Development of XBW in-wheel-motor-drive electric vehicle simulation platform

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Abstract. The unique distributed drive mode of the in-wheel-motor-drive electric vehicle (IWMDEV) is known as the ultimate form of automobile chassis technology. In order to meet the verification requirements of the SBW (steer-by-wire)/DBW (drive-by-wire)/BBW (break-by-wire) IWMDEV control algorithm, a 19 degrees of freedom (DOFs) dynamic model of the 4WID/4WIS/4WIB vehicle, including the vertical vibration, is established. According to the characteristics of XBW (x-by-wire) electric vehicle, modular design is used to design the structure and signal flow of the simulation platform. And the modeling methods and dynamic equations of each actuator are given. In addition, under different working conditions, the dynamic response quality of the simulation platform is compared and verified by CarSim. These experiments show that the simulation platform has high precision and can be used to analyze the transient and steady state response characteristics of the XBW IWMDEV under various working conditions.

1. Introduction

The XBW IWMDEV is the focus of current research in the field of electric vehicles [1]. The distributed drive mode subverts the traditional centralized drive structure, so a new theoretical control method of the whole vehicle is needed. At present, multi-body system dynamics analysis software, represented by CarSim/ADAMS/Simpack, can provide high precision models, but the underlying layers of these models are opaque to users. Therefore, the establishment of a practical simulation platform for 4WID/4WIS/4WIB IWMDEV is of great significance to the study of the stability control mechanism of XBW electric vehicle.

Research on the control of IWMDEV, a 7 DOFs 4VID vehicle model was used by Tokyo University Agricultural & Technology [2], University of Tokyo [3] and Le B [4]. Beside, Zong C [5] and Yang F [6] increase freedom of vehicle to 9, while Liu M [7] expanded the number to 14. However, the above 4VID/4VIS vehicle models do not fully consider the vertical vibration of the spring mass and unsprung mass, and do not take into account the dynamic response characteristics of the actuators (driving motor, steering motor, and electromagnetic brake). In fact, the installation of in-wheel motor increases the quality of unsprung mass. And thus, the vertical vibration of the unsprung mass has a significant impact on the dynamic quality of the whole vehicle [8]. In addition, the x-by-wire technology makes the vehicle more sensitive to the response of the actuators.

At present, the research on vehicle modeling is not sufficient for the above. Therefore, a vehicle model with 19 DOFs which considering vibration of sprung mass and unsprung mass is established in
In this paper, modular modeling method is adopted, and the dynamic equations and signal processing of the modules are given. In addition, the drive motor, the steering motor and the electromagnetic brake are analyzed and modeled in detail.

2. Structure of XBW Electric Vehicle

The XBW IWMDEV, as shown in figure 1. It is a highly redundant drive system, and its driving torque, wheel angle and braking torque of four wheels can be controlled independently. As a result of more controlled freedom and faster response of actuators, vehicle has the physical basis for more complex and precise control.

Because the platform has many degrees of freedom, and the coupling relationship between all directions is more complex, it is very easy to form an algebraic loop, which affects the operation efficiency and the later generation of C code. Hence, the modular structure and reasonable signal flow are need designed careful, which are shown in figure 2.

In figure 2, the blue dotted line stands for vehicle motion information. The black line indicates interactions. The red dotted line is the auxiliary signal of vehicle control. Among them, the meaning of each signal is shown below. Each module is independent of each other, which is convenient for later integrated control algorithm development and verification.
3. Vehicle modeling

The vehicle is made up of four parts, body, suspensions, wheels and tires. Thus, the IWMDEV can be simplified to a five particle system consisting of a sprung mass and four unsprung mass. Finally, the IWMDEV is abstract as model with 19 DOFs, which consists vehicle motion with 6 DOFs (as shown in figure 2), wheel motion (steering, rotate and jump) with 12 DOFs, and steering wheel motion.

3.1. Body dynamics model

The Oxzy right-handed vehicle coordinates, as shown in figure 3. And the origin O is the intersection of the vertical line of the mass centroid of the whole vehicle and the tilting center axis of vehicle.

According to Darren Bell’s principle, the balance equations of the translational motion and rotation motion of car body in the direction of x, y, z are simplified as equation (1) and equation (2).

\[ \begin{align*}
\sum m \cdot \dot{v}_x &= \sum F_{x\text{-front}} + \sum F_{x\text{-rear}} + \sum F_{x\text{-side}} + \sum M_{x\text{-front}} + \sum M_{x\text{-rear}} + \sum M_{x\text{-side}} + m \cdot g \cdot v_y + D_{px} \\
\sum m \cdot \dot{v}_y &= \sum F_{y\text{-front}} + \sum F_{y\text{-rear}} + \sum F_{y\text{-side}} + \sum M_{y\text{-front}} + \sum M_{y\text{-rear}} + \sum M_{y\text{-side}} + m \cdot g \cdot v_z + D_{py} \\
\sum m \cdot \dot{v}_z &= \sum F_{z\text{-front}} + \sum F_{z\text{-rear}} + \sum F_{z\text{-side}} + \sum M_{z\text{-front}} + \sum M_{z\text{-rear}} + \sum M_{z\text{-side}} + m \cdot g \cdot v_x + D_{pz}
\end{align*} \tag{1} \]

Where \[ \sum M_z = 0.5(F_{y\text{-front}} - F_{y\text{-rear}})dy - F_{z\text{-front}}dz + F_{z\text{-rear}}dz + F_{z\text{-side}}dy - F_{z\text{-side}}dy + F_{x\text{-side}}dz - F_{x\text{-side}}dz + (F_{x\text{-front}} + F_{x\text{-rear}})dx + (F_{x\text{-front}} + F_{x\text{-rear}})dx + (F_{x\text{-side}} + F_{x\text{-side}})dx + (F_{x\text{-side}} + F_{x\text{-side}})dx \tag{2} \]

In the above symbols, \( v_x, v_y, v_z \) denote the translational motion of vehicles in x, y and z directions respectively. \( q, p, \theta \) indicate vehicle pitch, roll and yaw rate respectively. \( \phi, \theta, \phi \) are the roll angle, pitch angle and the yaw angle of the vehicle respectively.

\( m, m_s \) and \( m_u \) are curb mass, sprung mass, unsprung mass of vehicle. \( d_f (d_r) \) is the distance from front (rear) axle to the centroid. \( d_{af} (d_{ar}) \) denotes front (rear) axle track width. \( h_p \) represents the horizontal distance of the centroid of the sprung mass to the origin of Oxzy. \( h_d \) is the vertical distance...
of the centroid of the sprung mass to the vehicle's tilting center. $I_x$, $I_y$ and $I_z$ indicate the moment of inertia of vehicle. $I_{xs}$, $I_{ys}$ and $I_{zs}$ indicate the moment of inertia of vehicle's sprung mass. $I_{xys}$, $I_{yzs}$ and $I_{xzs}$ are the inertial products of the vehicle sprung mass around the coordinate system $xy$, $yz$ and $xz$.

The lower foot $i=fl$ $(fr, rl, rr)$, is the relative position of parts on the vehicle (same below). $\delta_i$ is the steering wheel angle. $F_{xt_i}$ $(F_{yt_i})$ is the wheel ground force projection in the $xt$ $(yt)$ direction of tire coordinate $Oxtytzt$. $\Sigma M_x$, $\Sigma M_y$, $\Sigma M_z$ are tilting torque, pitching moment, yaw moment. $D_{Fx}$, $D_{Fy}$, $D_{Fz}$, $D_{Mx}$, $D_{My}$, and $D_{Mz}$ indicate the disturbance caused by the uncertain model error of the vehicle. $M_{z_i}$ is the self-aligning torque of tire $i$.

### 3.2. Suspension dynamic model

Here, the in-wheel motors and wheels are simplified as unsprung mass, while the elastic tyre are replaced by spring and damper, as shown in figure 4. The stiffness of suspension and tire are represented by $K_{s_i}$ and $k_{t_i}$, and $C_{Ds_i}$ and $C_{Dt_i}$ are the damping coefficient of suspension and tire. $m_{u_i}$ represents the unsprung mass of suspension. $Z_i$, $Z_{u_i}$, $Z_{r_i}$ and $Z_s$ respectively indicate the vertical coordinates of the connection point of suspension and body, the centroid of unsprung mass, the contact point of tire and ground, and the centroid of sprung mass. The active control force $Fac_i$ of suspension $i$ is considered in the model. And thus the dynamic equations of the vertical motion are as follows

$$m_{u_i}\ddot{z}_{u_i} = k_{t_i}(z_{r_i} - z_{u_i}) + C_{Dt_i}(\dot{z}_{r_i} - \dot{z}_{u_i}) + F_{z_i}$$

Where,

$$\dot{z}_p = z_i - d_j \cdot \theta + 0.5d_{off} \phi$$
$$\dot{z}_p = z_i - d_j \cdot \theta - 0.5d_{off} \phi$$

### 3.3. Wheel dynamics model

In the process of rotation, analysis (figure 5) of the force of the wheel can be found in document [9].

And thus the rotation about wheel axles of wheel $i$ as equation (6).

$$J_{w_i} + J_{dm_i}\dot{\omega}_i = M_{dm_i}\ddot{R} - Mr_{i}M_{b_i}\ddot{\theta} - C_{d_{dm_i}}\ddot{\omega}_i$$

Where, $J_{w_i}$ $(J_{dm_i})$ is the moment of inertia of wheel (in-wheel motor). $\omega_i$ represents the rotational speed of wheel. $M_{dm_i}$ is the output torque of in-wheel motor. $R_{i}$ is the unloaded radius of tire $i$. $M_{b_i}$ $(M_{f_i})$ is brake torque (rolling resistance moment). $C_{d_{dm_i}}$ rotation damping coefficient of in-wheel motor. $F_{z_i}$ represents the tire vertical force. $W_{z_i}$ is vertical force that suspension $i$ applies to the tire $i$, which is equal to $F_{z_i}$. $v_{w_i}$ is speed of wheel $i$.

### 3.4. Tire model and driver model

The simulation platform has many joint conditions. Hence, the complex coupling ‘magic formula’ [5] of tire model and preview-follower driver model [11] are adapted in the vehicle model.

### 4. Actuator modeling

Owing to the control structure, the dynamic response quality of IWMDEV is more sensitive to the dynamic performance of the actuators. Thus, the dynamic equation of actuators must be established.

#### 4.1. Four wheel independent DBW system

In practice, there are differences in the property of motors, so the difference between motors is marked by small foot mark $i$, which to facilitate the study of the balance control algorithm in the later period.
Where, $C_{tdm_i}$ is the torque coefficient of driving motor, $i_{dm_i}$ is the driving current of driving motor, the input control signal. $E_{dm_i}$ is the input voltage of driving motor. $C_{bdm_i}$ is the back EMF of in-wheel motor, and $R_{bdm_i}$ is the resistance of in-wheel motor.

The angular velocity of the outer-rotor of the motor is synchronized with the rotation angular velocity of the wheel. Therefore, the dual closed loop control of the torque and speed of the in-wheel motor must be completed, as shown in figure 6.

**Figure 6.** Double closed loop control structure for in-wheel motor.

### 4.2. Four wheel independent SBW system

Due to the elimination of mechanical restraint by steering trapezium, the wheel can turn to a large scale (-90°~+90°) independently. The structure of the suspension system is shown in figure 7 (a).

**Figure 7.** The structure and physical model diagram of the steering system.

**Figure 8.** Structure principle of electromagnetic brake.

An abstract physical model of the steering system is built in consideration of the efficiency of the simulation, which is showed in figure 7 (b). So there is equation (8).

$$\begin{align*}
J_{sm_i} \cdot \dot{\theta}_i &= C_{Tsm_i} \cdot i_{sw_i} - C_{Dsm_i} \cdot \dot{\theta}_i - T_{Rsm_i} / C_{Rsm_i} \\
L_{sm_i} \cdot i_{sw_i} &= E_{sw_i} - C_{Bsm_i} \cdot \dot{\theta}_i - R_{sm_i} \cdot i_{sw_i}
\end{align*}
$$

(8)

Where, $J_{sm_i}$ is the moment of inertia of the steering motor. $\theta_i$ is the steering motor output angle. $C_{Tsm_i}$ is the torque coefficient of the steering motor. $I_{sw_i}$ ($C_{Dsm_i}$) is the current steering motor (damping coefficient). $T_{Rsm_i}$ is the external steering resistance torque of wheel. $C_{Rsm_i}$ is reducer ratio. $L_{sm_i}$ ($R_{sm_i}$) is the inductance (resistance) of the steering motor. $E_{sw_i}$ is the motor input voltage. $C_{Bsm_i}$ is the back EMF coefficient of the steering motor. And we have

$$J_{ss_i} \cdot \dot{\theta}_i = T_{sw_i} + C_{Rsm_i} \cdot T_{fr_i} - T_{Dor_i} - M_{s_i}
$$

(9)

Where, $J_{ss_i}$ is the moment of inertia of the steering system. $T_{fr_i}$ is the friction moment. $T_{Dor_i}$ is the steering damping moment.
4.3. Four wheel independent BBW system
Electromagnetic braking unifies the dynamic form of the vehicle, and the principle structure is shown in figure 8. When electrifying, electromagnetic force $F_{bbem,i}$ overcomes the spring pulling force $F_{bst,i}$ to move the friction armature to the friction plate and contact with it, and then produces the braking torque. It is known that the current satisfies the exponential law after electricity [12].

$$i_{bs,i}(t) = \frac{u_{bs,i}}{R_{bs,i}} \cdot (1 - \exp(-t/T_i))$$

(10)

Where, the voltage on the electromagnetic coil is $u_{bs,i}$, the coil current is $i_{bs,i}$, and the coil resistance is $R_{bs,i}$. It is known from the electromagnetic theory that

$$L_{bs,i}(x_{bsag,i}) = N_{bs}^2 \cdot \frac{S_{bs}}{L_{bs,i}}$$

(11)

$$F_{bs,i} = (N_{bs} \cdot i_{bs,i})^2 \cdot \frac{u_{bs,i}}{s_{bs}} \cdot \left(2 \cdot x_{bsag,i}^2\right)$$

$L_{bs,i}$ is a coil inductor, which is a function of $x_{bsag,i}$ in the air gap. $N_{bs}$ is the number of turns of the brake coil. $S_{bs}$ is the cross section area of the magnetic path. The $F_{bsem,i}$ is the time function of the current after the combination. Thus, the braking torque formula is as equation (12).

$$M_{bs,i} = \int_{x_{bsag,min}}^{x_{bsag,max}} C_{fp} \cdot \left(\frac{F_{bsem,i}}{S_{fp}}\right) \cdot r_{fp}^2 \cdot dr_{fp} \cdot d\varphi$$

$$0 \leq x_{bsag,i} \leq x_{bsag,max}$$

$$x_{bsag,min} < x_{bsag,i}$$

(12)

$R_{fp,min}$ and $R_{fp,max}$ are the radius of the friction plate. The friction coefficient of friction disk is $C_{fp}$. $S_{fp} = \pi(r_{fp,max}^2 - r_{fp,min}^2)$ is the area of the friction plate.

5. Simulation results

![Simulation platform based on Simulink.](image)
Referring to figure 2, connecting the information flow of each module, the simulation platform based on Simulink is shown in figure 9. Theoretically, the simulation platform needs real vehicle data validation, but the real vehicle test is of high risk. However, it is a good way to use the mature and reliable vehicle commercial simulation software for comparative simulation. Therefore, the comparison model is set up by CarSim software. Considering the future research needs of vehicle handling and stability test, the following two working conditions are tested.

**Figure 10.** Steering wheel angle of condition 1.

**Figure 11.** Steering wheel angle of condition 2.

Working condition 1: \( v_x = 20 \text{ m/s} \), friction coefficient \( \mu_g = 0.8 \), step angle as shown in figure 10.

**Figure 12.** Simulation test of step input steering.

Working condition three: \( v_x = 25 \text{ m/s} \), friction coefficient \( \mu_g = 0.3 \), pulse input such as figure 11.

As shown in figure 12, except for the difference of the Side-slip Angle and the vertical vibration response of the vehicle, the response trend of the other parameters is basically the same, and the steady-state difference is also smaller. The two models show good consistency.

However, as shown in figure 13, the difference between the simulation results of the two models is slightly larger than the working condition one. This is mainly because of low adhesion coefficient, fast speed, and more radical angle of steering angle. Since the model established by CarSim takes into account the damping and friction between many components, the vibration energy of the system can be quickly dissipated, so that a new balance can be established quickly.
In general, under various speeds, road adhesion conditions and steering angle input conditions, the dynamic response characteristics of XBW IWMDEV model can be consistent with the comparison model. It shows that the simulation platform can characterize the dynamic response quality of the vehicle in a large range, and has a good simulation precision.

![Figure 13. Simulation test of plus input steering.](image)

6. Conclusions
On the basis of structural analysis, the modular division and signal design of the whole vehicle are carried out. Beside, a 19 DOFs time-varying coupling dynamic model of the XBW IWMDEV is established, which including the vertical motion of the sprung mass and unsprung mass. Furthermore, the detailed dynamic formula of each model is given. The experimental results under different conditions show that the simulation platform has wide range and high accuracy, and it can provide support for the future research of XBW IWMDEV stability control algorithm.

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