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Three Control Approaches for the Design of Car Semi–Active Suspension (Optimal Control, Variable Structure Control, Fuzzy Control)

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Abstract

The design of active or semi–active suspensions for modern cars is subject to real time contradictory requirements concerning on one hand ride comfort and on the other hand road holding and handling. However, due to the limitation of design methods for non–linear systems, the design of the suspension is done on the base of linear multivariable model; the performance is tested by simulation on more realistic models including non–linearities and delays. In this paper, we present, through the use of quarter car model, the design of semi–active suspension with Optimal Controller, Variable Structure Controller and Fuzzy Controller. The efficiency of the approaches and the performance of the different controllers are compared. Experiments of these threes approaches have been conducted by real experiments on a bench test end this paper.

1. Introduction

The use of electronic system for, mainly, engine control and chassis functions is increasing each year. Among different chassis function we consider in this paper, the suspension problem with three pattern realizations : passive suspension (the classical one with fixed characteristics of the spring and the damper) semi–active suspension (essentially the damping factor can change according to the running conditions of the car) active suspension (an extra force provided by an external power system is applied between the wheels and the body of the car). We will restrict our attention to the semi–active suspension and want to adopt in real time, by a closed loop system, the damping factor of the damper in the suspension system composed by a spring and the damper. For this, we consider three automatic control approaches well suited to the characteristics of the problem. In the rest of the paper we present the model of the system, the three methods and their applications both on simulation and on a real test bench.

2. Modeling

The design of an automatic suspension is often based on the following system (a "quarter of car ") and the model associated to it (see Fig. 1):

$$M_2\ddot{Z}_2 = -k_2(Z_2-Z_1) - c_2(\dot{Z}_2-\dot{Z}_1) + u \qquad (1)$$
$$M_1\ddot{Z}_1 = k_2(Z_2-Z_1) + c_2(\dot{Z}_2-\dot{Z}_1) - u - k_1(Z_1-Z_0) - c_1(\dot{Z}_1-\dot{Z}_0)$$

Z_0, Z_1, Z_2 are vertical position measured from an equilibrium position. It is convenient to choice as state variables:

$$X_1 = Z_2 - Z_1;\; X_2 = \dot{Z}_2;\; X_3 = Z_1 - Z_0;\; X_4 = \dot{Z}_1$$
$$X = [X_1\; X_2\; X_3\; X_4]^T \qquad (2)$$

And to get a state space model :

$$\dot{X} = AX + Bu + Gw \qquad (3)$$

Where u is the force applied by an additional device between wheel and body and w is a road disturbance ($w = \dot{Z}_0$); A, B, G matrices of appropriate dimensions.

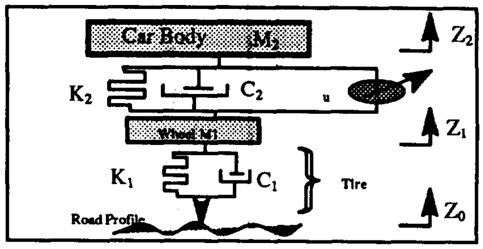

Fig.1 – A quarter car system

3. Optimal Controller

The force u is given by an additional damper with a variable damping factor and takes the form :

$$u = -C_2(t)[\dot{Z}_2 - \dot{Z}_1] = -C_2(t)[X_2 - X_4] \qquad (4)$$
$$= -C(t)[X_2 - X_4]$$

The model of the system becomes a bilinear model with respect to the "new" control variable C(t) :

$$\dot{X} = AX + B_c(X).C + Gw \qquad (5)$$

In term of physical variables (Fig 1), a common criterion to search for a compromise between comfort and road handling can be :

$$J = \frac{1}{2}\int_0^\infty [\ddot{Z}_2^2 + q_1(Z_2-Z_1)^2 + q_2\dot{Z}_2^2 + q_3(Z_1-Z_0)^2 + q_4\dot{Z}_1^2]dt \qquad (6)$$

where q_i (i = 1 à 4) are weighting factors i.e. design parameters. According to the state model, the criterion can be re–written as :

$$J = \frac{1}{2}\int_0^\infty [X^T Q_n X + X^T Q_c X] dt \qquad (7)$$

Where only the matrix Q_c depends on the control variable c(t). Applying the calculation of variation to the minimization of J with respect to c, under the state model constraint, with or without inequality constraint on c(t) gives a closed loop solution, c(X), through the resolution of a special type Riccati equation.

4. Variable Structure Controller

With this approach, we consider that the additional force is given by a damper with two characteristics (hard and soft for example). Then the control takes the form :

$u = u_{max}$ if $S(x) > 0$; $S(x) = K^T X$ $u = u_{min}$ if $S(x) < 0$

When the trajectory of the system, in the phase plane, encounters the sliding surface $S(x) = 0$, a sliding mode is defined on $S(x) = 0$ under the condition $S\dot{S} < 0$ .During the sliding mode $S(x) = 0 \rightarrow \dot{S}(x) = 0 \rightarrow K^T\dot{X} = 0$

$\dot{S}(x) = 0 = K^T\dot{X} = -K^T(AX + Bu + Gw) = 0$ .Then an equivalent control and an equivalent closed loop system can be defined during this sliding mode:

$$u_{eq} = -(K^T B)^{-1}[K^T AX + K^T Gw] \qquad (8)$$

$$\dot{X}_{eq} = AX_{eq} + Bu_{eq} + Gw \;= A^* X_{eq} + G^* w \qquad (9)$$

with

$A^* = [1 - B(K^T B)^{-1} K^T]A$; $G^* = [1 - B(K^T B)^{-1} K^T]G$

Through A^*, by a pole assignment technique, the vector K can be determined.

5. Fuzzy Controller

The philosophy with the fuzzy control is to take again into account some constraints on the actuator but doing this only with expertise and experience on the system, without using mathematical models. These expertise and experience are converted into fuzzy production rules and an on line fuzzy reasoning is made on these rules in order to get a solution for each situation encountered in real time. The used approach is similar to the MAMDANI's approach ; additionally, the two time scale properly of the system has been exploited designing a slow controller for the body , essentially comfort oriented and a fast controller , for the wheel, essentially road handling oriented, a fuzzy compromise between the two controllers is realized by a supervisor able to integrate general information on the vehicle.

6. Experiments

Experiments of these three approaches have been conducted in two ways : a) by simulation using non linear models of the system including delays, hysteresis, dynamics of the sensor and actuator, and performed on EASY5^{TM}/,. b) by real experiments on a test bench. Results in both situations are really in concordance (see some results in Fig 2 à 4).

7. Conclusions

Our work has been oriented toward the design of semi–active suspension using different tools to our disposal from the automatic control field. To take into account some constraints on the actuator and some specify of the problem we have considered three control techniques: optimization under constraint, variable structure control, and fuzzy control. These three approaches have been tested by simulation on realistic non linear models of the process and on a real test bench. Results are really satisfactory. As a future work, we will consider a general attitude control of a complete vehicle.

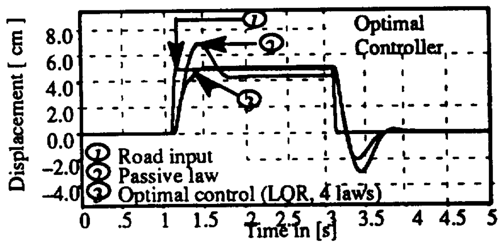

Fig.2 – Bench test results (optimal controller)

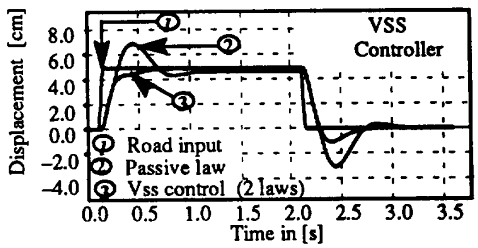

Fig.3 – Bench test results (VSS controller)

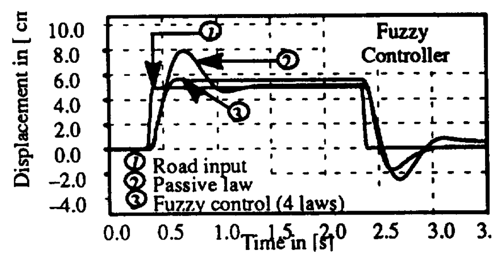

Fig.4 – Bench test results (Fuzzy Controller)

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