MODELING AND IMPLEMENTATION OF PID CONTROLLER IN VEHICLE RIDE COMFORT IMPROVEMENT USING BOND GRAPH

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SUMMARY

The proportional integral derivative (PID) controller method is a famous and influential approach used in a variety of engineering domain systems. This paper presents Bond Graph modelling and implementation of PID controller in the active quarter-vehicle suspension system for the purpose of achieving better ride comfort. Bond graph is a better tool for modelling multi-domain energy systems with control hardware associated with it. SYMBOL SHAKTI software is used to simulate the active vehicle suspension system, which is theoretically represented as a 4-DOF human Bio-dynamic model combined with a 3-DOF quarter automobile system. The suggested PID Controller's performance is contrasted with that of the passive model. To measure the effectiveness of the suggested PID controller suspension system, time domain evaluations of systems performance criteria are conducted. The findings show that a significant improvement in ride comfort is offered by the suggested Bond graph PID controller model of the active vehicle suspension.

KEYWORDS

7 DOF quarter Car Model, Bond graph Modeling, Bio-dynamic Human Model, Dynamic Simulation

NOMENCLATURE

v	Vehicle velocity (ms^{-1})
w	With of bump (m)
L	Wheel base (m)
Z_h	Head displacement (m)
Z_{ut}	Upper torso displacement (m)
Z_{lt}	Lower torso displacement (m)
Z_p	Pelvis torso displacement (m)
Z_{se}	Seat displacement (m)
Z_b	Car body displacement (m)
Z_w	Wheel displacement (m)
ISO	International Organization for Standardization

1. INTRODUCTION

Vehicle suspension isolates driver and occupants from the road irregularities to make the ride more comfortable. In other words we can say suspension system role is to provides better ride comfort and this purpose have gained more interest due to development of various control technologies which uses an active component which is controlled by microcontrollers and hence there achieves improvement in vehicle response. Numerous model reduction techniques that can systematically reduce a model can be found in the appropriate modeling literature. Some are based on bond graphs and power flow diagrams. Basis for bond graphs is the power transfer between system components.

This experiment illustrates how heavy road vehicles respond dynamically to impediment. Bond graph modeling approach was used to build a computational model of vehicle and analyze its dynamic behavior. This method was initially presented by Henry M. Paynter (Paynter, 1961). Bond graph is a great tool for describing vehicle dynamics with related control systems because they provide a clear visual depiction of all different sorts of interacting energy domains and thus offer an accurate and clear representation of modeling for a variety of physical systems (PETER J. GAWT, n.d.). Sensors, signal processing, and actuation are necessary for the controllers, and these components are incorporated and demonstrated using car models by Margolis et al. (Margolis & Shim, 2001), a 4-DOF quarter car model was developed and response in terms of vibration transferred to occupant body parts (head & thorax) was captured using Simulink and Bond graph tool (Mitra & Benerjee, n.d.). Additionally, the 2-DOF quarter car vehicle system's passive, semi-active, and active performances were determined by Satish kumar et al. (Sathishkumar et al., 2007) where as Gupta et al (Ashish & Vikas, 2012) used PI controller in Bond Graph and performs dynamic simulation of 6-DOF off road truck.

Instead of simply one portion of the operator's body, such as their hand or foot, the vibrations force their entire body to tremble. When exposure time exceeds the acceptable standard established by ISO 2631-1 (Standard, 1997), harmful consequences of whole-body vibration are felt. The experimental conditions and given results on the biodynamic responses of the standing and seated human body to whole-body vibration in various directions are thoroughly assessed by Rakheja et al. (Rakheja et al., 2010).

There were various attempts to improve passive suspension systems for automobiles for the purpose of lowering suspension stiffness and un-sprung mass and the ideal damping ratio for the optimal controllability. In order to find the vehicle suspension settings for the optimum human comfort, Farid et al. (Farid et al., 2011) optimized a 4-DOF quarter vehicle suspension system paired with a sitting human. A simulation study was performed to show effectiveness of proportional-integral sliding mode controller (Sam et al., 2004) The PID parameters were optimized for integrated active suspension system's using a teacher learning-based optimization (TLBO) by Mehta et al. (Mehta et al., n.d.)

The active suspension system based with 7-DOF is the model that is suggested in this research. This modelling exercise's major objectives are to demonstrate how the bond graph approach can be used to complex models and to highlight how easily plant and controller model fusion can be done using bond graph software. The bond graph model uses controller gains that were tuned using MATLAB/SIMULINK.

The Bond Graph PID controller is used for vehicle suspension system with the goal of lowering jerks and raising driver ride comfort. The controlled variable's value is established by this controller, which then computes the deviation between the actual and desired values and generates a control signal to reduce the difference to zero. The main objective of this work is to show how control system design can actually be based on such a basis.

2. QUARTER CAR MODEL

2.1 PHYSICAL MODEL

The integrated 3-DOF quarter car model linked with 4-DOF bio-dynamic driver body model as shown in Fig.1 taking human body as several lumped masses and are connected through springs and dampers, Human body receives direct excitation from the seat; C_{ij} and K_{ij} are the damping and stiffness between two body parts the subscripts i and j denote the first alphabet of the connected body part.

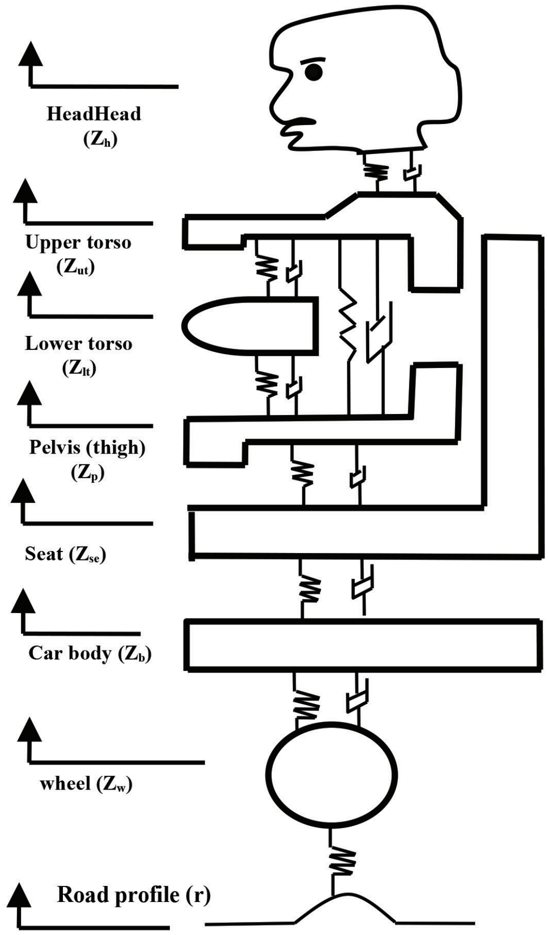


Figure 1. Physical model (Wan and Schimmels)

K_{se} and C_{se} are stiffness and damping coefficients of seat suspension system; Z_{se} is the seat excitation; *Zh, Zut, Zlt, Zp*, are various mass displacements and *Z* is the road input. *Cs* and *Ks* are the damping and stiffness of the car suspension respectively, The pneumatic tire's compressibility is denoted by the letter k_t.

Sprung mass refers to quarter car portion supported by springs, whereas un-sprung mass refers to the weight of the wheel assembly. The tyre was changed with a comparable stiffness but damping was ignored. For modelling suspension, tire, and passenger seat, parallel springs with dampers are employed.

2.2 MATHEMATICAL MODEL

A 7-DOF quarter car model is considered for analysis. Damping of tire is neglected. For passenger seat, suspension, tire, linear springs used in parallel with dampers. Assuming Z_b is vertical displacement at car body and suspension connection point. The vertical displacement of seat and car body connection point is $Z_{se.}$ Below given dynamic motion of equations for driver and car body is produced using Newton's second equation of motion and the notion of a free-body diagram.

Human Model Equation

$$m_h \ddot{Z}_h = -C_{hu}(\dot{Z}_h - \dot{Z}_{ut}) - K_{hu}(Z_h - Z_{ut}) \tag{1}$$

$$\begin{aligned} m_{ut}\ddot{Z}_{ut} = {} & C_{hu}(\dot{Z}_h - \dot{Z}_{ut}) + K_{hu}(Z_h - Z_{ut}) \\ & - C_{ul}(\dot{Z}_{ut} - \dot{Z}_{lt}) - K_{ul}(Z_{ut} - Z_{lt}) \\ & - C_{up}(\dot{Z}_{ut} - \dot{Z}_p) - K_{up}(Z_{ut} - Z_p) \end{aligned} \tag{2}$$

$$\begin{aligned} m_{lt}\ddot{Z}_{lt} = {} & C_{ul}(\dot{Z}_{ut} - \dot{Z}_{lt}) + K_{ul}(Z_{ut} - Z_{lt}) \\ & - C_{lp}(\dot{Z}_{lt} - \dot{Z}_p) - K_{lp}(Z_{lt} - Z_p) \end{aligned} \tag{3}$$

$$\begin{aligned} m_p\ddot{Z}_p = {} & C_{lp}(\dot{Z}_{lt} - \dot{Z}_p) + K_{lp}(Z_{lt} - Z_p) \\ & + C_{up}(\dot{Z}_{ut} - \dot{Z}_p) + K_{up}(Z_{ut} - Z_p) \\ & - C_{pse}(\dot{Z}_p - \dot{Z}_{sefr}) + K_{pse}(Z_p - Z_{sefr}) \end{aligned} \tag{4}$$

Seat Motion Equation

$$\begin{aligned} m_{se}\ddot{Z}_{se} = {} & +C_{pse}(\dot{Z}_p - \dot{Z}_{se}) + K_{pse}(Z_p - Z_{se}) \\ & - C_{se}(\dot{Z}_{se} - \dot{x}_{se}) - K_{se}(Z_{se} - Z_b) \end{aligned} \tag{5}$$

Quarter Car Body Motion Equation

$$\begin{aligned} m_b\ddot{Z}_b = {} & -C_s(\dot{Z}_b - \dot{Z}_w) - K_s(Z_b - Z_w) \\ & + C_{sefr}(\dot{Z}_{se} - \dot{x}_{se}) + K_{sefr}(Z_{se} - x_{se}) \end{aligned} \tag{6}$$

Wheel Motion Equation

$$\begin{aligned} m_w\ddot{Z}_w = {} & C_s(\dot{Z}_b - \dot{Z}_w) + K_s(Z_b - Z_w) \\ & - K_w(Z_w - r) \end{aligned} \tag{7}$$

2.3 BOND GRAPH MODEL

When physical systems are connected, energy plays a crucial role. Power ports are the connection points of a bond graph node that allow nodes to exchange energy with one another via a power bond as shown in Fig.2. A subsystem's power ports can be thought of as points of entry or exit for energy. Each energy port is represented as a connection that ties two sources of power, Effort and Flow, together.

Power = Effort (e) × Flow (f)

The bond graph utilizes eight elements for modeling, Three basic elements, R (Resistance), C (Capacitance), and I (Inertia), Two sources, SE (Effort Source) and SF (Flow Source), Two 2-port elements Transformer (TF) and Gyrator (GY) and Two junction elements, 1- (common flow) and 0- (common effort). All of them are linked together by lines called bonds and in a bond graph links

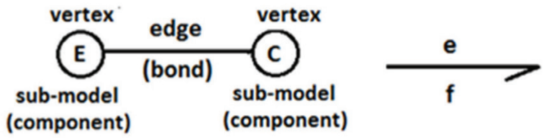


Figure 2. Bond representation

termed as powers ports are used to exchange energy between elements.

Three interfaces are present in the automobile model. First, the interaction between the car's body and its wheels, next its motion and its seats, and last seat interface with a sitting human model. Fig.3 shows 7 DOF passive quarter car Bond Graph model. The SYMBOLS 2000 (Samantaray, 2015) modeling and simulation program makes it easy to create comprehensive bond graph models.

Using same Bond Graph elements active quarter car model is formed. A flow triggered C-element link is attached to each 1-junction to record velocity and displacement of certain human body parts. Each body member's stiffness and damping are introduced by connecting C and R components at the 1-junction. Acceleration is captured on I-element. Finally BG model of human body parts is further attached with seat and wheel model.

Additionally, the BG model of the car body and wheels is attached at the 0-junction by incorporating C and R elements that reflect the stiffness (Ks) and damping (Cs) of the wheel suspension system. This creates the interface between the sprung mass (car body) and un-sprung mass (wheel). Tire damping is neglected and stiffness is introduced using C-element.

Fig.4 shows the Bond Graph implementation of PID controller designed in for the purpose of controlling discomfort transferred to human body parts due to road irregularity in form of acceleration and displacement. The proportional (P) term, the integral (I) term, and the derivative (D) term comprise a PID controller. The generalized PID controller equation is given by

$$u(t)=K_P e(t) + K_I \int e(t) + K_D \frac{de(t)}{dt} \tag{8}$$

The output u (t) of a PID controller is, in theory, equal to the total of the three terms. While e (t)= r (t)-y (t) indicates the feedback error signal between the reference signal r (t) and the output y (t), KP (Proportional constant), KI (Integration constant), and KD (Derivative constant). The controller's goal is to achieve predicted behavior for the model's output y (t) with respect to the set point r (t). Controller can be represented as bond graphs capsule and consequently constructed in the bond graph domain. The system's controller can measure any variable within the system, but it can only modify variables that relate to the system's physical sources. Stated differently, there are an

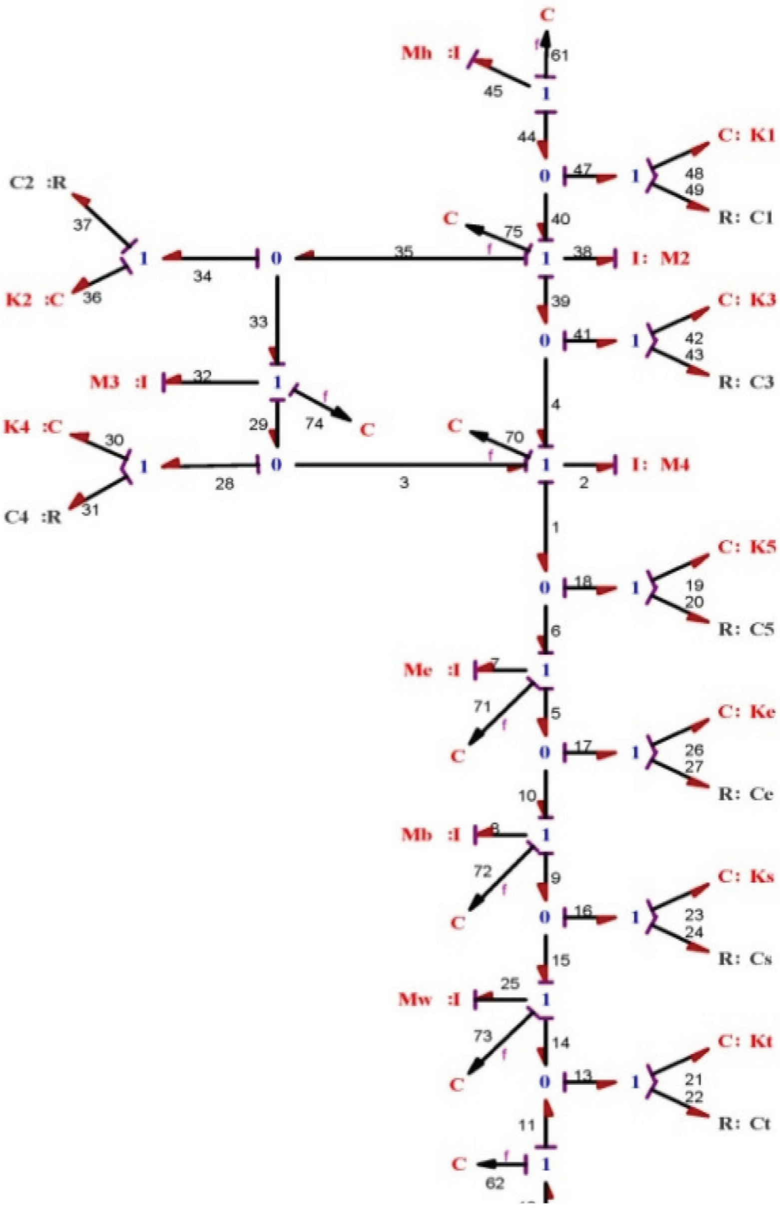


Figure 3. Integrated 7-DOF passive suspension quarter car Bond Graph model

endless number of virtual sensors but no virtual sources (PETER J. GAWT).

Proportional, integral and derivative gains are introduced in model using transformer (TF). For the effective functioning of PID controller selection of gain parameter is one of the most challenging task here in this work tuning is done using Zeigler-Nichols method and parameter used in simulation are K_P=1200, KI=100 and K_D=4450.

3. ROAD EXCITATION

A sinusoidal road profile bump of height (h) 0.1m and widths (w) of 3.7m shown in Fig. 5 is used for analysis. Vehicle is moving with velocity of 40 KMPH. As a function of time, the road conditions are given by

$$\begin{cases} Z = h * \sin\left(\dfrac{\pi . v}{w} * t\right) & \text{for } t < \dfrac{w}{v} \\ \quad = 0 & \text{for } t > \dfrac{L}{v} \end{cases} \tag{9}$$

4. SIMULATION STUDIES

The differential equations of the bond graph are solved using a fifth-order Runge-Kutta method. Simulation is conducted for 10 seconds to obtain distinct dynamic reactions. The simulation employs 1024 data points with

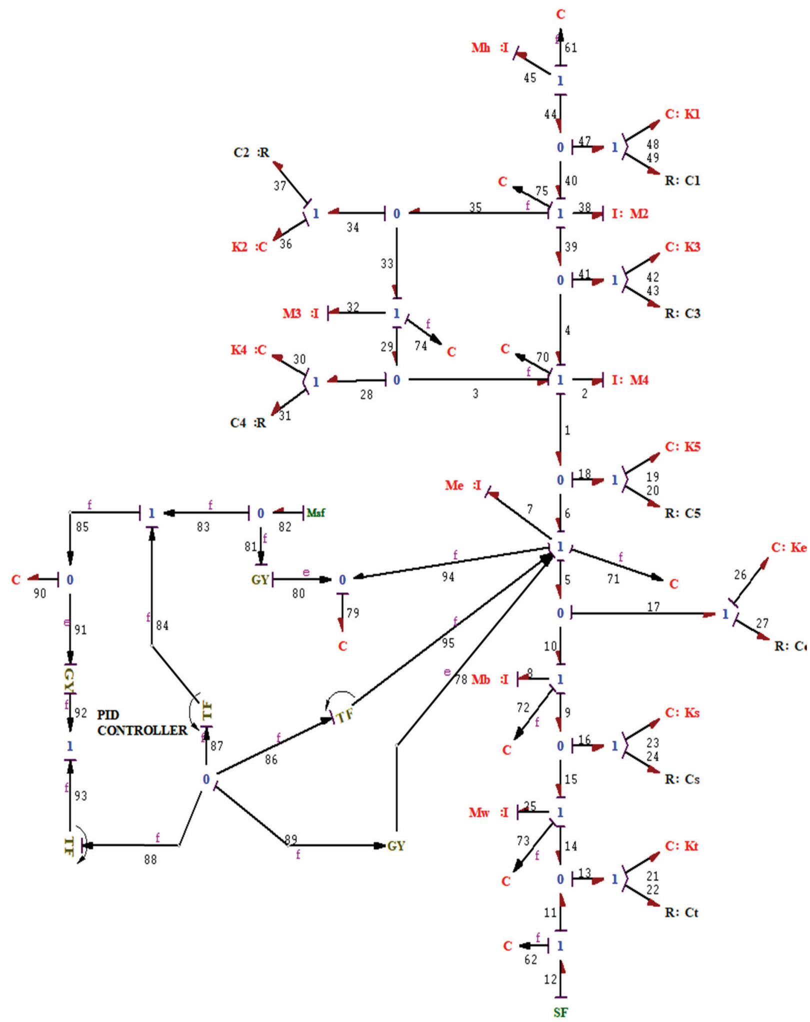


Figure 4. Integrated 7-DOF Active suspension quarter car Bond Graph model with PID controller

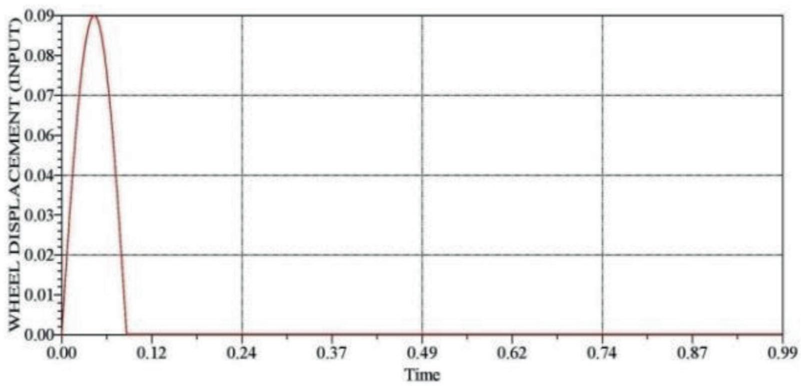


Figure 5. Sinusoidal road profile bump used for simulation

errors on the order of 5.0 x 10-4. Simulation parameters were taken from Farid et al. (Farid et al., 2011) and are listed in Table 1.

5. RESULTS & DISCUSSIONS

Acceleration and displacements of body components, occupant seats, and sprung mass are among the time-domain reactions investigated in this study when stimulated by artificially created sinusoidal inputs, results are obtained. Further Ride comfort was determined and compared the results of both passive and active (PID) model.

Fig. 6 and Fig. 7 shows vertical acceleration and displacement of body parts as well as for passenger seat and sprung mass respectively. Peak accelerations and

Table 1. Human and car model parameters by abbas et al. for simulation

Symbol	Parameters	Value
m_h	Head mass	4.17kg
m_{ut}	Upper torso mass	15 kg
M_{lt}	Lower torso mass	5.5 kg
M_p	Pelvis (thigh) mass	36 kg
C_{hu}	Dampig between head & upper torso	310 N-s/m
K_{hu}	Stiffness between head & upper torso	166990 N/m
C_{ul}	Dampig between upper torso & lower torso	200 N-s/m
K_{ul}	Stiffness between upper torso & lower torso	10000 N/m
C_{up}	Dampig between upper torso & pelvis	909.1 N-s/m
K_{up}	Stiffness between upper torso & pelvis	144000 N/m
C_p	Damping between lower torso & pelvis	330 N-s/m
K_{lp}	Stiffness b/w lower torso & pelvis	20000 N/m
C_{pse}	Damping between pelvis & seat	2475 N-s/m
K_{pse}	Stiffness b/w pelvis & seat	49340 N/m
C_{se}	Damping of passenger seat	150 N-s/m
K_{se}	Stiffness of passenger seat	15000 N/m
m_{se}	Mass of passenger seat	35 kg
m_w	Mass of wheel	35 kg
C_s	Damping coefficient of suspension	980 N-s/m
K_s	Stiffness coefficient of suspension	16000 N/m
K_t	Stiffness coefficient of tires	160000 N/m
m_b	Mass of vehicle body	250 kg

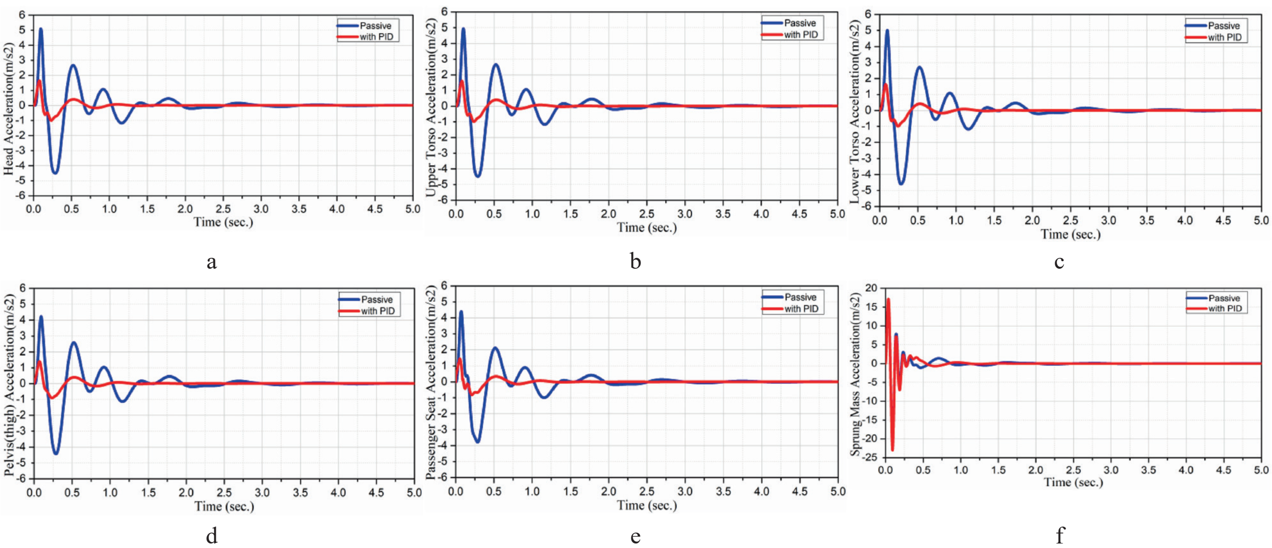


Figure 6. Acceleration response (a) Head (b) Upper Torso (c) Lower Torso (d) Pelvis (thigh) (e) Seat and (f) Sprung mass at 40 km/h

displacement of all body parts are observed nearly same. Acceleration in body parts measures the comfort level and it is observed in Fig.6 that body parts acceleration is decreased in term of peak acceleration and settling time. Fig.6 depicts the acceleration at various model components such as the head, upper torso, lower torso, pelvis, seat, and spring mass. The results of Fig.6 and Table 2 show that active (PID) suspension reduces the driver's vertical acceleration by 76.89% when compared to passive suspension for sinusoidal motion. Further there was reduction of 77.03%, 76.94%, 77.6% and 76.85% in acceleration in other body parts (upper torso, lower torso, pelvis) and seat respectively.

Fig.7 depicts the displacement at various model components such as the head, upper torso, lower torso, pelvis, seat,

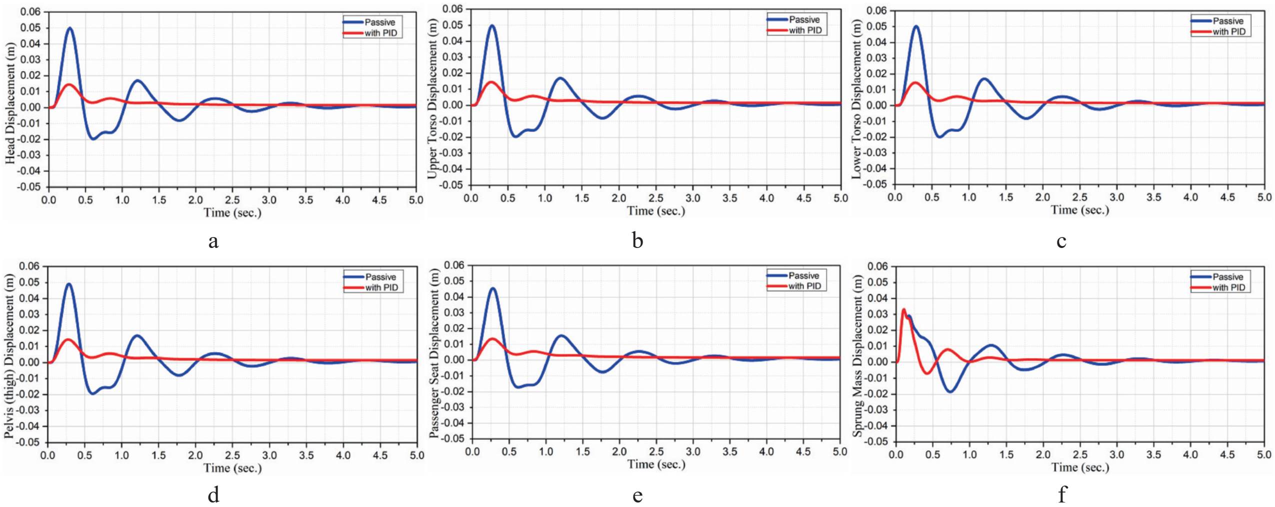


Figure 7. Displacement response (a) Head (b) Upper Torso (c) Lower Torso (d) Pelvis (thigh) (e) Seat (f) Sprung mass at 40 km/h

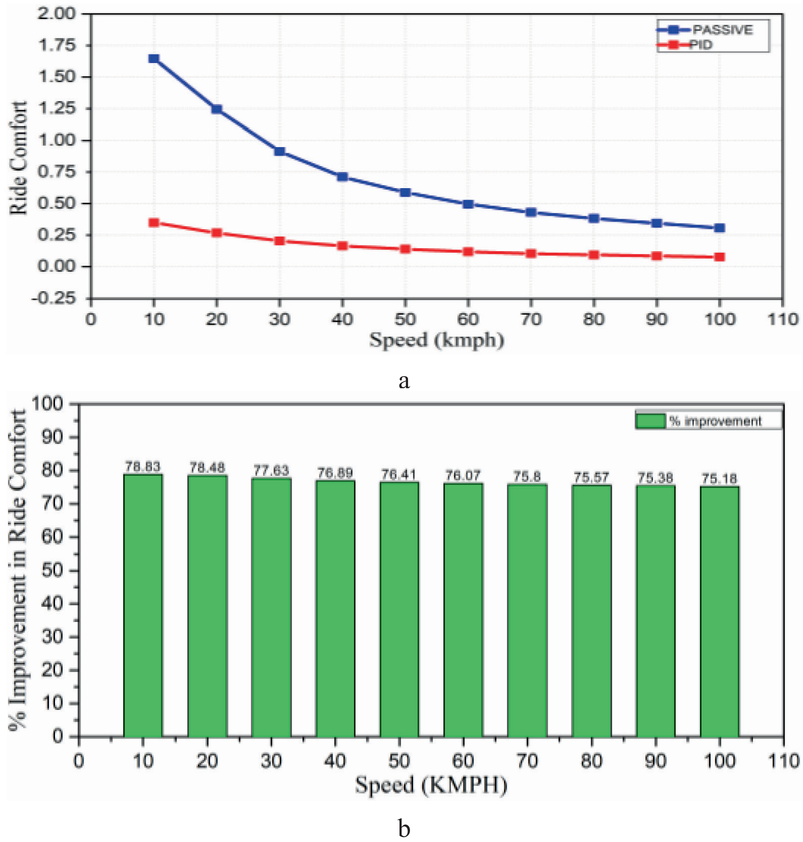
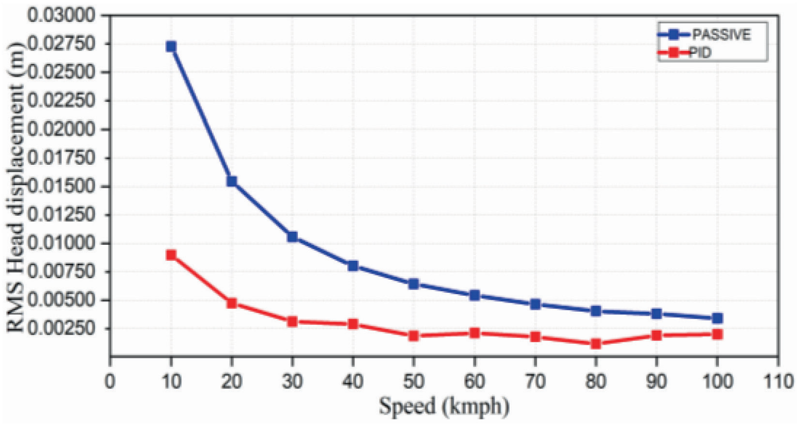


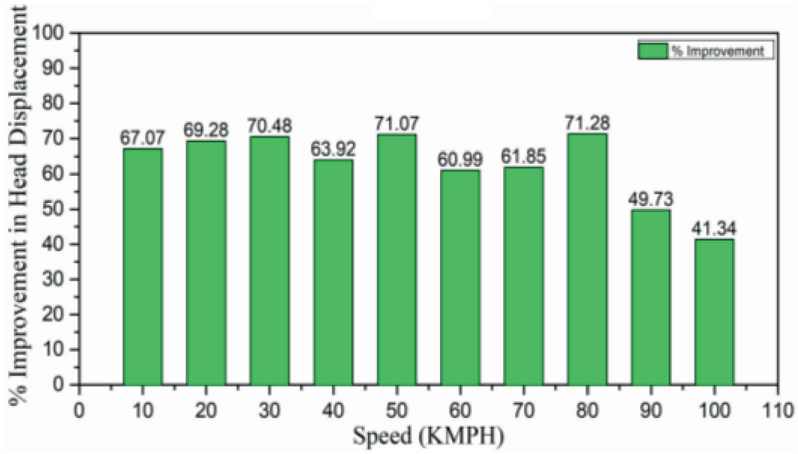
Figure 8. Ride Comfort improvement using PID (a) RMS (b) % improvement

and spring mass. The results of Fig.7 and Table 3 show that active (PID) suspension achieves reduction in RMS vertical displacement of body parts and seat by 63.90%, 63.86%, 63.99%, 63.66% and 62.17% respectively when compared to passive suspension for sinusoidal motion.

Body part acceleration and displacement, particularly of the head, is an essential concern for the occupants' health and safety (BS 6841-1987), since it is caused by force conveyed to the human body through seat contact as a reaction to disturbance from the road via the bump. Fig.8 and Fig.9 compares the RMS head acceleration (Ride Comfort) and head displacement response of a passive and active system for a vehicle travelling over a bump at different speeds ranging 10-100 KMPH. The percentage improvement in Ride Comfort and RMS head displacement is shown in Fig.8 (b) and Fig.9 (b) respectively and it is clear from the graph that Bond Graph



a



b

Figure 9. Head displacement improvement using PID (a) RMS (b) % improvement

Table 2. Percentage improvement in RMS acceleration at 40 KMPH

	Head	Upper Torso	Lower Torso	Pelvis	Seat	Sprung Mass
Passive	0.711033	0.704951	0.717287	0.677774	0.593875	1.582208
Active (PID)	0.164251	0.161895	0.165359	0.151805	0.137434	1.593864
% Improvement	**76.8997**	**77.03456**	**76.94654**	**77.60236**	**76.85806**	**-0.73667**

Table 3. Percentage improvement in RMS displacement at 40 KMPH

	Head	Upper Torso	Lower Torso	Pelvis	Seat	Sprung Mass
Passive	0.008013249	0.008001	0.008043	0.007934	0.007491	0.005657
Active (PID)	0.002892	0.002891	0.002896	0.002883	0.002833	0.00407
% Improvement	**63.90502**	**63.86835**	**63.99452**	**63.66343**	**62.17809**	**28.06441**

PID model is successfully employed and achieves large improvement in Ride Comfort as well as reduction in head vertical displacement.

6. CONCLUSION

The bond graph approach was used in this study to explain the dynamic behavior of a 7DOF passive vehicle suspension system based on a quarter automobile model linked with a lumped human biomechanical model in the temporal domain when subjected to sinusoidal input. Further effect of bump was reduced using novel Bond Graph modeled PID controller which shows satisfactory results. RMS responses (ride comfort and head displacement) compared for both passive and active vehicle system for velocities ranging from 10 to 100 KMPH. After analysing the results, it was discovered that employing a PID controller with a bond graph successfully improving ride comfort and also reduced vibration communicated to human body parts.

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