A New Comfort Oriented Semi-Active Suspension System with Jerk Driven Damper (JDD) Control

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A New Semi-Active Suspension System Based on Jerk Driven Damper (JDD) Control

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ABSTRACT

A new control strategy for semi-active suspension system in a road vehicle called Jerk Driven Damper (JDD) is proposed and analyzed in this paper. The control strategy for JDD system is extremely simple and it involves very common logic. JDD system requires a two state controllable damper and jerk sensor. A semi-active damper is incorporated into a single degree of freedom (1DOF) quarter car model subjected to base excitation. Here, two types of positive amplitude half sinusoidal type speed breakers (severe and smooth) with same height are considered as input to the vehicle. These proposed road inputs are used for study and simulation of passive, sky-hook (SH) control and acceleration driven damper (ADD) suspension systems. The optimality of JDD is examined over SH and ADD control which is observed with both 'severe' and 'smooth' speed breakers. It is shown that the JDD control shows better reduction in vertical acceleration when the vehicle comes across severe breaker. Later the vertical body acceleration response (comfort objective) of JDD control strategy is compared with various types of well-studied control strategies and shown to have better isolation.

Keywords: Semi-Active Suspension, Jerk Driven Damping, Switching Control

INTRODUCTION

The fundamental role of a vehicle suspension system is to isolate the vehicle body from the force transmitted by the external excitation. A passive suspension system is the simplest way to protect the vehicle from vibration caused by road. There is a trade-off with a passive suspension system: it requires a higher damping value at resonance and a low value of damping at higher frequency. Study of transmissibility for suspension system gives a basic idea for this trade-off. So, to meet the right compromise of damping, tuning of damper is required. A magneto rheological (MR) damper is proven as a sophisticated controlled damper [G. Z. *et al.* 2002]. A lot of work has been carried out in the area of controlled suspension system in which semi-active suspension system received more attention. The performance of any suspension is measured by the vertical acceleration of the road vehicle body. Higher performance is achieved by minimizing vertical acceleration. A number of possible semi-active suspension systems have been studied in the last few decades leading to significant improvement in performance [Emanuele *et al.* (2008), Sergio *et al.* (2005), Yanqing *et al.* (2008), and Y. Liu (2009)]. Y. Liu (2009) proposed one innovative control strategy named ADD and its optimality is noticed over SH control. Yanqing *et al.* (2008) proposed a new semi-active suspension system with two controllable dampers and two constant springs and a considerable improvement is noticed. In the above mentioned papers semi-active damping force is either proportional to chassis velocity (in SH control) or to chassis acceleration (in ADD). The main objective of this paper is, to propose an optimal control method, called jerk driven damper (JDD) for a semi-active suspension system on the basis of two state (on-off) controlled variable dampers and also to show the earlier proposed control strategies such as SH, ADD controls are not so optimal and we can have a better control strategy. Later the work has been extended up to the comparison of the performance of different control strategies on the basis of 'comfort objective' (the comfort objective of a suspension system is to have minimum vertical acceleration of the sprung mass). At the end, the trade-offs related to JDD suspensions are discussed.

QUARTER CAR MODEL

A 2DOF quarter car model incorporating a variable damper and a spring with constant stiffness between axel of the wheel and chassis is shown in Figure 1(a). The equivalence of this system is shown in Figure 1(b), under the assumption of very high stiffness and very low damping of tire.

For the given quarter car model, the following set of differential equation can be written:

$$m\ \ddot{x} = -b_s(\dot{x} - \dot{u}) - k(x - u) \quad \dots (1)$$

Equation (1) is governing nonlinear equation of the system and the nonlinearity is caused by the state variable damping coefficient b_s .

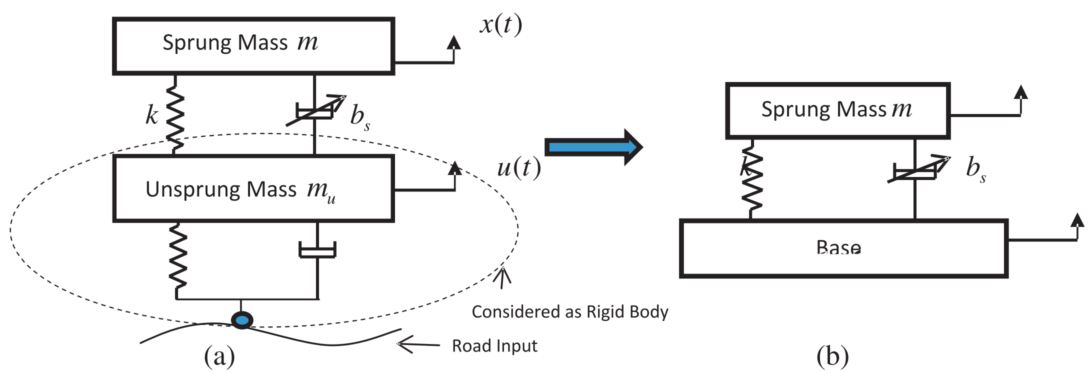

Fig. 1: 2 DOF Quarter Car Model and its Equivalent 1 DOF Model under the Assumption of Very High Stiffness and Very Low Damping of Tire

The symbols used in governing equation (1) are:

m is the sprung (body) mass of quarter car. m_{us} is the unsprung (tire, wheels, suspension links etc.) mass which is considered to be a rigid body. k and b_s are the fixed stiffness and variable damping of the suspension system respectively. x and u are the sprung mass and base displacement in the function of time.

ROAD PROFILE

Disturbance to the vehicle caused by road is not predictable and it can be random. Widely used road profile for the simulation is the response of a first-order filter to white noise [Elmadany *et al.* (1990)]. The road profile used for simulating the JDD suspension is a very common half sinusoidal speed breaker with positive amplitude. The dimensional data of the breaker has been taken from the residential road of ordinance factory estate Hyderabad.

Because, the road profile input to the vehicle is two half sinusoidal speed breaker with same heights and vehicle speed is considered same on both speed breakers so, the vehicle will vibrate with two different time periods. For the estimation of the road profile a half sinusoidal pulse of time duration t_1 can be considered. t_0 in equation (2) shows the time before the speed breaker starts. H is the amplitude of the sinusoidal wave which is the height of the speed breaker. Figure (2) (a) and (b) shows smooth and severe breaker profile respectively. Time before the breaker starts is taken as 0.5 sec and distance covered by the vehicle during this time is 2 m with the speed of 4 m/sec. The speed breaker height may be in the range of 0.5 to 0.7 m and width may be in the range of 0.35 to 3 m. For severe breakers width is considered 0.35 m and for smooth breaker width is considered 3 m for simulation purpose. Height for both the breakers is considered as 0.05 m.

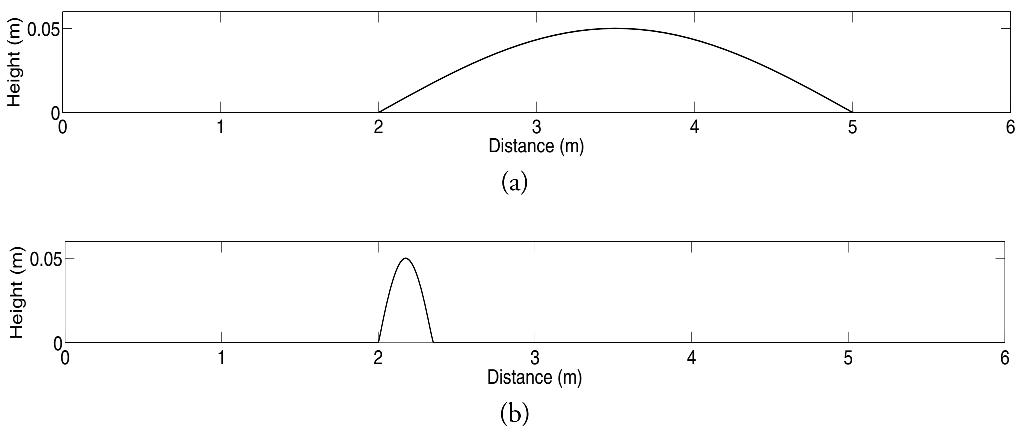

Fig. 2: Two Types of Speed Breakers of Same Height are Used for Simulation (a) Smooth Speed Breaker (b) Severe Speed Breaker

Road profile physics can be described according to the equation (2):

$$u(t) = \begin{cases} t_0 + H \sin \dfrac{\pi(t - t_0)}{t_1}, & for \quad t_0 \le t \le (t_0 + t_1) \\ 0, & \text{Otherwise} \end{cases} \qquad \ldots (2)$$

SKYHOOK(SH) AND ADD ALGORITHM

Skyhook Control: Skyhook suspension is a widely studied suspension system in which suspension damper is assumed to be fixed between chassis and sky. According to this configuration damper delivers a force proportional to chassis speed. It has been proven that this configuration has much advantage over other suspension systems [Sergio (2007)].

An on-off damper is a two state damper and it can take either maximum or minimum value of damping. Skyhook algorithm is approximated on the basis of two state dampers and the algorithm can be given as:

$$b_s(t) = \begin{cases} b_{\max}, & \text{if} \quad \dot{x}(\dot{x} - \dot{u}) \ge 0 \\ b_{\min}, & \text{if} \quad \dot{x}(\dot{x} - \dot{u}) < 0 \end{cases} \qquad \ldots (3)$$

ADD Control: The control algorithm for the two state on-off ADD suspension is given as:

$$b_s(t) = \begin{cases} b_{\max}, & \text{if} \quad \ddot{x}(\dot{x} - \dot{u}) \geq 0 \\ b_{\min}, & \text{if} \quad \ddot{x}(\dot{x} - \dot{u}) < 0 \end{cases} \qquad \dots (4)$$

ADD has proven its optimality when the objective is considered as minimizing the vertical acceleration [6]. ADD and skyhook has very similar and very simple models.

A comparative study of ADD and SH control has been done and its simulation result is plotted in Figures 3 and 4

JDD CONTROL AND ITS ANALYSIS

To have a better understanding of JDD working principle and control logic, equation (5) can be analyzed for the different cases of jerk force $m\dddot{x}$,

$$m\dddot{x} = \underbrace{-b_s(\ddot{x} - \ddot{u})}_{A} \; \underbrace{-k(\dot{x} - \dot{u})}_{B} \qquad \dots (5)$$

Equation (5) is the differentiation of equation (2) and a third order differential equation in the term of jerk force. Right hand side of the equation is considered as two part of algebraic term named A' and 'B'.

Case (1): At the any stage of the motion, let us assume that the jerk force is positive or zero and for this value of jerk force, the value of relative acceleration can be positive of negative at any instant. If relative acceleration is positive, then 'A' will be negative quantity and 'B' has to be a relatively big positive quantity. But our goal is not only to satisfy the equation, it is also to minimize the jerk force acting on the sprung mass. The goal can be achieved by increasing the magnitude of 'A' and can be done by replacing b_s by its maximum value.

Now, if relative acceleration is negative, then 'A' will be positive quantity and 'B' has to be either any positive quantity or a small negative quantity to satisfy the equation. If 'B' is any positive quantity, then to achieve the goal we need to minimize the damping value so that A and B together can give a less positive value. And if, 'B' is relatively a small negative quantity then also to achieve the goal, damping should be minimized. So to achieve this minimum value of damping, damper should be in off condition.

Case (2): Similar to the first case, at any instance of motion if the jerk force is negative, the value of relative acceleration can be negative or positive. If relative acceleration is negative, then 'A' will be positive and to satisfy the equation, 'B' has to be a negative quantity and comparatively large in magnitude. To minimize the jerk force, we require a large value of 'A' and it can be achieved by switching damper in its 'on' condition. If the relative acceleration is positive, 'A' will be a negative quantity and to satisfy the equation, 'B' has to be any negative quantity or relatively a small positive quantity. Similar to the first case, to achieve the goal minimum value of damping is required and damper can be set in its off state.

The following set of parameters has been chosen for the simulation purpose: sprung mass m =290 kg, suspension constant stiffness k =16182 N/m. $b_{\max}$ =1000 N.s/m and $b_{\min}$ =300 N.s/m. where $b_{\max}$ and $b_{\min}$ are the maximum and minimum coefficient of on-off damper respectively. The fixed damping of passive suspension is considered equal to the maximum value of damping in semi-active suspension system.

After analyzing both the cases, a control law can be proposed for the JDD suspension which satisfies all the above discussions. The control law is:

$$b_s(t) = \begin{cases} b_{\max}, & \text{if} \quad \dddot{x}(\ddot{x}-\ddot{u}) \geq 0 \\ b_{\min}, & \text{if} \quad \dddot{x}(\ddot{x}-\ddot{u}) < 0 \end{cases} \qquad \ldots (6)$$

For the better understanding of above discussion, one table can be prepared for both the cases.

Table 1: Illustration of the ADD control.

ases	*Jerk Force*	*Relative Acc.*	*Relative Velocity* $(\dot{x}-\dot{u})$	*Damper Condition*	*Damping Value*
1.	$m\dddot{x} \geq 0$	$(\ddot{x}-\ddot{u}) \geq 0$	Negative and larger in magnitude	On	Maximum
		$(\ddot{x}-\ddot{u}) < 0$	Any negative or small positive	Off	Minimum
2.	$m\dddot{x} < 0$	$(\ddot{x}-\ddot{u}) < 0$	Positive and larger in magnitude	On	Maximum
		$(\ddot{x}-\ddot{u}) \geq 0$	Any positive or small negative	Off	Minimum

The jerk of the sprung mass is proportional to the relative acceleration so, computer simulation can be done to get the time response for the vertical acceleration of sprung mass and it has been shown in section (7).

IMPLEMENTATION OF JDD

As described in the section (5), JDD control is based on two signals, relative acceleration and absolute jerk. The JDD suspension can be controlled in the same way as SH suspension is controlled. Song (1999) has mentioned a detailed study of SH suspension control for seat suspension. In the JDD suspensions, a jerk sensor and two accelerometers are used to measure the sprung mass jerk and the absolute acceleration of sprung mass and unsprung mass, respectively. A jerk sensor has been introduced to measure the jerk directly instead of using an accelerometer with rate filter [Yang *et al.* (2008)]. Relative accelerations can be calculated from the absolute acceleration of sprung mass and unsprung mass. As shown in Figure 5, relative acceleration signals and jerk signals are used to JDD control to determine the control voltage in the power stage circuits. Through a power stage circuit, the control voltage is transferred to the corresponding current 'I' for the MR damper. The damping can be changed according to the current 'I'supplied to the damper. The current 'I' which is determined by the JDD control logic can be decided by:

$$I = \begin{cases} \text{On}, & \text{if} \quad \dddot{x}(\ddot{x}-\ddot{u}) \geq 0 \\ \text{Off}, & \text{if} \quad \dddot{x}(\ddot{x}-\ddot{u}) < 0 \end{cases} \qquad \ldots (7)$$

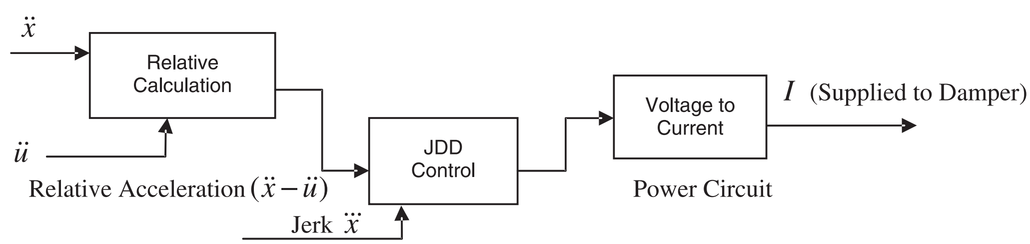

Fig. 5: Implementation of JDD Control in Suspension System

RESULTS AND DISCUSSION

The JDD suspension studied in section (5) is simulated for time response of the sprung mass vertical acceleration and vertical displacement with the maximum time step of 10^{-4} second. The simulation has been done for two different types of road inputs, i.e. a severe speed breaker and a smooth speed breaker shown in Figures 3 and 4. Figure 3 shows the comparison of passive, SH and ADD suspension systems with JDD scheme when the road disturbance is considered as a smooth breaker; whereas, the same comparison has been shown in the Figure 4 where the road disturbance is considered as a severe breaker. The compared result is tabulated below.

Table 2: Comparison of the Numerical Value of Sprung Mass Acceleration for Different Suspensions

Suspension Type	*Max. Disp. with Smooth Breaker in m*	*Max. Acceleration with Smooth Breaker in m/sec^2*	*Max. Disp. with Severe Breaker in m*	*Max. Acceleration with Severe Breaker in m/sec^2*
Passive	0.0694	1.912	0.01677	11.8
SH	0.06947	2.120	0.006865	8.106
ADD	0.07812	2.784	0.01856	4.837
JDD	0.07608	2.106	0.01639	4.179

Table 2 shows the great improvement in comfort objective when the disturbance to the vehicle is severe. The sprung mass acceleration for JDD control is approximately 13.6 per cent less than the ADD suspension when the road input is considered severe. But, when the smooth breaker is the disturbance, the sprung mass acceleration in JDD control is more than the passive suspension but less than ADD suspension and approximately equal to SH control. When the disturbance is severe, the magnitude of the maximum displacement is approximately same in both passive and JDD suspensions, but it is less than the maximum displacement in ADD suspension by 12 per cent. When the disturbance is smooth, the magnitude of the maximum displacement is approximately same in both ADD and JDD suspensions but, more than SH suspension. The above table shows the optimality of SH suspensions on the smooth breaker and shows better isolation of JDD suspensions on severe breaker.

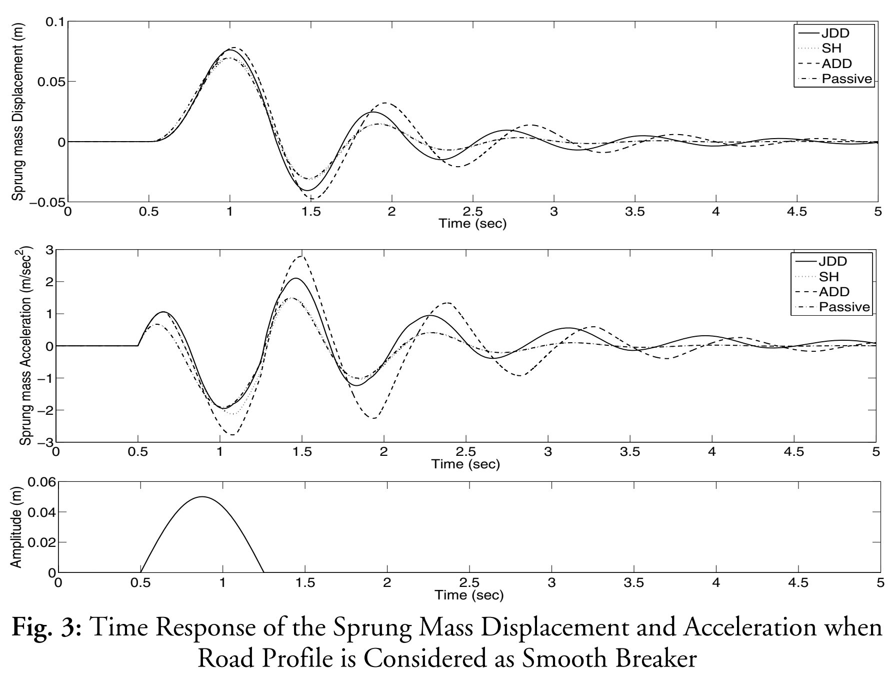

Fig. 3: Time Response of the Sprung Mass Displacement and Acceleration when Road Profile is Considered as Smooth Breaker

Frequency response of passive suspension suggests the use of higher damping at lower frequency and lower damping at higher frequency in order to achieve better performance. In this analysis, we used high damping for both the cases of smooth and severe breakers. This is good only for lower frequencies. From the Fourier transform analysis of smooth and severe breakers, we can see that lower frequency components are present in smooth breaker than in severe breaker. Because of these lower frequency components in smooth breaker, the sprung mass acceleration is least in passive suspension. Higher frequency components of severe breaker result in maximum value of sprung mass acceleration in passive suspension system.

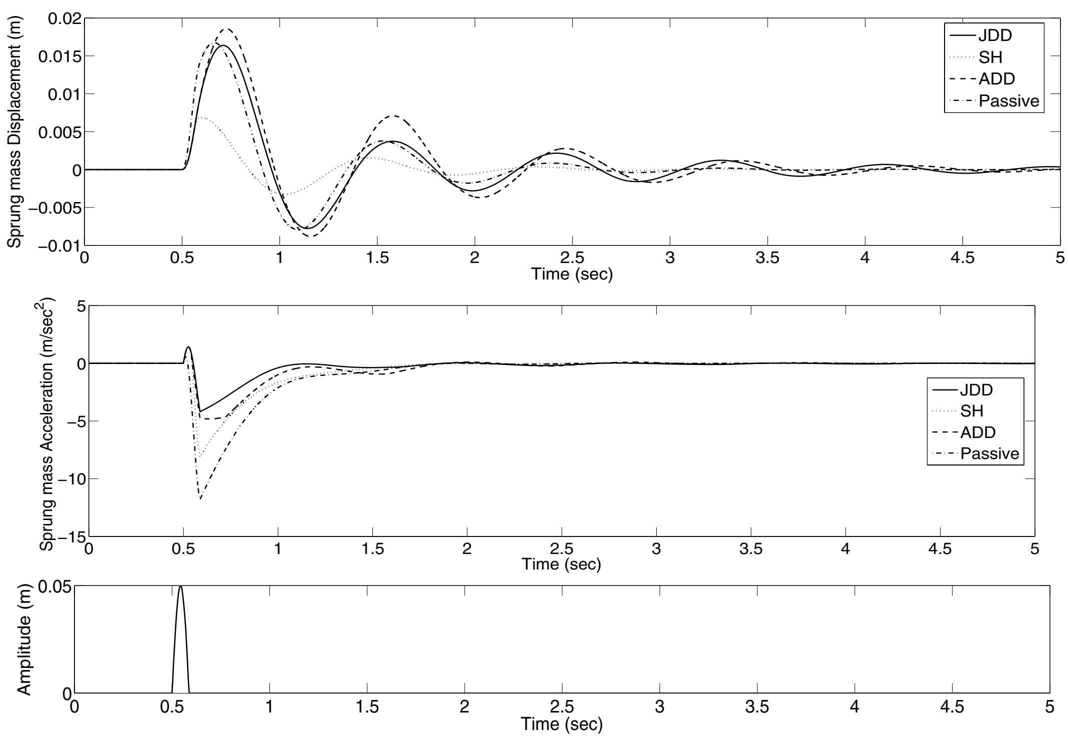

Fig. 4: Time Response of the Sprung Mass Acceleration and Displacement when Road Disturbance is Considered with Severe Speed Breaker

CONCLUSIONS

From the above discussions we can conclude that with the severe speed breaker as input to the vehicle, the JDD suspension gives comparatively better isolation for sprung mass. But, in the perspective of sprung mass displacement, SH control gives always a better isolation. In the case of smooth breaker, all kind of suspension gives approximately same time response for displacement, whereas passive control gives better acceleration response. JDD shows better isolation of acceleration than ADD on smooth breaker. So, we can conclude that on the severe speed breaker, in the perspective of comfort objective, the proposed JDD suspension system shows better isolation than SH and ADD semi-active suspension systems by 48.5 per cent and 13.6 per cent reduction respectively.

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