Research on the Distribution Strategy of Longitudinal Driving Force of Vehicle Driven by 8×8 In-wheel Motors

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Abstract. In order to meet the driving requirements of 8×8 in-wheel motor-driven vehicles, and to improve the adhesion performance of the vehicle at the same time, using the characteristics that each wheel can be controlled independently, a driving force distribution algorithm based on the optimal load of adhesion performance is designed. The mathematical model of the vehicle dynamics and the driving force distribution algorithm are built in Matlab/Simulink, and the effectiveness of the algorithm is verified through simulation tests, that is, it can meet the driver’s longitudinal dynamics requirements, take into account the limitations of the road and the motor, and reduce the load of the adhesion.

1. Introduction
As a high-mobility weapon and equipment, wheeled vehicles increasingly play an increasing role in various military conflicts. With the continuous development of distributed electric driving technology, there are more manners in arrangement of designing vehicles, and the power performance of the vehicles has been further improved. The driving force distribution strategy plays a great role in how to maintain power continuity and vehicle stability in complex working conditions. A considerable difference from traditional vehicles is that, distributed in-wheel motor-driven vehicles do not have differentials and differential locks between wheels and driving axles. When driving in conditions such as pavements with different adhesion coefficients, the driving force distribution strategy can avoid wasting driving force and keep the vehicle’s dynamic performance. Driving force distribution strategies can be divided into no optimization goal and setting optimization goal. The optimization goal can be the least of motor energy consumption, the least of tires’ utilization rate, etc. The optimization method can be ordinary least squares, generalized inverse matrix, quadratic programming and so on. It should take account of the more special conditions for 8×8 vehicles, such as driving on road with low adhesion coefficient, overcoming obstacles, driving on icy and snowy roads, etc. There are more constraints for 8×8 vehicles, it takes longer to calculate when using some optimization algorithms, and it is hard to solve the optimal value sometimes. According to the special needs of 8×8 distributed drive electric vehicles, this paper conducts longitudinal driving force distribution research. Based on a more mature strategy of 4×4 vehicles, a design for 8×8 vehicles driven by in-wheel motors is designed. The longitudinal driving force distribution strategy takes the all-wheel adhesion performance as the optimization goal, takes the road adhesion limit and the motor torque limit as the constraints, and coordinates the distribution of the driving force of each wheel according to the state and driving requirements of the vehicle.
2. Vehicle longitudinal dynamics control requirements
A major feature of the in-wheel motor-driven vehicle is that the torque of each drive wheel can be controlled independently. In view of this feature, control of vehicle longitudinal dynamics needs to meet these following requirements\(^{[12]}\):

1. Ensure the longitudinal driving force and yaw moment required by the vehicle;
2. Make full use of the advantage that the electric driving chassis can distribute the driving torque flexibly to each driving motor, so it can set the objective function and constraints to optimize the dynamic performance of the vehicle;
3. Try to avoid wheel skidding.

3. Constraints of vehicle longitudinal dynamics control
From the perspective of the entire vehicle and each driving wheel, vehicle longitudinal driving control needs to meet the following four constraints\(^{[13]}\).

- The driving control must meet the needs of the vehicle's longitudinal acceleration:
  \[\sum F_{ij} = F_{req}\]  
  \(F_{ij}\) is the driving force of each wheel. In order to meet the driver's acceleration needs, the sum of various resistances need to be overcome by \(F_{req}\). \(i = 1, 2, 3, 4\) represents 1 to 4 axles. \(j = 1, 2\) represents left or right of the vehicle.

- The driving control must meet the requirement of the vehicle's yaw moment:
  \[M = M_{req}\]  
  \(M\) is the additional yaw moment generated by the driving force of each wheel. \(M_{req}\) is the yaw moment requirement.

- The driving force generated by each driving wheel should not exceed the peak adhesion:
  \[F_{ij} \leq \mu F_{zij}\]  
  \(\mu\) is adhesion coefficient. \(F_{zij}\) is the vertical load of each drive wheel.

- The driving force generated by each driving wheel should not exceed the force corresponding to the peak torque of the motor:
  \[F_{ij} \leq F_{mij}\]  
  \(F_{mij}\) is the driving force corresponding to the peak torque of each driving motor.

These above are the constraints which contain acceleration requirement, yaw moment requirement, driving motor capacity limitation, and ground adhesion limitation. The constraints include 2 equalities and 16 inequalities.

4. Research on Distribution Strategy of Longitudinal Driving Force
For 8×8 in-wheel motor-driven vehicles, due to the large number of variables need to be controlled, it is difficult to calculate the driving force distribution under the constraints above directly. Therefore, the 8×8 vehicle can be regarded as a 4×4 vehicle, that is, combine the two driving wheels of front left, rear left, front right, and rear right into one driving wheel separately. In this way, the constraints change into 2 equations and 8 inequalities, and the quantity of variables that need to be calculated also reduces from 8 to 4. After completing the calculation of the driving force distribution, each driving wheel that has been allocated driving force is split into two wheels, and we can distribute driving force among the four driving wheels at the front and at the rear of the vehicle in the same way.
When the vehicle is regarded as a 4×4 in-wheel motor-driven vehicle, the constraints can be:

\[ F_{x1} + F_{x2} + F_{x3} + F_{x4} = F_{req} \]  
\[ \frac{B}{2} (F_{x1} + F_{x3}) + \frac{B}{2} (F_{x2} + F_{x4}) = M_{req} \]  
\[ |F_{xi}| \leq F_{mi} \]  
\[ |F_{wi}| \leq \mu F_{zi} \]

Organize and calculate the above formula:

\[ F_{x3} + F_{x3} = \frac{F_{req}}{2} - \frac{M_{req}}{B} \]  
\[ F_{x2} + F_{x4} = \frac{F_{req}}{2} + \frac{M_{req}}{B} \]

Let \( F_{req} / 2 - \frac{M_{req}}{B} = P_1 \), \( F_{req} / 2 + \frac{M_{req}}{B} = P_2 \), then put them into (3) and (4) respectively:

\[ P_2 - \mu \mu F_{z2} \leq F_{x4} \leq P_2 + \mu \mu F_{z2} \]  
\[ P_2 - F_{w2} \leq F_{x4} \leq P_2 + F_{w2} \]  
\[ P_1 - \mu \mu F_{z3} \leq F_{x3} \leq P_1 + \mu \mu F_{z3} \]  
\[ P_1 - F_{w1} \leq F_{x3} \leq P_1 + F_{w1} \]

This transforms the constraint condition with \( F_{x1}, F_{x2}, F_{x3}, F_{x4} \) four variables into a constraint condition with only \( F_{x3}, F_{x4} \) two variables.

The above are the constraints that need to be followed in longitudinal drive force distribution when the whole vehicle is regarded as a 4×4 in-wheel motor-driven vehicle. The constraints comprehensively consider the driver's requirements of the vehicle dynamics performance and the limitations of the adhesion and the driving motors. The constraints can be organized into the following form:

\[ \max(P_2 - \mu \mu F_{z2}, P_2 - F_{w2}, -\mu \mu F_{z4}, -F_{w4}) \leq F_{x4} \leq \min(P_2 + \mu \mu F_{z2}, P_2 + F_{w2}, \mu \mu F_{z4}, F_{w4}) \]  
\[ \max(P_1 - \mu \mu F_{z3}, P_1 - F_{w1}, -\mu \mu F_{z3}, -F_{w3}) \leq F_{x3} \leq \min(P_1 + \mu \mu F_{z3}, P_1 + F_{w1}, \mu \mu F_{z3}, F_{w3}) \]

In the above, \( F_{w1} = F_{w11} + F_{w21} \), \( F_{w2} = F_{w12} + F_{w22} \), \( F_{w3} = F_{w31} + F_{w41} \), \( F_{w4} = F_{w32} + F_{w42} \), \( \mu \mu F_{z1} = \mu \mu F_{z31} + \mu \mu F_{z21} \), \( \mu \mu F_{z2} = \mu \mu F_{z32} + \mu \mu F_{z22} \), \( \mu \mu F_{z3} = \mu \mu F_{z31} + \mu \mu F_{z41} \), \( \mu \mu F_{z4} = \mu \mu F_{z32} + \mu \mu F_{z42} \).

When the solution of (15) and (16) is not an empty set, the driving force distribution method can be further adopted to optimize the dynamic performance of the vehicle. Using all-wheel road adhesion performance as the optimization goal, the objective function is shown in the following formula [14].
This kind of driving force distribution strategy with all-wheel road adhesion performance as the optimization goal can reserve more adhesion capacity to meet the higher acceleration and yaw requirements that may arise. The advantage is that it can make the vehicle maintain and enhance the potential of vehicle’s mobility for military vehicles. The above objective function can reflect the impact of road adhesion on the whole vehicle. $\mu_i$ is the adhesion coefficient at the ground correspond to the i-th wheel, which can be estimated by observers. If $\mu_iF_i$ decrease, it will lead to $J$ increase. It can guide the trend of the longitudinal driving force change and play a role in reducing the load of adhesion. The constrained optimization problem is solved for the vehicle that is regarded as a vehicle driven by 4×4 in-wheel motor, that is, the minimum value of the equation (17) is found under the condition of satisfying (15) and (16). Bring (9) and (10) into the equation (17), and get the quadratic function after expansion [11]:

$$J = \sum \frac{F_i^2}{\mu_iF_i^2}$$  \hspace{1cm} (17)

For $J_1$, when $-\frac{b_1}{2a_1} < t_1$, $F_{i3}=t_1$ makes $J_1$ reach the minimum; when $-\frac{b_1}{2a_1} > t_2$, $F_{i3}=t_2$ makes $J_1$ reach the minimum; when $t_1 \leq -\frac{b_1}{2a_1} \leq t_2$, $F_{i3}=-\frac{b_1}{2a_1}$ makes $J_1$ reach the minimum. In the above, $t_1 = \max(P_1-\mu_1F_{i1}, P_1-\mu_1F_{i3}, P_1-\mu_1F_{i4}, P_1-\mu_1F_{i5}, P_1-\mu_1F_{i6}, P_1-\mu_1F_{i7}, P_1-\mu_1F_{i8})$, $t_2 = \min(P_1+\mu_1F_{i1}, P_1+\mu_1F_{i3}, P_1+\mu_1F_{i4}, P_1+\mu_1F_{i5}, P_1+\mu_1F_{i6}, P_1+\mu_1F_{i7}, P_1+\mu_1F_{i8})$.

For $J_2$, when $-\frac{b_2}{2a_2} < t_3$, $F_{i4}=t_3$ makes $J_2$ reach the minimum; when $-\frac{b_2}{2a_2} > t_4$, $F_{i4}=t_4$ makes $J_2$ reach the minimum; when $t_3 \leq -\frac{b_2}{2a_2} \leq t_4$, $F_{i4}=-\frac{b_2}{2a_2}$ makes $J_2$ reach the minimum. In the above, $t_3 = \max(P_2-\mu_2F_{i2}, P_2-\mu_2F_{i4}, P_2-\mu_2F_{i6}, P_2-\mu_2F_{i8}, P_2-\mu_2F_{i9}, P_2-\mu_2F_{i10}, P_2-\mu_2F_{i11}, P_2-\mu_2F_{i12})$, $t_4 = \min(P_2+\mu_2F_{i2}, P_2+\mu_2F_{i4}, P_2+\mu_2F_{i6}, P_2+\mu_2F_{i8}, P_2+\mu_2F_{i9}, P_2+\mu_2F_{i10}, P_2+\mu_2F_{i11}, P_2+\mu_2F_{i12})$.

So far, the driving force distribution calculation of the vehicle which regarded as a 4×4 in-wheel motor-driven vehicle based on the optimal of all-wheel adhesion performance has been completed. Then, each wheel is split into two, and the calculation mentioned above is performed on the four wheels at the front and rear of the vehicle separately.

The driving force constraints of the four wheels at the front of the vehicle can be:

$$F_{i11} + F_{i12} + F_{i21} + F_{i22} = F_{i1} + F_{i2}$$  \hspace{1cm} (20)

$$-\frac{B}{2}(F_{i11}+F_{i21}) + \frac{B}{2}(F_{i12}+F_{i22}) = (F_{i2} - F_{i1})\frac{B}{2}$$  \hspace{1cm} (21)

$$|F_{ij}| \leq F_{mij}$$  \hspace{1cm} (22)

$$|F_{ij}| \leq \mu_0F_{ij}$$  \hspace{1cm} (23)

In the above, $i=1,2$ represents 1 to 2 axles.

The driving force constraints of the four wheels at the rear of the vehicle can be:

$$F_{i31} + F_{i32} + F_{i41} + F_{i42} = F_{i3} + F_{i4}$$  \hspace{1cm} (24)

$$-\frac{B}{2}(F_{i31}+F_{i41}) + \frac{B}{2}(F_{i32}+F_{i42}) = (F_{i4} - F_{i3})\frac{B}{2}$$  \hspace{1cm} (25)

$$|F_{ij}| \leq F_{mij}$$  \hspace{1cm} (26)

$$|F_{ij}| \leq \mu_0F_{ij}$$  \hspace{1cm} (27)
In the above, \(i = 3,4\) represents 3 to 4 axles.

Because of the similar process mentioned above, the organization and calculation of these two parts will not be repeated. The optimal driving force distribution calculations above all need no empty sets in some constraint inequalities. However, when the required acceleration is big or the adhesion condition is poor, it may lead to an empty set in constraint inequalities. In this case, it can be changed to adopt the strategy of distributing the driving force evenly or according to axle load ratio. This will ensure the continuity of the power output.

5. Simulation

In order to verify the effectiveness of the longitudinal driving force distribution strategy designed, the strategy based on the optimal adhesion performance model and a dynamics mathematical model of an 8×8 in-wheel motor-driven vehicle are built in Matlab/Simulink. The dynamic model with 11 degrees of freedom, includes the longitudinal, lateral and yaw of the vehicle body, and the rotation of the wheels [15-16]. The equations of the longitudinal, lateral and yaw of the vehicle can be expressed as:

\[
m(u' - \omega) = \sum_{i=1}^{4} [(F_{a1} + F_{a2}) \cos \delta_i - (F_{a1} + F_{a2}) \sin \delta_i] + \sum_{i=3}^{4} [(F_{a1} + F_{a2}) \cos \delta_i - (F_{a1} + F_{a2}) \sin \delta_i] 
\]

\[
m(v' + u\omega) = \sum_{i=1}^{4} [(F_{a1} + F_{a2}) \sin \delta_i + (F_{a1} + F_{a2}) \cos \delta_i] + \sum_{i=3}^{4} [-(F_{a1} + F_{a2}) \sin \delta_i + (F_{a1} + F_{a2}) \cos \delta_i] 
\]

\[
I_o \alpha' = \sum_{i=3}^{4} [(F_{a1} + F_{a2}) L_i \sin \delta_i - (F_{a1} + F_{a2}) L_i \cos \delta_i + (F_{a2} - F_{a1}) B 2 \cos \delta_i + (F_{a1} + F_{a2}) B 2 \sin \delta_i] 
\]

\[
+ \sum_{i=3}^{4} [(F_{a1} + F_{a2}) L_i \sin \delta_i + (F_{a1} + F_{a2}) L_i \cos \delta_i + (F_{a2} - F_{a1}) B 2 \cos \delta_i + (F_{a1} + F_{a2}) B 2 \sin \delta_i] 
\]

The rotational dynamics equation of the wheel can be expressed as:

\[
T_{ij} - f F_{a1} R_i - F_{a1} R_i = J_i \alpha_{ij}
\]

The parameters of the vehicle are shown in the following table:

| Name                        | Symbol | Value  | Unit   |
|-----------------------------|--------|--------|--------|
| Vehicle Quality             | \(m\)  | 20000  | kg     |
| Vehicle Moment of Inertia   | \(I_z\)| 180000 | kg*m^2 |
| Center of Mass Height       | \(h\)  | 0.8    | m      |
| Distance of Axle1-CM        | \(L_1\)| 2.2    | m      |
| Distance of Axle2-CM        | \(L_2\)| 0.8    | m      |
| Distance of Axle3-CM        | \(L_3\)| 0.8    | m      |
| Distance of Axle4-CM        | \(L_4\)| 2.2    | m      |
| Wheelbase                   | \(B\)  | 3      | m      |
| Wheel radius                | \(R_i\)| 0.7    | m      |
| Wheel Moment of Inertia     | \(J_i\)| 150    | kg*m^2 |

The simulation experiment consists of three parts, simulate passing a distance of road with high-adhesion, a distance of road with different adhesion coefficients, and overcoming an anti-tank trench.

5.1. Accelerate rapidly on the road with high-adhesion

The vehicle travels at an initial speed of 3m/s. At \(t=1s\), the vehicle starts to accelerate, and at \(t=2s\), the acceleration reaches about \(3m/s^2\), and then it maintains this acceleration until \(t=5s\), the driver starts release the accelerator pedal slowly, the acceleration drops to \(0m/s\) at \(t=8s\), the road adhesion coefficient remains at 0.7 in the whole process.
5.2. **Accelerate slowly on the road with different adhesion coefficients**

The vehicle travels at an initial speed of 3 m/s. At \( t=1 \) s, the vehicle starts to accelerate, and at \( t=2 \) s, the acceleration reaches about 0.5 m/s\(^2\), and then maintains until the end of the experiment. At \( t=5 \) s, the first wheel on the left is simulated driving on the road with snow, and the adhesion coefficient reduces from 0.7 to 0.2. At \( t=5.96 \) s, the second wheel on the left drives on the snowy road. At \( t=6.43 \) s, the third wheel on the left drives on the snowy road. At \( t=7.72 \) s, all the wheels on the left drive on the snowy road, simulating the process of one side of the vehicle contacting the road with low-adhesion.
5.3. Overcome an anti-tank trench
The vehicle travels at a constant speed at an initial speed of 3m/s. At t=4s, axle 1 encounters an anti-tank trench 3m in length, when t=5s, axle 1 drives out of the anti-tank trench, at t=4.47s, axle 2 encounters the anti-tank trench, at t=5.47s axle 2 drives out of the anti-tank trench, at t=5.03s, axle 3 encounters the anti-tank trench, at t=6.03s, axle 3 drives out of the anti-tank trench, at t=5.5s, axle 4 encounters the anti-tank trench, at t=6.5s, axle 4 drives out of the anti-tank trench. This simulates the process of the vehicle overcoming the anti-tank trench.
6. Conclusion

Taking advantage of each wheel can be controlled independent, a longitudinal driving force distribution strategy based on the optimal adhesion performance is designed. The simulation experiment results show that this strategy:

1. Can meet the longitudinal dynamic performance requirements of the vehicle;
2. Can satisfy the limitations of ground adhesion capacity and motor capacity;
3. Can reduce the load of adhesion compared with the average distribution strategy.

References

[1] Mao M. The Design of Wheeled Armored Vehicles[M]. Beijing: National Defense Industry Press, 2018.
[2] Yu Z, P, Feng Y, Xiong L. Review on Vehicle Dynamics Control of Distributed Drive Electric Vehicle[J]. Journal of Mechanical Engineering, 2013, 49(8): 105-144.
[3] Liu M C. Study on Handling Stability Analysis and Control for 8 In-Wheel Motor Drive Vehicle[D]. Beijing Institute of Technology, 2015.
[4] OSBORNA R, SHIMB T. Independent control of all-wheel-drive torque distribution[J]. Vehicle System Dynamics, 2006, 44(7): 529-546.
[5] SHINO M, NAGAI M. Independent wheel torque control of small-scale electric vehicle for handling and stability improvement[J]. JSAE Review, 2003, 24(4): 449-456.
[6] Xiong L, YU Z P, Jiang W, et al. Research on Vehicle Stability Control of 4WD Electric Vehicle Based on Longitudinal Force Control Allocation[J]. Journal of Tongji University, 2010, 38(03): 417-421+426.
[7] Sun Y. Research on Yaw Stability Control of Distributed Drive Electric Vehicles[D]. Changchun: Jilin University, 2013.
[8] Yan C H. Torque Distribution and Control of Distributed Driving Electric Vehicles under Different Operating Conditions[D]. Hefei: Hefei University of Technology, 2020.
[9] Xiu N H A. Class of Improved Active Set Methods for Nonconvex Quadratic Programming Problem[J]. Mathematica Numerica Sinica, 1994, 16(4): 406-417.
[10] ONASSON M, AND REASSON J, SOLYOM S, et al. Utilization of actuators to improve vehicle stability at the limit: From hydraulic brakes toward electric propulsion [J]. Journal of Dynamic Systems Measurement and Control Transactions of the ASME, 2011, 133(5): 51003.1-51003.10.
[11] Xia C L. Research on Assisted Steering Control Method Based on Longitudinal Force Distribution [D]. Shanghai: Tongji University, 2007.
[12] Li K Q, Luo Y G, Guo J H. Advanced Vehicle System Dynamics and Control [M]. Wuhan: Huazhong University of Science and Technology Press, 2021.
[13] Chu W B, Luo Y G, Zhao F, et al. Driving Torque Coordination Control of Distributed Drive Electric Vehicles. [J]. Automotive Engineering, 2012, 34(3): 185-189.
[14] Bai H T. Drive Control Strategy Study Based on 4 In-wheel motor Drive Pure Electric Vehicle [D]. Changchun: Jilin University, 2015.
[15] Fauroux JC, Vaslin P. Modeling, Experimenting, and Improving Skid Steering on a 6x6 All-Terrain Mobile Platform [J]. Journal of Field Robotics, 2010, 27(2): 107-126.
[16] Li S Q, Yan X W, Jin L T. Study of Yaw Stability Control Strategy on Distributed Drive Electric Vehicle [J]. Journal of Chongqing University of Technology, 2021, 35(5): 65-73.