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Vibration Control of Semi-Active Suspension System using Modified Skyhook with Advanced Firefly Algorithm

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Abstract. The semi-active suspension (SAS) system is a partial suspension device used in the vehicle system to improve the ride comfort and road handling. Due to the high non-linearity of the road profile disturbances plus uncertainties derived from vehicle dynamics, a conventional Skyhook controller is not deemed enough for the vehicle system to improve the performance. A major problem of the implementation of the controller is to optimize a proper parameter as this is an important element in demanding a good controller response. An advanced Firefly Algorithm (AFA) integrated with the modified skyhook (MSky) is proposed to enhance the robustness of the system and thus able to improve the vehicle ride comfort. In this paper, the controller scheme to be known as MSky-AFA was validated via MATLAB simulation environment. A different optimizer based on the original firefly algorithm (FA) is also studied in order to compute the parameter of the MSky controller. This control scheme to be known as MSky-FA was evaluated and compared to the proposed MSky-AFA as well as the passive suspension control. The results clearly exhibit more superior and better response of the MSky-AFA in reducing the body acceleration and displacement amplitude in comparison to the MSky-FA and passive counterparts for a sinusoidal road profile condition.

1. Introduction
A connecting part of vehicle body and wheel or known as the suspension system is one of the important elements to attenuate the road disturbance and improve the vibration control between body and tires. It is directly related to the vehicle dynamics performance that always have a major concern by many researchers recently. A passive suspension system is a traditional device that is always promising a stable in performance and have a simple structure design. However, due to a limitation of the said system in satisfy the requirement under complex road profile conditions, the semi-active suspension system become a favourable solution as this system known as an adjustable control device [1].

Research of semi-active suspension control has been widely investigated by previous researchers and it is always growth over the time by introducing particular contribution for the sake of vehicle performance and robustness. A traditional skyhook controller as introduced by Karnopp *et al,* [2] is amongst of the earliest control studied which able to suppress the vehicle vibration body by adopting the skyhook damper installed between the sky and the body. However, the said controller having a difficulty in handling the vehicle performance that will inevitably deteriorate. To improve a drawback, a series of an improved skyhook control scheme have been put forward by scholars [3-4].

The established modified skyhook (MSky) controller that has been investigated by previous scholars are still suffering from various drawbacks in terms of parameter optimization process. This leads to good motivation in exploring more advanced and intelligent optimization method that can be able to employ with MSky control scheme. An advanced optimizer based on metaheuristic algorithm such as the particle swarm optimization (PSO), firefly algorithm (FA) and cuckoo search algorithm (CSA) recently has

proven that, the performance of any engineering applications employing using these techniques are able to be improved better than using conventional optimizers [5-6]

In this study, an advanced firefly algorithm (AFA) as introduced by Ab Talib *et al.* [7] is used to compute and optimize the MSky controller parameter. An MSky control strategy incorporating and intelligent AFA or known as MSky-AFA controller was implemented as a robust control scheme and a potential candidate to control the amount of the magneto-rheological (MR) damper current or voltage for semi-active suspension system.

The rest of the paper is organized as follows: Section 2 describes the mathematical modelling of semi-active suspension and MR damper systems. The controller strategy with intelligent optimization method is presented in Section 3. Section 4 shows the results based on the proposed controllers and it counterparts. Finally, the paper's conclusion is presented in Section 5.

2. Modelling of Semi-Active and MR Damper Systems

Referring to second newton law, a well validated mathematical model of semi-active suspension system is used to represent the simulation model in this study [7]. The parameter of the suspension model are taken by conducting the experimental work in the laboratory. The sprung mass value, m_s is set as 80.5 kg, unsprung mass value, m_u is 18.5 kg, damping coefficient, c_s is 1000 Ns/m and the value of the spring and tire stiffness, k_s and k_t are 45409 N/m and 274680 N/m, respectively. The use of MR damper in this study is due to a good performance to be as close as an active system is investigated by other scholars. A visualization of MR damper system based on the Spencer model is depicted in Figure 1.
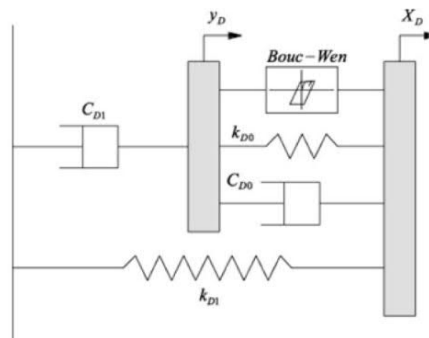

Figure 1. Spencer model

The damper force, F_{mr} based on this model can be predicted using the equations described as:

$$F_{mr} = C_{D1}\dot{y} + k_{D1}(x_D - x_0) \tag{1}$$

$$\dot{y} = \frac{1}{c_0 + c_{D1}}[\alpha z + c_{D0}\dot{x}_D + k_{D0}(x_D - y_D)] \tag{2}$$

$$\dot{z} = -\gamma|\dot{x}_D - \dot{y}_D|z|z|^{n-1} - \beta(\dot{x}_D - \dot{y}_D)|z|^n + A(\dot{x}_D - \dot{y}_D) \tag{3}$$

where y_D is internal displacement, x_D is a damper displacement, x_0 is the initial condition of damper deflection and z is the hysteretic restoring force.

3. Control and Optimization

As for the implementation of the MSky controller in this study, the related equation can be found in Equation 4. Corresponding to this, the desired force generated from the MSky controller will give a good impact to the vehicle's stability.

$$F_d = \begin{cases} C_{sky} v_s & if \quad -v_u(v_s - v_u) \geq 0 \\ 0 & if \quad -v_u(v_s - v_u) < 0 \end{cases} \tag{4}$$

The value of the MSky controller coefficient, C_{sky} is a critical element for the controller response as the performance of the system is depending on how well the controller is being tuned. Thus, an intelligent and advanced algorithm based on the AFA optimization strategy is adopted to the MSky control scheme. The AFA is amongst of an improvement from original FA which is modified element was made based on the scout position of the firefly's particle. The particle is behaving like a 'firefly' searching the best mate without any knowledge where their best mate is and only focusing on a particular mate without considering the other firefly in surrounding, which is might be brighter than that particular mate. There are three formulas of AFA to be known as the attractiveness, distance and movement. Equation 5 is representing the formula of the attractiveness, (β).

$$\beta(r) = \beta_0 e^{-\gamma r^m}, m \geq 1 \tag{5}$$

where r is defined as the distance of two particles, β_0 is initial attractiveness and γ is defined as the fixed light absorption coefficient. The distance between a couple of fireflies i and j at x_i and x_j, respectively, is expressed as:

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d}(x_{i,k} - x_{j,k})^2} \tag{6}$$

where $x_{i,k}$ is the kth component of the spatial coordinate x_i of ith firefly and d is the dimension s number. The movement of a firefly i when attracted to another lighter firefly j can be defined as:

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2}(x_j - x_i) + \alpha \varepsilon_i \tag{7}$$

where the second and third terms can be defined as due to the attraction and randomization respectively, α is randomization parameter, ε_i is a vector of random numbers drawn from a Gaussian distribution of uniform distribution. In other word, ε_i can be simply replaced by *rand* - 0.5, where *rand is* a number generator uniformly distributed in the range of [0, 1].

In this study, the parameter of AFA and FA optimizers are set to be as 100 and 30 for number of generation and firefly size, respectively. The alpha, beta and gamma are to be set as 0.3, 0.7 and 0.9, respectively. Additional parameters known as the constant value, η and limit (for AFA only) are also defined as 0.0001 and 4, respectively. As for the parameters of the AFA are completed, the process of integration with the MSky controller is conducted based on the improvement of the objective function (minimization of the body acceleration amplitude). Full configuration of the block diagram is shown in Figure 2.
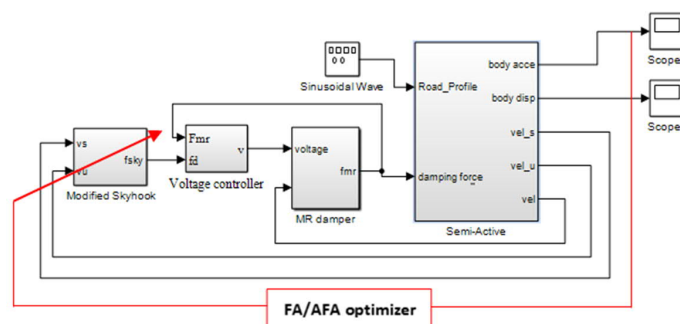

Figure 2. Full configuration of block diagram for MSky-AFA controller

4. Results and Discussions

The evaluation of the objective of this study is to reduce the vertical amplitude for both body acceleration and displacement. The proposed MSky-AFA is evaluated by comparing with the MSky-FA and passive system. A sinusoidal wave with 0.01 m amplitude is applied to be set as an input of the vehicle system. Using 100 number of generations, final stage of convergence state has obtained that the value of mean square error (MSE) of body acceleration is stagnated and remain constant when the value is about 4.67 and 10.92 for respective AFA and FA optimization strategies. Figures 3 and 4 are represent for the performance of the body acceleration and displacement, respectively. From the figures, it is worth to mention that, the performance of the MSky-AFA is obtained better than the MSky-FA and passive. For body acceleration response, the performance of MSky-AFA is better than other controller response is up to 64.3 % whereas for the body displacement response, MSky-AFA is able to improve the system with up to 55.1 % as compared to its counterparts. It is worth to mention that the force transmitted from the unsprung to sprung masses has been reduced in order improve the vehicle ride comfort for vehicle's body. Full report of the MSE and percentage improvement is depicted in Table 1.
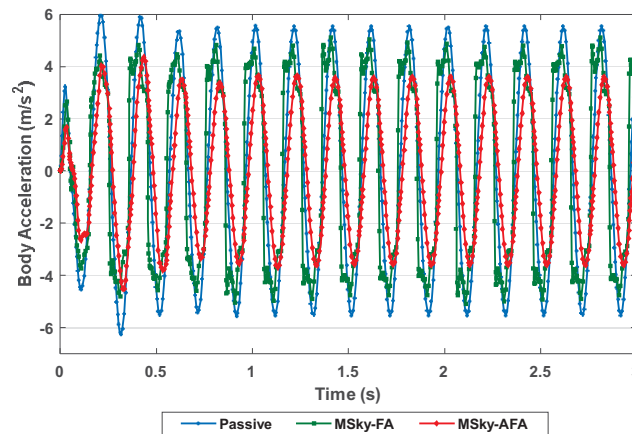

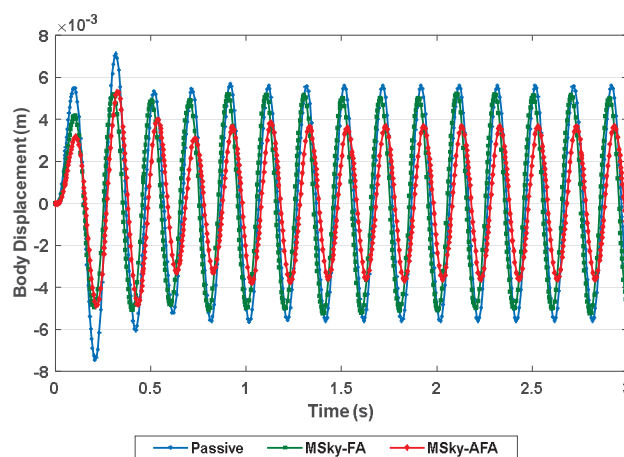**Figure 3.** Body acceleration response with sinusoidal wave input

Figure 4. Body displacement response with sinusoidal wave input

Table 1. MSE and percentange improvement of all parameters of interest

Parameters of interest	Passive	MSky-FA	MSky-AFA
Body Acceleration (m/s^2)	13.11	10.42 (20.51 %)	4.67 (64.3 %)
Body Displacement (m) (10^{-6})	1.36	1.27 (6.61 %)	0.61 (55.1 %)

5. Conclusion

A practical simulation control for the proposed MSky-AFA controller applied to the semi-active suspension system has been successfully developed and evaluated via a computer-based MATLAB simulation environment. The integration of the AFA optimization technique to the modified skyhook has been employed in order to improve the vehicle ride comfort for the system. It is worth noting that the MSky-AFA provides better results amongst the two MSky-FA and passive suspension controls. It is clearly implying that the said advanced firefly algorithm used to compute the Msky parameter value has provide better optimization process and able to improve the weaknesses of the original firefly algorithm. Further experimentation and testing should be carried out to show the effectiveness of the proposed controllers. Other intelligent optimization techniques should be also carried out that could be used to compute the parameter of the MSky controller for comparative assessment purposes.

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