Effect of Dynamics Control Strategy on Performance of FSEC Racing Car

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Abstract. The control strategy of driving system for the distributed electric drive DRe20 car of Tongji University DIAN Racing team is developed and optimized according to the competition rules of Formula Student Electric China (FSEC). The VI-grade and Matlab Simulink co-simulation experimental platform is established to study the effects of different dynamic control strategies, such as equal distribution, open-loop electronic differential and limited slip differential, on the performance of the DRe20 racing car. The simulation platform is also used to optimize the control algorithm and the setting of different parameters in the program, then the results of simulation analysis and optimization are applied to the actual car experiment, providing a lot of reference data for the adjustment of suspension system and electronic control system of the DRe20 car. The simulation and actual test results show that the limited slip differential control strategy we developed and optimized in 2020 can give full play to the design performance of the DRe20 car, and the comprehensive performances have been improved compared with those in previous years. The optimized dynamics control strategy has been applied to Tongji DIAN Racing car during the 2020 Formula Student Electric China competition, in which Tongji DIAN Racing Team wins the championship.

Keywords: Dynamics control strategy; FSEC; Simulation; Distributed electric drive.

1. Introduction

Formula Student Electric China (FSEC) is an automotive design and manufacturing competition for teams of students from automotive engineering-related disciplines [1]. Tongji University DIAN Racing Team's car has been used a distributed four-wheel drive powertrain since 2016. The distributed drive structure allows power output on multiple wheels to be deployed simultaneously, giving the car more freedom to actively control, so active control systems such as torque distribution are key to improving the performance and stability of the distributed drive cars [2], [3], [4], [5].

The function of the vehicle dynamics control strategy is to analyze the current sensor data of the vehicle according to the driver’s steering, acceleration and braking commands, and finally output a set of calculated torque control commands to each motor. This driving assistance system is designed to improve the stability of vehicle handling, so as to provide drivers with conditions to create faster lap speed. The control strategy must be well matched with the adjustment of the vehicle mechanical system in order to play the advantages of four-wheel drive.

A few articles reported studies on simulation analysis of FSEC racing chassis layout design [6], frame conditions [7], handling stability [8] etc., however, a little work has been reported on the dynamics control strategy of FSEC racing car. In this work, the simulation and actual test results of the dynamic control strategy of Tongji University DIAN Racing Team’s DRe20 racing car has been studied. It is expected that it can provide valuable references in the design and simulation experiments of the racing car for the subsequent teams participating in the FSEC competition.

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2. Dynamics Control Strategy of the DRe20 Racing Car

The dynamics control strategy of the DRe20 racing car takes the wheel speed as the final control target, and the motor speed is the direct control target. The steering geometry of the car is the basis of the speed control, which reduces the control program's dependence on sensor signals compared with the previous version, in addition to standardizing the control program and improving the safety and stability of the system. The whole control program is mainly composed of three modules: sensor signals input and data processing, power management and monitoring, motor torque dynamic distribution control, as shown in Figure 1.

![Figure 1. Schematic diagram of dynamics control strategy of the DRe20 racing car.](image)

2.1. Sensor Signals Input and Data Processing

The module of sensor signals input and data processing mainly converts various sensor signals into parameters and signal data required for vehicle dynamics calculation. Table 1 lists configuration of sensors and measured variables on the DRe20 racing car. The dynamic control and simulation software of the DRe20 car uses the DIN7000 coordinate system commonly used in the automotive industry, that is, the x-axis points to the forward direction of the car, the y-axis points to the left side of the forward direction, and the z-axis is vertically up.

Because there is no steering sensor in the front suspension, the front wheel angle is calculated through the data of the steering wheel angle sensor according to the mechanical parameters of the steering system. The steering system of the DRe20 racing car is designed in accordance with Ackermann geometry. The angles of the front left and right wheels can be obtained by the steering wheel angle [9], which provides the necessary basic data for calculating the relationship between the ideal speed of each wheel.

Since the Ackermann geometric relationship can only describe the steering center position of the vehicle at low speed ignoring the tire sideslip angle. In order to get the accurate calculation of the control target speed and realize electronic differential control, we consider the influence of the front and rear wheel’s sideslip angle on the steering center point at higher speed, calculate the forward displacement of the steering instantaneous center on the center line of the track compared with the center point of the rear axle, and then according to the geometric relationship in the chassis system, calculate the instantaneous radius $R_{ij}$ of each wheel under the condition of tire cornering. According to the motion law of rigid body, the velocity $V_{ij}$ of each wheel can be obtained. At the same time, through the measured data of the motor speed sensor of each wheel, the actual speed $V_{ij1}$ of each wheel relative to the ground coordinate system is calculated, and realize the electronic differential control by $V_{ij} - V_{ij1}$.

In the actual racing car, the sensor may fail, which leads to the failure of obtaining the corresponding accurate data. At this time, the dynamics control system should not only ensure the safety of the output, but also use other sensor’s signals to replace the output of the fault sensor on the premise of ensuring safety, so as to minimize the impact of the fault of individual sensors on the torque control system. For this reason, the sensors on the DRe20 racing car have been equipped with a self-test system, and the safety redundant processing of the signals in the program has been set up. When a sensor fails, the control system will enter the corresponding low-level mode to prevent dangerous output with less loss of the performance.
Table 1. Sensor configuration and measured variables on the DRe20 racing car.

| Sensor name            | Sensor position                                                   | Measured variables                                      |
|------------------------|-------------------------------------------------------------------|----------------------------------------------------------|
| Optical sensors        | The midpoint of the front axle                                    | Speed, Side deviation of the mass center                 |
| Gyroscope              | A projection of the mass center on the surface beneath the monomer shell | Acceleration and angular acceleration in x, y, z directions |
| Motor speed, Torque sensor | Integrated inside the motor                                    | Motor speed, torque, power                               |
| Angle sensors          | Next to the steering wheel universal section                     | Steering wheel angle                                     |
| Line displacement sensor | Acceleration and brake pedals                                  | Acceleration and brake pedal opening                      |
| Oil pressure sensor    | The front part of the monomer shell                              | Brake oil pressure                                       |
| High-voltage battery status sensor | Battery management unit integration | Battery output current and voltage                        |

2.2. Power Management and Monitoring

The module of the power management and monitoring uses feedback closed-loop control, and the system accurately regulates the output command of current torque according to the actual output power returned from accumulator management system (AMS).

2.2.1. Idea of dynamic power limitation

Previous programs put the power limitation strategy behind the torque calculation unit, which leads to the distortion of the torque calculation command in some control algorithms due to the hardware conditions and rules, and don’t give full play to the performance. The dynamic control program of the DRe20 car is changed to arrange the power limiter before the torque calculation unit, and the maximum available torque considering the power limitation condition is transmitted to the torque calculation unit. The control logic of the scheme is shown in Figure 2.

![Figure 2. Schematic diagram of the dynamic power control.](image)

2.2.2. Implementation of power management / power limitation

The motor used in DRe20 racing car is an A2370DD (DD5-14-10-pow-18600-B5) motor produced by AMK company. According to the motor power-speed characteristic curve provided by AMK, combined
with the total power limit of 80 kW required by the competition rules, the power management and power limit of this control strategy are as follows:

When the motor speed is lower than 8,800 rpm or in the range of 8,800 rpm-20,000 rpm, the drive distribution ratio $F_{z\text{Ratio}}$ meets the conditions as in formula (1), the total power of the motor will not exceed the power of 80 kW limit theoretically.

$$F_{z\text{Ratio}} < \frac{40 - P_{\text{max}}}{40}$$  \hspace{1cm} (1)

Where $P_{\text{max}}$ is the maximum output power of a single motor at this speed, and $F_{z\text{Ratio}}$ is the power allocated by the front wheels/total driving power.

According to the motor's maximum output power of 30 kW (without using field weakening control) at 10,800 rpm-12,800 rpm to calculate the $F_{z\text{Ratio}}$ value, when $F_{z\text{Ratio}}$ is less than 0.25, the total motor power will not exceed the rule limit of 80 kW at any speed. Therefore, when the program calculates that the motor is working in the above interval, the torque will not be limited during the torque command generation stage. When $F_{z\text{Ratio}}$ is larger, the formula (1) can be used to reversely deduce the degree of power limit under a certain $F_{z\text{Ratio}}$. For example, the output power of a single motor (rear wheel motor) should be limited to 28 kW or less for the front-to-rear distribution ratio of 3 : 7, which is often used by the vehicle team.

2.2.3. Feedback control

In order to realize the closed-loop control of driving power, the feedback control is added based on the power management strategy. The feedback control reads the voltage and current signals in AMS to calculate the current actual total output power of the vehicle, and compares it with the preset limit value, precisely adjust the current torque output command. The test results show that the maximum power output can reach 97% of the limit value without exceeding the set limit value with this power control strategy.

The new power management strategy has greatly improved the responsiveness and accuracy, thus greatly improving the power release of the motor. On the other hand, the controller directly outputs torque demand command, simplifies the repeated calculation of the corresponding parts of the torque calculation unit, and optimizes the structure of the whole control program.

2.3. Dynamic Distribution Control of the Motor Torque

The module of the dynamic distribution control of the motor torque mainly includes power torque calculation and second braking torque calculation. Two control units are used in power torque calculation, namely the open-loop electronic differential controller and the electronic limited slip differential controller with feedback control. Load transfer is considered in the second braking torque calculation, and the front and rear braking force distribution ratio is adjusted according to the size of vehicle braking deceleration.

For the distributed electric drive vehicles, the wheels on both sides are driven by two independent motors, so the speed of the two wheels is decoupled. Theoretically, the wheels on both sides have differential characteristics even if both sides have equal power output. But at this time, more longitudinal force of the tires is used to offset the torque difference between the inner and outer wheels due to the steering, so that the lateral force provided by the tires is reduced, and the steering limit of the vehicle is reduced, resulting in more sliding and wear of the tires. In order to improve this problem and take advantage of the distributed electric drive vehicle in control, this control strategy outputs different torques to the inner and outer wheels in the process of vehicle steering, so as to better follow their different wheel speeds, or use the torque difference between the inner and outer wheels to actively assist the vehicle steering.

2.3.1. The open-loop electronic differential controller

The open-loop electronic differential controls the torque output of the motor on each wheel in proportion to the speed of each wheel according to the steering geometry of the vehicle. The program structure of the open-loop electronic differential controller is shown in Figure 3. For the distributed drive electric vehicles, this control strategy can greatly improve the situation of dragging caused by mismatched motor
outputs on both sides during steering. Under steady-state steering, the open-loop electronic differential can provide better steering following characteristics, the force distribution of the inner and outer wheels is more reasonable, and the tire longitudinal slip is less.

2.3.2. The electronic limited slip differential (LSD) controller
The open-loop electronic differential speed controller can only distribute the torque to each motor in a fixed proportion according to the preset distribution formula, while the actual wheel slip will not be referenced by the control system and interfered. The control of wheel sliding depends entirely on the driver's control, and the electronic system does not interfere. In order to enhance the vehicle handling stability and safety in extreme conditions, the longitudinal slip of the wheel is introduced into the controller, and the torque output of each wheel is adjusted in real time according to the wheel slip, which is the function of the electronic limited slip differential (LSD) control module. The LSD controller takes the ideal speed of each wheel as the control target. The key point of the program is to use the vehicle speed data from the steering wheel displacement sensor and the optical sensor to calculate the speed of each wheel in a pure scrolling condition based on the geometric parameters of the vehicle, and then compare it with the motor speed (corresponding to the actual wheel speed), and get the output torque of each motor.

The LSD controller converts the speed of each wheel to the ideal speed of the motor, and then calculates the difference with the actual speed returned by the motor. The PID method is used for compensation control. Theoretically, the longitudinal slip rate of each wheel can be controlled within the setting range. This function can use the torque of the motor to control the wheel speed when the wheel has excessive slip, so as to restore the adhesion of the tire as soon as possible.

2.3.3. Setting of intervention time of the LSD System under vehicle extreme conditions
In the process of vehicle driving, there are many differences between transient state and steady state. Taking the two control methods used in the DRe20 car as an example, the open-loop electronic differential is suitable for improving the steering maneuverability of the vehicle in steady state, while the LSD controller can provide better stability in extreme conditions, and help the driver recover the grip of the wheel when the wheel slips, so as to quickly get out of control. However, if the control system which is suitable for extreme conditions is continuously intervened in the steady state, it may lead to the decline of vehicle performance, and make the driver feel a strong sense of intervention, which has a negative impact on the vehicle performance. Therefore, it is necessary to limit the intervention of the LSD system, so that it can automatically exit the work when the vehicle is in a steady state.

After a lot of tests, we compared the vehicle performance, safety and driver experience, and adopted the following ways to control the intervention of the LSD electronic auxiliary system: Only when the longitudinal slip rate of a wheel is more than 12% and the wheel speed is greater than 2 km / h (to prevent the electronic auxiliary system from intervening when reversing), the LSD system can be allowed to intervene to control the torque of the motor on the wheel. In addition, the driver can forcibly
turn off the LSD electronic auxiliary system through the control switch, so as to completely take over the control of the car.

3. Computer Simulation Test and Actual Measurement Results of the DRe20 Racing Car

The computer simulation test is carried out in two simulation environments, namely the Matlab Simulink and the VI-grade Simulink joint simulation platform. In the Matlab Simulink tool, the simulation verification of the double-shifting project and linear acceleration have been carried out. The main goal is to verify the effects of the open-loop electronic differential control and the LSD control during steering on the lateral limit and handling stability of the car. In the VI-grade co-simulation platform, tests were mainly carried out in 8-word loop and high-speed obstacle avoidance projects to analyze the transient and steady-state handling performance of the DRe20 racing car when turning.

In order to make the program as interchangeable as possible, the same program architecture and signal format as those on the actual car have been adopted in the signal processing of the program. The model verified in the simulation can be directly used in the real vehicle control program without additional compilation or rewriting. Through the co-simulation test, we can not only test the safety and performance improvement of the control strategy, but also find the change of vehicle performance caused by parameter adjustments and changes. The simulation test and the actual vehicle test provides a large amount of reference data for the adjustment of the vehicle's suspension system and the electronic control system, which plays a more important role.

3.1. Simulation and Actual Measurement Results of 8-word Loop with Different Control Strategies

In order to compare the theoretical limit differences of different control strategies, the following control strategies are simulated and tested in the co-simulation platform: equal torque distribution between left and right (Abbreviated as equal), the open-loop electronic differential and the electronic limited slip differential (LSD) control. The performance of the control strategy in 2019 is also included as a reference. The average lap speed (average time per lap) is one of the most intuitive performance data, which can strongly reflect the improvement effect brought by the dynamic control strategy. Figure 4 and Figure 5 respectively show the average lap speed results of the simulation and the actual vehicle measurement of the DRe20 racing car under above different control strategies.

It can be seen from Figures 4 and 5 that different control strategies have different effects on the performance of the DRe20 car. The changing trend of the simulation results with different control strategies is the same as that of the actual vehicle measurement results. The average lap speed of the electronic differential control and the LSD control strategy we have adopted in the 8-word loop project is significantly higher than that of the equal allocation and the control strategy in 2019. Because the LSD control strategy can improve the vehicle stability, non-professional drivers are more likely to approach the vehicle limit when driving the car with the LSD system. Therefore, in the actual test, the improvement after the introduction of the LSD control is greater than its theoretical influence, as shown in Figures 4 and 5.

![Figure 4. Simulation results of average lap speed under different control strategies for the DRe20 car.](image1)

![Figure 5. Actual measurement results of average lap speed under different control strategies for the DRe20 car.](image2)
It should be noted that for the electronic differential and the LSD control system, different parameter settings make the simulation results different. In the LSD control system, in order to achieve accurate control of speed, PID control is used for motor torque control. However, only when the PID parameters are set reasonably, the torque correction can best respond to the speed difference. Among them, the appropriate value of $P$ can be obtained by theoretical calculation of the physical characteristics of the motor, while the adjustment of the integral coefficient $I$ value is relatively difficult. Compared with calibration on the actual car, testing the change trend of the car performance with the $I$ value in the simulation platform can greatly speed up the process of parameter calibration on the actual car. In the 8-word loop project, we simulated the average speed of the car with different $I$ value in the LSD control system. The results are shown in Table 2.

### Table 2. The simulation results of the average speed with different $I$ value in the LSD system.

| $I$ value | Average speed (km h$^{-1}$) | $I$ value | Average speed (km h$^{-1}$) |
|----------|----------------------------|----------|----------------------------|
| 0.8      | 40.288215                  | 3.2      | 40.287826                  |
| 1.0      | 40.289070                  | 4.0      | 40.284611                  |
| 1.2      | 40.289491                  | 5.0      | 40.284384                  |
| 1.6      | 40.290395                  | 6.0      | 40.283953                  |
| 2.5      | 40.295797                  | 8.0      | 40.284265                  |

For the electronic differential controller, we also test the vehicle properties with different $N$ values, and find out the theoretical range of $N$ values with better lap speed results. The result recorded in Figures 4 and 5 is the data when $N = 4$. In the test, we found that the electronic differential control system has the best assisting effect on vehicle steering when $N = 3-5$ for the DRe20 car.

### 3.2. Simulation and Actual Measurement Results of High-speed Obstacle Avoidance Project with Different Control Strategies

The test of the high-speed obstacle avoidance track focuses more on the corresponding speed and stability of the car during transient steering. Except for the track layout, the rest of the test conditions are the same as those in the 8-word loop project. The high-speed obstacle avoidance track consists of a long straight line, high-speed corners, low-speed corners and a serpentine section around piles. Because the high-speed obstacle avoidance track is longer, the amount of data that needs to be loaded for the simulation is more than that of the 8-word loop, and the parameter adjustment also needs to consider the performance balance on the straight and curve track, only part of the optimization algorithm was simulated. Table 3 shows the simulation results of the high-speed obstacle avoidance track tests with different control strategies. Through the comparison of the data in Table 3, it can be seen that the torque distribution scheme of the open-loop electronic differential improves the average speed and extreme speed of the car in the track, and makes the car obtain greater peak lateral acceleration. However, after using the distributed torque control scheme with the LSD intervention, the acceleration at low speed and exiting corners has been improved, which shows that the LSD system can effectively control the torque output of the inner and outer wheels and prevent the car from turning too much when exiting corners and accelerating. The performance of the car is significantly improved.
Table 3. The simulation results of the high-speed obstacle avoidance test with different strategies.

| Variable                  | Equal     | Electronic Differential | LSD       |
|---------------------------|-----------|-------------------------|-----------|
| LAP TIME                  | 83.4185   | 83.4185                 | 83.4185   |
| LAT ACCEL MAX (G)         | 1.717823  | 1.78422                 | 1.615517  |
| LAT ACCEL MIN (G)         | -1.762442 | -1.763851               | -1.700291 |
| LON ACCEL MAX (G)         | 0.914473  | 0.919707                | 0.88547   |
| LON ACCEL MIN (G)         | -2.258094 | -2.259036               | -2.258796 |
| LON SPEED MAX (km h⁻¹)    | 82.586363 | 82.60808                | 82.574082 |
| LON SPEED MIN (km h⁻¹)    | 24.356803 | 24.51808                | 24.262452 |
| LON SPEED AVG (km h⁻¹)    | 51.859615 | 51.884002               | 51.922012 |
| STEERING MAX (rad)        | 2.57083   | 2.578573                | 4.114565  |
| STEERING MIN (rad)        | 1.485483  | 1.650693                | 1.620952  |

Figure 6. Record diagram of the LSD control intervention state during an actual test of the DRe20 racing car by Matlab script.

In the dynamic control strategy of the DRe20 racing car, the control system can switch between the open-loop electronic differential and the LSD manually or automatically, so as to adapt to the needs of more scenarios. Figure 6 records the result of an actual test in which the LSD intervention state is expanded to the position coordinates by Matlab script. The LSD state at the red points in the figure is the intervention state, while the gray points indicates that the LSD control is not intervened. It can be seen that our control strategy can be implemented well in actual vehicle operation. The open-loop electronic differential control scheme is applied in the long straight track to effectively improve the average speed and extreme speed of the car. At low speeds and acceleration when exiting corners, the LSD control is timely intervened to enable the car to exit corners and accelerate with higher stability. This effectively improves the comprehensive performance of the car, such as the average lap speed, extreme speed, stability and safety.

4. Conclusion

This article introduces the dynamics control strategy developed by the Tongji University DIAN Racing Team in 2020 season. The control strategy is optimized on the simulation platform, and the influence of each parameter setting on the effect of the control algorithm has been studied, and the best theoretical value of each parameter is obtained and analyzed. The influence of different control strategies on the
performance of the racing car has been researched. The simulation and actual vehicle test results show that the dynamics control strategy we developed this season can effectively improve the overall performance of the DRe20 racing car, and it has sufficient reliability and stability in the real-vehicle applications. This article has certain reference value and important significance for the subsequent FSEC teams in the development, design and simulation experiment of the dynamics control strategy.

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