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ScienceDirect
Journal of Terramechanics 44 (2007) 163–175
Journal of Terramechanics
www.elsevier.com/locate/jterra

Suspension settings for optimal ride comfort of off-road vehicles travelling on roads with different roughness and speeds

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Received 10 January 2006; received in revised form 18 April 2006; accepted 4 May 2006
Available online 11 July 2006

Abstract

This paper reports on an investigation to determine the spring and damper settings that will ensure optimal ride comfort of an off-road vehicle, on different road profiles and at different speeds. These settings are required for the design of a four stage semi-active hydro-pneumatic spring damper suspension system ($4S_4$). Spring and damper settings in the $4S_4$ can be set either to the ride mode or the handling mode and therefore a compromise ride-handling suspension is avoided. The extent to which the ride comfort optimal suspension settings vary for roads of different roughness and varying speeds and the levels of ride comfort that can be achieved, are addressed. The issues of the best objective function to be used when optimising and if a single road profile and speed can be used as representative conditions for ride comfort optimisation of semi-active suspensions, are dealt with. Optimisation is performed with the Dynamic-Q algorithm on a Land Rover Defender 110 modelled in MSC.ADAMS software for speeds ranging from 10 to 50 km/h. It is found that optimising for a combined driver plus rear passenger seat weighted root mean square vertical acceleration rather than using driver or passenger values only, returns the best results. Results indicate that optimisation of suspension settings using one road and speed will improve ride comfort on the same road at different speeds. These settings will also improve ride comfort for other roads at the optimisation speed and other speeds, although not as much as when optimisation has been done for the particular road. For improved ride comfort damping generally has to be lower than the standard (compromised) setting, the rear spring as soft as possible and the front spring ranging from as soft as possible to stiffer depending on road and speed conditions. Ride comfort is most sensitive to a change in rear spring stiffness.

Keywords: Ride comfort; Optimisation; Off-road; Rough roads; Four stage semi-active suspension system

1. Introduction

Numerous studies have been conducted on the description and improvement of ride comfort. To this end parameters, indicative of ride comfort (e.g. vertical acceleration, absorbed power), have been described and levels of acceptance laid down in standards such as ISO 2631-1 [1], BS 6841[2] and VDI 2057 [3]. With the introduction of active and semi-active suspensions, these criteria for acceptability have been applied in control systems to determine suspension settings to obtain required levels of ride comfort. Most applications have been for highway travelling in luxury cars equipped with adjustable dampers. In recent research, the focus has turned to ride comfort of off-road vehicles. This paper deals with the ride-comfort suspension settings required for off-road conditions. A full-3D model of a Land Rover Defender previously developed in the dynamic simulation package MSC.ADAMS [4], and verified against track tests, is used in the investigation.

The aim of the investigation is to determine the spring and damper settings that will ensure optimal ride comfort on different road profiles and at different speeds. These results are to be incorporated into a four stage semi-active hydro-pneumatic spring–damper system currently being developed at the University of Pretoria. Two settings are available in this semi-active suspension system – one

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0022-4898/$20.00 © 2006 ISTVS. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.jterra.2006.05.002

chosen to provide optimal ride comfort and the other to provide optimum handling. The question arises: to what extent do the optimal suspension settings vary for a road of given roughness if traversed at different speeds and what levels of ride comfort can be achieved in these cases? The other question to be addressed is: if an off-road vehicle travels over roads of different roughness at a specified speed, is there a significant difference in the optimal suspension settings pertaining to the different road conditions? From this investigation it is endeavoured to determine a speed and profile that can be used for further ride comfort optimisation in a model with more variables describing the suspension characteristics and also incorporating handling.

The three-dimensional vehicle model entails non-linear suspension characteristics. The standard vehicle suspension characteristics are used as baseline. The front and rear suspension characteristics are scaled with respect to the standard suspension by means of front damper and spring scaling factors and rear damper and spring scaling factors. For optimisation purposes the gradient-based Dynamic-Q algorithm, which has previously been used in conjunction with suspension optimisation [5,6] is used. There are four variables that can be adjusted: the rear and front spring scaling factors and the rear and front damper scaling factors.

In designing the hardware for a semi-active suspension, it is necessary to determine the optimal suspension settings that will best address ride comfort for roads varying from level and straight travelled at high speeds, to off-road conditions with severe unevenness and curvatures travelled at low speeds. Focussing on ride-comfort only, it is endeavoured to obtain the best settings that would improve the overall ride comfort. The question of optimised suspension settings for semi-active systems has been investigated from various angles by researchers. Gobbi et al. [7] used a simple two degree of freedom linear model to investigate the dynamic behaviour of passively and actively suspended vehicles running on randomly defined roads. Stochastic multi-objective optimisation is applied with the standard deviation of the vertical body acceleration to evaluate ride comfort, the standard deviation of the relative displacement between the wheel and vehicle body to evaluate working space and the standard deviation of the tyre radial force to evaluate road holding. The damping and stiffness is optimised for the active suspension case. The results indicate a trade-off between robustness and maximum mean performance. In his doctoral thesis Eriksson [8] indicated that for a bus subject to simulated road irregularities, the stiffness and damping associated with the rear axle suspension has a great influence on the discomfort within the bus. Elbeheiry and Karnopp [9] considered broadband stochastic roadway inputs, described in terms of a simplified displacement spectral density (PSD) at several intensity levels, to a quarter car model. The best possible isolation is sought subject to the constraint that the root mean square (RMS) suspension deflection remains constant. Fully active, limited active, optimal passive, actively damped and variable damper systems are considered and road input velocity is indicated to be white noise related. A policy for adapting suspension systems based on suspension travel is suggested. The idea proved to be suitable for road input resulting in large travel. Yoon and Hac [10] consider optimised control of semi active suspensions of a two degree of freedom (DOF) vehicle model for various road and speed conditions. Ground velocity input is modelled as white noise and the covariance thereof is described in terms of a road roughness parameter. The response of the system (body acceleration and tyre deflection) crossing two large bumps and an asphalt road at 20 m/s is given for suspensions with and without adaptive capability based on preview. Marzaband et al. [11] consider paved roads with roughness presented by an elevation spectral density and surface irregularity standard deviation of 0.01 m. A four-DOF half-car model is used to optimise suspension settings for ride comfort based on preview information. Tamboli and Joshi [12] determine values for the spring stiffness and damping coefficients when optimising for the mean square vertical acceleration of a vehicle travelling at different speeds over sinusoidal, highway and city type roads. A two-DOF model for half a car is used in the investigation. They point out that since the displacement spectral density (PSD) of the road input follows an exponentially decreasing curve it cannot be considered as white noise. Actual road information and a curve fitted PSD of the road are used as input. They find that for a heavy-duty truck with a wheelbase of 5.2 m, the root mean square acceleration response (RMSAR) increases with increasing speed and decreases as the wheelbase increases. Considerable reduction in RMSAR is obtained when the suspension coefficients are optimised for RMSAR on highway type road conditions. Lozia [13] analyses vehicle behaviour (lateral displacement and acceleration, yaw velocity and heading angle) for a full vehicle model during a lane change at 80 km/h on an even road, an average class D road and a poor road of class E [14] as obtained from a fast Fourier transform (FFT) of the PSD. He finds that road unevenness decreases lateral displacement by up to 23% of the lane width.

Gobbi et al. [15] optimised the vehicle suspension parameters for an artificial neural network-based vehicle model derived from a validated full vehicle model of a Fiat passenger car. The simulated vehicle passes over a randomly uneven road at 60 km/h, a non-symmetrical pothole at 40, 80 and 120 km/h, a symmetrical pothole at 40 and 80 km/h and a cleat at 30 and 50 km/h. Using multi-criteria optimisation, considerable improvement in comfort and road holding indices is obtained on a uneven road traversed at 60 km/h.

Ookubo et al. [16] develop and experimentally verify the yaw velocity, normalized with respect to the vehicle velocity, to steering angle ratio as a performance measure of handling on a rough road created from a road PSD. According to him this measure can be used to improve handling capability. For a quarter car linear model, Gobbi and Mastinu