Chapter 2

Experimental characterisation

Experimental data forms an integral part of many engineering endeavours. Among these are studies concerned with the development of mathematical models of a particular physical system of interest. Experimental data is of critical importance as it supplies the necessary input data to the mathematical models. The experimental data required as input to the models range from simple geometrical information to complex non-linear, hysteretic characteristics of force elements. Furthermore, experimental data is a prerequisite for model validation.

This study is concerned with the development of a validated mathematical model which is able to simulate the vertical behaviour of a leaf spring suspension system used on commercial vehicles. In order to create a validated model of the suspension system introduced in Chapter 1, various aspects need to be characterised experimentally in order to obtain the experimental data that will be required in the validation process. One of the required parameters is the forces between the suspension attachment points (i.e the hangers) and the chassis. In order to measure these forces a six component load cell was manufactured, calibrated, verified and validated. This process is briefly discussed in this chapter in paragraph 1 with a detailed discussion given in Appendix A. This chapter then continues with the experimental characterisation of the multi-leaf spring and parabolic leaf spring as well as the characterisation of the suspension system using the two different leaf springs. The characterisation of the multi-leaf spring and suspension system using the multi-leaf spring are discussed in paragraph 2. Paragraph 3 discusses the characterisation of the parabolic leaf spring and the suspension system using the parabolic leaf spring.

1. Six component load cell (6clc)

At the start of the experimental work it was clear that the reaction forces between the suspension attachment points and the chassis had to be measured. This requirement came from the aim of creating a validated suspension model for use in chassis durability analysis. In order to measure these forces, a six component load cell (6clc) was developed. The 6clc had to be able to measure the forces in all three directions and the moments about all three axis. With this information it is possible to obtain a complete picture of how the suspension system transmits the forces from the axle to the chassis and validate whether the suspension models can indeed predict these forces accurately.

The 6clc that was developed is shown in Figure 2.1. The 6clc consists of two parts that are connected to each other via six uni-axial load cells. One of the uni-axial load cells is shown in Figure 2.2. The six uni-axial load cells are connected between the two parts in such a way that all the degrees of freedom between the two parts are removed and so that each of the uni-axial load cells measures only tension-compression forces. The two parts of the 6clc are attached between the two bodies where the forces need to be measured. The use of two six component load cells will also make it possible to measure how the forces are distributed between the front and rear suspension attachment points. It is expected that without the radius rod and with the front and rear hanger having equal distance from the centre of the axle a vertical force on the leaf spring will divide equally between the front and rear hanger attachment points. However, this 50/50 force distribution will change when the front and rear hanger spacing is not equal. The 50/50 distribution may also be affected by the radius rod as well as combined loading that may act on the axle.

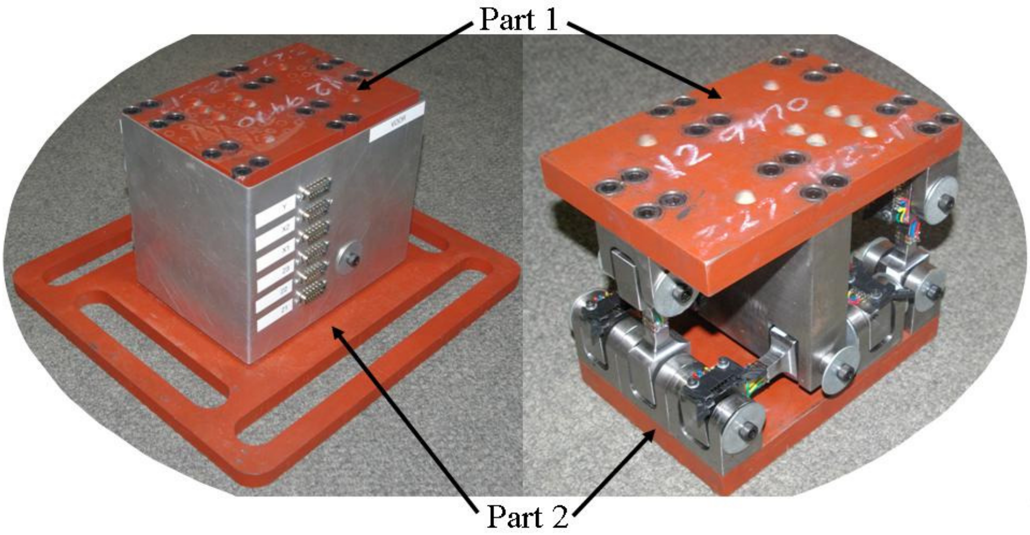


Figure 2.1. Six component load cell

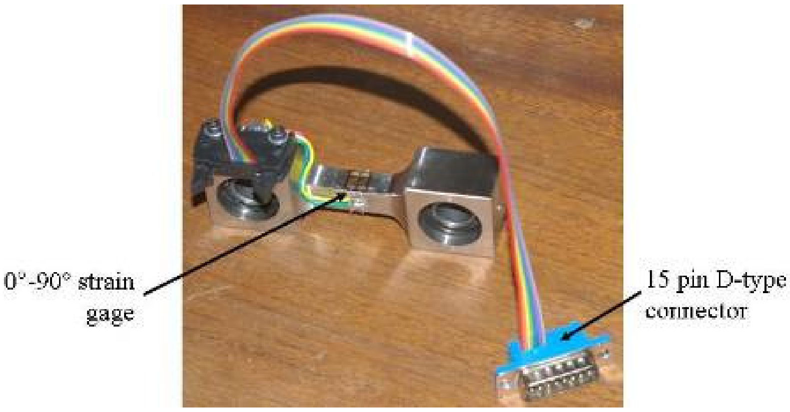


Figure 2.2. Uni-axial load cell used in the six component load cell

The 6clc shown in Figure 2.1 uses six of the uni-axial load cells shown in Figure 2.2. After 12 uni-axial load cells were calibrated they were incorporated into two 6clcs one being the front 6clc and the other one the rear 6clc. Appendix A gives a detailed discussion of the calibration of the uni-axial load cells. The verification of the concept of the 6clc as well as the verification of the ADAMS/Car model using analytical equations are also shown in detail in Appendix A. The model in ADAMS/Car was created to measure the equivalent forces and moments in the simulation environment in order to compare the virtual measurements to the physical measurements. The virtual 6clc will be used in Chapter 4 to compare the modelling results to the physical measurements. The derivation of the analytical equations and the modelling of the 6clc is discussed in detail in Appendix A. Appendix A also presents the validation of both the analytical equations and the ADAMS/Car model using experimental measurements. From the verification and validation results it was concluded that the physical and virtual 6clc is able to measure the forces that are transmitted from the suspension to the chassis. Figure 2.3 shows the use of the front and rear 6clcs in an experimental setup.

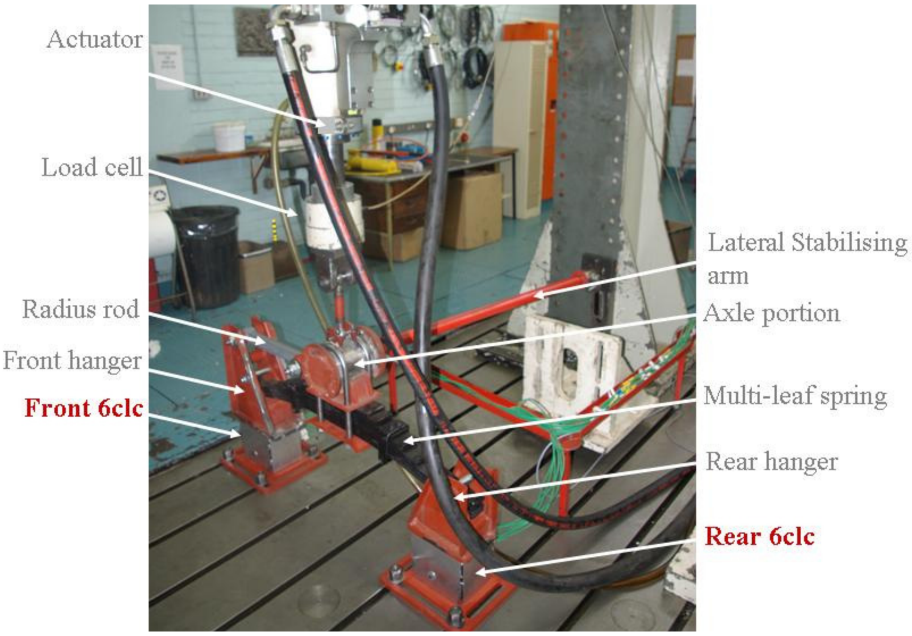


Figure 2.3. Use of front and rear 6clc in experimental setup

2. Characterisation of the suspension system using the multi-leaf spring

The various aspects of the suspension system that were characterised using the multi-leaf spring are shown in Figure 2.4. The tests are categorised into three major categories i.e. **vertical**, **lateral** and **longitudinal** characteristic. The vertical characteristics were considered the most important as the primary aim of the study is to obtain a validated mathematical model of the suspension system that could be used in durability analysis. The vertical characterisation was sub divided into three aspects i.e. the **force-displacement characteristic**, **roll stiffness** and the **complete** suspension. Only the force-displacement characteristics are relevant for this study and will therefore be presented. The characterisation of the roll stiffness and the characterisation of the complete suspension system as well as the lateral and longitudinal characterisation was done to have the experimental data available when the model is extended in future work. The experimental characterisation of interest to this study is shown in green in Figure 2.4 and will be presented in further detail in this chapter.

The force-displacement characterisation of the multi-leaf spring was done using two setups namely, the in-service setup and spring only setup. Details of the two setups will be given in paragraph 2.1.1 and paragraph 2.1.2. The effect of the U-bolt preload and the longitudinal spacing of the hangers on the force-displacement characteristic will be presented. The deflection shape of the leaf spring subjected to different loading and with different hanger spacings were also obtained. As indicated in Figure 2.4 three multi-leaf springs were used in the force-displacement characterisation. Two of them (New 1 and New 2) were brand new leaf springs that have not been used prior to the characterisation tests. The third leaf spring (Old) was taken from a commercial trailer that had done approximately 500 000 km.

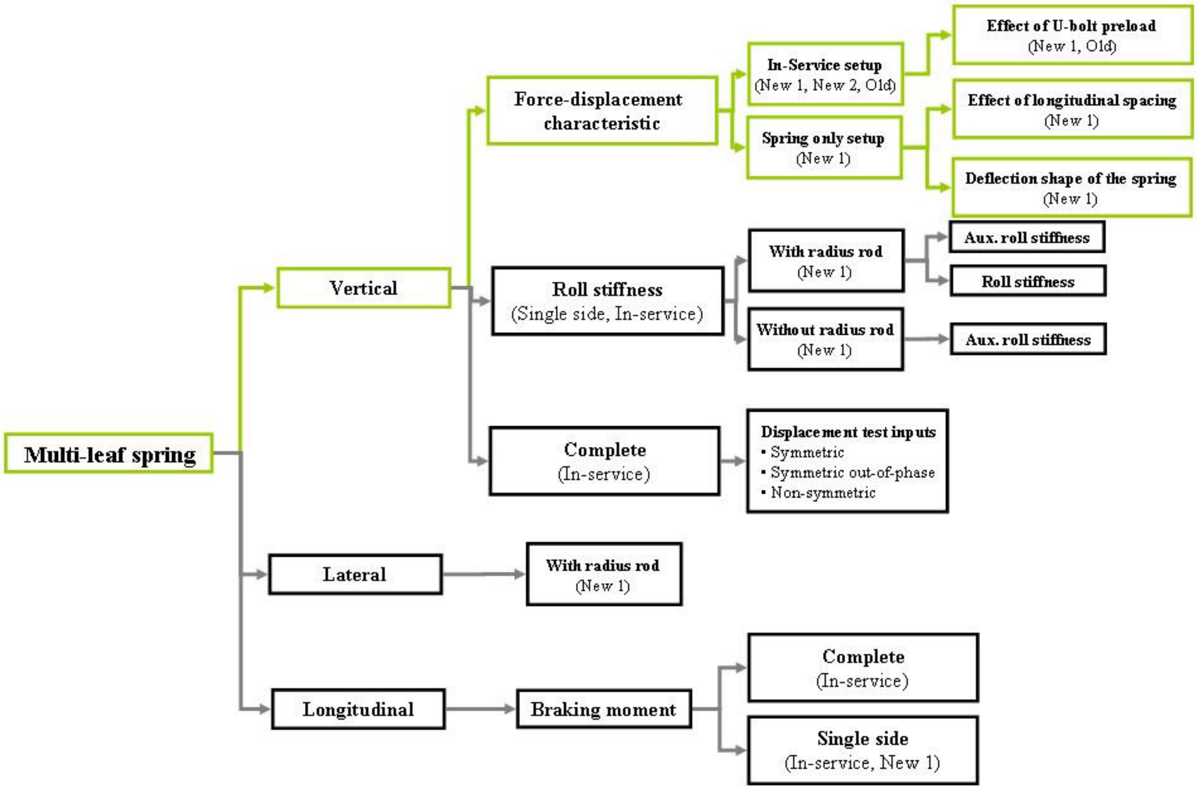


Figure 2.4. Overview of characterisation using the multi-leaf spring

2.1. Force-displacement characteristics

The force exerted by the leaf spring when deflected, is a function of the static load and the amplitude of the imposed displacement. Cebon (1986) and Fancher *et al.* (1980) found that the spring force is not dependent on the frequency of the imposed displacement. This would imply that the force-displacement characteristic does not need to be obtained at different input frequencies. To verify this, two displacement input signals were used that had frequencies of 0.05 Hz and 0.5 Hz, respectively. The force-displacement characteristics of the multi-leaf spring subjected to these two input signals are shown in Figure 2.5. Figure 2.6 shows the force-displacement characteristics when the amplitude is kept the same but the excitation frequency is swept from 0.05 Hz to 4 Hz. From Figure 2.5 and Figure 2.6 it can be observed that the force-displacement characteristic stays essentially the same irrespective of the excitation frequency. This seems to confirm that the force-displacement characteristic of the leaf spring is not dependent on the frequency of the displacement input. The experimental force-displacement characteristics shown in Figure 2.5 and Figure 2.6 were obtained with the multi-leaf spring in the in-service setup which is discussed in paragraph 2.1.1.

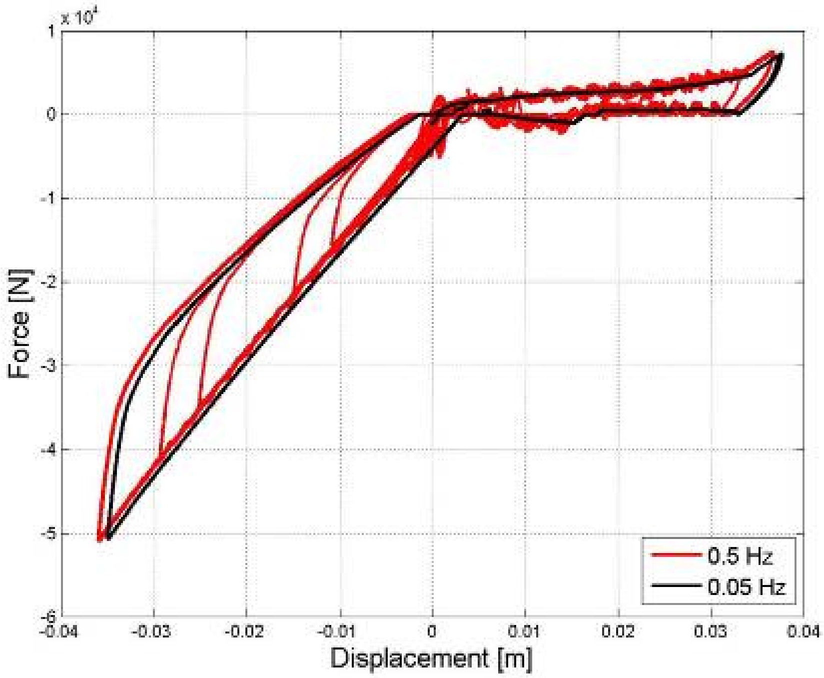


Figure 2.5. Compare force-displacement characteristics for different excitation frequencies

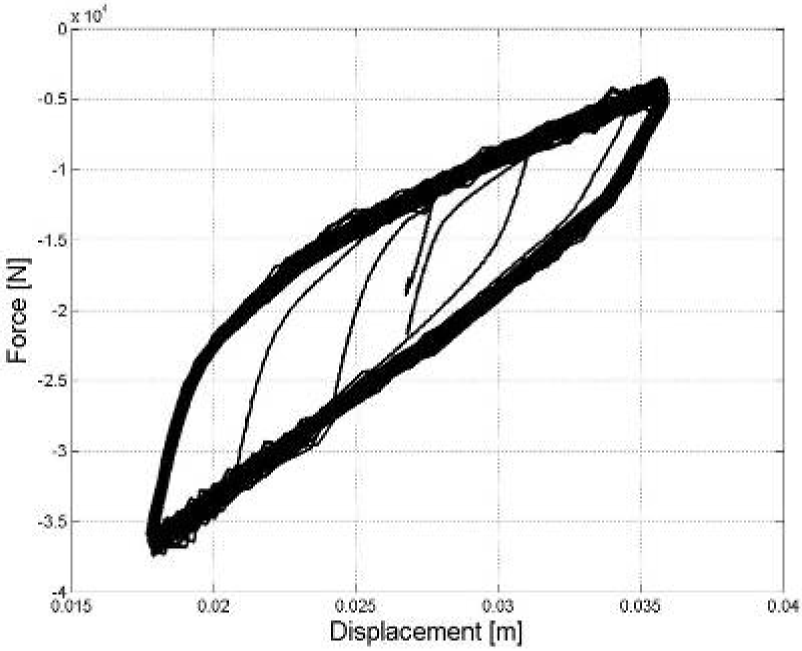


Figure 2.6. Force-displacement characteristic for sine sweep with frequencies ranging from 0.05 Hz to 4 Hz

From the results above and the findings of Cebon (1986) and Fancher *et al.* (1980) the spring force of the multi-leaf spring is therefore a function of the static load and the amplitude of the imposed displacement on the leaf spring:

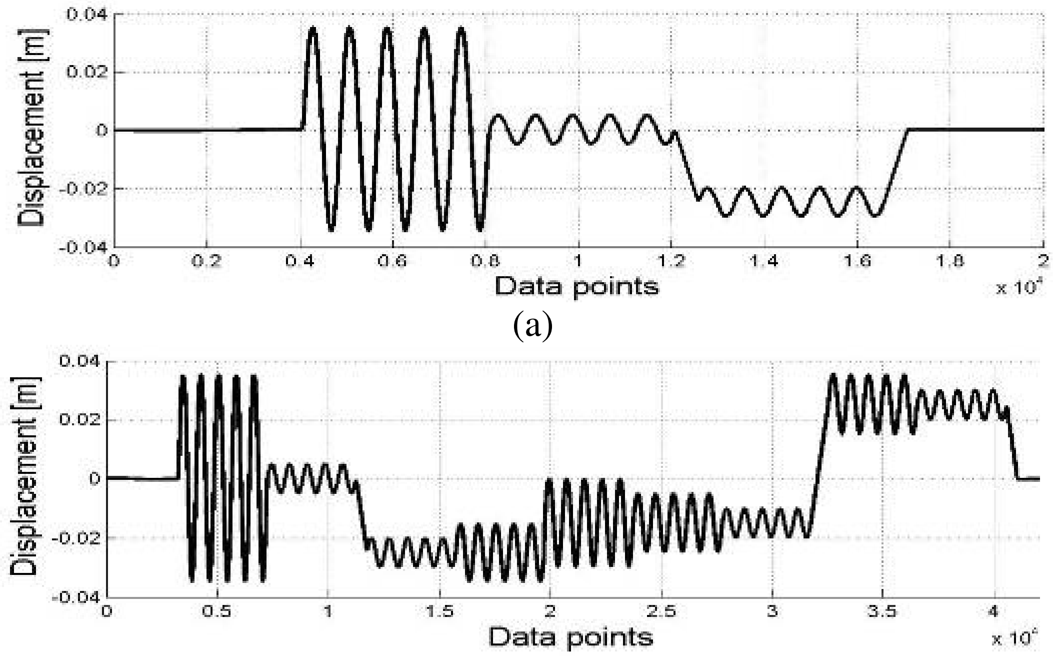
Leaf spring force = *f*(static load, amplitude of imposed displacement)

The force-displacement characteristic from the spring supplier is usually obtained from a test in which the spring is monotonically loaded. Therefore the supplier's force-displacement characteristic is not able to capture the hysteretic behaviour of the multi-leaf spring. For the purpose of this study a more comprehensive force-displacement characteristic of the leaf spring is required which should include the hysteretic behaviour.

The force-displacement characteristic for the multi-leaf spring is obtained using two different setups i.e. an in-service setup and a spring only setup. These two setups are discussed in paragraph 2.1.1 and 2.1.2. In order to characterise the dependency of the spring force on the static load and the amplitude of the imposed displacement, five displacement inputs were used in the force-displacement characterisation. The five displacement inputs can be categorised into two groups. The first group of signals consist of sinusoidal waves with a frequency of 0.25 Hz and varying static loads with different amplitudes. The two signals used in this group are shown in Figure 2.7. The second group consists of three random signals with their input frequency having a bandwidth of 0.6 Hz. Figure 2.8 shows the three random signals used. The random signal in Figure 2.8(a) only compresses the spring and has a rms amplitude of 19.2 mm. The random signal in Figure 2.8(b) compresses and extends the leaf spring and has a rms amplitude of 16.9 mm. The third random signal, shown in Figure 2.8(c) only extends the spring and has a rms amplitude of 23 mm. These displacement signals will be referred to as follows:

- Input displacement signal 1 - Figure 2.7(a)
- Input displacement signal 2 - Figure 2.7(b)
- Input displacement signal 3 - Figure 2.8(a)
- Input displacement signal 4 - Figure 2.8(b)
- Input displacement signal 5 - Figure 2.8(c)

Most of the force-displacement characteristics shown in this study were obtained using either Input displacement signal 1 or Input displacement signal 3.



(b)

Figure 2.7. Sinusoidal input signals with constant frequency but varying static loads and amplitudes

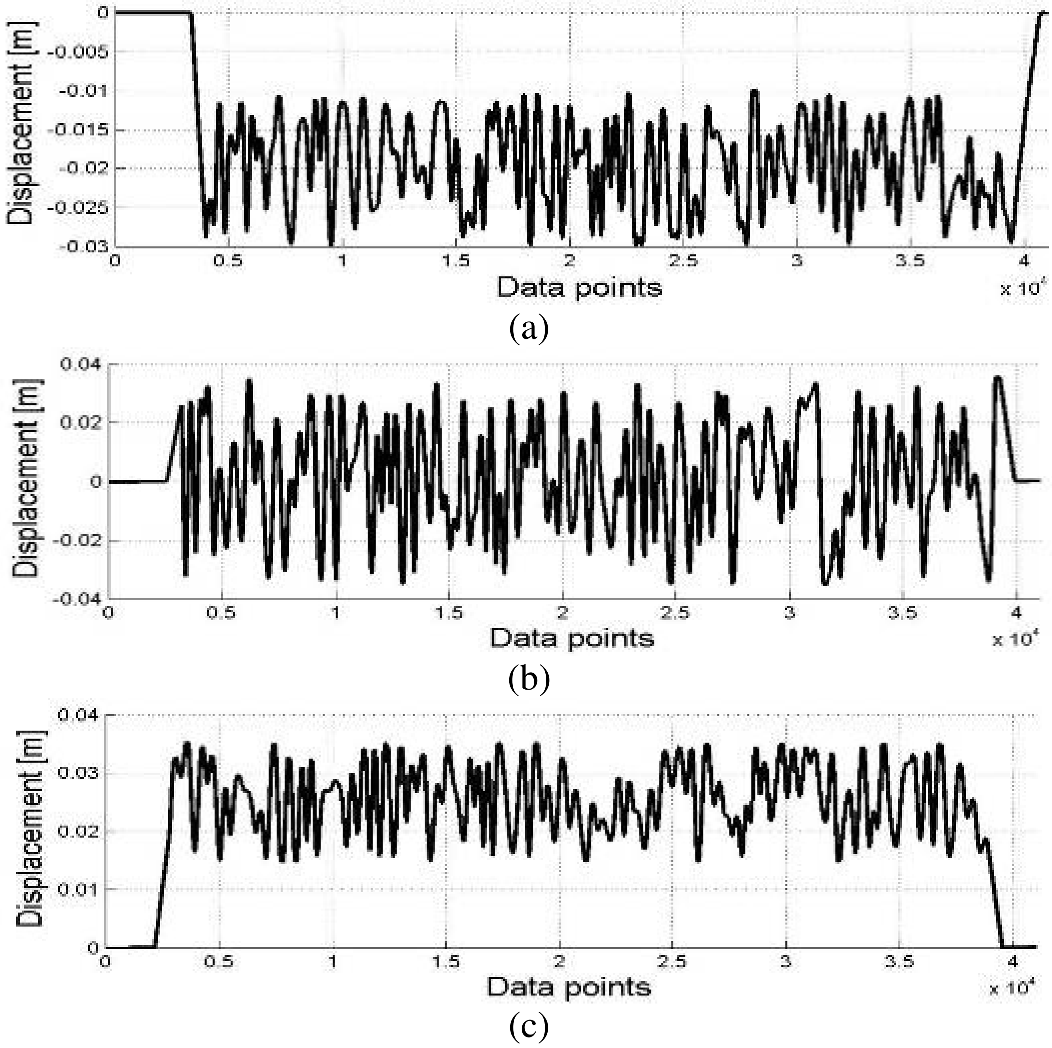


Figure 2.8. Random input signals. (a) Spring only compressed. (b) Spring compressed and extended. (c) Spring only extended

2.1.1. In-service setup

The in-service experimental setup is shown in Figure 2.9. The spring is constrained exactly as it would be when on the vehicle, meaning that the multi-leaf spring is supported by the front and rear hangers and the radius rod is connected between the front hanger and the axle. It should be noted that this setup only considers the one side of the suspension. In other words there is no coupling between the left and right hand springs as would be the case on the vehicle. A lateral stabilising arm is needed to prevent the single sided setup from tipping over when the actuator compresses the spring. The experimental setup includes the two six component lead cells (6clc) that are placed between the hangers and the laboratory floor (which represents the chassis of the vehicle). The measurements taken with the 6clcs enables the quantification of the input forces into the chassis of the vehicle. They also make it possible to check how the vertical force that the leaf spring develops is distributed between the front and rear attachment points.

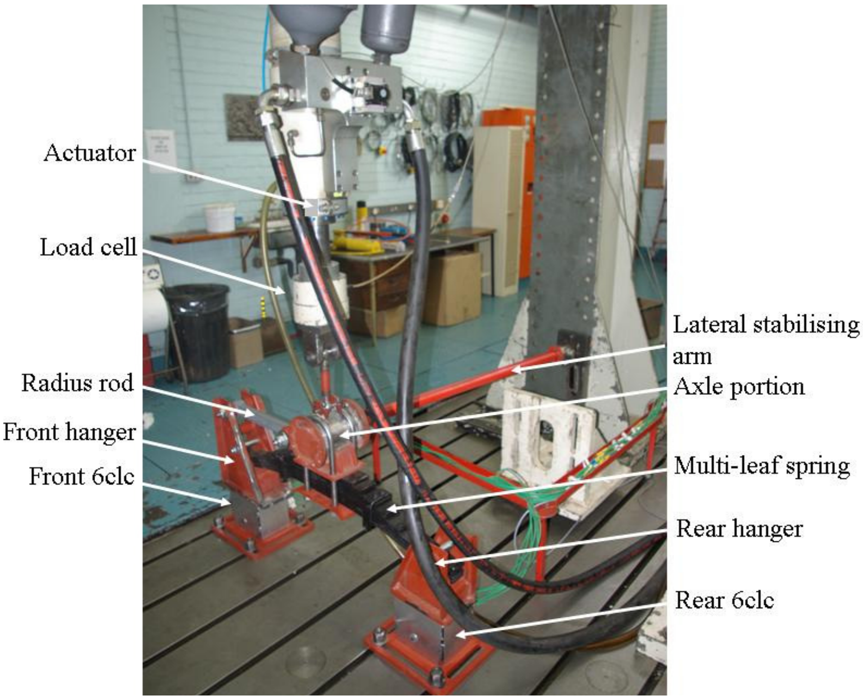
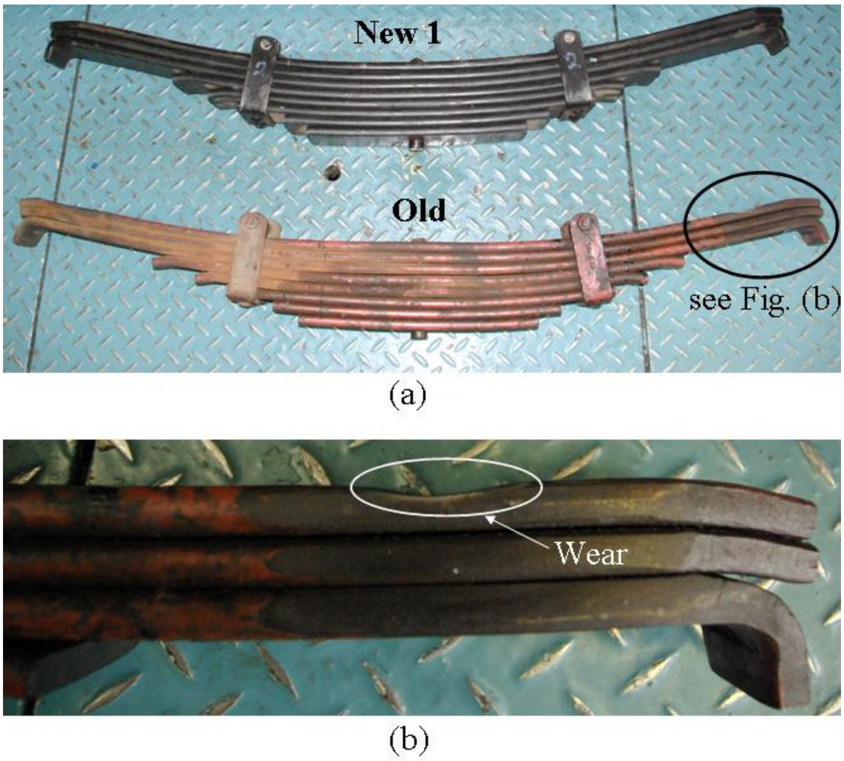


Figure 2.9. Experimental in-service setup of single sided suspension with the multi-leaf spring

The force-displacement characteristics were obtained for three multi-leaf springs. The leaf springs were all similar in that they all consisted of 8 blades, of which three were full length blades, with all of the blades having a uniform cross-section with a width of 76 mm and a thickness of 14 mm. Two of the leaf springs were new (New 1 and New 2) and the third leaf spring had been used on a vehicle and had done approximately 500 000 km (reference will be made to this spring as the old spring). Figure 2.10(b) shows the wear on the blade, of the old leaf spring, that was in contact with the wear plates in the hangers.



(a)

(b)

Figure 2.10. (a) New and old multi-leaf springs. (b) Wear on old multi-leaf spring

Figure 2.11 shows the force-displacement characteristics of the three multi-leaf springs. The characteristics obtained from the two new leaf springs are similar. It is interesting to note that the old spring's characteristics show a smaller hysteresis loop. The repeatability of the test is shown in Figure 2.12. One of the new multi-leaf springs (i.e. New 2) were characterised 7 times and it can be seen from Figure 2.12 that the characteristics obtained from run 2 and run 3 is similar with a small deviation between them and the other four runs (run 4 to 7) which again gave similar results. From this it can be seen that the experiment gives good repeatability.

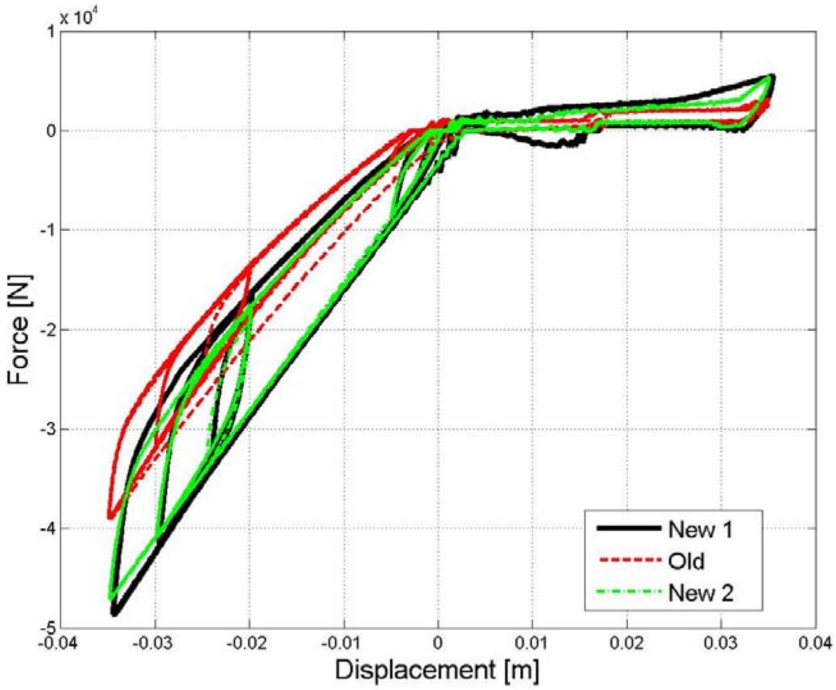


Figure 2.11. Comparison between the characteristics of the two new springs and the old spring

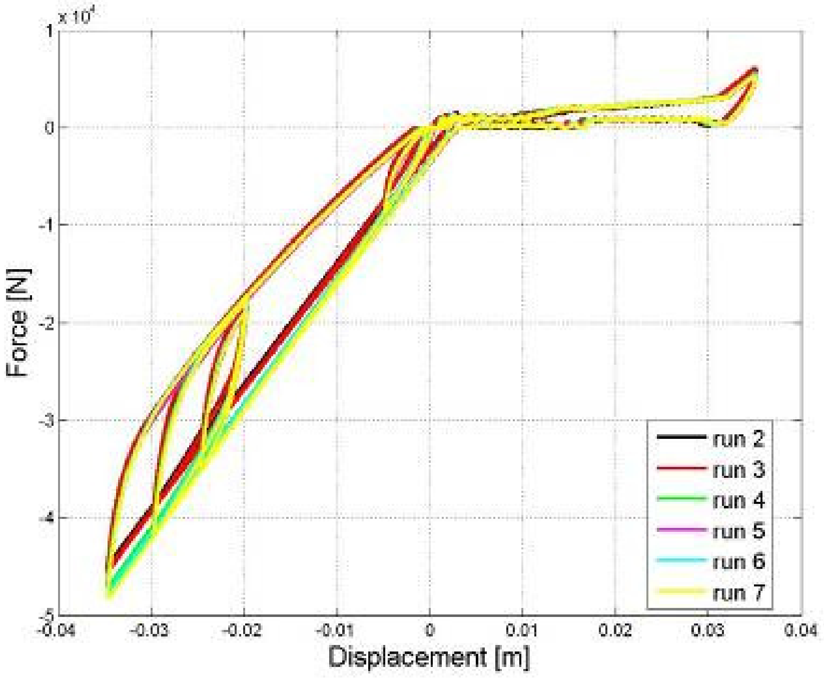


Figure 2.12. Comparison of seven separate measurements of the force-displacement characteristic of the same multi-leaf spring (New 2)

2.1.1.1. Effect of U-bolt preload on the force-displacement characteristic

An interesting and important observation was made concerning the effect of the U-bolt's preload on the force-displacement characteristic of the multi-leaf spring. The U-bolts are used to attach the axle to the leaf springs by looping the U-bolts around the axle and using a clamp plate to secure the axle via the U-bolts to the leaf spring (see Figure 2.13). This configuration constrains the multi-leaf spring and has an affect on the force-displacement characteristic of the multi-leaf spring.

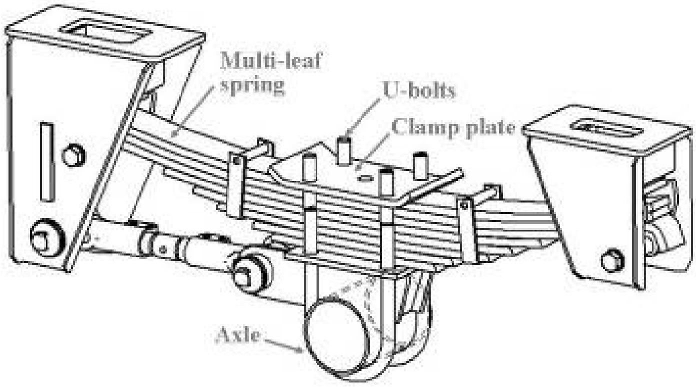


Figure 2.13. Attachment of axle to multi-leaf spring via U-bolts

Figure 2.14 shows the characteristics of the multi-leaf spring when the U-bolts are torqued to different values. The original characteristic shown in Figure 2.14 was obtained with the bolts torqued to the specified 450 N.m (Van De Wetering Engineering, 2001). The U-bolts were then completely loosened and torqued to a third of the specified value i.e. 150 N.m. After this the bolts were again torqued to the specified value of 450 N.m. The force-displacement characteristic of the spring was measured twice at each of the above mentioned values. From Figure 2.14 it can be observed that the multi-leaf spring's stiffness increases when the preload of the U-bolts are increased. The same trend is seen for the old spring which is shown in Figure 2.15. The effect is considerable and thus needs to be taken into account during suspension assembly.

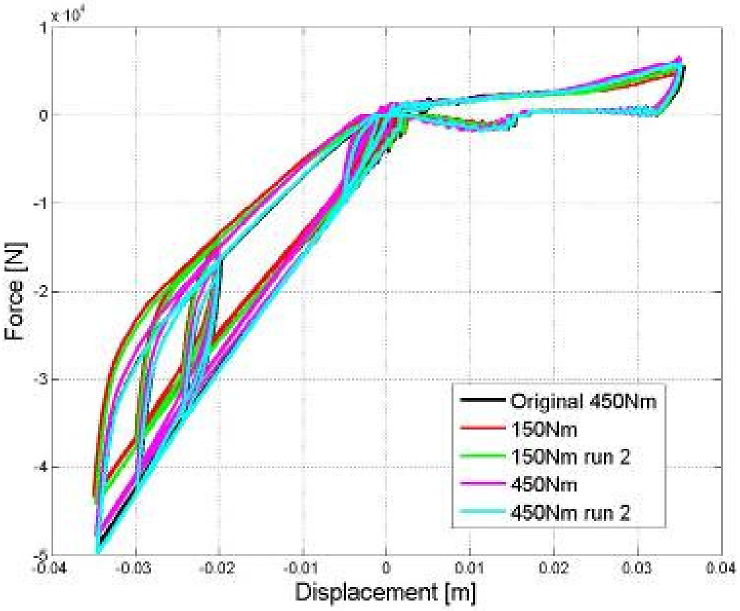


Figure 2.14. Effect of U-bolt preload on force-displacement characteristics of the multi-leaf spring New 1

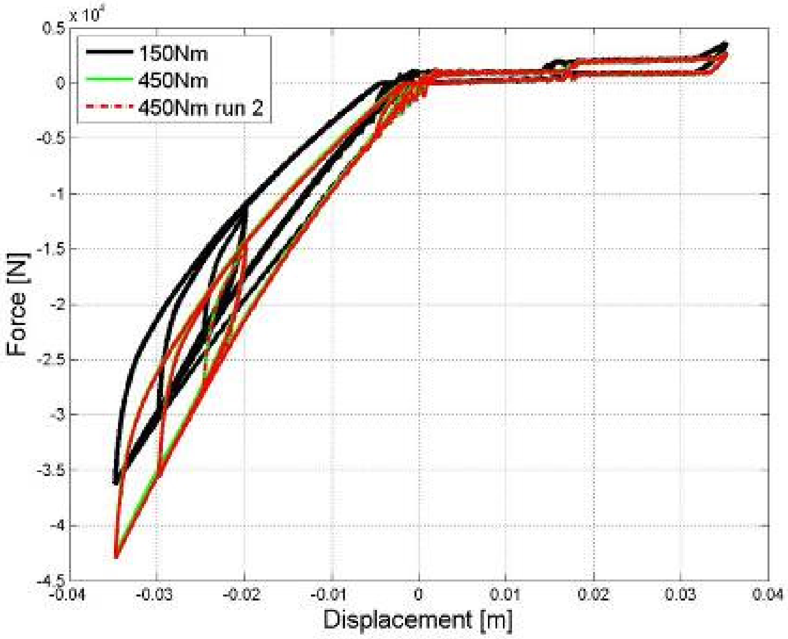


Figure 2.15. Effect of U-bolt preload on force-displacement characteristics of the old multi-leaf spring

2.1.2. Spring only setup

The experimental spring only setup is shown in Figure 2.16. The spring only setup of the multi-leaf spring differs from the in-service setup as the leaf spring in this setup is simply supported on bearings instead of the normal wear plates that are located in the front and rear hangers.

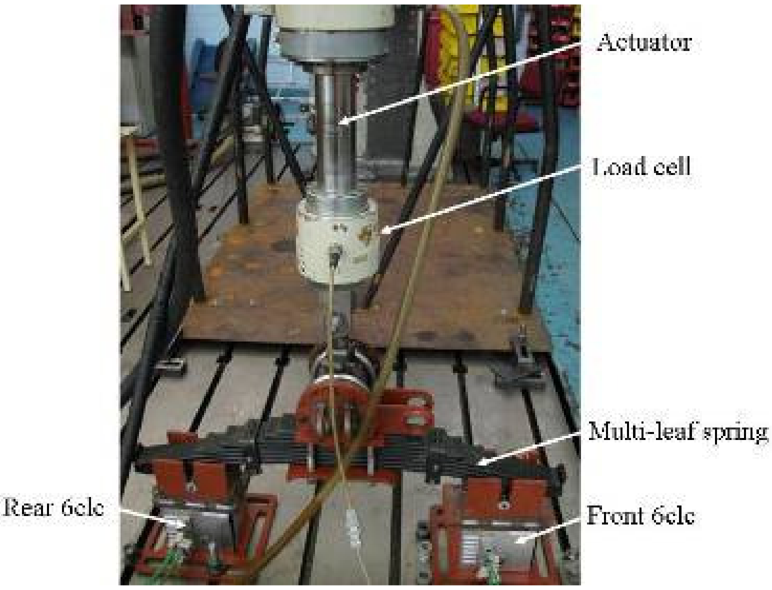


Figure 2.16. Experimental spring only setup of multi-leaf spring

The spring only setup uses bearing supports for two reasons. Firstly, the effect of friction between the leaf spring and the wear plates are eliminated. Secondly, with the spring only setup one has better control over the loaded length of the leaf spring. Also, any varying stiffness due to a change in the loaded length, which may be induced by the profile of the wear plates, is avoided. Figure 2.17 shows how the profile of the supports (in this case the profile of the wear plates) may affect the loaded length as the leaf spring is deflected.

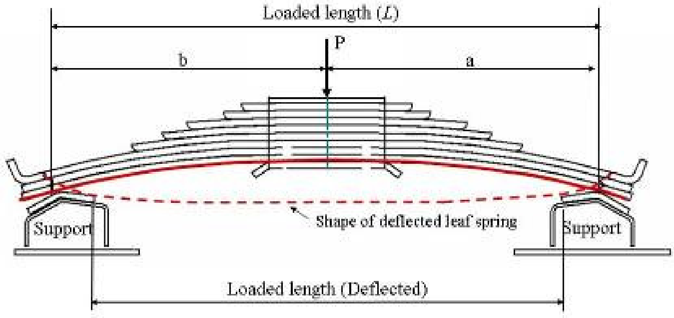


Figure 2.17. Changes in loaded length of the multi-leaf spring due to profile of the supports

With the use of bearings as supports for the leaf spring, the point of contact between the leaf spring and the bearing does not vary greatly as the leaf spring is deflected. This makes it possible to change the longitudinal hanger spacing, which changes the loaded length, and enables the effect of changes in the loaded length on the force-displacement characteristic to be investigated. The spring only setup only determines the characteristics of the multi-leaf spring and, unlike the in-service setup, ignores effects from other components such as for example the radius rod. The SAE spring design manual (1996) gives a guideline for measuring the load and rate of a leaf spring. This procedure is however not followed here because we would like to obtain the characteristic of the leaf spring for the configuration shown in Figure 2.16 which includes the attachment of the axle to the leaf spring via the U-bolts.

A comparison between the characteristics of the in-service and spring only force displacement characteristics, using the multi-leaf spring New 1, is shown in Figure 2.18 and Figure 2.19. The characteristics shown in these two figures were obtained with the input displacement signals 1 and 3 discussed in paragraph 2.1, respectively. Input displacement signal 1 had to be modified such that the spring is never extended. This is because with the spring only setup it was not possible to exert a force on the spring in the tensile direction. From the two figures it can be observed that the hysteresis loop differs slightly between the force-displacement characteristic obtained using the spring only and in-service setups. It can be concluded that the major contributor to the hysteresis loop is the inter-leaf friction with the friction between the spring and the wear plate having a smaller contribution. This also shows that the radius rod and its bushings has a negligible effect on the vertical force-displacement behaviour of the leaf spring.

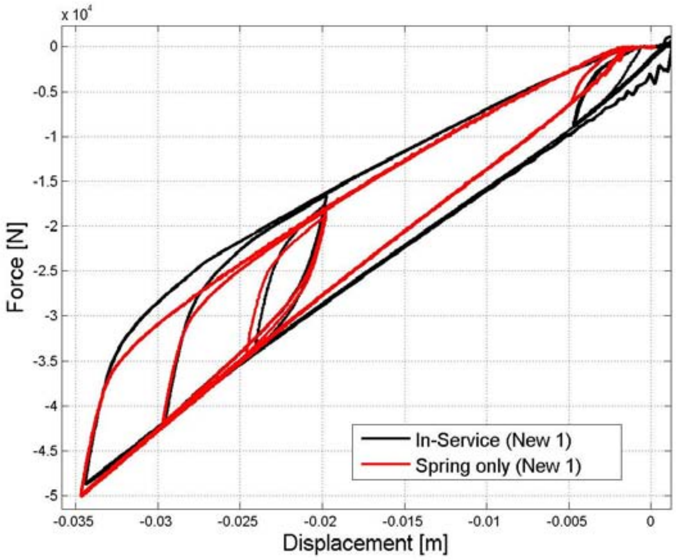


Figure 2.18. Comparison of in-service and spring only characteristics (input displacement signal 1 - modified)

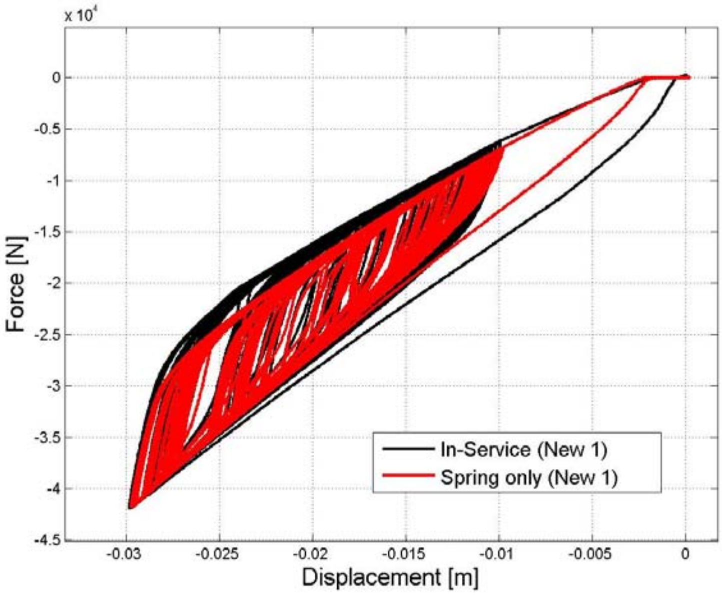


Figure 2.19. Comparison of in-service and spring only characteristics (input displacement signal 3)

2.1.2.1. Effect of longitudinal spacing of hangers

From simple beam theory it is known that the stiffness (*k*) of a simple beam is inversely proportional to the length (*l*) cubed ($k \propto \frac{1}{l^3}$). The stiffness of a multi-leaf spring is expected to have this same sensitivity with respect to the loaded length of the leaf spring. The loaded length was defined in Figure 2.17. The spacing of the front and rear hangers (see Figure 2.20) was changed to investigate the effect of different loaded lengths on the force-displacement characteristic of the leaf spring. Table 2.1 shows the different spacing values that were used. The centre spacing used for the Normal position given in Table 2.1, corresponds to the centre spacing between the hangers as used in the in-service setup when installed in the vehicle.

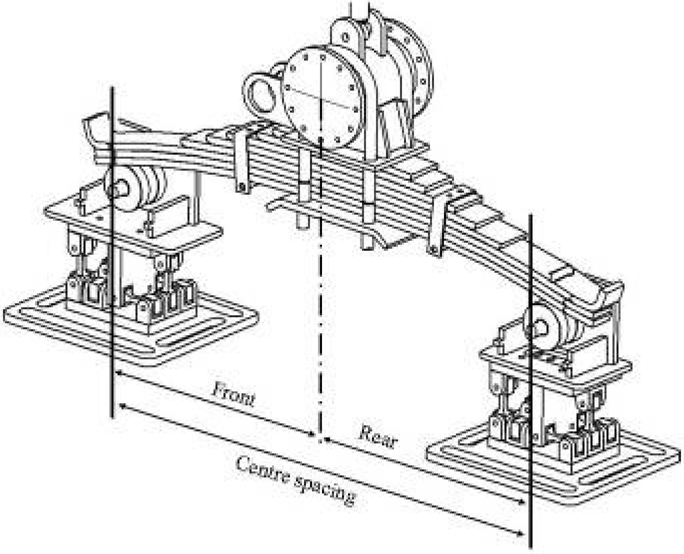


Figure 2.20. Centre spacing of hangers

Table 2.1. Spacing of hangers

Position	Centre spacing	
	Front [mm]	**Rear [mm]**
Min	**430**	**398**
Pos1	450	418
Pos2	470	438
Pos3	490	458
Normal	**510**	**478**
Pos4	530	498
Pos5	530	518

Figure 2.21 shows the effect of the longitudinal centre spacing of the hangers (or loaded length) on the force-displacement characteristic of the leaf spring. Using the loading section of the force displacement characteristic to calculate the stiffness of the leaf spring at the minimum spacing (Min) and the maximum spacing (Pos5), it is calculated that the leaf spring is approximately twice as stiff at the minimum position than at the maximum position. This indicates the significant change in spring stiffness that can be achieved, for the same spring, when the centre spacing (or loaded length) is changed.

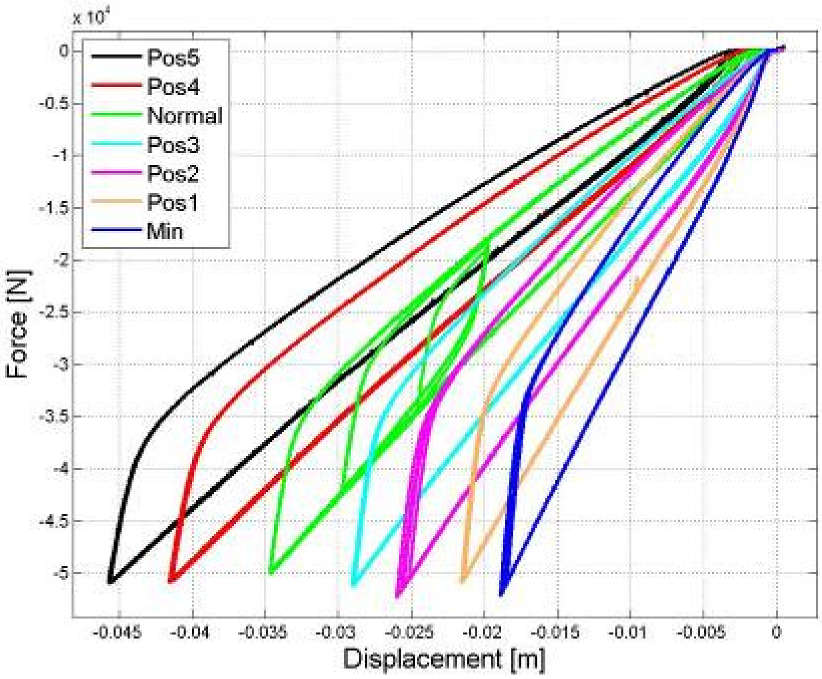


Figure 2.21. Effect of the longitudinal centre spacing of hangers on the force-displacement characteristic of the multi-leaf spring

2.1.2.2. Deflection shape of the multi-leaf spring

The deflection shape of the leaf spring was measured at three different loads for two of the positions given in Table 2.1 namely the Normal position and Pos5. The experimental setup for measuring the deflection shape is shown in Figure 2.22. The deflection shapes of the multi-leaf spring for both centre spacings used were obtained at three vertical loads i.e. 0 N, 25.9 kN and 51.9 kN. Figure 2.23 shows the deflection shapes of the spring at the three vertical loads for Pos5 and Figure 2.24 shows the deflection shapes of the spring for the normal position.

Figure 2.22. Experimental setup for measuring the deflection shape of the multi-leaf spring

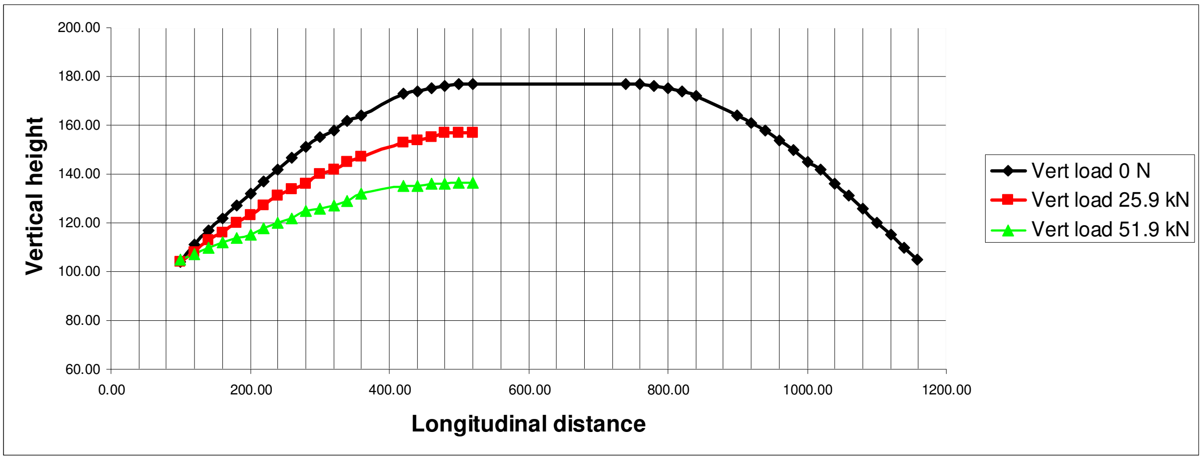


Figure 2.23. Deflection shape of the spring for Pos5

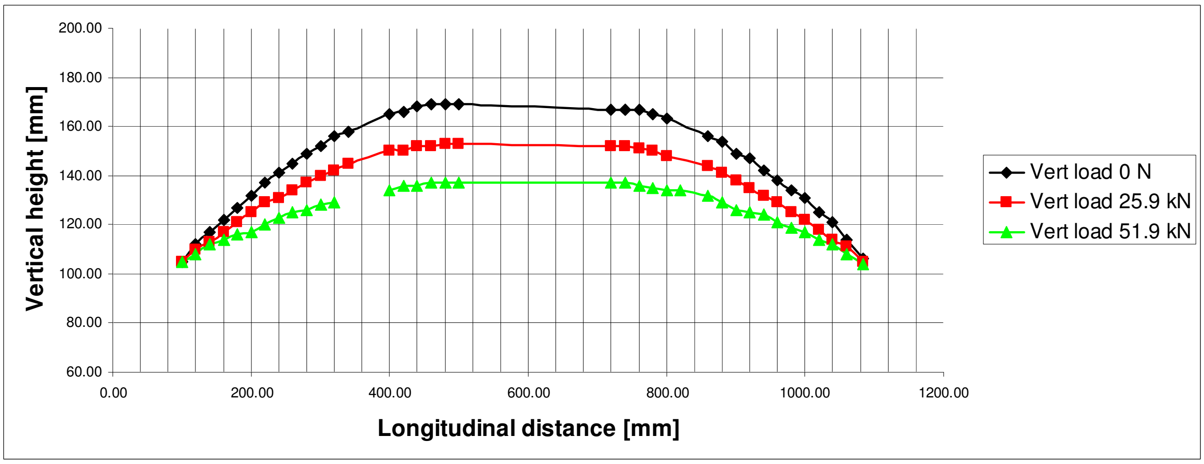


Figure 2.24. Deflection shape of the spring for the normal position

3. Characterisation of the suspension system using the parabolic leaf spring

The various aspects of the suspension system, using the parabolic leaf spring, that were characterised are shown in Figure 2.25. As already stated, the vertical characteristics were considered to be the most important. As can be seen from Figure 2.25 the lateral characterisation of the suspension system using the parabolic leaf spring was not performed as it was expected that the data obtained from the lateral characterisation done using the multi-leaf spring would give sufficient information. Furthermore, it was expected that the lateral characteristics of the suspension system would depend more on the radius rod than on the type of leaf spring used. For the parabolic leaf spring the aspects considered under the vertical characteristics of the suspension system did not include the complete suspension setup. The experimental characterisation of interest to this study is shown in green in Figure 2.25.

A similar process to that used to obtain the force-displacement characteristics of the multi-leaf spring will be followed to obtain the force-displacement characteristics of the parabolic leaf spring. The force-displacement characterisation of the parabolic leaf spring was done using the same two setups used for the multi-leaf spring namely, the in-service setup and spring only setup. Details of the two setups were given in paragraph 2.1.1 and 2.1.2. Unlike the characterisation of three multi-leaf springs only one parabolic leaf spring was characterised.

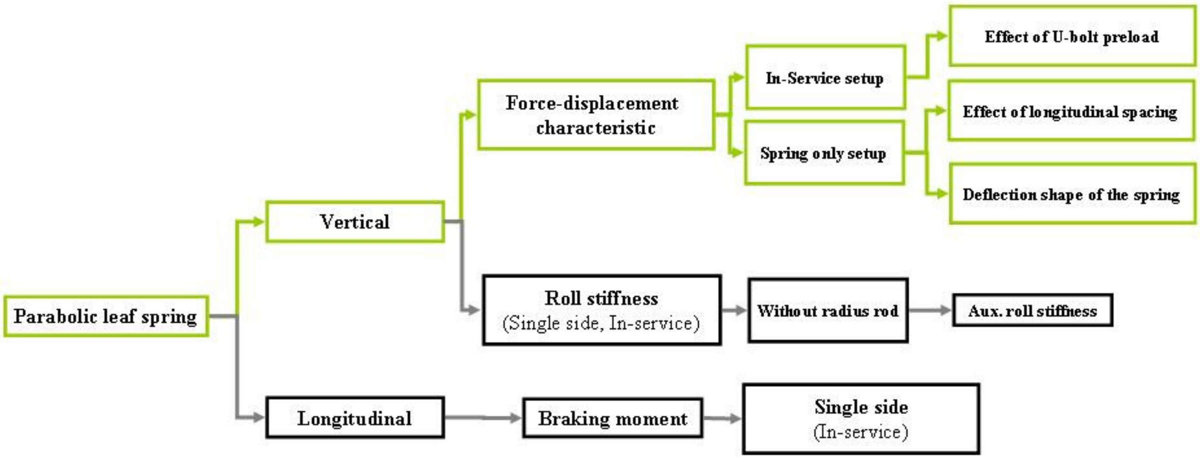


Figure 2.25. Overview of characterisation using the parabolic leaf spring

3.1. Force-displacement characteristic

As stated in paragraph 2.1, the force the leaf spring exerts when deflected is a function of the static load and the amplitude of the imposed displacement. The statements of Cebon (1986) and Fancher *et al.* (1980), that the force-displacement characteristic of a leaf spring does not depend on the input frequency, was confirmed to be true for the multi-leaf spring used in paragraph 2. The dependency of the force-displacement characteristic on the input frequency is also checked for the parabolic leaf spring. The same displacement input signals, which was used for the multi-leaf spring, are used as input to the parabolic leaf spring. The force-displacement characteristics of the parabolic leaf spring subjected to these input signals are shown in Figure 2.26 and Figure 2.27. Similar to the results obtained for the multi-leaf spring, the results for the parabolic leaf spring seem to indicate that its force-displacement characteristic is also not dependent on the excitation frequency. The experimental force-displacement characteristics shown in Figure 2.26 and Figure 2.27 were obtained using the in-service setup which was discussed in paragraph 2.1.1. The in-service setup using the parabolic leaf spring is shown in Figure 2.28.

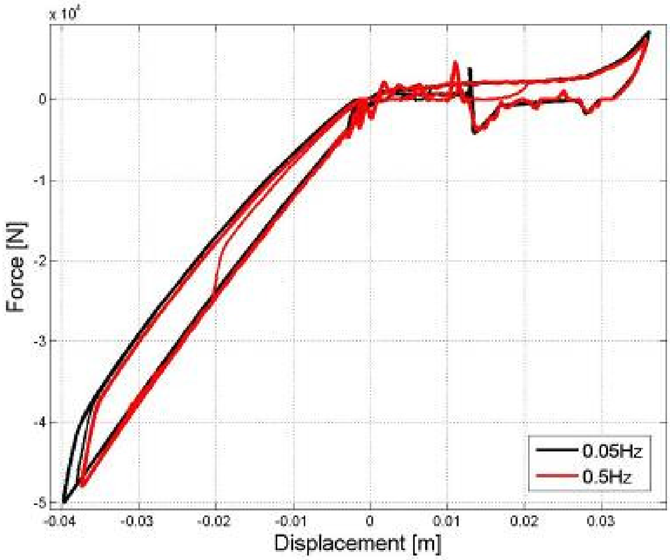


Figure 2.26. Compare force-displacement characteristics for different excitation frequencies

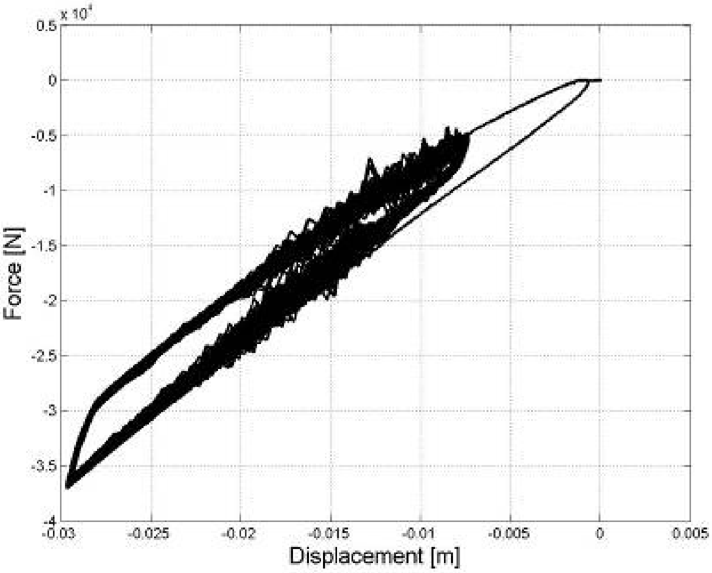


Figure 2.27. Force-displacement characteristic for sine sweep with frequencies ranging from 0.05 Hz to 4 Hz

From the above results it can be concluded that the spring force of the parabolic leaf spring, similarly to that of the multi-leaf spring, is a function of the static load and the amplitude of the imposed displacement on the leaf spring. The force-displacement characteristic of the parabolic leaf spring is obtained using two setups i.e. an in-service setup and a spring only setup. These two setups are the same as the setups used for characterising the multi-leaf spring and the reader is referred to paragraph 2.1.1 and 2.1.2 for the details of these setups. The force-displacement characteristic of the parabolic leaf spring is obtained using the same five displacement inputs as was used for the multi-leaf spring and presented in paragraph 2.1.

3.1.1. In-service setup

The in-service setup used to characterise the force-displacement characteristic of the parabolic leaf spring, shown in Figure 2.28, is exactly the same as the in-service setup used for characterising the multi-leaf spring in paragraph 2.1.1. The force-displacement characteristic of the parabolic leaf spring using input displacement signal 1 is shown in Figure 2.29.

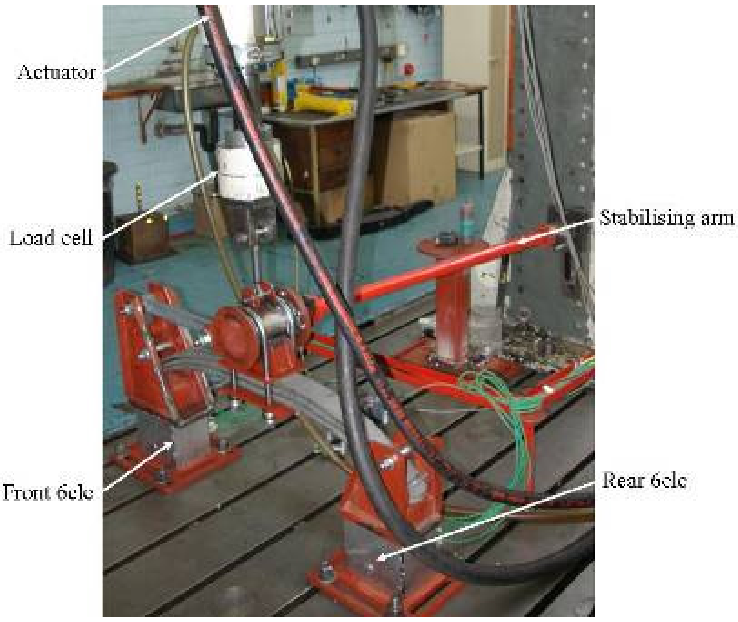


Figure 2.28. Experimental in-service setup of single sided suspension with parabolic leaf spring

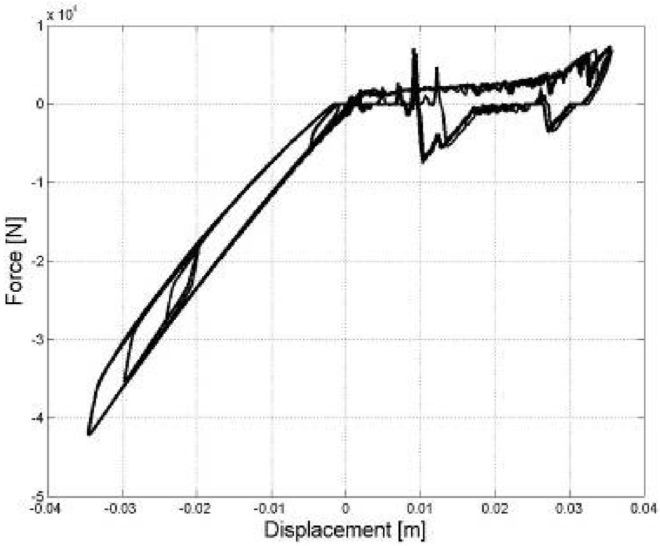


Figure 2.29. Force-displacement characteristic of parabolic leaf spring

3.1.1.1. Effect of U-bolt preload on force-displacement characteristics

An interesting observation was made with regards to the effect that the preload of the U-bolts has on the force displacement characteristic of the multi-leaf spring. The same observation is made with respect to the force-displacement characteristic of the parabolic leaf spring. Figure 2.30 shows the force-displacement characteristics of the parabolic leaf spring when the U-bolts are torqued to different values. The U-bolts were torqued to 150N.m and characterised twice. After this the U-bolts were torqued to 450N.m and again two characteristics were obtained. From Figure 2.30 it can be observed that the parabolic leaf spring's stiffness increases when the preload of the U-bolts is increased. This is similar to the results obtained for the multi-leaf spring.

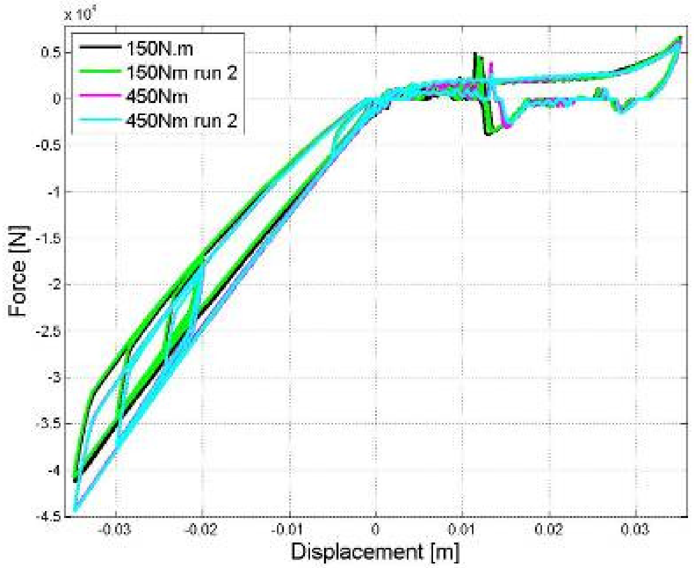


Figure 2.30. Effect of U-bolt preload on force-displacement characteristics of the parabolic leaf spring

3.1.2. Spring only setup

The spring only setup used in Figure 2.31 is exactly the same as the spring only setup used to obtain the force-displacement characteristic of the multi-leaf spring, obviously, except for the use of the parabolic leaf spring instead of the multi-leaf spring.

Figure 2.31. Experimental spring only setup of parabolic leaf spring

A comparison between the force-displacement characteristics of the parabolic leaf spring using the in-service and spring only setups is shown in Figure 2.32. Input displacement signal 1 was used to obtain the characteristics shown in Figure 2.32 but had to be modified such that the spring is never extended. This is because with the spring only setup it was not possible to exert a force on the spring in the tensile direction. From Figure 2.32 it can be observed that the hysteresis loop differs between the force-displacement characteristic obtained using the spring only and in-service setups. It can be concluded that the major contributor to the hysteresis loop is the inter-leaf friction with the friction between the spring and the wear plate having a smaller contribution. This is similar to the observation that was made when comparing the force-displacement characteristic of the multi-leaf spring using the spring only and in-service setups.

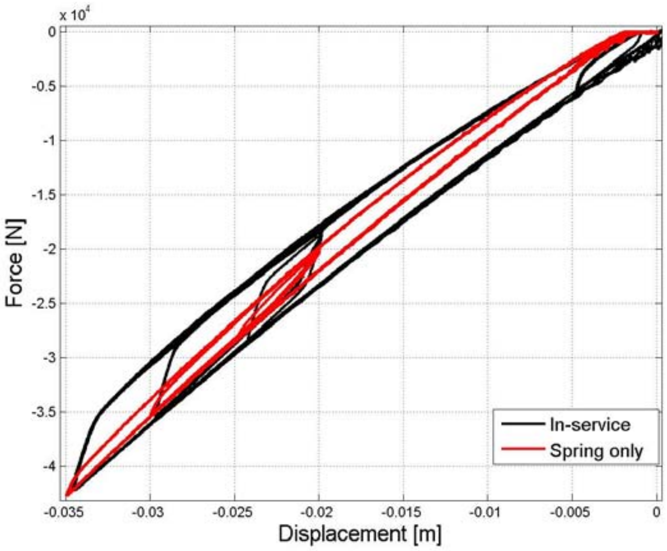


Figure 2.32. Comparison of in-service and spring only characteristics (input displacement signal 1 - modified)

3.1.2.1. Effect of longitudinal spacing of hangers

As with the multi-leaf spring in the spring only setup, the longitudinal spacing of the hangers was changed to investigate the effect the loaded length of the parabolic leaf spring has on its force-displacement characteristic. The spacing of the front and rear hangers (see Figure 2.20) was changed to investigate the effect it has on the force-displacement characteristic of the leaf spring. The same hanger spacing as was used for the multi-leaf spring shown in Table 2.1, is used for the parabolic leaf spring.

Figure 2.33 shows the effect the longitudinal centre spacing of the hangers (or loaded length) has on the force-displacement characteristic of the spring. Using the loading section of the force-displacement characteristic to calculate the stiffness of the parabolic leaf spring at the minimum spacing (Min) and the maximum spacing (Pos5), it is calculated that the parabolic leaf spring is approximately twice as stiff at the minimum position than at the maximum position. This indicates the significant change in spring stiffness that can be achieved, for the same spring, when the centre spacing (or loaded length) is changed. This shows the same increase in stiffness between the maximum and minimum hanger spacing as was obtained for the multi-leaf spring.

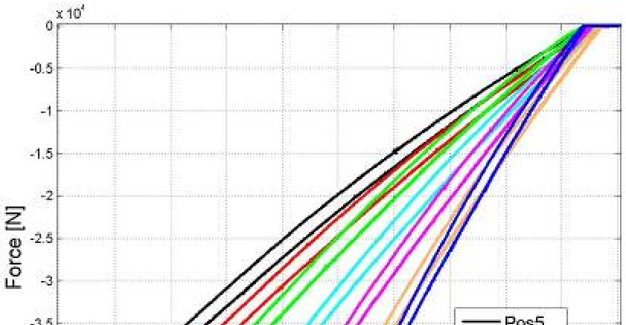


Figure 2.33. Effect of the longitudinal centre spacing of hangers on the force-displacement characteristic of the parabolic leaf spring

3.1.2.2. Deflection shape of the parabolic leaf spring

The deflection shape of the parabolic leaf spring was measured at three different loads for two of the positions given in Table 2.1. The two positions used were the Normal position and Pos5. The experimental setup for measuring the deflection shape of the parabolic leaf spring was similar to the setup used to measure the deflection shape of the multi-leaf spring (see Figure 2.22). The deflection shape of the parabolic leaf spring was obtained at three vertical loads i.e. 0 N, 25.9 kN and 51.9 kN. Figure 2.34 shows the deflection shapes of the parabolic leaf spring at the three vertical loads using the centre spacing of Pos5. Figure 2.35 shows the deflection shapes of the parabolic leaf spring for the Normal centre spacing.

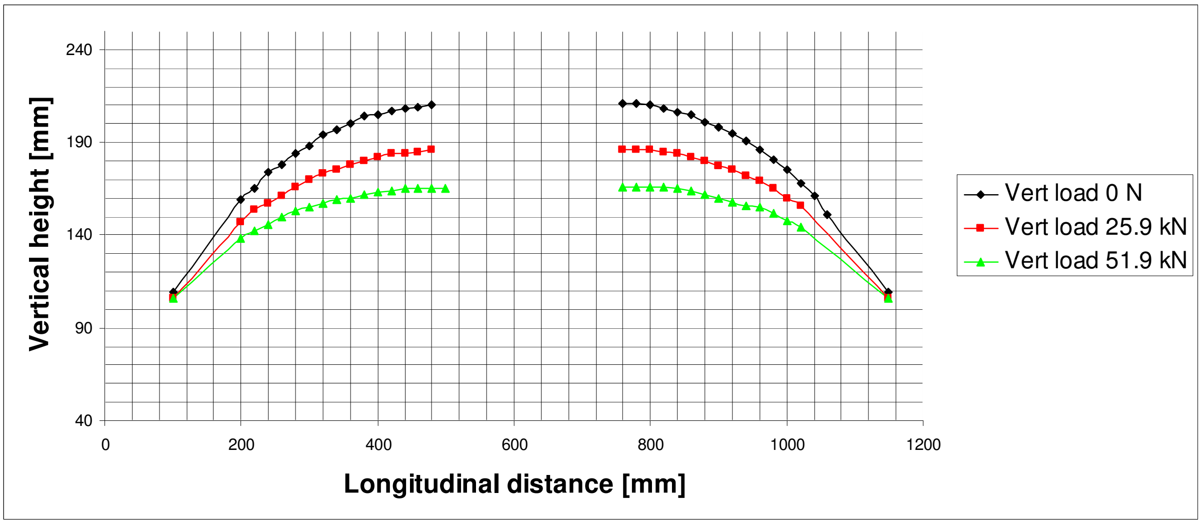


Figure 2.34. Deflection shape of the parabolic leaf spring for Pos5

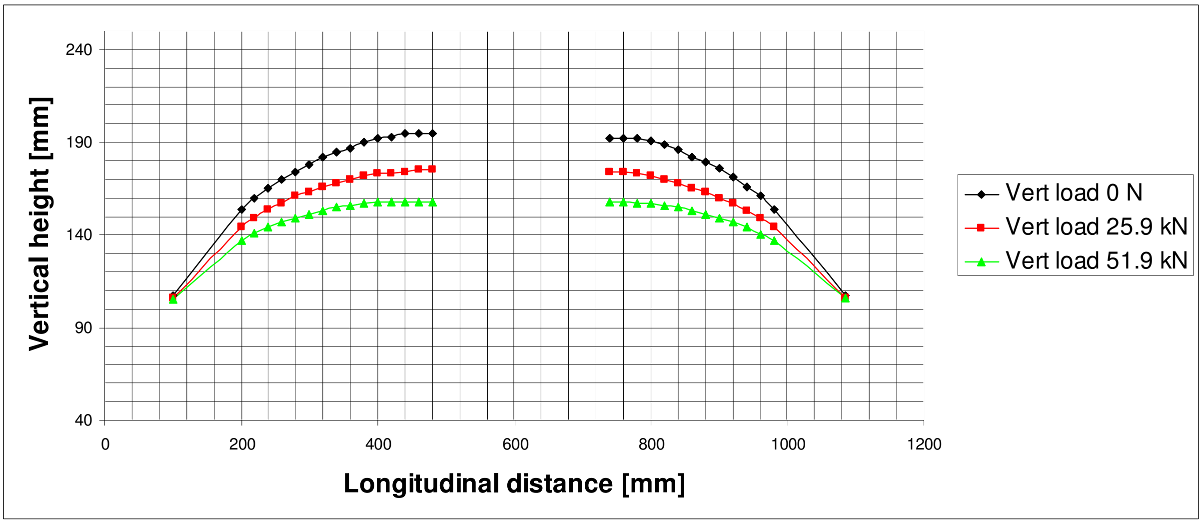


Figure 2.35. Deflection shape of the parabolic leaf spring for the Normal centre spacing

4. Conclusion

Various experimental characterisations were performed in order to obtain the required experimental data that is needed to validate the simulation models according to the goals set out in Chapter 1.

Figure 2.36 shows the comparison between the force-displacement characteristic of the multi-leaf and parabolic leaf spring. The difference in the force-displacement characteristic of the multi-leaf spring and parabolic leaf spring can be seen in this figure. The multi-leaf spring has a bigger hysteresis loop than the parabolic leaf spring. This implies that the multi-leaf spring will dissipate more energy than the parabolic leaf spring. It was shown that the force-displacement characteristics of both leaf springs react the same to changes in the preload of the U-bolts and to changes in the loaded length. It was also shown that the force-displacement of both leaf springs is independent of the excitation frequency.

The experimental data obtained in this chapter will be used to validate the mathematical models that are created in the chapters that follow.

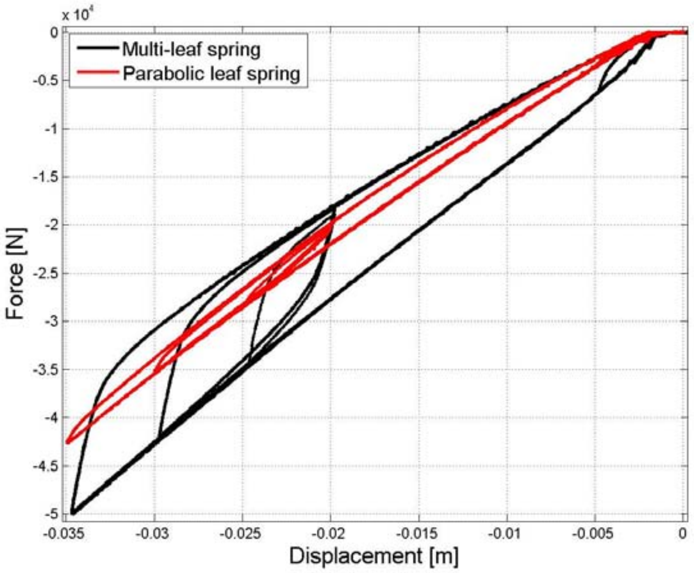


Figure 2.36. Force-displacement characteristic of the multi-leaf spring and parabolic leaf spring