Development of the Module Structure of In-wheel Motor and Double-wishbone Suspension with Torsion Bar

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Abstract
To develop new in-wheel-motor electric vehicle with compact chassis structure, using a double-wishbone suspension mechanism with zero toe-in fluctuation, a module structure composed of double-wishbone suspension with torsion bar, sensor, brake and in-wheel motor was presented, and a new method for analyzing and designing the stiffness and damping parameters of double-wishbone suspension with torsion bar was strictly derived. Then, the theoretical results above were successfully applied in the chassis development of new electric vehicles with four in-wheel motors, such as fuel cell mini-car with steer-by-wire, etc.

Keywords
double-wishbone suspension, torsion bar, in-wheel motor, electric vehicle, steer-by-wire

1. INTRODUCTION
The global auto industry is facing the energy and environmental protect problems, and the development of electric vehicles are the worldwide trend [Hrovat, 1988; Hori, 1998]. Electric Vehicles (Power Battery Vehicle, Hybrid Power Vehicle and Fuel Cell Vehicle) not only have the great significance for energy security and environment protect, but also integrate mechanics, material, electric, electronics, digit, information and intelligence into a whole part, which will enhance the technical competitiveness of Chinese auto industry. Therefore, in 2001, the Ministry of Science and Technology (MOST) set up the EV special project in the National High-Tech Plan. Prof. Dr. Gang Wan, president of Tongji University is the chief scientist of the project and takes charge of the "Fuel Cell Vehicle" project (No.2003AA501000, 2005AA501000) and other projects. Up to now, the advanced EV lab and hydrogen lab have been built, and "START" series fuel cell vehicles, "STEP ONE" hybrid vehicle, "Spring Light" series fuel cell mini-car have been developed, illustrated in Figure 1-3.

Fig. 1 "START Three" fuel cell vehicle

Fig. 2 "STEP One" hybrid vehicle

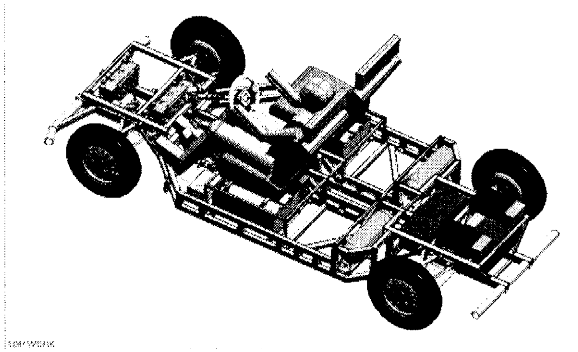

Fig. 3 "Spring Light Three" 4WD mini-car platform

The "Spring Light" series mini-car adopted four in-wheel motor modules which composed of in-wheel motors, brakes, sensors and double-wishbone suspensions with torsion bar, shown in Figure 4, and its chassis frame takes truss structure in which all the power parts and control units are plugged, Thus, the developed mini-cars have the advantages of simple structure, high efficiency, and large inner space etc.

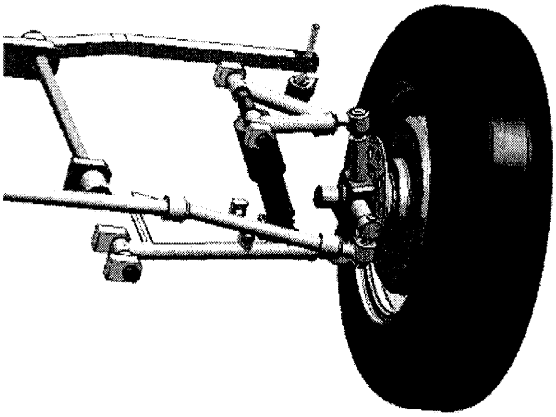

Fig. 4 The module structure of independent suspension and in-wheel motor

In this paper, the structure and the parameter analysis of the in-wheel motor module are discussed.

2. THE MODULE STRUCTURE OF IN-WHEEL MOTOR AND DOUBLE-WISHBONE SUSPENSION

The module structure of in-wheel motor and double-wishbone suspension is composed of in-wheel motor, sensors, double-wishbone mechanism, spring, shock absorber, disc brake and so on.

The objective of the module structure development is minimizing the number of parts, making the module structure in common use, so the front and rear suspensions were developed in the same structure. When they were used in the steering wheel compared with used in the non-steering wheel, the characteristics of the module structure (such as toe-in fluctuation) are usually different in kinematics.

The suspension development demands that the wheel alignments fluctuation should be little enough to minimize tire wear and resistance, which can improve the safety and economy of vehicle.

To eliminate the toe-in fluctuation above, we put forward a new structure of double-wishbone suspension with zero toe-in fluctuation for non-steering wheel, illustrated in Figure 5 (Patent No.200310107879.1). Using this mechanism, provided that the double-wishbone suspension's design parameters for the steering wheel satisfies the demands of the wheel alignment, the non-steering wheel can always keep zero toe-in fluctuation when it has identical parameters compared with the steering wheels.

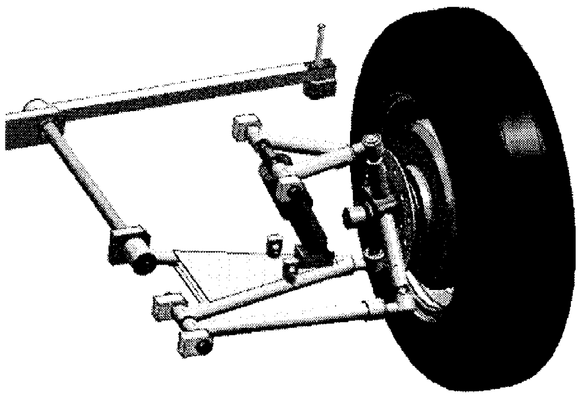

Fig. 5 Double-wishbone suspension mechanism for non-steering wheel with zero toe-in fluctuation

3. STIFFNESS AND DAMPING FEATURES ANALYSIS OF DOUBLE-WISHBONE SUSPENSION

The stiffness and damping features of double-wishbone suspension with torsion bar are nonlinear. The accurate nonlinear relationships are the foundation for accurate analyzing and selecting the stiffness of the torsion bar and the damping parameters of the shock absorber.

Figure 6 shows the schematic graph of double-wishbone suspension, and A, B, C, D are the joints of the mechanism. The torsion bar and the fixed hinge A of the upper control arm (or the fixed hinge D of the lower control arm) are fixed on the common axes. We abbreviate it upper torsion bar (or lower torsion bar). KJ means the shock absorber, and K, J are the joints. As can be seen in Figure 6, a reference coordinate D-yz is established, where D is the original, y axis is horizontal and z is vertical. Some parameters are listed below.

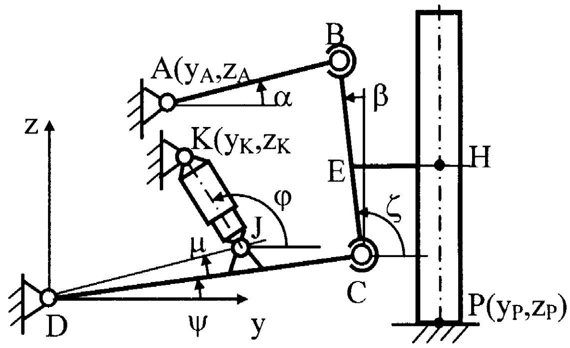

Fig. 6 Double-wishbone suspension mechanism

(1) structural parameters

L_1 - the length of arm AB

L_2 - the length of king-pin BC

L_3 - the length of arm CD

y_A, z_A - the coordinates of fixed hinge A
y_K, z_K - the coordinates of joint K of shock absorber KJ
a - EB
b - EH
L_4 - DJ
μ - $\angle$CDJ
(If the joint J of shock absorber KJ is connected with arm AB, then $L_4 = AJ$, $\mu = \angle BAJ$)

(2) kinematics parameters
α - the angle of arm AB
β - the inclination angle of king-pin BC
ξ - the angle of king-pin BC to y axis, $\xi = 90^\circ + \beta$
ψ - the angle of arm CD
φ - the angle of shock absorber KJ
r - the radius of wheel
y_P, z_P - the coordinates of the touch point P between wheel and ground

(3) dynamics parameters
m - the sprung mass
F_Z - the load of wheel
T - the torque of the torsion bar
K_T - the torsion stiffness of the torsion bar
K_P - the stiffness of the suspension
f - the eigenfrequency of the suspension
C_r - the damping ratio of the shock absorber
C_p - the damping ratio of the suspension
C_0 - the relative damping ratio of the suspension
F_r - the damping force of the suspension
V_{JK} - the relative velocity of the piston of the shock absorber

3.1 The relationship between the suspension stiffness and the torsion bar stiffness

The stiffness of suspension influenced on vehicle ride performance directly. Ergonomics pointed out that when the eigenfrequency value is 1.0~1.5Hz, the vehicle is the most comfortable. Provided that the single suspension stiffness is KP (N/m) and the sprung mass is m (kg), then the relationship between KP and m can be derived as formula 1.

$$k_P = (2\pi f)^2 m \tag{1}$$

Provided that the torsional stiffness of the torsion bar is KT (*Nm/rad*) and the torque of the torsion bar is T (Nm), then the relationship between KT and KP is derived respectively according to the different assembly of the torsional bar.

(1) Case1: the torsion bar is fixed on the upper control arm
According to the principle of imaginary work, we can obtain following the expression:

$$Td\alpha = K_T(\alpha + \alpha_0)d\alpha = F_Z dZ_P$$

so

$$F_z = \frac{K_T(\alpha + \alpha_0)}{\frac{dz_P}{d\alpha}} \tag{2}$$

Where, α_0 is the angle between the upper control arm AB and y when the distortion of the torsion bar is zero ($F_Z = 0$). Differentiating with respect to α, we get

$$\frac{dF_z}{d\alpha} = K_T \cdot \frac{\frac{dz_P}{d\alpha} - (\alpha + \alpha_0)\frac{d^2 z_P}{d\alpha^2}}{(\frac{dz_P}{d\alpha})^2}$$

Then the stiffness of the suspension KP can be described as

$$k_P = \frac{dF_Z}{dz_P} = \frac{\frac{dF_z}{d\alpha}}{\frac{dz_P}{d\alpha}} = K_T \frac{\frac{dz_P}{d\alpha} - (\alpha + \alpha_0)\frac{d^2 z_P}{d\alpha^2}}{(\frac{dz_P}{d\alpha})^3} \tag{3}$$

The expression shows the relationship between the stiffness of suspension KP and the torsional stiffness of the torsion bar KT or other structural parameters is obvious nonlinear. Formula (4) can be obtained by merging formula (2) with formula (3), which described the torsional stiffness of the torsion bar KT.

$$K_T = k_P \cdot (\frac{dz_P}{d\alpha})^2 + F_z \cdot \frac{d^2 z_P}{d\alpha^2} \tag{4}$$

Where, $\psi = \psi(\alpha)$, $\xi = \xi(\alpha)$, $\frac{d\psi}{d\alpha}$, $\frac{d^2\psi}{d\alpha^2}$, $\frac{d\zeta}{d\alpha}$, $\frac{d^2\zeta}{d\alpha^2}$, $\frac{dz_p}{d\alpha}$, y_p, z_p can be obtained respectively by the kinematics analysis of mechanism.

(2) Case2: the torsion bar is fixed on the lower control arm
Replacing α, α_0 by ψ, ψ_0 in expressions (2), (3) and (4),we get

$$F_z = \frac{K_T(\psi + \psi_0)}{\frac{dz_P}{d\psi}} \tag{5}$$

$$k_P = \frac{dF_Z}{dz_P} = \frac{\frac{dF_z}{d\psi}}{\frac{dz_P}{d\psi}} = K_T \frac{\frac{dz_P}{d\psi} - (\psi + \psi_0)\frac{d^2 z_P}{d\psi^2}}{(\frac{dz_P}{d\psi})^3} \tag{6}$$

$$K_T = k_P \cdot \left(\frac{dz_P}{d\psi}\right)^2 + F_z \cdot \frac{d^2 z_P}{d\psi^2} \tag{7}$$

where,

$$\frac{d^2 z_P}{d\psi^2} = \frac{\frac{d^2 z_P}{d\alpha^2} - \frac{d^2\psi}{d\alpha^2}\cdot\frac{dz_P}{d\psi}}{\left(\frac{d\psi}{d\alpha}\right)^2}, \quad \frac{dz_P}{d\psi} = \frac{\frac{dz_P}{d\alpha}}{\frac{d\psi}{d\alpha}}$$

ψ_0 is angle between the lower control arm CD and y when the distortion of the torsion bar is zero(Fz=0).

3.2 The relationship between the suspension damping characteristics and the damping parameters of shock absorber

According to the ride performance demands, the vertical damping ratio of suspension C_p is given by the expression below [Liu, 2001]:

$$C_P = 4\pi \cdot f \cdot m \cdot C_0 \tag{8}$$

Where, the relative damping ratio is 0.25-0.5, and the relationship between the vertical damping ratio of suspension and the damping ratio of the shock absorber is

$$C_r \cdot v^2_{JK} = C_P \cdot \left(\frac{dz_P}{d\alpha}\right)^2,$$

$$C_r = C_P \cdot \frac{\left(\frac{dz_P}{d\psi}\right)^2}{L_4^2 \sin^2(\varphi - \mu - \psi)} \tag{9}$$

$$C_P = C_r \frac{L_4^2 \sin^2(\varphi - \mu - \psi)}{\left(\frac{dz_P}{d\psi}\right)^2} \tag{10}$$

When the fixed joint J of shock absorber KJ is connected with the upper control arm AB, then L_4, AJ, $\mu = \angle BAJ$, and must replace the ψ as α.

3.3 New method for analyzing the stiffness and damping ratio of the suspension

The process of analyzing the stiffness and damping ratio of suspension is list below:

(1) According to the ergonomics demands, select suitable eigenfrequency f and correlative damping ratio C_0;
(2) Calculate the stiffness k_p and damping ratio C_P of suspension when the suspension is static balancing through expressions (1) and (8);
(3) Input necessary parameters and $F_z = mg$ into expressions (4) or (7), calculate the torsional stiffness of the torsion bar K_T;
(4) Get the value of α_0 or ψ_0 through expression (2) or (5) under the condition that the torsional load is zero;
(5) Calculate the damping ratio of the shock absorber C_r by expression (9);
(6) Calculate the relationship between k_P and the wheel vertical displacement through expression (3) or (6);
(7) Calculate the relationship between CP and the wheel vertical displacement through expression (10).

4. THE APPLICATIONS

Using theoretical results above, we have developed "Spring Light" series 4WD mini electric vehicles shown as Figure 7-11.

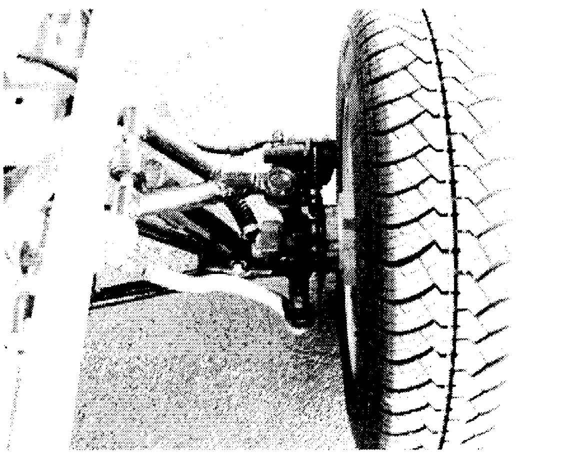

Fig. 7 The module structure of suspension and in-wheel motor

Fig. 8 "Spring Light Two" mini 4WD EV (10/2003)

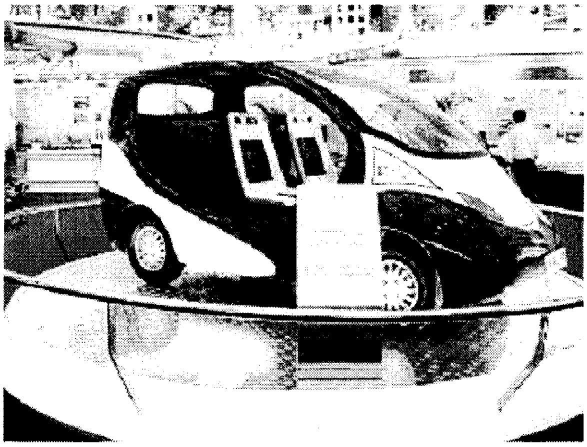

Fig. 9 "Spring Light Three" mini 4WD FCV with steer-

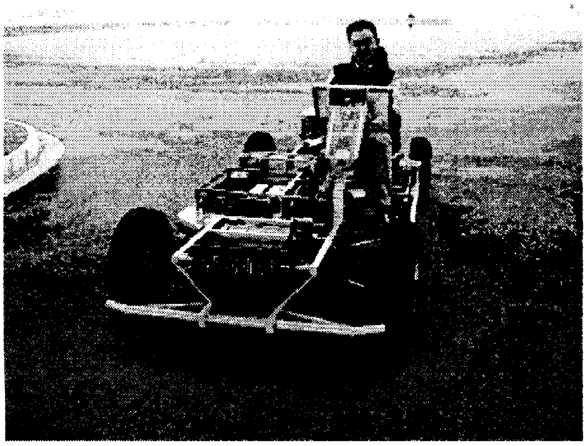

Fig. 10 The magnesium chassis of mini 4WD FCV with steer- by-wire (10/2005)

Fig. 11 "Spring Light Three" mini 4WD EV (10/2005)

5. CONCLUSIONS

Because of using a new mechanism of the double-wishbone suspension having zero toe-in fluctuation, the front and the rear suspensions adopting similar module structure became possible, which is helpful for reducing the quantity of suspension parts, and so the cost is reduced. Under different assembly conditions, the nonlinear function relationships of stiffness and damping are derived respectively. Then a new method and its software to calculate accurately and effectively the stiffness of the torsion bar and the damping ratio of the shock absorber are put forward.

The successful development of "Spring Light" series mini 4WD EV verified that the module structure and its designing method are useful.

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