Chapter 4

Multi-leaf spring suspension system model

Following a systematic modelling approach the validated elasto-plastic leaf spring model from Chapter 3 will now be used to model the spring only setup. The spring only setup reduces the complexity of the suspension system of interest by reducing the number of components that may contribute in various ways. The spring only setup isolates the multi-leaf spring and by using this setup, as an initial check, it can be validated that the forces at the attachment points can be predicted accurately. After the spring only model has been validated additional detail can be added to the model by adding other components such as the radius rod and the hangers with the wear plates. This will result in the in-service setup used in Chapter 2 that considers the additional components but neglects the interaction between the left and right hand leaf springs. Once the model of the in-service setup has been validated the model can be extended to include the interaction between the left and right hand side to represent the complete suspension. The systematic modelling approach described above is shown in Figure 4.1. This chapter will consider the modelling and validation, with respect to the forces at the attachment points, of the spring only setup. The extension of the spring only model falls outside the scope of this study.

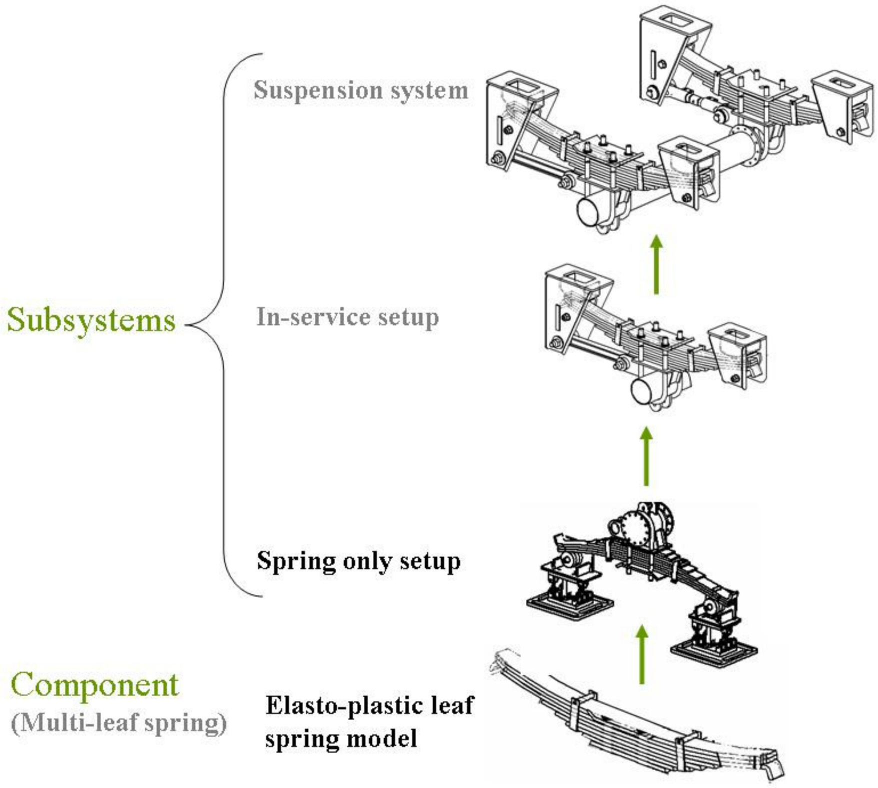

Figure 4.1. Systematic modelling approach

1. Introduction

Figure 4.2 shows the experimental spring only setup. The load cell between the actuator and the multi-leaf spring measures the spring force. The two 6clcs measure the forces that the leaf spring is transmitting to the chassis. These experimental measurements will be compared to the “measurements” taken on the simulation model which uses the 6clc model that was discussed in Appendix A. The model of the 6clc was created in ADAMS/Car to measure the equivalent forces and moments in the simulation environment in order to compare the virtual measurements to the physical measurements. The ADAMS/Car model of the 6clc was verified against analytical equations and both the analytical equations and the ADAMS/Car model was validated using experimental measurements. The verification and validation done on the 6clc is shown in detail in Appendix A. The validation results showed good correlation between the two models and the measured data when the experimentally calculated force orientation and application point was used as input to the two models. Four load cases were used to validate the 6clc models and good correlation was obtained for all the equivalent forces and for all four load cases used. From the results in Appendix A it was concluded that the ADAMS/Car model of the 6clc can be used to measure the equivalent forces and moments in the simulation environment and these virtual measurements can be compared to the physical measurements. Comparing the 6clc measurements from the experiment and from the model it can be validated whether the forces at the attachment points are accurately predicted.

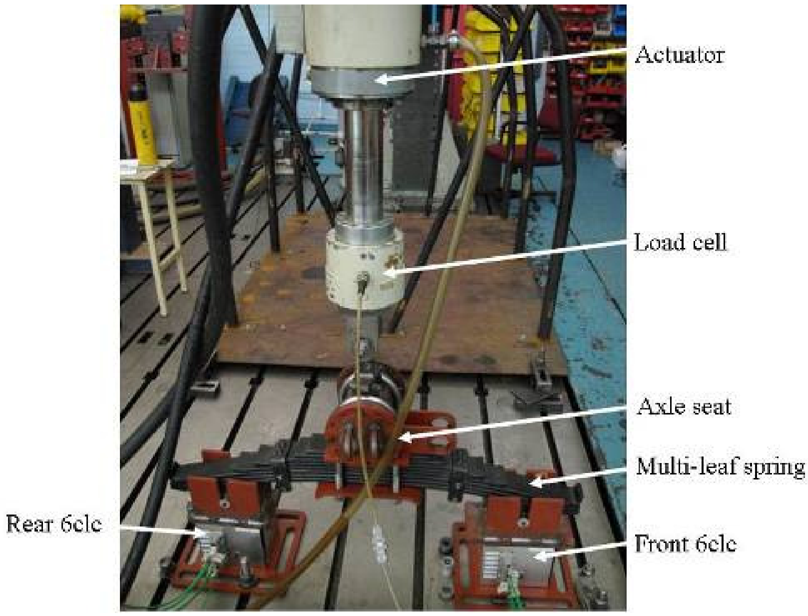

Figure 4.2. Spring only setup

The modelling approach that will be used to create a model of the spring only setup is indicated in Figure 4.3. The kinematics of the suspension system is solved in ADAMS which sends the displacement of the spring to the elasto-plastic leaf spring model in MATLAB via SIMULINK. SIMULINK is used to calculate the forces induced by the spring on the hangers. These forces are then applied to the model in ADAMS to determine the displacement at the next time step. This process is repeated for the duration of the displacement that is applied to the axle seat by the actuator. Paragraph two in this chapter will discuss the modelling of the spring only setup with the validation results presented in paragraph three.

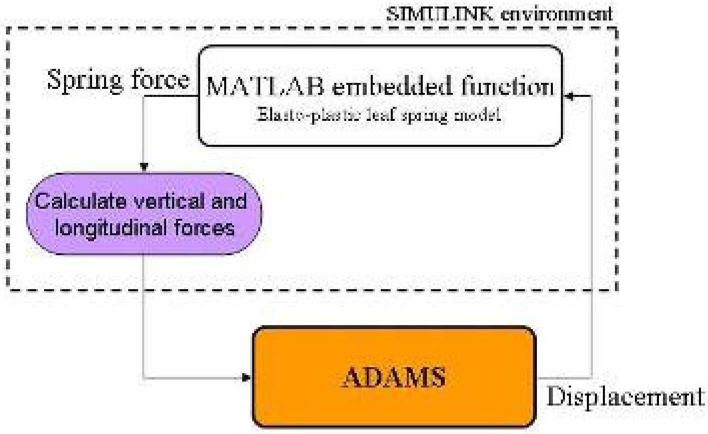

Figure 4.3. Co-simulation data flow between SIMULINK and ADAMS

2. Modelling of the spring only setup

The model of the spring only setup shown in Figure 4.4, with the exception of the multi-leaf spring, is simple. The modified hangers are connected to the front and rear 6clc with fixed joints. The modified hangers refer to the hangers having bearings that support the leaf spring instead of wear plates, found in the normal hangers. The 6clcs used in the model were modelled, verified and validated as discussed in Appendix A. The axle seat is connected via a link (geometry not included in Figure 4.4) and a revolute joint to the actuator. The axle seat is connected to the modified hangers via the ADAMS/Car leaf spring subsystem. This subsystem sends its displacement to SIMULINK and receives back the spring force (see Figure 4.3). It is also the ADAMS/Car subsystem of the leaf spring that regulates the motion between the axle seat and the modified hangers.

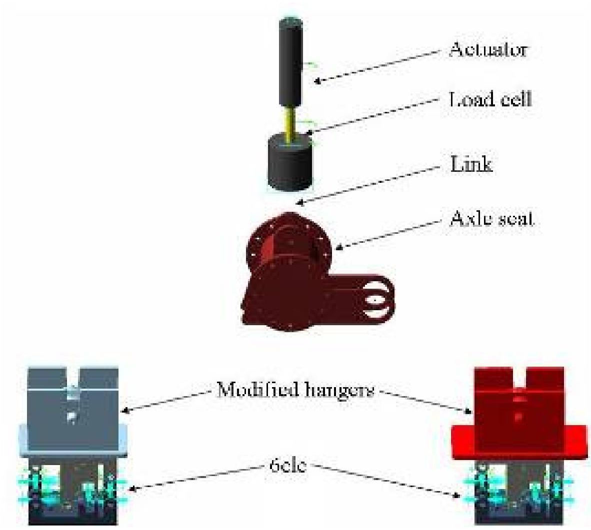

Figure 4.4. ADAMS/Car model of spring only setup

2.1. ADAMS/Car leaf spring model

The ADAMS/Car leaf spring model integrates the elasto-plastic leaf spring model into ADAMS/Car such that it can be used as a subsystem. Several of these subsystems can easily be included later in a vehicle model as required. Different models for the leaf spring was created in ADAMS/Car starting with the simplest one that calculates only the vertical force acting on the supports which is induced by the leaf spring when it is deflected. The following paragraphs describe the different models of the ADAMS/Car leaf spring model.

2.1.1. ADAMS/Car leaf spring Model 1

This model only considers the vertical movement and the vertical forces of the spring. To achieve this motion, a translational joint is placed between the axle seat and the front modified hanger to allow only the vertical translational degree of freedom of the axle seat. It should be noted that the use of the translational joint when a longitudinal force acts on the axle seat becomes inaccurate. When this suspension model is to be used in simulations where a longitudinal force is imposed on the axle seat (such as in braking simulations or in durability simulation with high obstacles) the use of the translational joint has to be reconsidered. The ADAMS/Car leaf spring model calculates the displacement of the spring and sends this to the elasto-plastic leaf spring model which is implemented in SIMULINK as an embedded MATLAB function. The elasto-plastic leaf spring model then solves for the spring force (F_s). Before the spring force is send back to ADAMS, the vertical forces acting at the front (F_{zR}) and rear (F_{zF}) hanger interface points (see Figure 4.5) are calculated. F_{zR} and F_{zF} are calculated by using Equation {4.1} and Equation {4.2}. Equation {4.1} and Equation {4.2} are obtained by simultaneously solving the equation of the sum of forces in the z-direction and the sum of moments taken about the axle seat.

$$F_{zF} = -\frac{l_r F_s}{l_r + l_f} \qquad \{4.1\}$$

$$F_{zR} = -\frac{l_f F_s}{l_r + l_f} \qquad \{4.2\}$$

The ADAMS model uses two point-point actuators which are placed between the axle seat and the front and rear hangers. The two point-point actuators are controlled by the forces F_{zR} and F_{zF}, respectively. The resulting force on the axle seat is the spring force F_s.

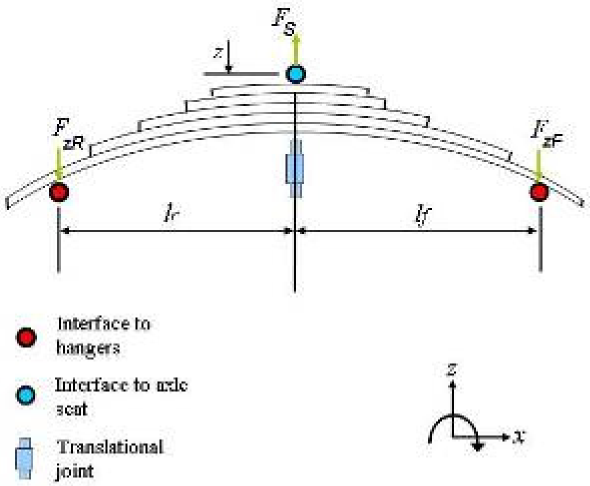

Figure 4.5. Schematic representation of ADAMS/Car leaf spring Model 1

2.1.2. ADAMS/Car leaf spring Model 2

This model includes both the vertical and longitudinal forces acting at the hanger interface points (see Fig. 4.6). The translational joint between the axle seat and front hanger limits the motion to only the vertical direction. As was mentioned in paragraph 2.1.1 the use of the translation joint when longitudinal forces act onto the axle seat should be reconsidered as this may cause inaccuracies. This model calculates the vertical forces (F_{zR}, F_{zF}, F_s) in exactly the same way as Model 1. Due to the translational joint this model exerts no longitudinal force on the axle seat. The longitudinal forces acting on the front (F_{xR}) and rear (F_{xF}) hangers are sent to ADAMS from SIMULINK and implemented in ADAMS as two point-point actuators placed between ground and the front and rear hangers, respectively.

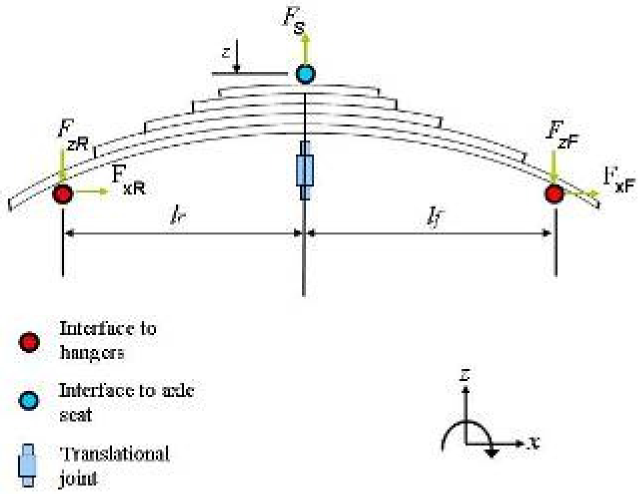

Figure 4.6. Schematic representation of ADAMS/Car leaf spring Model 2

The longitudinal forces F_{xR} and F_{xF} are simply calculated by taking the vertical forces (F_{zR} and F_{zF}) and relating them to the longitudinal forces (F_{xR} and F_{xF}) via the slope of the leaf spring at the point of contact between the leaf spring and the bearings. The assumption is made that the contact between the leaf spring and the bearing consists of a thin line. Figure 4.7 shows the forces acting at the point of contact between the leaf spring and the bearing. When we know the vertical forces (F_{zR} and F_{zF}) and the angle of the slope (α) we will be able to calculate the longitudinal forces (F_{xR} and F_{xF}). The vertical forces are obtained from the leaf spring model, whereas the angle of the slope is calculated by relating it to the deflection of the leaf spring.

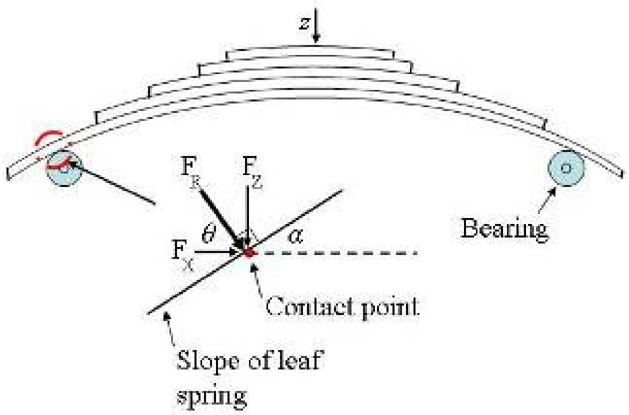

Figure 4.7. Forces at point of contact

The angle of the slope (α) of the leaf spring at the point of contact with the bearing is related to the deflection of the leaf spring (z) as follows. Table 4.1 and Table 4.2 shows the angles of the slope calculated from the experimentally measured deflection shapes of the leaf springs at three deflections for the front and rear contact points. The experimental setup and measurements of the deflection shapes were given in paragraph 2.1.2.2, Chapter 2. The deflection shape of the leaf spring at the normal position is given again here in Figure 4.8. In the figure it is indicated where the deflection at the three vertical loads, shown in Table 4.1 and Table 4.2, were obtained from.

Table 4.1. Angle of slope at front contact point

Vertical load [N]	**Deflection** (z) [m]	**Angle of slope** (α) [deg]
0	0	19.3
25.9	-0.016	14
51.9	-0.032	8.5

Table 4.2. Angle of slope at rear contact point

Vertical load [N]	**Deflection** (z) [m]	**Angle of slope** (α) [deg]
0	0	18.4
25.9	-0.015	14
51.9	-0.030	9.46

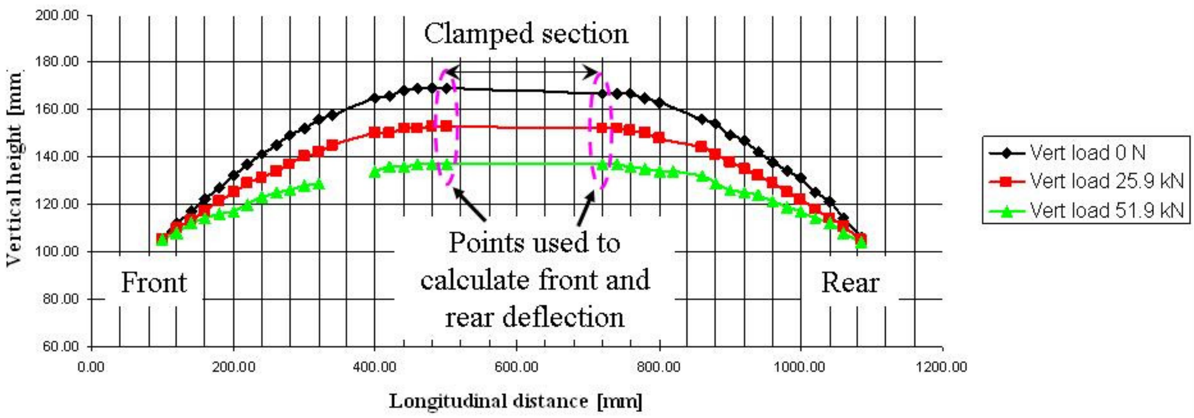

Figure 4.8. Deflection shape of the spring for the normal position

The values in Table 4.1 and Table 4.2 seem to have a linear relationship when viewed graphically. Therefore, the relationship between the angle of the slope and the deflection of the leaf spring can be given by Equation {4.3} and Equation {4.4} for the front and rear contact points, respectively.

$$\alpha_f = 337.5z + 19.3 \qquad \{4.3\}$$

$$\alpha_r = 298z + 18.4 \qquad \{4.4\}$$

The difference between the front and rear relationship between the angle of the slope and the deflection of the leaf spring may be due to the following possible cause. In this setup the lengths between the axle seat and the front and rear hangers (l_r and l_f) are not equal. Because the lengths (l_r and l_f) are different, the supports makes contact at a different longitudinal position on the leaf spring which means it is at a different part of the geometrical shape of the leaf spring. This implies that when the leaf spring has no vertical load on the leaf spring the clamped section of the spring will not be horizontal. As was observed in Figure 4.8. The front contact point is further away from the symmetry plane of the leaf spring than the rear contact point. This implies that the front and rear contact points are located on the leaf spring's geometrical shape such that it tends to tilt it clockwise (when viewing the spring in the orientation in Figure 4.8). This leads to the rear points that are used to calculate the deflection of the leaf spring, as indicated in Figure 4.8, to seem more deflected than the points used at the front. It can also be noted that as the vertical load is increased the difference in deflection of the front and rear points decreases. The relationship between the angle of the slope, at the front and rear contact points, and the deflection of the leaf spring have been established and presented as Eq.{4.3} and Eq.{4.4}. With the relationship between the angle of the slope and the deflection of the leaf spring known the relationship between the longitudinal and vertical forces at the front and rear contact points can now be determined.

From $\theta = 90° - \alpha$ and $\tan\theta = \frac{F_z}{F_x}$ we can obtain Equation {4.5} and Equation {4.6} which calculates the longitudinal force given the vertical force and deflection of the leaf spring.

$$F_{xF} = \frac{F_{zF}}{\tan(70.7° - 337.5z)} \qquad \{4.5\}$$

$$F_{xR} = -\frac{F_{zR}}{\tan(71.6° - 298z)} \qquad \{4.6\}$$

3. Validation of the spring only model

The model of the spring only model will now be validated against experimental measurements. The spring only model will be used with both ADAMS/Car leaf spring models that were discussed in the previous paragraph. The validation results using Model 1 and Model 2 of the ADAMS/Car leaf spring subsystem model is shown in the following two paragraphs.

3.1. Validation of the spring only model using Model 1

This paragraph presents the qualitative comparisons between the experimental measured data and the predicted data for the spring only setup using Model 1. Figure 4.9 shows the correlation between the measured and predicted spring force of the spring only setup. The correlation achieved is good and we could conclude that the model is an accurate representation of the physical system. However when we consider the equivalent forces and moments as measured by the two 6clcs it tells a different story. As expected the longitudinal and lateral forces measured by the 6clcs in the model measures zero (see Figure 4.10). This is due to the way this model was constructed. The vertical force shows good correlation when compared to the experimental data. It should be rather obvious that this should be the results for the forces at the attachment points, but it may have been neglected if the model was only validated against the spring force. This clearly shows the importance of correct model validation as discussed in Kat and Els (2011).

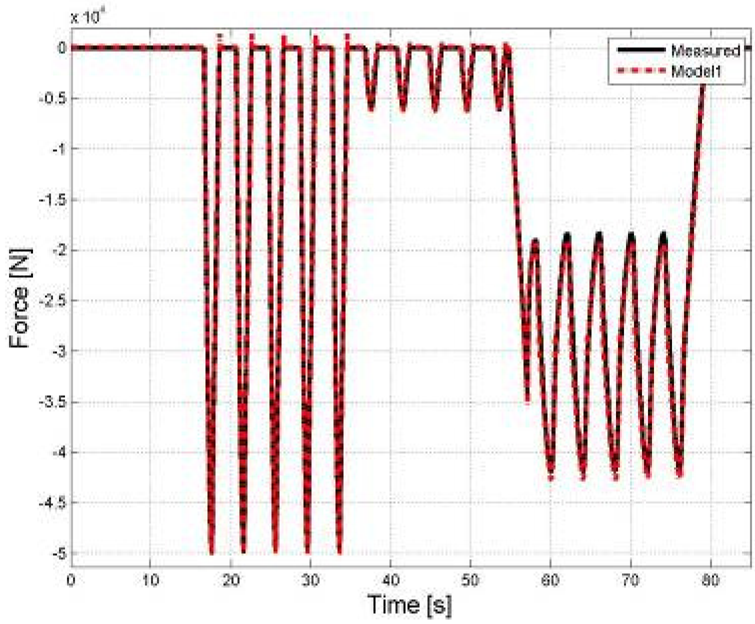

Figure 4.9. Comparison of measured and predicted spring force for the spring only setup using Model 1

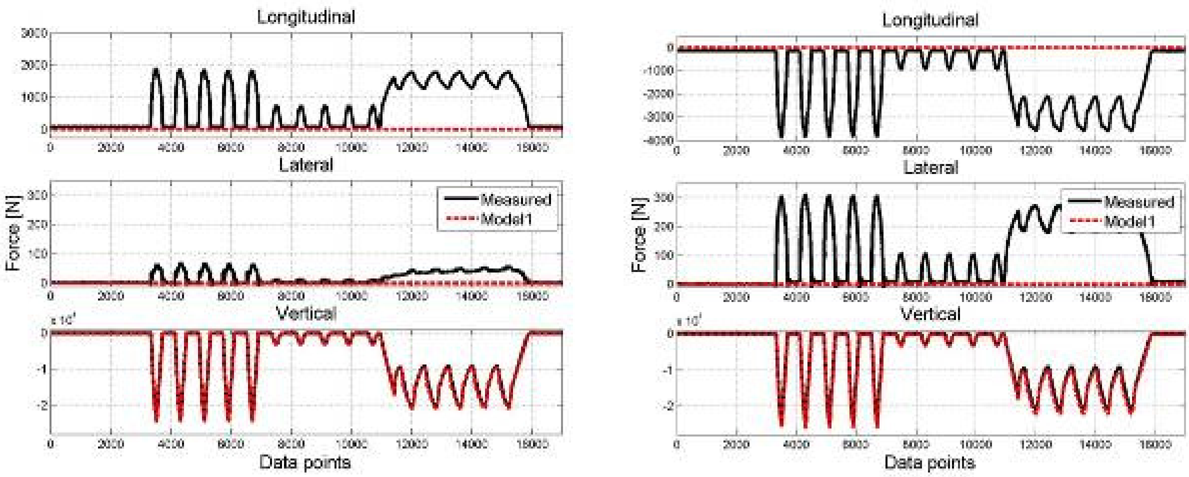

Figure 4.10. Equivalent forces measured by front (shown left) and rear (shown right) 6clcs

Figure 4.11 shows the correlation of the equivalent moments measured by the two 6clcs. It can be observed from this figure that all three moments from the model is zero. This is because the vertical force that the leaf spring imposes on the hanger acts at the centre of volume of the 6clc and thus does not induce any moments. However, the experimental measurement does indeed show that moments are induced, this is because in the experimental setup the vertical force from the leaf spring does not act exactly at the centre of volume. It is also true that in the experimental setup there is not only a vertical force imposed on the hanger but also longitudinal and lateral forces. Figure 4.11 may also indicate that there exists a discrepancy between the model and the experimental setup's points where the force acts on the hanger. The comparison of the equivalent vertical force in Figure 4.10 suggests that the vertical force is indeed predicted accurately, but the correlation of the equivalent moments (in Figure 4.11) and the correlation of the forces in the uni-axial load cells (in Figure 4.12) suggests that the application point of the vertical force, imposed by the leaf spring on the hanger, is not the same between the experimental setup and the model. Only the forces measured in the uni-axial load cells that are orientated in the vertical direction were shown (Figure 4.12). Due to the way this model was constructed the forces in the uni-axial load cells, measured by the 6clc in the longitudinal and lateral direction, are zero and therefore was not presented.

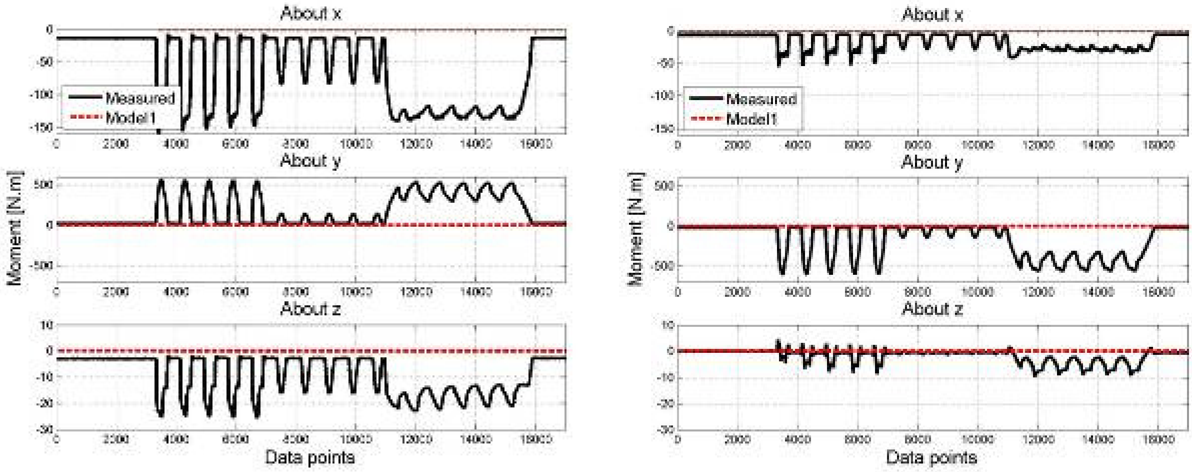

Figure 4.11. Equivalent moments measured by front (left) and rear (right) 6clcs

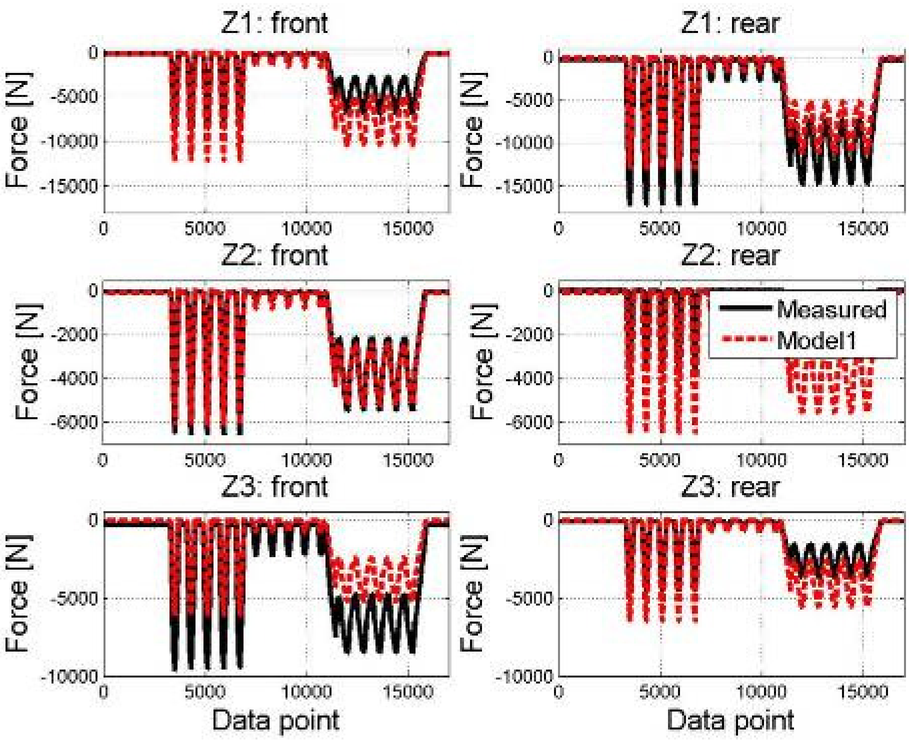

Figure 4.12. Reaction forces measured by front (left) and rear (right) 6clcs

3.2. Validation of the spring only model using Model 2

This paragraph presents the qualitative comparisons between the experimental data and the predicted data for the spring only setup using Model 2. From Figure 4.13 we observe a significant improvement in the longitudinal forces. The correlation of the longitudinal forces at the rear 6clc is good with the longitudinal forces of the front 6clc predicted by Model 2 being higher. Figure 4.14 shows the equivalent moments at the front and rear 6clcs. The model only predicts moments about the y-axis whereas the experimental measurements show moments about all three axis. This may be due to either the resultant force acting on the hanger being incorrect and/or that the application point is incorrect. From the comparisons of the equivalent force, in Figure 4.13, and the longitudinal and vertical uni-axial load cell forces (Figure 4.15 and Figure 4.16) we can see that we have a discrepancy in the orientation and the application point of the resultant force. The discrepancy in the orientation of the resultant force can be observed from Figure 4.13. The discrepancy in the application points of the front and rear hangers are more difficult to observe. If the three equivalent forces where predicted accurately any difference between the measured and predicted equivalent moments and reaction forces will then indicate that the application point is not correct. In this case the equivalent forces are not predicted accurately, mainly because the lateral forces are ignored by the model, and the equivalent moments do not show good correlation and we therefore have the situation that the discrepancy is due to a combination of the orientation and application point of the resultant force not being entirely accurate.

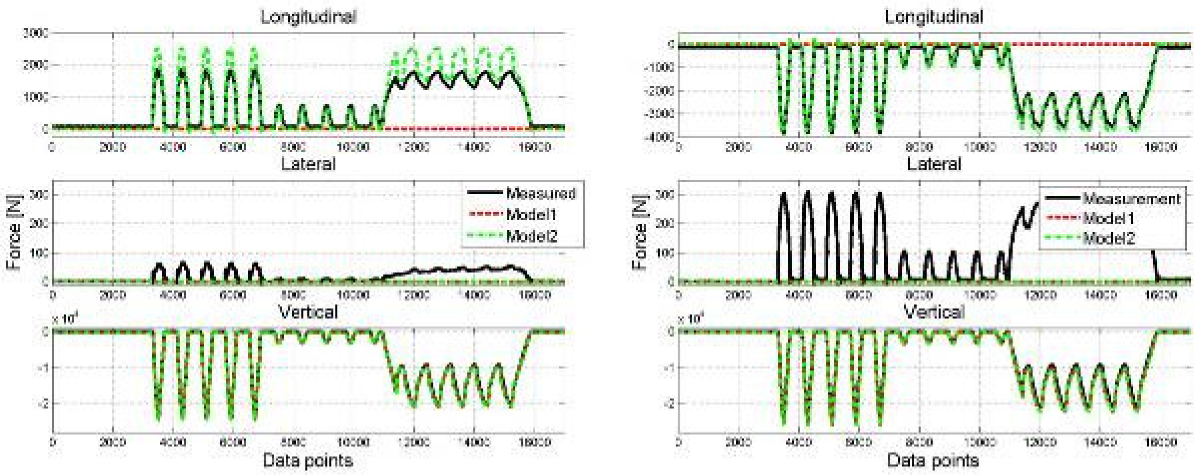

Figure 4.13. Equivalent forces measured by front (shown left) and rear (shown right) 6clcs

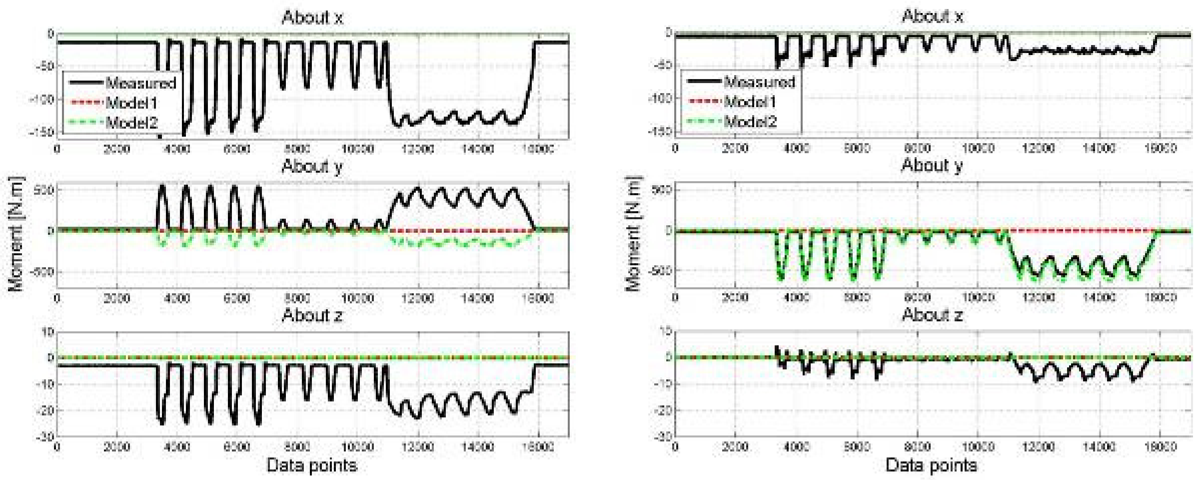

Figure 4.14. Equivalent moments measured by front (left) and rear (right) 6clcs

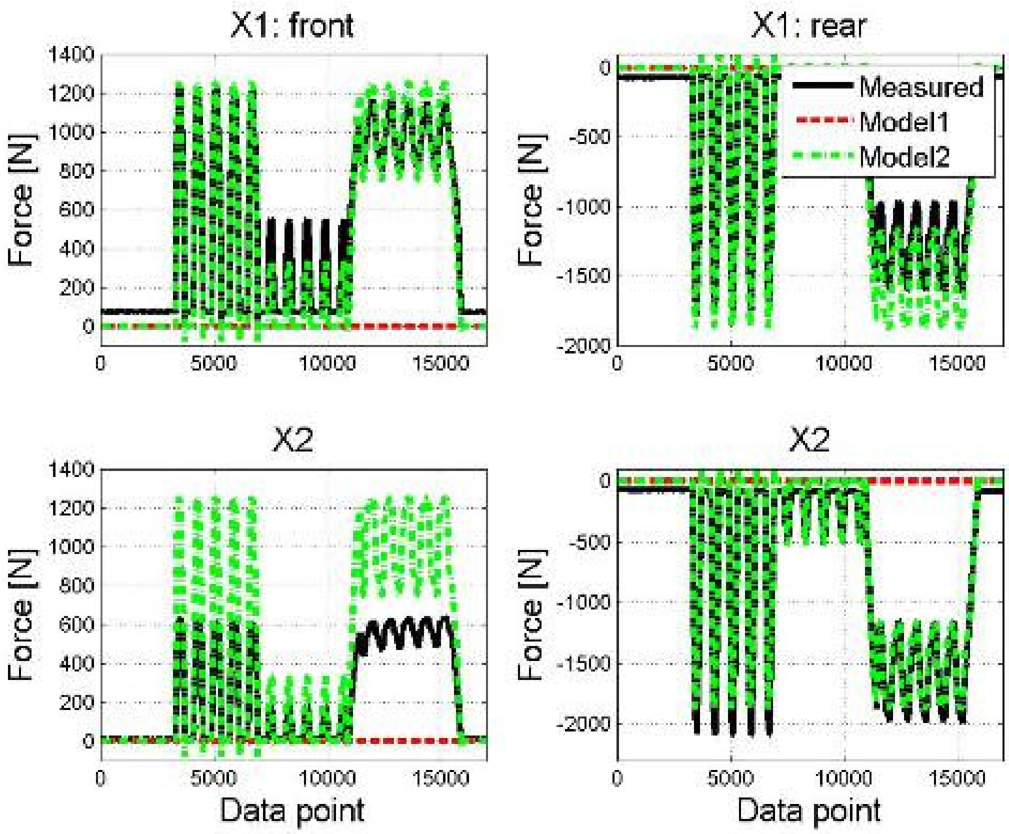

Figure 4.15. Reaction forces in longitudinal direction measured by front and rear 6clcs

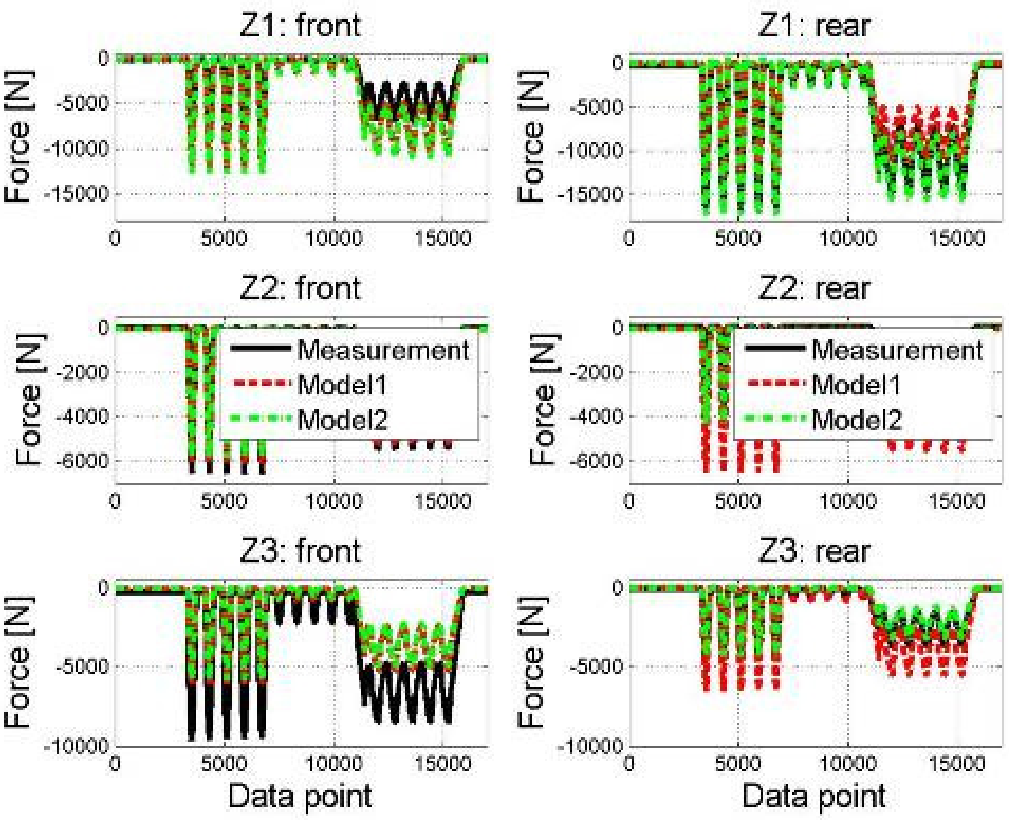

Figure 4.16. Reaction forces in vertical direction measured by front and rear 6clcs

4. Conclusion

The elasto-plastic leaf spring model from Chapter 3 was integrated into two ADAMS/Car models which were used to model the spring only setup. One of the two models only considered the vertical forces at the hanger attachment points (Model 1) with the other model considering both the vertical and longitudinal forces at the hanger attachment points (Model 2). The validation results indicate that Model 2 gives better predictions than Model 1. Both models give good predictions of the vertical equivalent force. The spring only model using Model 2, which included the longitudinal forces, is able to predict the longitudinal forces. The validation results showed good correlation for the longitudinal and vertical forces but it is clear from the validation results that the model of the spring only setup needs some refinement. The most probable cause for the discrepancies may be due to an incorrect application point of the resultant force to the two hangers. As mentioned, the use of the translational joint has to be reconsidered when this suspension model is to be used in simulations where a longitudinal force is imposed on the axle seat (such as in braking simulations or in durability simulation with high obstacles)

The validation results obtained for the spring only setup showed good correlation which can be improved by refining the model. The refinement of the spring only model as well as the extension of the model to include additional components in order to create an accurate model of the in-service setup, and ultimately, a model of the complete suspension system, will not be addressed in this study. The extension of the spring only model to the models shown in Figure 4.1 will be the subject of future work. Instead we will turn our focus to the verification and validation process in the next chapter. All the models that were created in this study were validated against experimental data. A qualitative validation procedure was followed by which superimposed graphical plots of the data were interpreted. The following chapter will discuss the verification and validation process as well as investigate the use of quantitative validation methods which are less subjective than the qualitative methods used.