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Optimization of State Feedback Controller using Artificial Bee Colony for Half-Car Suspension System

Mohd Fairus Abdolah[1], **Hairol Nizam Mohd Shah**[2], **Mohd Zamzuri Ab Rashid**[3], **Hyreil Anuar Kasdirin**[4], **Muhammad Evy Firdaus Mohd Zamri**[5]
[1,2,3,4,5]Centre for Robotics and Industrial Automation (CeRIA), Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia,
Email: mfairus@utem.edu.my

ABSTRACT

In general, a suspension system is a of the car. It sustains the vehicle weight on the road, maintain the tire-to-ground contact, diminish the influence of road irregularities, and at the same time provide ride comfort to the passenger. All these criteria are conflicting among each other, and a compromise between the road holding, load carrying, and passenger comfort is an inevitable for a passive suspension system. However, with active suspension system, these criteria can be achieved within acceptable performance. In this paper, a half-car active suspension system under the influence of an impulse road disturbance is discussed. A full state-feedback controller optimized by Artificial Bee Colony (ABC) algorithm is used to improve the road holding and ride comfort of the passengers. The performance of this controller is compared with conventional state feedback controller and determined by performing computer simulations using Matlab/Simulink software.

Key words : Active suspension system, Artificial Bee Colony, full state feedback, half-car system,.

1. INTRODUCTION

In this new era of technology, the automotive industry is now focusing on passenger safety and comfort. Thus, the suspension system plays a vital role to provide the ride comfort to the passengers by isolating the cabin from various road disturbances. The suspension system generally can be categorized into passive, semi-active and active suspension system. The passive suspension system uses conventional springs and dampers to store and dissipate the energy produced by the road disturbances. The design parameters are generally fixed thus leads to the trade-off between the ride comfort and road handling. The semi-active suspension system uses the conventional spring and externally controlled damper. Here, the damping coefficient is controlled based on the inputs from chassis acceleration sensor that measures the vertical acceleration of the vehicle's body. The active suspension system, however, use force actuators elements in a closed loop control system alongside with the passive suspension system. Based on the input from the various sensors that are associated with it, the force actuator provides adequate control force to the system. One of the advantages of this system is a wider range of control force and zero force-velocity constraints are available. Due to this, many researchers have proposed various control systems to enhance the active suspension system performance [1]–[6].

Passengers are the most important features of reliability when designing the suspension of the car includes comfort, motion, road handling and suspension operation [7]. The acceleration of the passenger was used as a measure of ride comfort. Travel and motion are the conditions of the suspension system, while tire deflection is linked to road handling. The purpose of using state feedback controller in half-car suspension system is to optimize the stability of the system response and to suppress the vibrations generated from the road unevenness. Through state feedback controller it also will improve the transient response and reduce settling time for the system. The derivative is taken from the output response of the device variable instead of the error signal to prevent the shift value of the error signal. A linear system of p inputs, q outputs and n state variables are written in the most general state space representation as follows:

$$\dot{x} = Ax + Bu \tag{1}$$
$$y = Cx + Du \tag{2}$$

where *x* is the state vector, *y* is the output vector, *u* is the input (or control) vector, *A* is the state matrix, *B* is the input matrix, *C* is the output matrix and *D* is the feed through or feed forward matrix. *D* is often chosen as the zero matrix for simplicity, i.e. the system is chosen not to feed directly through it.

Real-world optimization problems are largely hard to solve and contains high degrees of uncertainties. Solving such problems using conventional optimization algorithms leads to complex computational process. Thus, to find a solution for such problems many researchers has turns their interest to a meta-heuristic algorithm. A host of such algorithms have been developed namely Genetic Algorithms (GA) [8]–[11], Artificial Neural Network (ANN) [12]–[14] and Particle Swarm Optimization (PSO) [15]–[19]. These algorithms are well-equipped with their stochastic means to tackle such problems. Other algorithms that was developed by Karaboga in 2005 is the Artificial Bee Colony (ABC) algorithm. ABC is an optimization algorithm based on honeybee foraging's intelligent behavior. The invention is based on model of self-organization as well as method of calculation are based on swarm capabilities. A colony of honeybees may spread over a long distance and at the same time it accesses many food sources. Compared to other similar evolutionary algorithms, ABC has some attractive features and, in many cases, it proved to be more successful and have superior computational efficiency [20]. In addition, ABC uses no gradient-based information. It implements a versatile and well-balanced framework to adapt to the global and local exploration and exploitation within a short computation time. Therefore, this approach is useful in managing large and complex search spaces.

The design on half-car active suspension system employs the full state feedback controller optimized through ABC algorithm. The designed controller will improve the road holding and the ride quality of the passenger under the influence of road bumps as road disturbance.

2. VEHICLE SUSPENSION MODEL

In this section, the mathematical model of the half-car active suspension system is presented. Figure 1 shows the free body diagram of the system along with all the contact forces acting on the vehicle body and wheels. The model and parameters which was discussed in [21] are presented here and can be referred to Table 1.An equation of motion can be easily built from the model's free body diagram. The design can then be passed from this equation of motion to the Matlab/Simulink framework for simulation phase. The equations of motion for the half-car active suspension system can be developed as follows:

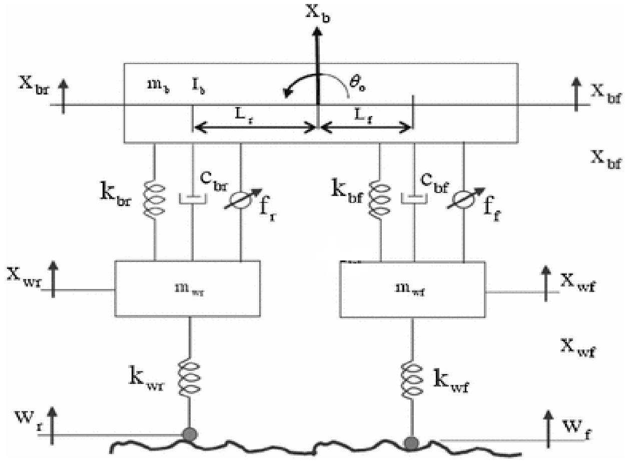

Figure 1: Half-Car Active Suspension System

Table 1: Parameter values for half-car active suspension system

Parameter	Value (unit)
Mass of car body, m_b	1794.4 (*kg*)
Moment of inertia of car body, I_b	3443.05 (*kgm*^{2})
Mass of the front wheel, m_{wf}	87.15 (*kg*)
Mass of the rear wheel, m_{wr}	140.04 (*kg*)
Stiffness of the front car body spring, k_{bf}	66824.2 (*N/m*)
Stiffness of the rear car body spring, k_{br}	18615 (*N/m*)
Stiffness of the front car tire, k_{wf}	1011115 (*N/m*)
Stiffness of the rear car tire, k_{wr}	1011115 (*N/m*)
Damping of the front car damper, c_{bf}	1190 (*Ns/m*)
Damping of the rear car damper, c_{br}	1190 (*Ns/m*)
Rotary angle car body at centre of gravity, θ_0	(*rad*)
Displacement of the car body at centre of gravity, x_b	(*m*)
Front body and wheel displacement, x_{bf} and x_{wf}	(*m*)
Rear body and wheel displacement, x_{br} and x_{wr}	(*m*)
Front and rear wheel displacement input, w_f and w_r	(*m*)
Front and rear actuator force input, f_f and f_r	(*N*)
Distance of the front and rear suspension location with reference to the centre of gravity of the car body, L_f and L_r	(*m*)

$$\begin{aligned} &m_b\ddot{x}_b + c_{bf}(\dot{x}_{bf} - \dot{x}_{wf}) + k_{bf}(x_{bf} - x_{wf}) \\ &\quad + c_{br}(\dot{x}_{br} - \dot{x}_{wr}) + k_{br}(x_{br} - x_{wr}) - f_f - f_r = 0 \end{aligned} \tag{3}$$

$$\begin{aligned} &I_b\ddot{\theta}_o + L_f[c_{bf}(\dot{x}_{bf} - \dot{x}_{wf}) + k_{bf}(x_{bf} - x_{wf}) - f_f] \\ &\quad - L_r[c_{br}(\dot{x}_{br} - \dot{x}_{wr}) + k_{br}(x_{br} - x_{wr}) - f_r] = 0 \end{aligned} \tag{4}$$

$$\begin{aligned} &m_{wf}\ddot{x}_{wf} - c_{bf}(x_{bf} - x_{wf}) - k_{bf}(x_{bf} - x_{wf}) \\ &\quad + k_{wf}(x_{wf} - w_f) + f_f = 0 \end{aligned} \tag{5}$$

$$\begin{aligned} &m_{wr}\ddot{x}_{wr} - c_{br}(x_{br} - x_{wr}) - k_{br}(x_{br} - x_{wr}) \\ &\quad + k_{wr}(x_{wr} - w_r) + f_r = 0 \end{aligned} \tag{6}$$

The constraints are:

$$x_b = \frac{(L_f x_{bf} - L_r x_{br})}{L} \tag{7}$$

$$\theta_o = \frac{(x_{bf} - x_{br})}{L} \qquad (8)$$

Therefore, substitute (7) and (8) into (3) and (4) yield,

$$\frac{m_b(L_f\ddot{x}_{bf} - L_r\ddot{x}_{br})}{L} + c_{bf}(\dot{x}_{bf} - \dot{x}_{wf}) + k_{bf}(x_{bf} - x_{wf}) + c_{br}(\dot{x}_{br} - \dot{x}_{wr}) + k_{br}(x_{br} - x_{wr}) - f_f - f_r = 0 \qquad (9)$$

$$\frac{I_b(\ddot{x}_{bf} - \ddot{x}_{br})}{L} + L_f[c_{bf}(\dot{x}_{bf} - \dot{x}_{wf}) + k_{bf}(x_{bf} - x_{wf}) - f_f] - L_r[c_{br}(\dot{x}_{br} - \dot{x}_{wr}) + k_{br}(x_{br} - x_{wr}) - f_r] = 0 \qquad (10)$$

The state space equation can be written as follow:

$$\dot{x} = A_{al}x_{al} + B_{al}u_{al} + G_{al}W_{al} \qquad (11)$$

where,

$$x_{al} = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \quad x_7 \quad x_8]^T = [\dot{x}_{bf} \quad \dot{x}_{wf} \quad \dot{x}_{br} \quad \dot{x}_{wr} \quad x_{bf} \quad x_{wf} \quad x_{br} \quad x_{wr}]^T$$

$$A_{al} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & a_{17} & a_{18} \\ a_{21} & a_{22} & 0 & 0 & a_{25} & a_{26} & 0 & 0 \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} & a_{37} & a_{38} \\ 0 & 0 & a_{43} & a_{44} & 0 & 0 & a_{47} & a_{48} \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B_{al} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & 0 \\ b_{31} & b_{32} \\ 0 & b_{42} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad G_{al} = \begin{bmatrix} 0 & 0 \\ g_{21} & 0 \\ 0 & 0 \\ 0 & g_{42} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$u_{al} = [f_f \quad f_r]^T, \quad W_{al} = -\begin{bmatrix} w_f \\ w_r \end{bmatrix}$$

where the non-zero elements of A_{al}, B_{al} and G_{al} matrices are:

$$a_{11} = -\frac{c_{bf}}{m_b} - \frac{L_f{}^2 c_{bf}}{I_b}, \qquad a_{12} = \frac{c_{bf}}{m_b} - \frac{L_f{}^2 c_{bf}}{I_b},$$

$$a_{13} = -\frac{c_{br}}{m_b} - \frac{L_f L_r c_{bf}}{I_b}, \qquad a_{14} = \frac{c_{br}}{m_b} - \frac{L_f L_r c_{br}}{I_b},$$

$$a_{15} = -\frac{k_{bf}}{m_b} - \frac{L_f{}^2 k_{bf}}{I_b}, \qquad a_{16} = \frac{k_{bf}}{m_b} + \frac{L_f{}^2 k_{bf}}{I_b},$$

$$a_{17} = -\frac{k_{br}}{m_b} - \frac{L_f{}^2 k_{br}}{I_b}, \qquad a_{18} = \frac{k_{br}}{m_b} + \frac{L_f{}^2 k_{br}}{I_b},$$

$$a_{21} = \frac{c_{bf}}{m_{wf}}, \qquad a_{22} = -\frac{c_{bf}}{m_{wf}},$$

$$a_{25} = \frac{k_{bf}}{m_{wf}}, \qquad a_{26} = -\frac{(k_{bf} + k_{wf})}{m_{wf}},$$

$$a_{31} = -\frac{c_{bf}}{m_b} + \frac{L_f L_r c_{bf}}{I_b}, \qquad a_{32} = \frac{c_{bf}}{m_b} - \frac{L_f L_r c_{br}}{I_b},$$

$$a_{33} = -\frac{c_{br}}{m_b} - \frac{L_f{}^2 c_{br}}{I_b}, \qquad a_{34} = \frac{c_{br}}{m_b} + \frac{L_f{}^2 c_{br}}{I_b},$$

$$a_{35} = -\frac{k_{bf}}{m_b} + \frac{L_f L_r k_{bf}}{I_b}, \qquad a_{36} = \frac{k_{bf}}{m_b} - \frac{L_f L_r k_{bf}}{I_b},$$

$$a_{37} = -\frac{k_{br}}{m_b} - \frac{L_r{}^2 k_{br}}{I_b}, \qquad a_{38} = \frac{k_{br}}{m_b} + \frac{L_r{}^2 k_{br}}{I_b},$$

$$a_{43} = \frac{c_{br}}{m_{wr}}, \qquad a_{44} = -\frac{c_{br}}{m_{wr}},$$

$$a_{47} = \frac{k_{br}}{m_{wr}}, \qquad a_{48} = -\frac{(k_{br} + k_{wr})}{m_{wr}},$$

$$b_{11} = \frac{1}{m_b} + \frac{L_f{}^2}{I_b}, \qquad b_{12} = \frac{1}{m_b} - \frac{L_f L_r}{I_b},$$

$$b_{21} = -\frac{1}{m_{wf}}, \qquad b_{31} = \frac{1}{m_b} - \frac{L_f L_r}{I_b},$$

$$b_{32} = \frac{1}{m_b} + \frac{L_r{}^2}{I_b}, \qquad b_{42} = -\frac{1}{m_{wr}},$$

$$g_{21} = \frac{k_{wf}}{m_{wf}}, \qquad g_{42} = \frac{k_{wr}}{m_{wr}}$$

The half car active and passive suspension system model and control systems have been developed using Matlab/Simulink tool. Figure 2 shows the Simulink model for the half-car active suspension system.

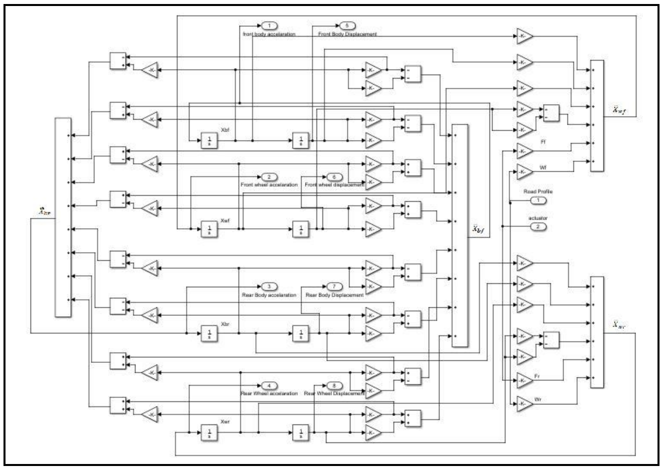

Figure 2: Block Diagram of Half-Car Active Suspension System

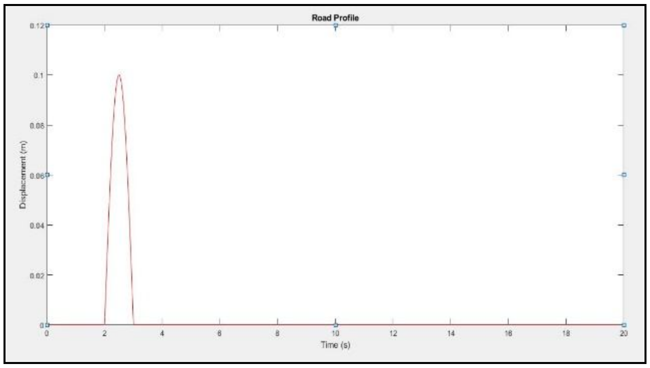

Figure 3: Road Disturbance

The performance of the active suspension system is analyzed subject to road disturbance as given by the following equations:

$$y(t) = \begin{cases} 0.1\sin(\pi t), & 2 < t \leq 3 \\ 0, & \text{otherwise} \end{cases} \tag{12}$$

This bump is 0.1 m height and is shown in Figure 3. This disturbance is applied to both of front and rear wheel displacement input, w_f and w_r, respectively.

3. CONTROLLER DESIGN

In the first section of this chapter, the state-feedback controller will be briefly stated and later, the algorithm of the artificial bee colony will be discussed to optimize the state-feedback controller.

3.1 State-Feedback Controller

State feedback controller in half-car active suspension system is to ensure the stability of the system response and to suppress the vibrations generated from the road unevenness. The controller also will improve the transient response and reduce settling time for the system.

Choosing the control signal, *u*=-*Kx* where *K* is the state feedback gain matrices. By substituting this control signal in in state equation, the following is obtained:

$$\dot{x} = A - BK \tag{13}$$

Through the ABC algorithms, the location of the optimized poles is searched within the allocated search space and by using the Matlab function ‘place’, the values for *K* can be calculated.

3.2 Artificial Bee Colony (ABC) Algorithm

ABC algorithm is based on the foraging behavior of honeybee’s colony. The colony is divided into three groups: (i) employed bees, (ii) onlookers and (iii) scouts. The employed bees search a food sources and make a local searching for a better food source in the neighborhood. The quality of food source corresponds to the fitness value. If a better food source is found, the employed bee forgets the old position and memorizes a better one. When the local searching process is completed, information about quality of all food sources is shared between employed bees and onlookers. At this stage, the probability is also employed to decide if a food source may be used by onlooker bee. The last group of bees (i.e. scouts) is responsible for random search for a new food source. The employed bee becomes scout when the food source is exhausted. The food source must be abandoned by employed bee if a better solution associated with it cannot be found in a predetermined number of attempts. It should be noted that search process is divided into local and global stages. The first one is realized by employed bees and, after sharing information, by onlookers, while the second stage is made by scouts. The pseudo code of employed bee phase, onlooker bee phase pseudo-code and pseudo-code of ABC algorithm for scout bee phase are given below.

Pseudo code of employed bee phase of ABC algorithm

```
for $i = 1$ to $\frac{sn}{2}$ do
    for $j = 1$ to D do
        Produce a new food source $\vec{v}_i$ for the employed bee of the food source $\vec{x}_i$ by using (14)

        $v_{ij} = \begin{cases} x_{ij} + \phi_{ij}(x_{ij} - x_{kj}), & if R_j < MR \\ x_{ij}, & otherwise \end{cases}$        (14)

        where $k \in \{1, 2, \ldots, sn\}$ is randomly chosen index that
        has to be different from $i$ and $\phi_{ij}$ is uniformly
        distributed random real number in the range of
        [−1,1]. $R_j$ is uniformly distributed random real
        number in the range of [0,1] and MR is a control
        parameter of ABC algorithm in the range of [0,1]
        which controls the number of parameters to be
        modified.
    end for
    If no parameter is changed, change one random parameter of the solution $\vec{x}_i$ by (15)

        $v_{ij} = x_{ij} + \phi_{ij}(x_{ij} - x_{kj})$        (15)

    where $j$ is uniformly distributed random integer number in the range [1, D].
    Evaluate the quality of $\vec{v}_i$
    Apply the selection process between $\vec{v}_i$ and $\vec{x}_i$ based on Deb’s method
    If solution $\vec{x}_i$ does not improve $failure_i = failure_i + 1$, otherwise $failure_i = 0$
end for
```

Pseudo-code for onlooker bee’s phase

```
t = 0, i = 1
repeat
  if random < $p_i$ then
    $t = t + 1$
    for $j = 1$ to D do
      Produce a new food source $\vec{V}_i$ for the onlooker bee
      of the food source $\vec{X}_i$ by using (14)
    end for
    Apply the selection process between $\vec{V}_i$ and $\vec{X}_i$ based
    on Deb’s method
    If solution $\vec{X}_i$ does not improve
    $failure_i = failure_i + 1$, otherwise $failure_i = 0$
  end if
  $i = i + 1$
  $i = i \, mod\left(\left(\frac{sn}{2}\right) + 1\right)$
until $t = \frac{sn}{2}$
```

Pseudo-code for scout bee phase of ABC algorithm

```
if cycle mod SPP = 0 then
  if max($failure_i$) > limit then
    Replace $\vec{X}_i$ with a new randomly produced solution
    by (2)
  end if
end if
```

The number of colony size, *NP* (i.e. sum of employed and onlooker bees) is recognized as a main parameter of ABC optimization algorithm. The number of food sources *FN* is usually set as the half of *NP*. The optimized parameters (coefficients of penalty matrices in this case) are represented by a *D*-dimensional vectors, each associated with the food source. Coefficients of *D* are limited by manually selected constraints named the lower, *lb* and the upper, *ub* bounds. Leaving the food source depends on control parameter called limit. It defines the number of attempts that should be done by employed bee to find a better food source, before it may leave considered source and becomes scout. The flowchart is illustrating the working of ABC algorithm is shown in Figure 4.

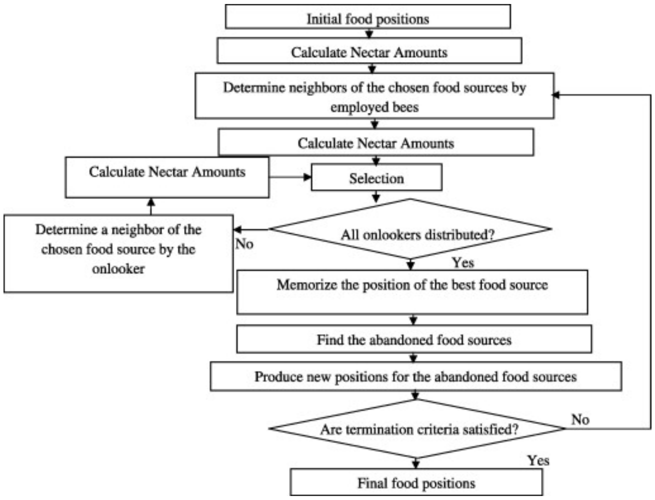

Figure 4: The Flowchart of ABC Algorithm

The implementation of ABC uses the number of population size is set to 50, the number of maximum iterations is 100, and the limit upper and lower boundary is -300 to 300. To implement the algorithm, *D* is set to 16 is assigned to represent sixteen variables of gain for controller.

4. RESULTS AND DISCUSSION

The outcomes are presented in terms of controller input and body acceleration. Details results and discussion will be discussed in the following section.

4.1 Controller Input

The force of actuator is between the body and the wheel of car in which the road disturbance can be actively cancelled, thus will improve ride comfort. The controller that being applied in this suspension system is similar to the force input. The force is divided in to two part which is front and rear. For the front part as shown in Figure 5, this system requires 3254 N force to control the actuator while for rear part of the car, as shown in Figure 6, requires about 2954 N of force.

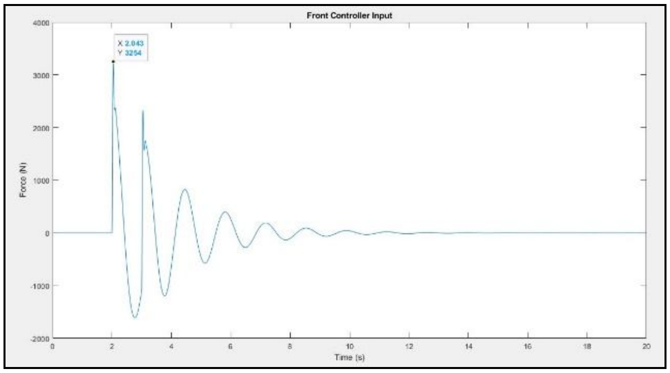

Figure 5: Front Controller Input

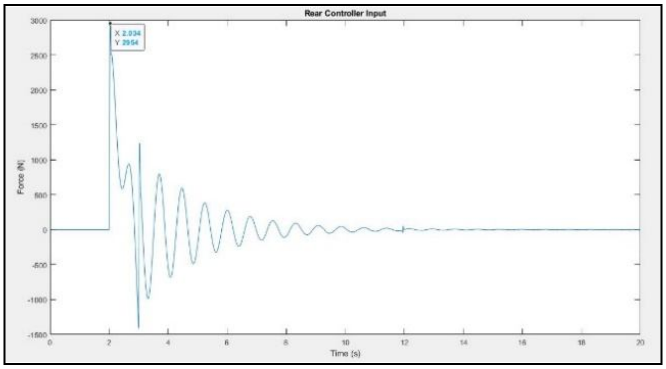

Figure 6: Rear Controller Input

4.2 Body Acceleration

To ensure better comfort of ride and handling of the road the car body reaction must always be controlled. Body acceleration shows if the system is responding well in terms of the car’s trajectories. This acceleration of the body must be reduced. Figure 7 and 8 below show the results for the front body acceleration of conventional State Feedback Controller and optimized State Feedback Controller while Figure 9 and 10 for the rear body acceleration.

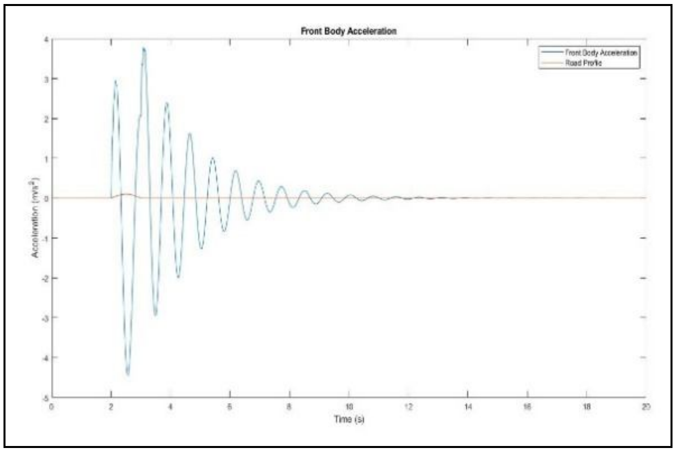

Figure 7: Front Body Acceleration of Conventional State Feedback Controller

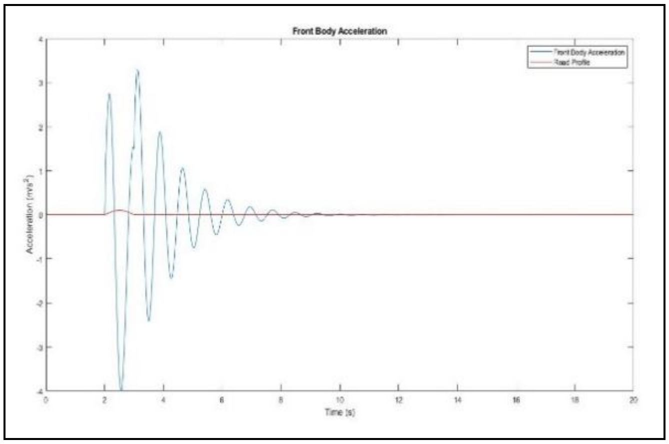

Figure 8: Front Body Acceleration of Optimized State Feedback Controller

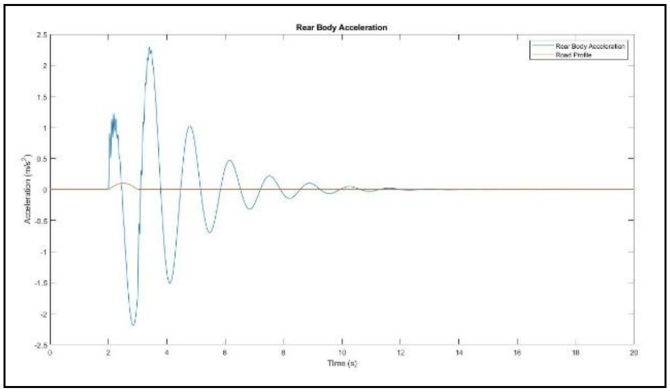

Figure 9: Rear body Acceleration of Conventional State Feedback Controller

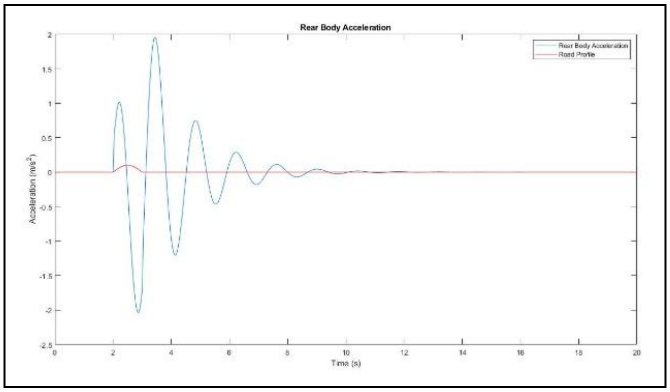

Figure 10: Rear Body Acceleration of Optimized State Feedback Controller

From Figure 7, the front body acceleration for conventional state feedback controller is 3.85 ms^{-2} while for optimized state feedback controller (Figure 8) is 3.3 ms^{-2}. This show that by using the optimized state feedback controller, the front body acceleration is reduced. The settling time of the front body acceleration for conventional state feedback controller is worst where the system takes more than 12 s for the car to isolate the vibration causes by the road disturbance compared to the optimized state feedback controller.

In Figure 9, the rear body acceleration for conventional state feedback controller is 2.35 ms^{-2} while the result in Figure 10 that applied the optimized controller is 1.95 ms^{-2}. It shows that the acceleration is reduced when applying the optimized state feedback controller. By reducing both the rear and front body acceleration of the car, this can provide comfort to the passenger and retaining the characteristic of road handling.

5. CONCLUSION

In this paper, the optimized state feedback controller by using Artificial Bee Colony algorithm for the half-car active suspension system is designed to improve the ride comfort and road holding ability. Under the influence of a road disturbance, the controller able to show improvement as compared to the conventional state feedback controller.

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