Evaluation of Effect of in-Wheel Electric Motors Mass on the Active Suspension System Performance using Linear Quadratic Regulator Control Method

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***Abstract*—This paper presents evaluation of effect of in-wheel electric motors mass on the performance of active suspension system by using one of more common control methods which is Linear Quadratic Regulator (LQR).Unsprung mass is one of the important parameters which effects on road holding and ride comfort behaviors in the vehicles, this effect obtained in this work by comparing the performance of the system using standard tire and tire with In-Wheel Electric Motor. Also, modeling and simulation of quarter car model completed to construct the Simulink model of the system using MATLAB software. The study summarized bad effect of increasing the weight of tires by add In-Wheel Motors to the system on the road traction and the vehicles drivers comfort, at the same time the suspension system with in-wheel motor needs high actuator force to work compared to the same system without in-wheel motor**

***Keywords*—suspension system,unsprung mass,In-wheel motors quarter car model,linear quadratic regulator,simulink model.**

I. INTRODUCTION

For many years vehicle dynamics engineers have struggled to achieve a compromise between vehicle handling, ride comfort and stability. The results of this are clear in the vehicles we see today. In general, at one extreme are large sedan and luxury cars with excellent ride qualities but only adequate handling behavior. At the other end of the spectrum are sports cars with very good handling but very firm ride quality. In between are any number of variations dictated by the vehicle manufacturer and target customer needs,[2].

Every automotive suspension has two goals: passenger comfort and vehicle control. Comfort is provided by isolating the vehicle's passengers from road disturbances like bumps or potholes. Control is achieved by keeping the car body from rolling and pitching excessively, and maintaining good contact between the tire and the road.

By and large, today's vehicle suspensions use hydraulic dampers (a.k.a. "shock absorbers") and springs that are charged with the tasks of absorbing bumps, minimizing the car's body motions while accelerating, braking and turning and keeping the tires in contact with the road surface. Typically, these goals are somewhat at odds with each other. Luxury cars are great at swallowing bumps and providing a plush ride, but handling usually suffers as the car is prone to pitch and dive under acceleration and braking, as well as body lean (or "sway") under cornering think Lincoln Town Car.

On the other end of the spectrum, stiffly sprung sports cars exhibit minimal body motion as the car is driven aggressively, as cornering is flat, but the ride quality generally suffers think Mazda Miata. Yes, there are a number of current vehicles that do a good job of providing an agreeable balance of ride and handling, such as a BMW 5 Series, the C6 Corvette and even the Cadillac SRV SUV. But Dr. Bose's goal was to offer a suspension design that would provide an even smoother ride than a top luxury car (such as the Lexus LS430 sedan) while simultaneously providing more body control than a top sports car (such as a Porsche 911).

Unfortunately, these goals are in conflict. In a luxury sedan the suspension is usually designed with as emphasis on comfort, but the result is a vehicle that rolls and pitches while driving and during turning and braking. In sport cars, where the emphasis is on control, the suspension is designed to reduce roll and pitch, but comfort is scarified.

A typical vehicle suspension is made up of two components: a spring and a damper. The spring is chosen based solely on the weight of the vehicle, while the damper is the component that defines the suspensions placement on the compromise curve. Depending on the type of vehicle, a damper is chosen to make the vehicle perform best in its application. Ideally, the damper should isolate passengers from low-frequency road disturbances and absorb high frequency road disturbances. Passengers are best isolated from low-frequency disturbances when the damping is high. However, high damping provides poor high frequency absorption. Conversely, when the damping is low, the damper offers sufficient high-frequency absorption, at the expense of low-frequency isolation. The need to reduce the effects of this compromise has given rise to several new advancements in automotive suspensions. Three types of suspensions that will be reviewed here are passive, fully active, and semi-active suspensions,[3].

II. IN-WHEEL MOTOR STRUCTURE

The in-wheel electric motor (also called wheel motor, wheel hub drive, hub motor or wheel hub motor) is an electric

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motor that is incorporated into the hub of a wheel and drives it directly.

In this work, only the effect of mass of the electric motor will take into account.

Figure(1) is a cross-section of the in-wheel electric motor system, which has a structure that aligns the hub, reducer section and the motor section in a series configuration.

Figures(2)and(3).show the Michelin active tyre with in-wheel motor and Bridgestone's Dynamic-Damping In-wheel Motor Drive System.

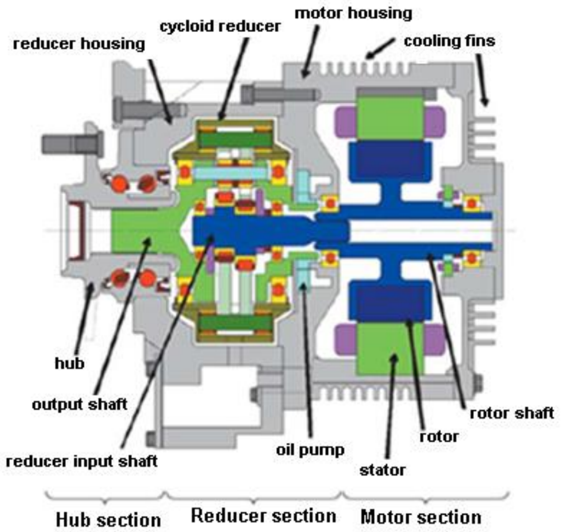

Fig. 1.Two Cross-section of IWM

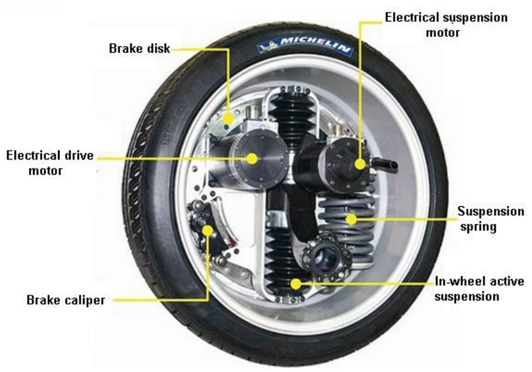

Fig. 2.Michelin active tire with in-wheel motor

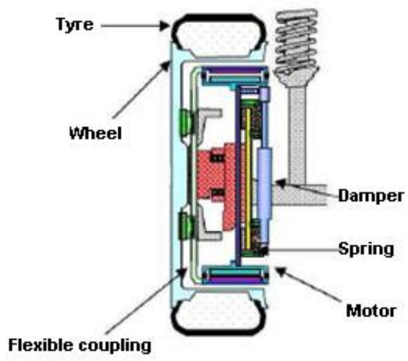

Fig. 3.Bridgestone's Dynamic-Damping In-wheel Motor Drive System.

III. ACTIVE SUSPENSION SYSTEM MATHEMATICAL MODEL

Designing a suspension system is an interesting and challenging control problem. Also, Suspension system modeling serves two purposes: understanding system dynamics and developing control strategies. Models are simplified representations of physical systems, allowing focus on important system dynamics.

When the suspension system is designed, a quarter car model (one of the four wheels) is used to simplify the problem to a 1D multiple spring-damper system. A diagram of this system is shown below in figure(4). This model is for an active suspension system where an actuator is included that is able to generate the control force F to control the motion of the vehicle body.

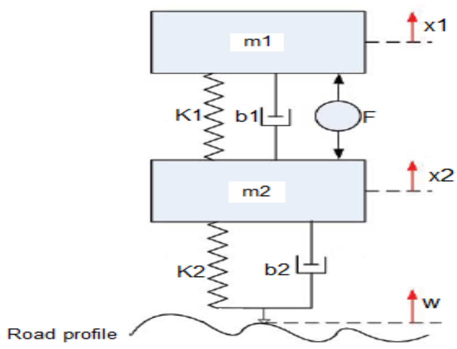

Fig. 4.Double Mass-Spring-Damper used to model Active Suspension Experiment

The suspension itself is shown to consist of a spring k_1 , a damper b_1 and an active force actuator F . The sprung mass m_1 represents the quarter-car equivalent of the vehicle body mass. The unsprung mass m_2 represents the equivalent mass due to the axle and tire. The vertical stiffness and damper of the tire is represented by the spring k_2 .and b_2 The variables x_1 , x_2 and w represent the vertical displacements from static equilibrium of the sprung mass, unsprung mass and the road respectively,[1].
From the figure above and Newton's law, we can obtain the dynamic equations as the following:

$$m_1\ddot{x}_1 = -k_1(x_1 - x_2) - b_1(\dot{x}_1 - \dot{x}_2) + F$$

$$m_2\ddot{x}_2 = k_1(x_1 - x_2) + b_1(\dot{x}_1 - \dot{x}_2) + b_2(\dot{w} - \dot{x}_2) + k_2(w - x_2) - F$$

IV. SYSTEM PARAMETERS

(w) Road displacement

(x_1) car body displacement

(x_2) Un-sprung mass displacement

(b_1) damping constant of suspension system =1000 N.m/s

(b_2) damping constant of wheel and tire =0 N.m/s

(K_1) spring stiffness constant =16000 N/m

(K_2) Tire stiffness constant =160000 N/m

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(m_1) quarter car body mass(sprung mass) =250 Kg

(m_2) unsprung mass =45 Kg

(mi) unsprung mass with in-wheel motor =(45+34)Kg*

(F) control force

*The unsprung mass with in-wheel motor =(tire mass+ In-wheel electric motor mass.

*The motor mass assumed as 79Ibs(34Kg) which selected from Protean Electric productions.

V. SIMULINK MODEL OF THE SYSTEM

figure(5) shows The Simulink model and system response of the active suspension system for quarter car model which built by using the above equations.

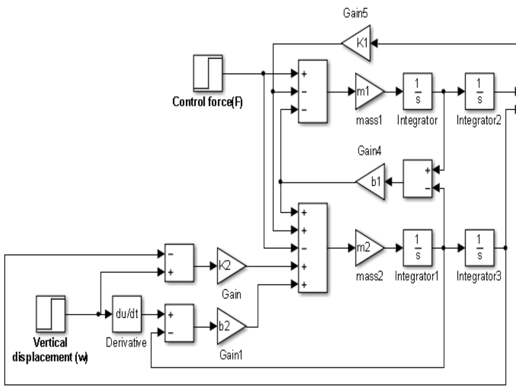

Fig. 5.Simulink diagram of active suspension system

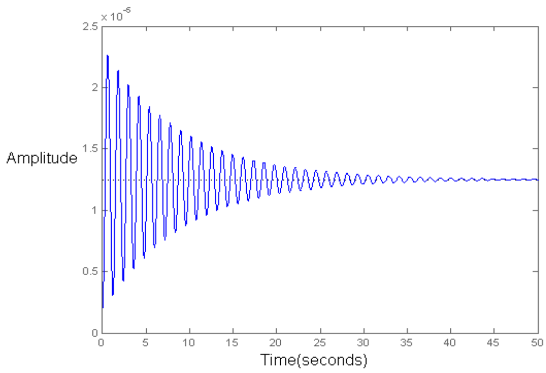

Fig. 6.Open-Loop Response to 0.1 m Step Disturbance of active suspension system.

Observing figure (6), it is necessary to improve the response of the suspension system through the control of the suspension control force F. the control method which will use to create the controller in this work is The Linear Quadratic Regulator (LQR).

VI. LINEAR QUADRATIC CONTROL(LQR)

The theory of optimal control is concerned with operating a dynamic system at minimum cost. The case where the system dynamics are described by a set of linear differential equations and the cost is described by a quadratic function is called the LQ problem. One of the main results in the theory is that the solution is provided by the linear-quadratic regulator (LQR**)**. The LQR is an important part of the solution to the LQG problem. Like the LQR problem itself, the LQG problem is one of the most fundamental problems in control theory,[9].

To design a full state-feedback controller for the system, state-space equations should be determined and then it can use Matlab program to find the value of the controller.

To find the controller matrix K ,it should Add the following command to the end of m-file and run in the MATLAB,K = lqr(A,B,Q,R).

In this study two controllers needed, one to the system without in-wheel electric motor and another one to the system with in-wheel electric motor.

The following program shows entering the system parameters and the state-space equations and the formula which used to find the matrix of the controller by Matlab.

```
%Quarter car model
k1=16000;b1=1000;b2=0;m1=250;m2=45;mi=79;k2=160000;

%state-space form
A1=[0 1 0 -1;-k1/m1 –b1/m1 0 b1/m1;0 0 0 1;k1/m2
b1/m2 –k2/m2 -(b1+b2)/m2];
A2=[0 1 0 -1;-k1/m1 –b1/m1 0 b1/m1;0 0 0 1;k1/mi
b1/mi –k2/mi -(b1+b2)/mi];
B1=[0;1/m1;0;-1/m2];
B2=[0;1/m1;0;-1/mi];
C=eye(4)
L=[0;0;-1;0];
Bp1=[B1 L];
Bp2=[B2 L]
Dp=zeros(4,2)
%Controller design
%Q=zeros(4,4);
%Q(2,2)=1e08;
R=0.0001;
C2=zeros(1,4);
%C2(1,1)=1 %for the suspension deflection
%C2(1,2)=1 %for comfort, the absolute velocity of sprung
mass
%C2(1,4)=1 %for the absolute velocity of unsprung mass
C2(1,3)=1 %for good road traction, high electric motor torque
p1=1000;
Q1=p1*C2'*C2
p2=1000*100;
Q2=p2*C2'*C2
K1= lqr(A1,B1,Q1,R)      %for the system without in-wheel
motor
K2 = lqr(A2,B2,Q2,R)      %for the system with in-wheel
motor
```

By run the program above we can get the value of K matrix (matrix gain) to use it to improve the system response in figure(5) in .Two values of K will used which are K1= [-0.0000 1.0274 -41.1156 -2.1412] to active suspension system without in-wheel electric motor(standard tire) and K2= 1.0e+03*[-0.0000 0.0989 -4.1495 -0.2158] to active suspension system with in-wheel electric motor.

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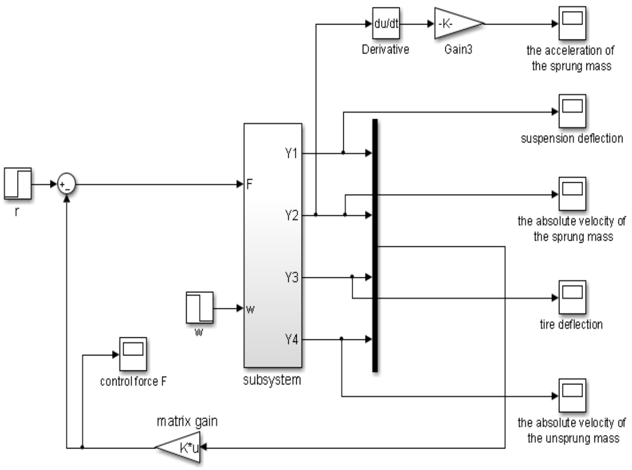

Fig. 7.Simulink model of active suspension system with controller.

VII. SIMULATION RESULTS AND DISCUSSIN.

Figures (8) to (13)show Analysis and results of suspension system for quarter car model for speed bump of 0.1 m (step input)and the effect of in-wheel electric motor mass on the system performance.

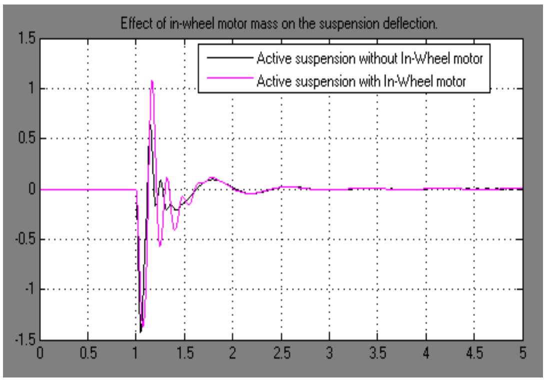

Fig. 8.Effect of IWM on the suspension deflection.

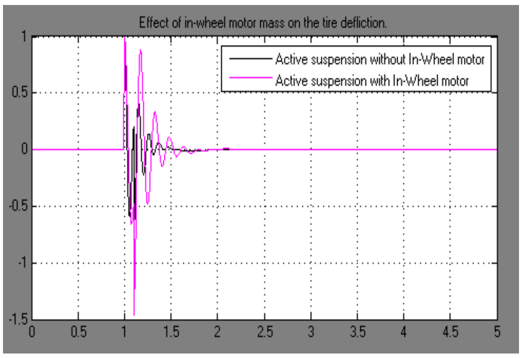

Fig. 9.Effect of IWM on the tire deflection.

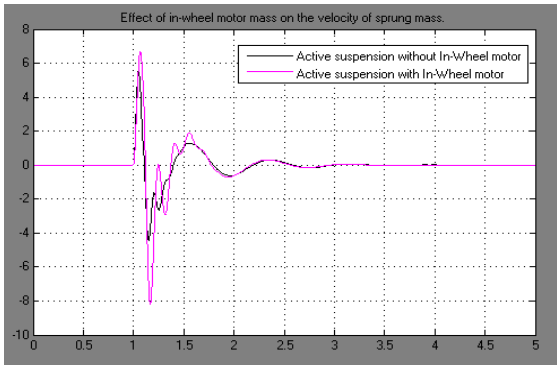

Fig. 10.Effect of IWM on the velocity of sprung mass.

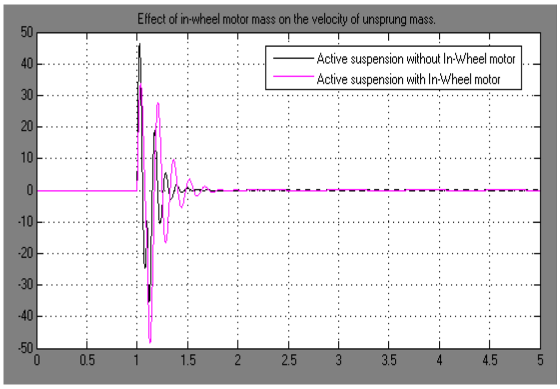

Fig. 11.Effect of IWM on the velocity of unsprung mass.

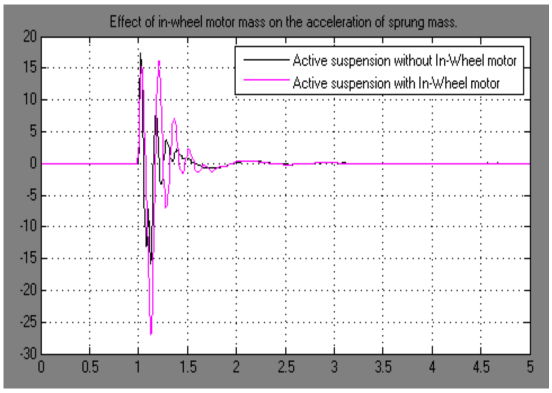

Fig. 12.Effect of IWM on the acceleration of sprung mass.

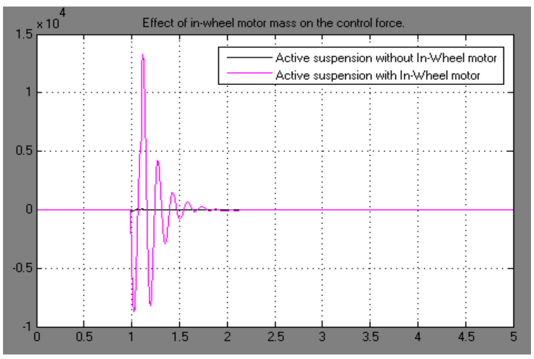

Fig.13 .Effect of IWM on the control force F.

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VIII. CONCLUSION

This study shows a significant effect of the in-wheel electric motor mass on the active suspension system performance, some of this effect was clear on the sprung mass velocity and suspension deflection which represent the driver comfort and the road traction respectively. At same time the study explained that the active suspension with in-wheel electric motor requires high actuator force compared with the active suspension system without in-wheel motor. Finally, using of in-wheel electric motors in the vehicles has various negative aspects which caused little reliability to use it.

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