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Overturning moment analysis using the Flat plank tyre tester

Leon Merkx

DCT 2004-78
Preface
This report is written to complete a short traineeship for the section Dynamics and Control. It is part of the curriculum for the fourth year. This report is written by Leon Merkx and it is supervised by Dr. Ir. I. Besselink and E. Meinders.
Abstract

Roll-over is becoming a more important issue in vehicle dynamics for two main reasons:

- SUV and MPV market share becomes higher and these types of cars have a higher risk of roll-over.
- Maximum speed rises for minivans, jeeps, etc and therefore the risk of roll-over is enforced.

Because roll-over experiments are expensive, simulating these events is an important issue. For these simulations it is important to model the overturning moment generated by the tyres. For that reason measurements are done on the Flat plank tyre tester to find out if it is possible to make good overturning moment measurements on this tyre testing machine.
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<th>Quantity</th>
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<tr>
<td>$K_x$</td>
<td>Longitudinal force in the measuring hub</td>
<td>N</td>
</tr>
<tr>
<td>$K_y$</td>
<td>Lateral force in the measuring hub</td>
<td>N</td>
</tr>
<tr>
<td>$K_z$</td>
<td>Vertical force in the measuring hub</td>
<td>N</td>
</tr>
<tr>
<td>$T_x$</td>
<td>Longitudinal moment in the measuring hub</td>
<td>Nm</td>
</tr>
<tr>
<td>$T_y$</td>
<td>Lateral moment in the measuring hub</td>
<td>Nm</td>
</tr>
<tr>
<td>$T_z$</td>
<td>Vertical moment in the measuring hub</td>
<td>Nm</td>
</tr>
<tr>
<td>$F_x$</td>
<td>Longitudinal force in the contact point</td>
<td>N</td>
</tr>
<tr>
<td>$F_y$</td>
<td>Lateral force in the contact point</td>
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<td>$M_x$</td>
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<tr>
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<td>Rolling resistance moment in the contact point</td>
<td>Nm</td>
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<td>$M_z$</td>
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<td>Nm</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Slip angle</td>
<td>rad</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Inclination angle</td>
<td>rad</td>
</tr>
<tr>
<td>$p_p$</td>
<td>Pneumatic scrub</td>
<td>m</td>
</tr>
<tr>
<td>$r_i$</td>
<td>Loaded radius</td>
<td>m</td>
</tr>
<tr>
<td>(Length from the centre of wheel to the contact point)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_o$</td>
<td>Unloaded radius</td>
<td>m</td>
</tr>
<tr>
<td>(Introduced to make parameters dimensionless in the Magic Formula model for overturning moment)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{z0}$</td>
<td>Nominal load</td>
<td>N</td>
</tr>
<tr>
<td>(Introduced to make parameters dimensionless in the Magic Formula model for overturning moment)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$q_{saX}$</td>
<td>Parameter of the Magic Formula model for overturning moment</td>
<td>-</td>
</tr>
<tr>
<td>$h$</td>
<td>Difference in height between centre of measuring hub and track</td>
<td>m</td>
</tr>
<tr>
<td>$h'$</td>
<td>Difference in height between centre of wheel and track</td>
<td>m</td>
</tr>
<tr>
<td>$a$</td>
<td>Distance from centre of measuring hub to wheel centre</td>
<td>m</td>
</tr>
<tr>
<td>$a_{mh}$</td>
<td>Distance from centre of measuring hub to the rim</td>
<td>m</td>
</tr>
<tr>
<td>$a_{ET}$</td>
<td>ET value of the wheel.</td>
<td>m</td>
</tr>
</tbody>
</table>
1. Introduction

More and more cars have a high centre of gravity, due to the growing market share of MPV's and SUV's. Roll-over is becoming a more important issue in vehicle dynamics. It is mostly dependent on the height of the centre of gravity. Conventional cars will slide before roll-over can occur. This is due to the low centre of gravity of these cars. Lateral accelerations needed to roll-over are not reached. Therefore roll-over accidents are mostly caused by tripping (A car rolls over due to an impact with an obstacle.). However SUV's and MPV's can come into a situation where lateral accelerations do get high enough to roll-over on even roads (without a tripping mechanism).

Real roll-over tests are precious, risky and hard to measure. That is why it is important to be able to simulate the behaviour precisely with a computer model.

There are three important factors that determine the roll-over of a car:

- **Height of the centre of gravity:** If the car is higher, the roll angles will be higher and the car rolls over quicker.
- **Anti roll bar stiffness:** If the car’s roll stiffness is higher, the roll angles will be lower and the car rolls over less quickly.
- **Overturning moment of the tyres:** The forces and moments generated by the tyres contribute to the roll-over moment.
- **Track width:** If the car is smaller, the roll angles will be higher and the car rolls over quicker.

The subject of the traineeship will be:

- Is it possible to make a correct measurement of the overturning moment on the Flat plank tyre tester?
- Can the Magic Formula tyre model be verified with these measurements? The model is based on measurements on the Flat track tyre tester and it is uncertain if the Magic Formula can still be used.

The report is divided in the following chapters:

First of all the overturning moment will be explained in chapter 2. This will include the definition and the characteristics. The Magic Formula model will also be given which is used for simulation models.

In chapter 3 the Flat plank tyre tester will be explained and how it will be used to measure the overturning moment.

In chapter 4 the measurement data will be analysed and will be fitted with the Magic Formula model.

In chapter 5 some conclusions are drawn and in chapter 6 some recommendations are given.
2. Overturning moment

2.1. Definition

The overturning moment is the moment around the longitudinal axis of the wheel contact point. This can be seen in figure 2.1, in which all forces, moments and angles of the tyre are projected. These are all according to the adapted ISO convention [ref. 8].

The occurrence of the overturning moment is best explained with figure 2.2. When a tyre slips sideways, the tyre also tends to move sideways and the load distribution changes. The vertical load moves outside the contact point and a moment results: the overturning moment. Figure 2.2. shows that the overturning moment is the product of vertical load and pneumatic scrub. Both overturning moment and pneumatic scrub will have NEGATIVE sign when converted according to the adapted ISO convention.
2.2. Characteristics

In figure 2.3 the overturning moment characteristics are shown when the wheel stands up straight ($\gamma = 0$).

![Figure 2.3. Overturning moment against slip angle with constant inclination angle ($\gamma = 0$) and various vertical loads [ref. 1]](image)

It can be seen that the overturning moment switches sign when the vertical load changes. This is due to the fact that small vertical loads only use part of the tyre contact area. So the pneumatic scrub will be of opposite sign than the lateral force. The overturning moment will become negative. When the load increases the entire contact area is used. The pneumatic scrub gets the same sign as the lateral force and the overturning moment will become positive. This is shown in figure 2.4.

![Figure 2.4. Overturning moment and vertical load difference](image)
The inclination angle changes have an important effect on the overturning moment. Positive inclination angles shift the curves upward and negative inclination angles shift the curves downward. This shift in the curves is due to the shift of the contact point (C) which determines the pneumatic scrub (and thus the overturning moment). This phenomenon is explained in figure 2.5. The characteristics with inclination angle effects are shown in figure 2.6.

![Figure 2.5. Overturning moment and inclination angle difference](image)

![Figure 2.6. Overturning moment against slip angle with various inclination angles and constant vertical load [ref. 1]](image)
Another important factor is the width of a tyre. A relatively small tyre will reach a full tread contact earlier. That is why the switch point between negative overturning moment and positive overturning moment will occur earlier. This is explained in figure 2.7. In this figure two tyres of different width will be exposed to the same vertical load and lateral force.

![Figure 2.7. Overturning moment and different tyre width](image)

### 2.3. Magic Formula model (overturning moment)

The TNO model used for the modeling of the overturning moment has been developed to fit the measurements of the Flat track tyre tester [ref. 4]. The model consists of eleven parameters. Without going into the details the model is the following (in ISO):

\[
M_x = F_z r_o [y_1 + y_2 + y_3]
\]

where

\[
y_1 = q_{x3} F_y / F_{x0}
\]

\[
y_2 = q_{x4} \cos(q_{x5} \arctan^2(q_{x6} F_z / F_{x0})) \sin(q_{x7} \gamma + q_{x8} \arctan(q_{x9} F_y / F_{x0}))
\]

\[
y_3 = (q_{x10} \arctan(q_{x11} F_z / F_{x0}) - q_{x12}) \gamma + q_{x11}
\]

It must be possible to represent overturning moment correctly in a range of 20 degrees of slip angle and 10 degrees of inclination angle with this model.

In this model also a Magic Formula model for the lateral force is needed. This is extensively documented in [ref. 7] and will not be repeated in this report.
3. Measurements / Experiments

3.1. Flat plank tyre tester

The Flat plank tyre tester can be used to measure tyre behavior at a low speed. The machine is shown in figure 3.1.

A flat steel track moves horizontally. If this track rolls over the tyre forces and moments are generated in the wheel centre. These forces and moments are measured with the measuring hub and can be transformed to forces and moments in the contact point.

The following parameters can be adjusted, these include:
- Side slip angle
- Inclination angle
- Constant vertical load or fixed axle height
- Track angle
- Track speed
- Braking

Instructions on how to operate the Flat plank tyre tester and a more detailed description can be found in the manual [ref. 5].

3.2. Transformation of forces and moments

It is important to transform the measured values into forces and moments in the contact point. First the forces measured with the strain gauges need to be transformed into forces and moments in the centre of the measuring hub. According to figure 3.2, these forces can be transformed as follows: (These are NOT the forces from Labview, but the forces converted in Adapted ISO convention.)
Figure 3.2. Measuring hub [ref. 6]

\[ K_x = G_{x1} + G_{x2} \]
\[ K_y = G_y \]
\[ K_z = G_{z1} + G_{z2} \]
\[ T_x = (a + b)G_{z1} + bG_{z2} \]
\[ T_y = 0 \text{ ("Free rolling tyre") } \]
\[ T_z = (a + b)G_{z1} + bG_{z2} \]

Now, according to figure 3.3, it is possible to transform the forces and moments in the measuring hub to the forces and moments in the contact centre:

Figure 3.3. The different axes
How to measure the loaded radius \( r_l \) correctly will be explained in the next section.

### 3.3. Measurement of loaded radius

The loaded radius is the most important variable in the computation of the overturning moment. Small changes in the loaded radius have a large effect on the overturning moment. This is due to the fact that the overturning moment is relatively small compared to the other moments and forces. An error of a \( \text{mm} \) can easily cause errors of 10 \( \text{Nm} \) in overturning moment. This will be explained with the following example. An error of a \( \text{mm} \) in is an error of 3% in the loaded radius. The error in the product with the lateral load (of e.g. 3 \( \text{kN} \)) will then be 9 \( \text{Nm} \). Of course, this will also be the error in the overturning moment.

The loaded radius can not be measured directly, instead the height between the wheel centre and the track and the inclination angle must be measured.

The adjustments in inclination angle can be achieved in two ways. The inclination angle itself can be adjusted and the track angle can be adjusted. Both methods have pros and cons and they are summed:

#### Inclination angle adjustment:
- It is difficult to adjust the inclination angle, because the procedure is difficult and it is difficult to get the angle right.
- The ET value (distance from wheel to wheel centre plane, see also in figure 3.5.) plays a role in determining the wheel centre and thus the loaded radius.

#### Track angle adjustment:
- Original vertical load need to be split in a vertical load on the track and an additional lateral force on the track.
- Width of the tyre plays an important roll in determining the loaded radius, because it determines where the tyre contacts the track.
- The ET value plays a role in determining the wheel centre (and thus the loaded radius).

The inclination angle adjustment seems to be the best option, because it can be computed in the most direct way. According to figure 3.4. and 3.5. the loaded radius can be computed as follows:

\[
\begin{align*}
F_x &= K_x \\
F_y &= K_y \cos(\gamma) + K_z \sin(\gamma) \\
F_z &= -K_y \sin(\gamma) + K_z \cos(\gamma) \\
M_x &= T_x - K_y r_i \\
M_y &= K_x r_i \cos(\gamma) + T_z \sin(\gamma) \\
M_z &= -K_x r_i \sin(\gamma) + T_z \cos(\gamma)
\end{align*}
\]
The height between the wheel centre and the track could also be kept constant on the Flat plank tyre tester (instead of using a constant vertical load). This is not done, because one still has to calibrate the height correctly. If one measures height dynamically (e.g. with a LVDT) you also have to calibrate the height once. The fixed axle height option only introduces a problem, because you no longer have a constant vertical load on the tyre.

### 3.4. Measurement accuracy

It is important to do the measurement with high accuracy. Small errors in particular quantities lead to severe errors in the overturning moment. Not only the loaded radius is important (as stated in the previous section). Static values of lateral force and the overturning moment in the wheel centre are important as well.
A static lateral force of 40 N may seem harmless (especially when the dynamic lateral force is in the order of thousands), but it will introduce a static overturning moment. The cause of this error could be an inaccuracy in the inclination angle and the track angle. A combined angle of 1 degree will result in a static lateral force which is approximately 2% of the load.

Somewhat the same can be said about the overturning moment in the wheel centre. The inaccuracy of the inclination angle plays a role, it introduces an overturning moment (see section 2.2.). The distance between the hub axle and the wheel centre can introduce a static overturning moment as well. An error of 1 mm will cause 2.5 Nm in the overturning moment.

3.5. Measurement procedure

The measurement procedure can be outlined in the following steps:

1. **The inclination angle and track angle need to be set to zero degrees.** Therefore the static lateral force needs to be cancelled. The inclination angle can be measured precisely by turning the slip angle to 90 degrees. The track angle can no longer influence the static lateral force and the inclination angle can be adjusted. The static lateral force is purely due to the inclination angle. If the inclination angle is adjusted, it is possible to adjust the track angle. Of course this needs to be done with a slip angle of zero degrees on a non-moving track. If the static lateral force is close to zero, both inclination angle and track angle are set to zero. The angle between track and tyre is exactly 90 degrees.

2. **The height between the wheel centre and the track needs to be measured precisely.** This needs to be done to be able to compute the loaded radius. It is measured by screwing a long bolt in the centre of the measuring hub and measure the distance till the track. Now the height can be measured with an accuracy of 0.5 mm, which is a reasonable accuracy.

3. **The distance between camber axis and the wheel centre needs to be ‘measured’.** (For simplicity the design sketches are used.)

4. **Adjust the inclination angle if necessary.** A digital clinometer can best be used for this purpose.

5. **Reset all channels when the tyre is free.** All forces and the height variation are set to zero. The reference height is also set and can be read from the measuring rule on the back of the machine. (This reference height and the height variation has to be used to compute the loaded radius.)

6. **Start measurement.**
4. Comparing and analysing the measurements

In this chapter the measurement results are shown for a Continental tyre (205/55 R16). In section 4.1, the raw data is shown. In section 4.2, the results are shown for lateral force, overturning moment and self aligning moment. The last section is used to fit lateral force and the overturning moment with the use of the Magic Formula.

4.1. Raw measurement data

In this section the raw data of the Flat plank tyre tester is shown. The data is computed and presented with Matlab. For now only a few measurements are shown. Measurements are done with different vertical loads (2, 4 and 6 kN), different slip angles (-10, -5, -2, -1, 0, 1 and 2 degrees) and different inclination angles (-10, -5, 0 and 5 degrees). For now only a subset of the measurements is shown.

In figure 4.1, the moments and forces in the contact point (point C in figure 3.4.) are shown for a vertical load of 6 kN and an inclination angle of zero degrees. These moments and forces are plotted against travelled distance and with various slip angles.

The vertical load is kept constant pretty well with the use of the constant vertical load mechanism. Longitudinal force and rolling resistance moment are both negative, which indicates braking. The self aligning moment also behaves as expected. This corresponds with the literature (§3 in ref 1.). All plots show relaxation effects. After travelling a certain distance a steady state value is reached.

The lateral force for large slip angles is showing a strange dip at the end. It can be seen that this leads to a dip in the overturning moment as well. The lateral force with a slip angle of 10 degrees in the dip is the same as the lateral force with slip angle of 5 degrees in the top. When looking at the overturning moment the same can be said. This phenomenon will be explained in section 4.1.1.

There is also a static overturning moment. This static value is assumed to be zero. When the inclination angle is zero, the overturning moment needs to be zero when the tyre is not moving. These are errors in the setup of the Flat plank tyre tester and need to be compensated for. This is shown in section 4.1.2.

The lateral force also has a static value and is assumed to be zero. This can not be seen in figure 4.1, but it will be shown in 4.1.3.
Figure 4.1. Measurements of the forces and moments in the contact point for various slip angles ($F_z = 6\, kN$ and $\gamma = 0\, degrees$)

4.1.1. The dip in the lateral force

The cause of this dip must be investigated. All measurements are done with the tyre in a certain mode (valve down) and the Flat plank tyre tester in a certain starting position. The cause could be the Flat plank, the tyre or the measuring hub. First of all the starting position of the Flat plank is changed, but this does not lead to changes in the position of the dip. Secondly the tyre is removed from the measuring hub and installed 180 degrees rotated. The tyre is placed with the valve downwards and in the normal starting position. Again it leads to the same results or in other words the measuring hub is not the cause of the dip. The tyre remains as the possible cause. The tyre is turned 180 degrees in the starting position (with the valve upwards). The dip now shifts a meter, which equals half the perimeter of the tyre. The conclusion must be that there is a defect in the tyre.

The results are shown in the next two figures. Figure 4.2. shows the results with the valve upwards and figure 4.3. shows the results with the valve downwards.
Figure 4.2. Measurement with valve upwards
($F_z = 2\ kN$ and $\gamma = 0$ degrees)

Figure 4.3. Measurement with valve downwards
($F_z = 2\ kN$ and $\gamma = 0$ degrees)
The influence of inclination angle is shown in figure 4.4. The dip is best seen with an inclination angle of 0 degrees. In the other inclination angles the dip is less severe. The defect must therefore be in the middle of the tyre.

![Graphs showing lateral force with different inclination angles](image)

*Figure 4.4. Lateral force with different inclination angles (Fz = 6 kN)*

### 4.1.2. Static overturning moment

The overturning moment has a certain value, when the load is applied and the tyre is not rolling. This is assumed to be zero. These static values are shown in figure 4.5. The vertical load is slowly enlarged and reduced with a tyre at a standstill. The static overturning moment will be used in the computed overturning moment to compensate for the error in the setup.

Figure 4.5. shows the static overturning moments which correspond with the three vertical loads which are used.

\[
F_z = 2 \text{ kN} \Rightarrow M_{r,stat} = 1 \text{ Nm}
\]
\[
F_z = 4 \text{ kN} \Rightarrow M_{r,stat} = -7 \text{ Nm}
\]
\[
F_z = 6 \text{ kN} \Rightarrow M_{r,stat} = -13 \text{ Nm}
\]
4.1.3. Static lateral force

In the previous section the static overturning moment is explained. The same can be said about the static lateral force and the same measurement will show the static lateral force. This is shown in figure 4.6. The static lateral force will be used in the computed lateral force to compensate for the error in the setup.

Figure 4.5. Static measurement of overturning moment

Figure 4.6. Static measurement of lateral force
The static lateral force for the three vertical loads are retrieved from figure 4.6.

\[ F_z = 2 \text{ kN} \Rightarrow F_{y,\text{stat}} = 21 \text{ Nm} \]
\[ F_z = 4 \text{ kN} \Rightarrow F_{y,\text{stat}} = 18 \text{ Nm} \]
\[ F_z = 6 \text{ kN} \Rightarrow F_{y,\text{stat}} = 15 \text{ Nm} \]

4.2. Results

The results are retrieved from the pure data by computing the mean value of a part of the measurement. Only the part is used where the relaxation effects no longer play a role, the mean is computed from 0.5 m till the end. The results are shown in figure 4.7. for one specific measurement.

![Graphs showing static forces and moments](image)

**Figure 4.7. Determining the steady-state forces and moments in the contact point**

\( (F_z = 2 \text{ kN and } \gamma = 0 \text{ degrees}) \)

If this fitting is done for all measurements, it is possible to show the effects of different loads and inclination angles on lateral force, overturning moment and self-aligning moment. These results are shown in the following three sections.
4.2.1. Steady-state lateral force characteristics

The lateral force characteristics are shown in figure 4.8. The characteristics for small slip angles correspond with those that are expected from the literature (§3 in ref 1.). Positive changes in inclination angle result in an upward shift of the lateral force curve. For high slip angles this behavior is not observed.

![Graphs showing lateral force characteristics](image)

*Figure 4.8. Steady-state lateral force characteristics as function of slip angle for three vertical loads*
4.2.2. Steady-state self aligning moment characteristics

The self aligning moment characteristics are shown in figure 4.9. The characteristics are as expected on the basis of the studied literature (§3 in ref 1.).

\[ y = -10 \text{ deg} \]
\[ y = -5 \text{ deg} \]
\[ y = 0 \text{ deg} \]
\[ y = 5 \text{ deg} \]

Figure 4.9. Steady state self aligning moment characteristics as function of slip angle for three vertical loads
4.2.3. Steady-state overturning moment characteristics

In figure 4.10 the overturning moment characteristics as function of slip angle are plotted for four constant inclination angles to stress the effect of different load.

![Graphs showing overturning moment characteristics](image)

*Figure 4.10. Steady state overturning moment characteristics as function of slip angle for four different constant inclination angles*

If there is an inclination angle of zero degrees the shift of the pneumatic scrub is best seen (explained in figure 2.4.), since there are no other effects present.

The other subplots show the camber effects. Positive inclination angles will result in a positive shift (explained in figure 2.5.). If the load becomes higher this shift becomes higher. This last phenomenon can be explained, because the overturning moment is the product of pneumatic scrub and vertical load.
In figure 4.11 the steady-state overturning moment characteristics are plotted for three constant vertical loads to stress the effect of different inclination angles.

![Graphs showing steady-state overturning moment characteristics](image)

**Figure 4.11. Steady state overturning moment characteristics as function of slip angle for three constant vertical loads**

The pneumatic scrub characteristics are shown in figures 4.12. and 4.13. The pneumatic scrub characteristics must have the same shape as the overturning moment characteristics, because it is the product of pneumatic scrub and (constant) vertical load. It also has to be small, the pneumatic scrub can not be larger than half of the width of the tyre. The resultant vertical load would then be outside of the contact area of the tyre. The width of the tyre is 205 mm and the pneumatic scrub is not larger than 7 cm.
Figure 4.12. Steady-state pneumatic scrub characteristics as function of slip angle for four different constant inclination angles

Figure 4.13. Pneumatic scrub characteristics as function of slip angle for three different constant vertical loads
4.3. Magic Formula tyre model fit

The lateral force and overturning moment characteristics are fitted with the Magic Formula tyre model.

4.3.1. Steady-state lateral force characteristics

The Magic Formula characteristics for the lateral force are plotted in figure 4.14. The markers indicate the measured values and the lines show the fitted values. The figure shows that the fitted values correspond quite well with the measured values.

![Graphs showing magic formula fit results for steady-state lateral force characteristics](image)

*Figure 4.14. Magic Formula fit results of the lateral force characteristics as function of slip angle*
4.3.2. Steady-state overturning moment characteristics

The Magic Formula characteristics for the overturning moment are plotted in figure 4.14. The markers indicate the measured values and the lines show the fitted values. The fit shows resemblance, but is not quite the same. Especially the inclination angles unequal zero are not good.

*Figure 4.15. Magic Formula fit results of the overturning moment characteristics as function of slip angle*
5. Conclusions

During this research experiments were done on the Flat plank tyre tester to measure the overturning moment generated by a tyre. These measurements are fitted with the Magic Formula tyre model to verify the model, which is based on measurements done on the Flat track tyre tester.

The conclusion of this research has to be that the Flat plank tyre tester is capable of doing fairly good overturning moment analysis. All possible causes for inaccuracies are minimized and that is why the inaccuracy in the overturning moment will be low enough.

- The track angle and inclination angle can be set within tenths of degrees. This results in an error of 5 – 10 %, due to the higher/lower lateral force.
- The static lateral force and static overturning moment are very close to zero. This results in a small absolute error (1 – 2 Nm).
- The loaded radius can be computed with an error of half a mm. This results in an error of 10 – 20 %.

All these inaccuracies combined will result in an error of approximately 10 % - 25 % in the overturning moment. At first this may seem a lot, but one has to keep in mind that the order of the overturning moment is a lot smaller than the vertical load (especially for inclination angles close to zero).

The Magic Formula fit for the overturning moment is not as good as expected. The shape of the fit is quite good, but it can not fit these data properly through the measured points. Especially the inclination angles unequal zero are not so good. This could be due to two reasons:

- The tyre used now behaves different than the tyres which are used to model the Magic Formula.
- The Flat plank tyre tester gives different results than the Flat track tyre tester on which the Magic Formula is based. Flat track tyre tester uses a much higher speed and has a different setup. This can effect the overturning moment results.
6. Recommendations

6.1. The research

Because it was found that the measurement results could not be fitted accurately with the Magic Formula, measurement results with the Flat plank tyre tester and the Flat track tyre tester obtained under exactly the same conditions need to be compared. If the Flat track tyre tester gives different results with the same tyre under the same conditions, both machines need to be analysed thoroughly.

The Magic Formula needs to be modified, if it appears that the Flat track tyre tester gives the same results, because it was found that the tyre behaves differently in comparison to the tyres used to develop the current Magic Formula model.

6.2. Flat plank tyre tester

In this section some recommendations are given to make the Flat plank tyre tester easier to work with.

- **Labview:** The Labview model is not clear. It desperately needs to be rebuild. This need to be done by a programmer or a mechanical engineer with extended Labview experience.
  - The code must be structured in layers/subclasses. Only then the code is maintainable, readable and extendable.
  - The user interface must be split into a main menu and several separate windows. In the main menu it must be possible to open separate windows (some for input, output and options).
  - The axis system is not chosen properly [ref. 5]. There are four conventions used in vehicle dynamics and the used axis system in Labview and in the manual is not one of them. In this report the adapted ISO convention (Besselink) [ref. 8] is used. This could be used instead.
  - Initialisation is done several times in a loop and has to be done only once.
- **Trigger:** The trigger needs to be changed. It is better to use the rotational speed sensor of the plank to trigger a measurement (or trigger it manually).
- **Track alignment:** The Flat plank tyre tester shakes when the left side of the plank (front view) reaches the centre of the machine. There are also small vibrations in the measurements due to the track. Track alignment is already proposed in [ref. 6], but it is not possible to remove these vibrations. The only remedy: Do not use the constant height mechanism but use the constant force mechanism instead.
- **Braking:** The disk brake needs to be checked. If it can not be used properly, it needs to be replaced with some other braking mechanism.
- **Motor control:** The three motors (slip angle, track angle and track velocity) can be coupled with the computer. This makes the machine a lot more user friendly.
- **Side slip angle:** The side slip angle is measured with an encoder. This measures relative angles to the starting position. This starting point needs to be measured more precisely.
- **Additional sensors:** Some additional sensors are needed, which measure inclination angle and track angle.
- **Wiring**: The wiring needs to be checked and marked. There are loose connectors and unmarked wires.

- **Constant force mechanism**: The operating device is at the front of the machine. This is not practical.
References

Books

   ISBN 0 7506 5141 5
   ISBN 0 201 56947 7

Articles


Course material

A. Matlab files for the results

In this chapter the Matlab files will be shown for the processing of the results. In the next chapter the corresponding Matlab structures will be shown.

A.1. Loadfile.m

```matlab
function hub = LoadFile(file)
%-----------------------------------------------------------------------------------------------------
% LoadFile
% % All data is imported from labview en directly converted to % the adapted ISO convention.
%-----------------------------------------------------------------------------------------------------

eval(['data=load(''' file ''');']);

Für
len = length(data(:,1));
hub.forces.Kx = data(:,1);
hub.forces.Ky = data(:,2);
hub.forces.Kz = data(:,3);

%moments
hub.forces.Tx = data(:,4);
hub.forces.Ty = zeros(1,len);
hub.forces.Tz = -data(:,5);

%wheel parameters
hub.wheel.angle = -data(:,9);
hub.wheel.velocity = data(:,8);
hub.wheel.slipangle = data(:,12);
hub.wheel.dh = data(:,6)/1000;

%track parameters
hub.track.displacement = -data(:,11);
hub.track.velocity = data(:,10);

A.2. LoadedRadius.m

function rl = LoadedRadius(h, gamma, a_et, a_offset)
%-----------------------------------------------------------------------------------------------------
% LoadedRadius
% % Computation of the loaded radius
%-----------------------------------------------------------------------------------------------------

%Distance from turning point measuring hub to front of measuring hub
a_mb = 0.3;

%Distance from turning point measuring hub to wheel centre
a = a_mb + a_offset - a_et;

%Distance from wheel centre to track (lateral to track)
h1 = h + a*sin(gamma);

%Loaded radius (Distance from wheel centre to track in wheel plane)
rl = h1/cos(gamma);

A.3. Conversion2AdaptedISO.m

function forces = Conversion2AdaptedISO(hub, rl, gamma)
%-----------------------------------------------------------------------------------------------------
% Conversion2AdaptedISO
% % Convert the forces and moments in the wheel centre to forces and % moments in the contact point
%-----------------------------------------------------------------------------------------------------
```
%moments conversion
forces.Fx = hub.forces.Kx;
forces.Fy = hub.forces.Ky*cos(gamma) + hub.forces.Kz*sin(gamma);
forces.Fz = -hub.forces.Ky*sin(gamma) + hub.forces.Kz*cos(gamma);

%forces conversion
forces.Mx = hub.forces.Tx - hub.forces.Ky.*rl;
forces.My = hub.forces.Kx.*rl*cos(gamma) + hub.forces.Tz*sin(gamma);
forces.Mz = -hub.forces.Kx.*rl*sin(gamma) + hub.forces.Tz*cos(gamma);

A.4. Input.m

function input = Input(file)
%-------------------------------------------------------------------
% Input
% % Check file, chop the data and put into an object
% % Input:
% % - file: file (format ...\l.p...a.h.g...)
% % - default path: path, which is added to file if necessary
% % Output:
% % - input: object with all input parameters hidden in the filename
% l -> load
% p -> pressure
% a -> slipangle
% h -> reference height
% g -> inclination angle (optional, default = 0)
% _ -> text for additional info (eg a number)
%-------------------------------------------------------------------

(The code is not added due to the complexity and the fact that the code does not provide extra insight.)

A.5. ComputeData.m

function [hub,forces,rl]=ComputeData(input,wheel)
% ComputeData
% % Compute all measured data
%-------------------------------------------------------------------

%Load the measured values from labview
hub = loadfile(input.file);

%Compute the distance between track and turning point of measuring hub
h = ones(1,length(hub.wheel.dh))';
h = 0.3715 - input.refh*h - hub.wheel.dh;

%Convert gamma from degrees to radials
gamma = pi*input.gamma/180;

%Compute loaded radius
rl = LoadedRadius(h,gamma,wheel.et,wheel.offset);

%Compute forces
forces = conversion2AdaptedISO(hub, rl, gamma);

A.6. Fast.m

% Fast
% One specific Labview data file is analysed.
% This can be used to quickly check if all data, generated with Labview is correct. It plots the measured values and the forces/moments in the contact point


34
clear all
close all

% Default settings for used wheel
wheel.et = 0.05;
wheel.offset = 0.06;
defaultpath = 'e:\tue\stage\data\';

% Fetch the required parameters for the analysis
file = input('Which file do you want to analyse? (Enter filename):','^');

% Fetch all data from the filename
input = input(file, defaultpath);

if input.valid
    input.gama = -input.gama;
    % Compute all data
    [hub, forces, rll] = ComputeData(input, wheel);
    % Plot all
    PlotAll(hub, forces, rll, 'k')
else
    disp('The file isn't valid')
end

A.7. FitStaticForces.m

function staticforces = FitStaticForces(hub, forces, input)
%----------------------------------------------------------
% FitStaticForces
% All relevant static moments/forces are computed with a polynomial fit of zero degree only in the constant part of the measurement.
% These moments/forces are the overturning moment, self aligning moment and lateral force.
%----------------------------------------------------------

if input.angle < 2.5
    % Long relaxation length
    disp_begin = 1.2;
    % No dip compensation
    disp_end = 0;
else
    % Short relaxation length
    disp_begin = 0.5;
    % Dip compensation
    disp_end = 3;
end

% Set the range
tStart = 1;
tEnd = length(forces.Mx);
for i = 1:tStart:tEnd
    if hub.track.displacement(i) > disp_begin
        % Starting point
        tStart = i;
        break
    end
end
if disp_end == 1
    for i = tStart:tEnd:
        if hub.track.displacement(i) > disp_end
            % Ending point
            tEnd = i;
            break
        end
    end
end

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% Find xf and yf for the fit
for i = tStart:1:tEnd
    xf(i - tStart + 1) = i - tStart + 1;
    fy(i - tStart + 1) = forces.Fy(i);
    mx(i - tStart + 1) = forces.Mx(i);
    mz(i - tStart + 1) = forces.Mz(i);
end

% Fit the lateral force and overturning moment
fitFy = polyfit(xf, fy, 0);
fitMx = polyfit(xf, mx, 0);
staticforces.Mz = polyfit(xf, mz, 0);

% Correction by setting the static lateral force and overturning moment to zero
%(See forcesweep file with camber zero for used values)
switch input.load
    case 2000
        staticforces.Fy = fitFy - 21;
        staticforces.Mx = fitMx + 1;
    case 4000
        staticforces.Fy = fitFy - 18;
        staticforces.Mx = fitMx - 7;
    case 6000
        staticforces.Fy = fitFy - 15;
        staticforces.Mx = fitMx - 13;
    otherwise
        staticforces.Fy = fitFy;
        staticforces.Mx = fitMx;
end

A.8. Measurement.m

%------------------------------------------------------------
clear all
close all

% Plot parameters
files = {'12p25a2h5g0_top.fptt', '12p25a1h5g0_top.fptt', ...}
 colors = {'b', 'r', 'k', 'm', 'g'};
defaultpath = 'e:\tue\stage\data\';

% Default settings for used wheel
wheel.et = 0.05;
wheel.offset = 0.05;

% Initialisation
maxi = min(length(files), 7);
for i = 1:maxi
    file = files{i};
    % Fetch all parameters from the filename
    input = Input(file, defaultpath);

if input.valid

%Display file parameters
disp(['Computation for file: ' input.file])
disp(['Load: ' num2str(input.load/1000,2) ' kN'])
disp(['Tyre pressure: ' num2str(input.pressure,2) ' bar'])
disp(['Slip angle: ' num2str(input.angle) ' degrees'])
disp(['Inclination angle: ' num2str(input.gamma) ' degrees'])

%Compute all measured data
[hub,forces,rl] = ComputeData(input,wheel);

%Plot all data
PlotOverturning(hub,forces,rl,colors{i})
PlotAll(hub,forces,rl,colors{i})

%Compute all static forces
staticforces = FitStaticForces(hub,forces,input);

%Plot fitted data
PlotStaticForces(hub,forces,input,staticforces,colors{i})

%Store all computed data
eval(['hub',num2str(i),'=hub;
rl',num2str(i),'=rl;
forces',num2str(i),'=forces;
input',num2str(i),'=input;
staticforces.Mx(',num2str(i),')=staticforces.Mx;
staticforces.Fy(',num2str(i),')=staticforces.Fy;
staticforces.Mz(',num2str(i),')=staticforces.Mz;
angles(',num2str(i),')=input.angle;'])

end

%Save all fitted data
fz = input.load;
eval(['save ..\data\l',num2str(input.load/1000),'.g',num2str(input.gamma),'.fittedfy fittedmx fittedmz angles fz files'])

%Clear all local data
clear hub rl forces input wheel maxi i file staticforces fz angles

A.9. PlotAll.m

function [] = PlotAll(hub,forces,rl,color)
%----------------------------------------------------------
% PlotAll
% % All pure data imported from labview is plotted in figure 11 and
% % figure 13 (resp. forces/moments and remaining data) from
% % one specific measurement.
% % All forces/moments in the contact point is plotted in figure 12 from
% % this specific measurement.
% % All forces/moments are in the adapted ISO convention.
%----------------------------------------------------------

A.10. PlotOverturning.m

function [] = PlotOverturning(hub,forces,rl,color)
%----------------------------------------------------------
% PlotOverturning
% % All overturning data is plotted in figure 1 from
% % one specific measurement.
%----------------------------------------------------------

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A.11. PlotStaticforces.m

function [] = PlotStaticforces(hub,forces,input,staticforces,color)
%------------------------------------------------------------------------
% PlotStaticforces
% All relevant static moments/forces are plotted in figure 2 from
% one specific measurement.
% These moments/forces are the overturning moment, self aligning moment
% and lateral force.
%------------------------------------------------------------------------

A.12. PlotMeasurement.m

%----------------------------------------------------------
% PlotMeasurement
% All data from all measurements is plotted in six different
% figures.
% The first plot shows the lateral load. The next two plots show
% the overturning moment. The fourth plot shows the self aligning
% moment. The last two plots show the pneumatic scrub.
%----------------------------------------------------------
### B. Matlab structures for the results

#### B.1. Hub structure

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>hub</td>
<td>This structure contains all Labview data converted in the adapted ISO convention. This structure consists of the following fields “forces”, “wheel” and “track”.</td>
</tr>
<tr>
<td>forces</td>
<td>This structure contains all forces and moments in the measuring hub according to adapted ISO. This structure consists of the following fields “Kx”, “Ky”, “Kz”, “Tx”, “Ty” and “Tz”.</td>
</tr>
<tr>
<td>Kx</td>
<td>Longitudinal force in the measuring hub.</td>
</tr>
<tr>
<td>Ky</td>
<td>Lateral force in the measuring hub.</td>
</tr>
<tr>
<td>Kz</td>
<td>Vertical force in the measuring hub.</td>
</tr>
<tr>
<td>Tx</td>
<td>Longitudinal moment in the measuring hub.</td>
</tr>
<tr>
<td>Ty</td>
<td>Lateral moment in the measuring hub.</td>
</tr>
<tr>
<td>Tz</td>
<td>Vertical moment in the measuring hub.</td>
</tr>
<tr>
<td>wheel</td>
<td>This structure contains all wheel parameters. This structure consists of the following fields “angle”, “velocity”, “slipangle” and “dh”.</td>
</tr>
<tr>
<td>angle</td>
<td>The rotational angle of the wheel.</td>
</tr>
<tr>
<td>velocity</td>
<td>The rotational velocity of the wheel.</td>
</tr>
<tr>
<td>slip angle</td>
<td>The slip angle of the wheel</td>
</tr>
<tr>
<td>dh</td>
<td>The height difference from a certain reference point.</td>
</tr>
<tr>
<td>track</td>
<td>This structure contains all track parameters. This structure consists of the following fields “forces”, “wheel” and “track”.</td>
</tr>
<tr>
<td>displacement</td>
<td>The track displacement.</td>
</tr>
<tr>
<td>velocity</td>
<td>The track velocity.</td>
</tr>
</tbody>
</table>

#### B.2. Forces structure

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>forces</td>
<td>This structure contains all forces and moments in the contact point according to adapted ISO. This structure consists of the following fields “Fx”, “Fy”, “Fz”, “Mx”, “My” and “Mz”.</td>
</tr>
<tr>
<td>Fx</td>
<td>Longitudinal force in the contact point.</td>
</tr>
<tr>
<td>Fy</td>
<td>Lateral force in the contact point.</td>
</tr>
<tr>
<td>Fz</td>
<td>Vertical force in the contact point.</td>
</tr>
<tr>
<td>Mx</td>
<td>Longitudinal moment in the contact point.</td>
</tr>
<tr>
<td>My</td>
<td>Lateral moment in the contact point.</td>
</tr>
<tr>
<td>Mz</td>
<td>Vertical moment in the contact point.</td>
</tr>
</tbody>
</table>
### B.3. Input structure

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td>This structure contains all input parameters which are hidden in the filename. This structure consists of the following fields “file”, “valid”, “load”, “pressure”, “angle”, “refh” and “gamma”.</td>
</tr>
<tr>
<td>file</td>
<td>Complete filename.</td>
</tr>
</tbody>
</table>
| valid | Is the filename of the following form: `1_p_a_h_g_n_fptt`  
  - l → load in kN  
  - p → pressure in tenths of bars  
  - a → slip angle in degrees  
  - h → reference height in cm  
  - g → inclination angle in degrees (optional, default is zero)  
  - n → number (optional)  
  - .fptt → “flat plank tyre tester” file extension |
| load  | Vertical load in N. |
| pressure | Tyre pressure in Bar. |
| angle | Slip angle in degrees. |
| refh | Reference height in m. |
| gamma | Inclination angle in degrees. |
C. Matlab files for the Magic Formula fit

In this chapter the Matlab files will be shown for the Magic Formula fit.

C.1. MagicFormulaFy

function Fy = MagicFormulaFy(x, alpha, gamma, Fz);
%--------------------------------------------------------------------------
% MagicFormulaFy
% This is the function to compute the Fy component of the magic formula.
% Input:
% - x: Magic Formula parameters
% - alpha: slip angle
% - gamma: inclination angle
% - Fz: Vertical load
%--------------------------------------------------------------------------
global FzO
% Parameters of the Magic Formula
pcyl = x(1);
pdy1 = x(2);
pdy2 = x(3);
pdy3 = x(4);
peyl = x(5);
pey2 = x(6);
pey3 = x(7);
pey4 = x(8);
pky1 = x(9);
pky2 = x(10);
pky3 = x(11);
phy1 = x(12);
phy2 = x(13);
phy3 = x(14);
pvyl = x(15);
pvy2 = x(16);
pvy3 = x(17);
pvy4 = x(18);

% Computation of the Fy component of the Magic Formula
Dz = (Fz - FzO)/FzO;
gammay = gamma;
shy = (phyl + phy2*Dz) + phy3*gammay;
Svy = Fz * ((pvyl + pvy2*Dz) + (pvy3 + pvy4*Dz) * gammay);
alphay = alpha + shy;
Ey = (peyl + pey2*Dz) * (1 - (pey3 + pey4*gammay)*sign(alphay));
muy = (pdyl + pdy2*Dz) * (1 - pdy3*gammay^2);
Cy = pcyl;
Dy = muy*Fz;
Ky = pky1 * Fz0 * sin(2 * atan(Fz/(pky2*Fz0))) * (1 - pky3*abs(gammay));
By = Ky / (Cy*Dy);
Fy = Dy * sin(Cy * atan(By*alphay - Ey*(By*alphay - atan(By*alphay)))) + Svy;

C.2. FyObj

function f = FyObj(x);
%--------------------------------------------------------------------------
% FyObj
% This is the objective function for Fy to compute the parameters

% for the Magic Formula fit (Fy component).
% The objective function is based on a least square fit.

global gamma Fz Fy alpha
f = 0;
for i = 1 : 1 : length(Fy)
    MFFY(i) = MagicFormulaFy(x, alpha(i), gamma(i), Fz(i));
    f = f + 100 * sqrt(((Fy(i) - MFFY(i))^2)/(Fy(i)^2));
end
f = f/length(Fy);

% Visualise how the fit is doing
figure(11)
plot(alpha,MFFY,'r.',alpha, Fy, 'ko')
drawnow

C.3. FyCon

function [g, geq] = FyCon(x)

% This is the constraint function for Fy to compute the parameters
% for the Magic Formula fit (Fy component).
% This function computes inequality constraints and equality
% constraints.

global FzO
global all_gammas all_loads

%Parameters of the Magic Formula
pcyl = x(1);
pdy1 = x(2);
pdy2 = x(3);
pdy3 = x(4);
peyl = x(5);
pey2 = x(6);
pey3 = x(7);
pey4 = x(8);
pkyl = x(9);
pky2 = x(10);
pky3 = x(11);
phyl = x(12);
phy2 = x(13);
phy3 = x(14);
pvy1 = x(15);
pvy2 = x(16);
pvy3 = x(17);
pvy4 = x(18);

%Inequality constraints (<= 0)
i = 0;
for il = 1 : length(all_gammas)
    for i2 = 1 : length(all_loads)
        i = i + 1;
        dFz = (all_loads(i2)-FzO) / FzO;
        gammay = all_gammas(il)*pi/180;
        Ey = (pey1 + pey2*dFz) * (1 - (pey3 + pey4*gammay));
        g(2*i-1) = Ey - 1;
        Ey = (pey1 + pey2*dFz) * (1 + (pey3 + pey4*gammay));
        g(2*i) = Ey - 1;
    end
end
% Equality constraints (= 0)
seq = [1];

**C.4. MagicFormulaMx**

Function \( \text{Mx} = \text{MagicFormulaMx}(x, \alpha, \gamma, F_z, F_y) \);

```matlab
% This is the function to compute the Mx component of the Magic Formula.
% Input:
% - x: Magic Formula parameters
% - alpha: slip angle
% - gamma: inclination angle
% - Fz: vertical load
% - Fy: lateral force
```

```matlab
global Fz0 R0
global gamma Fz Fy Mx alpha

% Global parameters
qsxl = x(1);
qsx2 = x(2);
qsx3 = x(3);
qsx4 = x(4);
qsx5 = x(5);
qsx6 = x(6);
qsx7 = x(7);
qsx8 = x(8);
qsx9 = x(9);
qsx10 = x(10);
qsx11 = x(11);

% Computation of the Mx component of the Magic Formula
y1 = qsx3 * Fy/Fz0;
y2 = qsx4 * cos(qsx5 * (atan(qsx6*Fz/Fz0)^2) * sin(qsx7*gamma + qsx8*atan(qsx9*Fy/Fz0)));
y3 = (qsx10 * atan(qsx11*Fz/Fz0) - qsx2)*gamma + qsx1;

Mx = Fz * R0 * (y1 + y2 + y3);
```

**C.5. MxObj**

Function \( f = \text{MxObj}(x) \);

```matlab
% This is the objective function for Mx to compute the parameters
% for the Magic Formula (Mx component).
% The objective function is based on a least square fit.
```

```matlab
global gamma Fz Fy Mx alpha
global MFFyParams

f = 0;
for i = 1 : 1 : length(Fy)
    MFFy = MagicFormulaFy(MFFyParams, alpha(i), gamma(i), Fz(i));
    MFX(i) = MagicFormulaMx(x, alpha(i), gamma(i), Fz(i), MFFy);
    f = f + 100 * sqrt(((Mx(i) - MFX(i))^2)/(Mx(i)^2));
end

f = f/length(Fy);
```

% Visualise how the fit is doing
figure(12)
plot(alpha,MFX,'r.',alpha,Mx,'ko')
drawnow
The fitted data is loaded into variables. Only those measurements are given which are given with the arrays all-gammas and all-loads.

```matlab
function [] = LoadFittedData()
    global all_gammas allLoads
    gamma Fz Fy Mx alpha
    i = 0;
    for il = 1 : length(all_gammas)
        for i2 = 1 : length(all_loads)
            eval(['load ..\data\l',num2str(all_loads(i2)/1000), ...
            'g',num2str(all_gammas(il))]);
            i = i + 1;
            gamma(i) = all_gammas(il)*pi/180;
            Fz(i) = all_loads(i2);
            Fy(i) = fittedfy(i3);
            Mx(i) = fittedmx(i3);
            alpha(i) = angles(i3)*pi/180;
        end
    end
end

C.7. MagicFormulaFit

% MagicFormulaFit
% The procedure to fit/plot the components Fy and Mx with the Magic Formula

clear all
close all

%Constants
global Fz0 R0
Fz0 = 4000;
R0 = 0.3;

%Files which are used
global all_gammas all_loads
all_gammas = [0,5,-5,-10];
all_loads = [2000,4000,6000];

%Fetch all data
global gamma Fz Fy Mx alpha
LoadFittedData

%Compute parameters of the Fy component and the Mx component (Magic formula)
global MFyParams MMxParams

%Setting options for fmincon-algorithm for Fy
options = optimset('fmincon');
options = optimset(options,' TolX',1.0e-2,' TolScale','off',' Display','iter');
%Call of fmincon for Fy
x0 = [1.3 1 0 0 1/100 0 0 0 15 1 0 0 0 0 0 0 0];
[x, fval,exitflag] = fmincon('FyObj',x0,[],[],[],[],[],[],'FyCon',options)

MFyParams = x;
```
PlotMagicFy

% Setting options for fminunc-algorithm for Mx
options = optimset('fminunc');
options = optimset(options, 'tolx', 1.0e-4, 'LargeScale', 'off', ...   'HessUpdate', 'bfgs', 'Display', 'iter');

% Call of fmincon for Mx
x0 = [1 1 0 1 1 0 1 0 0 0];
[x, fval, exitflag] = fminunc('MxObj', x0, options);
MFMxParams = x;
PlotMagicMx

clear x x0 fval exitflag options

C. 8. PlotMagicFy

%-------------------------------------------------------------
% PlotMagicFy
% The measured lateral force data is plotted against the Magic
% Formula fit.
%-------------------------------------------------------------

C. 9. PlotMagicMx

%-------------------------------------------------------------
% PlotMagicMx
% The measured overturning moment is plotted against the Magic
% Formula fit.
%-------------------------------------------------------------