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Full Vehicle Suspension System with In-Wheel Electric Motors

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Abstract

    The objective of this paper is to study the performance of a vehicle suspension system using full model and four In-wheel electric motors. The suspension system of vehicle typically evaluated by its ability to produce good passenger comfort, road handling, improve and capture the basic performances of the vehicle suspension such as the body absolute velocity, suspension travels, wheel deflection and body pitch angle. The simulation is performed based on the mathematical model of the full car suspension system by using MATLAB/SIMULINK software. It is known that the In-Wheel motors will increase the mass of the wheel which called the unsprung mass. This paper summarized a bad effect of increasing the mass of wheels by add In-Wheel Motors to the vehicle suspension system on the vehicle drivers comfort and the road traction.

Keywords*:* Unsprung mass, Suspension system In-wheel motor, Simulink model, full car model

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INTRODUCTION

Traditionally the designs of vehicle suspensions have been compromise between a three conflicting criteria's which namely passenger comfort, road handling, and load carrying. The suspension systems must support the vehicle, provide effective isolation of passengers, provide directional control using handling maneuvers and the load disturbance. Best ride comfort of passenger requires a soft suspension, while insensitivity to apply the loads requires stiff suspension. Best handling of vehicle requires a suspension setting somewhere between it. According to these conflicting demands, the design of suspension has to be something that can compromise the two problems.

Suspensions consist of the system of springs, shock absorbers, and linkages which connects the vehicle with its wheels. By other meaning, the suspension system can be defined as a mechanism which physically separates the body of car from the car wheels. The major function of the vehicle suspension system is to decrease the acceleration in the vertical direction which transmitted to the passengers that directly provides the road comfort. The main three types of the vehicle suspension system are; active, passive, and semi-active suspension systems. Traditional suspensions consist of dampers and springs which are referred to as passive suspension, if the suspension system is controlled externally, it is known as a semi-active or active suspension.

The passive suspension has ability to store the energy via springs and to dissipate it via dampers. Generally its parameters are fixed, being chosen to enhance a certain level of compromise between load carrying, ride comfort, and road handling, and. The active suspension system has ability to dissipate, store, and to introduce the energy to the system. It varies the parameters depending on some operating conditions.

MATERIALS AND METHODS

This study aims to analyze and study the effect of In-Wheel motors mass on the vehicle suspension systems using full vehicle model which basically contents of unsprung mass, sprung masses, dampers and springs. To achieve the main target of this paper, the unsprung mass will considered as two states ,where the first one is a standard tire and the second one is In-Wheel electric motor.

The analysis of this work needs a certain steps to show the effect of In-Wheel motor mass on the system which is modeling and simulation of the full vehicle suspension system. Building the Simulink model of the system will be obtained by Matlab software.

STRUCTURE OF IN-WHEEL MOTOR

The In-wheel motors (also called wheel hub drive, wheel motor, hub motor or the wheel hub motor) is an electric motor which is incorporated into the wheel hub a wheel and drives it directly. In this study, only the effect of the electric motor mass will take into considerations.

Figure(1) illustrates a cross-section an in-wheel electric motor system, which has a structure that aligns the motor section, reducer section, and the hub section in a series configuration. Figures (2)and(3) illustrate the Michelin active tire with in-wheel electric motor and Bridgestone's Dynamic-Damping In-wheel Drive System.
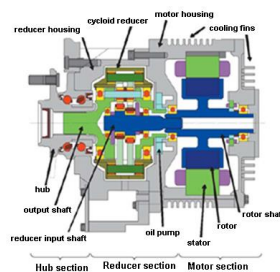

Figure 1: Cross-section of In-wheel motor.

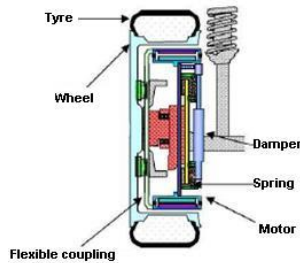**Figure 2: Michelin active wheel with in-wheel motor.**

Figure3: Bridgestone's Dynamic Damping In-wheel Motor.

SUSPENSION SYSTEM

In the full vehicle suspension system model, the vehicle body or sprung mass is free to heave pitch and roll, which means the full vehicle dynamics includes the movement and rotation on the vertical, lateral and longitudinal directions; therefore, the vehicle, vertical, lateral, and longitudinal dynamics must be contemplated for a complete vehicle model. The main function of the suspension system is to connect the sprung mass which represents the vehicle body to the four unsprung masses which are front-right, front-left, rear-right rear-left, and wheels. They are free to bounce in the vertical direction relative to the sprung mass.

Figures 4 and 5 show a full vehicle model: vertical model, horizontal model, and the tire model. The pitch , heave and roll motions of the vehicle body are considered. Also, the lateral and longitudinal velocities and the yaw rate included. The three DOF of the vehicle body at the center of gravity (c.g.) is depicted in Figure 4. This model obtains both of the longitudinal and lateral forces of each tire from the tire model. The forces in x direction and y direction of the horizontal model

calculates only the horizontal performance of the vehicle. The vertical model is made seven DOF and four DOF of the four wheels, as obtained in Figure 5. In Figure 4 which represents the horizontal vehicle model, V is the vehicle velocity, $\dot{\varphi}$ is the yaw rate, δ is the front wheel steering angle, and β is the side slip angle. The lengths L_f and L_r indicate the longitudinal distance from the c.g. to the front wheels and the rear wheels respectively, and L_w is the track width or the lateral distance between left and right wheels. Let the longitudinal and lateral tire forces given by F_x^{ij} and F_y^{ij} respectively, and a_{ij} is the slip angle of the wheel. The superscript or subscript $i=f,r$ refers to the front and rear tires, while the superscript or subscript F_y *and* F_x indicates the tire forces. Then the equations of motion of the vehicle body are:
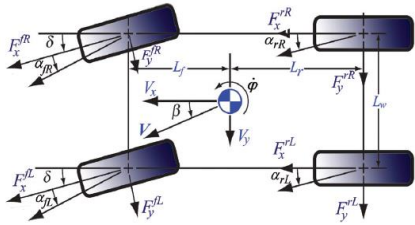

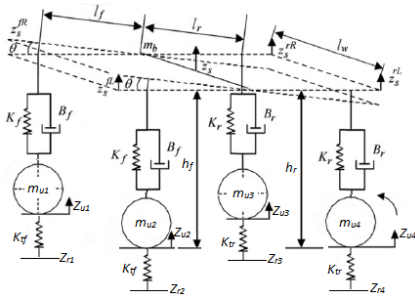**Figure 4: 3 DOF vehicle model or horizontal model**.

Figure 5: Vertical vehicle model.

$$\dot{v}_x = \frac{1}{m}\left[\left(F_x^{fL} - F_x^{fR}\right)\cos\delta - \left(F_y^{fL} + F_y^{fR}\right)\sin\delta + \left(F_x^{rL} + F_x^{rR}\right) + \dot{\emptyset}v_y\right] \tag{1}$$

$$\dot{v}_y = \frac{1}{m}\left[\left(F_y^{fL} + F_y^{fR}\right)\cos\delta + \left(F_x^{fL} + F_x^{fR}\right)\sin\delta + \left(F_y^{rL} + F_y^{rR}\right) - \dot{\emptyset}v_x\right] \tag{2}$$

$$\ddot{\varphi} = \frac{1}{I_\varphi}[L_f \quad (\quad F_x^{fR} \quad + \quad F_x^{fL} \quad) \quad \sin\delta + L_f(F_y^{fR} \quad +$$
$$F_y^{fL})\cos\delta - L_r(F_y^{rL} + F_y^{rR}) + \frac{L_w}{2}\left(F_x^{fR} - F_x^{fL}\right)\cos\delta + \frac{L_w}{2}(F_x^{rR} - F_x^{rL}) +$$
$$\frac{L_w}{2}\left(F_y^{fL} - F_y^{fR}\right)\sin\delta]$$

(3)

Where I_ϕ is the moment of inertia of the vehicle about its yaw and m is the vehicle mass.

In the vertical model shown in Figure 5, let Zs and z_s^{ij} are the vertical displacement of the vehicle body at the center and the corner respectively, Z_{ri} is the road profile at each tire, m_b is the mass of the vehicle without the mass of the front and rear wheels m_{ui} , θ is the body pitch angle, h_i is the vertical distance from the c.g. to the center of the rear and the front wheel at the equilibrium. The spring and damping constants are Ki and B_i respectively. All the lumped parameters associated with the passive suspension system.

For a small values of θ and after applying a force balance analysis to the model in Figure 5, the equations of motion can be derived to the equilibrium at static positions. The equations which are describing the sprung mass are:
For rolling motion of the sprung mass:

$$\ddot{\emptyset} = \frac{h_f}{I_\theta}\left\{\left(F_y^{fL} - F_y^{fR}\right)\sin\delta + \left(F_x^{fR} - F_x^{fL}\right)\cos\delta + h_r(F_x^{rR} - F_x^{rL}) - \frac{L_w}{2}\left(K_f Z_s^{fR} +\right.\right.$$
$$\left.B_f \dot{Z}_s^{fR} + K_r Z_s^{rR} + B_r \dot{Z}_s^{rR}\right) + \frac{L_w}{2}(K_f Z_s^{fL} + B_f \dot{Z}_s^{fL} + K_r Z_s^{rL} + B_r \dot{Z}_s^{rL})\right\}$$

(4)

For pitching motion of the sprung mass:

$$\ddot{\theta} = \frac{h_f}{I_\theta}\{(F_x^{fL} + F_x^{fR})\cos\delta + (F_y^{fL} + F_y^{fR})\sin\delta - h_r(F_x^{rL} + F_x^{rR}) - L_f(K_f Z_s^{fL} + B_f \dot{Z}_s^{fL} + K_f Z_s^{fR} + B_f \dot{Z}_s^{fR}) + L_r(K_r Z_s^{rL} + B_f \dot{Z}_s^{rL} + K_r Z_s^{rR} + B_r \dot{Z}_s^{rR})\}$$

(5)

For bouncing of the sprung mass:

$$\ddot{z} = \frac{1}{m_b}\{m_g - (K_f Z_s^{fL} + B_f \dot{Z}_s^{fL} + K_f Z_s^{fR} + B_f \dot{Z}_s^{fR}) - (K_r Z_s^{rL} + B_r \dot{Z}_s^{rL} + K_r Z_s^{rR} + B_r \dot{Z}_s^{rR})\}$$

(6)

Where:

$$z_s^{fR} = z_s + l_f\theta - \frac{l_w\emptyset}{2}$$

(7)

$$z_s^{fL} = z_s + l_f\theta + \frac{l_w\emptyset}{2}$$

(8)

$$z_s^{rR} = z_s - l_f\theta - \frac{l_w\emptyset}{2}$$

(9)

$$z_s^{rL} = z_s - l_f\theta + \frac{l_w\emptyset}{2}$$

(10)

$$\dot{z}_s^{fR} = \dot{z}_s + l_f\dot{\theta} - \frac{l_w}{2\emptyset}$$

(11)

$$\dot{z}_s^{fL} = \dot{z}_s + l_f\dot{\theta} + \frac{l_w}{2\emptyset}$$

(12)

$$\dot{z}_s^{rR} = \dot{z}_s - l_f\dot{\theta} - \frac{l_w}{2\emptyset}$$

(13)

$$\dot{z}_s^{rL} = \dot{z}_s - l_f\dot{\theta} + \frac{l_w}{2\emptyset}$$

(14)

And also for each wheel motion in vertical direction:

$$m_{u1}\dot{Z}_{u1} = B_f(\dot{z}_s^{fR} - \dot{Z}_{u1}) + K_f(z_s^{fR} - Z_{u1}) - K_{tf}Z_{u1} + K_{tf}Z_{r1}$$

(15)

$$m_{u2}\dot{Z}_{u2} = B_f(\dot{z}_s^{fL} - \dot{Z}_{u2}) + K_f(z_s^{fL} - Z_{u2}) - K_{tf}Z_{u2} + K_{tf}Z_{r2}$$

(16)

$$m_{u3}\dot{Z}_{u3} = B_r(\dot{z}_s^{rR} - \dot{Z}_{u3}) + K_r(z_s^{rR} - Z_{u3}) - K_{tr}Z_{u3} + K_{tr}Z_{r3}$$

(17)

$$m_{u4}\dot{Z}_{u4} = B_r(\dot{z}_s^{rL} - \dot{Z}_{u4}) + K_r(z_s^{rL} - Z_{u4}) - K_{tr}Z_{u4} + K_{tr}Z_{r4}$$

(18)

VEHICLE PHYSICAL PARAMETERS

The vehicle parameters values which are used in the paper simulations are listed below in table 1.

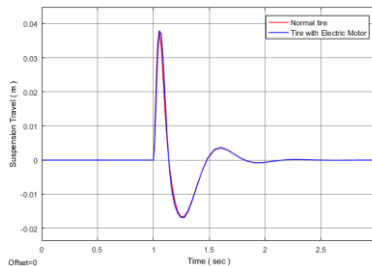Table 1: *Full suspension system parameters*

Parameter	Value	Parameter	Value
m	1136 Kg	I_θ	2.765 Kgm^2
mb	1013 Kg	I_ϕ	614 Kgm^2
mu_1	63 Kg	h_f	0.59 m
mu_2	63 Kg	h_r	0.59 m
mu_3	60 Kg	r_{eff}	0.365 m
mu_4	60 Kg	K_f	36297 N/m
L_f	1.15 m	K_r	19620 N/m
L_r	1.65 m	B_f	3924 Ns/m
L_w	1.082 m	B_r	2943 Ns/m
I_φ	2.765 Kgm^2	g	9.81 m/s^2

SIMULATION RESULTS AND DISCUSSION

This section of the paper presents the suspension system performance. Simulations based on the mathematical model for full car model by using MATLAB/SIMULINK are performed.

Performances of the suspension system in term of ride quality, road holding, and car handling are observed, where road disturbance Z_{ri} is assumed as the input for the system. Parameters that observed and obtained are the suspension travel, tire deflection for Front and Left tires, the absolute velocity of the body, and the body pitch angle for full car model. Road disturbance or road profile is taken as a step signal. The main goal of this work is to achieve small amplitude value for the tire deflection and suspension travel.

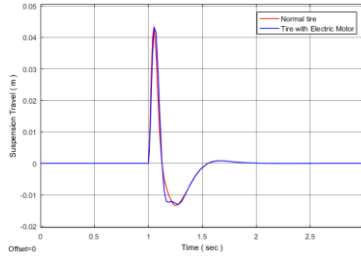**Figure 5: Suspension Travel of Front Right and Left tires.**

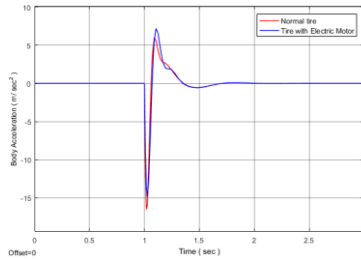**Figure 6: Suspension Travel of Rear Right and Left tires.**
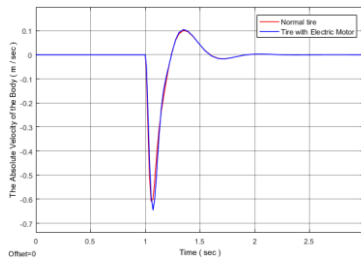

Figure 7: Body Acceleration.

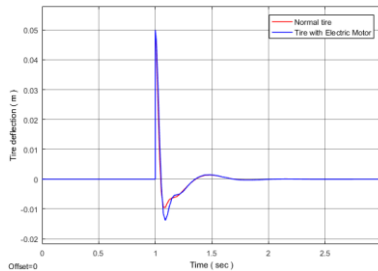**Figure 10: The Absolute Velocity of the Body.**

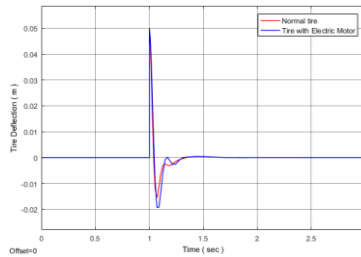**Figure 8: Tire Deflection for Front Right and Left tires.**

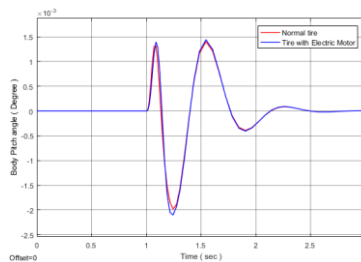**Figure 9: Tire Deflection for Rear Right and Left tires.**

Figure 11: Body Pitch Angle.

CONCLUSIONS

This study demonstrates eloquent effects of the In-wheel electric motor mass on the suspension systems performance, some of these effects was clear due to the suspension deflection and sprung mass velocity which represent the road traction and the driver comfort respectively. At same time the study explained that the suspension system with in-wheel electric motor requires a good selection of the vehicle parameters. Finally, it's obvious that from the computer simulations, using of In-wheel electric motor in the vehicles has bad aspects which caused a little reliability to use it.

REFERENCES

[1] Robert L.W. & Kent L.L., "Modeling and Simulation of Dynamic System", *Prentice-Hall*, Second Edition,1997.

[2] Rosheila Darus, "Modelling and control of active suspension for car model," *Master* thesis, May 2008.

[3] Hrovat, D. & Tseng, T., "Some Characteristics of Optimal Vehicle Suspensions Based on Quarter Car Model", *IEEE Proceedings of the 29th Conferences on Decision and Control*, December, Honolulu, Hawaii: IEEE. 1990. 2232-2237

[4]Abdussalam Ali Ahmed, Başar Özkan, " Using of Fuzzy PID Controller to Improve Vehicle Stability for Planar Model and Full Vehicle Models", *International Journal of Applied Engineering Research*, ISSN 0973-4562 Volume 12, Number 5 (2017) pp. 671-680.

[5]R.Rajamani, "Vehicle dynamics and control", *Springer Science & Business Media*, 2011.

[6]Arjon Turnip, Hanif Fakhrurroja, Hanif Fakhrurroja, "Estimation of the Wheel-Ground Contact tire Forces using Extended Kalman Filter," *International Journal of Instrumentation Science*, 2013, 2(2): 34-40

[7] H. Xiao, W. Chen, H. Zhou, and J. W. Zu, "Integrated vehicle dynamics control through coordinating electronic stability program and active suspension system", *International Conference on Mechatronics and Automation*,2009, pp. 1150-1155.

[8] Wuwei Chen, Hansong Xiao, Liqiang Liu, Jean W. Zu and HuiHui Zhou, "Integrated Control of Vehicle System Dynamics: Theory and Experiment", *Advances in Mechatronics, InTech*, 2011.