Expert Systems with Applications xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Intelligent road adaptive suspension system design using an experts' based hybrid genetic algorithm

Stratis Kanarachos [a,*], Andreas Kanarachos [b]

[a] Faculty of Engineering & Computing, Coventry University, Coventry CV12JH, UK
[b] Mechanical Engineering Department, Frederick University, Nicosia 1093, Cyprus

A R T I C L E I N F O

Article history:
Available online xxxx

Keywords:
Intelligent suspension system
Road adaptive
Hybrid genetic algorithms

A B S T R A C T

There is an increasing demand for vehicles suitable for both on and off road driving characterized by superior comfort and handling performance. This is problematic for most suspension systems because there is a trade off balance between vibration reduction, suspension travel, actuator effort, road holding capability, as well as noise and fatigue requirements. Only in the UK every 11 min a car is getting damaged because of potholes. In this paper, a method to design an intelligent suspension system with the objective to overcome the trade-off barrier using the smallest actuator is presented. An experts' based algorithm continuously monitors the road excitation in relation to the suspension travel and adapts accordingly the suspension system. It is shown that by applying genetic algorithm it is possible to optimally tune the system. However, the global optimum is hard to find due to the problem nonlinearity. A hybrid genetic algorithm that improves the probability of successfully finding the best design is presented. The simulation results show that the proposed intelligent system performs for – well known in the literature scenarios – better than others and remarkably this is achieved by reducing the actuator's size.

1. Introduction

There is an increasing demand for vehicles suitable for both on and off road driving characterized by superior performance. Only in the UK every 11 min a car is getting damaged because of potholes. The major design targets of a vehicle suspension system are to isolate the driver and vehicle from road irregularities such as a bumps, pot holes, unpaved surfaces and to maximize its road holding performance (Song, Zhao, Wang, & Niu, 2014). It is well known that a linear passive suspension system cannot satisfy all requirements simultaneously. A passive soft suspension will reduce acceleration and maximum road induced forces at the cost of increased wheel hopping, which eventually reduces road grip. The opposite happens with a hard suspension. Many solutions such as active and semi-active suspension have been proposed in the past (Gohrle, Schindler, Wagner, & Sawodny, 2014). In view of the complexity and power demands for active suspension systems the design interest nowadays is focusing on semi-active suspensions. These seem to cope with the latest demands for car production, customer interests and needs and also with the latest developments in the area of electronics, sensors, tunable dampers and magneto- and electro-rheological actuators (Poussot-Vassal, Spelta, Sename, Savaresi, & Dugard, 2012).

Previous research focused more on suspension feedback control and has been investigated extensively in the last decade for active and semi-active suspension concepts. There exist various control concepts like the linear-quadratic (LQ) state-vector feedback, neural networks, clipped control, $H\infty$ controllers, fuzzy control, etc (Brezas, Smith, & Hoult, 2015; Kanarachos, 2012; Soleymani, Montazeri-Gh, & Amiryan, 2012; Tung, Juang, Lee, Shieh, & Wu, 2011; Tusset, Rafikov, & Balthazar, 2009). In conclusion, all control concepts aim at introducing additional forces to the suspension system, while the physical structure of actuators and sensors determines the final control system design.

Designing a suspension system is generally a hard task because the problem is multi-objective and highly nonlinear due to system's nonlinearities like limits of the rattle space distance, of the actuators dynamics (power and force limits), the nonlinearities embedded in the control law and also fatigue requirements (amplitude and number of cycles). A powerful tool for solving such problems is experts' knowledge and global optimization (Kanarachos, Koulocheris, & Spentzas, 2005). For example, in passive suspension system design particle swarm optimization and genetic algorithm were innovatively combined for Pareto optimal design of a five-degree of freedom vehicle vibration model (Mahmoodabadi, Adljooy Safaie, Bagheri, & Nariman-Zadeh, 2013). Poussot-Vassal

* Corresponding author. Tel./fax: +44 (0)2477657720.
E-mail addresses: stratis.kanarachos@coventry.ac.uk (S. Kanarachos), eng.ka@frederick.ac.cy (A. Kanarachos).

http://dx.doi.org/10.1016/j.eswa.2015.06.047
0957-4174/© 2015 Published by Elsevier Ltd.

Nomenclature

m_1	sprung mass
m_2	unsprung mass
c_1	damping constant
D	artificial damping constant
k_1	spring constant
k_2	tire vertical stiffness
z_0	road disturbance
z_1	sprung mass displacement
z_2	un-sprung mass displacement
$\tilde{z}_R$	estimated rattle space distance
$z_0(t)$	road disturbance
$z_{0d}(t)$	deterministic road disturbance
$z_{0r}(t)$	stochastic road disturbance
$z_{R\text{lim}}$	rattle space distance limit
$z_{t\text{lim}}$	tire deflection limit
f_{act}	actuator force
$f_{c\text{lim}}$	actuator force limit
f_c	control force
T_{act}	actuator force time constant
T_{pred}	control law constant
z_{switch}	control law constant
$f_{act\text{lim}}$	control law constant
$\dot{u}$	control input rate
u	control input
v	parameter set

Subscripts

i	iteration
opt	optimized
μ	mean value
σ	standard deviation

Superscript

j	population member

et al. (2008) formulated the semi-active suspension design as a Linear Parameter Varying Problem and solved the resulting Linear Matrix Inequalities problem using genetic algorithm. In active suspension evolutionary algorithms, such as the cultural and niche algorithm, were combined to design a Fuzzy-PID controller and optimize control rules (Wang et al., 2015).

Although standard control design methods add valuable knowledge to the design of a vehicle suspension system, the problem itself is a system design problem with non-negligible nonlinearities, which – and this is interesting – can positively contribute to the optimization of the design. A step in this direction was taken in (Huang, Lin, & Chen, 2010) in which a road adaptive suspension system is presented. That line of thought is extended in this paper by designing an intelligent road adaptive suspension system. An experts' based algorithm continuously monitors the road input in relation to the suspension travel and determines the system behavior. The main objective is to optimize system performance, overcome the trade-off barrier and minimize the size of the actuator. A large actuator has increased space requirements, is noisier, consumes more energy and induces higher loads to the vehicle structure. The overall system performance is optimized using genetic algorithm. It is shown that the direct application of genetic algorithm does not always lead to the optimum solution. In this context, an automated design procedure that improves the probability of success has been developed and is described. The simulation results show that the proposed intelligent system performs better for – well known in the literature scenarios – than others and remarkably this is achieved by reducing the actuator's size.

The rest of the paper is organized as follows: In Section 2 the mathematical model of the vehicle is presented. In Section 3 the intelligent suspension system is explained. The numerical results are illustrated and discussed in Section 4. In Section 5 details and practical guidelines on how to apply the genetic algorithm are given. In Section 6 conclusions and future research directions are drawn.

2. The system model

2.1. The quarter-car model

When suspension modeling and control are considered, the well-known vertical quarter-car model is often used (Brown, Pusey, Murugan, & Le, 2013; Koch, Fritsch, & Lohmann, 2010). This model allows studying the vertical behavior of a vehicle according to the suspension type (Savaresi, Poussot-Vassal, Spelta, Sename, & Dugard, 2010). More advanced models can be used for studying the pitch and roll motion of the vehicle but the vertical behavior, comfort and chassis forces in this direction can be mainly determined using this simple model.

The mathematical model with semi-active suspension is shown in Fig. 1. Wheel and axle (unsprung mass m_2) are connected to the car body through a passive spring with the spring coefficient k_1, a modulated damper with the passive damping coefficient c_1 and a variable force element $f_{act}(t)$, while the tire is modeled as a spring k_2. The car body is represented by the mass m_1 and the road disturbance by $z_0(t)$. The equations of motion of the vehicle are the following:

$$\begin{aligned} m_1\ddot{z}_1 + c_1(\dot{z}_1 - \dot{z}_2) + k_1(z_1 - z_2) - f_{act} = 0 \\ m_2\ddot{z}_2 - c_1(\dot{z}_1 - \dot{z}_2) - k_1(z_1 - z_2) + f_{act} + k_2(z_2 - z_0) = 0 \end{aligned} \quad (1)$$

where z_1 is the displacement of the sprung mass and z_2 is the displacement of the unsprung mass.

2.2. Road disturbances

Of major importance for the lay out of the suspension is the definition of the road disturbances. The road disturbances must mirror the real driving conditions and include discrete disturbances $z_{0d}(t)$

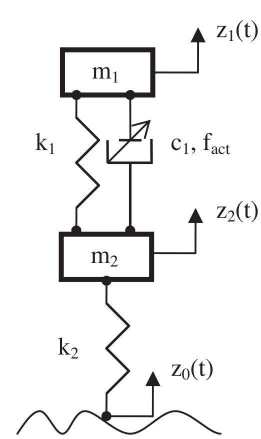

Fig. 1. Quarter car model with semi-active suspension.

Please cite this article in press as: Kanarachos, S., & Kanarachos, A. Intelligent road adaptive suspension system design using an experts' based hybrid genetic algorithm. *Expert Systems with Applications* (2015), http://dx.doi.org/10.1016/j.eswa.2015.06.047