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OPTIMISATION OF A FUZZY LOGIC CONTROLLER USING GENETIC ALGORITHMS

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Abstract. The scope of this paper is to present an optimised fuzzy logic controller used in suspension system for ground vehicles. The vehicle system is described by linear differential equations subject to many types of road irregularities. The fuzzy logic rules are optimised such that the maximum value of vertical and rotary acceleration of vehicle body at the passengers seats are minimised from the view point of ride comfort under the geometrical constraints of the car. The simulation results show that the proposed fuzzy logic controller improved the vehicle ride comfort.

Key Words. Fuzzy logic controller, optimisation, genetic algorithms, semi-active suspension systems

1. INTRODUCTION

Advanced suspension systems play a vital role in the performance of modern vehicles. They must support the vehicle body, keep the rider's comfort within permissible allowances, retain the vehicle stability during various handling actions, control body and wheel attitude, and minimise the vertical force variation of the road-to-tire contact. Another trade-off exists between the rider's comfort and safety and the economics of producing advanced suspensions. Presently, advanced suspensions implemented in modern vehicles are often described in confusing and conflicting ways. Therefore a great effort is made nowadays to develop or perfect adaptive or active suspension systems for vehicles [1,20]. These systems, compared to the passive ones [7,11,14,18,19], have a superior performance, but are very expensive, technically very complicated, much less reliable, require regular service and some of them consume non negligible quantities of energy. The semi-active system achieves some performance capabilities of fully active systems with components close to passive ones in terms of cost and complexity. The idea was to employ a spring to support the isolated mass in parallel with an adjustable damper whose force-velocity relationship could be modulated. Investigation of active and semi-active suspensions of ground vehicles in transportation is recently increasing [3-6,8,9,12,13,16,17,21-27]. However the semi-active suspensions which are denoted as less expensive alternatives to the active suspensions replace the active force generators by adjustable suspension parts according to the dynamic response of the vehicles.

2. SYSTEM DESCRIPTION

2.1 Notation

stiffness coefficient of springs	$\mathbf{k}_i$
time	$\mathbf{t}$
acceleration	$\mathbf{a}_i$
damping coefficient	$\mathbf{c}_i$
vertical displacement	$\mathbf{x}_i$
sprung mass angle	**è**$_i$
sprung mass	$\mathbf{M}$
sprung mass rotational velocity	**ù**
unsprung mass	$\mathbf{m}_i$
forward velocity	$\mathbf{v}$
velocity	$\mathbf{u}_i$
frequency	$\mathbf{f}$
car body lengths	$\mathbf{L}_i$

Indices

Road surface	**0**
Unsprung mass	**1**
Sprung mass	**2**
Front	**f**
Rear	**r**
sprung mass	**M**

2.2 Vehicle model

We considered a half car model Fig. 1. The elastic coefficient for tyre is k_1=155900 [N/m] and the damping coefficient is c_1=2500 [Ns/m]. The sprung mass is m_2=580 [kg], the mass inertia J=400[kg.m^2] and the unsprung mass m_1=29 [kg].

The system of differential equations of motion for both linear models can be brought in the form:

$$
\begin{aligned}
\dot{x}_{1f} &= u_{1f} \\
\dot{x}_{1r} &= u_{1r} \\
\dot{x}_{M} &= u_{M} \\
\dot{q}_{M} &= w_{M}
\end{aligned}
$$

$$
\begin{aligned}
\dot{u}_{1f} &= [k_{1f}(x_{0f} - x_{1f}) + k_{2f}(x_M + q_M L_1 - x_{1f}) + \ldots \\
&\ldots + c_{1f}(u_{0f} - u_{1f}) + c_{2f}(u_M + w_M L_1 - u_{1f})]/m_{1f} - g \\
\dot{u}_{1r} &= [k_{1r}(x_{0r} - x_{1r}) + k_{2r}(x_M - q_M L_2 - x_{1r}) + \ldots \\
&\ldots + c_{1r}(u_{0r} - u_{1r}) + c_{2r}(u_M - w_M L_2 - u_{1r})]/m_{1r} - g \\
\dot{u}_{M} &= [k_{2f}(x_{1f} - x_M - q_M L_1) + k_{2r}(x_{1r} - x_M + q_M L_2) + \ldots \\
&\ldots + c_{2f}(u_{1f} - u_M - w_M L_1) + c_{2r}(u_{2r} - u_M + w_M L_2)]/M - g \\
\dot{w}_{M} &= L_1 k_{2f}(x_{1f} - x_M - q_M L_1) - L_2 k_{2r}(x_{1r} - x_M + q_M L_2) + \ldots \\
&\ldots + L_1 c_{2f}(u_{1f} - u_M - w_M L_1) - L_2 c_{2r}(u_{2r} - u_M + w_M L_2)]/J
\end{aligned}
$$

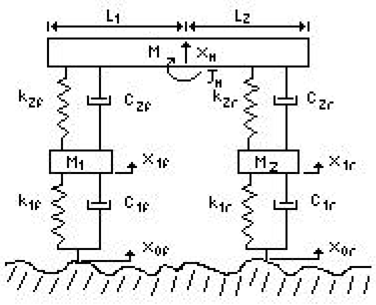

Fig.1 Half car model

2.3 Road excitations

Excitations by road irregularities can be considered, either deterministic or random. In the following, we focused our interest to two of them corresponding to the transition of obstacles: step function and harmonic excitation.

The step function excitation that we considered is:

$$
x_{0f}(t) = \begin{Bmatrix} 0 \ldots\ldots\ldots t < 0.5 \\ vt \ldots\ldots 0.5 \le t \le 0.5 + \dfrac{0.06}{v} \\ 0.06 \ldots. t > 0.5 + \dfrac{0.06}{v} \end{Bmatrix}
$$

The quasi-impulse excitation due to road irregularities is:

$$
x_{0f}(t) = \begin{Bmatrix} 0 \ldots\ldots\ldots\ldots\ldots t < 0.5 \\ A[1 - \cos(2\pi f(t - 0.5))] \ldots\ldots 0.5 \le t \le 0.5 + \dfrac{1}{f} \\ 0 \ldots\ldots\ldots\ldots\ldots t > 0.5 + \dfrac{1}{f} \end{Bmatrix}
$$

which is a cosine shaped bump of height 0.04m (peak to peak), with a wavelength proportional to the forward velocity of the car.

2.4 Solution of Equations

The system of differential equations of motion of the model was solved numerically on a PC-Pentium III computer. The Matlab 5.3 program was used to perform the numerical simulations. Since it is necessary to solve the equations at each step of the optimisation process, it is important to select an appropriate and fast solution method. Our preference was for the Runge - Kutta fourth order method with a variable time step. Convergence to the solution did not present any problem.

3. FUZZY LOGIC CONTROL

A semi-active suspension to be proposed here is realised by changing the damping coefficients of the front and rear dampers. Each fuzzy controller makes use of six inputs, three from the front and three from the rear suspension sensors:

- unsprung mass acceleration a_{1i}
- sprung mass acceleration a_{2i}
- suspension travel $x_{12}=(x_1-x_2)$.
- relative velocity of sprung-unsprung mass

In Fig. 2 & 3 are shown the initial membership functions for the eight inputs and the output. The data that define these fuzzy sets compose the initial vector for the optimisation procedure. The abbreviations at the input membership functions stand respectively for: large negative (L-), small negative (S-), very small (VS), small positive (S+) and large positive (L+). The use of two-sided Gaussian membership functions instead of standard trapezoidal ones achieved a smoother response and eliminated a problem of slight unsteadiness in the region of 'small' excitations.

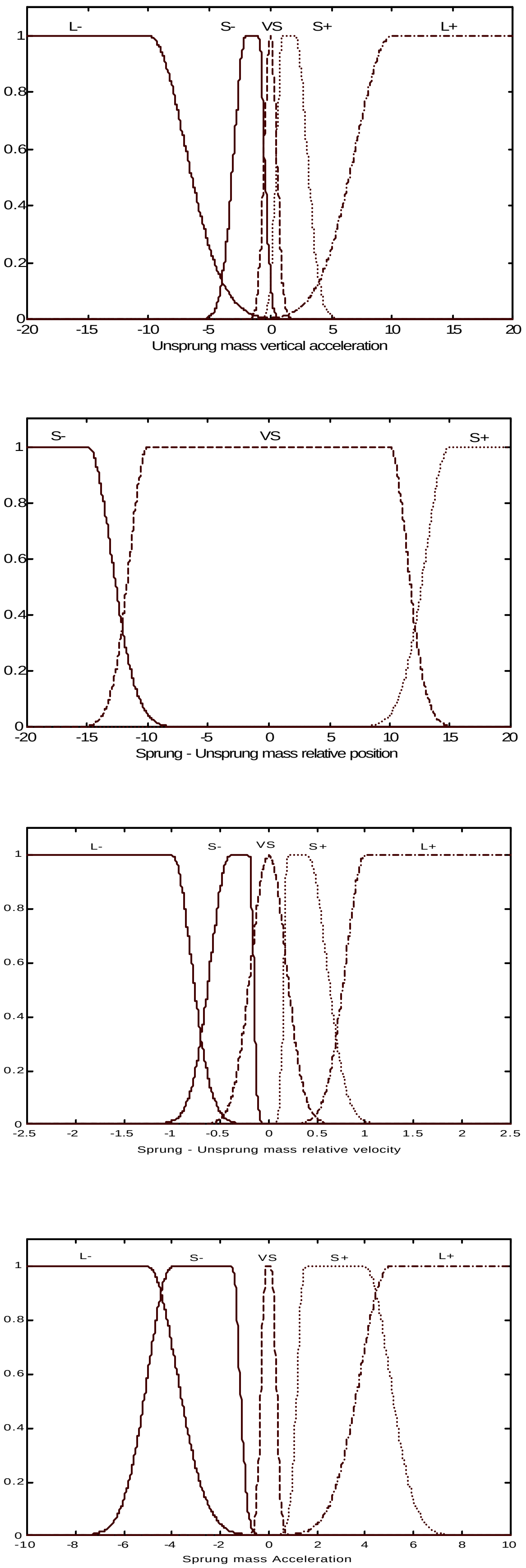

Fig.2 Input membership functions

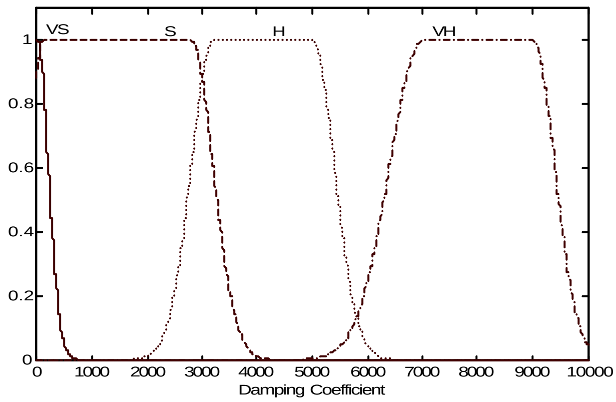

Fig.3 Output membership functions

Each non-symmetric side of the Gaussian membership functions is a parameter for the optimisation procedure. The main objective in designing and optimising the fuzzy controller was increasing passenger comfort i.e. minimising the sprung mass linear and rotational acceleration. The goal is to absorb the energy due to the road excitation in the least time and with the least sprung mass acceleration. The fuzzy rules for the front half–car controller and the rear half-car controller, shown in Table 1, describe strategies to handle each case.

Table1.Fuzzy Rules

A_{1f}	A_{2f}	X_{12f}	U_{12f}	A_{1r}	A_{2r}	X_{12r}	U_{12r}	C_{2f}	C
	S+ or L+		S- or L-					VS	
	S- or L-		S+ or L+					VS	
	S+ or L+		S+ or L+					VH	
	S- or L-		S- or L-					VH	
VS	VS	VS	VS					S	
					S+ or L+		S- or L-		V
					S+ or L+		S+ or L+		V
					S- or L-		S+ or L+		V
					S- or L-		S- or L-		V
				VS	VS	VS	VS		S
	S+		S-		S-		S+	H	H
	S-		S+		S+		S-	H	H

4. REGENERATIVE EVOLUTION STRATEGY

The novel *Regenerative Evolution Strategy* (RES) used to determine the parameter vector **w** is based on the two membered (one parent and one offspring) method [15]. It is the minimal concept for an imitation of organic evolution and the two principles of mutation and selection are taken as rules for variation of the parameters and for recursion of the iteration sequence. Fitness of individuals is measured by means of an objective function to be minimised. However, although theoretically, the “asymptotic” convergence (whatever “asymptotic” means) of the algorithm towards the global optimum is assured, its performance and its ability to reach the global optimum in practical applications is not been proven.

Therefore, a *Regenerative Evolution Strategy* is proposed, that includes:

- a *deterministic* choice of the parent vector and in
- an *iterative* use of the evolution (mutation, selection) algorithm.
- an *adaptation* of the search space according to the number of successful mutations

In the initialization phase of the new method, the parent vector **w**(0) which determines the exact shape of the fuzzy sets is chosen according to our intuition, our experience and the dynamic system’s specifications.

At the time the search algorithm has converged to a value **w**(1), it is not expected or assumed that the method has converged towards the global optimum. It is therefore necessary to *regenerate* the evolution algorithm. The regeneration is activated, by

- *increasing* the initial value of the standard deviation ó (two or three times more than its $ó_{initial}$ initial value) and by
- *restarting* the optimization procedure assuming that the last found vector **w**(1) is the new starting vector.

The iterative use of the procedure increases the probability to identify the global minimum. The new method has been already successfully applied to a number of parameter optimization problems and has reached the global optimum in all investigated cases, while the Evolution Strategy failed [10].

The flow chart of the *Regenerative Evolution Strategy* is shown in the following. If the value of the standard deviation becomes too small, the method is regeneratively applied (increase of the standard deviation and restart the optimisation procedure):

Regenerative Evolution Strategy Flowchart

Step 1 :Let $w_1 = w_{initial}$, $s = s_{initial}$, i = 0 , k = 0 , suc = 0

Step 2 : Compute $f(w_1)$

Step 3 : $w_2 = R(P(w_1, s), k)$, $k \in [0,1]$,

$$P(x, w_1, s) = \frac{1}{s\sqrt{2p}} \exp\left[-\frac{1}{2}\left(\frac{x - w_1}{s}\right)^2\right]$$

Step 4 : i = i + 1 , k = k +1

Step 5 : Compute $f(w_2)$

Step 6 : if $f(w_2) < f(w_1)$ then $w_1 = w_2$, suc = suc + 1

Step 7 : if k = 5n
if suc > k / 2 then $s = s / 0.85$
else $s = s * 0.85$
suc = 0 , k = 0

Step 8 : **Regeneration :** if $s < e$ then
$s = s_{initial}$

Step 9 : if termination criterion satisfied then END
else goto **Step 3 .**

The vector to be optimised contains the data of the two-sided non-symmetric Gaussian membership functions.

Geometrical constraints were applied, regarding the relative displacements of the different masses of the model, in order not to have design incompatibilities in the working space of the suspension:

$$|x_2 - x_1| < 0.15m \quad \text{and} \quad |x_1 - x_0| < 0.08m$$

5. NUMERICAL RESULTS

In Fig. 4 & 5 we present numerical results to quasi-impulse excitation. The vehicle velocity is kept constant at 10m/s and the cosine frequency 8Hz.

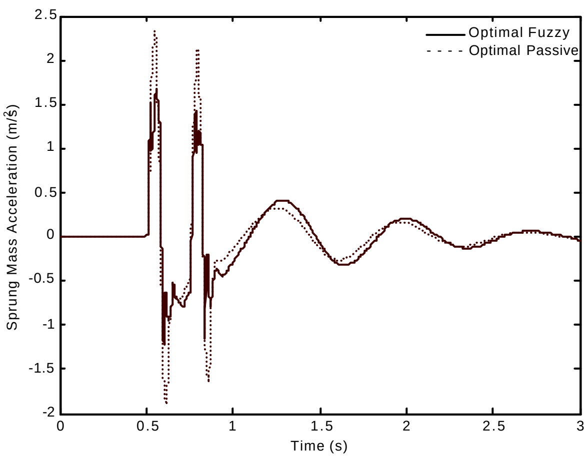

Fig.4 Sprung mass vertical acceleration

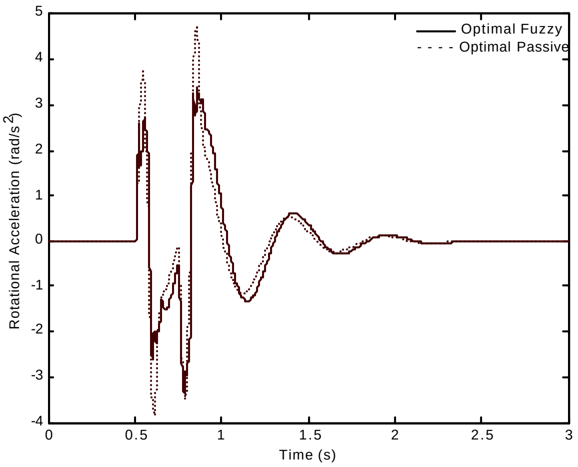

Fig.5 Sprung mass rotational acceleration

In Fig. 6 & 7 we present numerical results to step excitation. The vehicle velocity is kept constant at 10m/s.

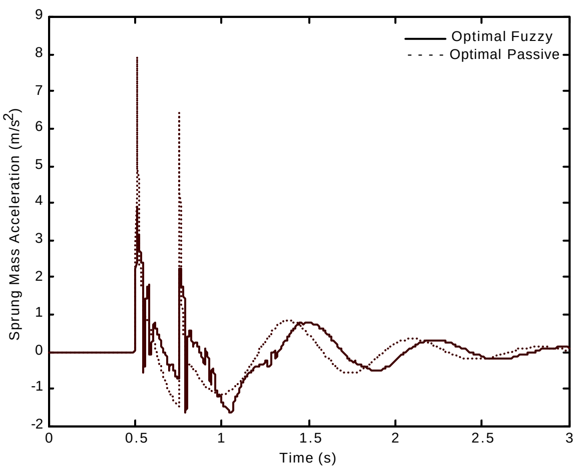

Fig.6 Sprung mass vertical acceleration

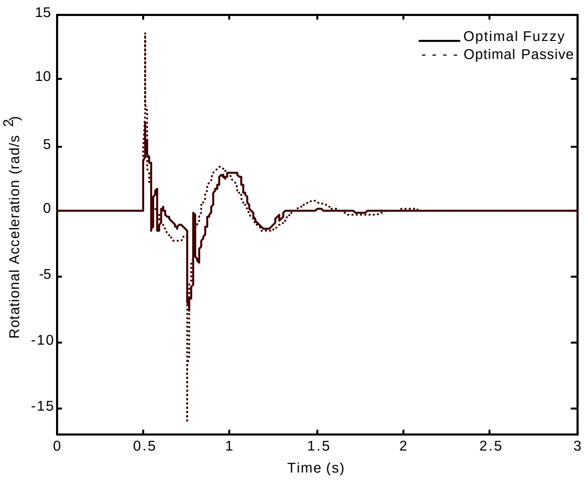

Fig.7 Sprung mass rotational acceleration

As can be seen, the peak value of the suspended mass linear and rotational acceleration is neatly improved in the case of the semi-active half car model with fuzzy controller, compared to the optimised passive one. The semi-active model achieves equivalent or even better results in other performance criteria, such as peak pitching angle and settling time.

6. CONCLUSIONS

This paper proposed the construction of a fuzzy logic controller for use in passenger cars. The sprung and unsprung mass accelerations, the suspension travel and its time derivative were treated as the input variables and the damping coefficient of the suspension was adjusted as the output variable in the fuzzy control rules at every suspension location.

The performance of this suspension system was evaluated by considering a half car model and was proved to contribute greatly to the reduction of the peak acceleration of the suspended mass. The simulation results indicate that the proposed semi-active suspension is much improved in vertical and rotational acceleration. A future extension is planned by considering full car model with preview.

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