Chapter 6

Conclusions and Recommendations

This chapter presents the final conclusions and the recommendations for future work. The recommendations are done such that it corresponds to the chapter the work was presented in the study.

1. Conclusions

The aim with this study was to obtain a validated simulation model of a leaf spring suspension system that can be used in durability simulations. A systematic approach was followed by starting at component level, obtaining the necessary validated models and then proceeding by including more detail to the model, continuously validating the model until a model of the complete suspension system is obtained. In order to validate the models created in this study extensive experimental characterisation was performed to obtain the necessary data that would be required in the parameterisation and validation of the various models.

The study started at component level with the modelling of two leaf springs. Validated models, able to represent the multi-leaf and parabolic leaf spring, was developed in Chapter 3. A novel elasto-plastic leaf spring model was proposed that could emulate the complex behaviour of both leaf springs without requiring the microscopic modelling of complex physical phenomena such as the tribological processes. The elasto-plastic leaf spring model gives accurate predictions of the behaviour of both the multi-leaf spring as well as the parabolic leaf spring. In addition to the physics based elasto-plastic leaf spring model a non physics-based neural network model was also used to model the multi-leaf spring. A simple feed forward neural network was constructed that was able to emulate the vertical behaviour of the multi-leaf spring. It was however shown that the neural network model is not able to predict the correct response for inputs that fall outside the range of the training data used. Therefore, it is required that a comprehensive set of experimental data be available in order to construct a training data set that covers the entire working range of the inputs to the neural network. Alternatively, the neural network can be used as a gray-box by using the elasto-plastic leaf spring model to generate the required training data as the elasto-plastic leaf spring model required a lot less experimental data in order to parameterise it.

The elasto-plastic leaf spring model was integrated into an ADAMS/Car subsystem and was used to model the spring only setup in Chapter 4 using ADAMS-SIMULINK co-simulation. The results showed that the model of the spring only setup is able to predict the vertical and longitudinal forces acting at the suspension attachment points. The results obtained indicated that the elasto-plastic leaf spring model can be integrated into a suspension model in order to predict the forces that are transmitted on to the chassis. The spring only setup can now be extended to include more detail.

Chapter 5 discussed the verification and validation process. A quantitative validation metric was proposed that is able to give an accurate representation of the agreement/disagreement between two signals. The modified percentage relative error validation metric that was proposed is based on the well-known relative error. The challenges associated with using a simple metric such as the relative error when comparing periodic signals around zero was addressed and was compared to two other validation metrics. The three validation metrics were compared by applying them to various signals and it was shown that the modified percentage relative error always gives a true representation of the agreement/disagreement between two signals. The modified percentage relative error was used to compare the accuracies of the two formulations of the elasto-plastic leaf spring model as well as the neural network model. It was shown that the elastic-linear formulation of the elasto-plastic leaf spring model was slightly more accurate than the elastic-linear formulation. The comparison between the elastic-nonlinear formulation and the neural network model showed that the neural network model, after some refinement, will be more accurate. Along with the comparison of the two modelling techniques' accuracies their computational efficiencies were also compared. The neural network showed a computational efficiency that is three times faster than the elasto-plastic leaf spring model.

The elasto-plastic leaf spring and neural network leaf springs can now be used in further studies to obtain more detailed models of the suspension system. The recommendations for future work are given next.

2. Recommendations

This study addressed various aspects concerning the physical suspension system, its components and the various models that were created. From the work done in this study the following recommendations can be made for future work concerning the physical systems and models concerned.

2.1. Chapter 2

Chapter 2 looked at the experimental characterisation of the multi-leaf spring and parabolic leaf spring. The suspension system was also characterised using either the multi-leaf spring or the parabolic leaf spring. Two 6clcs were manufactured, calibrated, verified and validated. It was concluded that the most probable cause for the discrepancy between the virtual measurements and physical measurements of the 6clc was due to the uncertainties of the exact size of the resultant force applied to the 6clc and the exact point of application. It is recommended that a more precise experimental setup be used to obtain the experimental data to validate the 6clc model. In this setup attention should be given especially to the measurement of the applied force's orientation as well as its point of application.

In the experimental characterisation two setups were used namely, the spring only setup and the in-service setup. The two setups were used to show the dependency of the force-displacement characteristics of the two leaf springs on certain parameters (such as the loaded length). In future work the force-displacement characteristics of both the multi-leaf spring as well as the parabolic leaf spring should be obtained using a support profile that induces a continuous loaded length change of the leaf spring. This data can then be used to validate the leaf spring model that attempts to replicate the observed behaviour. This property may give the vehicle designer significant scope for fine-tuning the suspension characteristics by simply modifying the profile of the spring supports.

2.2. Chapter 3

In this chapter attention was given to the modelling of the multi-leaf spring and the parabolic leaf spring. Two models were used to model the vertical behaviour of the multi-leaf spring i.e. the elasto-plastic leaf spring model and a neural network model. Only the elasto-plastic leaf spring model was used to model the parabolic leaf spring. The recommendations for future work on the two modelling techniques are given in the following two paragraphs.

2.2.1. Elasto-plastic leaf spring model

Future work on this model should include:

- Ramberg-Osgood formulation

  Two formulations were presented for the elasto-plastic leaf spring model namely the elastic-linear and elastic-nonlinear formulations. The development and feasibility of another formulation that is based on the the Ramberg-Osgood relations (Dowling, 1999) should be investigated. The Ramberg-Osgood relationship may give a hybrid method between the elastic-linear model and the elastic-nonlinear model. It is postulated that this formulation will only require knowledge of stiffness of the solid beam (k), and the stiffness of the layered beam during loading and unloading (k_{UL} and k_L) but will be able to predict the smooth transition between the solid beam stiffness and the layered beam stiffness.

- Investigate alternative methods for handling the friction.

  The elasto-plastic leaf spring model does not handle the friction as a separate quantity but includes it in the two parameters of the layered beam stiffnesses (k_L and k_{UL}). This is the reason why the layered beam has two stiffnesses in the elasto-plastic leaf spring model. If the friction can be accurately captured by a parameter specific to the friction it would imply that a single value may be obtained for the layered beam stiffness. This may then enable the friction and the layered beam stiffness to be calculated theoretically. It was already shown that the solid and layered beam stiffnesses can be calculated theoretically, it should however be investigated whether it will be possible to calculate the friction theoretically.

- Visualization of slip planes

  The slip planes were observed visually with a simple experiment in Chapter 3 (see Figure 3.5). The insight gained from using stereography to measure the displacement field over the entire leaf spring as the spring is deflected will be valuable and will serve as further confirmation of the different phases (i.e. solid beam - transition – layered beam)

- Theoretical stiffness of leaf springs

  Apply the equations presented in Appendix B to calculate the stiffness of other types of leaf springs such as leaf springs with blades having a parabolic thickness profile. It was shown in this study that the two stiffness regimes (solid beam and layered beam) of a multi-leaf spring can be theoretically calculated using the equations presented in

Appendix B. The theoretical calculation of the stiffness of the parabolic leaf spring can be investigated in future work.

The equation in Appendix B used to calculate the stiffness of the layered beam does not include any frictional effects, whereas the physical leaf spring has friction that influences the stiffness. Methods should be investigated which will be able to account for the frictional effect and enable the theoretical calculation of the hysteresis present in multi-leaf springs.

- Supports inducing continues loaded length change

  The combined elasto-plastic leaf spring model and the model accounting for changes in the loaded length should be used in future work to investigate the ability of the model to simulate a leaf spring in which the supports induce a continuous change in the loaded length as the leaf spring is deflected.

- Source of nonlinearity in parabolic leaf spring

  It was mentioned in paragraph 3.2 in Chapter 3 that the parabolic leaf spring has some nonlinear behaviour in the layered beam region which the elasto-plastic leaf spring model is not able to capture. It was stated that the cause for the nonlinear behaviour is not exactly clear but it is believed to be due to the friction process. The source for the nonlinear behaviour should be investigated. Once the source has been determined it would make it possible to refine the elasto-plastic leaf spring model in order to capture this behaviour more accurately.

2.2.2. Neural network model

It was shown that a neural network is able to emulate the vertical behaviour of the multi-leaf spring. It was also shown that the neural network is not able to predict the correct response when given inputs that fall outside the range of the training set. It was shown in paragraph 4.1.2 of Chapter 3 that the neural network leaf spring model is dependent on the excitation frequency whereas it was shown in Chapter 2 that the physical multi-leaf spring's force-displacement characteristic was independent of the excitation frequency. From this it is postulated that the choice of input variables to the neural network might influence the ability of the network to generalize the behaviour and predict the correct response for inputs that fall outside the range of the training set. It is proposed that the use of different inputs to the neural network, and its affect on the ability of the neural network to predict the response for inputs outside the range of the training set, be investigated.

2.3. Chapter 4

After the validated leaf spring models, created in Chapter 3, the spring only model was the next step in the systematic approach. The elasto-plastic leaf spring model was integrated into a subsystem model of the spring only setup. The model showed that it was able to give good predictions of the forces that are transmitted to the chassis. The model of the spring only setup should be refined and extended to include the radius rod. This will then effectively model the in-service setup which is the next step in the systematic approach that was shown in Figure 4.1. The experimental characteristics have already been obtained to validate all the models up to and including the complete suspension system.

2.4. Chapter 5

This chapter presented a validation metric that can be used in a quantitative validation process. The validation metric is based on the simple relative error. The challenges associated with using the relative error on periodic signals around zero were addressed. The proposed modified percentage relative error validation metric was applied to several case studies and compared to two other validation metrics that were identified from a literature study. The results from the modified percentage relative error metric indicated that it is able to represent the true overall relative error between two signals. The *m%RE* validation metric should be extended to quantify model and experimental measurement uncertainties. The use of the relative error's characteristic (discussed in paragraph 2.2.1 in Chapter 5) to quantify the tendency of the model to over-or under predict should be investigated and incorporated into the *m%RE*.