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Output Feedback vs. State Feedback Controllers in Weighted Multiple Model Adaptive Control for Mechatronic Suspension System

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ABSTRACT

In control design process of vehicle mechatronic suspension systems, the uncertainties and nonlinearities of the system are important problems which need to be tackled to avoid poor performance or even possible instability of the closed loop system. To overcome these challenges, in this work, a weighted multiple model adaptive control (WMMAC) approach is proposed and developed for mechatronic suspension system. Two schemes, output feedback (PID) and state feedback (LQG) candidate controllers corresponding to four operating mode conditions were optimally designed a priori, are designed. A multi-controller generates a control input made up of the sum of weighted values of all candidate controllers. Simulation tests demonstrated that the system produces significantly improved performance compared to passive suspension systems. In addition, the RMS measurements and the performances of these schemes are summarised as well as they are compared against passive system. The proposed design showed remarkable improvements in ride comfort and safe handling for mechatronic suspension system.

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INTRODUCTION

In the automotive industry, mechanical systems of the car, are being revolutionized into mechatronic systems (Schöner, 2004). These include the development of mechatronic suspension systems (Fischer, 2004; Fu-Cheng, 2008; Sankaranarayanan, 2008) as practical realizations of active and semi-active suspensions.

Adaptive control methods based on switching of fixed controller parameters, also known as Multiple Model Adaptive Control (MMAC) have, in recent times, received the attention of the control community. Early work on this type of control was for use in the F-8C aircraft (Athans, 1975).

In this work, we implement PID & LQG WMMAC mechatronic suspension system where the candidate controllers correspond to uncertainties in both, the vehicle sprung mass and the road profile input. The benefit of this approach is in that it provides greater flexibility by not being limited by a time-invariant control law. Given that the sprung mass and road profile may vary widely during vehicle operation, a fixed control law may not provide optimal performance over the whole parameter range. Conservative adaptive control systems are only adaptable to small parameter changes, but MMAC provides the ability to cope with sudden parameter variations and WMMAC maintains performance over intermediate modes for which the candidate controllers were not optimized.

Suspension model:

A quarter car suspension model, as shown in Figure 1, was used in this study. From Newton's second law of motion, this system can be described by the state space model given by:

$$\begin{aligned}\dot{x}(t) &= A_i x(t) + B_i u(t) + L_i r_p(t) \\ y(t) &= C_i x(t) + D_i u(t) + w\end{aligned}\quad (1)$$

where A_i, B_i, L_i, C_i, D_i are system parameters for $i = 1..n$ modes, hence n is the number of models. The vehicle parameters of quarter car suspension system model are shown in Table 1.

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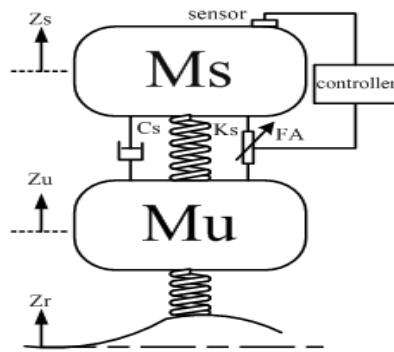


Fig. 1: Quarter car suspension model.

Table 1: Model parameters.

Parameter	Value	Units
m_{s1}, m_{s2}	280,380	[kg]
m_u	35	[kg]
k_s	16000	[N/m]
k_t	160000	[N/m]
c_s	1000	[Ns/m]

Probability estimation and weighted control input:

In this work, a probability estimator was used to provide weights for the control inputs coming from each candidate controller. Assume a first order Markov chain with probability P , from time t to time $t + \tau$. Let μ_{ij} be the probability of a transition from candidate model i to candidate model j , defined by:

$$P\{m_j(t + \tau) | m_i\} = \mu_{ij}(t) \quad , \quad \sum \mu_{ij} = 1 \quad (2)$$

where m_i denote model i and n is candidate models.

The weight μ is an array of continuously updated probability values for the candidate models. For any candidate model i , μ_i may take a value in the range of 0 to 1, where 0 implies a complete mismatch and 1 indicates a perfect match between the operating condition dynamics and that of candidate model i .

Assume that the starting point is a no load condition, i.e. the sprung mass is at the minimum operating value and the road profile is very smooth. Then, all candidate controllers are assigned equal weights;

$$\mu_i(0) = \frac{1}{n}.$$

The estimated probability weight at time t is then given by

$$\mu_i = \left(\frac{1}{(y - y_i)^2} / \left(\sum_{i=1}^n \frac{1}{(y - y_i)^2} \right) \right) \quad , \quad i = 1, \dots, n. \quad (3)$$

where y is the actual plant output and y_i is the output of candidate model i . A moving average window is used to filter out noise. Hence,

$$\hat{\mu}_i(t) = 0.98\hat{\mu}_i(t - \tau) + 0.02\mu_i(t) \quad (4)$$

subject to the constraints

$$\hat{\mu}(t) = \sum_{i=1}^n \hat{\mu}_i(t) \quad \text{and} \quad 0 \leq \hat{\mu}_i(t) \leq 1 \quad (5)$$

For every candidate model, an optimal state feedback controller is designed to produce acceptable plant performance over the operating region to which it is assigned. The actual control input is a weighted sum of all the controller signals.

$$d_{sd}(t) = \sum_{i=1}^n \hat{\mu}_i u_i(t) \quad (6)$$

where $d_{sd}(t)$ is the actuator control force and u_i is the control signal from controller K_i , corresponding to candidate model i .

Multicontroller design:

To ensure overall stability, the candidate controllers were designed according to the rules and conditions of AMC (Kuipers&Ioannou 2010). The multicontroller transfer function is given by

$$K(s, \mu, d_{sd}(t)) = C_c(\mu, d_{sd}(t)) (sI - A_c(\mu, d_{sd}(t)))^{-1} B_c(\mu, d_{sd}(t)) \quad (7)$$

where s is the Laplace variable. The control law is then given by

$$u(t) = -K(s, \mu, d_{sd}(t)) e(t) = -\sum_{i=1}^n \mu_i K_i e(t) \quad (8)$$

where $r(t)$ is the reference input.

Simulation tests:

When the two PID-WMMAC and LQG-WMMAC schemes are subjected to excitation of real road profile during 20 (seconds), the RMS measurements' values and the performances of each scheme compared to passive suspension system are obtained as shown in Table 2. The table indicates that both schemes have significant results compared to passive system.

Table 2: PID and LQG WMMAC vs. passive performances compression.

	Passive System	PID WMMAC	LQG WMMAC
$\ \ddot{Z}_S\ _{RMS}$ Performance	1.13 m/s ² -	0.826 m/s ² 26.25%	0.54 m/s ² 51.93%
$\ F_{tf}\ _{RMS}$ Performance	924.5 N -	509.5 N 44.9%	584.3 N 36.8%
$\ Z_S - Z_u\ _{RMS}$ Performance	0.0067 m -	0.0036 m 45.45%	0.0057 m 15.27%

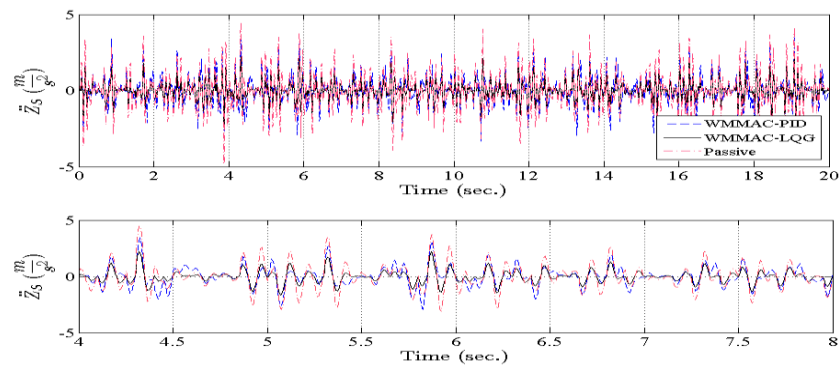


Fig. 2: Body acceleration responses of both schemes versus passive system.

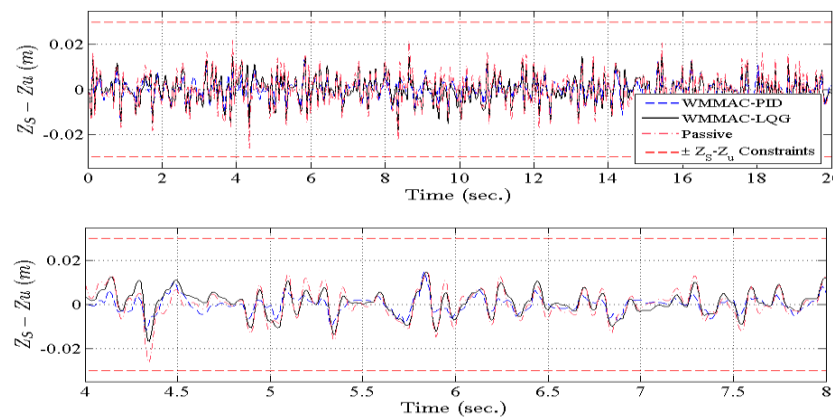


Fig. 3: Suspension deflections responses of both schemes vs. passive system.

It could be seen that PID-WMMAC has high performances on tyre force and suspension deflection in comparison with LQG-WMMAC. At the same time, the ride performance is much better in LQG-WMMAC. Accordingly, the main goal of this study is to achieve ride comfort as well as not to lose too much of handling

(Tyre force). In fact, these results show the right logic in which the two schemes were proposed. The first scheme (PID-WMMAC) was proposed to control the suspension system when subjected to single bump/step road profile, while the second scheme (LQG-WMMAC) was proposed to control the suspension system when subjected to random stochastic road profile, which is applied in this run.

Figures 2-4 illustrate the relevant measurement signals of an exemplary interval of real road profile in comparison with the measurement signals of the passive system. The findings reveal that the two WMMAC schemes; PID and LQG show significant performances. The peaks of the body acceleration signal and the suspension deflection parameter are significantly reduced. The tyre force parameters show a slight reduction without losing its role. The slight increase of the limits (given as red dotted lines) on the tyre force and the suspension deflections are kept and the actuator does not saturate.

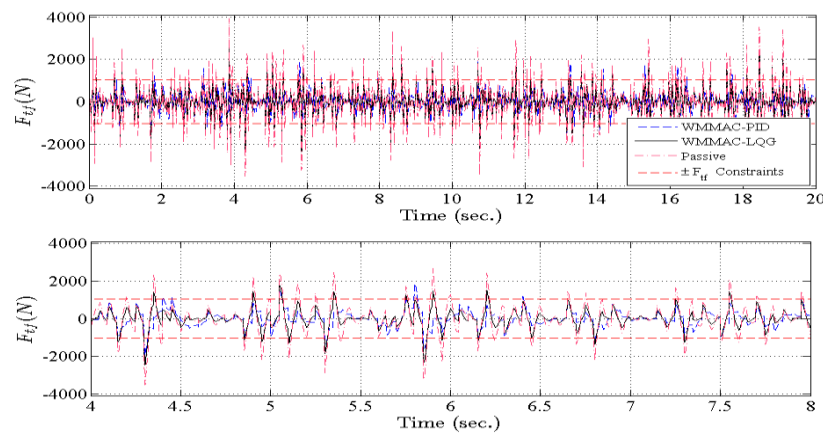


Fig. 4: Tyre force responses of both schemes vs. passive system.

Conclusion:

We have presented an implementation of WMMAC in a mechatronic suspension application. A model of quarter car suspension was used and the candidate controllers were based on sprung mass values and road profile types. PID and LQG of WMMAC schemes were implemented. Simulation tests were performed with the system subjected to varying sprung mass values, road height profiles and vehicle velocity. The RMS measurements and performances comparisons between these two schemes were discussed. The results showed that the WMMAC suspension system produced markedly improved performance compared to passive systems. In future, the WMMAC suspension will be tested against half and full car models suspensions.

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