Active Control of In-Wheel Motor Electric Vehicle Suspension Using the Half Car Model

[1] عباس حسين حمود
Abbas Hussein Hammood
abbas.h.hammood@almamonuc.edu.iq
كلية المأمون الجامعة

[2] حيدر باقر مهدي
Hayder Baqer Mahdi
Hayder.baqer@almamonuc.edu.iq
كلية المأمون الجامعة

Abstract:

In recent years, electric vehicles are becoming more mainstream. Even though in-wheel electric motor vehicles have been developed as prototype vehicles, they have not become common yet. One of the reasons for this is that when an electric motor is placed in the wheel it becomes heavier, which tends to worsen the road holding properties of the vehicle. Active suspensions are currently used in some high-end vehicles to improve passenger comfort, vehicle handling and road holding. In this paper an active suspension is used show that it is possible to mitigate the road holding problems caused by in-wheel electric vehicles. The ground-hook method is used for the control strategy. First, a quarter car model is used to show that adding a weight to the wheel does actually decrease the road holding performance of the vehicle. Afterwards, the active suspension is shown to be able to improve the road holding properties of the vehicle to acceptable levels. The simulations are also repeated with a half car model. They also show that increasing the tire mass worsens the road holding performance of the vehicle. However, this bad performance can be reversed by the ground-hook active suspension. Simulations

also show that the ground-hook controller worsens the passenger comfort level in the vehicle.

Keywords—active suspension, road holding, ground-hook, electric vehicle, in-wheel motor.

I. Introduction

The suspension system is the one of the most important part of an automobile that isolate the vehicle from road shocks, vibrations and provide comfort effect to the occupant [1][2]. Automotive suspensions are divided into three forms namely passive, semi-active, and active suspension system. Passive suspensions are always used and continuous improvements have been made by research. It is impossible to get both ride comfort and road holding demands in the same time for passive suspension car. Passive suspension systems are the most favorite and are widely used because of their low cost and high reliability. This type of system is considered as open loop system [2]. Passive suspension consists of conventional spring (the spring is pressed and stretched to absorb the wheel movement) and damper which is a shock absorber that works on the vibration motion of the vehicle. The main aim of using damper is to slow down and minimizing the vibration magnitude caused by the road. The damper connected in parallel with spring which was fixed and it is impossible to change externally by any signal [3][4]. So, it should need a spring which can be stiff and soft simultaneously [3][4][5]. Researchers have made a lot of improvements over the years and most of these experts think that the passive suspension are hard to be improved. A ground-hook control is one of the control strategies applied to the automotive suspension. A ground-hook controller is used to improve the road holding for both quarter and halfcar models. This controller method supposes that it is virtually connecting a damper between the unsprung mass and the ground [6]. The ground-hook main task is to reduce the vertical displacement of the tire and keep the ground-tire contact force in a narrow area as possible to the main value [7]. Ground-hook has improvement when compared with passive suspension model. The use of the half car model to show the effects of the ground-hook controller is the main contribution of this paper. The goal is to design control strategy namely ground-hook controller to improve road handling for the vehicle.

I. Quarter Car Model

A. Quarter Car Model Passive Suspension System

Quarter Car model is the most popular model that is used in analysis of automotive suspensions and design. The main reason to use this model is that it is simple, it can give reasonably accurate information and predict lot of important properties about the full car, Figure 1 shows a passive suspension system for a quarter car in which the wheel is connected to the body of the car by passive parameters (spring and damper), and the tire is represented as a spring and the damper of the tire is neglected. The quarter car structural model involved mass of car (m_s) and mass of tire (m_u). There are three vertical displacement types included in quarter car, the vertical displacement for the mass of car (z_s), the vertical displacement for the mass of tire (z_u) and the vertical displacement for the road (z_r).

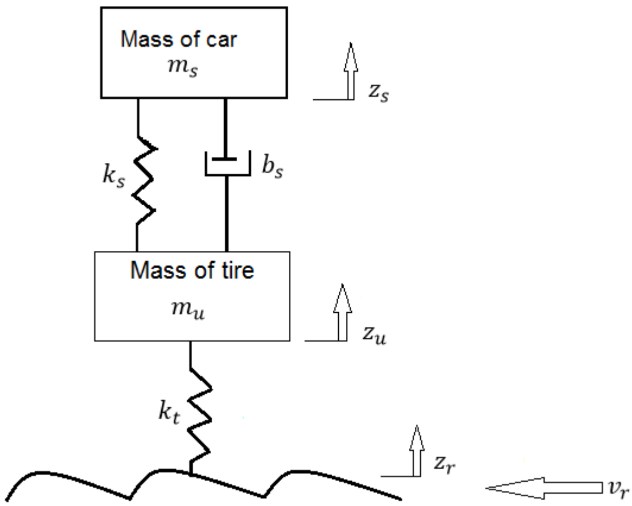

Figure I. Passive suspension system for a quarter car model

B. Quarter Car Model Forces

$$\sum f = ma \quad (1)$$

The variables are: (f_s) force of spring, (f_b) force of damper, (f_t) force of tire, (m_s) mass of car, (m_u) mass of tire, ($\ddot{z_s}$) the acceleration for mass of car, ($\dot{z_s}$) the velocity for mass of car, (z_s) position for mass of car, ($\ddot{z_u}$) the acceleration for mass of tire, ($\dot{z_u}$) the velocity for mass of tire, (z_u) position for mass of tire.

$$-f_s - f_b = m_s\ddot{z_s} \quad (2)$$

$$m_s\ddot{z_s} = -k_s(z_s - z_u) - b_s(\dot{z_s} - \dot{z_u}) \quad (3)$$

$$\ddot{z_s} = -\frac{k_s}{m_s}(x_1) - \frac{b_s}{m_s}(x_2) + \frac{b_s}{m_s}(x_4) \quad (4)$$

$$f_s + f_b - f_t = m_u\ddot{z_u} \quad (5)$$

$$m_u\ddot{z_u} = k_s(z_s - z_u) + b_s(\dot{z_s} - \dot{z_u}) - k_t(z_u - z_r) \quad (6)$$

$$\ddot{z_u} = \frac{k_s}{m_u}(x_1) + \frac{b_s}{m_u}(x_2) - \frac{b_s}{m_u}(x_4) - \frac{k_t}{m_u}(x_3) \quad (7)$$

From eq. (4) and eq. (7) we will get the matrix of A

$$A = \begin{bmatrix} 0 & 1 & 0 & -1 \\ -\frac{K_s}{m_s} & -\frac{b_s}{m_s} & 0 & \frac{b_s}{m_s} \\ 0 & 0 & 0 & 1 \\ \frac{K_s}{m_u} & \frac{b_s}{m_u} & -\frac{K_t}{m_u} & -\frac{b_s}{m_u} \end{bmatrix} \quad (8)$$

$$L = \begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \end{bmatrix} \quad (9)$$

c. In-Wheel Motor Electric Vehicle

The In-Wheel Motor Electric Vehicle (IWM EV) is one of the common types of the electric vehicles, the suspension system of (IWM EV) is almost doubled the mass of the wheel by adding the mass of an electric motor to the mass of the wheel. The in-wheel motor (IWM) is placed in the wheel empty space [8]. It was known there is relative relationship between the body vibration and the mass of the wheel, when the mass of the wheel increased the body vibration also increased that's affecting on passenger comfort [8]. An (IWM EV) has extra wheel mass because of the electric motor mass added to the mass of wheel, which lead to discomfort for the passenger and also not safety on the road [9]. The increase of unsprung mass cause the vehicle to get worse riding comfort and handling stability [10,11]. Which affecting on the tire-road contact [11].

$$(m_u + m_i) = m_t \quad (10)$$

$$n_1 = m_t \ddot{z_u} \quad (11)$$

$$n_1 = f_s + f_b - f_t \quad (12)$$

$$n_2 = k_s(z_s - z_u) + b_s(\dot{z_s} - \dot{z_u}) \quad (13)$$

$$n_3 = -k_t(z_u - z_r) \quad (14)$$

$$n_1 = n_2 + n_3 \quad (15)$$

$$\ddot{z_u} = \frac{k_s}{m_t}(x_1) + \frac{b_s}{m_t}(x_2) - \frac{b_s}{m_t}(x_4) - \frac{k_t}{m_t}(x_3) \quad (16)$$

From eq. (4) and eq. (16) we will get the matrix of A

$$A = \begin{bmatrix} 0 & 1 & 0 & -1 \\ -\frac{k_s}{m_s} & -\frac{b_s}{m_s} & 0 & \frac{b_s}{m_s} \\ 0 & 0 & 0 & 1 \\ \frac{k_s}{m_t} & \frac{b_s}{m_t} & -\frac{k_t}{m_t} & -\frac{b_s}{m_t} \end{bmatrix} \quad (17)$$

The L matrix is shown in eq. 9.

D. Ground-hook Control

A ground-hook control introduces a damper connected virtually to the ground as modelled in Figure 2, (c_{grd}) connected between the mass of the wheel and the fixed imaginary frame on the ground. The (c_{grd}) is a ground-hook damping coefficient. The damper (c_{grd}) is connected to m_u (the mass of tire) instead of m_s (the mass of the car). The ground-hook controller improves vehicle road holding by minimizing the upper and lower peaks of wheel displacement and tire deflection [12].

$$f_{grd} = c_{grd}(\dot{z_u} - \dot{z_r}) \qquad (18)$$

$$B = \begin{bmatrix} 0 \\ \frac{1}{m_s} \\ 0 \\ -\frac{1}{m_t} \end{bmatrix} \qquad (19)$$

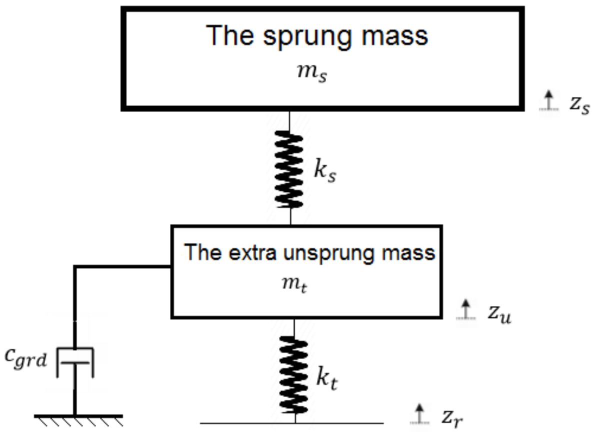

Figure II. In-wheel motor electric quarter vehicle model with ground-hook controller

The real state space of vehicle is

$$\dot{x} = Ax + Bu \quad (20)$$

$$y = Cx + Du \quad (21)$$

A is the state matrix, B is the input matrix, C is the output matrix and D is the direct transmission matrix.

x is state vector and u is control vector

Where:

$$x_1 = z_s - z_u \quad (22)$$

$$x_2 = \dot{z_s} \quad (23)$$

$$x_3 = z_u - z_r \quad (24)$$

$$x_4 = \dot{z_u} \quad (25)$$

x_1 is the car suspension deflection, x_2 is the sprung mass velocity, x_3 is the tire deflection and x_4 is the unsprung mass velocity.

The ground-hook controller is compared with passive suspension for both (normal vehicle and in-wheel motor electric vehicle). The simulations were carried out in MATLAB/Simulink.

Parameter for normal quarter vehicle model passive suspension system

Mass of car m_s=250 kg, mass of tire m_u=40 kg, the spring stiffness k_s=16000, the tire stifness k_t=160000, the damper b_s=1000.

Parameter for in-wheel motor quarter electric vehicle model passive suspension system

Mass of car m_s=250 kg, mass of tire m_u=40 kg, mass of in-wheel motor m_i=45 kg, the spring stiffness k_s=16000, the tire stifness k_t=160000, the damper b_s=1000. (m_i) $is\ the\ mass\ of\ in - wheel\ motor.$

Parameter for in-wheel motor quarter electric vehicle with ground-hook controller

Mass of car m_s=250 kg, mass of tire m_u=40 kg, mass of in-wheel motor m_i=45 kg, the spring stiffness k_s=16000, the tire stifness k_t=160000, ground-hook damping coefficient (c_{grd}) =5000.

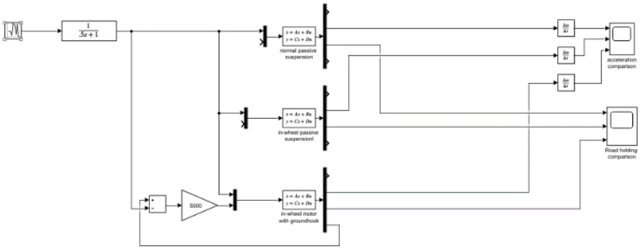

Figure III. MATLAB simulation for quarter vehicle model with normal passive, in-wheel motor passive suspension system and in-wheel motor with ground-hook controller

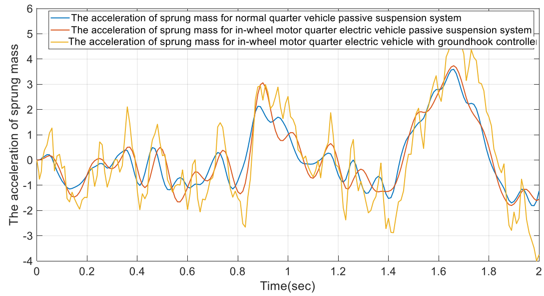

Figure IV. Comparison in acceleration of sprung mass for quarter vehicle between normal passive, IWM EV passive and IWM EV with ground-hook controller

Figure V. Comparison in tire deflection for quarter vehicle between normal passive, IWM EV passive and IWM EV with ground-hook controller

E. Ground-hook and Sky-hook Control Comparison

A sky-hook control introduces a damper connected virtually to the sky, (c_{sky}) connected between the mass of the car and the fixed imaginary frame to the sky. The (c_{sky}) is a sky-hook damping coefficient. The damper (c_{sky}) is connected to m_s (the mass of the car). The sky-hook controller improves comfort of the occupants inside the car by minimizing the upper and lower peaks of car body displacement and acceleration of sprung mass[13].

$$f_{sky} = -c_{sky}(\dot{z}_s) \quad (26)$$

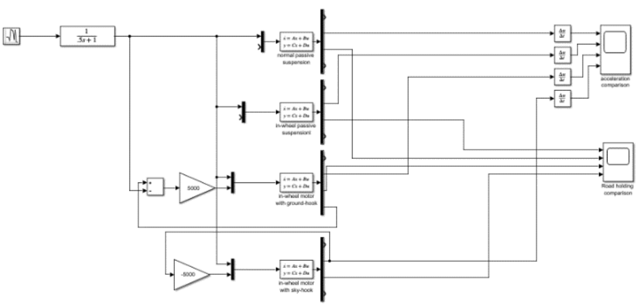

Figure VI. MATLAB simulation for quarter vehicle model with normal passive, in-wheel motor passive suspension system, in-wheel motor with ground-hook controller and in-wheel motor with sky-hook controller

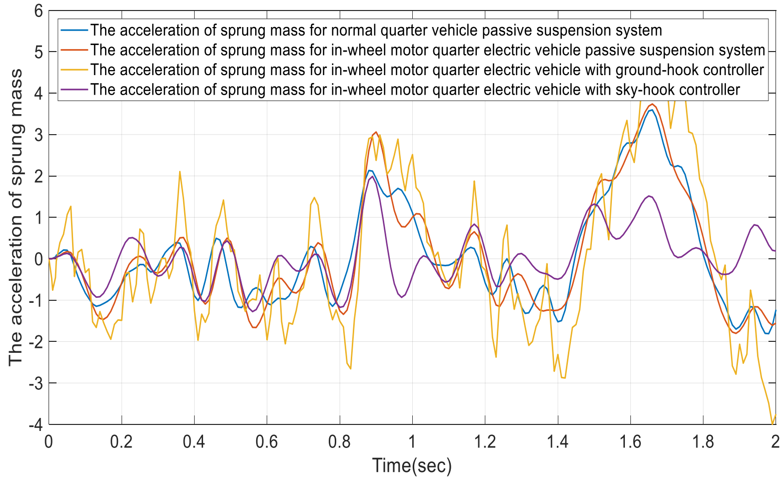

Figure VII. Comparison in acceleration of sprung mass for quarter vehicle between normal passive, IWM EV passive, IWM EV with ground-hook controller and IWM EV with sky-hook controller

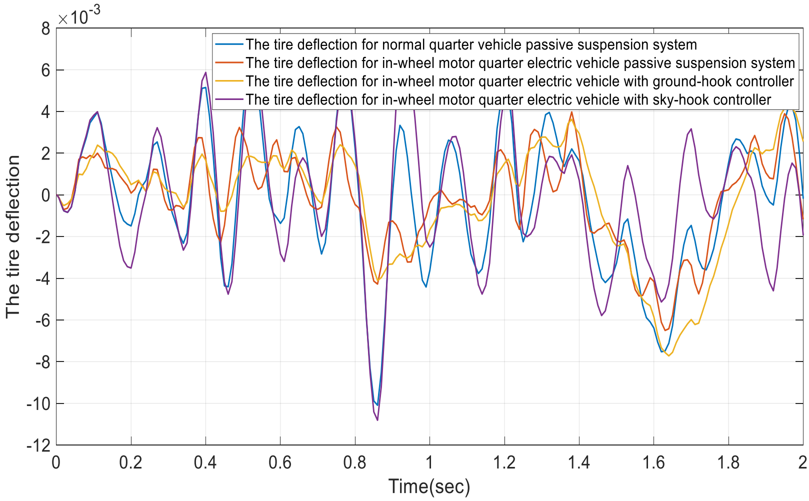

Figure VIII. Comparison in tire deflection for quarter vehicle between normal passive, IWM EV passive, IWM EV with ground-hook controller and IWM EV with sky-hook controller

I. Half Car Model

A. Half Car Model Passive Suspension System

It is presented as a linear four-Degree-of-Freedom (4-DOF) system. The vehicle body has two motions of heave and pitch and the front and rear tires motions are also involved in the half car. A single mass of car is connected to two wheels masses at each corner. Vertical and pitch motion is appropriate for sprung mass while only vertical motion for both unsprung masses. The pitch motion for the half car sprung mass is represented and the vertical displacements for the front tire (z_{u1}) and for the rear tire (z_{u2}) are also be introduced.

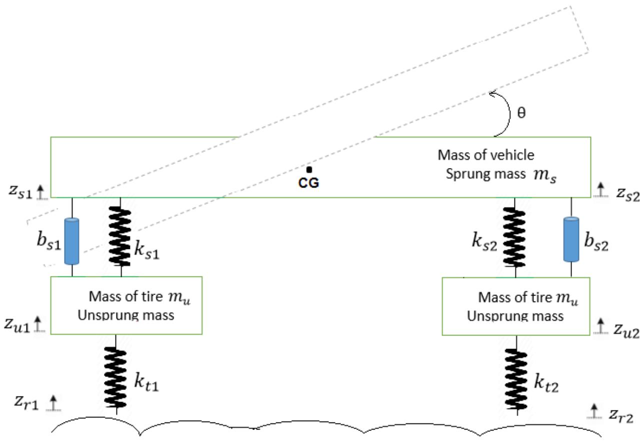

Figure IX. Passive suspension system for half car model (4-DOF)

B. Half Car Model Forces

x state vector is [z(z_s),v($\dot{z}$),(θ),($\dot{\theta}$), z_{u1} , $\dot{z_{u1}}$, z_{u2} , $\dot{z_{u2}}$]

Position of sprung mass z(z_s), velocity of sprung mass ($\dot{z}$), the pitch angle (θ), yaw response ($\dot{\theta}$), z_{u1}(position of front tire), $\dot{z_{u1}}$ (absolute velocity for unsprung mass front tire), z_{u2} (position of rear tire), $\dot{z_{u2}}$ (absolute velocity for unsprung mass rear tire)

u is the input vector [z_{r1}, z_{r2}].

$$a_1 = m_s\ddot{z} \tag{27}$$

$$a_2 = k_1\,(z_1 - z_{u1}) + b_{s1}(\dot{z_1} - \dot{z_{u1}}) \tag{28}$$

$$a_3 = k_2(z_2 - z_{u2}) + b_{s2}(\dot{z_2} - \dot{z_{u2}}) \quad (29)$$

$$a_1 + a_2 + a_3 \quad (30)$$

$$z_1 = z - lf\ \theta \quad (31)$$

$$\dot{z_1} = \dot{z} - lf\ \dot{\theta} \quad (32)$$

$$z_2 = z + lr\ \theta \quad (33)$$

$$\dot{z_2} = \dot{z} + lr\ \dot{\theta} \quad (34)$$

$$\ddot{z} = \left(-\frac{k_1}{m_s} - \frac{k_2}{m_s}\right)z + \left(\frac{k_1 lf}{m_s} - \frac{k_2 lr}{m_s}\right)\theta - \left(\frac{b_{s1}}{m_s} + \frac{b_{s2}}{m_s}\right)\dot{z} + \left(\frac{b_{s1} lf}{m_s} - \frac{b_{s2} lr}{m_s}\right)\dot{\theta} + \frac{k_1}{m_s} z_{u1} + \frac{b_{s1}}{m_s}\dot{z_{u1}} + \frac{k_2}{m_s} z_{u2} + \frac{b_{s2}}{m_s}\dot{z_{u2}} \quad (35)$$

$$(m_u + m_i)\ddot{z_{u1}} = -F_t + F_s + F_b \quad (36)$$

$$b_1 = m_t \ddot{z_{u1}} \quad (37)$$

$$b_2 = -k_{t1}(z_{u1} - z_{r1}) + k_1(z_1 - z_{u1}) \quad (38)$$

$$b_3 = b_{s1}(\dot{z_1} - \dot{z_{u1}}) \quad (39)$$

$$b_1 = b_2 + b_3 \quad (40)$$

$$c_1 = \ddot{z_{u1}} \quad (41)$$

$$c_2 = -\frac{k_{t1}}{m_t} z_{u1} - \frac{k_1}{m_t} z_{u1} - \frac{b_{s1}}{m_t} \dot{z_{u1}} \quad (42)$$

$$c_3 = \frac{k_1}{m_t} z + \frac{b_{s1}}{m_t} \dot{z} \quad (43)$$

$$c_4 = -\frac{k_1 lf}{m_t} \theta - \frac{b_{s1} lf}{m_t} \dot{\theta} \quad (44)$$

$$c_5 = \frac{k_{t1}}{m_t} z_{r1} \quad (45)$$

$$c_1 = c_2 + c_3 + c_4 + c_5 \quad (46)$$

$$d_1 = m_t \ddot{z_{u2}} \quad (47)$$

$$d_1 = -f_t + f_s + f_b \quad (48)$$

$$d_2 = -k_{t2}(z_{u2} - z_{r2}) + k_2(z_2 - z_{u2}) \quad (49)$$

$$d_3 = b_{s2}(\dot{z_2} - \dot{z_{u2}}) \quad (50)$$

$$d_1 = d_2 + d_3 \quad (51)$$

$$e_1 = \ddot{z_{u2}} \quad (52)$$

$$e_2 = -\frac{k_{t2}}{m_t} z_{u2} - \frac{k_2}{m_t} z_{u2} - \frac{b_{s2}}{m_t} \dot{z_{u2}} \quad (53)$$

$$e_3 = \frac{k_2}{m_t} z + \frac{b_{s2}}{m_t} \dot{z} \quad (54)$$

$$e_4 = \frac{k_2 lr}{m_t}\theta + \frac{b_{s2} lr}{m_t}\dot{\theta} \qquad (55)$$

$$e_5 = \frac{k_{t2}}{m_t} z_{r2} \qquad (56)$$

$$e_1 = e_2 + e_3 + e_4 + e_5 \qquad (57)$$

$$g_1 = I\ddot{\theta} - k_1(z_1 - z_{u1})lf + k_2(z_2 - z_{u2})lr \qquad (58)$$

$$g_2 = -b_{s1}(\dot{z_1} - \dot{z_{u1}})lf + b_{s2}(\dot{z_2} - \dot{z_{u2}})lr \qquad (59)$$

$$g_3 = g_1 + g_2 \qquad (60)$$

$$r_1 = \left(\frac{k_1 lf}{I} - \frac{k_2 lr}{I}\right) z + \left(\frac{b_{s1} lf}{I} - \frac{b_{s2} lr}{I}\right)\dot{z} \qquad (61)$$

$$r_2 = -\left(\frac{k_1 lf^2}{I} + \frac{k_2 lr^2}{I}\right)\theta - \left(\frac{b_{s1} lf^2}{I} + \frac{b_{s2} lr^2}{I}\right)\dot{\theta} \qquad (62)$$

$$r_3 = -\frac{k_1 lf}{I} z_{u1} - \frac{b_{s1} lf}{I}\dot{z_{u1}} \qquad (63)$$

$$r_4 = \frac{k_2 lr}{I} z_{u2} + \frac{b_{s2} lr}{I}\dot{z_{u2}} \qquad (64)$$

$$\ddot{\theta} = r_1 + r_2 + r_3 + r_4 \qquad (65)$$

Parameter for half vehicle model passive suspension system

Mass of car m_s=1200 kg, mass of tire m_u=40 kg, the right spring stiffness k_1=16000, the left spring stifness k_2=16000, the right tire stiffness k_{t1}=160000, the left tire stifness k_{t2}=160000, the right damper b_{s1}=1000, the left damper b_{s2}=1000, the distance from the front wheel to the center of gravity (lf= 1.1 m), the distance from the rear wheel to the center of gravity (lr= 1.3 m), I is the mass moment of inertia.

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{lf}{I} & \frac{lr}{I} \\ 0 & 0 & 0 & 0 \\ \frac{K_{t1}}{m_u} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \frac{K_{t2}}{m_u} & 0 & 0 \end{bmatrix} \quad (66)$$

Parameter for in-wheel motor half electric vehicle (IWM EV) passive suspension system

Mass of car m_s=1200 kg, mass of tire m_u=40 kg, mass of in-wheel motor m_i=45 kg, the right spring stiffness k_1=16000, the left spring stifness k_2=16000, the right tire stifness k_{t1}=160000, the left tire stifness k_{t2}=160000, the right damper b_{s1}=1000, the left damper b_{s2}=1000, the distance from the front wheel to the center of gravity (lf= 1.1 m), the distance from the rear wheel to the center of gravity (lr= 1.3 m).

The A matrix is shown in eq. 70.

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{lf}{I} & \frac{lr}{I} \\ 0 & 0 & 0 & 0 \\ \frac{K_{t1}}{m_t} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \frac{K_{t2}}{m_t} & 0 & 0 \end{bmatrix} \quad (68)$$

Parameter for in-wheel motor half electric vehicle (IWM EV) with ground-hook controller

Mass of car m_s=1200 kg, mass of tire m_u=40 kg, mass of in-wheel motor m_i=45 kg, the right spring stiffness k_1=16000, the left spring stifness k_2=16000, the right tire stifness k_{t1}=160000, the left tire stifness k_{t2}=160000, the distance from the front wheel to the center of gravity (lf= 1.1 m), the distance from the rear wheel to the center of gravity (lr= 1.3 m), the ground-hook damping coefficient $c_{grd1}, c_{grd2} = 10000$, z_{r1}(random ground input 1) , z_{r2} (random ground input 2), f_{grd1}(ground-hook force 1), f_{grd2} (ground-hook force 2)

u is the input vector [z_{r1} , z_{r2} , f_{grd1} , f_{grd2}].

$$B=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{m_s} & \frac{1}{m_s} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{lf}{I} & \frac{lr}{I} \\ 0 & 0 & 0 & 0 \\ \frac{K_{t1}}{m_t} & 0 & -\frac{1}{m_t} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \frac{K_{t2}}{m_t} & 0 & -\frac{1}{m_t} \end{bmatrix} \quad (69)$$

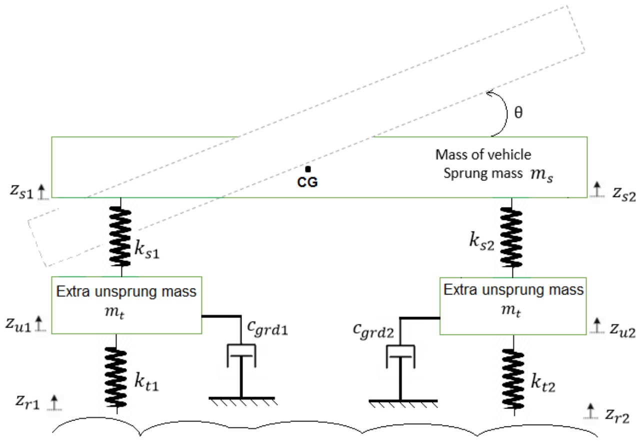

Figure X. In-wheel motor half electric vehicle with ground-hook controller

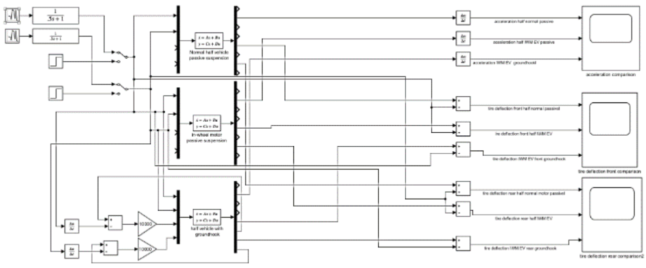

Figure XI. MATLAB simulation comparison for half vehicle between normal passive, in-wheel motor passive and in-wheel motor with ground-hook controller

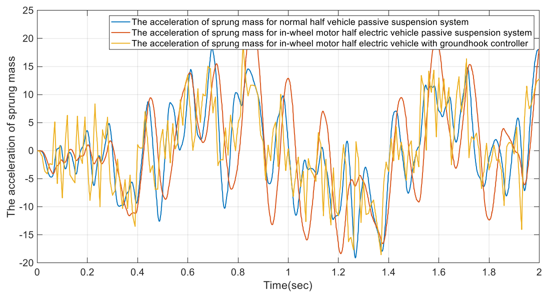

Figure XII. Comparison in acceleration of sprung mass for half vehicle between normal passive in-wheel motor passive and in-wheel motor with ground-hook controller

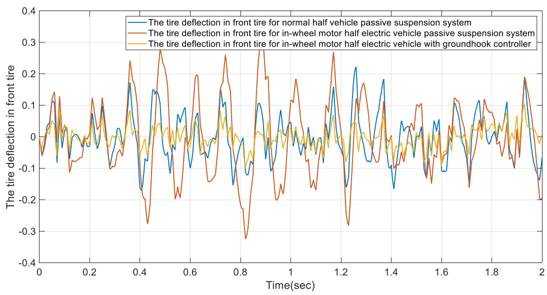

Figure XIII. Comparison in tire deflection front tire for half vehicle between normal passive in-wheel motor passive and in-wheel motor with ground-hook controller

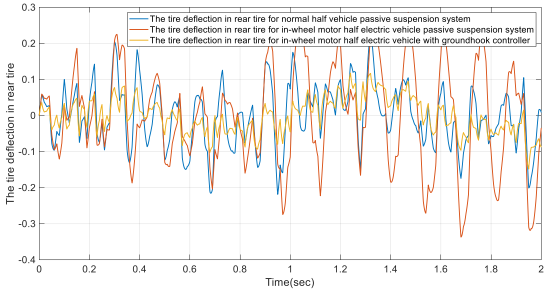

Figure XIV. Comparison in tire deflection rear tire for half vehicle between normal passive in-wheel motor passive and in-wheel motor with ground-hook controller

c. Simulation and Analysis

Figures IV, V, VI, VII shows the simulations for the passive and active quarter car models. Figures XII, XIII and XIV shows the simulations for the passive and active half car models. Figure IV, VI and Figure XII compares the accelerations of the vehicle bodies for the normal passive vehicle, the (IWM) passive vehicle, the (IWM) ground-hook active suspension vehicle and the (IWM) sky-hook active suspension vehicle. The acceleration is commonly used to measure passenger comfort. According to Figure IV, VI and Figure XII the added weight of the in-wheel electric motor does not have much of an impact on the acceleration and vehicle comfort. However, the ground-hook active suspension increases the acceleration and diminishes passenger comfort while the sky-hook active suspension decreases the acceleration and improves the comfort for the occupants inside the car. Figure V, Figure VII, Figure XIII and Figure XIV show the tire deflections for the normal passive vehicle, the (IWM) passive vehicle, the (IWM) ground-hook active suspension vehicle and the (IWM) sky-hook active suspension vehicle. The added weight of the in-wheel motor increases the tire deflection dramatically. Therefore, it is observed that the road holding properties of the tire is worse for the in-wheel motor passive suspension system and also worse for sky-hook controller active suspension because the sky-hook controller only improves the comfort of the passengers. However, the ground-hook controller active suspension is able to decrease the tire deflection to values close to the passive suspension. Therefore, the ground-hook controller is able to reach its goal of improving road holding. This simulation shows that the ground-hook controller is able to eliminate the negative effects of an (IWM EV) in terms of road holding. However, this is done at the cost of decreasing passenger comfort. The sky-hook controller is able to improve the comfort for the passengers of an (IWM EV), and fails to improve the road holding. It should be noted that the gain of the controller for the ground-hook controller can be adjusted to decrease the negative effects on passenger comfort. However, this will decrease the effectiveness of the ground-hook controller.

I. Conclusion

A passive suspension system for both normal passive vehicle and IWM EV without any controller, IWM EV with ground-hook controller and IWM EV with sky-hook controller were analyzed using MATLAB/Simulink. The simulations show that the ground-hook controller improves road holding by reducing the tire deflection for the IWM EV. The sky-hook is shown to improve the comfort for the occupants inside the car. In the case of decreasing or increasing unsprung mass, there is an opposite relationship between size of unsprung mass and road holding. When the unsprung mass is decreased, better road holding response is achieved. On the other hand, increasing the unsprung mass for IWM EV (adding the mass of electric motor 45 kg), by increasing the unsprung mass of the front and rear wheel assemblies results in worse road holding which directly affects the ground contact with the tire. This is the reason for worse road holding for IWM EV. When the ground-hook controller is used for IWM EV, better road holding and good contact with the road is achieved. This is because the ground-hook controller provides better isolation from road disturbances by reducing upper and lower peaks of the tire deflection. But the sky-hook controller fails to improve the road holding because it is used to provide comfort for the passengers. These results were shown with simulations using both the quarter car model and the half car model.

References

[1] **Nouby M. Ghazaly, Ahmad O. Moaaz, "The Future Development and Analysis of Vehicle Active Suspension System", Journal of Mechanical and Civil Engineering (IOSR-JMCE) 2014.**

[2] **Vivek Kumar Maurya and Narinder Singh Bhangal, "Optimal Control of Vehicle Active Suspension System", Journal of Automation and Control Engineering 2018.**

[3] **John Ekoru "Intelligent Model Predictive/Feedback Linearization Control of Half-Car Vehicle Suspension Systems" thesis 2012.**

[4] **Fischer, D. and Isermann, "Mechatronic semi-active and active vehicle suspensions", Control Engineering Practice, 2004.**

[5] **Canale, M., Milanese, M. and Novara, "Semi-active suspension control using fast model-predictive techniques", IEEE Transactions on Control Systems Technology, 2006.**

[6] **M. FARID ALADDIN, JASDEEP SINGH, "MODELLING AND SIMULATION OF SEMI-ACTIVE SUSPENSION SYSTEM FOR PASSENGER VEHICLE", Journal of Engineering Science and Technology, 2018.**

[7] **M. VALÁŠEK , M. NOVÁK , Z. ŠIKA & O. VACULÍN, “Extended Ground-Hook - New Concept of SemiActive Control of Truck's Suspension”, Extended GroundHook - New Concept of Semi-Active Control of Truck's Suspension, Vehicle System Dynamics, 2007.**

[8] **Hossein Salma ni, Milad Abbasi, Tondar Fahimi Zand , Mohammad Fard and Reza Nakhaie Jazar, “A new criterion for comfort assessment of in-wheel motor electric vehicles”, Journal of Vibration and Control, 2020.**

[9] **Yechen Qin, Chenchen He, Peng Ding, Mingming Dong, Yanjun Huang, “suspension hybrid control for in-wheel motor driven electric vehicle with dynamic vibration absorbing structures”, IFAC Papers OnLine 51-31 (2018).**

[10] **Fangwu Ma, Jiawei Wang, Yang Wang, Longfan Yang, 2969. “Optimization design of semi-active controller for in-wheel motors suspension”, 2018.**

[11] **Jialing Yao, Shuhui Ding, Zhaochun Li, Shan Ren, Saied Taheri, Zhongnan Zhang, “Composite Control and Co-Simulation in In-Wheel Motor Electric Vehicle Suspension”, The Open Automation and Control Systems Journal, 2015.**

[12] **Patil, I. and Wani, K., “Design and Analysis of Semi-active Suspension Using Skyhook, Ground Hook and Hybrid ControlModels for a Four Wheeler”, SAE Technical Paper 2015.**

[13] **Pipit Wahyu Nugroho, Weihua Li, Haiping Du, Gursel Alici, and Jian Yang, “An Adaptive Neuro Fuzzy Hybrid Control Strategy for a Semiactive Suspension with Magneto Rheological**

Damper", Hindawi Publishing Corporation Advances in Mechanical Engineering, 2014.

[14] Rajesh Rajamani, "Vehicle Dynamics and Control", Department of Mechanical Engineering University of Minne