6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Preamble

In this chapter, a brief summary will be provided followed by conclusions and recommendations. The primary comments in the conclusions and recommendations are focussed on the mathematical modelling of the semi-active spring/damper, while the secondary comments are general observations about the system.

Examples of semi-active damper rig tests, as well as full-scale vehicle tests were developed locally and internationally by various organisations. Locally semi-active damper systems were mainly evaluated on large military off-road vehicles. For this study, an existing semi-active spring/damper system was analysed and the characteristics of the suspension system is supplied in this document. No examples of a semi-active spring/damper system like the one discussed in this document could be found in the literature. Conceptual suspension layouts utilising two or more hydro-pneumatic springs were found, however no test or simulations results were presented by the authors.

Most of the high mobility military vehicles make use of hydro-pneumatic suspensions and some of them are fitted with ride height adjustment systems. Although hydro-pneumatic suspensions are more expensive than conventional suspension elements, they are popular because of their non-linear characteristics, compact structure and other features such as ride height control and lockout.

Five ways of mathematically modelling a hydro-pneumatic spring were discussed in Chapter 2. The different methods imply varying levels of complexity, of which the real gas thermal time constant method would be classified as the most complex and the polytropic and ideal gas approach the least complex. The anelastic model was found to be a possible way of simulating the thermal behaviour of a hydropneumatic spring, since it is mathematically similar to the thermal time constant model. The hydro-pneumatic spring in this study was modelled with the real gas thermal time constant approach proposed by Els (1993), while the semi-active damper part was modelled using interpolation in look-up tables. Both the hydraulic valves were modelled by a first order delay, as a function of relative pressure across the valve, while the hydraulic flow model was constructed from first principles, making use of conservation of mass principles. The mathematical models of the semi-active hydro-pneumatic spring, the semi-active hydraulic damper and the hydraulic flow were successfully integrated into a single model. All the mathematical models were programmed in Matlab/Simulink and measured displacement and valve switching signals were used to drive the mathematical model to compare it with measured data.

Sine sweep tests were performed at a fixed excitation amplitude from $0Hz$ to $15Hz$, therefore it was not possible to comment on the validity of the frequency response of the spring/damper system. As part of the experimental tests, a ride height adjustment scheme was evaluated, which does not require any external power source and only remove hydraulic fluid from the system when one of the accumulators is isolated. Discrepancies between measured and simulated results can be attributed to amongst others gas leaks in the experimental units, unaccounted effects such as bearing friction and modelled hydraulic damping effects in the pipes.

6.2 Conclusions

The following *primary* conclusions can be made from this study:

- *Acceptable correlation was obtained between the mathematical model and the experimental results.*

  Analysis results from the simulation model were correlated with measured data from the experimental setup. These correlations included the passive characteristics, the workspace test, step response, random input response and sine sweep tests. Good correlation was obtained for the characterisation simulations, while the correlation for the workspace test was good at low excitation frequencies only.

  In most cases, good correlation was obtained for the step response simulations in terms of absolute measures, such as relative strut displacement. For the random input simulations the absolute correlations was not good, however the statistical, i.e. RMS correlations were in general very good.

  Good correlation was also obtained for the sine sweep simulations and the model was able to predict phenomenon such as suspension squat for the damper “on” spring “off” condition.

  Transmissibility graphs indicated that the mathematical model was able to predict the resonance frequency fairly well, however the peak values did not correspond very well.

- *The anelastic model proved to be the most promising in terms of simplicity, computational efficiency and programming effort.*

  As an alternative way of modelling the hydro-pneumatic spring, an anelastic model making use of a polytropic main spring was compared to the real gas thermal time constant spring model. It was found that the hysteresis loop seen in the hydro-pneumatic spring characteristic is only encountered at very low excitation frequencies (below the vehicle body natural frequencies) and that the anelastic model was able to match the real gas thermal time constant model predictions for steady state conditions at higher excitation frequencies. Although the real gas thermal time constant model yielded good results in general, it is too complicated for first order vehicle dynamics simulations.

The following *secondary* conclusions can be made from this study:

- From the background in Chapter 1 and the literature overview in Chapter 2, it is clear that a lot of research has been done in the field of semi-active suspension systems. Most of this work was done on semi-active dampers, although a few studies were also performed on frequency dependent springs and springs with variable spring rates.

- Physical tests revealed that for the four operating conditions of the spring/damper system, very different SDOF responses could be expected. The test results showed that the spring/damper system can supply spring and damper characteristics associated with good ride comfort, as well as good handling in a single package. For good ride comfort the hydro-pneumatic spring can be set to the soft state, while controlling the damper semi-actively and for good handling both the spring and damper can be set to the hard state.

- Measured valve response times between 180ms and 40ms for the spring and damper valves did not seem to be too slow for semi-active control, although a faster response would enable more precise control, especially of the unsprung mass.

6.3 Recommendations

The following *primary* recommendation can be made:

- *The anelastic model seems to be a viable alternative to the more complicated real gas thermal time constant model and should be investigated in more detail.*

For full 3D dynamic vehicle models, the real gas thermal time constant will be adding complexity to the model that might not contribute significantly to the fidelity of the vehicle model. Using an anelastic model should result in good overall vehicle response, without too much complexity. A non-linear anelastic model can easily be constructed by making use of a polytropic process and the polytropic constant can either be determined through experimental tests, or by making use of the real gas thermal time constant model, as was done in this study.

The following *secondary* recommendations can be made:

- Since a lot a research has been done on semi-active dampers and not much on semi-active springs, it is recommended that a dedicated semi-active spring control strategy be developed and tested. The reason for this is that a spring is a displacement dependent force element, while a damper is a velocity dependent element. Switching from the "on" state to the "off" state during cornering might unsettle the vehicle.

- Most semi-active control strategies only cater for improving either ride comfort or handling, therefore it would be worthwhile to develop a control strategy for the spring/damper that is able to handle most driving conditions. A combination of reaction driven (react to suspension inputs) and input driven (react to driver inputs, i.e. throttle, brake and steering) control can be followed.

- The possibility of ride height control by selectively opening and closing the spring valve should also be further investigated and a control strategy developed.

- The experimental setup worked well for the tests conducted in this study, but can be modified to include the tyre, in order to be more representative of an actual vehicle application. Including the tyre in the test setup would add higher frequency dynamics at approximately the wheel hop frequency, which would increase the demand on the bandwidth of the semi-active control strategies and the valve response times.

- An unknown factor in the single degree of freedom test setup used in this study is the frictional losses in the linear bearings of the sprung mass. Misalignment of the bearings might account for substantial losses, which are not easily determinable. A hardware-in-the-loop (HIL) test setup might be more useful for performing single degree of freedom simulations and for expanding the dynamic model. In a HIL simulation, frictional losses and other effects such as a tyre can be added and their influence on the results can be quantified.

- Pilot operated logic element valves are used to channel the hydraulic fluid in the spring/damper system. These valves perform well at high pressure differences, but are slow at low pressure differences. A project investigating alternative hydraulic valves, which are both fast acting and permit high flow rates would be a useful for improving the bandwidth of the current system.

- Since standard components were used in the construction of the spring/damper unit, a packaging exercise would be required, in order to determine the optimal layout of accumulators and pipes in a vehicle set.

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