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油圧式ー機械式ハイブリッド制御装置を使用した小型電気自動車のスキッド制御技術に関する研究

Research on Skid Control of Small Electric Vehicle with Hydraulic-Mechanical Hybrid Brake System

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1. Introduction

In recent years, environmental problems have spread around the world. To cope with this problem, electric vehicle have widely used. As we know, the fundamental of a driving method for electric vehicle can be separate into two types, which are one motor system and in-wheel motor system. There are many advantages by using in wheel motors such as motors torque generation is faster and accurate, motors can be installed in 2 or 4 wheels, and motors torque can be known precisely. For a small electric vehicle, in-wheel motor is more suitable than one motor.

Although small electric vehicle have a great in-wheel motor, the safety equipment of small electric vehicle is not sufficient because it only contains seat belts as safety equipment. The hydraulic unit of Antilock Brake System (ABS) cannot install into small electric vehicle because there is no space. Therefore, small electric vehicles employ a mechanical brake system rather than a hydraulic brake system. The demerit of the mechanical brake system is the stiffness of the system is smaller than the hydraulic brake system and the response performance of the braking force also low. As such, small electric vehicles may be considered to provide insufficient safety.

In fact, on slippery surfaces, even professional drivers can't stop as quickly without ABS as an average driver can with ABS. So, it is important to install ABS into small electric vehicle. ABS can prevent wheels from locking up and provide the shortest stopping distance on slippery surfaces. The Insurance Institute for Highway Safety (IIHS) has conducted several studies trying to determine if cars equipped with ABS are involved in more or fewer fatal accidents. It turns out that in a 1996 study, vehicles equipped with ABS were overall no less likely to be involved in fatal accidents than vehicles without ABS.

2. Objective

The purpose of the present study is to improve the safety and stability systems of small electric vehicle. In this research, we introduce the simulation model of hydraulic-mechanical hybrid brake system with Antilock Brake System (ABS). The main focus of this research is to investigate the effect of the ABS operational with control of regenerative brake on turning motion. The vehicle motion during braking in a small electric vehicle was simulated for an ABS combined with a hydraulic-mechanical hybrid brake system. By using the equation of motion along the longitudinal and lateral axis, the yawing moment equation of motion, and the rolling moment equation of motion, the characteristics of a vehicle when driving and braking was investigated.

3. Antilock Brake System (ABS)

3.1 Composition of ABS

Fig. 1 shows the composition of Antilock Brake System (ABS).

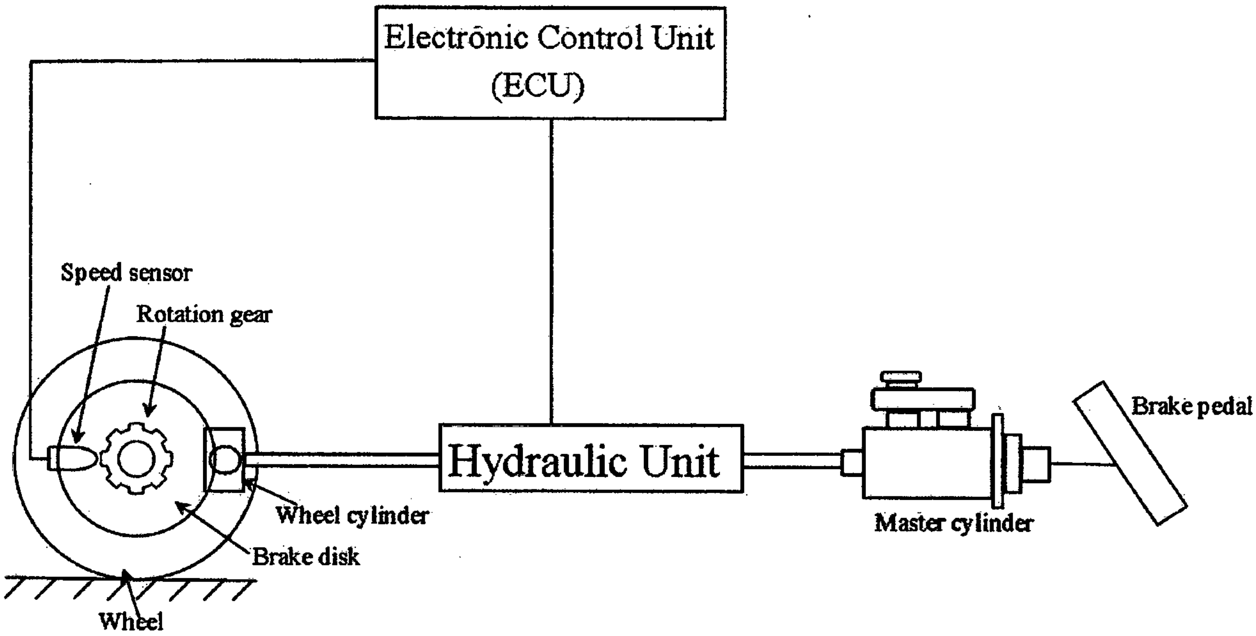


Fig.1 Composition of ABS

There are three main components to an ABS system:

1. Speed sensors

The speed sensors are located at each rear tire and it can provide information either the wheel is lock or not. This sensor produces an AC voltage signal that varies in frequency according to the output of rotation gear speed.

2. Hydraulic Unit

Fig.2 shows the composition of hydraulic unit, which are

Right before wheel locks up, it will experience a rapid deceleration. If left unchecked, the wheel would stop much more quickly than any car could. It might take a car five seconds to stop from 90 km/h under ideal conditions, but a wheel that locks up could not stop spinning in less than a second.

The ECU knows that such a rapid deceleration is impossible, so it reduces the pressure to that brake until it sees acceleration, then it increase the pressure until it sees the deceleration again. It can do this quickly before the tire can actually significantly change speed. The result is that the tire slows down at the same rate as the car, with the brakes keeping the tires very near the point at which they will start to lock up. This gives the system maximum braking power.

3.2 Operational of ABS

The braking model depends on the decrease of kinetic energy. When the driver applies the brake in order to slow the vehicle, the speed of the wheels become slightly slower than the speed of the body, which is traveling along under its own inertia. This difference in speed is called slip ratio. Here we define the slip ratio as the following equation:

$$\lambda = \frac{V - r\omega}{V} \times 100 \quad [\%]$$

where u denotes the vehicle speed, and $R\omega$ is the wheel speed. R and ω are the radius of the tire and the rotational speed of the tire. This ratio can vary from 0 (perfect match between wheel and vehicle speeds) to the 1 (the wheel is locked), and it is shown that the wheel is both rolling and sliding.

Typical tire characteristics during braking are shown in Fig.3. It can be seen that the side force and the friction coefficient are depend on the slip ratio. In a driving condition ($\lambda = 0$) , friction coefficient is 0 and cornering force will having a maximum value. When a driver steps on the brake pedal, the slip ratio is increase and the cornering force will decrease, and tire lock will occur if $\lambda = 100$. In this situation, cornering force is almost 0 and the braking force will lost. From this graph, at a maximum value of friction coefficient (μ_{max}), we plot the optimum value of slip ratio (λ_{opt}). According to the braking pressure, the stable region of slip ratio is between 0 to λ_{opt}. If the slip ratio is over λ_{opt}, the tire was easy to lock.

The ABS is designed to control the wheel slip ratio in stable region so that a maximum friction coefficient is obtained and a suitable side force is maintained. It is important to maintain the side force because it guarantees the vehicle stability. In order to ensure the system do not move under the unstable region of operation, the ABS will control the operation of IN valve and OUT vale. When tire lock occurs, i.e., when the slip ratio become 100%, the IN valve is closed, the OUT valve is opened, and the pumps begin to operate. The pressure in the wheel cylinder and the braking force are decreased. As a result, the slip ratio become small, and the friction coefficient and the side force become large. When the slip ratio become too small, the IN valve open and the OUT valve close again. The pressure in the wheel cylinder and the braking force are increased, and the slip ratio then becomes large. This mechanism will repeatedly until the vehicle totally stop.

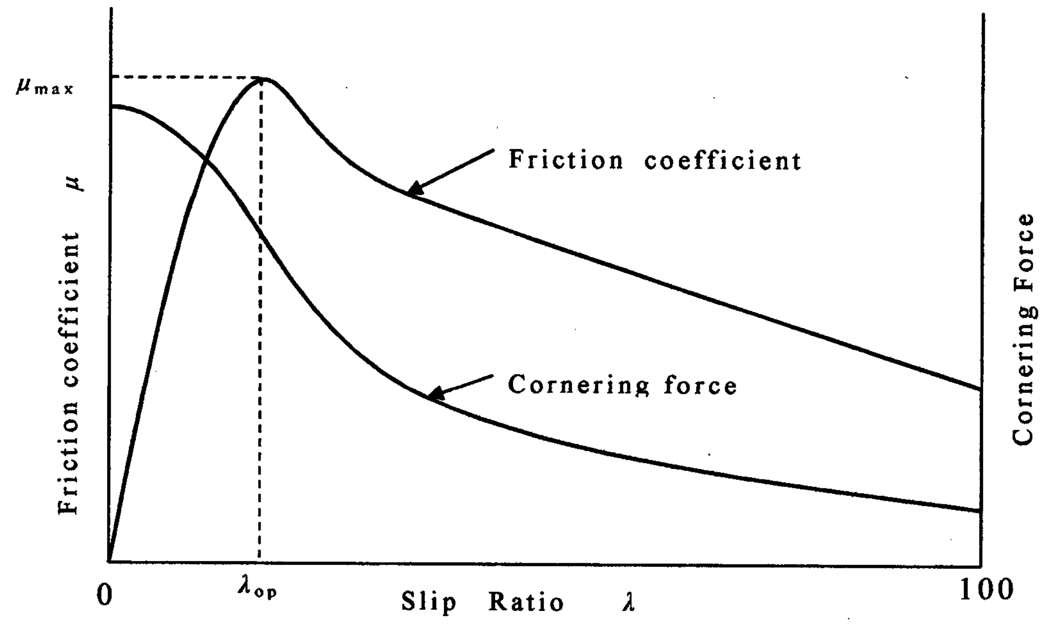


Fig.3 Tire characteristic

4. Simulation

The main symbols in basic equations and programming was shown in Table.1.

4.1 Main Symbol

Table.1 Variable in Basic Equations and Programming

Symbol	Physical Meaning	Variable in programming	Unit	Inertial Value
A_f	Area of front wheel cylinder	areaF	m^2	2.83x10^{-3}
A_r	Area of rear wheel cylinder	areaR	m^2	7.07x10^{-4}
d_f	Diameter of front wheel cylinder	diaF	m^2	0.06
d_r	Diameter of rear wheel cylinder	diaR	m^2	0.03
h_f	The front roll center height from the ground	-	-	-
h_r	The rear roll center height from the ground	-	-	-
h_s	Distance between the vehicle center of gravity and the roll axis	heightS	m	0.105
I	Yaw inertia moment of a gravity point	YAWINERTIA	kgm^2	1470
I_{zzs}	Yaw inertia moment of upper side of spring	inertiaZZS	kgm^2	100.0
I_{zzu}	Yaw inertia moment of lower side of spring	inertiaZZU	kgm^2	1370.0
J_f, J_r	Inertia moment of tire	inertia, inertiaR	kgm^2	$J_f = 0.428$

				$J_r = 2.53$
K_{cf}, K_{cr}	Camber thrust factor of suspension	CAMBERTHRUSTF , CAMBERTHRUSTR	N/rad	10.0
$K_{\emptyset f}$	Roll rigidness of front suspension	FRONTROLLRIGIDFNESS	N/rad	500.0
$K_{\emptyset r}$	Roll rigidness of rear suspension	REARROLLRIGIDFNESS	N/rad	250.0
l_f, l_r	Distance between the front and rear axles to the center of gravity	length, lengthR	m	l_f= 0.746 l_r= 0.534
m	Mass of vehicle	mass	kg	326
m_s	Sprung mass	massUpper	kg	262.5
P_f, P_r	Initial brake pressure	pressureFront, pressureRear	MPa	1.8
r_f, r_r	Radius of tire	radF,radR	m	0.230
susKFAI	Roll rigidness of suspension	ROLLRIGIDNESS	N	
T_f, T_r	Braking Torque	torqueFL,torqueFR, torqueRL,torqueRR	Nm	
t	Calculation time	cycletime	sec	
U_p	Vehicle velocity at X direction	velocityU_p	km/h	30.0
V_p	Vehicle velocity at Y direction	velocityV_p	km/h	0
W_{fl}	Load on wheel	loadFL,loadFR, loadRL,loadRR	N	$W_{fl} = 740.5$, $W_{fr} = 740.5$, $W_{rl} = 1034.5$, $W_{rr} = 1034.5$

W_s	Vehicle body weight	-	kg	362.24
$X_{fl}, X_{fr}, X_{rl}, X_{rr}$	Friction force of tire	frictionFL,frictionFR, frictionRL,frictionRR	N	
$Y_{fl}, Y_{fr}, Y_{rl}, Y_{rr}$	Cornering force	forceFL,forceFR, forceRL,froceRR	N	0
$\ddot{y}$	Vehicle lateral acceleration	-	-	-
β_p	Side slip angle of gravity point	betaP	rad	0
$\beta_{fl}, \beta_{fr}, \beta_{rl}, \beta_{rr}$	Side slip angle of tire	betaFL,betaFR, betaRL,betaRR	rad	0
$\mu_{fl}, \mu_{fr}, \mu_{rl}, \mu_{rr}$	Friction coefficient between tire and road surface	myuFL,myuFR, myuRL,myuRR	-	0
μ_p	Friction coefficient between drum and shoe	myuDrum	-	0.4
ϕ	Roll angle	faiP	rad	-
$\rho_{fl}, \rho_{fr}, \rho_{rl}, \rho_{rr}$	Slip ratio	roFL,roFR, roRL,roRR	-	
ω_p	Yaw angular velocity of gravity point	omegaP	rad/s	0
$\omega_{fl}, \omega_{fr}, \omega_{rl}, \omega_{rr}$	Yaw angular velocity of tire	omegaFL,omegaFR, omegaRL,omegaRR	rad/s	0
δ	Steer angle	delta	deg	10.0
$V_{fl}, V_{fr}, V_{rl}, V_{rr}$	Tire rotational speed	syuusokuFL,syuusokuFR, syuusokuRL,syuuso	m/s	

		kuRR		

4.2 Vehicle Model

In this research, the small electric vehicle was modeled by the four wheels model.

4.2.1 Vehicle Ride Model

The vehicle ride model is represented as 4 degrees of freedom (DOF) system. It consists of a single sprung mass (car body) connected to four unsprung masses (front-left, front-right, rear-left and rear-right wheels) at each corner. The sprung mass is free to heave, pitch and roll while the unsprung masses are free to bounce vertically with respect to the sprung mass. Fig.4 shows the vehicle ride model. The details of this vehicle are as below:

- Small Electric Vehicle (TOYOTA COMS LONG)
- Mass : 3195 N
- Wheelbase :1280 mm
- Wheel track front : 840 mm
- Wheel track rear : 815 mm
- Rear In-wheel motor x 2 : 0.29 kW

- Passenger capacity : 1 Person
- Rear wheel drive

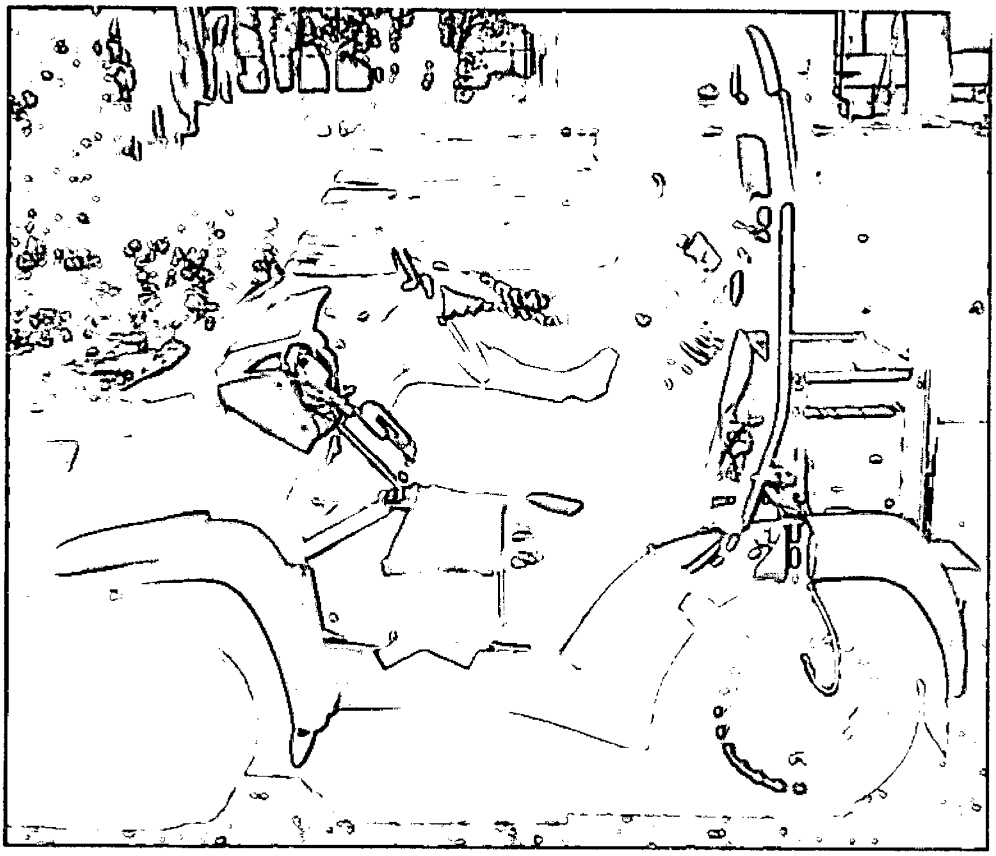


Fig.4 Vehicle ride model

4.2.2 Suspension System

Fig.5 shows the vehicle handling model. The vehicle body and wheels are connected to each other by soft and elastic connection to improve the vehicle ride comfort. This mechanism is generally called the suspension system and the vehicle body is called the sprung mass,

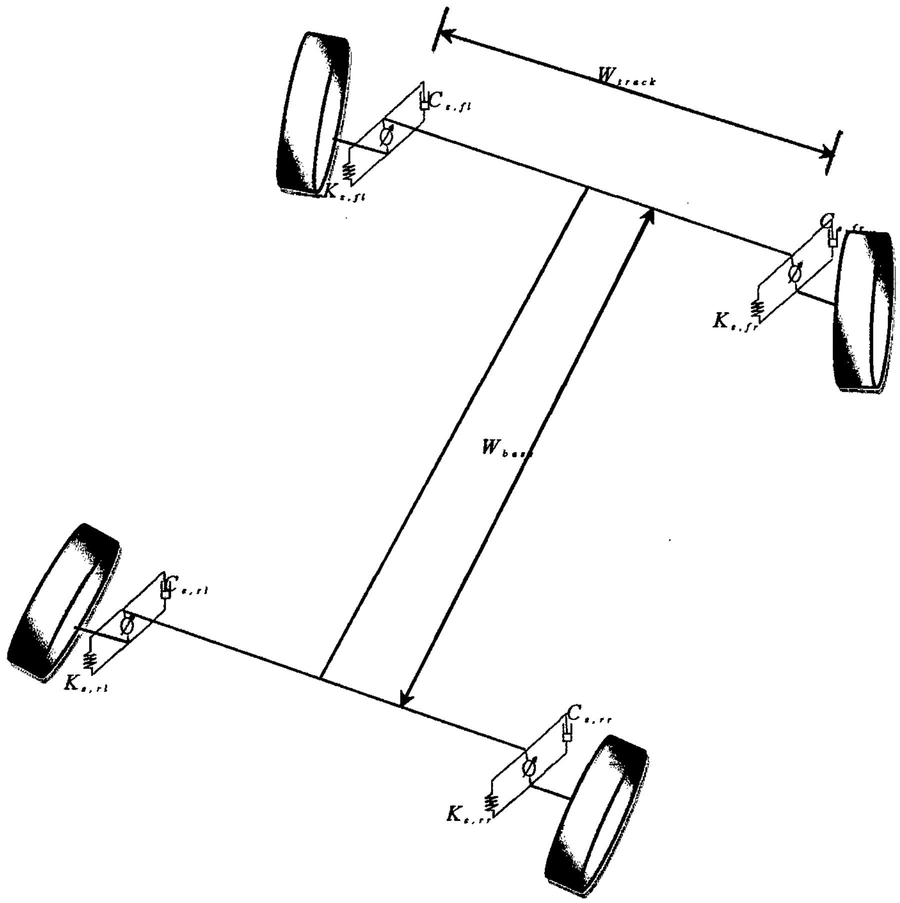


Fig.5 Vehicle Handling Model

while the wheels are called the unsprung mass. The suspension system between the wheels and vehicle body allows a relative up-down displacement between the vehicle body and the wheels. In this model, the suspensions system consists of viscous damper and spring elements. From Fig.5, C_s is a suspension damping, while K_s is a suspension spring stiffness.

The vehicle dynamic model was shown in Fig.6, where $m_s$is a sprung mass, $m_u$is a unsprung mass h_s is a height from roll axis to the

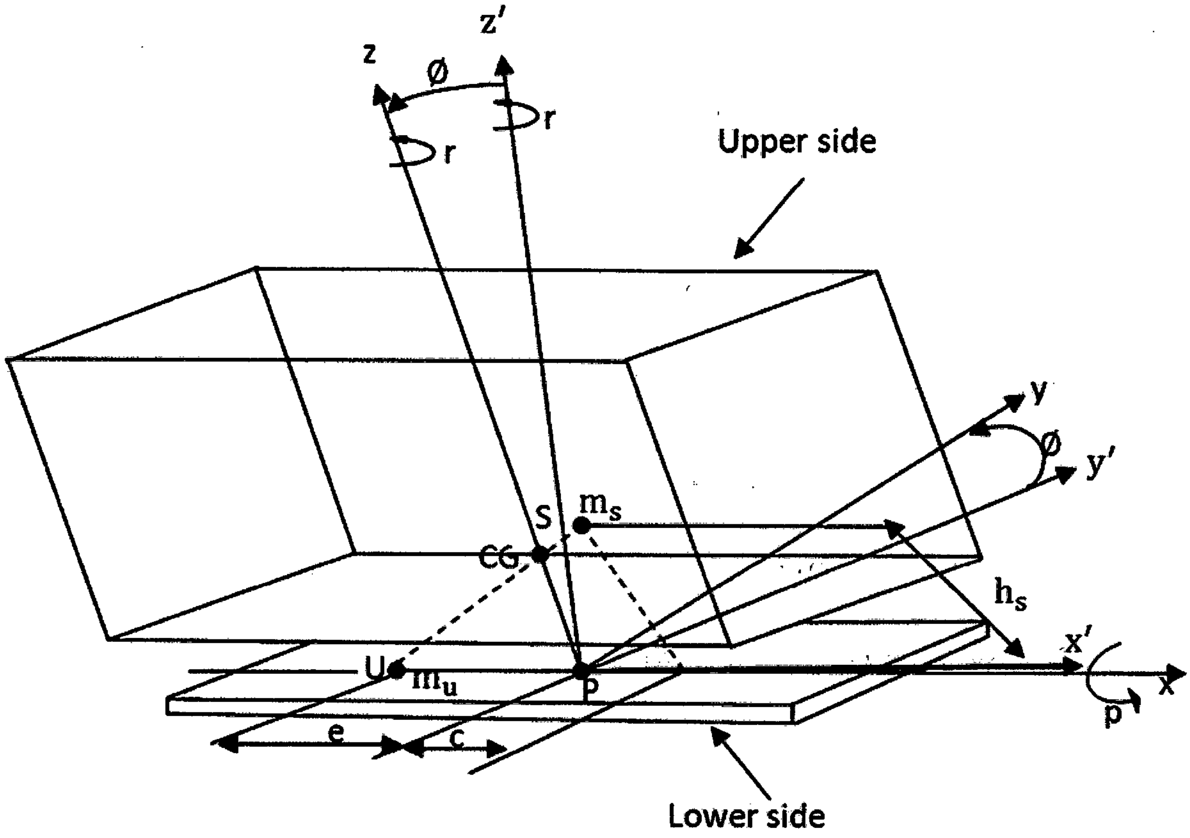


Fig.6 Vehicle Dynamic Model

gravity point of upper side of spring, CG is center of gravity, S is a gravity point of upper side, U is a gravity point of lower side, e is a length from the center of the lower side of spring to the z axis, c is a length from the center of the upper side of spring to the z axis, ϕ is a roll angle, p is a roll angular velocity and r is a yaw angular velocity.

When the vehicle moves laterally, a centrifugal force acts at the vehicle center of gravity, causing the vehicle to tilt to the direction of the centrifugal force. This tilt is called the vehicle roll. In this simulation, the suspension system is considered, and then the vehicle will have a roll degree of freedom that is produced together with vehicle lateral motion.

In general, the front and rear wheel roll centers are determined by the suspension system configuration. The roll center is the vehicle's instantaneous rotation center in the plane perpendicular to the vehicle's longitudinal direction, which contains the left and right wheels' ground contact point.

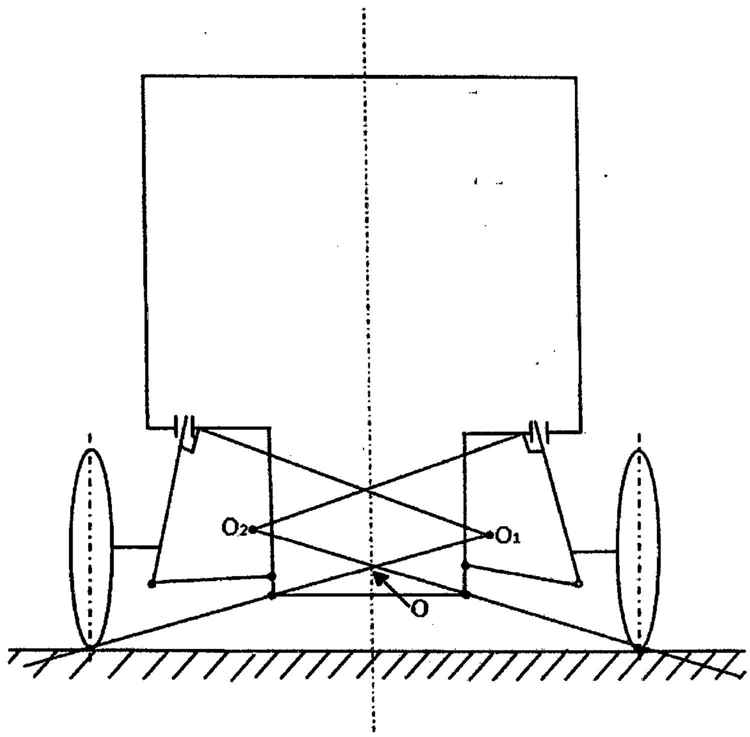


Fig.7 Roll center for Macpherson Strut suspension

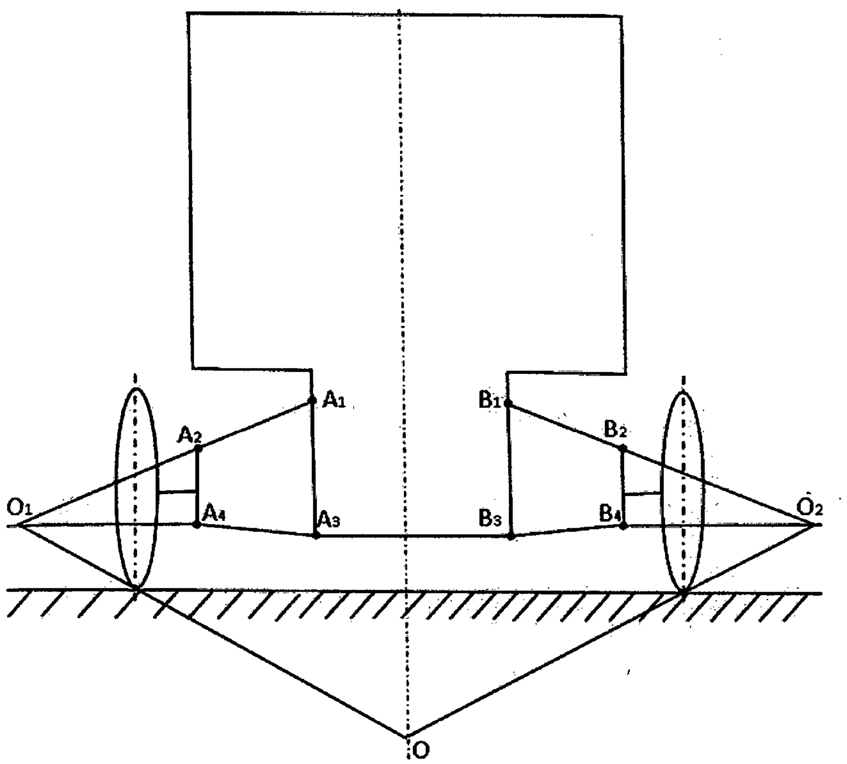


Fig.8 Roll center for double wishbone suspension

In our small electric vehicle, we use Macpherson Strut for a front suspension and Double Wishbone for a rear suspension. Fig.7 and Fig.8 shows the roll center for Double Wishbone suspension and Macpherson Strut suspension. This suspension allows each wheel to move independently, relative to the vehicle body. If the vehicle body is fixed, the instantaneous rotation centers of the left and right unsprung mass relative to the vehicle body are the points 0_1 and 0_2, respectively. When the vehicle body rolls during cornering, the wheel contact points with the ground, A and B, are fixed and the unsprung masses must roll around them. As a result, the point 0_1 and 0_2 will move. 0_1 and 0_2 are the virtual points on the vehicle body as well as on the unsprung masses. Consequently, the vehicle body instantaneous rotating center, or the roll center is the intersection of the extended lines, which is the point O.

It is clear that the position of the roll center can move during suspension movement and it is dependent on the structure of the suspension system. In this simulation, we considered that the suspension system and the vehicle are symmetrical on the left and right, and the roll center is always on the symmetric axis. In this case, it is the height of the roll center that is dependent on the suspension system structure. The point O on Fig.7 and Fig.8 are the roll center when roll angle is zero; if the vehicle rolls, the roll center will also move.

Here, we also considered that if the roll angle is not large, the movement of the roll center is small, and it is possible to assume that the roll centers are fixed at point O. The roll center at the front and rear may not have the same height above the ground and the roll axis is not necessary parallel to the vehicle longitudinal axis.

Fig.9 shows the roll center and center of gravity (CG) heights. The centrifugal force acting at the center of gravity produces a rolling moment around the roll axis resulting in a constant roll angle. If the vehicle body rolls, the left and right vertical springs of the suspension

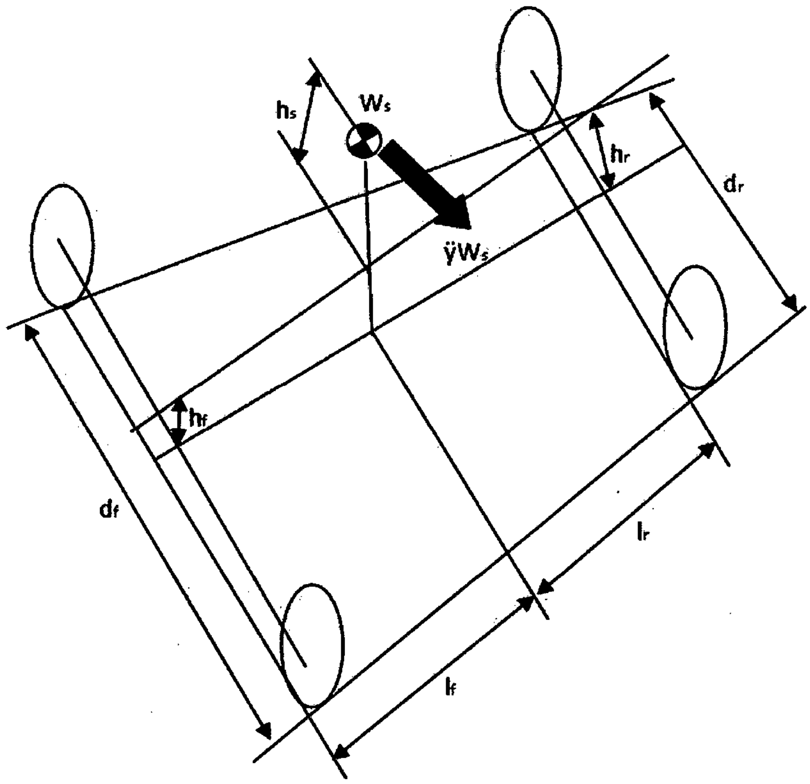


Fig.9 Roll center and CG

heights system will be stretched at one side and be compressed on the other side. This produces an equilibrium moment to the rolling moment due to the centrifugal force. The magnitude of the moment produced by the stretched and the compression of the spring per unit roll angle are called the roll stiffness.

When the vehicle body rolls, the left and right wheels at both front and rear axles will increase in load at one side and decrease in load at the other side. This is called the load transfer due to roll. The equation of load transfer as shown below:

$$\Delta W_f = \frac{Y_S}{d_f}\left(\frac{h_s}{1+\frac{K_{\phi r}}{K_{\phi f}} - \frac{W_s h_s}{K_{\phi f}} + \frac{l_r}{l} h_f} \right)$$

$$\Delta W_r = \frac{Y_S}{d_r}\left(\frac{h_s}{1+\frac{K_{\phi f}}{K_{\phi r}} - \frac{W_s h_s}{K_{\phi r}} + \frac{l_f}{l} h_r} \right)$$

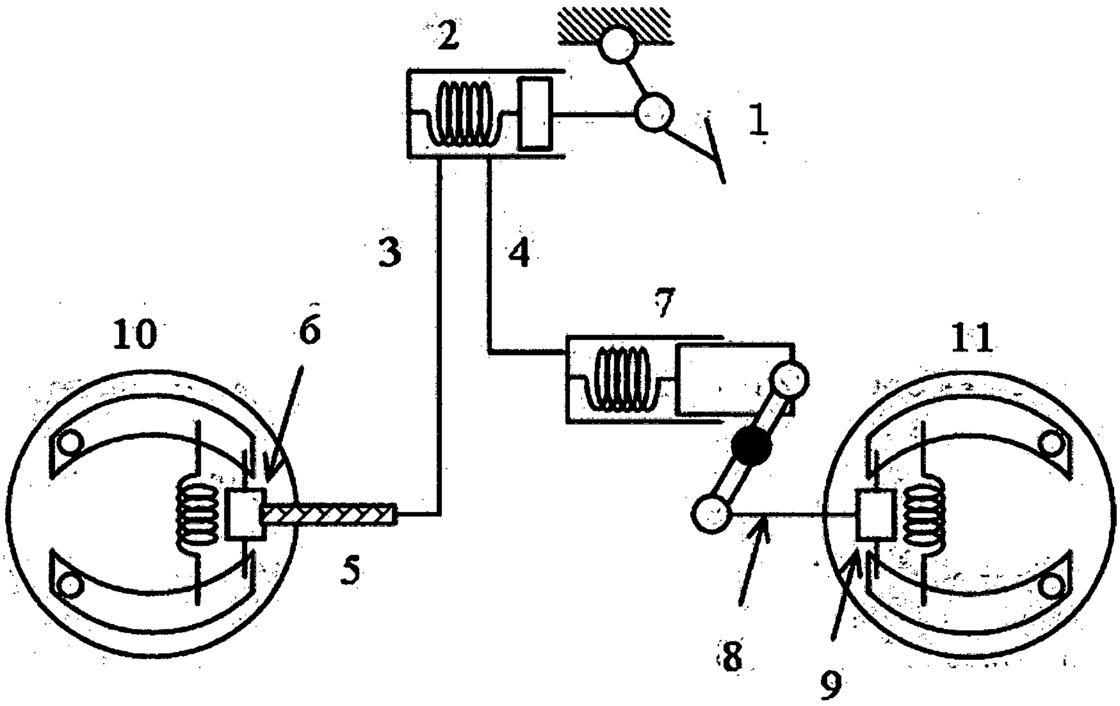
Furthermore, a load transfer at the front and rear wheels are basically proportional to the front and rear roll stiffness ratios to the total roll stiffness, respectively.

4.3 Braking System

In this research, the braking system of our small electric vehicle is a hydraulic-mechanical hybrid brake system.

4.3.1 Hydraulic-Mechanical Hybrid Brake System

Fig.10 shows the model of a hydraulic-mechanical brake system represented as two wheel drive vehicle and both left and right side of the brake system have the same mechanism. The front brake system is a hydraulic braking system while the rear brake system is a mechanical braking system. In mechanical brake system, the braking pressure



1:Brake Pedal	2:Master Cylinder	3:Front Brake Tube	
4:Rear Brake Tube	5:Brake Hose	6:Wheel Cylinder	
7:Power Cylinder	8:Wire	9:Link	10:Front Drum Brake

Fig.10 Hybrid Brake System

generated in the master cylinder is directed into a power cylinder. The piston pulls a wire connected to the brake shoe. The rigidity of the spring is equal to the total of the rigidities of the wire and the power cylinder.

4.3.1 Regenerative Brake

In braking systems, friction is used to counteract the forward momentum of a moving vehicle. As the brake pads rub against the wheels or a disc that is connected to the axles, excessive heat energy is created. This heat energy dissipates into the air, wasting as much as 30 percent of the vehicle's generated power. Over time, this cycle of friction and wasted heat energy reduces the vehicle's fuel efficiency. More energy from the engine is required to replace the energy that was lost by braking.

Regenerative braking is used to recoup some of the energy that is lost while the vehicle is stopping. The energy that is recouped during braking is saved in a storage battery and used later to power the motor whenever the vehicle is using its electric power source.

Our small electric vehicle still use conventional brake pads, but electric motors help the vehicle brake during stop-and-go driving at slower speeds. As the driver applies the brakes by pressing down on a conventional brake pedal, the electric motors reverse direction. The torque created by this reversal counteracts the forward momentum and eventually stops the car.

The equations of front and rear braking torque, T_{BF} and T_{BR} are:

$$T_{BF} = BEF_f \times R_f B_f \qquad (4.3.1.1)$$

$$T_{BR} = BEF_r \times R_r B_r \times T_R \qquad (4.3.1.2)$$

where BEF_f is a brake effective factor, R_f and R_r are diameter of front and rear brake shoe, B_f and B_f are braking force of front and rear, and T_r is a regenerative brake torque. The regenerative brake torque was proportion to the rear tire angular velocity, ω_r and the equation of regenerative brake torque is:

$$T_R = C_r \omega_r \qquad (4.3.1.3)$$

where C_r is a coefficient. The equation of regenerative brake force is:

$$B_{rR} = \frac{T_R}{R_r} \qquad (4.3.1.4)$$

4.4 Simulation Model

In this research, we combined hydraulic-mechanical hybrid brake system with ABS. Fig.11 shows the simulation model of hydraulic-mechanical hybrid brake system. The hydraulic unit of ABS was installed between the master cylinder, which generates the braking pressure and power cylinder, which generates the braking force. This simulation model consists of four components.

1. Pressure Source Unit

The first component is a pressure source unit. The pressure source unit is a model of the master cylinder. The damper and spring represent the damping force of the brake fluid and the return spring in the master