CDTire:
State-of-the-art Tire Models for Full Vehicle Simulation

2012 Americas HyperWorks Technology Conference
Dr. Manfred Bäcker, Axel Gallrein
Fraunhofer Society

- Fraunhofer Society 2010
  - Non-profit
  - 60 institutes
  - 18,000 employees
  - 1.65 bill. Euro

- Fraunhofer ITWM
  - 220 employees
  - 18 mill. Euro
  - Transport, fluid and material simulation
  - Dynamics and durability
  - Image processing
  - Optimization
  - Finance
  - High performance computing
Agenda

- Overview
  - CDTire Model Family
  - Parameterization
  - How CDTire works with MotionSolve

- Introducing new models
  - CDTire 30/HPS
  - CDTire 50

- On-going developments
  - CDTire NVH
  - Tire / soil interaction
Tire Simulation in Vehicle Development

**Driver model**
- Open loop
- Closed loop
- Optimal control

**Vehicle model**
- MBD model
- FEA model
- Subsystems

**Tire model**
- MBD model
- FEA model
- Linearization

**Road model**
- Rigid surface
- Soil
- Multi pass
MBD Tire Models - - - - vs. - - - Application Fields

Typical computational effort

- Empirical
- Frequency-based
- Rigid ring
  - Emperical contact
- Flexible belt
  - Brush-type contact
- FEA

Typical number of simulations

- Handling
- NVH
- Active safety
- Ride/Comfort
- Durability
- Crash

© Fraunhofer ITWM
MBD Tire Model Family CDTire

Typical number of simulations

Typical computational effort

- Empirical
- Frequency-based
- Rigid ring
  Emperical contact
- Flexible belt
  Brush-type contact
- FEA
- CDTire 20
- CDTire 30
- CDTire 40
- CDTire MC
- TireTool

DOFs

- $10^0$
- $10^1$
- $10^2$
- $10^3$
- $10^4$
- $10^5$

REPs

- $10^0$
- $10^1$
- $10^2$
- $10^3$

- Handling
- NVH
- Active safety
- Ride/Comfort
- Durability
- Crash

DOFs

- $10^0$
- $10^1$
- $10^2$
- $10^3$
- $10^4$
- $10^5$

REPs

- $10^0$
- $10^1$
- $10^2$
- $10^3$
MBD Tire Model Family CDTire

- **Model 20**
  - Rigid ring
  - Physical tangential contact formulation

- **Model 30**
  - Flexible ring
  - Brush type contact

- **Model 40**
  - Flexible Belt
  - Independent sidewalls

- **Model MC**
  - Large belt curvature
  - Large inclination angles

- **Adaptive models (automatic switching)**
  - Model 2030
  - Model 2040
CDTire 20

- Model details
  - Rigid ring
  - Physical tangential contact formulation

- Road surfaces
  - Arbitrary 3D
  - Long wavelength

- Typical applications
  - Handling (Durability)
  - Active safety

- Real-time factor
  - 3 - 6
CDTire 20: Application Scenario Handling

Validation Results: Cornering Event
(CPG090 Figure 8 GVW 35PSI Nominal Shock)

Publication
CDTire 30

- Model details
  - Flexible ring
  - Brush type contact formulation
  - Accumulated sidewall

- Road surfaces
  - Trackwise 2D
  - Arbitrary wavelength

- Typical applications
  - Ride & Comfort
  - Durability

- Real-time factor
  - 10 - 30
CDTire 30: Application Scenario Durability

- Publication
CDTire 40

- Model details
  - 3D structure
  - Brush type contact formulation
  - Independent sidewalls

- Road surfaces
  - Arbitrary 3D

- Typical applications
  - Ride & Comfort
  - Durability

- Real-time factor
  - 40 - 100
CDTire 40: Application Scenario Special Events

Publication

CDTirePI: Parameterization via Measurements

- **Measurements**
  - Geometry (cross section, footprint)
  - Modal analysis
  - Static (stiffness’s, on cleat)
  - Steady-state (long. + lateral slip)
  - Transient (90°+45° cleat runs)

- **Optimization schemes**
  - Local
  - Fuzzy (expert knowledge build into rule sets)
TireTool: Parameterization via FEA tire model
TireTool: Parameterization via FEA tire model

Cross section
- Cross section scan
- Contour measurement

2D model
- CT-Scan cords
- Tire weight
- Shore A

3D model
- Modes and frequencies
- Static stiffness's

Virtual measurements
- Cleat runs
- Ground-out
- ...

Fine tune
TireTool: Parameterization via FEA tire model

- Measurements
  - Geometry (cross section, footprint)
  - Modal analysis
  - Static (vertical stiffness)
  - Material
  - CT

- Output is Abaqus model
Tire-Tool: Parameterization via FEA tire model

90° cleat run 40x40mm, 11 km/h, CDT40 validation

- Longitudinal Force
  - Measurement
  - Simulation

- Vertical Force
  - Measurement
  - Simulation

- LDE test rig @ Fraunhofer
  - Kistler P530 hub
  - Max. 12 km/h
  - Max. Fz 30 kN
  - Up to rim contact
Tire-Tool: Parameterization via FEA tire model

90° cleat run 40x40mm, 11 km/h (FEA validation), 30 and 40 km/h (prediction)
TireTool: Parameterization via FEA tire model

- 3D continuum
- 2D shell

Reduction of degrees-of-freedom (dofs)
- Proper orthogonal decomposition (POD)
- BMBF joint project „Multi-disciplinary Simulation and Non-linear Model Reduction (SNiMoRed)"

Reissner-Mindlin hypothesis
How CDTire works with MotionSolve

- Cooperation Altair / Fraunhofer
  - Altair is exclusive reseller for CDTire4MotionSolve
  - Distributed with HyperWorks 11.0
  - Integrated visual support in development
- Tire models
  - 20 / 30 / 40 / 2030 / 2040
- Road models
  - RSM1000 (parametric obstacles)
  - RSM1002 (drum model)
  - RSM2000 (large digital data)
  - RSM3000 (OpenCRG)
  - RSM1100 (User API)
- Full .adm compatibility
- Full CDTire.ini support (parallelization)
Introducing new models

- Model 20
  - Rigid ring
  - Physical tangential contact formulation
- Model 30
  - Flexible ring
  - Brush type contact
- Model 40
  - Flexible Belt
  - Independent sidewalls
- Model MC
  - Large belt curvature
  - Large inclination angles

New developments

- Model 30/HPS
  - C/C++ High Performance Solver
  - Real-time capable
- Model 50
  - Materialized sidewalls
  - Geometrical non-linear elastic shell discretization
- Model NVH
  - Flexible rim
  - Cavity mode
Introducing new models

Application scenarios
- Model 30/HPS
  - MIL / SIL / HIL cascade
  - Vehicle performance optimization
- Model 50
  - Large deformation, ground-out
  - Handling on rough road
- Model NVH
  - Up to 300 Hz

New developments
- Model 30/HPS
  - C/C++ High Performance Solver
  - Real-time capable
- Model 50
  - Materialized sidewalls
  - Geometrical non-linear elastic shell discretization
- Model NVH
  - Flexible rim
  - Cavity mode
CDTire 30/HPS

- Master integrator (typically larger time steps)
  - Iteration scheme
  - Step size control
- Slave integrator (typically smaller time steps)
  - Iteration schemes (HPS: PECE, Newmark)
  - Master step size control
- Tunable controls:
  - Master iteration
  - Slave iteration
  - Slave step size

- Secured time step
- MBS-solver
- Estimated rim states at $t+Dt$
- Tire model solver
- Tire forces at $t+Dt$

$dt =$ minor step of tire model integrator

$Dt =$ MBS step size

$Dt =$ new time step to be calculated by MBS-solver

$Dt =$ tire states from $t$ to $t+Dt$ using much smaller minor steps $dt$
CDTire 30/HPS

- Scenario: 4 cleats (20x20mm), 40 km/h, 3 sec
- C/C++ High Performance Solver
  - Efficient memory storage and access
  - Efficient implicit Newmark with special projector in Newton-Iteration
  - Choice of deterministic integrator settings (fixed step, fixed iterations)
  - Parallelizable incl. road surface models (OpenCrg, RSM2000, RSM1000)

CDT30 (explicit integrator)
Real time factor = 1.8

CDT30/HPS (explicit integrator)
Real time factor = 1.1

CDT30/HPS (implicit integrator, var. step)
Real time factor = 0.6

CDT30/HPS (implicit integrator, determ.)
Real time factor = 0.8
CDTire 30/HPS: Application Scenario Test Rig

- Scenario MIL / SIL / HIL: Implementation used as component on real test rigs
- Road profile and driving rule can be used as excitation of the test rig
- No test track measurement needed (usually used as target for iteration process)
CDTire 30/HPS: Application Scenario Drive Simul.

- Scenario MIL / SIL / HIL: Component in Drive Simulator
- VAR-Simulator (Versatile Augmented Reality)
CDTire 50

- Functional element modeling
- Element stacking in pre-processing
- FD shell discretization

```
<table>
<thead>
<tr>
<th>Element</th>
<th>Contact FrC Elmt</th>
<th>Steel Cord FrC Elmt</th>
<th>Lateral FrC Elmt</th>
<th>Circumferential FrC Elmt</th>
<th>Shear FrC Elmt</th>
<th>Bending FrC Elmt</th>
<th>Inflation Press FrC Elmt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tread layer</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Steel Cord Layer #1</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Steel Cord Layer #2</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Carcass Layer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rubber Layer</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Inflation Pressure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

Belt cells only

Belt and sidewall cells

© Fraunhofer ITWM
CDTire 50

- Scenario: 18 cleats (10x10,…,20x20mm), 40 km/h, 10 sec
- C/C++ High Performance Solver
  - Efficient memory storage and access
  - Efficient implicit Newmark with special projector in Newton-Iteration
  - Choice of deterministic integrator settings (fixed step, fixed iterations)
  - Parallelizable incl. road surface models (OpenCrg, RSM2000, RSM1000)

CDT50 (explicit integrator)
50 cross sections
12 segments
Real time factor = 49
CDTire NVH

- Method NVH – FEA tire
  - Steady state transport analysis (relative kinematic ALE description)
  - Rim and road (footprint) excitation
  - Condensation of road excitation: Track-wise time delay as phase shift

- Internal Fraunhofer research project (MEF)
  - Cavity possible
  - Flexible rim possible
CDTire NVH

- Linearization around Stationary rolling state
- Transient Equations of motion
- Add Gyroscopic forces
- Linear State space equation
- Laplace Transform
- Condensation of Road excitation

- Internal Fraunhofer research project (MEF)
  - Solver independence
  - Linearization and
  - Transient
CDTire NVH

- Switch to „eulerian“ description by adding gyroscopic forces
- Leads to frequency split for rotating tires
- Example is free hanging tire, but rotating
CDTire NVH

- Simulated experimental modal analysis
- Spacial acceleration measurement
- Free rim, constant rot. velocity $w = 85 \text{ rad/s}$
Tire / Soil interaction

- No deformation
  - Rigid surface

- Local deformation, decoupled
  - Terrain response

- Local deformation, coupled
  - Bulldozing effect

- Terrain compaction
  - Multipass

- Tangential mass transport
  - Slip sinkage

- Diskrete Element Method
  - DEM
Tire / Soil interaction

- Simple pressure-sinkage relations
  - Bekker: \( p(z) = (k_c/b + k_\Phi) \cdot z^n \)
  - Reece: \( p(z) = (c \cdot \kappa_c + \gamma_s \cdot b \cdot \kappa_\Phi) \cdot (z/b)^n \)
    
    \( (k_c, k_\Phi, \kappa_c, \kappa_\Phi, n): \) pressure-sinkage parameters,
    \( \gamma_s: \) weight density, \( c: \) cohesion of terrain

- Instantaneous soil deformation
- No sinkage “propagation”
- Localized parameter, i.e. \( k = k(x,y), \ n = n(x,y) \)
- Tangential frictional contact
- Implementation in C/C++
- Python interface for rapid evaluation of alternative sinkage models
Spreading the Application Range

Typical number of simulations

<table>
<thead>
<tr>
<th>DOFs</th>
<th>REPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^0$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>$10^1$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>$10^2$</td>
<td>$10^1$</td>
</tr>
<tr>
<td>$10^3$</td>
<td>$10^0$</td>
</tr>
<tr>
<td>$10^4$</td>
<td></td>
</tr>
<tr>
<td>$10^5$</td>
<td></td>
</tr>
</tbody>
</table>

Typical computational effort

- Empirical
- Frequency-based
- Rigid ring
- Empirical contact
- Flexible belt
- Brush-type contact
- FEA

CDTire NVH

CDTire 20

CDTire 30

CDTire 40

CDTire MC

CDTire HPS

CDTire 50

TireTool

Handling

NVH

Active safety

Ride/Comfort

Durability

Crash

TireTool

© Fraunhofer ITWM
CDTire: State-of-the-art Tire Models for Full Vehicle Simulation

2012 Americas HyperWorks Technology Conference
Dr. Manfred Bäcker, Axel Gallrein
manfred.baecker@itwm.fraunhofer.de
axel.gallrein@itwm.fraunhofer.de

Thank you for your attention!