Validation of a Motorcycle Tyre Estimator using SimMechanics Simulation Software

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Abstract

The tyre is a very important part of the motorcycle when concerning motorcycle dynamics. The tyres largely determine what it feels like to drive the motorcycle, because the tyres are solely responsible for transferring forces and moments to and from the road. To determine the performance of a tyre, these forces and moments should be identified. It can, unfortunately, be difficult to measure these tyre forces and moments. A relatively cheap and universally usable method is to determine the tyre forces through state estimation. The Motorcycle Tyre Estimator (MCTE) is a software tool with the goal to estimate the tyre characteristics of any tyre, fitted under any motorcycle.

Because a motorcycle is a nonlinear dynamic system, an Extended Kalman Filter (EKF) is used in the MCTE as a state estimator.

To validate the MCTE, several steps have to be taken. Because of the unavailability of a crucial sensor, validation could only take place by using simulation data generated by a SimMechanics model. The simulation data itself therefore has to be validated before it can be used as a reference. To accomplish this, the simulation data is compared to the measurements of two Yamaha FJR1300 motorcycles.

For each FJR1300 motorcycle a SimMechanics model has been created, because they have different weight distributions and sensor positions. A comparison of the two models showed that the differences between the two models were small, in fact smaller than the differences in the measurements of the real motorcycles. When comparing the simulation results to the measurement results, the results of the two measurements and the two simulation models are very similar. This proves that the simulation models are accurate and can be used to validate the results of the MCTE.

Although the current version of the MCTE is able to estimate the motorcycle movements well, the tyre slip angle and the tyre forces and moments are not estimated correctly. This is caused by the method of estimation in the current version: an estimation is made of all tyre forces and moments in combination. Although this combination of tyre forces and moments may indeed result in the correct movement of the motorcycle, the individual components of the forces and moments are not estimated correctly.

As the results of the first MCTE version were found unsatisfactory, an attempt was made to improve it by adding a very basic, tuneable tyre model for the tyre moments. This was done by simplifying the moment relations that are used in the Magic Formula. This may help to improve the future versions, by using the estimator to estimate the tyre forces and moments one by one and using this basic tyre model when needed.
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<th>Definition / Description</th>
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<tr>
<td>ABS</td>
<td>Antilock Braking System</td>
</tr>
<tr>
<td>COG</td>
<td>Centre of Gravity</td>
</tr>
<tr>
<td>CP</td>
<td>Contact Point</td>
</tr>
<tr>
<td>CS</td>
<td>Coordinate System</td>
</tr>
<tr>
<td>ECTS</td>
<td>European Credit Transfer System</td>
</tr>
<tr>
<td>EKF</td>
<td>Extended Kalman Filter</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>KF</td>
<td>Kalman Filter</td>
</tr>
<tr>
<td>MATLAB</td>
<td>Matrix Laboratory</td>
</tr>
<tr>
<td>MCSE</td>
<td>Motorcycle State Estimator</td>
</tr>
<tr>
<td>MCSE-FJR</td>
<td>The FJR1300 motorcycle that is instrumented by TNO and is used to gather test data for the MCSE and MCTE.</td>
</tr>
<tr>
<td>MCTE</td>
<td>Motorcycle Tyre Estimator</td>
</tr>
<tr>
<td>MF</td>
<td>Magic Formula</td>
</tr>
<tr>
<td>OXTS</td>
<td>Oxford Technical Solutions</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions per Minute</td>
</tr>
<tr>
<td>TNO</td>
<td>Netherlands Organization for Applied Scientific Research</td>
</tr>
<tr>
<td>TU/e</td>
<td>Eindhoven University of Technology</td>
</tr>
<tr>
<td>WFS</td>
<td>Wheel Force Sensor</td>
</tr>
<tr>
<td>WFS-FJR</td>
<td>The FJR1300 motorcycle that is equipped with Wheel Force Sensors</td>
</tr>
</tbody>
</table>
# List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_y)</td>
<td>Lateral acceleration</td>
<td>(m/s^2)</td>
</tr>
<tr>
<td>(\text{DD} \phi)</td>
<td>Roll acceleration</td>
<td>(\text{rad/s}^2)</td>
</tr>
<tr>
<td>(\text{Dr})</td>
<td>Yaw acceleration</td>
<td>(\text{rad/s}^2)</td>
</tr>
<tr>
<td>(\text{Dv}_y)</td>
<td>Time derivative of lateral velocity</td>
<td>(m/s^2)</td>
</tr>
<tr>
<td>(\text{D} \delta)</td>
<td>Steering rate</td>
<td>(\text{rad/s})</td>
</tr>
<tr>
<td>(\text{D} \phi)</td>
<td>Roll rate</td>
<td>(\text{rad/s})</td>
</tr>
<tr>
<td>(\text{F}_{y1})</td>
<td>Lateral force for the front wheel</td>
<td>(N)</td>
</tr>
<tr>
<td>(\text{F}_{y2})</td>
<td>Lateral force for the rear wheel</td>
<td>(N)</td>
</tr>
<tr>
<td>(\text{F}_{yz, \theta})</td>
<td>Lateral force attributed to side slip angle</td>
<td>(N)</td>
</tr>
<tr>
<td>(\text{F}_z)</td>
<td>Normal / Vertical force</td>
<td>(N)</td>
</tr>
<tr>
<td>(H)</td>
<td>Matrix relating the \textit{a priori} state estimate to the measurements (z_k)</td>
<td>-</td>
</tr>
<tr>
<td>(k)</td>
<td>Indication of time step</td>
<td>-</td>
</tr>
<tr>
<td>(K)</td>
<td>Kalman gain</td>
<td>-</td>
</tr>
<tr>
<td>(m)</td>
<td>Mass</td>
<td>(kg)</td>
</tr>
<tr>
<td>(\text{M'}_{zo})</td>
<td>Term of aligning moment caused by pneumatic trail</td>
<td>(Nm)</td>
</tr>
<tr>
<td>(\text{M}_{x1})</td>
<td>Overturning moment for the front wheel</td>
<td>(Nm)</td>
</tr>
<tr>
<td>(\text{M}_{x2})</td>
<td>Overturning moment for the rear wheel</td>
<td>(Nm)</td>
</tr>
<tr>
<td>(\text{M}_{z1})</td>
<td>(Self) aligning moment of the front wheel</td>
<td>(Nm)</td>
</tr>
<tr>
<td>(\text{M}_{z2})</td>
<td>(Self) aligning moment of the rear wheel</td>
<td>(Nm)</td>
</tr>
<tr>
<td>(\text{M}_{zo})</td>
<td>Residual term of aligning moment</td>
<td>(Nm)</td>
</tr>
<tr>
<td>(P_i)</td>
<td>\textit{a priori} error covariance</td>
<td>-</td>
</tr>
<tr>
<td>(P_i)</td>
<td>\textit{a posteriori} error covariance</td>
<td>-</td>
</tr>
<tr>
<td>(Q)</td>
<td>Process noise covariance</td>
<td>-</td>
</tr>
<tr>
<td>(q_{Dz10})</td>
<td>Parameter describer the variation of the peak residual torque with camber squared</td>
<td>-</td>
</tr>
<tr>
<td>(q_{Dz8})</td>
<td>Parameter describing the variation of the peak residual torque with camber</td>
<td>-</td>
</tr>
<tr>
<td>(r)</td>
<td>Yaw rate</td>
<td>(\text{rad/s})</td>
</tr>
<tr>
<td>(R)</td>
<td>Measurement noise covariance</td>
<td>-</td>
</tr>
<tr>
<td>(r_c)</td>
<td>Crown radius / radius of tyre cross section</td>
<td>(m)</td>
</tr>
<tr>
<td>(R_e)</td>
<td>Effective rolling radius</td>
<td>(m)</td>
</tr>
<tr>
<td>(R_o)</td>
<td>Unloaded tyre radius</td>
<td>(m)</td>
</tr>
<tr>
<td>(T)</td>
<td>Rotation matrix</td>
<td>-</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>$t_o$</td>
<td>Pneumatic trail</td>
<td>m</td>
</tr>
<tr>
<td>$u$</td>
<td>Input</td>
<td>-</td>
</tr>
<tr>
<td>$v$</td>
<td>Measurement noise</td>
<td>-</td>
</tr>
<tr>
<td>$v_x$</td>
<td>Forward / Longitudinal velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>$v_y$</td>
<td>Lateral velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>$w$</td>
<td>Process noise</td>
<td>-</td>
</tr>
<tr>
<td>$x$</td>
<td>State</td>
<td>-</td>
</tr>
<tr>
<td>$\hat{x}_i$</td>
<td>state estimate</td>
<td>-</td>
</tr>
<tr>
<td>$y$</td>
<td>Output</td>
<td>-</td>
</tr>
<tr>
<td>$z$</td>
<td>Measurement</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>Lateral slip angle of the front wheel</td>
<td>rad</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>Lateral slip angle of the rear wheel</td>
<td>rad</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Steering angle</td>
<td>rad</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>Inclination angle of the front wheel</td>
<td>rad</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>Inclination angle of the rear wheel</td>
<td>rad</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Roll angle</td>
<td>rad</td>
</tr>
<tr>
<td>$\lambda_{xx}$</td>
<td>Tyre scaling factor related to ‘xx’</td>
<td>-</td>
</tr>
</tbody>
</table>
Chapter 1: Introduction

1.1 – Internship at Yamaha Motors

This report is the final product of a three month internship period at Yamaha Motors at the Advances Systems Research Division located in Iwata, Japan.

This internship was a good opportunity for several reasons:

- It posed a chance to work at a company that is involved in high-tech research.
- The internship concerns motorcycle tyres and dynamics, a challenging field of research that matches my Master track and specialization.
- Yamaha is an internationally well-known company, which increased the odds that the internship was well arranged.

1.2 – Motivation for research

For the motorcycle dynamics, the tyre is the most important part of the motorcycle. It is the motorcycle’s only means to transfer forces to the road. This means that the tyres largely determine the motorcycle’s performance and “ride feeling”. Unfortunately, these tyre forces are not easily measured. Yamaha Motors, however, possesses special wheels to measure tyre forces using strain gauges. These wheels, however, have a very high price and can only be used for one type of motorcycle. In this case, they are used on a Yamaha FJR1300, which will be called the WFS-FJR from now on (WFS is an abbreviation of “Wheel Force Sensor”).

Another disadvantage of these wheels is that they are heavier than normal wheels and therefore make it impossible to do swift dynamic manoeuvres. A different method needs to be applied to determine the tyre characteristics for a multitude of different motorcycle models and for different sets of tyres. This method should also pose no limitations to the types of manoeuvres that can be executed and it should therefore be as light as possible.

The method that meets both requirements is by determining the tyre forces through state estimation. State estimation is performed by combining (noisy) measurements and a model of the dynamic system in a Kalman filter. In Chapter 2, the Kalman filter will be dealt with in more detail. State estimation can be used for many scientific and engineering problems and is used in the MCTE to determine the tyre characteristics.

A distinction should be made between the Motorcycle State Estimator (MCSE) and the Motorcycle Tyre Estimator (MCTE). The MCSE has different states and outputs than the MCTE and is used for a different purpose. The MCTE, in particular, uses no fixed tyre characteristics during estimation. This makes sense, because the purpose of the Tyre Estimator is to determine these tyre characteristics. In the MCSE, the tyre characteristics are fixed, as the goal of the MCSE is not to determine tyre characteristics, but other states of the motorcycle such as lateral velocity, acceleration, yaw rate, roll angle, etc. Once the development work on the MCSE is finished, it may be implemented on a real motorcycle as, for instance, a rider support system. The MCTE is a subproject of the MCSE project. The main purpose is the estimation of tyre characteristics, which makes the choice for the best suitable tyre for a certain purpose objective and easy. In order to get a good estimation of the tyre forces and moments, additional (expensive) velocity and slip angle sensors are necessary. See Table 1 for the characteristic differences between the two estimators.

The MCTE may, in the future, also be used in addition to the MCSE when an unknown tyre is used: The MCTE is used first to determine the unknown tyre characteristics and these results will then be used in the internal model of the MCSE.
Table 1.1 - Characteristic differences between the MCSE and MCTE

<table>
<thead>
<tr>
<th>Usage</th>
<th>Sensors</th>
<th>Movement</th>
<th>Tyre</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCSE</td>
<td>Real-Time</td>
<td>Cheap</td>
<td>Estimate</td>
</tr>
<tr>
<td>MCTE</td>
<td>Offline</td>
<td>Expensive</td>
<td>Estimate</td>
</tr>
</tbody>
</table>

1.3 – Goal of this internship

My assignment is to assist in the development, testing and validation of a Motorcycle Tyre Estimator (MCTE) which is designed by TNO for Yamaha. Assisting in the development is done by checking each new version of the MCTE Software that is launched by TNO, to give feedback and to report strange behaviour or unexpected results. Testing and validation of the MCTE was planned to be done by using test measurements, but as a result of unfortunate delays and miscommunications with the supplier of a crucial sensor, this was no longer a possibility during this internship period. Testing and validation of the MCTE will therefore be done by using simulation data only.

1.4 – Project history

As stated in section 1.3, the Motorcycle State Estimator (MCSE) project is executed in cooperation with TNO Automotive.

Phase 1 of the State Estimator project concerned the creation of an estimator that could estimate forces and moments, lateral movement, roll angle etc. by using simulation data as input. It was determined that this estimator was accurate to about 20 degrees of roll angle. The deviations above 20 degrees of roll angle occurred because that model used a linearization around zero degrees roll angle. It is a simplification of Prof. Pacejka’s motorcycle model, which can be found in chapter 10 of [3].

To create the input data for the estimator, the so called “Virtual motorcycle” was used. This is a SimMechanics model that is a simplification of reality, but more complex than the estimator’s analytical model. The advantage of this SimMechanics model is that many sensors can be placed inside the model. These sensors give the “true” output and this output can be compared to the output of the estimator for validation purposes, [4].

In Phase 2a, the instrumentation of two FJR1300s was realized to create the possibility to capture and use real test data. One was sent to Yamaha (the MCSE-FJR), and one was kept at TNO for further development and to facilitate the transfer of future developments to Yamaha. The Virtual Motorcycle consists of seven parts: Main body, swing arm, sprung front fork, unsprung front fork, front and rear wheel and the rider. The mass, centre of gravity and inertia properties of these parts were determined by tests. This phase was also used to gather measurement data. Finally, the simulation model was validated by comparing measurement results with simulation results, [5].

A new estimator model for the real motorcycle, called the FJR-MCSE 2, was created in Phase 2b to obtain more accurate results for roll angles larger than 20 degrees. Also, a Simulink Replay model was made to allow tuning of the State Estimator on a PC, [6].

Phase 3 contains the development of the MCTE and the in-plane dynamic behaviour of the MCSE. This development phase is started in November 2008 and is planned to end in April 2009.
1.5 – Structure of this report

Chapter 2 gives a brief introduction about the most important part of the MCTE, the (Extended) Kalman Filter, or (E)KF. This EKF is the algorithm that takes care of the actual estimation of the unknown states of the motorcycle. This chapter explains the working principle and the function of this EKF and also points to the importance of tuning in order to obtain accurate results.

After Chapter 2 has given more insight in the workings of the MCTE, chapter three will be a first step into validation of the MCTE. In Chapter 3, Yamaha’s two test motorcycles will be introduced and the measurement results will be compared to establish whether these results are similar or not. In case of similar results, both measurement results can be used to validate the SimMechanics simulation results that are presented in Chapter 4.

Chapter 4 will give a brief introduction to SimMechanics and the SimMechanics simulation results will be presented. These are compared to the measurement results from Chapter 3 for validation of the simulation model and its results. This step is necessary, because simulation is the only way to validate the MCTE during my internship at Yamaha Motors. This is due to a delay in the arrival of a CorrSys lateral slip angle sensor, without which no measurement input for the MCTE could be created.

Chapter 5 will use the simulation model that is validated in chapter 4 to validate the estimated results of the MCTE. In Chapter 6, a simple tuneable tyre model is derived from Magic Formula relations for overturning and aligning moment. This model may help to improve the estimated results in future versions of the MCTE. The conclusions and recommendations are given in Chapter 7.
Chapter 2: State Estimation in the MCTE

The MCTE is an application of state estimation. The goal of state estimation is clear: estimating the state of a system. Normally, a dynamics system is a black box: the input $u$ may be known, the output $y$ may be measured, but what happens internally (the state of the system, $x$) is unknown. An estimator can be seen as a servo feedback system. In a feedback system, the measurement error is minimized by changing the input by using a controller. This is different in an estimator where the measurement error is minimized by changing the state, where a certain gain factor $K$ can be compared with the controller of a feedback system. In order to accomplish this, an estimator needs two underlying models, both either linear or nonlinear: a system model and a model that relates the state to measurements. These are also called the system equations and sensor equations, respectively.

The main difference between regular applications of state estimation and the MCTE is that the MCTE estimates the tyre forces and moments without a tyre model. The motorcycle motions are estimated first and consequently, the tyre forces and moments that cause this motion are estimated. This estimation is done by using an Extended Kalman filter. The reason that no tyre model is used is that the goal of the MCTE is to find the tyre characteristics of any set of tyres that is fitted on the measurement motorcycle.

The Extended Kalman filter will be briefly addressed in section 2.1 and section 2.2 will define the signals that are used in the MCTE’s Extended Kalman Filter.

2.1 –The (Extended) Kalman Filter

Quoting from [1], “The Kalman filter is a set of mathematical equations that provides an efficient computational (recursive) means to estimate the state of a process, in a way that minimizes the mean of the squared error. In a sense, it is a recursive least squares method, based on Gaussian noise processes. The filter is very powerful in several aspects: It supports estimations of past, present, and even future states, and it can do so even when the precise nature of the modelled system is unknown.” This is why the Kalman filter is a crucial part of the MCTE.

The Kalman filter can either be used for continuous or discrete time systems. Mixed or hybrid forms (e.g. continuous model dynamics with discrete measurements) of the Kalman filter are also possible [10][11]. In this report we will discuss the Extended Kalman filter for a discrete time system, as this form is used in the MCTE.

As mentioned above, two models are necessary to make Kalman filtering possible:

1. A set of equations that relate the state and input at the previous time step $(k-1)$ to the state in the current time step $(k)$, also called the system equations $f$.

$$x_k^- = f(x_{k-1}, u_{k-1}) \quad (2.1)$$

2. A set of equations that relate the state to measurements, also called the sensor equations $h$.

$$z_k = h(x_k^-) \quad (2.2)$$

For the contents of the input vector $u$, the state vector $x$ and the measurement vector $z$, the reader is referred to Table 2.1 in Section 2.2.
The concept of each Kalman filter is shown schematically in Figure 2.1.

![Figure 2.1: Global concept of a Kalman Filter cycle](image)

First, the “Time Update” phase of the filter is executed. In this phase, the system equations of the system (which can either be linear or nonlinear) are used to determine the new state, the so-called \(a\text{-priori}\) state \(x_k\). Because of modelling errors (e.g. unmodelled dynamics) in the system equations \(f\), the \(a\text{-priori}\) state will not be the same as the actual system state. The only way to know how large the error is, is to compare it with real measurements. Therefore, the \(a\text{-priori}\) state is used to calculate the sensor output by the sensor equations \(h\) (which can either be linear or nonlinear). The difference between the calculated sensor output and the actual sensor output is a measure of the state error, as well as the modelling error of the sensor equation \(h\). The measurement error is multiplied by a gain matrix \(K\), which is called the Kalman gain. The result of this multiplication is added to the \(a\text{-priori}\) state, which results in the final (corrected) state estimate. After this the loop starts again.

The matrix gain \(K\) is determined from several other matrices. First of all, the error-covariance matrix \(P\) is used. Inside, \(P\) stores information on the reliability of the state estimates. Because the actual state is unknown, \(P\) is an estimate as well. When the values of \(P\) (mainly the diagonal entries) are small, the reliability is high.

Furthermore, because a motorcycle is a nonlinear system, the Jacobians of the system equation and the sensor equation are also needed at every time step. These are first order approximations of the system and the sensor equation respectively around the current state estimate. These matrices are used to provide the direction (slope) of the solution. It is also assumed that all signal errors have Gaussian properties: zero mean and a variance. These variance characteristics are required for the sensor signals (stored in matrix \(R\)) and for the state signals (in matrix \(Q\)). The \(Q\) and \(R\) matrices can be seen as tuning matrices. The \(Q\) matrix tells the Kalman Filter which signal is believed to be more reliable compared to other signals.

When \(Q\) and \(R\) are constant, the values of \(P\) and \(K\) will stabilize and then remain constant. If this is the case, \(Q\) and \(R\) can be pre-computed by running the filter off-line or by determining a steady-state value of \(P\) [1]. This tuning of \(Q\) and \(R\) is essential in order to obtain the best possible results from the Kalman filter. It can be a laborious task that is mainly based on experience and/or trial and error.

Figure 2.2 shows the EKF cycle in more detail.
In Figure 2.2, $\hat{x}$ is the estimate of the state $x$ and the ‘0’ in $f(\hat{x}, u, 0)$ means that a process noise, due to lack of better information, is assumed to be zero. The subscript $k$ indicates the time step, where $k$ indicates the current and $k-1$ indicates the previous time step.

Furthermore,

$$A = A(x, u) = \frac{\partial f}{\partial x} \bigg|_{x=\hat{x}_{k-1}, u=u_{k-1}}$$

$$W = W(x, u) = \frac{\partial f}{\partial w} \bigg|_{x=\hat{x}_{k-1}, u=u_{k-1}}$$

$$H = H(x) = \frac{\partial h}{\partial x} \bigg|_{x=\hat{x}_{k-1}}$$

$$V = V(x) = \frac{\partial h}{\partial v} \bigg|_{x=\hat{x}_{k-1}}$$

The subscript $k$ is dropped here, but please keep in mind that in fact these Jacobian matrices are different at every time step.

A drawback of the EKF is that the distributions of various random signals are no longer normal after undergoing their respective nonlinear transformations. The EKF therefore only approximates optimality by linearization, [1][10].

Also, the linearized transformations are only reliable if the error propagation can be well approximated by a linear function. If this condition does not hold, the linearized performance can be extremely poor, [2].
2.2 – The signals of the MCTE’s EKF

In the following section, the input, state, output and measurement signals for the MCTE will be defined.

The internal structure of the MCTE as it is used by the EKF is listed in Table 2.1.

<table>
<thead>
<tr>
<th>Input (u)</th>
<th>State (x)</th>
<th>Output (y)</th>
<th>Measurements (z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_x)</td>
<td>(v_y)</td>
<td>(\alpha_1)</td>
<td>(r) (Landmark)</td>
</tr>
<tr>
<td>(\delta)</td>
<td>(Dv_y)</td>
<td>(\alpha_2)</td>
<td>(D\phi) (Landmark)</td>
</tr>
<tr>
<td>(D\delta)</td>
<td>(r)</td>
<td>(\gamma_1)</td>
<td>(\varphi) (OXTS)</td>
</tr>
<tr>
<td>(D\phi)</td>
<td>(D\gamma)</td>
<td>(\gamma_2)</td>
<td>(v_y) (CorrSys front)</td>
</tr>
<tr>
<td>(DD\phi)</td>
<td>(F_{y1})</td>
<td></td>
<td>(v_y) (CorrSys rear)</td>
</tr>
<tr>
<td>(F_{y1})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{y2})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(M_{x1})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(M_{x2})</td>
<td></td>
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</tr>
<tr>
<td>(M_{z1})</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(M_{z2})</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The list of symbols on page 6 can be referenced to identify the written names and units of the signals presented in Table 2.1.

The names between parentheses (e.g. “(Landmark)”) indicate which sensor is used to measure the signals. The input \(u\) in itself controls the movement of the motorcycle. The inputs are considered to be accurate, they are not treated as estimations and are not affected by the EKF. The state \(x\) consists of the data that is estimated with the help of the internal model, input \(u\), measurements and the EKF (see section 2.1 for more information about the workings of the EKF). For the MCTE, the state of the system is not completely equal to the desired output of the system. The output \(y\) consists of all data of interest. It is calculated at each time step after estimation of the state. For the MCTE, this \(y\)-data is all that is necessary to make an MF-fit to identify the tyre characteristics. The output \(a_y\) is a reference signal that is used to verify the correctness of the state \(x\). The forces and moments are taken directly from the state vector \(x\).
Chapter 3: Comparison of measurement results

The purpose of this chapter is to introduce the two FJR1300 test motorcycles and compare the measurement results of the two FJR1300 motorcycles to validate the MCSE-FJR’s tyre force and moment estimation and to check whether the measurement results of the two FJR1300s are similar. If that is the case, the simulation results can be checked by comparing to both motorcycles’ measurement results.

3.1 – The WFS-FJR and the MCSE-FJR

Yamaha’s Advanced Systems Research Division has two different FJR1300 motorcycles for development of the MCSE and MCTE.

The motorcycle that was built first is the so called WFS-FJR. This motorcycle is equipped with special wheels that can measure forces and moments by implementation of strain gauges in the wheels. It also features a GPS, ABS sensors that can be used to measure the wheels’ angular velocities, a steer angle sensor, a steer torque sensor, a throttle and engine RPM sensor, gyro sensors and suspension stroke sensors. This motorcycle can be used to validate the wheel force and moment estimation results of the MCTE Tool.

The other motorcycle is called the MCSE-FJR and is, although it is also an FJR1300, in many ways different from the WFS-FJR. As mentioned in Chapter 1, it is instrumented by TNO Automotive. It contains similar sensors as the WFS-FJR, but it also contains an additional acceleration and gyro-sensor: the OXTS RT3100. The OXTS sensor also includes a GPS receiver and can therefore be used to determine the motion, position and orientation of the motorcycle. This sensor also contains hard- and software to calculate many output signals based on its measurements, such as the lateral slip angle. The OXTS is therefore used as a validation device. The MCSE-FJR uses standard wheels and therefore no tyre forces or moments are measured. Because it is a newer FJR1300 model, some parts are different. For instance, the rear arm is 35 mm longer than the one of the WFS-FJR. The weight distribution is also somewhat different. Another difference between the two models is that the MCSE-FJR features a semi-automatic gearbox as an extra option. It is however still possible to shift “the regular way” on the MCSE-FJR.

The most important added features of the two motorcycles are presented in Table 3.1.
<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
<th>Picture</th>
<th>Description</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete Motorcycle</td>
<td>Complete Motorcycle</td>
<td><img src="image1.png" alt="Picture" /></td>
<td>Complete Motorcycle</td>
<td><img src="image2.png" alt="Picture" /></td>
</tr>
<tr>
<td>Steer angle and steer torque sensor</td>
<td>Front and Rear (Rear shown)</td>
<td><img src="image3.png" alt="Picture" /></td>
<td>Front and Rear (Rear shown)</td>
<td><img src="image4.png" alt="Picture" /></td>
</tr>
<tr>
<td>Suspension stroke sensors</td>
<td>On tank</td>
<td><img src="image5.png" alt="Picture" /></td>
<td>Under seat, Landmark</td>
<td><img src="image6.png" alt="Picture" /></td>
</tr>
<tr>
<td>Wheel force sensors</td>
<td>Front and Rear (Rear shown)</td>
<td><img src="image7.png" alt="Picture" /></td>
<td>Not present</td>
<td></td>
</tr>
<tr>
<td>Gyro + Acceleration sensor</td>
<td>Not present</td>
<td></td>
<td>OXTS RT3100</td>
<td><img src="image8.png" alt="Picture" /></td>
</tr>
<tr>
<td>Signal processing</td>
<td>Rear box (also contains GPS)</td>
<td><img src="image9.png" alt="Picture" /></td>
<td>Rear box</td>
<td><img src="image10.png" alt="Picture" /></td>
</tr>
</tbody>
</table>
3.2 – Measurements

When performing test measurements, the ordinary set of tests performed by Yamaha riders consists of eight different manoeuvres, six of which are steady state circle tests. All circle driving tests are driven with a circle radius of 20 m. Three circle tests are left turns at 20 km/h, 30 km/h and 35 km/h. Three circle tests are right turns at 20 km/h, 30 km/h and 35 km/h. The last two tests are straight runs at 20 km/h and 35 km/h. The axis system that is used to indicate the x-direction, y-direction and z-direction is presented in Figure 3.1, where x is the longitudinal, y is the lateral and z is the vertical direction. An example of measurement results from the Hamaoka test course of the WFS-FJR and MCSE-FJR when driving a steady state circle manoeuvre at 30 km/h is presented in Figure and Figure . These measurements were done on December 4th, 2008.

In Figure 3.2, the first row of graphs represents the acceleration in x-, y- and z-direction. The second row of graphs represents the roll, rate and yaw rate. The third row of graphs represents the roll angle and pitch angle. The pitch rate and yaw angle are not displayed, because that information is not useful when considering a steady state circle manoeuvre. The measured acceleration in z-direction is the result of the effect of gravity on the acceleration sensor. This phenomenon is discussed in detail in Appendix A.

When comparing both motorcycles in Figure 3.2, what can be noticed immediately is that the accelerations, angular velocities and roll angle are all very similar. Only the pitch angle seems somewhat different, although it has the same shape. The pitch angles are very small, however.

What is very remarkable in Figure 3.3 is the very coarse signal that is received from the WFS-FJR’s GPS. This has to do with problems with data transfer. The full GPS sensor data was too large to log at 100 Hz and therefore the signal is truncated. An attempt was made to solve this, but it was unsuccessful. Fortunately, the MCSE-FJR’s GPS signal is accurate. The WFS-FJR also has a steering angle offset, which is different after every set of runs. It seems that shutting down the electronics also resets the steering angle sensor. In Figure 3.3, this steering angle has been corrected for this offset. The offset is displayed in the bottom (28.34 degrees for the WFS-FJR). For the MCSE-FJR, the steering angle is almost equal to zero for every run, so it does not need correction. The steering torque is a parameter that is influenced by many things, as is shown in section 4.8 of [8]. It is therefore difficult to determine where the difference in steering torque between the two motorcycles originates from.

The suspension strokes for the rear suspension are different, but this is because the positions and orientations of the steering stroke sensors on the two motorcycles are also different. For that reason, these two measurement results cannot be compared.
Figure 3.2 - Accelerations, angular velocities and angles of the WFS-FJR and the MCSE-FJR. Test data from Hamaoka test course, 4th of December 2008, Rider S.
Figure 3.3 - Various other measurement data of the WFS-FJR and the MCSE-FJR.
Test data from Hamaoka test course, 4th of December 2008, Rider S

When combining the measurement results of a complete set of runs in one plot, it is useful to represent on measurement signal in a test run with its average value, so a single point. In order to obtain the average values for many measurements and store these values in MS Excel, a MATLAB m-file was written to assist in this laborious task. First, the straight run test at 35 km/h was used to determine the offset of the steering angle for the WFS-FJR. Once this was known, the plots like the ones shown in Figure 3.2 en Figure 3.3 could be produced. By looking at these plots, the time period when the motorcycle is at steady state can be determined. This time period was entered manually as input to the m-file to calculate the average values for each measurement run. The data that is used to display the average results is from a test on Hamaoka test course on September 23rd, 2008. These results are depicted in Figure 3.4.
Chapter 3: Comparison of measurement results

It can be concluded from Figure 3.4 that the steer angle and steer torque are somewhat different on both motorcycles. In this case the MCSE-FJR’s steering torque is larger. This has to do with the fact that tyres were changed between September and December and that the older tyre that was used in September might have had a different internal structure due to aging, wear and a possible change of composition by the manufacturer. The difference in rear suspension stroke is again found in this figure, but as mentioned before, these two measurements cannot be compared.

Figure 3.4 – Measured motorcycle movement data comparison as a function of roll angle. Test data from Hamaoka test course, 23rd of September 2008, Rider S
Chapter 3: Comparison of measurement results

In Figure 3.5, the measured lateral force, overturning moment and aligning moment from the WFS-FJR motorcycle are compared with the estimated lateral force, overturning moment and aligning moment of the MCSE-FJR motorcycle. These estimations are not from the MCTE, but from the MCSE. The MCSE contains the tyre model that is used on the actual measurement motorcycle and is therefore able to obtain results that are close to the measured values from the WFS-FJR motorcycle. The lateral force is almost equal for both motorcycles, but larger differences are found when looking at the aligning torque. The aligning torque is a variable that is easily influenced by small changes in the motorcycle or the tyre. As will be shown in Chapter 6, the aligning torque is, according to the Magic Formula, influenced by many tyre parameters, by camber angle and by slip angle in a long equation. It is therefore a variable that is difficult to estimate correctly.

Due to the many small differences between the two motorcycles, it is difficult to interpret the differences that are found in the measurement results. When looking at the measurements as a whole, it can be concluded that although there are some differences between the measurement (or estimation) results of the WFS-FJR and MCSE-FJR motorcycle, the general results are similar. For this reason the simulation results can be compared to both FJR1300’s measurement results.
Chapter 4: SimMechanics simulations

Before validation of the MCTE is possible, the simulation model has to be validated first. As mentioned before, the MCTE will be run with input from the simulation model as a crucial sensor from CorrSys was not yet available, which made it impossible to use measurements as MCTE input. For more information about modelling the CorrSys sensor and an acceleration sensor in SimMechanics, see Appendix A. The validation of the MCTE will be done by comparing the MCTE’s estimated results to the results of the simulation model. The simulation software that was used by Yamaha is SimMechanics. SimMechanics will be briefly introduced in section 4.1. In section 4.2, the simulation results are presented and in section 4.3 the simulation results are compared to the measurement results of the WFS-FJR and MCSE-FJR motorcycles.

4.1 – About SimMechanics

“SimMechanics is a block diagram modelling environment for the engineering design and simulation of rigid body machines and their motions, using the standard Newtonian dynamics of forces and torques”, [7]. It is a plug-in of the MATLAB modelling environment called Simulink.

A SimMechanics model of the FJR1300 was available at Yamaha and it can be used to simulate motorcycle manoeuvres while collecting data from sensors that are placed inside the model. This way, a lot of information about the motorcycle movement, but also forces and moments, can be obtained quickly and easily. Because information can be extracted easily during a run of the SimMechanics model by placing sensors inside the model, the necessary input data to run the MCTE can be obtained from SimMechanics simulations. Before this is done, the SimMechanics model will be validated by comparing the results of the simulation to measured results.

Figure 4.1 - Top view of motorcycle during SimMechanics simulation

An option of SimMechanics is to show an animation of the modelled system while running the simulation. The SimMechanics motorcycle while running a steady state circle manoeuvre is displayed in Figure 4.1.

Figure 4.2 shows the same simulation that is displayed in Figure 4.1, but the screenshot was taken from the front of the SimMechanics motorcycle to clearly show the roll angle of the motorcycle, which is about 30 degrees in the presented case.
4.2 – Simulation results

Figure 4.3 – Simulated motorcycle movement data comparison as a function of roll angle
Chapter 4: SimMechanics simulations

Figure 4.3 shows the averaged data of the motorcycle movement output of the SimMechanics model. Average data from the SimMechanics model is easy to obtain and this is done automatically in the MATLAB run m-file. The simulated manoeuvres are tuned to be identical to the manoeuvres that were driven in the measurements. The initial speed and target roll angle can be set in the simulation model. By changing the target roll angle the driven circle radius is influenced. When the driven circle was approximately 20.5 meters (in reality, the test drivers also keep some distance from the 19.5 m markers), the simulation results were saved. Only a right turn is simulated as a left turn would deliver the same information, because symmetric tyres are assumed. The simulation is performed at forward velocities of 20 km/h, 25 km/h, 30 km/h and 35 km/h.

Just as in the measurement data, there is some difference between the two motorcycles in steering angle and steering torque. However, the difference in steering torque is the other way around in the simulations: the steering torque of the MCSE is larger in the simulations and this is also the case for the measurements of September 23rd, 2008, but not for the measurements of December 4th, 2008. The difference in the simulations is smaller than the differences in the measurements, however.

Figure 4.4 shows that there are also some differences in the simulated tyre data, but these differences are small. It can therefore be concluded that the differences between the two motorcycles in the simulations are smaller than in the measurements.

![Figure 4.4 – Simulated tyre data comparison as a function of roll angle](image)
4.3 – Comparison of Measurements and Simulations

Because the simulations were tuned to be the same manoeuvres as the measurements, the results of measurements and simulations can be compared. The average data of the simulations is, when available from the simulation, plotted on top of the measurement results in Figure 4.5.

Overall, the results of the simulations correspond well to the measurements. The simulation results for steer angle and steer torque are both more in correspondence with the WFS-FJR motorcycle. Please note that the results from the simulations have been mirrored so they can also be compared to left turn measurements. This is possible with the simulation model, because it assumes symmetric tyres and will therefore produce identical results for a left and right turn at the same speed, roll angle and steer angle.
Chapter 4: SimMechanics simulations

Figure 4.6 - Comparison of tyre data for measurements and simulations

When comparing the tyre data in Figure 4.6, the simulation corresponds well with the measurements concerning the tyre forces and moments. The simulation results for lateral slip angle, however, show some deviations from the measurements of the MCSE-FJR, especially for the rear wheel. Although the absolute difference in slip angle is very small, the relative difference (percentage) is large. Further investigation may reveal why the slip angles in simulations are different from the measured slip angles.

Overall it can be concluded that in general the WFS-FJR simulation model produces similar results to the MCSE-FJR simulation model and the simulation results are similar to the measurement results. This shows that validation of the MCTE results is possible with the use of the SimMechanics model. This validation is done in Chapter 5.
Chapter 5: Validation of the MCTE results

In this chapter, the MCTE’s estimation results are compared to the output of the SimMechanics model in order to validate the MCTE results. This will be done for a steady state manoeuvre in section 5.1 and for a dynamic slalom manoeuvre in section 5.2.

5.1 – Steady state circle manoeuvre

The plots that will be shown in this section will compare the simulated (from sensors in the SimMechanics model) data that is available in the input “vdxdata.mat” file of the MCTE to the estimated output of the MCTE. In this way it can be checked whether the estimator produces an accurate representation of the true values that were captured during simulation. Figures 5.1 to Figure 5.9 show the comparison for a steady state circle manoeuvre:

![Vehicle motion data plots](image)

Figure 5.1 - Comparison of vehicle motion data (Blue = simulated, Red = estimated)
Chapter 5: Validation of the MCTE results

Figure 5.2 - Slip angle front versus time

Figure 5.3 - Slip angle rear versus time

Figure 5.4 - \( F_y \) (CPI) front versus time

Figure 5.5 - \( F_y \) (CPI) rear versus time

Figure 5.6 - Overturning moment (CPI) front versus time

Figure 5.7 - Overturning moment (CPI) rear versus time
In Figure 5.1, the estimations of the motorcycle motion data are compared to the simulated data. The motorcycle motions are estimated well as in most plots no blue line can be seen. This means the estimation lies completely on top of the true value from the simulation. Only a small error for the yaw rate can be spotted: it is estimated a little too low.

In Figure 5.2 to Figure 5.9, CPI means Contact Point Interface and indicates that the reference frame with its origin on the contact point of tyre and road is used. The x- and y-directions are parallel to the road and the z-direction is normal to the road. The estimated tyre data that is shown in Figure 5.2 to Figure 5.9 shows large errors in the estimations. There is a large difference between the true input from the simulation and the output of the MCTE. The reason that the simulated data is called “Measured” (Sim) in Figure 5.2 to Figure 5.9 is because normally measured data is used as MCTE input, which is now substituted by simulation data. TNO was contacted about the results as the deviations are so large. It was explained that the current MCTE version was the first version of the estimator, at least the first version in which the tyre forces and moments are not estimated with the use of a tyre model. The estimation would be improved in future updates of the MCTE. The large errors are suspected to originate from the fact that the MCTE estimates the combination of forces and moments that are necessary to let the internal model follow the measured data. The combination of forces and moments that is estimated will produce the correct vehicle motions (as is proven by looking at Figure 5.1), but the individual components of the forces and moments are not estimated correctly.
5.2 – Slalom manoeuvre
To test the MCTE with a more dynamic manoeuvre, a simulation of a simulation of a slalom manoeuvre from TNO is now used as input. The results are shown in Figure 5.10 to Figure 5.18.

Figure 5.10 - Comparison of vehicle motion data (Blue = "measured", Red = estimated)
Chapter 5: Validation of the MCTE results

Figure 5.11 - Slip angle front versus time

Figure 5.12 - Slip angle rear versus time

Figure 5.13 - Lateral force (CPI) front vs time

Figure 5.14 - Lateral force (CPI) rear vs time

Figure 5.15 - Overturning moment (CPI) front versus time

Figure 5.16 - Overturning moment (CPI) rear versus time
Figure 5.17 - Aligning moment (CPI) front versus time

Figure 5.18 - Aligning moment (CPI) rear versus time

The same conclusion can be drawn as from the steady state circle manoeuvre: The vehicle motions as depicted in Figure 5.10 are estimated correctly (again, a small error is present for the yaw rate), but the tyre data as depicted in Figure 5.11 to 5.18 is not estimated correctly. A possible solution for this is presented in Chapter 6.
Chapter 6: Improving the MCTE

Because the results of the MCTE that were validated in Chapter 5 were found unsatisfactory, a solution to improve the results was needed. TNO suggested to program basic mathematical relations for the overturning and aligning moment. These equations should have a physical background and only make use of estimations of camber angle and lateral force, as these two can be estimated reasonably well. In the next two sections, two versions of these equations will be presented.

The inspiration for the physical relation describing overturning moment and self aligning moment could be found in the Magic Formula. However, the relations that are used in the Magic Formula have to be simplified, because the Magic Formula uses many tyre parameters and some variables in the physical relations that are, at the time of estimation, unknown.

6.1 – Simplifying Magic Formula relations for \( M_x \)

A simplified relation for the overturning moment that neglects tyre deformation can be found in [3], equation (10.60):

\[
M_x = -r_c F_z \tan \gamma
\]  

(6.1)

In (6.1), \( M_x \) is the overturning moment [Nm], \( r_c \) is the cross section radius of the tyre (half of thickness of the tyre when it is considered to be a torus) [m], \( F_z \) is the normal force on the tyre [N] and \( \gamma \) is the camber angle [rad]. This equation gives satisfactory results in determining the overturning moment, as can be seen when inspecting Figure 6.1 and Figure 6.2. The results in those figures are tuned by searching the right value for \( r_c \), which proved to be 0.061 m for the front tyre and 0.116 m for the rear tyre. The value of 0.061 m for the front tyres corresponds well with reality as the width of the front tyre of the FJR motorcycles is 0.12 m. The value of 0.116 m for the rear tyre is somewhat larger than in reality, because the width of the rear tyre is only 0.18 m. This (small) deviation from reality may be caused by the negligence of deformation effects of the tyre.

6.2 – Simplifying Magic Formula relations for \( M_z \)

The aligning torque for pure side slip is described by formula (10.E33) in [3]:

\[
M_{zo} = M'_{zo} + M_{zro}
\]

(6.2)

In (6.2), the aligning torque is split in two components: the component that is caused by the pneumatic trail \( (M'_{zo}) \) and the component that is called the residual term \( (M_{zro}) \).

The \( M'_{zo} \) term is given by equation (10.E34) in [3]:

\[
M'_{zo} = -t'_0 \cdot F_{y_0, \gamma=0}
\]

(6.3)
In (6.3), the $t_o$ term is the pneumatic trail, and it is a very complex relation depending on mainly the slip angle and camber angle, but also on many tyre parameters. To simplify matters, $t_o$ will be considered to be a constant that will need to be determined by tuning. $F_{yo, \gamma=0}$ represents the lateral force that is attributed to the side slip and not the camber angle (only indirect through camber induced side slip), but because this term is unknown, the regular $F_y$ will be used in the simplified equation. It is now assumed that only the total $F_y$ is available as an estimate.

The $M_{zo}$ term and some components in that term are given by equations (10.E37), (10.E47), (10.E46) and (10.E38), respectively:

$$M_{zo} = M_{zo} (\alpha_r) = D_r \cos \left[ \arctan (B_r \alpha_r) \right]$$

$$D_r = F \cdot R \cdot \alpha \left[ (q_{Dz6} + q_{Dz7} \cdot d \gamma \cdot \lambda_{kr}) + (q_{Dz8} + q_{Dz9} \cdot d \gamma \cdot \lambda_{kr}) \right]$$

$$B_r = q_{Bz9} \left[ \frac{\lambda_{kr}}{\lambda_{kr} + q_{Bz10} B_z C_y} \right]$$

$$\alpha_r = \alpha^* + S_{hr}$$

(6.4)
Where $R_o$ is the unloaded radius of the tyre and $S_{Rr}$ is a term that introduces the camber induced side slip into the equation.

An attempt is made to simplify (6.4) greatly. This simplification will not be without consequences as a lot of detail and therefore completeness of the equation will be lost. But, as stated above, this simplification is necessary. The reasoning behind the simplification can be read in the paragraph below.

Because $q_{Bz9}$ has a value of around 6 in the tyre property file that is used in the SimMechanics model for the FJR1300s, this value is taken to be 6. All $\lambda_{xx}$ values that are found in (6.4) are scaling parameters that are initially equal to 1 can therefore also be disregarded. The term \cos\[arctan(B, \alpha_r)] > 0.7, because $\alpha_r$ can be considered small (<0.15) and therefore this term is completely replaced by the value 1. The parameter $q_{Bz10}$ equals zero in that tyre property file, so the $q_{Bz10}B_{C_y}$ term is neglected. Because $\alpha$ is small, the term $\cos' \alpha$ is also considered to equal one and is therefore disregarded. This great simplification leaves:

$$M_{zo} = D_r = F_r R_o \left( \frac{(q_{Dc;5} + q_{Dc;7}df_z) \lambda_{Mr}}{(q_{Dc;5} + q_{Dc;9}df_z) \lambda_{Kz}} \lambda_{Kz}^+ + \left( q_{Dc;10} + q_{Dc;11}df_z \right) \lambda_{Mr} \right)$$

In (6.5), the scaling factors $\lambda_{xx}$ are considered to equal one and the terms containing $df_z$ are neglected as variations in $f_z$ are negligible. The variable $\gamma_z$, which is $\gamma$ multiplied with a scaling factor (considered equal to one), can be represented by only $\gamma$. Furthermore, $q_{Dc;5}$ is very small ($<0.011$) and is therefore disregarded.

All that remains is the following:

$$M_{zo} = M'_{zo} (\text{simpl}) + D_r (\text{simpl}) = -t_o \cdot F_y + F_r R_o (q_{Dc;8} \gamma + q_{Dc;10} \gamma \gamma)$$

For a left turn, $F_y$ is positive and $\gamma$ is negative. The parameter $t_o$ is positive and the parameters $q_{Dc;8}$ and $q_{Dc;10}$ are both negative. The two components in (6.6) therefore have opposite sign; in a left turn $M'_{zo}$ has a negative sign and therefore has an aligning effect. This means that by this effect the steering torque that needs to be delivered by the rider in a left turn is increased. If the steering torque of the rider is negative (rider blocking the handlebars, motorcycle steers more into the turn if the rider releases the handle bars), it will become less negative. $D_r$ has a positive sign for a left turn and therefore has a disaligning effect. This increases the difficulty of finding the correct values for parameters that need to be tuned later, because there are more possible ways to arrive at a solution for $M_{zo}$. The signs of the components switch when a right turn is executed, because $F_y$ gets the opposite sign and $\gamma$ gets the opposite sign.

The parameter $q_{Dc;5}$ resembles the “variation of peak factor Dmr (= peak residual torque) with camber” and $q_{Dc;10}$ is the “variation of peak factor Dmr with camber squared”. With tuning of the values for $t_o, q_{Dc;8}$ and $q_{Dc;10},$ an approximation for the aligning moment can be found, but it may not have the robustness of the complete equation from the Magic Formula, and may therefore not have the desired accuracy. After some tuning attempts of $t_o, q_{Dc;8}$ and $q_{Dc;10}$ and the goal to achieve accurate results for both a steady state circle manoeuvre and a slalom manoeuvre, the following values are found:

$t_o = 0.022, q_{Dc;8} = -0.08$ (compared to -0.04432 which is found in the tyre property file) and $q_{Dc;10} = -0.15$ (-0.08 in tyre property file).

With this tuning, the results are as presented in Figure 6.3 and Figure 6.4.
Because of the effect of $F_z$, the approximated result is smaller for the front tyre and larger for the rear tyre, as $F_{z\text{,front}} = 1722 \text{ N}$ and $F_{z\text{,rear}} = 2066 \text{ N}$. This error is difficult to reduce as both terms in the equation (so also $F_y$) are dependent on $F_z$. The result for the front aligning torque is much more accurate than the result for the rear aligning torque, but a different tuning can give very different results.

Concluding about the simplified relations for $M_x$ and $M_z$, the relation for $M_x$ seems to be simple and accurate enough. It was acknowledged that the relations for $M_z$ may have been simplified too much. Again, this has everything to do with the limited information that is available during state estimation.

These basic relations already provide a closer match to the simulated data than the estimations of the current version of the MCTE. Making use of these basic relations for the tyre moments and changing the estimation procedure so that it estimates the forces and moments one by one can therefore assist in the improvement of the MCTE results.
Chapter 7: Conclusions and Recommendations

This chapter will give the conclusions that can be drawn from this report and give some recommendations for further research.

Conclusions

- Although the WFS-FJR and MCSE-FJR motorcycles are different in many ways, most measurement results do not differ much.
- Although the WFS-FJR and MCSE-FJR SimMechanics models are tuned and adapted to resemble the real motorcycles as good as possible and are therefore different, the simulation results are similar.
- The differences between the results of the simulations are smaller than the differences in the results of the measurements.
- The SimMechanics model results are very similar to the MCSE measurement results, which makes validation of the MCTE by simulations a good alternative to validation by real measurements.
- The MCTE results are at this moment good concerning the vehicle motions.
- The MCTE results concerning slip angle and tyre forces and moments are at this moment not reliable, which has to do with the method of estimation: estimating the combination of all forces and moments does not result in the right estimate for each individual component.
- It is possible to achieve a good approximation for the overturning moment and a reasonable one for the aligning moment when a simplification of the Magic Formula relations is used.

Recommendations

- Validation of the MCTE should (and will, in the near future) be done by using measurements as well as simulations.
- 1. The slip angles which are estimated by the MCSE differ from the slip angles which are collected in simulations. The estimation of lateral velocity should therefore be checked, as this influences the lateral slip angles.
   2. The slip angles that are estimated in the MCTE are also different than the slip angles from the simulation.
   3. Due to these observations, it is recommended to do more research concerning the slip angle estimations from the MCSE, MCTE and the collected slip angles from the simulation model in order to identify the cause of these differences.
- The found relations for the aligning moment should be improved for the rear wheel and should also be tested and validated for different manoeuvres and different speeds.
- A different estimation strategy should be applied. Estimation of all forces and moments combined did not give satisfactory results. Pre-programmed relations/equations for overturning moment and aligning moment can be used to improve the estimations, because this may make it possible to estimate the forces and moments in two or more steps.
Bibliography


Appendix A: Additions to the SimMechanics model

CorrSys sensor blocks, which represent the Corr and an acceleration sensor that resembles the output of a real acceleration sensor. These two additions will be discussed in more detail below.

**CorrSys sensor blocks**

Since the 2008-12-22 update of the MCTE, measurements of forward and lateral velocity ($v_x$ and $v_y$) by the CorrSys sensors are a necessary input for the MCTE. This means, that in order to use simulation data as input for the MCTE, that these signals from the CorrSys sensors also have to be generated in the SimMechanics model. To accomplish this, TNO has created blocks that can be used in SimMechanics that will measure the forward and lateral velocity of the motorcycle in the same way that the CorrSys sensor does.

The CorrSys sensor’s workings can be compared to an optical mouse: it measures the velocity and slip angle at the front and/or at the rear by a 2-axis non-contact optical sensor.
The SimMechanics equivalent of this sensor is displayed in Figure 1.

In Figure 1, it can be seen that the CorrSys sensor is connected to the unsprung front fork (FA). The sensor and the unsprung front fork are isolated from the rest of the model in Figure 1, but this is only done to highlight the sensor and its connection to the sub body. It can also be seen that the outputs of the CorrSys are indeed \( v_x \) and \( v_y \).

Figure 1 - CorrSys sensor in SimMechanics

The contents of the CorrSys Front block are depicted in Figure 2.

Figure 2 - Contents of the Corrsys Front block

The “Conn2” block is the connection to “FA” and the “CorrSys_Front” body is welded and therefore fixed to “FA” on a location defined in the “CorrSys_Front” body block. The weld bridges the space between “FA” and the “CorrSys_Front” body. On the right hand side, the actual body that is used for the sensor, “corrsys CP (level)” is fixed to the ground (“Ground1”) with only a planar joint in between (x- and y-movement and the yaw angle are degrees of freedom). This “Ground1” is a fixed point in world coordinates and is located underneath the initial position of the CorrSys_Front body, at road level. In order to successfully connect the measured “corrsys CP (level)” body block to the motorcycle, some additional degrees of freedom are necessary to make sure that the motorcycle can manoeuvre as usual. These additional degrees of freedom are “Custom Joint2” that adds the pitch and vertical degree of freedom and the “Custom Joint1” that adds the roll degree of freedom. The “corrsys CP (level)” local body velocity is measured by “wheel Sensor2” and the local \( v_x \) and \( v_y \) are the outputs of this block, as could also be seen in Figure 1. The Rear Corrsys block is identical to the front Corrsys block, but is connected to the “Main body” instead of the “FA” and is located behind the rear wheel.
**Acceleration sensor in SimMechanics**

As the SimMechanics model is used to generate input signals for the MCTE, the signals should resemble real measurement signals. As an acceleration sensor’s workings are based on the measurement of reaction forces that are caused by accelerations, the acceleration that is caused by gravity is measured by a real acceleration sensor. If the bottom plane of the sensor is parallel to the world, the z-acceleration is measured \(9.81 \text{ m/s}^2\) (positive, because the sensor measures a reaction force in negative z-direction). This result can also be explained by imagining the following: what if you were somewhere in space and unaffected by any gravitational force, what would cause a reaction force of \(m \times 9.81\) that is sensed in negative z-direction? Only an acceleration of \(9.81 \text{ m/s}^2\) in positive z-direction!

As the reaction force that is caused by gravity works in negative z-direction in world coordinates, this means that when the motorcycle is placed on its right side, an acceleration of \(9.81 \text{ m/s}^2\) in y-direction is measured by a real acceleration sensor. Of course, gravity does not change orientation when the motorcycle changes orientation.

As SimMechanics’ acceleration sensors measure pure accelerations (not based on force measurements), this additional effect of gravity is not present. To make sure that the SimMechanics’ acceleration sensor output resembles a real acceleration sensor, this effect of gravity has to be added to the local body. To transfer position, velocity or acceleration of a body from local coordinates to world coordinates, the rotation matrix (of course, measured in world coordinates) can be used. In this case, it is desired to transform the acceleration component due to gravity from world coordinates to local coordinates. In order to accomplish this, the inverse of the rotation matrix can be used. Because the rotation matrix belongs to a special orthogonal group of matrices, its inverse is equal to its transpose, which simplifies calculation. Finally, by pre-multiplying the gravity effect vector \([0;0;9.81]\) with the transpose of the rotation matrix, the gravity effect vector is transformed to local coordinates and can be added to the standard SimMechanics acceleration sensor output. The contents of the SimMechanics block that represents the real acceleration sensor are presented in Figure 3.

**Figure 3 - Contents of the acceleration sensor subsystem in SimMechanics (from right to left)**
In Figure 3, both “Conn1” and “Conn2” are connections to the centre of gravity of the “Main body”. Two connections are used, because one body sensor, “Local Acc”, measures accelerations in the local coordinate system while the other one, “Rotation Matrix (Abs)”, measures the rotation matrix in world coordinates. In the “Matrix Multiplication” block, the following embedded MATLAB-file runs:

```matlab
function y = fcn(u)
% This block supports an embeddable subset of the MATLAB language.
% See the help menu for details.

y=[0;0;0];
g=[u(10);u(11);u(12)];

T=zeros(3);
T(1)=u(1);
T(2)=u(2);
T(3)=u(3);
T(4)=u(4);
T(5)=u(5);
T(6)=u(6);
T(7)=u(7);
T(8)=u(8);
T(9)=u(9);

% The Rotation Matrix T should be inverted to give the correct
% representation of the world coordinate vector g in local coordinates.
% (T transforms the world coordinate axis system to the local axis system,
% so to transform a vector in world coordinates to the "same" vector,
% but then expressed in local coordinates, the inverse of T is needed.)
% Because The Rotation Matrix is of SO(3), the inverse is
% equal to the transpose of the matrix.

y=T.'*g;
```

The rotation matrix that is measured from the “Rotation Matrix (Abs)” sensor is broken up into its 9 components and is transported in SimMechanics in this way. To build the rotation matrix from its 9 components, first an empty matrix of 3x3 is created and then each component is put on the right place. The gravity effect vector is built up using the last three input elements. Finally, the output is created by pre-multiplying the gravity effect vector with the transpose of the rotation matrix, as described above.

The output is the local body’s acceleration in local x-, y- and z-direction, with added gravity effect vector in local coordinates. The acceleration in local z-direction is not needed and therefore the “Selector” block only chooses the first two outputs, local x-acceleration and local y-acceleration.