Chapter 13

Outlines of Three Advanced Dynamic Tire Models

Chapter Outline

INTRODUCTION

Three relatively recent and advanced dynamic tire models have been discussed at a CCG Seminar held at the Technical University in Vienna, September 2010. These commercially available models are: *FTire*, *RMOD-K,* and *SWIFT.* Over the years, the models have been further developed and the applicability has been widened. The present chapter outlines the present state of these models. The contents of the ensuing sections have been contributed by the original developers. For further study, we refer to the indicated literature.

The three models manifest different ways of approach, different levels of complexity, and as a result differences in computational effort. Agreement with experimental data may be significantly different depending on the type of application. The three models all aim at similar motion input ranges and types of application. These include: steady-state (combined) slip, transients, and

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higher frequency responses, covering at least the rigid body modes of vibration of the tire belt. The models are designed to roll over three-dimensional road unevennesses, typically exhibiting the enveloping properties of the tire.

The program packages offer simplified and/or more refined versions that may be chosen depending on less or more demanding types of application. Of course, considerable differences in required computation time are involved.

Remarks

Obviously, the complex physically based models (*RMOD-K* and *FTire*) are better suited to examine the effects of the change of a physical parameter such as material stiffness and details of tire structure. The more empirically oriented models are better equipped to investigate the effect of changing performance parameters such as cornering and vertical stiffnesses without affecting remaining properties.

13.1. THE *RMOD-K* TIRE MODEL (Christian Oertel)

13.1.1. The Nonlinear FEM Model

Within the *RMOD-K* tire model family, the latest model is *RMOD-K FEM*, a single purpose nonlinear finite element code including HEX8 and HEX20 elements. It is able – by use of the Green–Lagrange strain tensor – to handle large rotations which occur during rolling and includes embedded continuous rebar layers for carcase, belt, and ply-caps as well as a kind of micro-buckling feature in the fiber material model.

The contact algorithm in *RMOD-K FEM* is divided into the normal contact problem based on the total Lagrangian formulation of structure deformation and the tangential contact problem in Eulerian formulation, including adhesion and sliding area (both formulations combined in the framework of the ALE formulation in steady-state rolling case). An interface transfers information between Lagrangian and Eulerian meshes, which normally differ in density. Pressure distribution and contact velocities are transferred toward the Eulerian mesh and tangential contact forces are transferred back to the Lagrangian mesh. In Figure 13.1, the variable mesh density and the penalty contact sensors are shown. Due to the single purpose orientated software design, the code has performance as well as robustness advantages in relation to multipurpose codes. The model produces results such as global static stiffness, steady-state force and moments, modal analysis, transfer functions from contact patch to spindle, and dynamic transient analysis with arbitrary uneven roads. Most of the model parameters are obtained from the geometry of the tire cross section including the layer positions via a pre-processor. The remaining values such as material parameters – if unknown or unavailable – are determined automatically by optimization based on measurements of the vertical stiffness

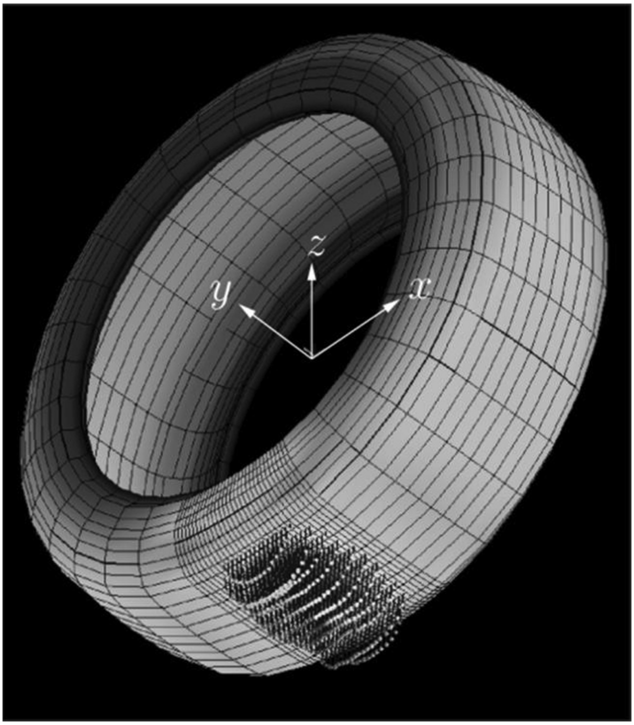

FIGURE 13.1 *RMOD-K FEM*, loaded tire with contact.

and few of the inflated tire modes. Once the model parameters are known, the model can also serve as parametrization tool for simplified models. This can be done directly by comparing the element stiffness and mass matrixes of the simplified model with those of *RMOD-K FEM* or in the conventional way by comparing model results.

13.1.2. The Flexible Belt Model

The model *RMOD-K FB (flexible belt),* cf. Oertel (1997) and Oertel and Fandre (1999), gives also a detailed finite element description of the actual tire structure, but uses a number of simplifications in order to obtain a massive reduction of computational effort. The model uses the original load path of tires like *RMOD-K FEM* – load transfer via the pre-stressed sidewall without radial spokes. It features a flexible belt modeled by discrete rebars and the simplification of combing all different layers in one position relative to the cross section by analytically pre-processed QUAD 4 elements (cf. see Figure 13.2). Additional bending stiffnesses represent the rubber matrix. The belt is connected to the rim with a simplified sidewall model with pressurized

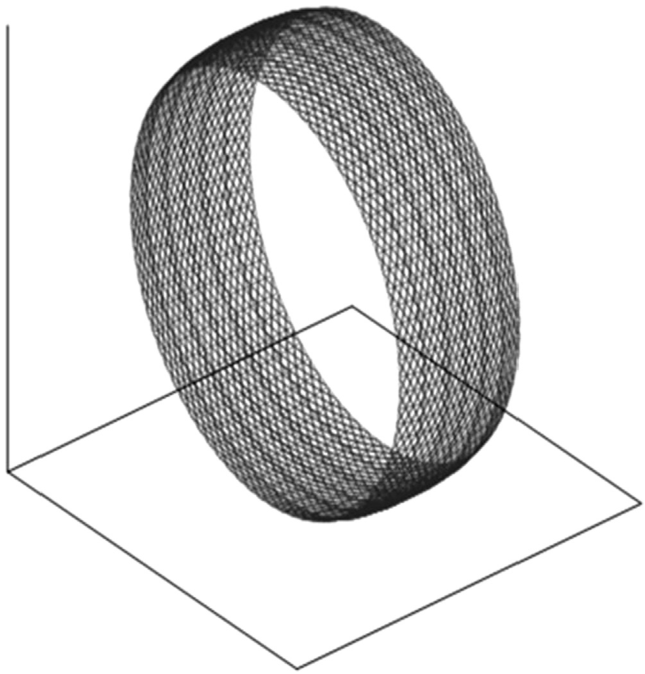

FIGURE 13.2 *RMOD-K FB*, belt model.

air. Road contact is realized through an additional tread or sensor layer, a simplified HEX8 element. In a grid of sensor points at the outer tire surface, the normal and frictional forces are calculated. The contact area shape – with possible gaps – and contact pressure distribution result from computing the normal contact problem with the rolling and the structural deformation of the tire. Three-dimensional uneven surfaces can be generated and dealt with very well by this sophisticated model. A friction function included allows the generation of both adhesion and sliding areas with friction levels that depend on temperature (*WLF* transformation) and contact pressure. The complexity of the model may be controlled, depending on the type of application by changing the mesh density in the belt or sidewall area. The computational effort, however, is much smaller than that of *RMOD-K FEM* and the latest version of the simplified model offers parallel computing and therefore reduces the computational effort with respect to the hardware. Interfaces to the main MBS codes as well as to some FE codes are available. An additional feature is the misuse module, where a second load path between the inner surface of the tire and the rim can establish and very high wheel load can be handled up to plastic deformation of the rim, which is included in the misuse module, cf. Oertel and Fandre (2009).

13.1.3. Comparison of Various *RMOD-K* Models

Comparing the results obtained from *RMOD-K FEM* with those of the reduced finite element approach *RMOD-K FB*, it can be seen that both models lead to similar global results like vertical stiffness or steady-state force and moments while internal measures like Cauchy fiber stress may differ due to the simplifications. In Figure 13.3, the radial displacements for some circumferential node paths of both models are shown. Despite the slightly different meshes, the results are nearly identical. The two models address different fields of applications. *RMOD-K FEM* is used to work on tire design and durability by virtual

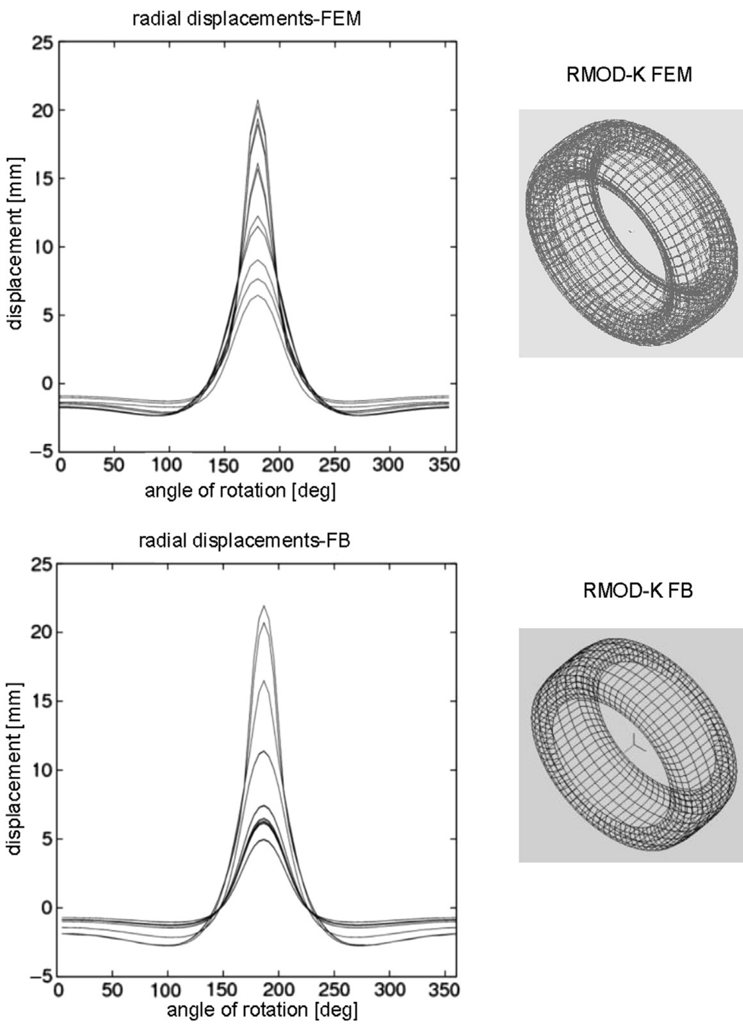

FIGURE 13.3 Radial structure deformation, *RMOD-K FEM and RMOD-K FB.*

prototypes of the tire, typical questions dealt with in tire industry. *RMOD-K FB* is mainly used in the field of full vehicle dynamics by OEM with multi-body or hybrid models to investigate ride comfort, to compute load collectives and to calculate vehicle misuse loads. A much simpler model is available, which is based on a rigid belt representation and a separate model for the calculation of the footprint dimensions and the pressure distribution, *RMOD-K RB* (rigid belt).

Contact dynamics is analytically treated in the areas of adhesion. Applications are limited to smooth roads and ca. 100 Hz. The field of application is handling and controller design, so this type of model may be called *mechatronics* tire and used together with *simulink* vehicle and controller models.

Finally, a model for steady-state tire behavior – the *RMOD-K formula* – completes the tire model family. It is based on physical modeling, including adhesion and sliding area and contains a discrete contact area in order to handle larger camber angles. *RMOD-K formula* is much faster than real time and can be used in microcontroller applications. It becomes available as freeware in 2011. For these models also handling and fitting, aids are available.

One of the subjects of ongoing research and development is to build up a unique parametrization and a process chain across the entire *RMOD-K* model family, which will result in a reduction of cost and time with respect to the amount of needed measurements and which will simplify the process of parametrization.

The reader is referred to Oertel and Fandre (2009) for more details. Furthermore, we mention the website for up-to-date information: www.rmod-k.com.

13.2. THE *FTire* TIRE MODEL (Michael Gipser)

13.2.1. Introduction

FTire (Flexible Ring Tire Model) belongs to the class of strictly mechanics-based tire models, suitable for use in general vehicle dynamics simulations. *FTire* development started in 1998, using certain ideas and numerical concepts of the 'coarse-mesh' FE model *DNS-Tire* (Dynamic Nonlinear Spatial Tire Model), cf. Gipser (1996, 1998), as well as the nonlinear 'rigid-ring' model *BRIT* (Brush and Ring Tire Model), cf. Gipser (1997, 1998).

FTire's complexity is below that of detailed FE models, but far above classical 'point contact' models. Consequent use of mechanically consistent, highly nonlinear structure, and friction models allows 'safe' extrapolation into operating conditions not covered by respective laboratory experiments. *FTire* returns plausible dynamic tire forces even at multiple high-frequent excitation, caused by road height profile and deformation, friction variation, suspension vibrations, drive and brake torque, tire nonuniformity and imbalance, temperature and pressure variation, and misuse events. This is *not* achieved by overly compromising computing time. Depending on activation of subsystems and on timely and spatial resolution, FTire simulation only takes about 1–50 times real time. Due to *FTire*'s multicore support, all tires of a vehicle can be simulated in parallel at the same computation speed.

FTire constitutes a full tire simulation environment. More than just a single model, it provides a scalable tire model kit, ranging from parallelized, real time capable versions for hardware-in-the-loop application, up to high-resolution realizations, connected to explicit FEA solvers. Upon demand, *FTire* provides a tread pattern, a tread temperature distribution, and a tread wear model, as well as visco-elastic rim and road models. Assisting tools are available for editing the model data file, for parametrization and data fit, for static, steady-state, and modal analysis, for visualization, for linearization, for DOE studies, for model export, and more. Parametrization may be based on laboratory measurements, on tire design data, on similarity considerations, or on combinations of these.

Using numerically robust co-simulation, *FTire* is made available as tire model plug-in for most of the relevant commercial simulation environments, covering MBS, FEA, specialized vehicle dynamics, and system simulation approaches. It is been used for nearly all rubber-tired types of vehicles, including motorcycles, aircrafts, and all-terrain vehicles.

FTire applications comprise primary and secondary ride, handling on flat and uneven road surfaces, tire forces influenced by suspension control systems, NVH, mobility, tire-imperfection-induced suspension and steering vibrations, misuse, and road load prediction for durability.

13.2.2. Structure Model

Like in many other detailed tire models, the kernel of *FTire* consists of two main components. The first one, the *structure* model, describes the tire's structural stiffness, damping, and inertia properties. The second one, the *tread* model, comprises evaluation of height, compliance, and friction coefficient of the road surface, as well as the computation of resulting ground pressure and shear stresses in the contact patch. Basis of the structure model is a set of flexible bodies (called *belt segments*, typically using nearly 50–500 of them), being *FTire*'s image of the tire's belt layer structure. Each belt segment has $4+x$ dynamic degrees of freedom (Figure 13.4):

- longitudinal, lateral, and vertical *displacement* of the center point,
- *rotation* angle about the circumferential axis, and
- flexible *bending* in lateral direction, described by x-independent shape functions.

These segments, their internal degrees of freedom, and the rim (which itself is either assumed to be stiff, elastic, or visco-elastic) are interconnected by several nonlinear, inflation pressure-dependent force elements. These force elements comprise nonlinear translational and rotational stiffnesses, bending stiffnesses along all three axes, respective damping elements (most of them assumed to be

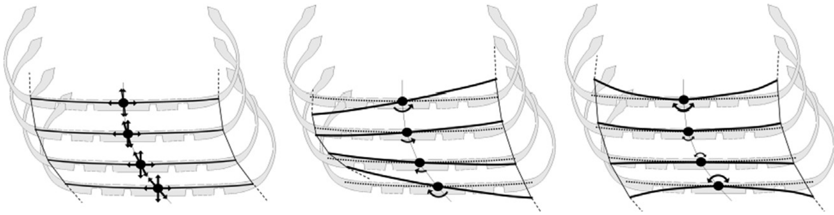

FIGURE 13.4 Belt segments' degrees of freedom: translation, torsion, lateral bending.

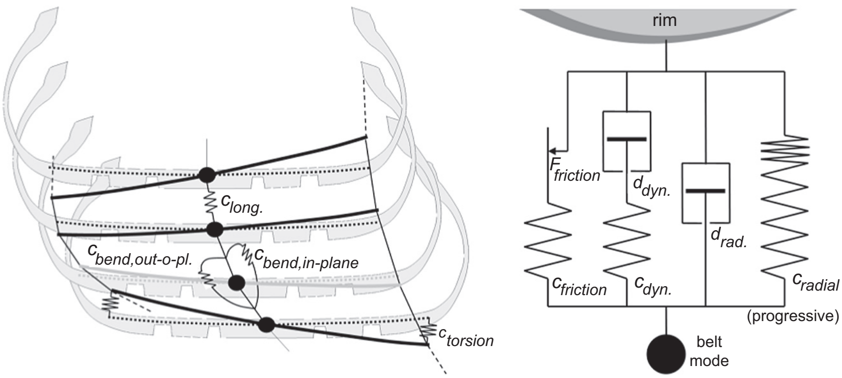

FIGURE 13.5 Some structural force elements.

linearly viscous), as well as certain Maxwell and hysteresis elements (Figure 13.5). In addition, the segments are subject to inflation pressure forces in radial direction, and to forces and moments generated by the tread model.

As an example, the right image of Figure 13.5 shows the combined *radial force element* of one single belt segment. Circumferential and transversal elements are placed analogously. Maxwell elements are used to describe the dynamic tire stiffening at higher rolling speeds, whereas several dry friction elements (only one of them being shown in the image) accurately approximate rubber hysteresis.

All stiffness values depend on inflation pressure. The *cold* inflation pressure is treated as an *operating condition* and might arbitrarily be modified during a running simulation. The *actual* inflation pressure depends on cold inflation pressure and tire temperature, which is the output of the thermal model, if activated.

Several types of optional tire imperfections complete the structure model, comprising static and dynamic imbalance, radial and tangential nonuniformity, ply-steer, conicity, and detailed geometrical run-out.

13.2.3. Tread Model

Between each two adjacent belt segments, several mass-less contact and friction elements (Figure 13.6 *top*) are placed. Their number per segment, typically between 10 and 200, can be chosen by the user, depending on the desired road height resolution. These contact elements constitute the *tread* model.

The contact elements are placed along approximately parallel lines (cf. Figure 13.6 *top*). The actual global positions of the belt points to which the contact elements are attached to are determined by smooth interpolation, using the coordinates of the four nearest-by belt segments.

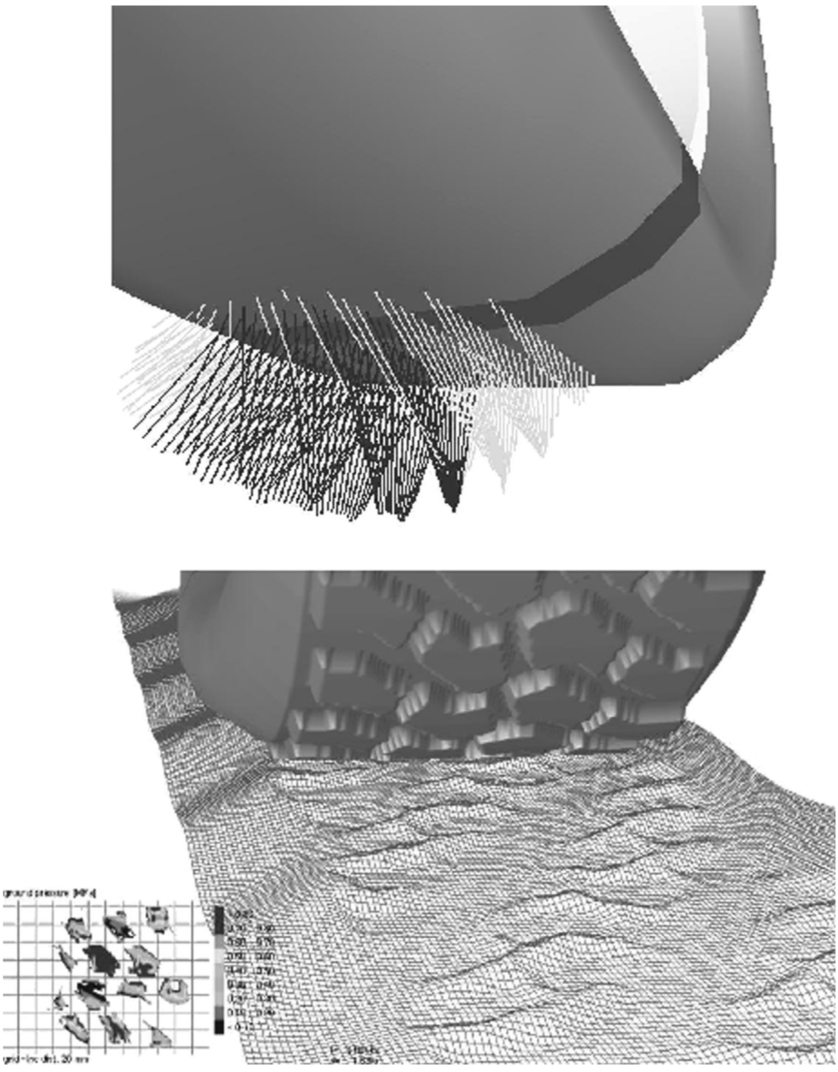

FIGURE 13.6 Tread model: contact forces during parking maneuver (*top*) and combination with visco-elastic road surface (*bottom*).

If the tread pattern is given in terms of a black-and-white or gray-scale bitmap file, the contact elements' lengths (that is, the local tread rubber thickness) is set by *FTire*, according to this pattern. In Figure 13.6 *bottom*, the computed contact pressure of such a model is shown, when rolling over a visco-elastic road surface. Clearly, a larger number of contact elements is required to exactly resolve more detailed patterns, like those of passenger-car tires. *FTire*'s computing time increases less than linearly with the total number of contact elements.

The road tangential plane is computed individually for each contact element, by evaluating the road height in three different locations near the contact element. This is necessary to resolve obstacle sizes far below the contact patch length. Road surface may depend on time, like it does for four-post test-rigs and rotating drums. In that case, both normal and tangential surface velocities are taken into account as well.

Each contact element's normal force is a nonlinear function of radial deflection and deflection velocity, describing tread rubber compression stiffness and damping. The normal force, the tangential sliding velocity, and the local friction coefficient are used to compute the tangential friction forces, and by this the shear stress. The local friction coefficient is a function of position, ground pressure, sliding velocity, and tread temperature.

13.2.4. Model Data and Parametrization

Ease of parametrization had been an important objective during development of *FTire*. A clear distinction is made between data used in the model equations (*pre-processed* data) and data to be supplied by the user (*basic* data). The idea is to define only basic data which can be obtained by standard laboratory measurements in a cheap, repeatable, and reliable way, and which at the same time yield enough information to completely and unambiguously determine all internal pre-processed tire data.

FTire can be parametrized by using a standardized measurement procedure, recently defined by a working group of major German car manufacturers. Given the respective measurement files, the software *FTire/fit* can nearly automatically derive from this an *FTire* data file, together with a respective validation report.

Detailed information on *FTire* and its tools can be found on www.cosin.eu, *FTire*'s homepage. For further reading, we refer to the references: Gipser (2000), (2006), (2007).

13.3. THE *MF-Swift* TIRE MODEL (Igo Besselink)

13.3.1. Introduction

Already after the first publications in 1987 and 1989, the *Magic Formula* has quickly become a very popular tire model to describe the steady-state forces and moment occurring under various slip conditions. Its typical field of application is vehicle-handling studies. With the advent of vehicle control systems such as anti-lock brakes, possibly on rough roads, the need developed for a tire model also capable of describing the transient and dynamic tire behavior accurately. This marked the starting point of the development of the *SWIFT* tire model, the acronym indicating *Short Wavelength Intermediate Frequency Tire model*. The model should be able to handle frequencies up to 60–80 Hz and wavelengths of 0.1–0.2 m. An important feature is that the *Magic Formula* has been maintained, as this has proved to be an accurate and well-established model. Research on the *SWIFT* model was done by three PhD students at the Delft University of Technology under the supervision of Professor Pacejka. Peter Zegelaar focused on the in-plane dynamics and Jan-Pieter Maurice looked at the out-of-plane dynamics, notably in connection with lateral slip variations. Later, Hans Pacejka developed the turn slip and camber aspect (spin) that covers the final input slip component of the dynamic model. After initial work of Zegelaar, Antoine Schmeitz developed the obstacle enveloping model that enables the assessment of the flat so-called effective road plane. Recent developments, like the inclusion of tire inflation pressure in the model, have been developed in cooperation with the Eindhoven University of Technology.

13.3.2. Model Overview

Various aspects of the *SWIFT* model have already been explained in detail in Chapters 9 and 10 of this book; the discussion will be limited to an overview here. For an impression of the model configuration, see Figure 13.7. The four main elements comprising the *SWIFT* tire model are:

- *Magic Formula*: describing the steady-state forces and moments of a tire rolling at various slip conditions. The full set of equations can be found in Section 4.3.2.
- *Contact patch slip model*: the tire forces and moments do not respond instantaneously to variations in slip of the contact patch body; the differential equations describing this behavior have been given in Section 9.3.1.
- *Rigid ring*: at higher frequencies the wheel (rim and tire combination) cannot be considered as a single body anymore. Therefore, the wheel has been split into two rigid bodies, which are interconnected via springs and dampers. The ring is connected with the contact patch through so-called residual springs with dampers (Figure 9.27).
- *Obstacle enveloping model*: to cope with short wavelength road undulations, a method using elliptical cams has been developed (Figure 10.11).

The structure of the tire model and software implementation allows the user to select the level of complexity: for handling studies, it may be sufficient to use only the *Magic Formula*; for the analysis of wheel shimmy on a flat road

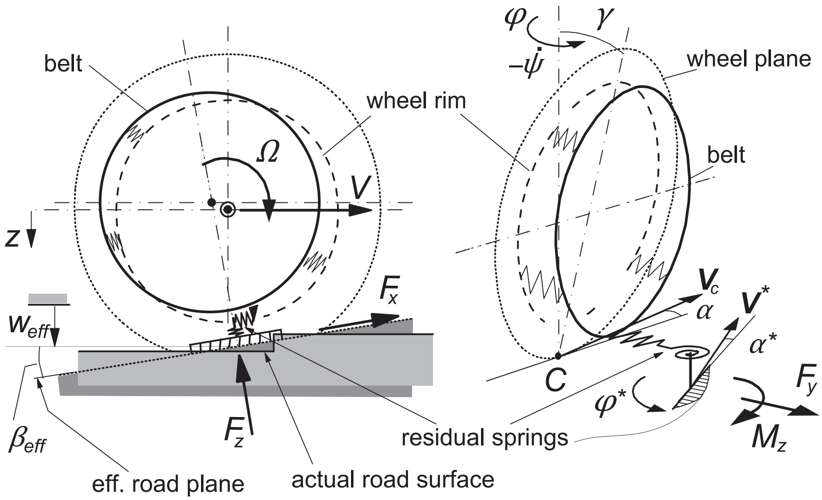

FIGURE 13.7 General configuration of the *SWIFT* model featuring rigid belt ring, residual stiffnesses, contact patch slip model, and obstacle enveloping model that produces the effective road inputs.

surface, contact patch and rigid ring dynamics may be switched on and for calculation of suspension forces on a 3D uneven road surface the enveloping model and all further features are switched on. This is advantageous for calculation time, as an appropriate representation without overhead can be selected for the task at hand.

13.3.3. MF-Tire/MF-Swift

The Dutch organization for applied research TNO also contributed to the development of the tire model and has turned them into commercial software, which is sold under the name "Delft-Tire". The first software product was the *Magic Formula Tire Model* implementation in various multi-body software packages, known as *MF-Tire*. In particular, *MF-Tire* version 5.2 achieved the status of an industry standard for modeling passenger-car tires in the late 1990's. The software program *MF-Tool* is used to process measurements and determine the parameters of the tire model. For some years, various separate tire models were available (e.g., motorcycle tires: *MF-MCTire*, early versions of *SWIFT*), but more recently all functionality has been combined into a single tire model known as *MF-Tire/MF-Swift*. Figure 13.8 gives an impression of the TNO *Delft-Tire* tool chain, which supports all steps from tire measurements, parameter identification to multi-body simulations.

For more detailed information, we suggest to contact TNO. The website address reads: www.delft-tire.com.

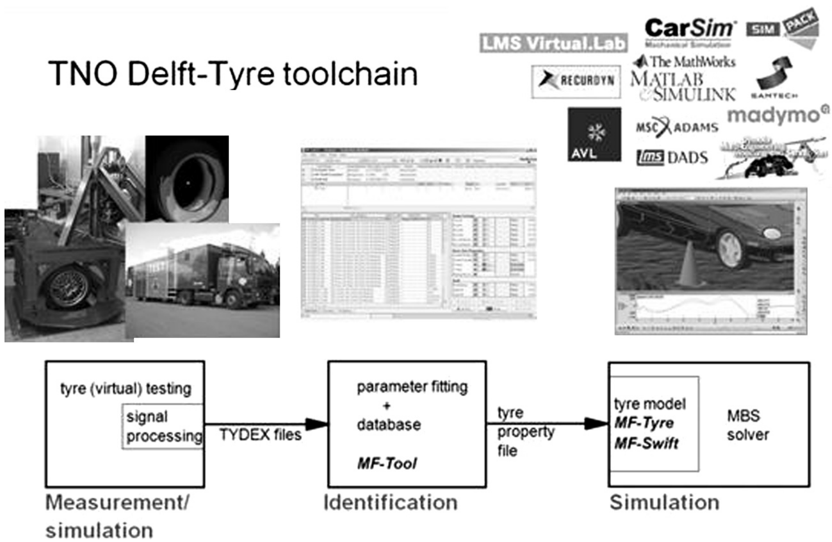

FIGURE 13.8 TNO Delft-Tire tool chain.

13.3.4. Parameter Identification

The parameter identification process should not be underestimated, as it may prove to be difficult to find a parameter set, which matches the various tests best. Typically, numerical optimization techniques are used to obtain the "best" parameters by minimizing the difference between measurements and model output. The empirical *SWIFT* tire model has advantages here, as the model consists of a number of relatively independent elements. In a physical tire model, all characteristics are interlinked: changing e.g., a material stiffness could affect everything from vertical stiffness, to cornering stiffness and relaxation length. This means that all tire tests have to be analyzed, to evaluate the effect of a parameter change. For the *SWIFT* model, the identification process is split up in a number of consecutive, small optimization problems. With *MF-Tool* a *Magic Formula* fit is made within 10 minutes and a full *SWIFT* data set (including *Magic Formula*) can be fitted in less than an hour, which is comparatively fast. The structure of the TNO *MF-Tire/MF-Swift* tire property file is explained in Appendix 3. This appendix also gives an introduction to the tests required and ways to estimate tire model parameters. It is important to note that the tests required for the identification of tire model parameters have been standardized, so the measurement data requirements for *MF-Swift*, *FTire,* and *RMOD-K* are almost the same.

13.3.5. Test and Model Comparison

In Chapters 4, 9, and 10, various graphs have been given, comparing test and tire model results, see e.g., Sections 4.3.6, 9.4.2 and 10.2. These cases concern the reproduction of tire behavior measured on a test bench. Obviously, the tire model combined with an accurate vehicle model should be in agreement with measurements on an instrumented vehicle. A good example is given by Schmeitz, Versteden and Eguchi (2011). This study focuses on the calculation

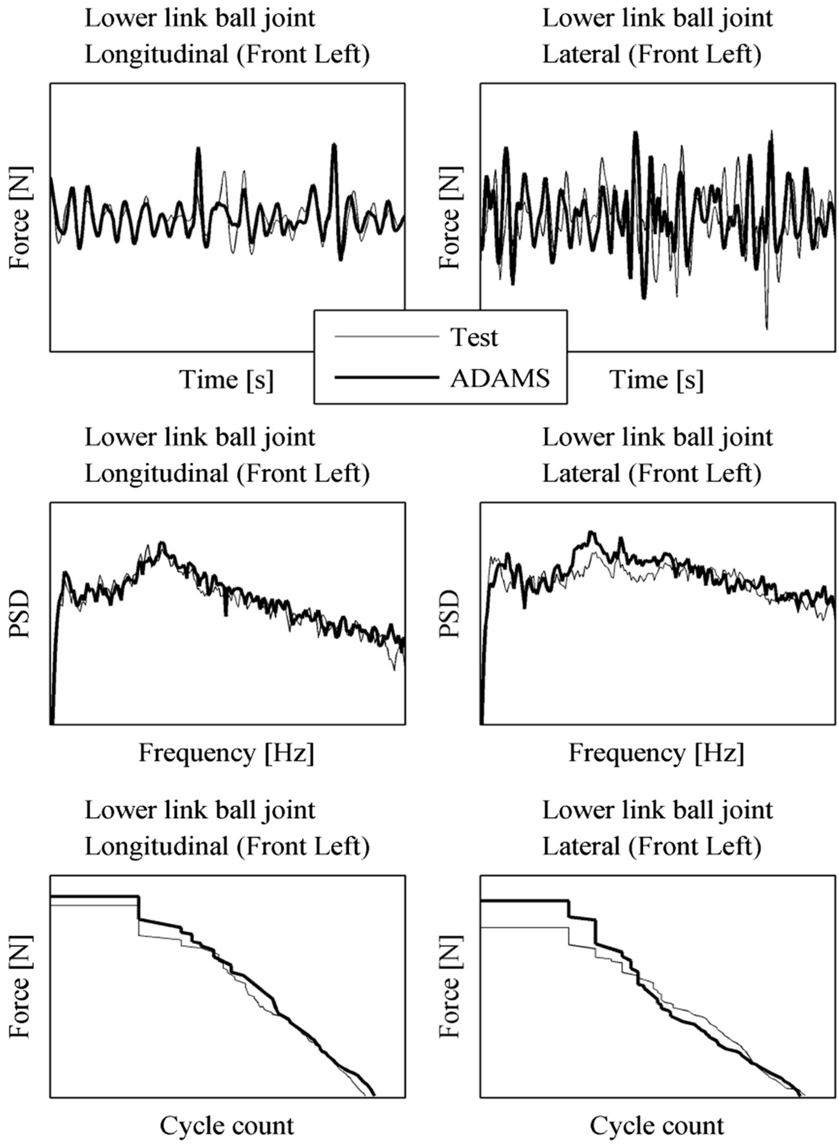

FIGURE 13.9 Measured and simulated lower link ball joint forces in the time domain (detail shown), frequency domain, and cycle count for the base vehicle (*ADAMS*: full vehicle model including *MF-Swift*).

of suspension loads while driving over a digitized 3D road surface. It appears that the calculated forces from the full vehicle simulation model agree quite well with measurements. Also, the effects of changes to tire and suspension parameters are captured fairly accurately. Figure 13.9 gives an impression of the results obtained.