

Vibration Control of MR-Damped Vehicle Suspension System Using PID Controller Tuned by Particle Swarm Optimization

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ABSTRACT

Proportional integral derivative (PID) control technique is the most common control algorithm applied in various engineering applications. Also, particle swarm optimization (PSO) is extensively applied in various optimization problems. This paper introduces an investigation into the use of a PSO algorithm to tune the PID controller for a semi-active vehicle suspension system incorporating magnetorheological (MR) damper to improve the ride comfort and vehicle stability. The proposed suspension system consists of a system controller that determine the desired damping force using a PID controller tuned using PSO, and a continuous state damper controller that estimate the command voltage that is required to track the desired damping force. The PSO technique is applied to solve the nonlinear optimization problem to find the PID controller gains by identifying the optimal problem solution through cooperation and competition among the individuals of a swarm. A mathematical model of a two degree-of-freedom MR-damped vehicle suspension system is derived and simulated using Matlab/Simulink software. The proposed PSO PID controlled suspension is compared to both the conventional PID controller and the passive suspension systems. System performance criteria are evaluated in both time and frequency domains, in order to quantify the success of the proposed suspension system. The simulated results reflect that the proposed PSO PID controller of the MR-damped vehicle suspension offers a significant improvement in ride comfort and vehicle stability.

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INTRODUCTION

Proportional integral derivative (PID) control algorithm is widely applied in engineering systems and has been highly accepted in vehicle industry. Nowadays, a lot of researchers prefer to obtain the PID controller gains through optimization algorithms such as Genetic algorithm (GA) and Particle swarm optimization (PSO) techniques. PSO is originally contributed by Kennedy, Eberhart and Shi [1], [2] and was first introduced for simulating social behaviour in ref. [3] as a stylized representation of the movement of organisms in a bird flock or fish school. PSO algorithm is a metaheuristic that makes few or no assumptions about the optimized problem and can search very large spaces of candidate solutions.

PSO algorithm optimizes a problem by having a population (called a swarm) of candidate solutions (called particles), and moving these particles around in the solution space according to simple mathematical formula over the particle's position and velocity. The particles fly through solution space having two essential reasoning capabilities: their memory of their own best position and knowledge of the global or their neighborhood's best. These interactions result in iterative improvement of the quality of problem solutions over time.

For instance, PSO technique was found a very beneficial in parameter identification [4] and optimum structural design of a composite disk using piezoelectric layers [5, 6].

Currently, the design of a better quality vehicle suspension system becomes a vital development objective for the automotive industry. The ideal suspension system should have the capability to improve the ride comfort and vehicle stability. In general, the simplicity, applicability and robustness of controllers are designer's targets in industry to have a successful implementation of their controllers. MR fluid dampers are adaptive control devices that have received considerable interest due to their mechanical simplicity, high dynamic range, low power requirements, large force capacity, and robustness. MR dampers have been applied over a wide range of vibration control applications: from automobiles [7, 8] to railway vehicles [9] and civil structures such as buildings [10, 11].

MR dampers are semi-active control devices since it is only the voltage applied to its coil that can be commanded directly. Hence, in addition to a system controller that calculates the desired damping force required for the system to achieve a good performance, a damper controller is also required. This latter controller determines the voltage to be applied to the damper such that its actual force

tracks the desired force. Different control strategies have been introduced and assessed for the system controller: e.g. skyhook control [12, 13 and 14], H_∞ control [15, 16, 17], adaptive control based on neural network [18], robust control [19], Fuzzy Logic control [20, 21], sliding mode control [7,22,23], Linear Quadratic Gaussian control (LQG) [8, 24], and optimized PID controller using GA [25]. The last control strategy is chosen as a system controller in this article.

The novel contribution of this paper is the application of the PSO algorithm to tune the PID controller gains of vehicle MR damped suspension system as a system controller, for the first time. Control performance criteria are evaluated in the time and frequency domains in order to quantify the suspension effectiveness for the two alternative system controllers (PSO PID and C PID), as well as uncontrolled MR suspension (zero applied voltage) and passive suspension systems. The rest of this article is organized as follows: an overview of the quarter vehicle model is introduced in the next section contained brief details of the MR damper model. This is then followed by a description of the proposed semi-active control algorithm focusing on system and damper controllers. Finally, the results obtained for different road disturbance inputs are presented and discussed.

QUARTER VEHICLE MODEL

Figure 1 shows the two-degree-of-freedom (2DOF) system that symbolizes the quarter vehicle suspension system. It contains an upper mass, m_b , representing the vehicle body mass, as well as a lower mass, m_w , representing the wheel mass and its connected parts. The vertical motions of the system are described by the displacements x_b and x_w whereas the excitation due to road disturbance is x_r . The suspension spring stiffness is k_s and the tyre spring stiffness is k_t (tyre damping neglected). The data used here for the quarter vehicle system is chosen from ref. [26] and listed in Table 1. Newton's second law is applied to the quarter vehicle model and the equations of motion of m_b and m_w are as follows:

$$\begin{aligned} m_b \ddot{x}_b + k_s(x_b - x_w) + f &= 0 \\ m_w \ddot{x}_w - k_s(x_b - x_w) + k_t(x_w - x_r) - f &= 0 \end{aligned} \quad (1)$$

where, the force from the damping device is given by

$$f = \begin{cases} c_s(\dot{x}_b - \dot{x}_w), & \text{for passive suspension} \\ f_{MR}, & \text{for semi-active suspension} \end{cases} \quad (2a,b)$$

where, c_s being the coefficient for the passive suspension's damper. The proposed semi-active suspension system can be represented in the state space form as follows:

$$\dot{w} = Aw + Bf_{MR} + Dx_r \quad (3)$$

where,

$$w = [x_b \quad x_w \quad \dot{x}_b \quad \dot{x}_w]^T$$

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{k_s}{m_b} & \frac{k_s}{m_b} & 0 & 0 \\ \frac{k_s}{m_w} & -\frac{k_s + k_t}{m_w} & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & -\frac{1}{m_b} & \frac{1}{m_w} \end{bmatrix}^T$$

and

$$D = \begin{bmatrix} 0 & 0 & 0 & \frac{k_t}{m_w} \end{bmatrix}^T$$

Table 1. Quarter vehicle suspension parameters [26].

Parameter	Symbol	Value (Unit)
Mass of vehicle body	m_b	375 (kg)
Mass of vehicle wheel	m_w	29.5 (kg)
Suspension stiffness	k_s	20.58 (kN/m)
Damping coefficient	c_s	772 (Ns/m)
Tyre stiffness	k_t	200 (kN/m)

For the semi-active suspension, the MR damper force f_{MR} depends on the time histories of the applied voltage to the magnetic coil v and the relative displacement $x = x_b - x_w$ across it. x is also referred to as the suspension working space (SWS). The voltage signal v is calculated by the control system, which is described in the next section. For given signals v and x , the force f_{MR} is determined by equation (4), modified Bouc-Wen model, which has been adjusted from [23] for use in a vehicle suspension as illustrated in Figure 2.

$$f_{MR} = c_1 \dot{y} + k_1(x - x_0) \quad (4)$$

$$\dot{y} = \frac{1}{c_0 + c_1} \{ \alpha z + c_0 \dot{x} + k_0(x - y) \} \quad (5)$$

$$\begin{aligned} \alpha &= \alpha(u) = \alpha_a + \alpha_b u, \\ c_1 &= c_1(u) = c_{1a} + c_{1b} u \\ c_0 &= c_0(u) = c_{0a} + c_{0b} u \end{aligned} \quad (6)$$

$$\dot{z} = -\gamma |\dot{x} - \dot{y}|^n |z|^{n-1} z - \beta (\dot{x} - \dot{y}) |z|^n + \delta (\dot{x} - \dot{y}) \quad (7)$$

$$\dot{u} = -\eta(u - v) \quad (8)$$

where, y is the internal movement of the MR damper, u is the output signal from a first-order filter and z is an evolution parameter to grant the hysteretic behaviour. k_1 represents the accumulator stiffness. c_0 and c_1 represent the viscous damping coefficients for high and low damper velocities, respectively. η is presented to regulator the

stiffness at high damper velocity. Also, x_0 is used to simulate the effect of the MR damper accumulator. The shape and scale of the hysteresis effect of the MR damper can be predicted by γ , β , δ and η .

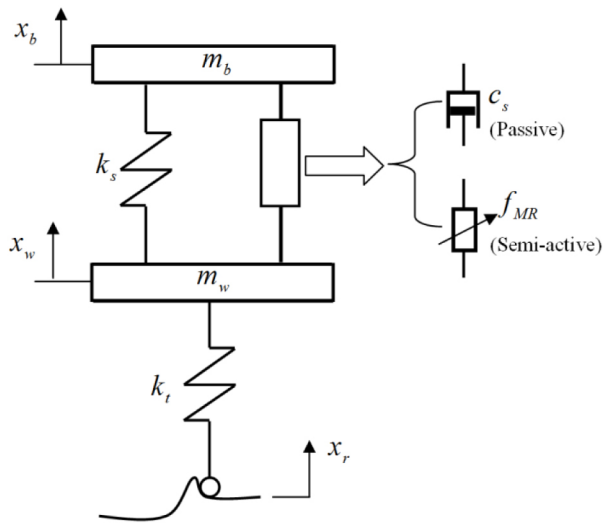


Figure 1. Quarter-vehicle suspension model.

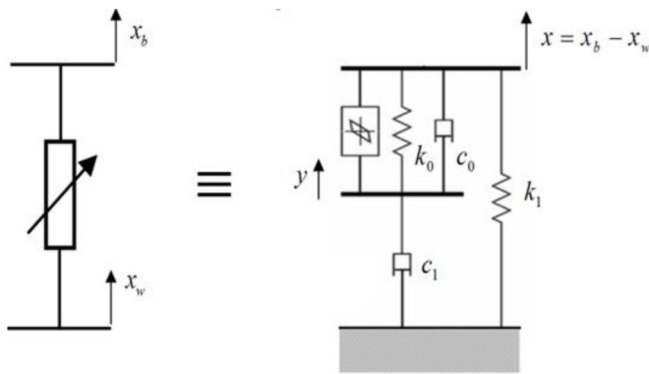


Figure 2. Modified Bouc-Wen model adapted for use in the quarter-vehicle suspension model

The Modified Bouc-Wen model parameters are listed in Table 2 and used to describe the behaviour of the MR damper as employed in ref. [23]. In order to estimate f_{MR} using equation (4), equations (5), (6), (7), (8) have to be implemented along with equations (1) and (4) i.e. three additional state variables (y , z , u) are presented. System performance criteria such as suspension working space (SWS), vertical body acceleration (BA) and dynamic tyre load (DTL) are assessed for all investigated systems under different road profiles.

Table 2. Modified Bouc-Wen model parameters [23].

Symbol	Value (Unit)	Symbol	Value (Unit)
c_{0a}	784 (Ns/m)	α_a	12441 (N/m)
c_{0b}	1803 (Ns/Vm)	α_b	38430 (N/Vm)
k_0	3610 (N/m)	γ	136320 (m-2)
c_{1a}	14649 (Ns/m)	β	2059020 (m-2)
c_{1b}	34622 (Ns/Vm)	A	58
k_1	840 (N/m)	n	2
x_0	0.0245 (m)	η	190 (s-1)

SEMI-ACTIVE CONTROL STRATEGY

The complete semi-active MR damped vehicle suspension system is shown in Figure 3. As stated previously in the introduction, it contains two controllers; a system controller and a damper controller. The system controller uses the dynamic responses of the plant to calculate the desired damping force f_d according to PID controllers. The damper controller predicts the voltage v applied to the damper in order to track its actual force f_{MR} to the desired force f_d . The following sub-sections provide a brief description of the system controller and the damper controller considered in this study.

System Controller using PID Algorithm

This section gives a brief description of the system controller algorithm in this paper, which are mainly a PID controller based on the mathematical calculations of Ziegler-Nichols closed loop method and the proposed PID controller optimized using PSO.

Classical PID Controller using Ziegler-Nichols Method

PID controllers are perhaps the most widely used control methods. They can provide quick response, good stability and small steady state errors in engineering systems with known parameters. PID controller technique consists of three gains only: proportional, integral and derivative. The control input f_d is given by

$$f_d = k_p e + k_i \int e dt + k_d \frac{de}{dt} \quad (9)$$

$$e = x_d - x \equiv x_d - SWS \quad (10)$$

where e is the control error, x_d is the desired relative displacement between body mass and wheel mass and x is the actual relative displacement of suspension system that known as SWS . k_p is the proportional gain, k_i the integral gain and k_d the derivative gain. The gains k_p , k_i and k_d of the PID controller was calculated based on Ziegler-Nichols closed loop method [27] and set to $k_p = 5640$, $k_i = 3807$ and $k_d = 2920$.

Optimized PID Controller using PSO

PSO algorithm is a computational method which optimizes a specified problem by iteratively trying to enhance a candidate solution regarding a given measure of quality. Firstly, PSO algorithm searches about the optimum solution by initializing some random particles in the solution space. Each particle has a position vector $y_p^{(j)}$ contains random values of the parameters required to be optimized. By substituting these positions in the optimization problem, their fitness values can be obtained and memorized. Through iterations, each particle continuously updates its position and its velocity to the next position from the knowledge of its best position $b_p^{(j)}$ and the global best position $g^{(j)}$ found by all particles in the solution space. Equation (11), shows the mathematical formula governing the updating of any particle's position;