# 1 INTRODUCTION

## 1.1 Preamble

The basic concept of land vehicle transportation has not changed much in the last few decades, although much progress was made in improving and optimising vehicle design and technology. The quest to always go faster, further and more comfortably, has lead in recent years to the development of advanced suspension systems. An improved suspension system allows a vehicle to achieve higher speeds over rougher terrain, and results in better handling, as well as improved ride comfort.

Passive suspension systems (suspensions without controllable elements), always represent a compromise between ride comfort and handling, since a stiff suspension is required for good handling, while a more compliant suspension is needed for good ride comfort. Implementing a controllable suspension (adaptive, slow-active, semi-active, fully-active see Chapter 2 for definitions) is therefore an attempt to narrow the gap between the opposing requirements for optimal ride comfort and handling.

This study focuses on a semi-active suspension system, consisting of a two-state switchable hydraulic damper, as well as a two-state switchable hydro-pneumatic spring. The different elements of the spring/damper system are characterised and a mathematical model is developed to predict the system performance.

In Chapter 1, an introduction and background is given. The background leading up to the development of the semi-active hydro-pneumatic spring/damper system, investigated in this study, is supplied and the working principle of the spring/damper system is explained. The purpose and scope, defining the extent of the research, is also discussed.

In Chapter 2, a brief discussion of the applicable literature is presented. The literature survey includes hydro-pneumatic springs and semi-active dampers, with specific reference to the application of this technology in heavy off-road vehicles.

Chapter 3 describes the development of the mathematical model of the semi-active spring/damper system. The mathematical model, as well as all the sub-models, is discussed in detail, with reference to the applicable literature.

In Chapter 4, the characteristics of the two-state hydro-pneumatic spring, the two-state hydraulic damper and the solenoid valve are presented. The experimental setup used to characterise the semi-active hydro-pneumatic spring/damper system, as well as the single degree of freedom setup is described. Single degree of freedom test results are also presented in Chapter 4.

In Chapter 5, the mathematical model is verified using experimental data obtained from the characterisations and the single degree of freedom tests. The deficiencies of the current mathematical model are highlighted and areas for further refinement are defined.

In Chapter 6, conclusions are reached and recommendations made for future research into modelling this type of suspension system.

## 1.2 Background

In this section the background leading up to the development of the semi-active spring/damper system is presented.

The current research activity began in 1990, with a literature survey into advanced suspension systems (Nell 1990). This survey was part of an investigation conducted for the South African armaments procurement agency (Armscor). The literature survey concluded that future military vehicles would be highly mobile in order to enhance the survivability of the vehicle. This can be achieved by, amongst others, increasing the power to weight ratio or by optimising the suspension (Hohl 1986). An optimised passive suspension will however only be optimal for a certain combination of obstacle and vehicle speed (Nell 1991).

One way of enhancing the vibration isolation or ride comfort limited mobility of a vehicle is to introduce semi-active dampers (detail about the working of a semi-active damper can be found in Chapter 2). The development of semi-active dampers for wheeled vehicles started with simulations of a vehicle fitted with semi-active dampers, using DADS (Dynamic Analysis and Design System) software. The simulation results confirmed results obtained by other researchers in this field (Salemka & Beck 1975; Miller & Nobles 1988; Hrovat & Margolis 1981, Nell & Steyn 1994).

The first semi-active damper prototype is shown in Figure 1-1. In this figure, the external control valve and connecting pipes can clearly be seen.

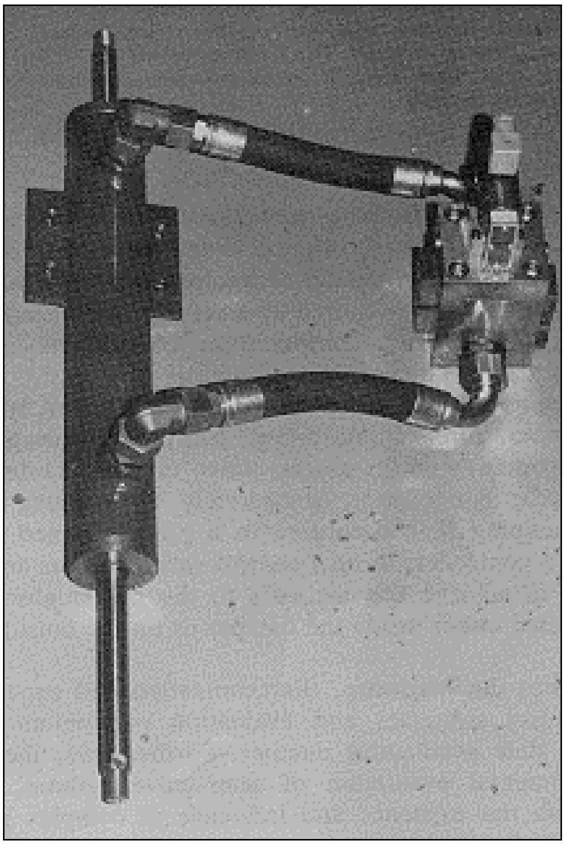

**Figure 1-1: First experimental semi-active damper**

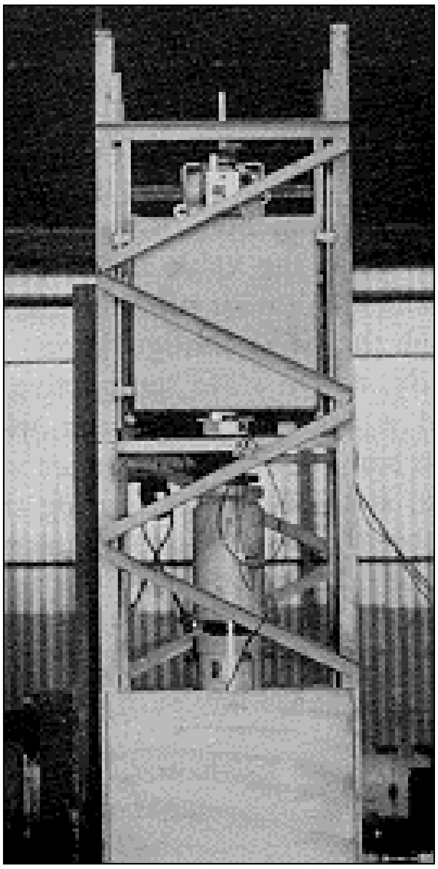

**Figure 1-2: First single degree of freedom test rig**

This damper was designed for a vehicle with a wheel load of approximately 2,5 metric tons. The semi-active damper was tested on a SDOF (single degree of freedom) test rig consisting of a 2,5 ton sprung mass (supported in linear bearings) and a linear coil spring. A $250kN$ Schenck hydraulic actuator was used to provide the required road inputs. The semi-active damper control signal was supplied by a personal computer. Figure 1-2 shows a photograph of the single degree of freedom test rig.

Three well-known semi-active damper control strategies were evaluated on the single degree of freedom test rig. They were the strategies of Karrnopp, Hölscher and Huang, and Rakheja and Sankar (Nell & Steyn 1994). It was found that the acceleration feedback strategy of Hölscher and Huang (Nell & Steyn 1994) proved to be the most successful at reducing the RMS acceleration on the sprung mass.

Nell (1993) developed an alternative control strategy, taking into account roll, pitch, lateral and vertical vehicle motion. This control strategy was evaluated on a 4x4 mine protected vehicle with a GVM of 12 tons, shown in Figure 1-3.

**Figure 1-3: 4x4 mine protected test vehicle fitted with semi-active dampers**

The semi-active dampers used on the 4x4 test vehicle can be seen in Figure 1-4. In this figure the external damper valve block, as well as the piping, is still clearly visible.

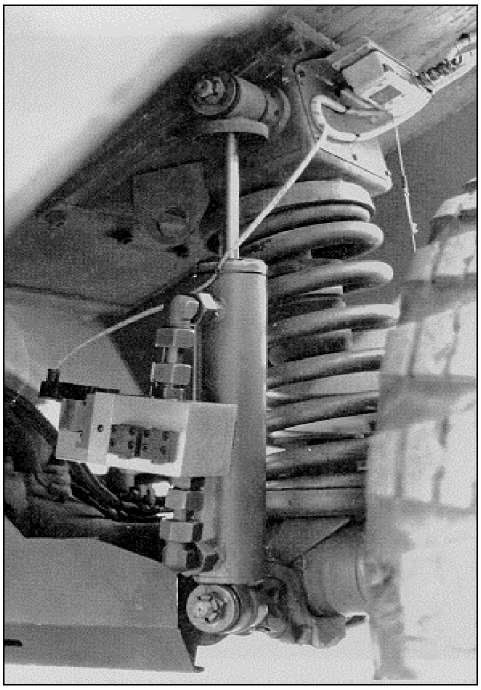

**Figure 1-4: Semi-active damper fitted to 4x4 test vehicle**

Tests were performed at speeds of between 15*km/h* and 55*km/h* over the Belgian paving track at the Gerotek Vehicle Test Facility and other typical off-road terrains. Improvements in ride comfort of up to 48% were recorded, with an average improvement of around 25%.

The next generation of semi-active dampers were fitted to a 6x6 armoured personnel carrier with a GVM of 17,4 tons. Semi-active dampers were fitted to all six wheel stations of the vehicle and were controlled by a dedicated computer, making use of solid state gyroscopes and accelerometers as input parameters. Figure 1-5 shows the vehicle during a high speed double lane change manoeuvre.

**Figure 1-5: 6x6 armoured personnel carrier fitted with semi-active dampers**

The ride comfort of the vehicle was improved by between 4% and 31% over different off-road terrains and at different vehicle speeds, while the maximum double lane change speed was improved by 9,4%. Roll velocity was also reduced and almost neutral steering was achieved.

Figure 1-6 shows the semi-active damper fitted to the 6x6 test vehicle. This damper was improved by including the valve block and ducts into a single assembly, bolted to the side of the damper i.e. the packaging was improved.

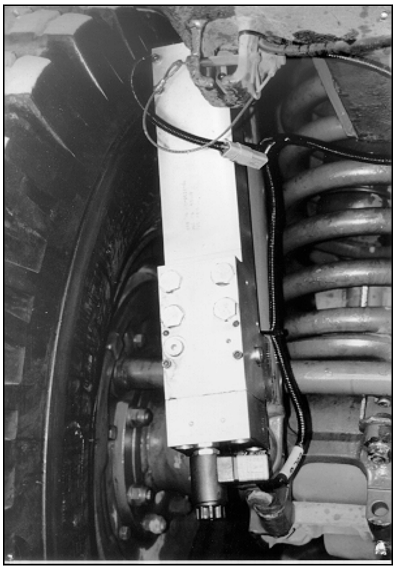

**Figure 1-6: Semi-active damper fitted to 6x6 APC**

The next step in semi-active damper research was the development of a semi-active rotary damper. The rotary damper was as a joint venture between Reumech Ermetek from South Africa and Horstman Defence Systems from the United Kingdom. Horstman Defence Systems was responsible for the damper design and manufacturing, while Ermetek developed the controller, integrated the damper onto the vehicle and installed the control valves and sensors. The test vehicle used to evaluate the performance of these dampers was the GV6 self-propelled howitzer shown in Figure 1-7.

**Figure 1-7: GV6 self-propelled howitzer fitted with semi-active rotary dampers**

The GV6 is a 6x6 vehicle of 47 tons GVM and is normally fitted with conventional translational dampers. Figure 1-8 shows a photograph of the semi-active rotary damper fitted to the experimental vehicle.

**Figure 1-8: Semi-active rotary damper fitted to the experimental vehicle**

The rotary damper supplies a maximum damping torque of 28*kNm* in the "on" state. Ride comfort tests were performed over the APG (Aberdeen Proving Grounds) track, Belgian paving track and the Fatigue track at the Gerotek VTF (Vehicle Test Facility). An improvement of between 25% and 58% in pitch velocity was achieved over the APG track, while improvements of between 7% and 15% were attained over the Belgian paving and Fatigue tracks. Figure 1-9 indicates the typical improvement in pitch velocity over the APG track at a vehicle speed of 24*km/h*.

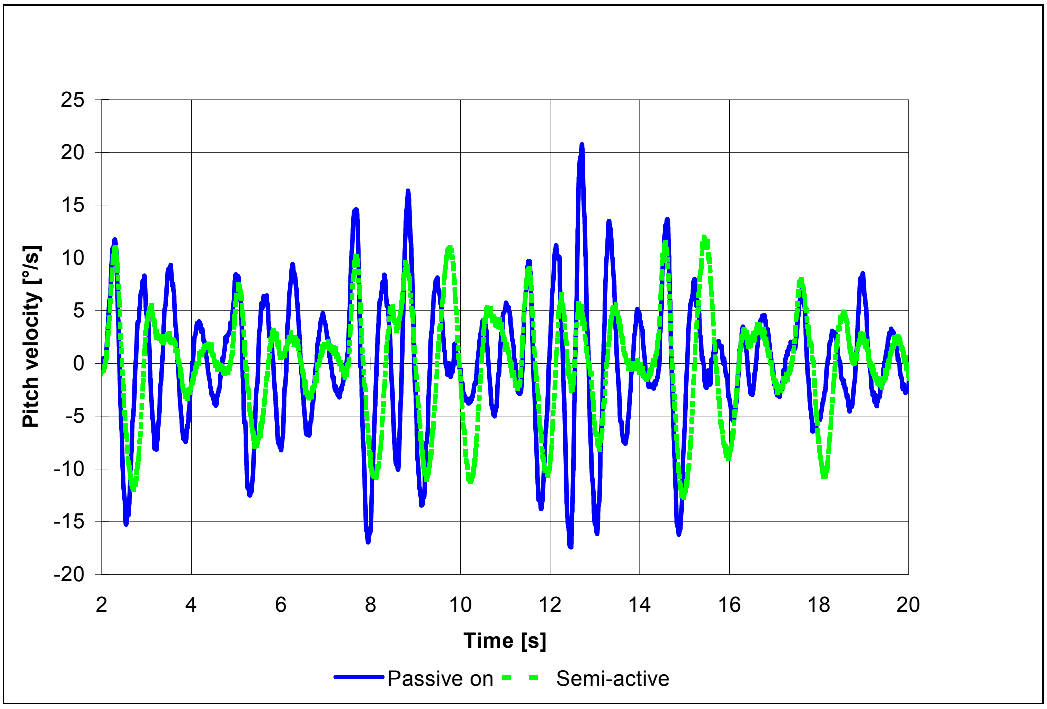


**Figure 1-9: Pitch velocity of the GV6 vehicle over the APG track**

Laboratory tests revealed that the valve response times are between 60 and 250 milliseconds, which is considered slow for semi-active control (Els & Giliomee 1998). Since the valve response times are dependent on the damper velocity, better performance increase was achieved over rougher terrains, such as the APG track.

The next evolution in semi-active suspensions, which is also the subject of this study, was developed during 1996/97. This system consists of a two-state semi-active hydraulic damper and a two-state semi-active hydro-pneumatic spring. The semi-active spring/damper system was developed for a vehicle with a static wheel load of 3000*kg*. The system was developed as result of two previous studies conducted by Nell and Steyn (1994) and Els (1993), into semi-active dampers and hydro-pneumatic springs. A brief explanation of the working principle of this suspension unit is supplied in the next paragraph.

The switching between high and low characteristics for both spring and damper are made possible by channelling hydraulic fluid with solenoid valves (refer to Figure 1-10). The spring/damper unit consists of a hydraulic strut (1), two Nitrogen filled accumulators (2&3), a hydraulic damper (4) and two solenoid valves (5&6).

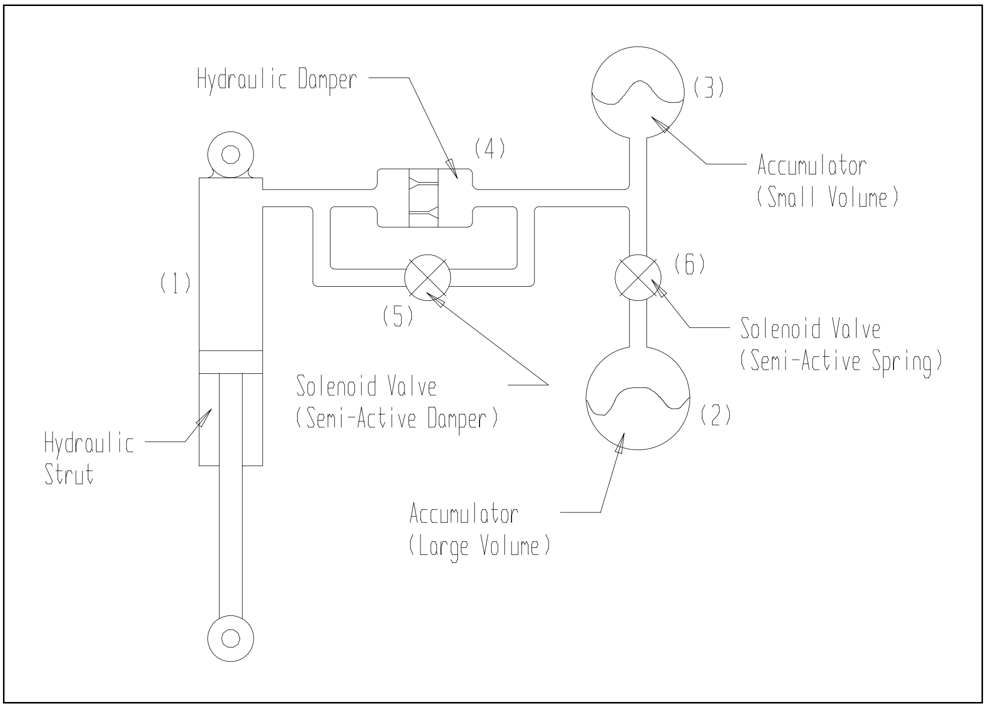


**Figure 1-10: Schematic layout of the semi-active spring/damper unit**

The low spring rate is achieved by compressing a large volume of gas consisting of two separate chambers (2&3). By sealing off one of the chambers (2), a smaller gas volume (3) is compressed and a higher spring rate is achieved. Spring rates can be individually tailored by changing the two gas volumes. For low damping the hydraulic damper (4) is short-circuited by opening a by-pass valve (5). For high damping this valve is closed and the hydraulic fluid is forced through the damper resulting in a higher damping force.

The characteristics of this suspension unit, as well as the tests and test results are discussed in detail in Chapter 4. The mathematical model of the suspension system is explained in Chapter 3.

## 1.3 Purpose and scope of this study

This study investigates the properties and mathematical modelling of an existing semi-active hydro-pneumatic spring/damper system. The reason for conducting this study is that semi-active suspension systems are currently the only means of further improving the ride comfort and handling of heavy off-road vehicles, cost effectively. Semi-active suspensions are cheaper than active suspensions because no external hydraulic power source is needed and inexpensive solenoid valves can be used to control the unit. Semi-active suspension systems are therefore commercially viable and worthwhile investigating.

A mathematical model of the semi-active spring/damper unit is developed to be used in a 3D multi-body vehicle simulation model. It is important to be able to simulate a full vehicle including the hydraulics, since the results will be used to size components such as pipe diameters, accumulator volumes, strut stroke and other components (designed for strength and durability). The mathematical model was developed in Simulink, which makes it modular, flexible and easy to integrate into a full vehicle simulation model in third party software such as DADS (Dynamic Analysis and Design System) or ADAMS (Advanced Dynamic Simulation of Mechanical Systems). An alternative and less complex model for first order 3D simulations is also proposed.

The following aspects are addressed in this study:

- Literature study about hydro-pneumatic springs and the modelling thereof
- Literature study of semi-active dampers
- Mathematical modelling of the semi-active spring/damper unit
- Measured spring, damper and valve characteristics
- Single degree of freedom (quarter car) rig tests
- Validation of the mathematical model
- Conclusions and recommendations

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