. The results were shown in Fig. 10 and Fig. 11. It can be seen that, due to the increase of vehicle steering Angle, the mathematical value of uncontrolled yaw velocity fluctuates greatly and the response time increases significantly. The difference between the actual and the ideal value is 0.15-0.25rad /s. After the recalculation and distribution of vehicle yaw moment by sliding mode control, the actual value curves at 30km/h and 70km/h can be basically simulated to be reasonable value curves, indicating that the actual yaw velocity can operate well with the ideal value.

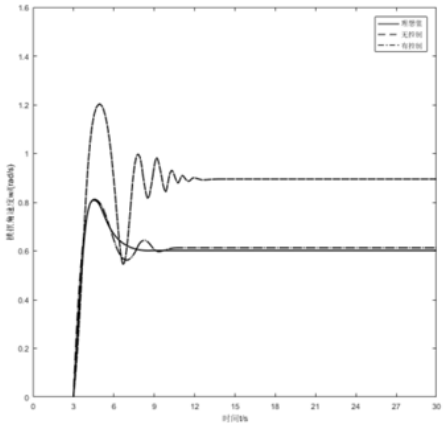

Figure 10: V=30km/h

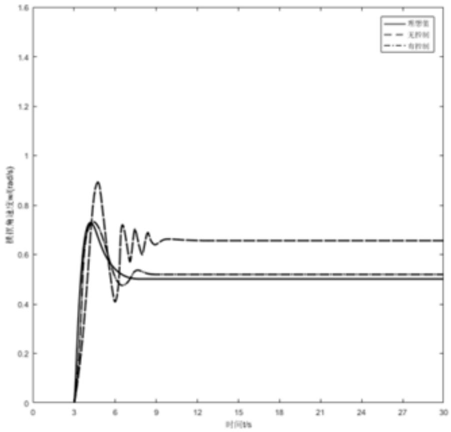

Figure 11: V=70km/h

Table 2: Yaw Rate Data

		30km/h		70km/h	
		5°	**20°**	**5°**	**20°**
Maximum	Control	0.25	0.8	0.18	0.75
	Uncontrol	0.295	1.2	0.23	0.9
Minimum	Control	0.194	0.553	0.153	0.5
	Uncontrol	0.19	0.55	0.15	0.4
$\lvert W - W_{rd} \rvert$	Ideal	0.2	0.6	0.155	0.52
	Control	0.002	0.003	0	0.005
	Uncontrol	0.05	0.25	0.025	0.15

Through the analysis of the experimental results, it can be seen that by controlling the wheel slip rate and the yaw rate, the vehicle can quickly reach a stable level. When the vehicle turns, the slip rate can be reduced and controlled within 20%. The yawing motion can be suppressed by adjusting the yaw moment of the vehicle. There is no difference between the actual and the ideal value of yaw velocity after stabilization, when vehicle can run smoothly at low or high speed.

Conclusion

1. Slip rate and yaw angle speed are selected as the factors reflecting vehicle stability based on the causes of vehicle instability. Slip rate changes caused by vehicle speed changes are analyzed on the basis of Ackermann model and controlled by logic threshold method. Vehicle instability caused by vehicle yaw angle speed is analyzed on the basis of 2 DOFs linear model. Feedback torque is controlled by sliding mode control algorithm so that actual yaw rate tracks the desired yaw rate.
2. 2The model is simulated in MATLAB/Simulink. When the front wheel angle and speed are input, the controlled slip rate always keeps in a stable range of 0%~20%, and the uncontrolled slip rate reaches the maximum of 32%. According to relevant data, the controlled yaw angular velocity can basically track the ideal rate except for the light fluctuation before stabilization, while there are problems without control, such as large fluctuation and inability to reach the ideal rate. It shows that this control strategy can significantly improve the slip rate and yaw rate of the vehicle.
3. Analyzing the principle and simulation of control strategy, the proposed control strategy can suppress vehicle slip and yaw motion at the same time. Compared with the strategy with single variable, the former can perform more effective in maintaining vehicle stability [5, 8, 13]. Experiment shows that the control strategy is able to guarantee the steering stability of the dual in-wheel hub motor-driven EV.

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