FTire: High-End Tire Model for Vehicle Simulation in SIMPACK

The tire is undoubtedly both the most important and the most complex vehicle suspension component. With this in mind, tire simulation today requires more than the mathematical approximation of a hand full of steady-state, deflection- and slip-based force/moment characteristics on ideally flat or constantly curved surfaces. And it requires more than sensing the road below the tire at a single point, or an ‘equivalent volume’ approach, which condenses the complex geometrical road surface shape into one value. Neglecting this would result in oversimplified tire dynamics and rough road influence. This is what ‘classical’ tire models have done since the earliest vehicle dynamics simulations.

Instead, the increasing complexity of state-of-the-art vehicle models requires a versatile, robust and multi-purpose tire model that can be used not only in ‘classical’ handling application scenarios, but also with highly dynamic road excitations, misuse scenarios, and any component test rig application, simultaneously.

**IDEAS DRIVING FTIRE DEVELOPMENT**

A modern tire simulation model is expected to be a virtual reproduction of the true tire, covering all of its vehicle dynamics-relevant aspects and their respective cross-correlation, and providing reliable insight into the dynamic behavior of the tire. Such an accurate tire model has to take into account many different kinds of external or internal excitations, for example:

- short-waved road irregularities (Fig. 1)
- sharp-edged and/or high obstacles with small extensions like cleats and stones
- location- and time-dependent road friction properties and water film depth
- high-frequency rim oscillations induced by active suspension control systems
- variable inflation pressure
- variable tire and road surface temperature
- actual tire imbalance wear state
- tire imbalance, non-uniformity, run-out and other imperfections
- rim flexibility
- road surface flexibility and/or plasticity

Due to the nonlinear and high-frequency nature of most of the tire dynamics aspects, a physics-based model appears to be the only option. The intrinsic benefit of physics-based models is that there is no need to find and ‘build in’ the tire behavior for every single combination of tire input signals, tire states and operating conditions. Rather, as with the real tire, the behavior is a consequence of fewer but more reliable physical principles.

The art of tire modeling is no longer the Sisyphean task of implementing ever more artificial influencing factors, trying to take into account every new observed phenomenon. Rather, it comes down to deciding which physical effects may be neglected or simplified under certain conditions. The remaining simplified model still observes all related physical principles. To a certain extent, and in clear contrast to pure mathematical approximations, such models are able to extrapolate conditions not completely covered by a respective experiment. For example, consider the real tire’s main structure. This structure is composed of a ‘nearly’ axisymmetric placement of carcass, belt, and bead, arranged in layers and embedded into different types of rubber compound as matrix material. In FTire, SIMPACK’s high-end tire model, this structure is replaced by a closed chain of small nonlinearly flexible bodies. Despite this obvious simplification, the following are automatically observed:

- well-known relationships between different modes and mode-shapes, and their dependency on load and rolling speed

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Fig. 1: Tire structure distortion on Belgian block road
500 to 2500 DOFs, assigned to a ring of belt segments:

- translation along x/y/z
- rotation about longitudinal axis
- bending with 3 to 9 shape functions

Belt segments coupled to each other and to rim by a large set of nonlinear spring/damper elements, reflecting the tire’s structural stiffness properties.

Fig. 2a: Structure model: belt segments

- impulse and energy conservation
- structure distortion under different kinds of static loads
- relationships between local and global stiffness
- symmetry and defined of linearized mass and stiffness matrix, etc.

FTire arranges the physics-based tire description into subsystems, well-defined system boundaries and interface signals which have clear physical meaning. This allows easy activation and deactivation of certain tire model extensions, without replacing the data-file or changing the model interfacing.

To complete this 'model scope on demand' approach, two more aspects have to be mentioned:

- FTire is scalable with respect to timely and spatial resolution of structural discretization and road surface sensing. This is achieved by strictly decoupling physical data and numerical settings. Whatever internal time step, segment number or tread block number is chosen, the prescribed static, modal and steady-state properties used to determine internal physical parameters will be precisely matched by FTire. This is achieved in a fully automated way, during the so-called data pre-processing phase, which is repeated if numerical settings are changed.
- Several of the subsystem models were introduced to extend FTire's scope of application, e.g., road surface description, soft-soil model and rim flexibility model, which may be replaced with user-written versions using standardized C-code interfaces.

By the means listed above, the tire model variant actually used is tailored to the application, saving computing time without the need to maintain different tire models or tire model data files.

The most important development aspect of FTire is the design and implementation of feasible, reliable, and affordable methods to determine the parameters of the physical submodels.

After this, the inherent numerical complexity of some of the models requires the development of optimized ODE and PDE solvers, running in co-simulation with the MBS, FEM, or system dynamics solver. Today, it is expected that tire models run in real-time, for HiL and driving simulator applications. FTire does so, after some internal tuning, but with the original core model.

CORE MECHANICAL MODEL

FTire’s core model is a special, MBS-like arrangement of nonlinear elasticity, dissipative and inertia elements which replace the real tire structure (Fig. 2a/b). Selection of these elements and their parameterization is such that belt distortion under a wide range of relevant external loads on flat or non-flat surface matches that of the real tire in a detailed way. Lower-order eigenfrequencies, mode shapes (including bending modes), and modal damping values are matched sufficiently well at the same time. Stiffness parameters and internal belt normal forces are influenced by actual inflation pressure (Fig. 2c).

The related parameterization takes respective measurements of the global tire stiffness under different conditions, as well as eigenfrequencies and related mode shapes, for use in a parameter identification (PI) pro-

Fig. 2b: Structure model: radial force elements
implemented in internal, switchable subsystems (Fig. 4):

- Extra contact elements for tire misuse simulations, like belt-to-rim contact (bottoming), sidewall-to-curb contact, and rim-to-curb contact
- Several modifications of the core mode parameters, to take into account different types of tire imperfections such as imbalance, non-uniformity, tread gauge variations, conicity, ply-steer and more
- A thermal model, predicting the filling gas temperature as well as the tread surface temperature field. It is driven by heat generated in all dissipative and friction elements of the mechanical core model, as well as by cooling through convection, radiation and a transfer of heat into the environment. In turn, the temperatures influence both inflation pressure (and by this indirectly structural stiffness), and tread friction characteristics
- A tread wear prediction model, driven by local friction power and tread temperature (Fig. 5)
- A flexible and visco-elastic rim model, which can be replaced by a user-provided model
- A soft soil model, based on the Bekker-Wong soil equation [7] which can be replaced by a user-provided terramechanical soil model (Fig. 6)
- A fluid-dynamics-based filling gas vibration model, driven mainly by time- and location-dependent variations of the tire cross section, to predict excitation and influence of ‘cavity modes’

PARAMETERIZATION
In FTire’s parameterization procedure, a clear distinction is made between data used internally in the model equations (‘preprocessed’ data), and data to be supplied by the user (‘basic’ data). Basic data are obtained by standard laboratory measurements, or by equivalent simulations with an FEM model, if available.

SUBSYSTEMS
Next to the core model, FTire optionally provides several extensions, most of which are
These standard measurements are selected to be as inexpensive, repeatable, significant, and as reliable as possible. Observing this, a standardized measurement procedure—which was recently defined by a working group of German car manufacturers—has been recommended. Comprehensive software (FTire/fit, Fig. 7) is available to automate the parameterization and validation process (Fig. 8a/b), based upon these measurements. However, such methods require significant training and expertise in tire dynamics. Certain test laboratories provide ‘turn-key’ FTire data files.

INTERFACING AND NUMERICS

FTire is run in co-simulation, thus completely decoupling the integration of its huge number of internal state variables from SIMPACK’s DAE solver. As with all other supported simulation environments, the interface between SIMPACK and FTire is realized by an easy to apply, but comprehensive application programming interface. This API, called CTI (cosin tire interface), handles:

- exchange of system signals between vehicle and tire model
- loading of tire and road data files
- specification of operating conditions
- requests for extra output
- control of FTire’s animation
- provision of TYDEX/STI output
- provision of key tire data, as required by the calling vehicle model
- selection of user-defined submodels
- specification of FTire’s ‘speed mode’, a collection of settings to influence FTire’s speed of computation (up to real-time

Fig. 5: Tread wear model activated
capability for simultaneous computation of all tires of a vehicle
and much more. The use of these capabilities is under sole control of the calling solver. CTI and FTire are packed into a single

dynamic library (cti.dll in Windows systems and libcti.so in Linux systems), without any extra dependencies.

FTire’s specialized ODE/PDE solver updates tens of thousands of state variables (including 3D displacements, temperature, friction
and wear state of all contact elements) once per internal time step. The duration of this time step can be chosen, but is typically around 0.2 ms.

The integrator deals with potentially extremely large non-linear structure deformations, locally unstable friction characteristics, and high numerical stiffness of the structure’s equations of motion.

The integrator takes full advantage of FTire’s numerical properties, like the nearly axisymmetric tire structure and clear discrimination between stiff and non-stiff system components. It guarantees certain static and modal properties of the discretized model, independent of actual numerical settings like internal step-size and mesh resolution. Although using a constant internal step-size is preferable, CTI and FTire can be connected to any step-size- and order-controlling external solver. However, FTire’s performance is best if the solver step size does not change too often.

CONCLUSION

Nearly 15 years of intense development, preceded by 15 years of experience in tire modeling, have made FTire the most comprehensive and frequently used physical tire model today. Providing the complete tool chain to create, analyze, and process data for both tire and road surface properties, it is available

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Fig. 7: Sequential parameter identification, using direct data, static properties, steady-state measurements, and dynamic cleat tests for in-plane and out-of-plane excitation

Fig. 6: FTire on soft soil model: pressure distribution and road surface deformation
in all important vehicle simulation environments. FTire is used by several dozen OEMs, tire manufacturers, tier-1-suppliers, and research institutes world-wide and can be applied to almost all types of ground vehicle and aircraft tires. It has become the first choice for ride comfort, handling, durability, and mobility applications.

REFERENCES

[1] FTire documentation and more material: www.cosin.eu

Fig. 8a: Cleat test validation, v = 5 km/h (blue = measurement, red = FTire)

Fig. 8b: Cleat test validation, v = 40 km/h (blue = measurement, red = FTire)