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Design and analysis of a BELBIC controlled semi active suspension system

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Abstract. The vehicle dynamics gives lot of consideration to quality of ride and the value of comfort. These two are dependent on the suspension system of the vehicle. Researchers are doing a lot of work in the field of improving these two parameters. A lot of approaches and control systems like ANN, GA based system, fuzzy and hybrid control systems have been formulated, simulated and tested. This paper deals with mathematical modeling and simulation of passive and semi active system. The semi active system modeled here contains a new approach of using intelligent controller based on Brain functioning with emotional signal, known as BELBIC. The use of this controller has not been tested for suspension system as identified through rigorous literature survey. The both systems are simulated for their response to disturbance of road as step function and as profile of cosine shape. The results of passive and proposed semi active system were analyzed to compare their performance in terms of displacement of sprung mass and suspension travel as well as their settling time. The BEL controlled system has performed very good. The displacement of sprung body has been reduced in both the cases of road disturbances. The response against step input is better than cosine. Similarly settling time has also shown in improvement for step and cosine function.

1. Introduction

From the time of inventions of the automobiles, quality of ride and the control of the vehicle are of utmost importance for the engineers. The comfort of vehicle ride gets affected by transfer of vibrations because of undulations in road e.g. bumps and humps. Engineers are putting lot of efforts right from the beginning for developing better and better suspension systems for the vehicle. Initial suspension design was the use of coil and leaf springs, further which were integrated with damper or shock absorbers. It is the early eighties when with tremendous advancement in the field of electronics have led the automotive design engineers to develop suspension system based on mechatronics approach. Since then a lot of work has been performed for the continuous improvement in the design of suspension by introducing semi active and active suspension using advanced control systems like Fuzzy system, PI, PID etc. Now with the introduction of number of control techniques which are nature or biological system inspired the more sophisticated and better performing suspension systems are developed and are under the process of development.

A M Solovyov et al.[1] considered mechanical system dynamics under the effect of external force with taking care of damper’s nature of hysteresis. Bouc-Wen model has been considered as mathematical
expression for damper hysteresis. The work is simulated and results show that MR damper has very good efficiency in resonance as well as outside resonance zone. Kareem Hassan et al. [2] worked on simulation of passive and semi active suspension using LabView. The practical and theoretical results were compared. The semi active suspension with PID controller performance was better than passive in terms of parameters like settling time, peak overshoot, deflection of wheel and wheel position. Da Shan Huang et al.[3] worked on simulation model of quarter car 2 degree of freedom system. A PID controlled semi active system is modeled and simulated and gains of PID are optimized by genetic algorithm. The results shows drastic significant improvement in ride comfort. Mohamed Hassan et al.[4] worked on study of the behavior of one fourth car active suspension in comparison to passive suspension for road holding and ride quality. Two types of road disturbances were used for the purpose of analysis, a random profile and a step function input. The result reveals that suspension with twin accumulator gives significant improvements in ride quality in comparison to passive suspension. The use of PI controller has shown improvement in displacement of wheel and vehicle body. Jiangbo Wang [5] worked on mathematical modeling of roughness of road based on power spectral density. They worked on it by random method of integral white noise. A 2 DOF vehicle model was prepared in Matlab/Simulink for the analysis. They studied the effect of road profile generated on vehicle subjected to random road profile. Guoliang Hu et al.[6] worked on analyzing the MR damper characteristics and modeling of quarter model of car. A hybrid fuzzy controller is designed for analysis. The results showed that hybrid fuzzy controlled suspension has much better ride quality and comfort. Shida Nie et al. [7] proposed a modified skyhook acceleration driven damping algorithm for ride comfort. A two degree of freedom model of vehicle is simulated and results showed and improvement up to eighteen percent. Fitri Yakub et al.[8] simulated a one fourth model of car to analyse the effect of road disturbance on vehicle’s performance. A feedback controller of state type is used for the work and showed reduction in vibration caused by road disturbance. Wentao Liu et al.[9] carried research on different types of mechanical model of MR damper. The work was focused on analyzing the characteristics of these various models to design a damper based on the results. Jumi Bharali et al.[10] modeled three degree of freedom suspension system. Three controllers LQR, Fuzzy-LQR and PID were designed for the analysis. The performance of semi active system comes out better than passive system, and Fuzzy-LQR based system proves to be best among the three modeled systems. Manuel Brazz Cesar et al. [11] worked on a single degree of freedom structure under the excitation of earthquake. The designed a controller based on emotional learning of brain (BEL controller). The system showed very improved results against the excitation when used with BEL controller. Alvaro Vargas Clara et al.[12] developed a new controller known as Brain Emotional Learning Based Intelligent Controller (BELBIC). Its effect on controlling the unmanned ground vehicle is analyzed. The results shows that new controller is very robust and better than PID controller. Jae Won Kim [13] worked on mathematical modeling of inverted pendulum system with rotary motion. A novel intelligent controller based on brain learning was designed. The performance of newly proposed BELBIC controller proved to be very robust and effective. Al Shahriar et al. [14] modeled a passive suspension system in Matlab/Simulink environment. They simulated the bounce and pitch response of the vehicle. They formulated a cosine road profile and simulated its effect on the suspension system. Ehsan Lofti et al. [15] worked on new approach in Belbic controller known as generalized belbic system. The proposed controller has proved to be very robust in controlling the plant output. The proposed controller can be used for non-linear systems also and its use on other control systems can be investigated. Reshma Ravi et al. [16] studied a brain emotional based intelligent controller and design of this controller for spring mass system with damper. The model is simulated and its performance is compared with PID controlled system. The performance of the belbic controller comes out to be better than PID. Arpit Jain et al. [17] proposed a new intelligent controller for tank reactor with continuous stirrer used in chemical field. The controller proposed is based on emotional learning principle of brain known as BELBIC. The simulation is carried out in Matlab/Simulink environment and proposed intelligent controlled system gives very good results. This work also deals with the design of new biologically inspired controller based on learning of emotions.
by human brain. In rigorous literature survey not much work has been identified for the use of this controller in semi active suspension system.

2. Mathematical Model of Suspension System

Mathematical model of suspension with passive configuration as well as semi active has been created in this work. A one fourth model of car with degree of freedom two in number is taken for the development of said model in mathematical form. For passive system configuration spring, damper arrangement is taken whereas for semi active configuration an intelligent controller has been introduced as a part for spring damper system to make it a closed loop system. Also the damper considered is with smart fluid damper known as magneto rheological fluid. The figure 1 shows one fourth passive model and figure 2 one fourth model of semi active suspension for vehicle[1]. Rigid body consideration of vehicle with suspension for the purpose of analysis has been taken. The tire of vehicle is modelled as to give combined effect of stiffness and damper, therefore represented as a combination of damper and spring in the model[2].

![Figure 1. Passive 1/4th suspension](image1)

![Figure 2. Semi Active 1/4th suspension](image2)

From proposed 2DOF (degree of freedom) configuration of vehicle suspension, equation of motion for sprung and un-sprung mass are obtained using free body diagram as equation (1), equation (2).

\[ M_{SR} \ddot{X}_{SR} + K_S(X_{SR1} - X_{US2}) + C_S(\dot{X}_{SR1} - \dot{X}_{US2}) = 0 \]  
\[ M_{US} \ddot{X}_{US2} + K_t(X_{US2} - W_{RD}) + C_t(\dot{X}_{US2} - \dot{W}_{RD}) - K_S(X_{SR1} - X_{US2}) - C_S(\dot{X}_{SR1} - \dot{X}_{US2}) = 0 \]

Based on the above two equations state space modelling of the 1/4th car model is done. The matrix of state space form in generalised form is represented by equation (3), equation (4).

\[ \dot{Y} = AY + BV \]  
\[ X = CY + DV \]

Equation (3) and (4) deals with following matrix:

A = state space, B = input, C = output, D = transmission, V = System Input.

Let,

\[ Z_1 = X_{SR1}, Z_2 = \dot{X}_{SR1} = \dot{Z}_1, Z_3 = X_{US2}, Z_4 = \dot{X}_{US2} = \dot{Z}_3 \]

Therefore equation (1), (2) are rewritten as equation (5), equation (6).

\[ \dot{Z}_2 = -\frac{K_S}{M_{SR}}[Z_1 - Z_3] - \frac{C_S}{M_{SR}}[Z_2 - Z_4] \]  
\[ \dot{Z}_4 - \frac{C_t}{M_{US}}W_{RD} = \frac{K_S}{M_{US}}Z_1 + \frac{C_s}{M_{US}}Z_2 - \frac{[K_s + K_t]}{M_{US}}Z_3 - \frac{[C_t + C_s]}{M_{US}}Z_4 + \frac{K_t}{M_{US}}W_{RD} \]

For passive type of suspension the matrix for input and matrix for output data of state space model are formed and given by equation (7), equation (8) respectively[3][4].
The state space model for suspension with intelligent controller is created from equation (9), equation (10) obtained by free body diagram of figure 2.

\[
M_{SR} \ddot{z}_{SR} + K_s(z_{SR} - z_{US}) + F_C = 0 \tag{9}
\]

\[
M_{US} \ddot{z}_{US} - K_s(z_{SR} - z_{US}) + K_t(z_{US} - z_{RD}) + G_t(\dot{z}_{US} - \dot{z}_{RD}) - F_C = 0 \tag{10}
\]

Let,

\[E_1 = z_{SR}, E_2 = \dot{z}_{SR} = \dot{E}_1, E_3 = z_{US}, E_4 = \dot{z}_{US} = \dot{E}_3\]

The state space model for suspension semi active type is represented by equation (11), equation (12) respectively[5][6].

\[
\begin{bmatrix}
\dot{E}_1 \\
\dot{E}_2 \\
\dot{E}_3 \\
M
\end{bmatrix}
= \begin{bmatrix}
0 & K_s & 0 & 0 \\
-\frac{1}{M_{SR}} & 0 & M_{SR} & 0 \\
0 & -\frac{K_s}{M_{US}} & 0 & C_t \\
-K_s & 0 & -[K_t + K_s] & 1
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_3 \\
M
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
-\frac{1}{M_{US}}
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_3 \\
M
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
-\frac{1}{M_{US}}
\end{bmatrix}
\begin{bmatrix}
F_C \\
F_{Z_{RD}}
\end{bmatrix}
\tag{11}
\]

\[
\begin{bmatrix}
\dot{Z}_{SR} \\
\dot{Z}_{US} \\
\dot{Z}_{RD}
\end{bmatrix}
= \begin{bmatrix}
1 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_3 \\
M
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
F_C \\
F_{Z_{RD}}
\end{bmatrix}
\tag{12}
\]

3. Intelligent Controller BELBIC:
The intelligent controller based on biological behaviour of human brain in response to emotions has been designed. The controller is known as BELBIC (Intelligent controller based on brain’s emotional learning). Functioning of human brain’s ‘Limbic System’ is principle of its working. Significant components of brain’s limbic system are Amygdala, Thalamus, Sensory cortex and Orbitofrontal Cortex[11]. Generally the role of motivation and emotion are overlooked while studying the human behaviour and performance. The driving force for us is Motivation, without which no one would do anything. Emotions on the other hand are the indicators how good or bad is the course of action taken due to motivation, whether further action is required or not. We can also say emotions are continuous feedback to human system of learning. The BELBIC system receives one or more than one signal but gives only one output. It is a system that generates action on the basis of sensory inputs resulted from stimulus or external source and reward a signal generated internally also known as emotional cue [12]. Thalamus sends sensed input to amygdala and orbitofrontal cortex receives signal from amygdala, it also receives emotional reward from unspecified source as till today its origin is unclear [13]. The output of the limbic system is difference of outputs of orbitofrontal cortex and amygdala. Figure 3 shows the general structure for BEL intelligent controller.
The mathematical expression for BELBIC system is described by equation (13) to equation (17)[14].

\[
\begin{align*}
A_{BEL} &= G_{AG} \times I_{SI} \\
O_{OFC} &= G_{OFC} \times I_{SI} \\
\frac{dG_{AG}}{dt} &= \alpha \times I_{SI}(I_{ES} - A_{BEL}) \\
\frac{dG_{OFC}}{dt} &= \beta \times I_{SI}(A_{BEL} - O_{OFC} - I_{ES}) \\
O_{Model} &= (A_{BEL} - O_{OFC})
\end{align*}
\]

Here \( I_{SI} \) is sensory input, \( O_{OFC} \) is output of OFC, \( O_{Model} \) is output of model, \( G_{AG} \) and \( G_{OFC} \) are the gains of amygdala and OFC respectively. \( G_{AG} \) always gets increased depicting the behaviour of emotional learning increment against each input. The rates of learning in the system are given by alpha and beta. Generally same value is assigned to them; otherwise a higher value to the alpha is assigned [15].

\[I_{SI} = I_{ES} = |E_r|\]

Where,

\[E_r = \text{Error signal}\]

\[K_{SI}, K_{ES} \text{ and } K_{E3} = \text{Gains for sensory input and emotional signal}\]

Figure 3 and figure 5 shows the Simulink block structure of emotional signal and orbitofrontal cortex respectively [17].

4. Simulink Model of Passive, BELBIC Controlled Suspension

The model for the purpose of simulation was prepared in the Matlab/Simulink environment [16]. For our proposed model of BELBIC for control of suspension system sensory input (\( I_{SI} \)) and emotional signal or reward (\( I_{ES} \)) is given as:

\[I_{SI} = K_{SI} \times E_r\]

\[I_{ES} = K_{ES} \times |E_r| + K_{E3}\]

Where,

\[E_r = \text{Error signal}\]

\[K_{SI}, K_{ES} \text{ and } K_{E3} = \text{Gains for sensory input and emotional signal}\]

Figure 4 and figure 5 shows the Simulink block structure of emotional signal and orbitofrontal cortex respectively [17].

\[\text{Figure 3. BELBIC Structure}\]

\[\text{Figure 4. Emotional Signal Simulink Structure}\]
The input parameters for the Simulink model are given as per table 1.

| S.No | Parameter         | Value  | S.No | Parameter                        | Value     |
|------|-------------------|--------|------|----------------------------------|-----------|
| 1.   | Sprung Mass, \(M\) | 242 Kg | 5.   | Tire Damping Co-efficient, \(C_t\) | 1510 N-s/m|
| 2.   | Unsprung Mass, \(M_{US}\) | 42 Kg  | 6.   | Suspension Spring Stiffness, \(K_s\) | 6010 N/m  |
| 3.   | Tire Stiffness, \(K_t\) | 140000 N/m | 7.   | Suspension Damping Co-efficient, \(C_s\) | 305 N-s/m |
| 4.   | Bump Height, \(W_{RD}\) | 10 cm  |      |                                  |           |

The model is simulated for the response of un-sprung and sprung mass displacement, their settling time.

5. Simulation

The model for both suspension i.e. passive type and one with controller is simulated in Simulink. The models are simulated for road disturbance as input to the system. Step and Cosine function inputs are given to the system for analysis. The gain coefficient in the proposed controller based on emotional learning of brain was identified by trial and error method [16]. The model is tested for its response under different values of gain, and the gains obtained are \(K_{S1} = 300\), \(K_{E2} = 200\), \(K_{E3} = 2000\). The simulation results for the bounce, suspension travel and time to settle down for sprung body in case of input as step function is shown in figure 6 and figure 7. The Sprung mass displacement is very high in comparison to BEL system.
Suspension travel response of BEL controlled suspension system is given by figure 7, the response obtained shows significant improvement in case of BEL controlled system.

Figure 7. Suspension Travel (Step Input)

Figure 8 represents the response of both types of suspension system for cosine profile cleat. It can be observed that there is significant reduction in overshoot as well as settling time for intelligent controlled system.

Figure 8. Sprung Mass Displacement

Suspension travel is also improved for cosine input to the system in case of BEL system as shown by figure 9. The settling time has also improved very significantly in this case.

Figure 9. Suspension Travel
6. Result and Discussion
The BELBIC controlled suspension system response when compared with passive type has shown much improved performance. The percentage reduction in bounce and time for settle down has shown significant improvement and are shown in tabulated form in table 2 and table 3 respectively. This shows that newly adapted approach of emotional learning of mind for creating the controller for suspension has significant scope for further work in this field.

Table 2 Overshoot Response

| Type of Suspension | Passive | BELBIC | % overshoot reduction for BELBIC |
|--------------------|---------|--------|---------------------------------|
| Sprung Mass Displacement | 0.1713 0.0521 | 0.1008 0.0357 | 41 31 |
| Suspension Travel   | 0.0683 0.0506 | 0.0128 0.0237 | 81 53 |

Table 3 Settling Time Response

| Type of Suspension | Passive | BELBIC | % settling time reduction for BELBIC |
|--------------------|---------|--------|-----------------------------------|
| Sprung Mass Displacement | 8 9 1.5 5 | 81 44 |
| Suspension Travel   | 8 8 1.5 4 | 81 50 |

7. Conclusion
The simulation result of semi active suspension system with novel approach of BELBIC controller shows improvement in ride comfort when compared with passive system. The following observations are obtained:

- For step input a significant improvement is shown in sprung mass displacement and suspension travel. The improvement is 41% and 81% respectively for BELBIC controlled system.
- For step input a significant improvement is shown in settling time of sprung mass displacement and suspension travel. The improvement is 81% and 81% respectively for BELBIC controlled system.
- For cosine input improvement in sprung mass displacement and suspension travel is 31% and 53% respectively for BELBIC controlled system.
- For cosine input a significant improvement is shown in settling time of sprung mass displacement and suspension travel. The improvement is 44% and 50% respectively for BELBIC controlled system.

The overall result of simulation work shows that BELBIC controlled semi active suspension system performance is significantly improved. The response against step input is better than cosine because step input is a Heaviside function. In this function value clips between zero to highest magnitude directly, therefore the error signal to BEL controller will be very high resulting in high value of damping force generated by the system. This will result in sharp reduction in sprung mass displacement. In case of cosine input, the profile of bump is smooth semi-circular type where error signal change is not as high as for step, correspondingly damping force generated will also be low in comparison to step input response.

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