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Optimal vehicle suspension characteristics for increased structural fatigue life

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Abstract

Heavy off-road vehicle suspension systems face unique challenges. The ride comfort versus handling compromise in these vehicles has been frequently investigated using mathematical optimisation. Further challenges exist due to the large variations in vehicle sprung mass. A passive suspension system can only provide optimal isolation at a single payload. The designer of such a suspension system must therefore make a compromise between designing for a fully-laden or unladen payload state. This work deals with suspension optimisation for vehicle structural life. The paper mainly addresses two questions: (1) What are the suspension characteristics required to ensure optimal isolation of the vehicle structure from road loads? and (2) If such optimal suspension characteristics can be found, how sensitive are they to changes in vehicle payload? The study aims to answer these questions by examining a Land Rover Defender 110 as test vehicle. An experimentally validated non-linear seven degree-of-freedom mathematical model of the test vehicle is constructed for the use in sensitivity studies. Mathematical optimisation is performed using the model in order to find the suspension characteristics for optimal structural life for the vehicle under consideration. Sensitivity studies are conducted to determine the robustness of the optimal characteristics and their sensitivity to vehicle payload variation. Recommendations are made for suspension characteristic selection for optimal structural life.

Keywords: Off-road vehicles; Structural life; Mathematical optimisation; Dynamic modelling

1. Introduction

Manufacturers in the commercial vehicle sector have great pressure on them to increase the payload capacity of the vehicle without exceeding the legal vehicle mass restrictions. This can only be achieved by reducing the mass of the vehicle structure. This is to be accomplished without compromising the reliability of the vehicle's structural and other systems.

The goal of reducing vehicle mass drives designers to explore the use of exotic materials, novel construction techniques and innovative structural geometry. The reduction of input loads to the vehicle structure must also be keenly considered. These loads may be due to payload requirements or road loads, passed to the vehicle structure through the tyres, wheels and suspension system. The focus here is on the selection of vehicle suspension characteristics as these parameters are under the control of the vehicle designer.

In order to address the problem some metric must be identified to represent the quality of the suspension isolation in terms of damage to the vehicle structure. The challenge in defining such a metric is that changes in load levels are not a direct measure of changes in fatigue damage to the structure. A simple parameter such as standard deviation of suspension forces will therefore not provide unambiguous insight into the influence of suspension characteristics on fatigue damage in the vehicle structure. The discussion of input loads to the vehicle structure naturally leads to the suggestion of cumulative fatigue damage as suitable metric.

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Literature on the selection of suspension characteristics for ride comfort or handling can be found for virtually any type of vehicle. The amount of literature available on the selection of suspension characteristics for fatigue damage to the vehicle structure stands in sharp contrast to this. The focus seems to have been on the prediction of road loads on vehicle structures and subsequently fatigue life of these structures [1,2].

Zeiler and Barkey [3] did however conduct an analytical study into the effect of suspension characteristics on fatigue damage. They used an unvalidated linear pitch-bounce vehicle model combined with the Forman crack growth law to calculate the sensitivities of fatigue damage to spring and damper characteristics. Their results indicate a decreasing fatigue life when spring and damper rates are increased. No suggestion is made as to what the optimal characteristics may be.

The ideal vehicle suspension system would provide near optimal isolation at different speeds over varying road profiles for widely varying payloads. A passive system cannot function optimally under these varying conditions and will inevitably result in a compromised solution. The large changes in the sprung mass of heavy vehicles present even greater challenges in selecting suitable suspension characteristics. A laden vs. unladen compromise thus exists, which is in many ways analogous to the ride comfort vs. handling compromise so often investigated in vehicle dynamics research.

The promise of ideal behaviour over a wide range of operating conditions makes active suspension systems attractive for solving these challenges. It is however well known that the energy consumption of these systems make their use prohibitive. Semi-active or adaptive suspension systems offer many of the advantages of active systems at a fraction of the energy requirements and complexity [4]. These systems have consequently been suggested to remedy the laden vs. unladen compromise in heavy vehicles [4,5].

1.1. Chosen test platform

The test vehicle chosen for the current study is a Land Rover Defender 110 fitted with an experimental hydro-pneumatic suspension system, referred to as the **4 S**tate **S**emi-active **S**uspension **S**ystem or $4S_4$. The $4S_4$ was developed as a solution to the ride comfort vs. handling compromise for off-road vehicles [6]. The system has the ability to switch semi-actively between four passive states. The four states are obtained by switching independently between a high and a low spring rate and a high and a low damping rate. The working principle of a $4S_4$ suspension strut is illustrated in Fig. 1. The system also has load-levelling capability.

The system, as currently implemented on the Land Rover, only utilises two of the states. The two states (stiff spring, high damping and soft spring, low damping) are currently optimised for handling and ride comfort respectively. It is suggested that the system may have the potential to solve the problems associated with high payload variations by optimising the stiff spring and high damping characteristics for the fully laden vehicle while the soft spring and low damping characteristics are optimised for the unladen vehicle. Semi-active control then simply

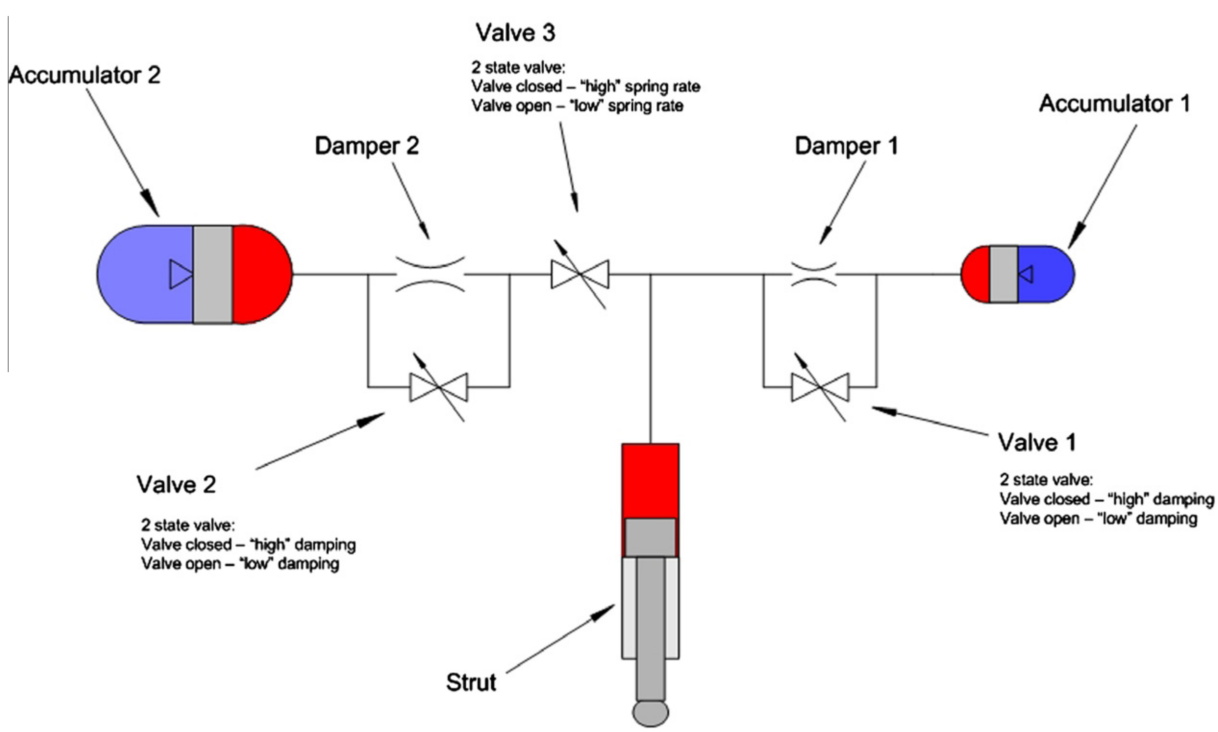

Fig. 1. The $4S_4$ working principle.