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DESIGN OF AN ARTIFICIAL INTELLIGENCE-BASED NON-LINEAR CONTROLLER OF A 3-DOF QUARTER ACTIVE VEHICLE SUSPENSION SYSTEM USING AN ELECTRO-HYDRAULIC

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Abstract
A vehicle usually encounters road disturbances and an active vehicle suspension system is used to minimize the impact of these road disturbances to ensure a comfortable ride. Vehicles usually comes in contact with sudden road disturbances, such as depression, bumps, acceleration and deceleration, etc and this could lead to an uncomfortable ride and road accidents. So, in this work, a three degree of freedom quarter active vehicular suspension system is modelled and an electro-hydraulic actuator is also modeled for this system. Then an Artificial Intelligence (AI) based non-linear controller is designed for this system, due to which the system becomes more stable, robust and minimizes the uncertainty in the system. A simulation model has been created using MATLAB/Simulink to analyze the impact of road disturbances on a vehicle's suspension system. The results are verified for two different road cases such as no-off-roading case and off-roading case at different speeds and these results shows that the active suspension system model is stable than passive suspension system as the controller is used to improve the system response by stabilizing overshoot, undershoot and settling time of the system.

INTRODUCTION

A suspension system of a vehicle is the vehicle components and systems linking the vehicle frame or body and wheels. The main function of a suspension system is to provide a comfortable and smooth ride to individuals in the car by reducing the effect of road surface bumps and vibrations. (Kashem et al., 2015).[2]. The Quarter Car model is frequently used to model the suspension system as it captures many characteristics of the vehicle body (M.Iftikhar et al. 2022).

The figure for the active vehicle suspension system is shown in the figure below:

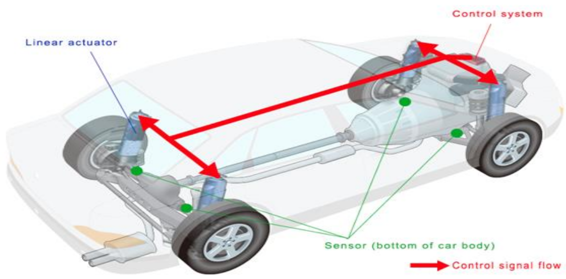


Figure 1: Active Suspension System of Vehicle[7].

The block diagram for the quarter vehicle active suspension system is shown in the figure below:

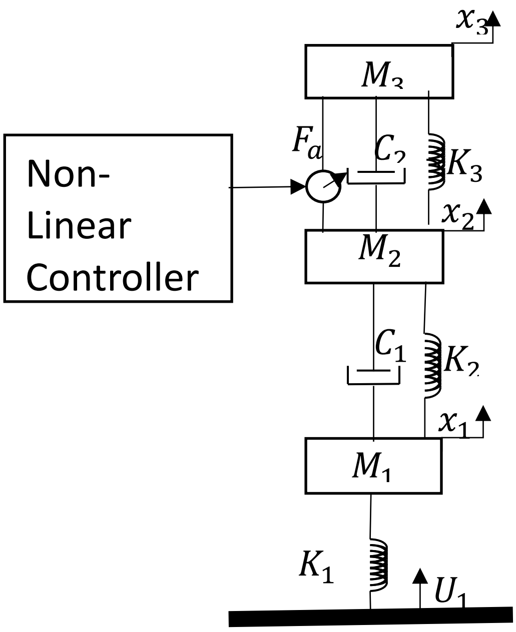


Figure 2: Block diagram of an active quarter vehicle suspension system

When the vehicle is passed through road disturbance, then this lead to rider discomfort, damage to the vehicle and road accidents. Therefore, a quarter vehicle active suspension system is being used to make the system more stable and reduce these risks of instability and ride discomfort. In this work, the response of the suspension system has been determined and checked for two different cases. Case 1 is for no off-roading which means that the road is a straight road. Here in this research, the step input is taken as a straight road. The output response of this system will be checked for different speeds of 20km/hr and 80km/hr for both passive and active suspension system.
Similarly, Case 2 is for vehicles passing through an off-road. This is not a straight road of roads, the road is taken as this case has infinite spikes which means that this road has many disturbances. The response for this case has been checked for vehicle speeds of 20km/hr and 80km/hr for both passive and active suspension system. In this research paper, AI nonlinear controller has been designed using trial and error method of Zeigler-Nicholas theorem which control the non-linear dynamics and makes the system robust and stabilized at different speeds for both cases. The response for higher speeds is more stable. The sliding mode control method is a non-linear control method that is developed to achieve accuracy and control performance of this system and is robust in handling uncertainties. The overshoot, undershoot and settling time of this system for both passive and active suspension system are checked and compared and this shows that the active suspension system is more stable and robust system as compared to the passive suspension system. This active system maintains vehicle stability, improve rider quality and enhance the overall performance of the suspension system.

LITERATURE REVIEW:

A vehicle suspension system consists of combination of components and the devices that connect the body or frame to the wheels in a vehicle. Suspension system enhances a comfortable ride, helps to maintain control of the road, and contributes to the stability of the vehicle (Kashem et al., 2015).
In this research work heave motion of the vehicle has been controlled. There are different types of vehicle motion: **Heave motion** is the vertical up and down motion caused by roads bumps and humps. **Pitch motion** is the angular motion of a vehicle about transverse axis. **Roll**

motion is the angular motion of a vehicle about longitudinal axis (R.N 2014).

A suspension system has two main types i.e., a passive suspension system and an active suspension system. Iftikhar.M, et.al, in his research, used an active suspension system that is most likely to be used as the results shown by this system are much more stable than that of the passive suspension system. A PID controller was used, which shows stable overshoot, settling time and rise time values for speed of 20m/s, however for higher speeds, the vehicle shows unstable response (Iftikhar.M. et al ,2022).

Liba.A, used Generalized Kalman-Yakubovich-Popov (KYP) lemma to lower the H∞ norm from disturbance to regulated output in order to reduce body vertical vibration in the 4–8 Hz frequency range. Time domain constraints are ensured while designing a state feedback controller through linear matrix inequality (LMI) optimization. Simulations using a quarter-car model with an active suspension system shows the effectiveness of this system.

Figure shows the system with weighting functions responds better to finite frequency controllers and decreases body vertical acceleration. Controller I offers excellent time domain features, but selecting a weighting function is challenging due to balancing weight complexity and parameter precision (Libi.A, 2023).

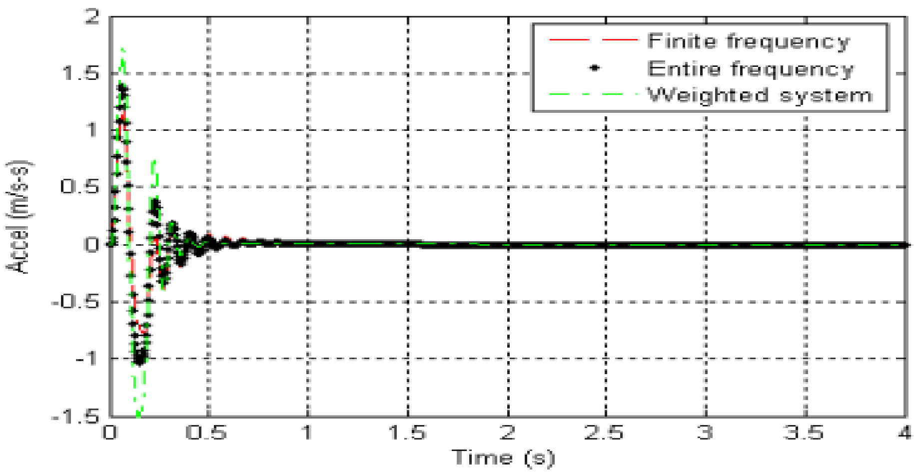


Figure 3: Time - domain response of body vertical acceleration(Libi.A, 2023).

Wu, Hang et al. in his research is focused on the electromagnetic coupling effects in hub-driven electric vehicles and utilized a PID based robust preview control strategy to mitigate these forces and enhance ride comfort. While the study demonstrated improvements in vehicle stability under varying road conditions, it too relied on linear PID control, which is limited when addressing severe non-linear disturbance like road bumps. Below is the response for an active suspension system under random road when the speed is 10m/s and the response shows the comparison between a passive system, robust control and robust preview control when the speed is 10m/s but this response is only stable for linear systems while for non-linear systems, a controller must be designed and modeled to get a stable and robust response. (Wu, Hang et al. 2024)

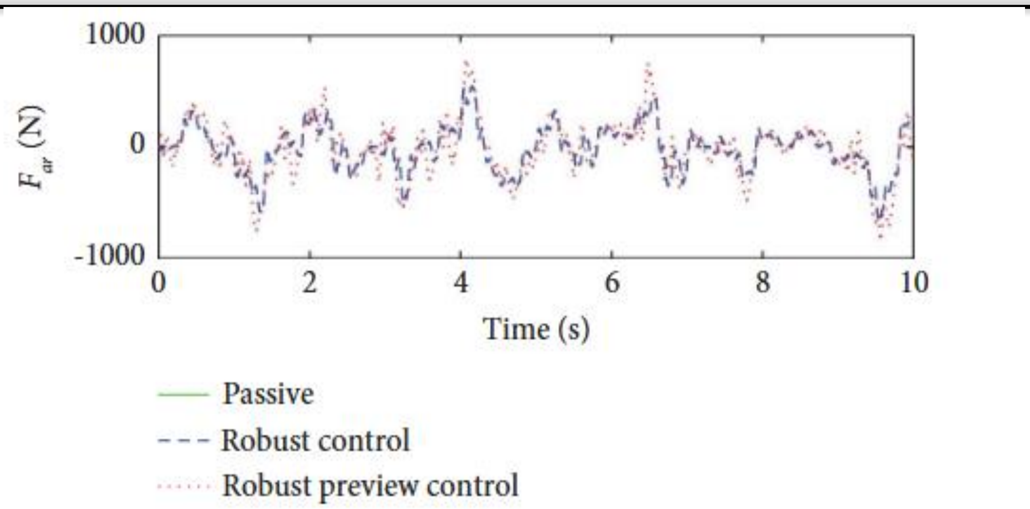


Figure 4: Active Suspension System Response Under Random Road At 10 m/s Speed (Wu, Hang et al. 2024).

MATHEMATICAL MODELLING:

The modelling of the quarter vehicle passive and active suspension system is done here and then the setup is done in Simulink/MATLAB. The three degree of freedom system for quarter vehicle suspension system for active suspension system is modelled mathematically in this section based on the approach of Al Ghanim. et al. The block diagram for this system is given below:

Now form the above block first model the vehicle suspension system:

First find equation for mass M1:

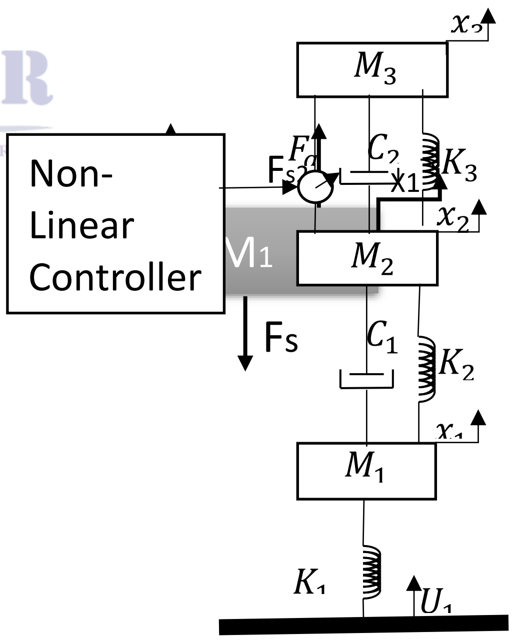


Figure 6: Three DOF Active vehicle suspension system.

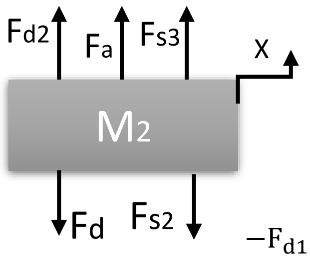
Using newton's 2nd law:

$$\sum F = m_1\ddot{X}_1 \quad (1)$$

$$F_{d1} + F_{s2} - F_{s1} = m_1\ddot{X}_1 \quad (2)$$

$$m_1\ddot{X}_1 + K_1(X_1 - U_1) - K_2(X_2 - X_1) - C_1(\dot{X}_2 - \dot{X}_1) = 0 \quad (3)$$

Now for Mass M2, we again uses Newton's 2nd law of Motion:

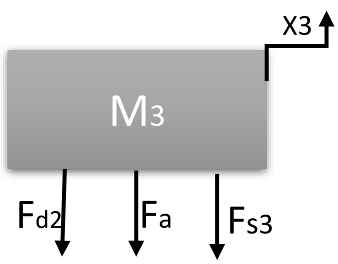


$$\sum F = m_2\ddot{X}_2 \quad (4)$$

$$-F_{d1} - F_{s2} + F_{s3} + F_{d2} + Fa = m_2\ddot{X}_2 \quad (5)$$

$$m_2\ddot{X}_2 + C_1(\dot{X}_2 - \dot{X}_1) + K_2(X_2 - X_1) - K_3(X_3 - X_2) - C_2(\dot{X}_3 - \dot{X}_2) + Fa = 0 \quad (6)$$

Use Newton's 2nd law of equation again to find M3:



$$\sum F = m_3\ddot{X}_3 \quad (7)$$

$$-F_{d2} - F_{s3} - Fa = m_3\ddot{X}_3 \quad (8)$$

$$m_3\ddot{X}_3 + C_2(\dot{X}_3 - \dot{X}_2) + K_3(X_3 - X_2) - Fa = 0 \quad (9)$$

After the modeling of quarter vehicle suspension system, hydraulic actuator is being modelled for this from [10]:

$$F_{ai} = A_h P_{li} \quad (10)$$

$$\dot{x}_{vi} = \frac{1}{\tau}(k_{vi}v_i - x_{vi}) \quad (11)$$

$$Q_i = C_d\omega . x_{vi}\sqrt{\frac{1}{\rho}\left(P_s - sgn(x_{vi})(P_{li})\right)} \quad (12)$$

$$\dot{P}_{Li} = \frac{4B_e}{V_t}\left[Q_i - C_{tp}P_{li} - A_h(\dot{z}_{si} - \dot{z}_{ui})\right] \quad (13)$$

$$\alpha = \frac{4\beta_e}{V_t}, \quad \beta = \alpha C_{tp}, \quad \gamma = \alpha . C_d\omega\sqrt{\frac{1}{\rho}}$$

$$\dot{P}_{Li} = \gamma . x_{vi}\sqrt{(P_s - sgn(x_{vi})(P_{Li}))} - \beta . P_{Li} - \alpha . A_h(\dot{z}_{bi} - \dot{z}_{wi}) \quad (14):$$

CONTROLLER DESIGN:

ANN-SMC frameworks are able to manage system uncertainties and unmodeled dynamics using the adaptive nature of Artificial Neural Networks (ANNs). The AI based non linear controller sliding phase is tuned by using Ziegler Nicholas trial and error theorem and then applied in the SMC controller. Then the Artificial neural network is trained by using the reaching phase values that have already been tuned in SMC which will stabilize the output response of the vehicle at different speeds

As a result of the SMC law, the system states are kept on a sliding surface based on tracking error and derivatives of tracking error. After being trained on live data, the ANN estimates non-linearity or disruptions in system dynamics that are unidentified and after identifying, ANN makes sure that the system is stable and robust.

There are three components to the control law: compensating for chattering, switching control, and equivalent control, which stabilizes the nominal system during shocks. Final control input is expressed as follows:

$$u = u_{eq} + u_{sw} + u_{ANN} \quad (15)$$

The sliding surface is expressed as:

$$s = \dot{e} + \lambda e \quad (16)$$

The value of sliding surface is determined by determined by the trial and error method of the Ziegler-Nicholas theorem ans the value is taken as 1.5.

The ANN approximates unknown dynamics:

$f(x) \approx \hat{f}_{NN}(x)$ (17),

The switching term is given as:

$$u_{sw} = -k.\,sgn(s) \quad (18)$$

The control input implemented is:

$$u = \hat{f}^{-1}(x)\left(-k.\,sgn(s) - \hat{f}_{NN}(x)\right) \quad (19)$$

This ensures the robust performance and will stabilize this system.

The ANN has one input and one output and there are two layers in this ANN based controller as shown in the figure below:

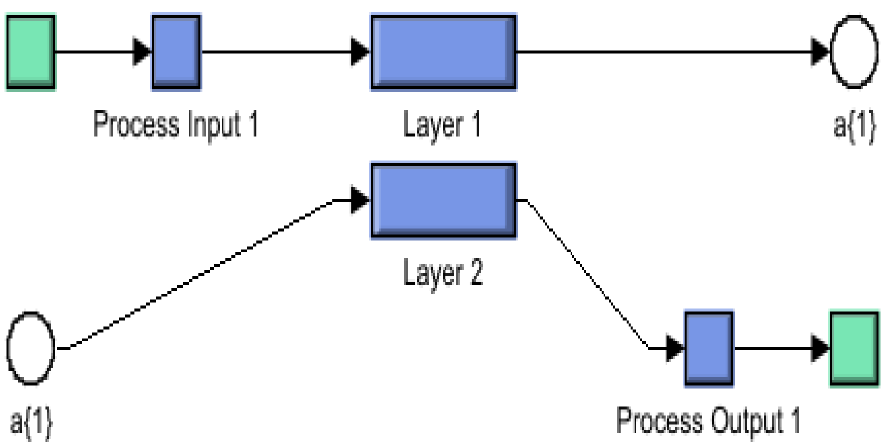


Figure 7: AI dynamics and hidden layer

Figure 7 shows the Artificial neural network of the active suspension system and the shows that there is single input and single output in this system and the hidden layers are 2.

EXPERIMENTAL SETUP:

The experimental setup of the quarter vehicle passive and active suspension system is done in Simulink and then the output response is checked with and without controlling forces at different input speed for different road input cases.

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The figure for passive quarter vehicle suspension system is given below:

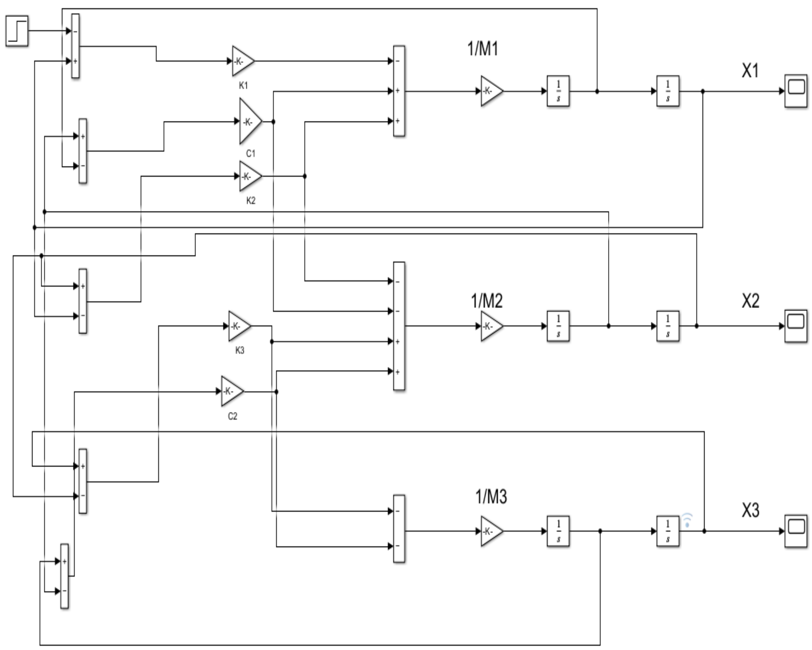

Figure 8: Simulink Model of Passive Vehicle Suspension System

The Simulink model for the active quarter vehicle suspension system is given in the figure below:

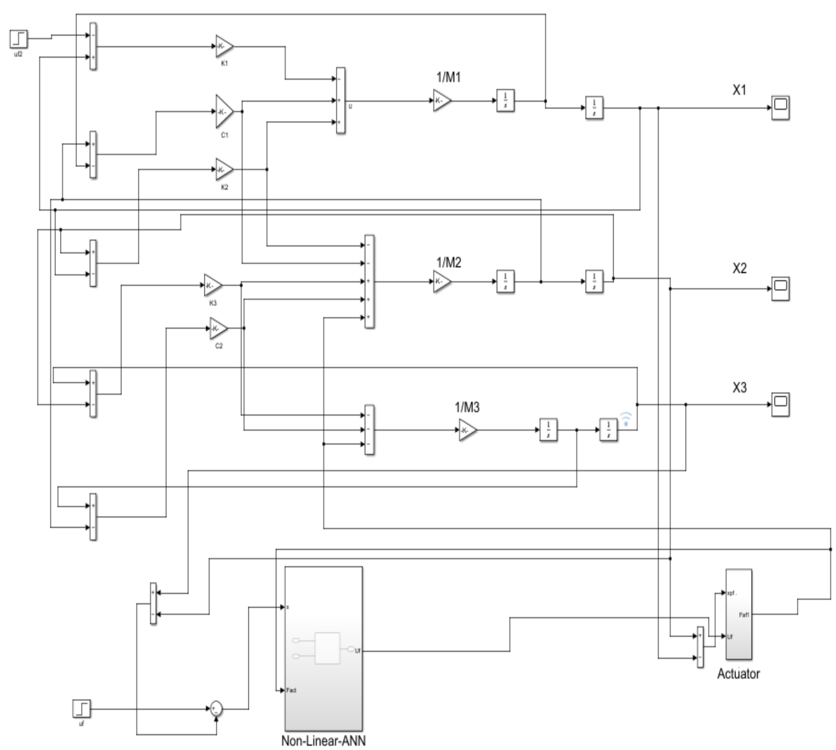

Figure 9: Active vehicle suspension system

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The active vehicle suspension system consist of un-sprung Mass, Sprung Mass and Seat along with the Driver's or Passenger's mass, actuator and Non Linear Controller. Below figure 10 shows the Artificial Intelligence based Non Linear Controller designed in this research.

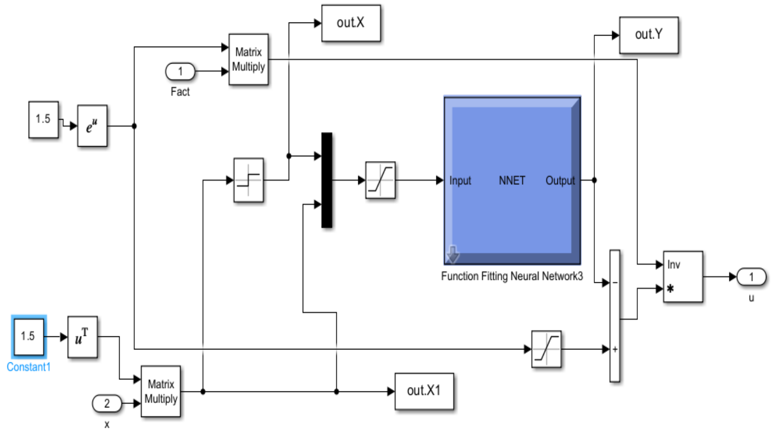


Figure 10: Artificial Neural Network based Non Linear Controller

The system parameters are given in table below:

Parameters	Symbol	Values	Unit
Unsprung mass of Axle	M1	87.15	Kg
Sprung mass of vehicle Chassis	M2	897.5	Kg
mass of the seat and passenger	M3	125	Kg
stiffness of tyre	K1	120	KN/m
stiffness of seat	K3	5000	N/m
Damping coefficient of seat	C2	1000	Ns/m
Spring constant of axle	K2	36350	N/m
Damping coefficient of axle	C1	1200	Ns/m
Input (road excitation)	U(t)		

All the above values for both the suspension systems for Simulink model are taken from (J.A.Calvo, 2005), (Ammar Majid Hameed Al-Ghanim, 2016) and these values are of the Mercedes-Benz S- Class Saloon E.

RESULTS AND DISCUSSIONS:

Result of PSS and ASS for step AS Road input to wheel at speed of 20Km/hr

The response of the active and passive suspension systems is verified by using two different road cases.

Case 1: No Off-Roading Case

Step input is taken as the road input for the no off-roading case. In this case the vehicle is following a straight road road and there is almost no disturbance in this road. The results for both active vehicle suspension system and passive vehicle suspension system for the step input are checked for different speeds such as 20km/hr, and 80km/hr.

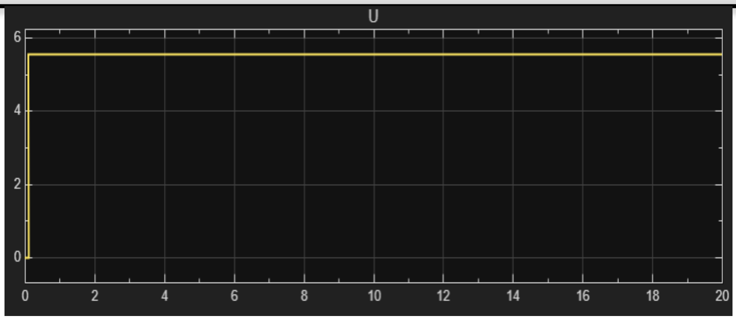


Figure 11: Step input as road input

The above figure shows that a step input is given as a road reference for the vehicle at 20km/hr.

Case 2: Off-Roading Case

Random Road Input

A random road input is taken as an off-roading case where the road has a lot of disturbances and this road profile is taken from [12].

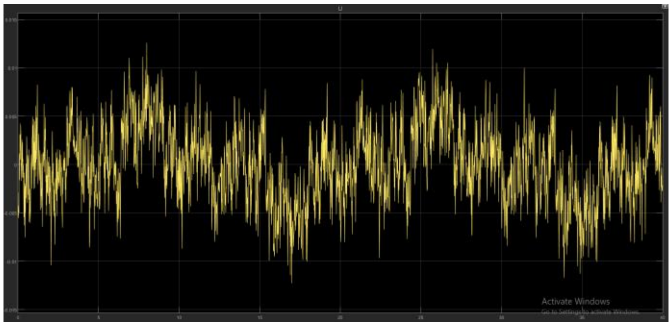


Figure 12: Random input as road input

The vehicle response has been checked for both active and passive system for case 1 and 2 and at different speeds of 20km/hr and 40km/hr.

Passive Vehicle Suspension System:

The seat response of passive suspension system is checked at different speeds and then compare between the overshoot, undershoot and settling time responses of both the systems.

For step input:

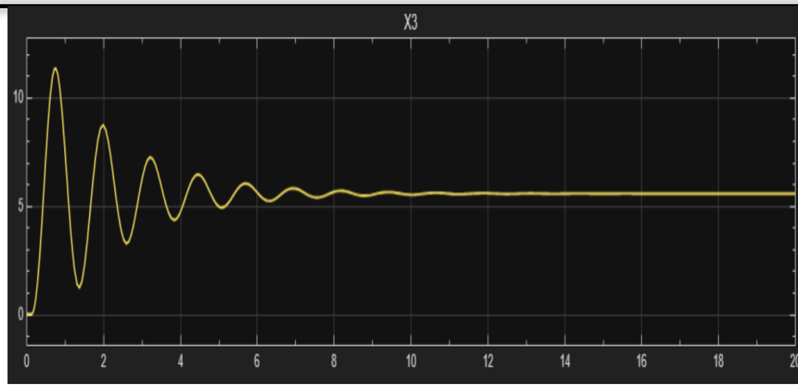


Figure 13: Seat Response at 20km/hr

The figure 13 above shows the seat response of a passive suspension system when the speed is 20km/hr. The overshoot, undershoot and settling time is almost 42.15%, 46.77% and 14s respectively. The input reference for this road is no Off-road or a strai
ght road.

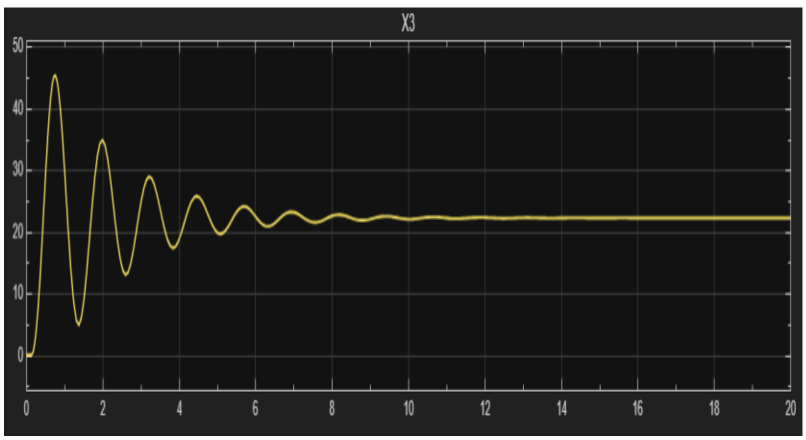


Figure 14: Seat Response at 80km/hr

The figure 14 shows the seat response of a passive suspension system when the speed is 80km/hr. The input for this road is No-Off-road case. The overshoot, undershoot and settling time is almost 58.24%, 39.65% and 14s respectively.

For Random Road Input:

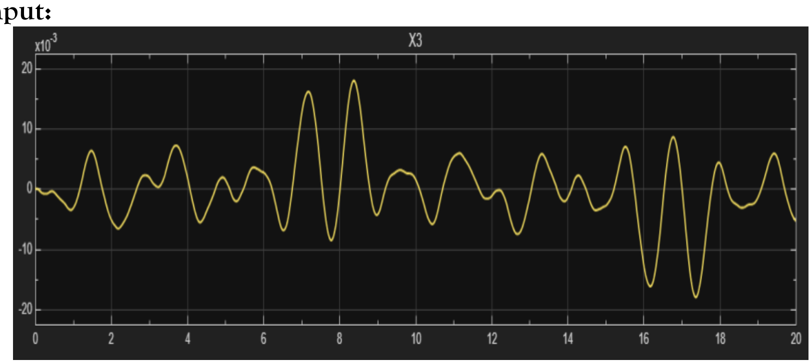


Figure 15: Seat Response at 20km/hr

Figure 15 shows the seat response of a passive suspension system when the speed is 20km/hr and the road is considered as a random road or this is an Off-roading case. The seat response shows that overshoot is 106.3023 , undershoot is 116.9973 and settling time 17.034s respectively.

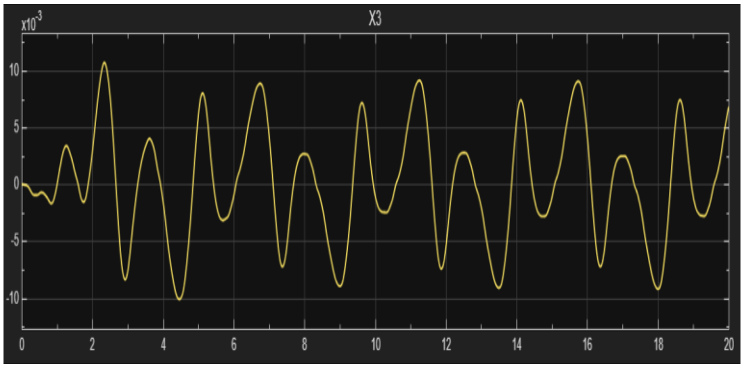


Figure 16: Seat response at 80km/hr

The above figure 16 shows the seat response of a passive suspension system for and off-roading case when the speed is 80km/hr. The seat response shows that overshoot is 113.32%, undershoot is 124.20% and settling time 17.75s respectively.

Table 01: Passive Suspension System Dynamics For Off Roading And No Off Roading Cases:

Seat response for the PASSive Suspension System for No-Off Roading And Off-Roading Road INPUTs			
Speed VariatIon	Over-shoot	Under-shoot	Settling time
Case1 no-OFF-ROADING			
20km/hr	42.15%	46.77%	14s
80km/hr	58.24%	39.65%	14s
CASE 2 OFF-ROADING			
At 20km/hr	106.3023%	116.9973%	17.034s
At 80km/hr	113.32%	124.20%	17.75s

Table 1 above shows the overshoots, undershoots and settling time of a passive suspension system when the speeds are varied such as at 20km/hr and 80km/hr.

Active Suspension System:

The seat response of the active vehicle suspension system is checked and then the vehicle dynamics are noted for both off-road and No-off road at the speeds of 20km/hr and
80km/hr.

For Step Input:

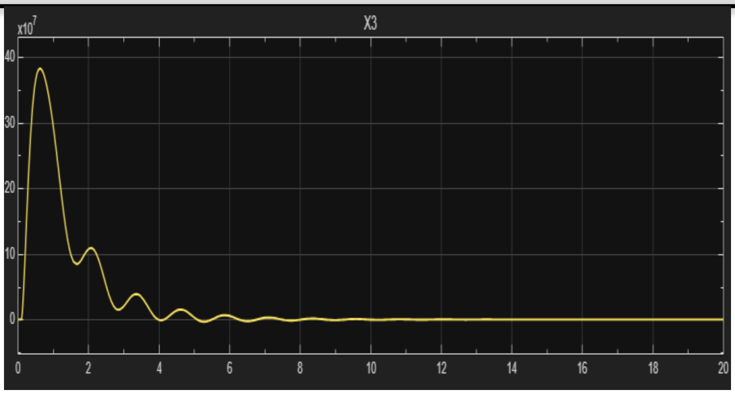


Figure 17: Seat response at 20km/hr

The figure 17 shows the seat response of an active quarter vehicle suspension system for No-off-roading case when the speed is 20km/hr. The seat response shows that overshoot is 1.997%%, undershoot is 4.85% and settling time 7.34s. This response shows more stable dynamics than the passive suspension system.

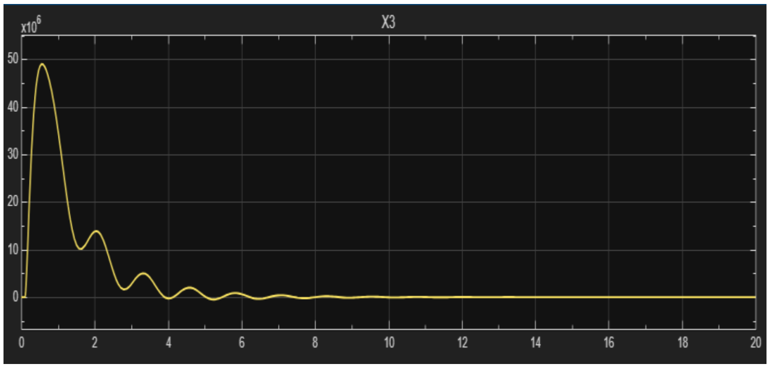


Figure 18: Seat response at 80km/hr

The figure 18 shows the seat response of an active quarter vehicle suspension system for the No-off-roading case when the speed is 80km/hr. The seat response shows that overshoot, undershoot and setteling time is almost 1.01%, 6.15% and 7.34s respectively.

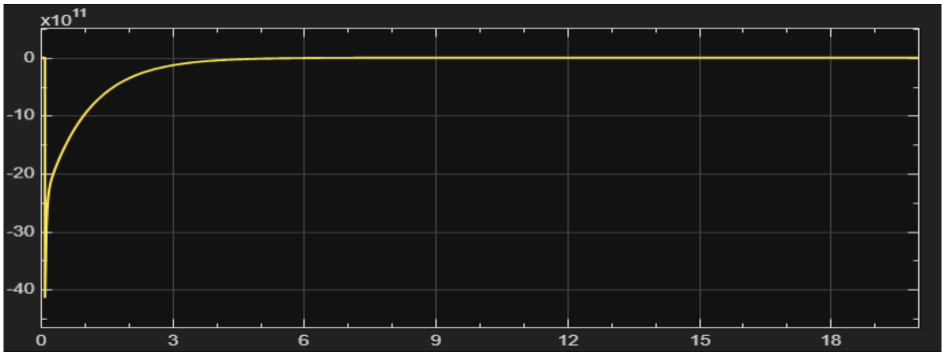
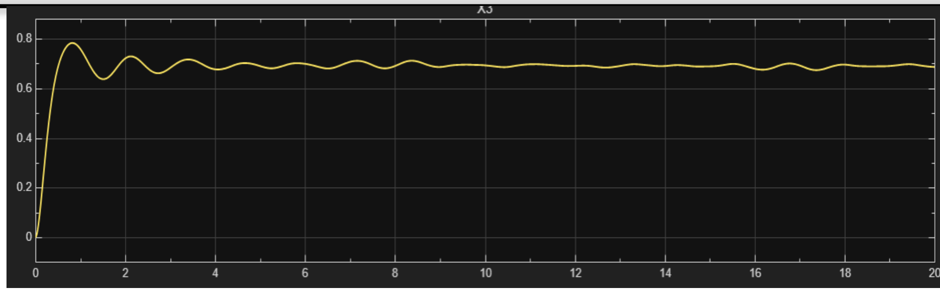


Figure 19: Controlling Force Response At Step Input

The above figure 19 shows the response of the actuator which is used for controlling force. The actuator is basically used along with the AI based non-linear controller to control the non-linear dynamics in the system.



Off-Roading Case:

Figure 20: Seat response at 20km/hr

The above figure 20 shows the seat response of an active quarter vehicle suspension system for the Off-roading case when the speed is 20km/hr. The seat response shows that overshoot is 13.0682%, undershoot is 8.043% and settling time is and 11.03s. The active vehicle system response is stable and robust as compared to the passive suspension system response as shown in the figure 17 for Off-roading case.

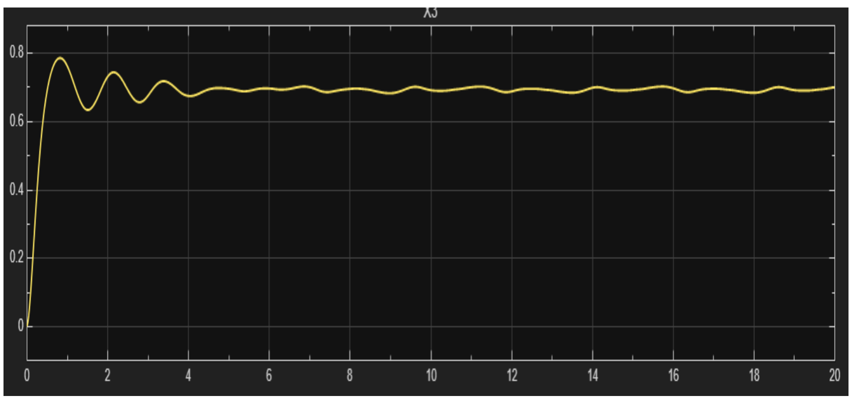


Figure 21: Seat response at 80km/hr

The above figure 21 shows that the seat response of an active quarter vehicle suspension system for the Off-roading case when the speed is 80km/hr. The seat response shows that overshoot is 13.0682%, undershoot is 8.9296% and settling time is and 11.11s.

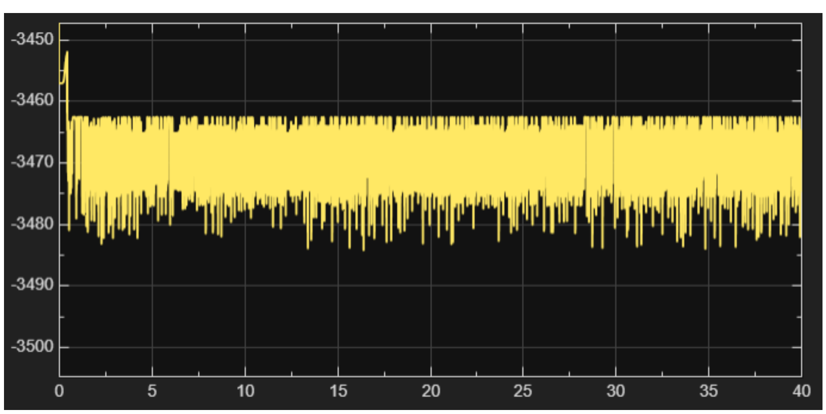


Figure 22: Controlling Force Response At Step Input

The above figure 22 shows the response of the actuator for the off-roading case. The actuator used along with controller controls the non-linear and unstable dynamics of the system.

Table 02: Active Suspension System Dynamics For Off Roading And No Off Roading Cases:

Seat response for the Active Suspension System for No-Off Roading And Off-Roading Road INPUTs			
Speed Variation	Over-shoot	Under-shoot	Settling time
CASE1: no OFF-ROADING			
At 20km/hr	1.997%	4.85%	7.34s
At 80km/hr	1.01%	6.06%	7.46s
CASE2: OFF ROADING			
At 20km/hr	13.0682%	8.0430%	11.03s
At 80km/hr	13.0682%	8.9296%	11.11s

By comparing the passive and active suspension system and checking results for different road cases, it is noted that the results for the active suspension system is more stable than that for the passive suspension system.

For Case 1:

In this case the road is considered to be a straight road and there is no off roading condition involved here so the step input is taken as the road input for this case. The overshoot for the step input for passive suspension system at 20km/hr is almost 42%, the undershoot is 46.77% and the settling time for this system is 34s and for active suspension system the values becomes almost 2%, 4.85% and 9.34s respectively. Now, when the speed is increased and is 80km/hr, the overshoot, undershoot and settling time for passive suspension system 58.2%, 39.65% and 34s and for active suspension system these values reduced to almost 1.01%, 6.06% and 9.46s respectively.

For Case 2:

This is off roading case in which the road is considered to have many disturbances and different points and the road input has infinite spikes which shows the disturbances in the road profile. The overshoot, undershoot and settling time for this case for passive suspension system at 20km/hr is almost 106%, 116% and 36.034s and for active suspension system these values reaches 13.0682%, 8.043% and 13.03s respectively. Similarly at 80km/hr the values for overshoot, undershoot and settling time for passive suspension system is 113.32%, 124.2% and 36.75s and for active suspension system these values becomes almost 13.0682%, 8.9296% and 13.11s respectively.

By comparing both the active and passive vehicle suspension systems, it is noted that the results for active vehicle suspension system along with AI based non-linear controller is stable than passive vehicle suspension system and the active vehicle suspension system shows robustness at speeds of 20km/hr and 80km/hr for both the off roading and no-off roading cases.

The above figures; Figure 21 and Figure 24 shows the actuator response which along with the controller controls the non-linear dynamics of the system and stabilize the system. The actuator is used to control the unstable system dymaics and make the system more stabilized and robust.

CONCLUSION:

This research has improved vehicle stability and ride comfort by developing a quarter-vehicle active suspension system using Artificial intelligence based non-linear controller. This system has mitigated road disturbances and improved the suspension system performance by utilizing a 3 degree-of-freedom model to address heave motion and the vehicle system is checked on both off-roading and no-off-roading cases at different speeds for active and passive vehicle suspension system. The active and passive systems are compared for both the cases and the active systems shows that the overshoot, undershoot and of the vehicle seat is reduced in active vehicle and has more stable and robust response which ensures the ride comfort, vehicle stability and robustness in this system. By comparing both the systems, it is concluded that active vehicle suspension system is more stable as compared to the passive suspension system. The results are checked for both the cases, Case 1 is considered as No off roading case and case 2 as Off Roading case. Results shows that active suspension system for No-Off-Roading case shows more stable and robust response than the active suspension system for the Off-Roading case at the speeds of 20km/hr ans 80km/hr. Hence this shows a stable and robust however this can be further improved by using an adaptive controller in the future.

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