

ORIGINAL ARTICLE

Vibration Suppression of a 5 DOF Pitch-plane Suspension Model Using Genetic Algorithm Assisted Fuzzy Controller

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ABSTRACT

In this paper, Active vibration suppression of a 5 degree of freedom (DOF) vehicle suspension system model is considered. In the proposed vehicle model, the impact of the wheel-axle-brake assemblies' masses has also been taken into account. In other words, the model replicates a pitch-plane vehicle suspension with two independent spring-damper sets in front section, two spring-damper sets in rear section and a spring-damper set as the driver's seat suspension system. A fuzzy system in charge of the applied force to the driver's seat, concerning the comfortable ride benchmark is exploited. In addition, to find out the optimal value of fuzzy system parameters, genetic algorithm (GA) is applied on the basis of minimizing both vibrations and accelerations of the driver's seat. Simulation results verify the competence of the proposed GA assisted fuzzy controller (GAF) in comparison with prevalent approaches.

Key words: Active control, fuzzy logic control, genetic algorithm, 5 degree of freedom vehicle model.

Introduction

Since the vibration isolation capacity of the conventional passive or semi-active suspension systems is constrained, active suspension systems have emerged during the previous years to accomplish a ride at ease and sufficient maneuverability in a variety of driving situations.

Many active controllers have been established for diverse models of suspension systems during the preceding years (D'Amato and Viassolo, 2000; Guclu, 2005; Huang and Chen, 2006), albeit intelligent approaches characterize a sound performance amongst them. For instance, Yildirim (2004) proposed neural network schemes to resolve this problem and contrasted them with PID, PI and PD controllers and inferred that the proposed scheme can assure the robustness of the adaptive system in the presence of uncertainties. Ahn (1996) proposed a hybrid vibration suppressor system, which exploited an artificial neural network. The research acknowledged that the hybrid model provides a better performance in comparison with the passive system. Chou scrutinized the competence of grey-fuzzy control for a quarter car suspension system model (Chou, 1998).

On the other hand, a probe through straightforward but plausible models unearths that the vibration response of vehicles to various excitations can be inspected through the study of diverse in-plane models (Ahmed, 2002). In related literature, half-car model (Rao and Narayanan, 2008) in addition to the pitch-plane suspension vehicle model (Martynowicz and Sapin, 2005; Sapin and Roso, 2005) is put into the spotlight for the aim of studying bounce and pitch motions. Spinski and Rosol (Sapinski and Rosol, 2008) considered an autonomous control system (ACS) for a 3 DOF pitch-plane suspension model. They presumed trifling contributions owing to the

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wheel-axle-brake assemblies' masses and tires stiffness. It signifies that the road input is postulated to be the same as the wheels input.

Continuing the efforts of previous researchers, firstly a more clear-cut model is developed by proposing a 5 DOF pitch-plane model of the system. The proposed model represents a vehicle suspension system, which incorporates four spring-damper sets in front and rear sections and a driver's seat suspension with the fifth spring-damper set. In the proposed model, the effect of wheel-axle-brake assemblies' masses on the suspension system is also taken into account by adding two more degrees of freedom. Then, a novel fuzzy controller is suggested to restrain the vibrations of the proposed model. Moreover, GA is utilized to determine optimal values of fuzzy controller parameters which boosts the overall performance drastically.

Proposed 5 DOF Model of A Vehicle:

Fig. 1 depicts the diagram of the 5 DOF pitch-plane suspension model. In this model, two subsystems can be recognized: a 4 DOF system which consists of a suspended beam that is the model of body with two unsprung masses and a 1 DOF system comprising a mass which is the model of driver's seat. In this figure, m_{ur} is the rear unsprung mass, m_{uf} is the front unsprung mass, m_s is the sprung mass and m_c is the mass of driver's seat. Additionally, k_{tr} is the elasticity factor of the rear wheel-axle-brake assembly, k_{tf} is the elasticity factor of the front wheel-axle-brake assembly, k_{sr} is the elasticity factor of the rear spring, k_{sf} is the elasticity factor of the front spring and k_c is the elasticity factor of the seat spring. It should be taken into consideration that, C_{sr} is the damping coefficient of the rear damper, C_{sf} is the damping coefficient of the front damper and C_c is the damping coefficient of the seat damper.

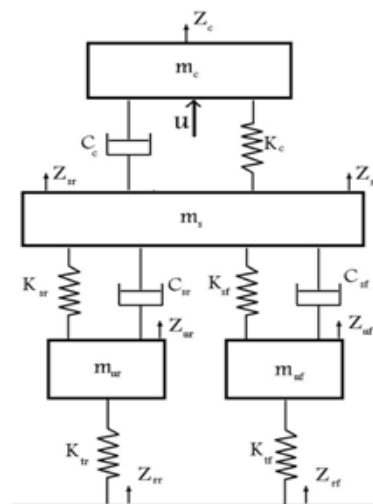


Fig. 1: Vehicle model

The absolute displacement of rear unsprung mass, front unsprung mass, the rear edge of sprung mass, the front edge of sprung mass and the seat are denoted by z_{ur} , z_{uf} , z_{sr} , z_{sf} and z_c respectively., I , a and b represent the mass moment of inertia of the vehicle about a centroidal axis, the distance between the driver's seat and front edge of sprung mass, and the distance between the driver's seat and rear edge of sprung mass, respectively. The applied force in the driver's seat suspension is controlled actively and is represented by u . All the dampers are passive. Relation 1 demonstrates the relation between state variables.

$$\begin{aligned}
 x_1 &= z_{uf} - z_{rf} & x_6 &= \dot{z}_{ur} \\
 x_2 &= \dot{z}_{uf} & x_7 &= z_{sr} - z_{ur} \\
 x_3 &= z_{sf} - z_{uf} & x_8 &= \dot{z}_{sr} \\
 x_4 &= z_{sf} & x_9 &= z_c - z_s \\
 x_5 &= z_{ur} - z_{rr} & x_{10} &= \dot{z}_c
 \end{aligned} \tag{1}$$

The state space equation is shown in relation 2:

$$\begin{aligned}\dot{X} &= AX + Bu + L\dot{w} \\ Y &= CX\end{aligned}\quad (2)$$

Where w is the road profile, u is the control force applied by groundhook force controller and matrixes A, B, L are as follows:

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ A_{31} & A_{32} & A_{33} & A_{34} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & A_{42} & A_{43} & A_{44} & 0 & A_{46} & A_{47} & A_{48} & A_{49} & A_{5,10} \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & A_{75} & A_{76} & A_{77} & A_{78} & 0 & 0 \\ 0 & A_{82} & A_{83} & A_{84} & 0 & A_{86} & A_{87} & A_{88} & A_{89} & A_{8,10} \\ 0 & 0 & 0 & A_{94} & 0 & 0 & 0 & A_{98} & 0 & 1 \\ 0 & 0 & 0 & A_{10,4} & 0 & 0 & 0 & A_{10,8} & A_{10,9} & A_{10,10} \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{m_c} \end{bmatrix} \quad L = \begin{bmatrix} -1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad C = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}^T \quad (4)$$

(4) and unknown elements are defined below in Equation (5):

$$\begin{aligned} A_{44} &= -\frac{c_{sf}}{m_s} - \frac{b \times c_c}{m_s(a+b)} - \frac{a^2 c_{sf}}{I} & A_{86} &= -\frac{k_{sr}}{m_s} - \frac{b^2 k_{sr}}{I} & A_{49} &= +\frac{k_c}{m_c} \\ A_{48} &= \frac{-c_{sr}}{m_s} - \frac{ac_c}{m_s(a+b)} + \frac{abc_{sr}}{I} & A_{87} &= \frac{c_{sr}}{m_s} + \frac{b^2 c_{sr}}{I} & A_{5,10} &= +\frac{c_c}{m_c} \\ A_{84} &= -\frac{c_{sf}}{m_s} - \frac{bc_c}{m_s(a+b)} + \frac{abc_{sf}}{I} & A_{94} &= -\frac{b}{a+b} & A_{75} &= -\frac{k_{tr}}{m_{ur}} \\ A_{88} &= -\frac{c_{sr}}{m_s} + \frac{ac_c}{m_s(a+b)} - \frac{b^2 c_{sr}}{I} & A_{10,4} &= \frac{bc_c}{m_c(a+b)} & A_{76} &= -\frac{k_{sr}}{m_{ur}} \\ A_{42} &= -\frac{k_{sf}}{m_s} - \frac{a^2 k_{sf}}{I} & A_{98} &= -\frac{a}{a+b} & A_{77} &= -\frac{c_{sr}}{m_{ur}} \\ A_{43} &= \frac{c_{sf}}{m_s} + \frac{a^2 c_{sf}}{I} & A_{10,8} &= \frac{ac_c}{m_c(a+b)} & A_{78} &= +\frac{c_{sr}}{m_{ur}} \\ A_{46} &= \frac{-k_{sr}}{m_s} + \frac{abk_{sr}}{I} & A_{31} &= -\frac{k_{tf}}{m_{uf}} & A_{89} &= +\frac{k_c}{m_c} \\ A_{47} &= \frac{c_{sr}}{m_s} - \frac{abc_{sr}}{I} & A_{32} &= \frac{k_{sf}}{m_{uf}} & A_{8,10} &= +\frac{C_c}{m_c} \\ A_{82} &= -\frac{k_{sf}}{m_s} + \frac{abk_{sf}}{I} & A_{33} &= -\frac{c_{sf}}{m_{uf}} & A_{10,9} &= -\frac{k_c}{m_c} \\ A_{83} &= \frac{c_{sf}}{m_s} - \frac{abc_{sf}}{I} & A_{34} &= \frac{c_{sf}}{m_{uf}} & A_{10,10} &= -\frac{C_c}{m_c} \end{aligned}$$

Ga Assisted Fuzzy Controller:

In this section, GA assisted fuzzy controller is introduced. To acquire a precise vibration isolator in a stressful environment the following procedure is carried out:

- 1- Partitioning a fuzzy controller on the basis of the experts' comprehension about vibration dynamics.
- 2- Applying GA with the intention of find out the optimal value of different parameters of the fuzzy controller based on diminishing both vibrations and accelerations of the driver's seat.

Each phase will be elaborated subsequently.

Fuzzy Controller:

The block diagram of the system and its controller is depicted in figure 2. It can be deduced from the figure, that the proposed fuzzy controller (FL) has two inputs and one output. The first input is the error ($e(t)$), namely the difference between the actual position and desired position of the seat, and the second input is the error derivative ($\dot{e}(t)$). The output of proposed FL is the control signal $u(t)$ applied to the actuator which supplies the driver's seat with the planned force.

The pivotal initiative which lies behind the fuzzy controller is that when the actual position is distant from the preferred one, a superior force is required, when the distance augments, the desired force is much larger and vice versa. In order to achieve an efficient controller, we first setup inputs and output membership functions as can illustrated in figures 3, 4, and 5 respectively. Then, a set of suitable rules were identified as follows.

- If (Error is Z) or (Rate is Z) then (Voltage is Z)
- If (Error is PB) or (Rate is P) then (Voltage is NB)
- If (Error is NB) or (Rate is N) then (Voltage is PB)
- If (Error is PS) or (Rate is P) then (Voltage is PS)
- If (Error is NS) or (Rate is N) then (Voltage is NS)
- If (Error is NS) and (Rate is P) then (Voltage is PS)
- If (Error is PS) and (Rate is N) then (Voltage is NS)

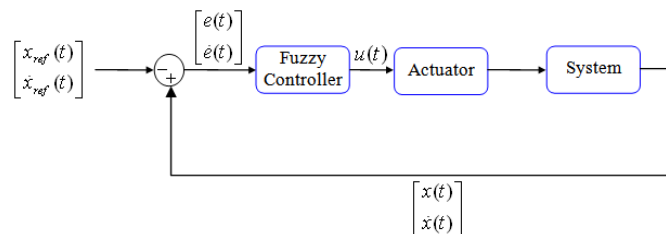


Fig. 2: Closed loop block diagram with FLC

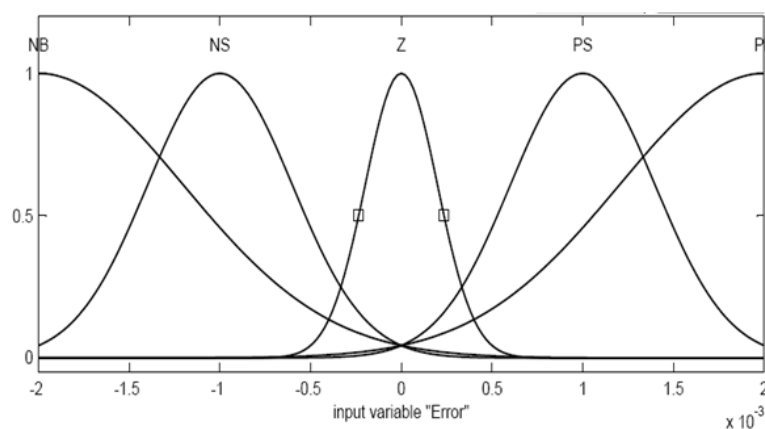


Fig. 3: Error membership functions

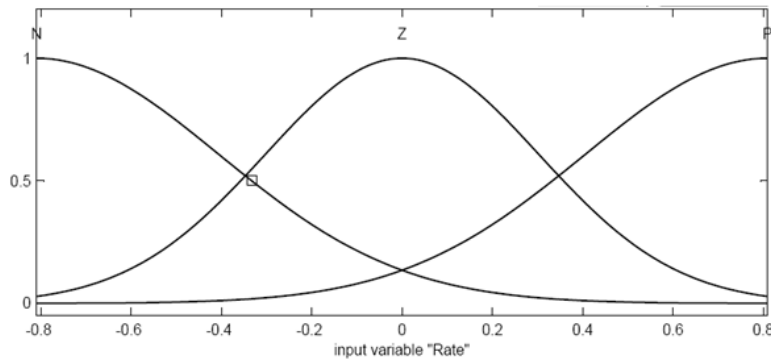


Fig. 4: Error derivative membership functions

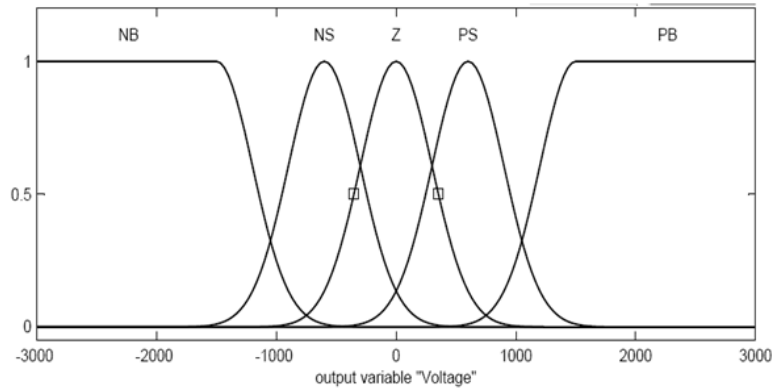


Fig. 5: Force membership functions

Applying GA:

As a result of the intricacy and nonlinearity of the proposed fuzzy controller, tuning its parameters is a rather prolonged practice. Consequently, we employed GA to attain the optimal value of its parameters regardless of mankind expertise. The objective of GA is to dwindle the tracking error and acceleration of the driver's seat. Hence, we defined the fitness function accordingly:

$$\text{Fitness Function} = \text{norm}\left(\frac{d^2(e(t))}{dt^2}\right) + 10\text{norm}(e(t)) \quad (6)$$

To run GA, it is needed to construct a dataset of inputs and desired outputs of the system. To provide this dataset, we applied four typical inputs to the system as relation 7 and calculate $e(t)$ for all of them:

$$\begin{aligned} 1) \quad w_1(t) &= \begin{cases} 0.05 & t < 0.5 \\ 0 & \text{otherwise} \end{cases} \text{ meter} \\ 2) \quad w_2(t) &= \begin{cases} 0.15 & t < 0.5 \\ 0 & \text{otherwise} \end{cases} \text{ meter} \\ 3) \quad w_3(t) &= \begin{cases} 0.05 \sin 20(t - 0.5) & 0.5 < t < 0.5 + \frac{\pi}{20} \\ 0 & \text{otherwise} \end{cases} \text{ meter} \\ 4) \quad w_4(t) &= \begin{cases} 0.15 \sin 20(t - 0.5) & 0.5 < t < 0.5 + \frac{\pi}{20} \\ 0 & \text{otherwise} \end{cases} \text{ meter} \end{aligned} \quad (7)$$

The aim of GA is searching for optimal value of fuzzy system parameters which minimize fitness function over mentioned inputs.

GA was run in the following steps.

- I) Set the initial parameters for GA: population size, crossover type and probability, and mutation probability.
- II) Create the initial population randomly.
- III) Reckoning of a fitness value for each subject.
- IV) Selection of the subjects that will mate according to their share in the population global fitness.
- V) Apply the genetic operators (crossover, mutation...).
- VI) Repeat Steps III to VI until the generation number is reached.

Simulation Results:

In this section, enhancement of vibration isolation fulfilled by the proposed technique is manifested. To assess the efficiency of the novel approach and to judge it against another existing controller, namely GA aided PID controller (Herreros et al., 2002), two examples are contemplated. It is important to note that the parameters of PID controller where optimized using GA exactly in the same manner of our proposed method.

Example 1:

Road disturbance as input of the system where considered to be the same as the following function.

$$D_1(t) = \begin{cases} 0.1 & t < 0.5 \\ 0 & \text{otherwise} \end{cases} \text{ meter} \quad (8)$$

Time responses of the bounce motion, relative displacement and corresponding acceleration for the step road input are given in figures 6, 7 and 8. It can be interpreted from these figures that proposed method succeeds to reduce the magnitudes of bounce motion acceleration significantly. In particular, reduced accelerations indicate that the ride comfort is improved. Also, the absolute and relative displacements of the fuzzy controlled active suspension system vanish faster than that of passive and PID controlled ones.

For the first example, the root mean square error (rms) of Absolute displacement, Relative displacement and Acceleration obtained from using proposed scheme and GA aided PID controller are indicated in table 1.

Example 2:

As for the second case study, a limited sinusoidal road input is applied to the vehicle model. This kind of road surface irregularity is one of the most encountered conditions in practice. The sinusoidal road input is formulated as below.

$$D_2(t) = \begin{cases} 0.1 \sin 20(t - 0.5) & 0.5 < t < 0.5 + \frac{\pi}{20} \\ 0 & \text{otherwise} \end{cases} \text{ meter} \quad (9)$$

Time responses of the bounce motion, relative displacement and corresponding acceleration for the sinusoidal road input are given in figures 9, 10 and 11. It is seen from these figures that the magnitudes for the bounce motion displacement and acceleration are significantly decreased for fuzzy controlled case in comparison with PID controller. These results confirm the efficiency of the fuzzy controller and its superior to PID controller. Table 2 highlights the effectiveness of the proposed method in comparison with conventional schemes.

Conclusions:

In this study, a 5 DOF pitch-plane vehicle suspension model was inspected. To elucidate, an active force actuator was applied to the driver's seat model so as to isolate it from vibrations. We constructed a fuzzy controller with the aim of managing the active force of actuator based on experts' acquaintance about the dynamics of driver's seat vibrations. Furthermore, to benefit from an optimal fuzzy system, we took advantage of GA. The proposed GA assisted fuzzy controller was compared with a GA aided PID controller. Simulation results corroborate that the novel approach provides a crucial improvement in suppressing various vibrations.

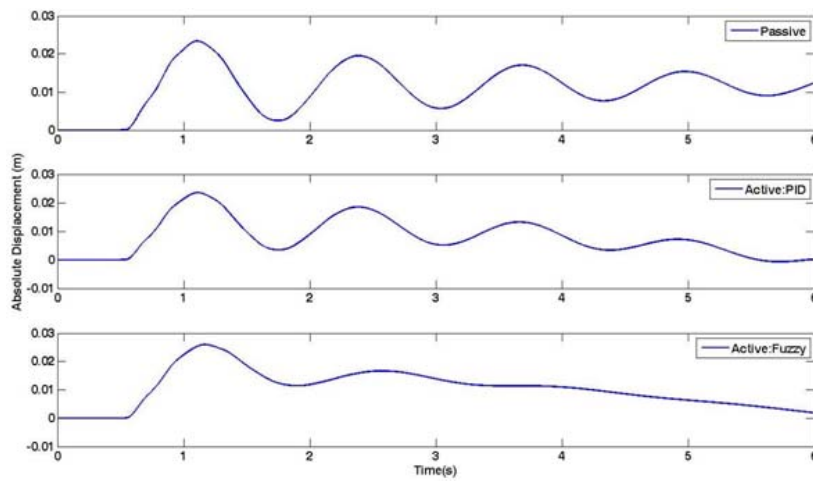


Fig. 6: Absolute displacement (Step disturbance)

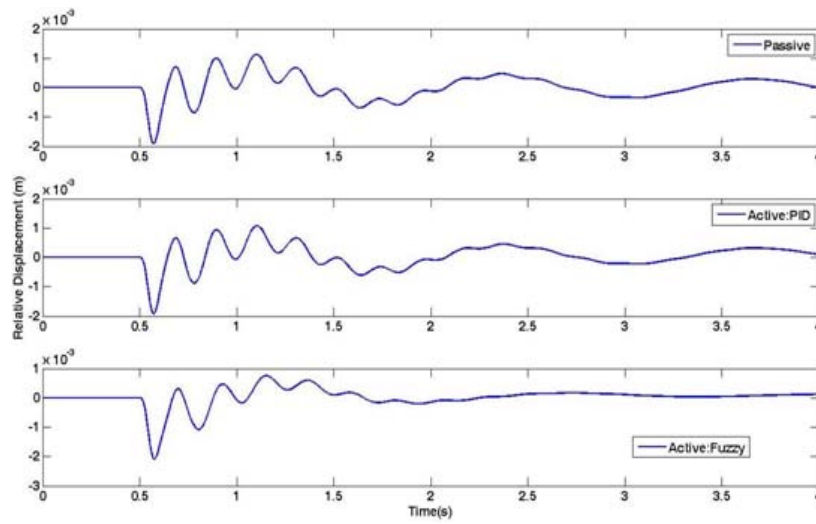


Fig. 7: Relative displacement (Step disturbance)

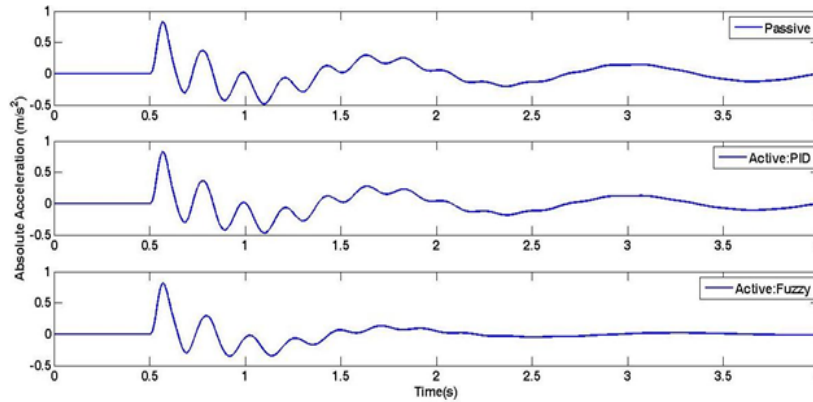


Fig. 8: Absolute acceleration (Step disturbance)

Table 1: Result of example 1.

Criteria	Uncontrolled	Proposed method	PID
Absolute displacement rms (m)	1.1054	0.9745	0.8250
Relative displacement rms (m)	0.0272	0.0236	0.0266
Acceleration rms (m/s ²)	11.6664	8.5580	11.0600

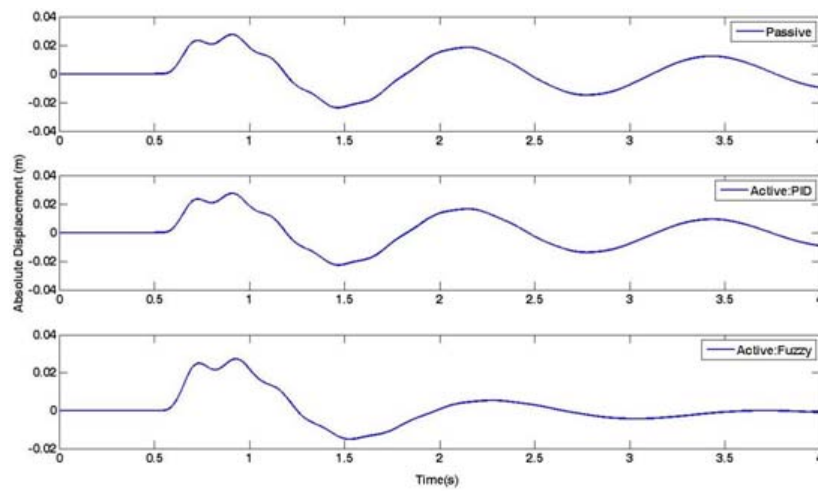


Fig. 9: Absolute displacement (Sinusoidal disturbance)

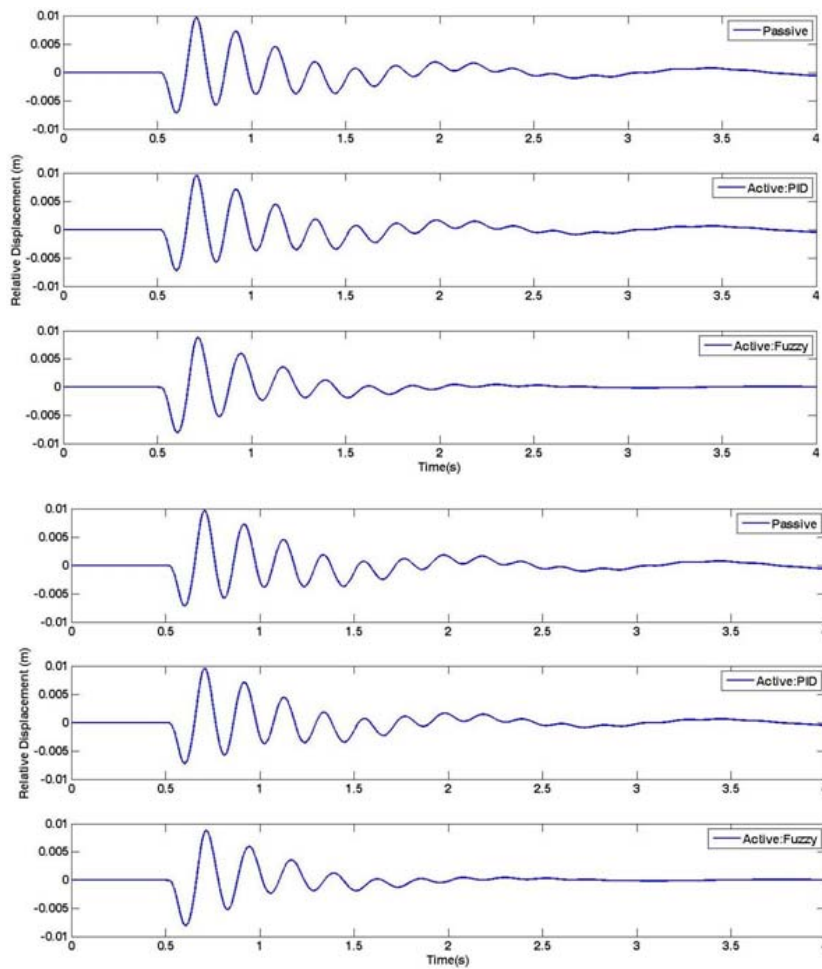


Fig. 10: Relative displacement (Sinusoidal disturbance)

Table 2: Results of example 2

Criteria	Uncontrolled	Proposed Method	PID
Absolute displacement rms (m)	0.8393	0.5910	0.7883
Relative displacement rms (m)	0.1335	0.1173	0.1302
Acceleration rms (m/s ²)	57.4513	49.6121	56.2354

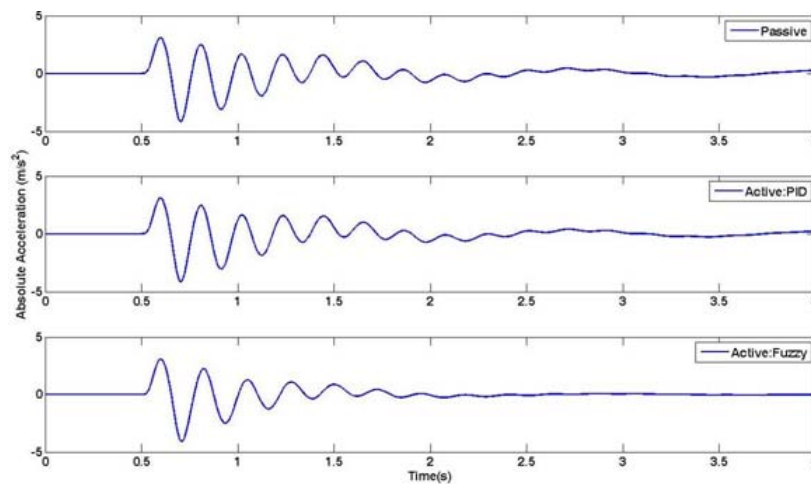


Fig. 11: Absolute acceleration (Sinusoidal disturbance)

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