EUROPEAN MECHANICS SOCIETY

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Analysis of Stresses in Vehicle Driveline Systems using a Flexible Multibody Approach

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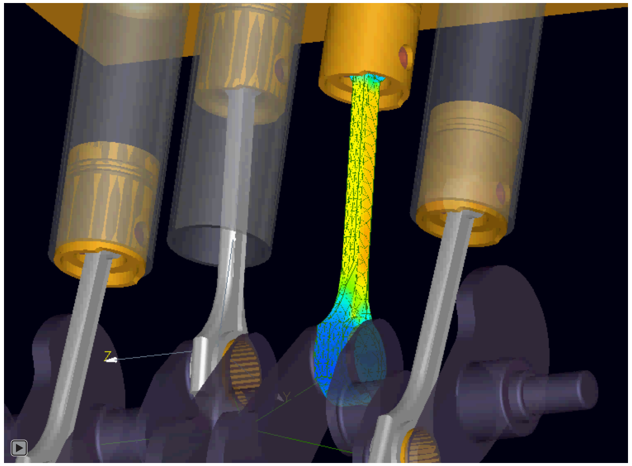
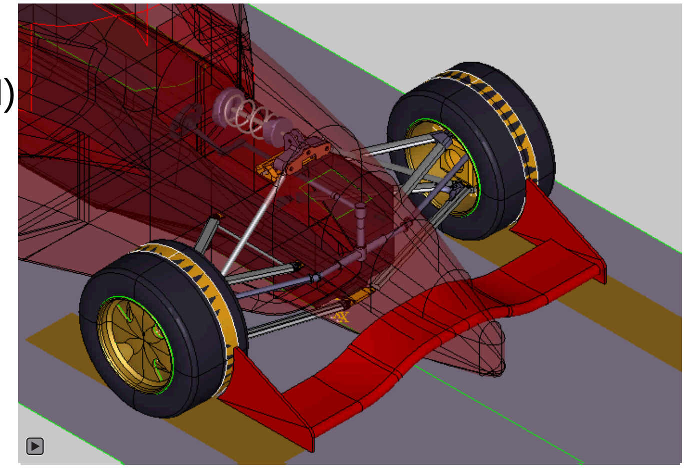
LTAS

Driveline modeling



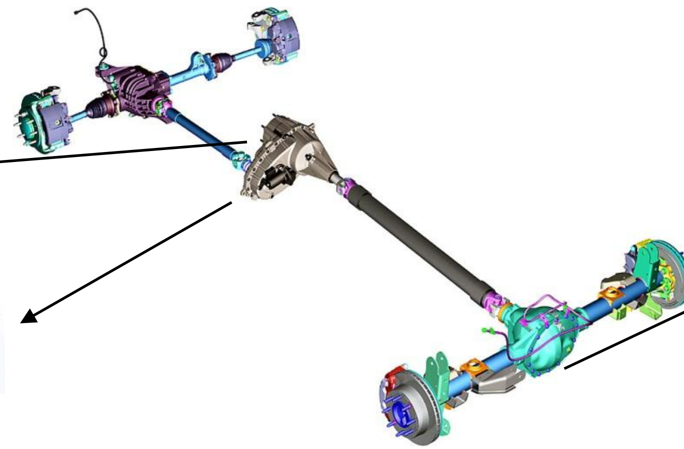
(Courtesy: LMS- SAMTECH)



Motor

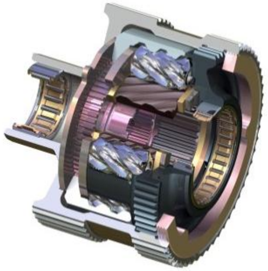
Vehicle dynamics

Transmission line



Gear box

Clutch



Differential

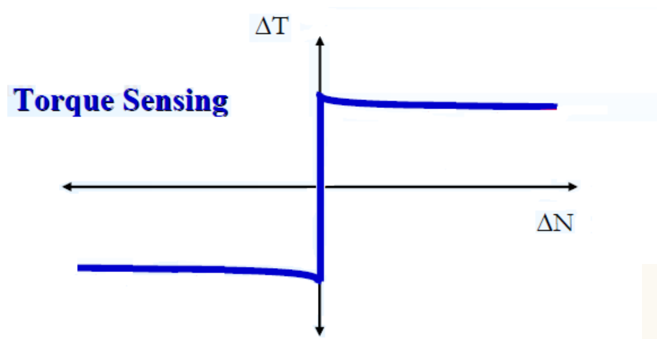
- Complex phenomena involved: backlash, stick-slip, contact, discontinuities, hysteresis, non linearities ➔ Numerical problems

Outline

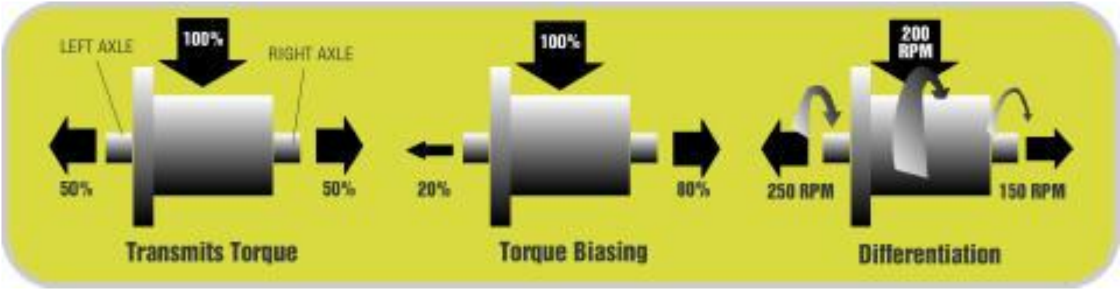
- Description of the application: TORSEN differentials
- Gear pair model
- Contact element + lubricating squeeze film formulations
- Model description & numerical results
- Differential included in a full vehicle model
- Conclusion

TORSEN differential

- Limited slip differential
  - Allow a variable torque distribution between the output shafts ➔ avoid spinning when ground adherence is not sufficient on one driving wheel
- Torque transfer before differentiation (torque sensing)
- Full mechanical system

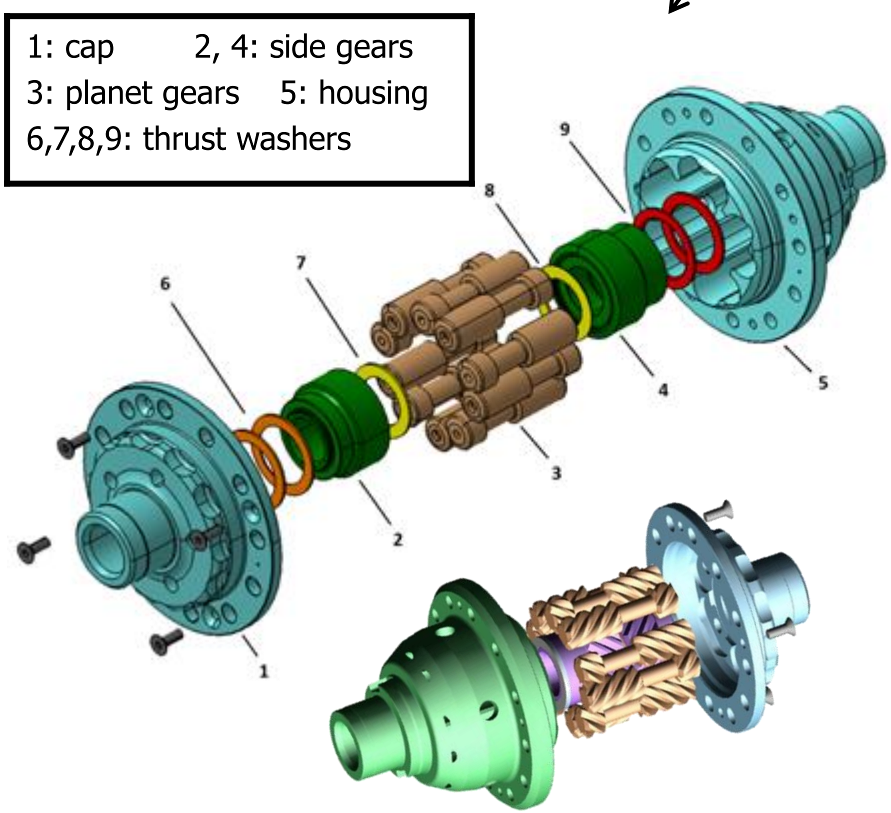


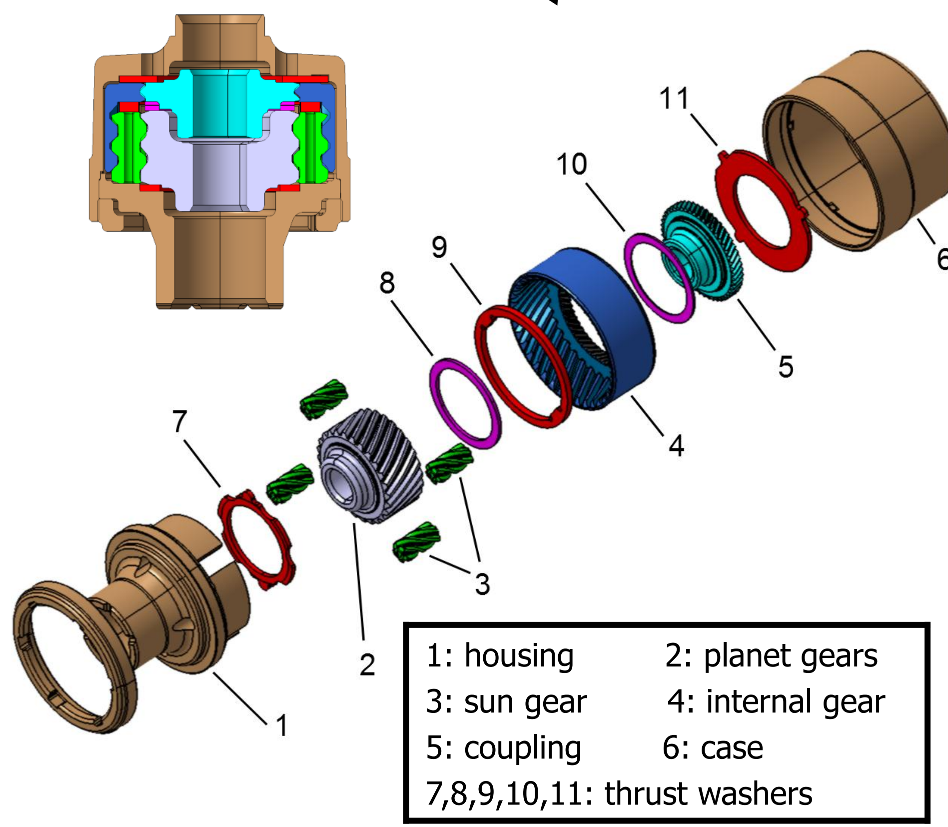
JTEKT



Type B & C TORSEN differentials

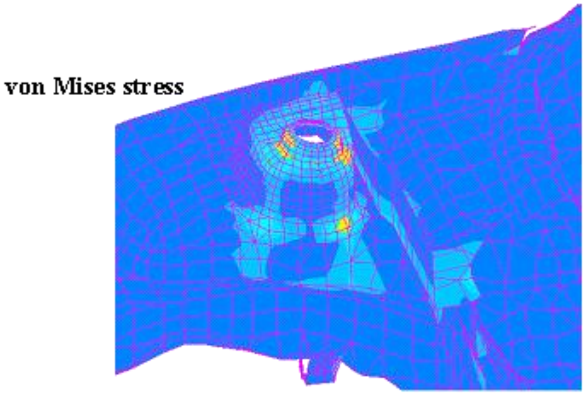
- Housing, helical gear pairs and thrust washers
- Locking due to relative friction gears ↔ washers & gears ↔ housing
- 4 working modes
- Front/rear differential (<u>type B</u>) & central differential (<u>type C</u>)



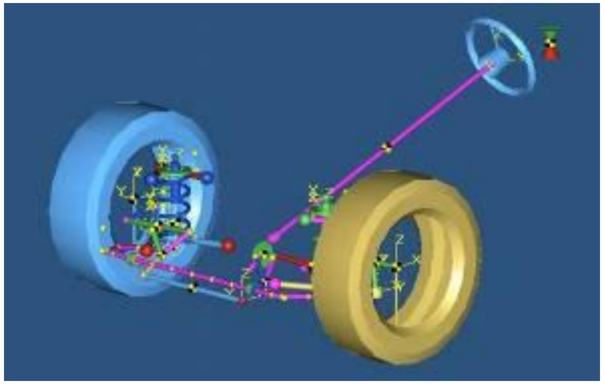


Evolution of vitual prototyping

- Finite Element: structural analysis of components



- Multibody system: mechanism of rigid bodies



- Flexible Multibody systems:
  System approach (MBS)
  & structural dynamics (FEM)

FE coordinates

- Many interactions between transmission components are due to flexibility

  ➔ nonlinear finite element method based on the absolute nodal coordinates

- Software: Samcef Field/MECANO
- Rigid ***and*** flexible bodies
- Parametrization of rotations with the cartesian rotation vector + updated Lagrangian approach

- Equations of motion

Penalty factor

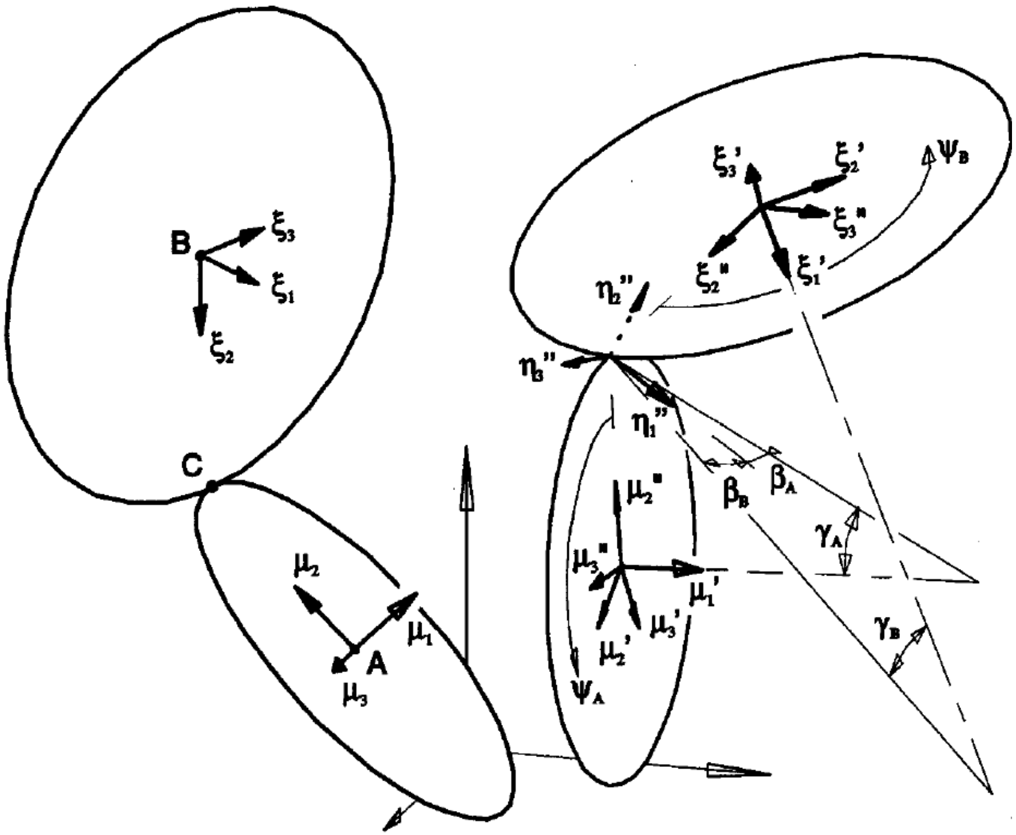
Scaling factor

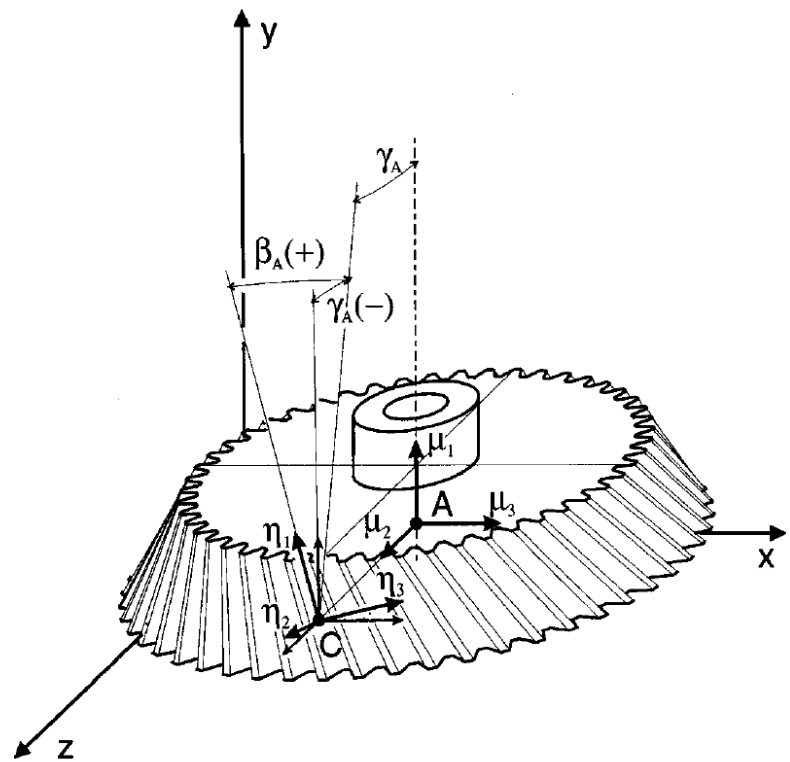
$$
\begin{aligned}
M(q)\ddot{q} + g^{gyr}(q,\dot{q}) + g^{int}(q) + \Phi_q^T(p\Phi + k\lambda) &= g^{ext}(t) \\
k\,\Phi(q,\dot{q},t) &= 0
\end{aligned}
$$

Constraints: joints, rigidity

Gear pair element

- Flexible joint between two physical nodes: one at the center of each wheel (rigid body).
- Any kind of gear pairs : spur gear, bevel gear, helical gear, worm gears…

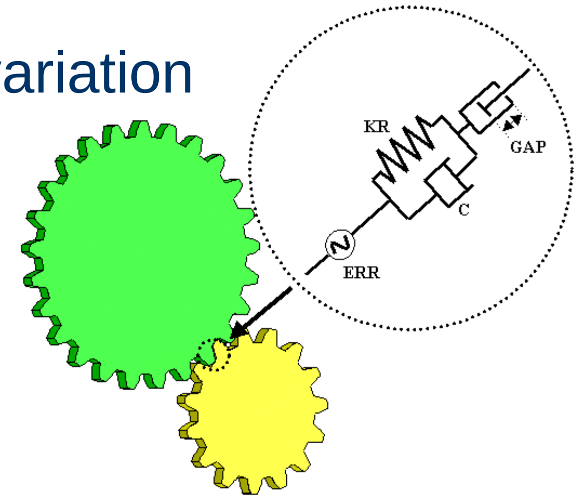




(A. Cardona, 1995)

Gear pair element

- Flexibility : spring (KR) and damper (C)
- Time fluctuation of mesh stiffness due to variation of number of teeth in contact (ISO 6336)
- Backlash (GAP)
- Load transmission error (ERR)
- Misalignment



- 15 variables

$$q = \{x_A^T \;\; \Theta_A^T \;\; x_B^T \;\; \Theta_B^T \;\; \psi_A \;\; \psi_B \;\; u_m\}$$

Deformation of the gear mesh in the hoop direction

12 dof

3 redundant coordinates

3 constraints

$$\mathcal{F} = k\lambda_1 \longleftarrow \phi_1 = (-\psi_A \, z_A + \psi_B \, z_B)\frac{m_n \;\; \cos\alpha_n}{2} + u_m \;\; \cos\alpha_n = 0$$

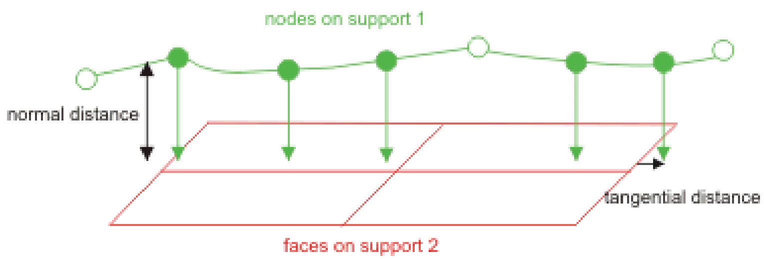
$$\phi_2 = (x_C^A - x_C^B).\eta_3^{\prime\prime A} = 0$$

$$\phi_3 = \eta_2^{\prime\prime A}.\eta_3^{\prime\prime B} = 0$$

Normal contact force

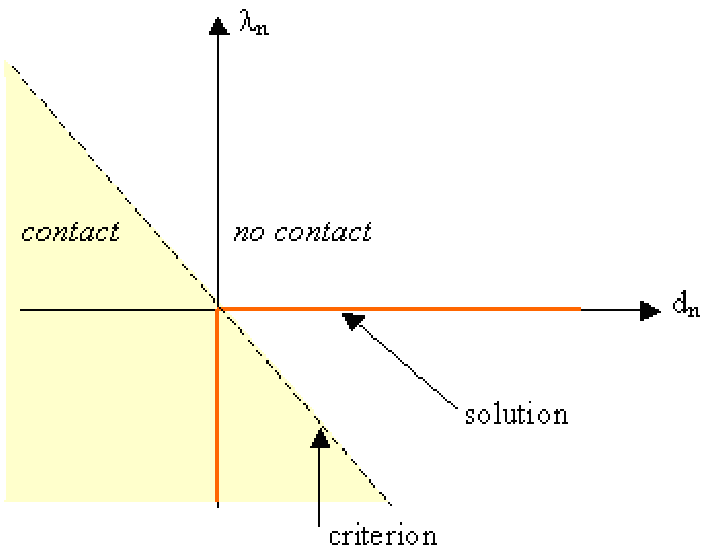
Contact condition

- Augmented lagrangian method
- Flexible/rigid or flexible/flexible contact
- 2 steps : - projection of slave nodes on master surface(s)



$$
\begin{aligned}
\delta d_n &= \underline{n}^T \; B \; \delta \underline{q} \\
\delta \Delta u_1 &= \underline{t}_1^T \; B \; \delta \underline{q} \\
\delta \Delta u_2 &= \underline{t}_2^T \; B \; \delta \underline{q}
\end{aligned}
$$

- definition of the contact condition



<u>Contact criteria</u>

$$
\begin{aligned}
\sigma_n &= k\lambda_n + p d_n \\
\sigma_{t_1} &= k\lambda_1 + p\Delta u_1 \\
\sigma_{t_2} &= k\lambda_2 + p\Delta u_2
\end{aligned}
$$

(k = scaling factor , p=regularisation parameter)

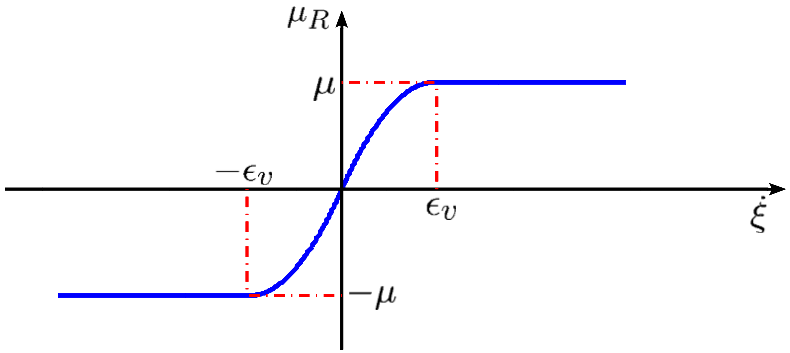
Contact condition

- Friction

$$F_{fr} = \mu_R \; |F_{norm}|$$

Regularization to avoid discontinuities

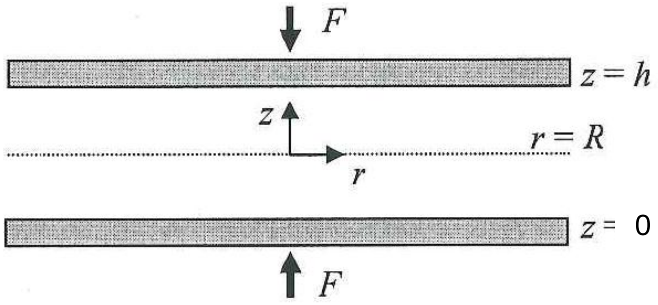
$$\mu_R(\dot{\xi}) = \begin{cases} \mu(2 - \frac{|\dot{\xi}|}{\epsilon_v})\frac{\dot{\xi}}{\epsilon_v} & |\dot{\xi}| < \epsilon_v \\ \mu\frac{\dot{\xi}}{|\dot{\xi}|} & |\dot{\xi}| \geq \epsilon_v \end{cases}$$



- Contact formulation not adapted in case of high relative axial velocity at contact establishment ➔ impacts problems
  - ➢Solutions:
    - ✓Penalty method to allow a small penetration between the two contacting bodies and relax slightly the discontinuity
    - ✓Squeeze film modelling of the lubricating oil

Squeeze film modelling

- <u>Assumptions</u>:
  - 2 plates (2h<<R)
  - Newtonian fluid
  - Isothermic fluid in steady state
  - No sliding on walls
  - Axisymmetric (cylindrical coordinates)



- Continuity equation $$\frac{1}{r}\frac{\partial}{\partial r}(r\ v_r) + \frac{\partial v_z}{\partial z} = 0$$

- Momentum equation (radial component): inertia terms, elongation gradient and $\frac{v_r}{r^2}$ neglected)

$$\frac{\partial p}{\partial r} = \mu \frac{\partial^2 v_r}{\partial z^2}$$

Squeeze film modelling

- Boundary and initial conditions

$$v_r = 0,\ z = 0, h \qquad \frac{\partial v_r}{\partial z} = 0,\ z = 0$$

$$p = p_{atm},\ r = R \qquad h = h_0,\ t = 0$$

- Momentum equation ➔ velocity profile

$$\frac{\partial p}{\partial r} = \mu \frac{\partial^2 v_r}{\partial z^2} \xrightarrow{\int\int \mathrm{d}z^2} v_r = -\frac{1}{2\mu}\frac{\partial p}{\partial r}\left[h\ z - z^2\right]$$

- Continuity equation ➔ pressure profile

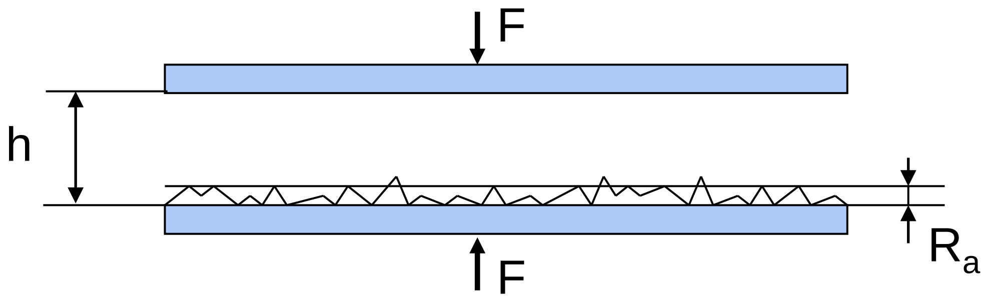
$$\frac{1}{r}\frac{\partial}{\partial r}(r\ v_r) + \frac{\partial v_z}{\partial z} = 0 \xrightarrow{\int\int \mathrm{d}r\mathrm{d}z} \frac{\partial p}{\partial r} = 6\mu \frac{\dot{h}}{h^3}\ r$$

- Force applied on plates

$$F(h, \dot{h}) = -\frac{3\pi\mu R^4 \dot{h}}{2h^3}$$

Squeeze film modelling

- Thrust washers of TORSEN differentials are rough
  ➔ contact between the two metallic bodies when $h < R_a$

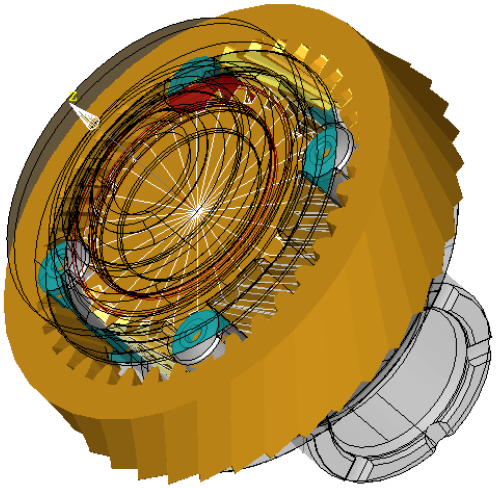


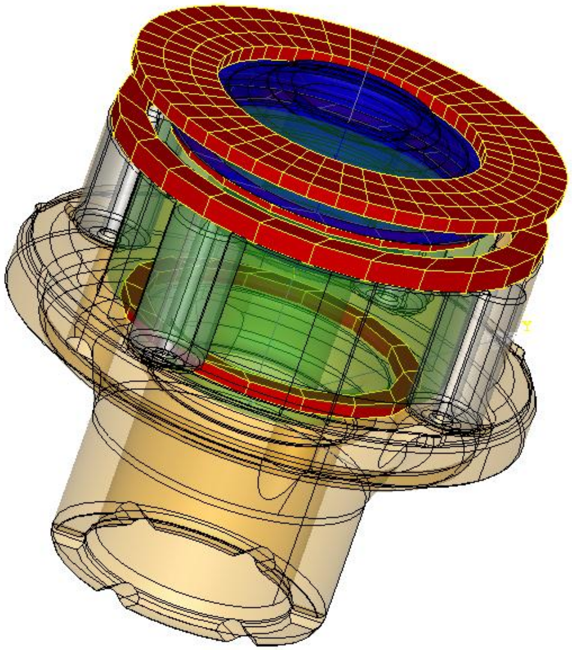
$$F(h,\dot{h}) = \begin{cases} \dfrac{3\pi\mu R^4 \dot{h}}{2h^3} & if \quad h > R_a \\ \dfrac{3\pi\mu R^4 \dot{h}}{2h^3} + F_{contact(metal-metal)} & if \quad h < R_a \end{cases}$$

- *Remark*: avoid the bad numerical conditioning of the squeeze film model when $h, \dot{h} \cong 0$

Model description

- <u>Assumptions</u>: - joints between Planet gears and housing modeled as cylindrical joints
  - contact SG/washer 3 and CPL/washer 4 neglected
- 18 bodies:
  - *9 rigid: gear wheels, housing*
  - *9 flexible: thrust washers, case, driveshafts*
- ≈ 43000 generalized coordinates
- Constraints :
  - 8 gear pair elements
  - 5 contact relations
  - 4 hinges
  - 1 screw joint

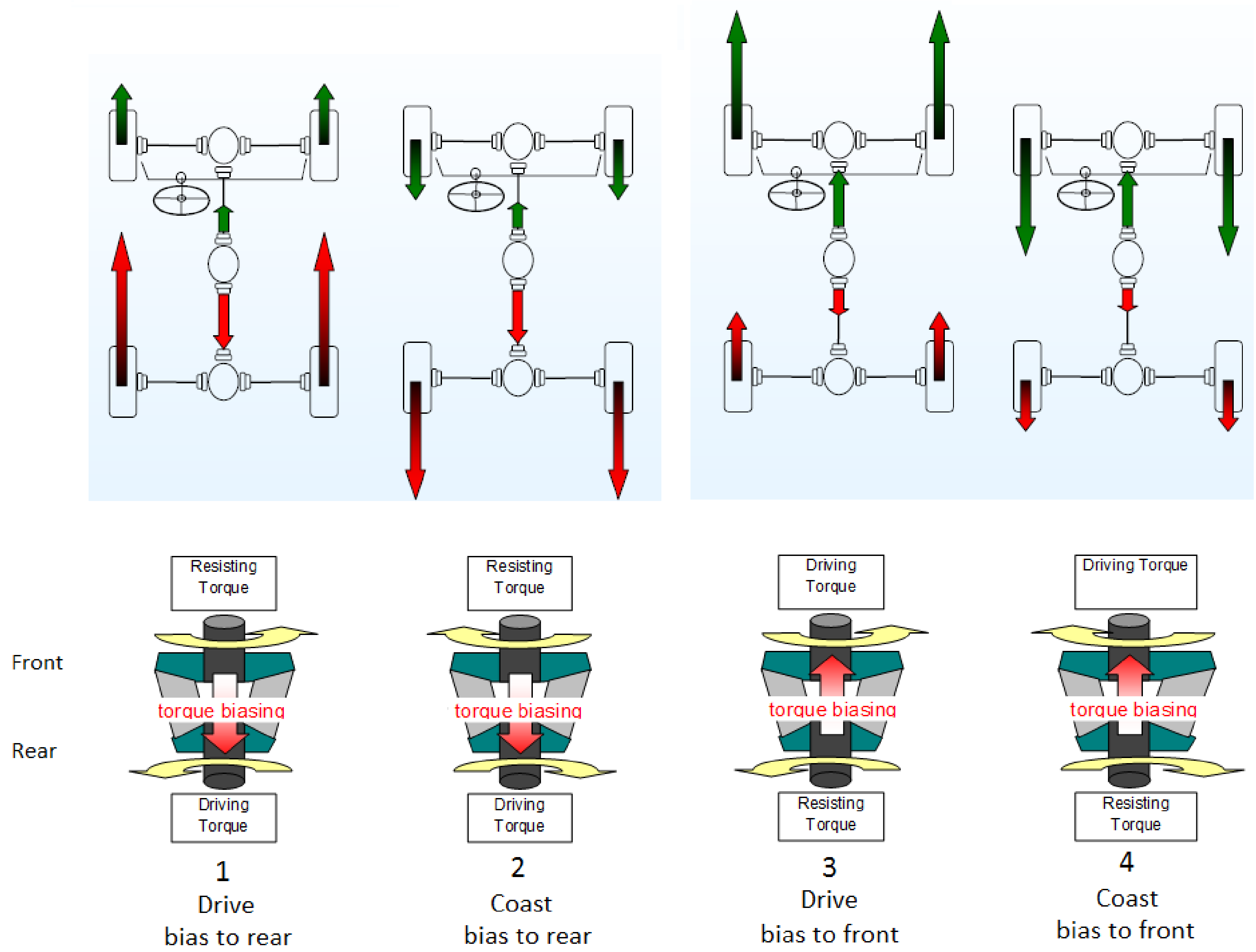




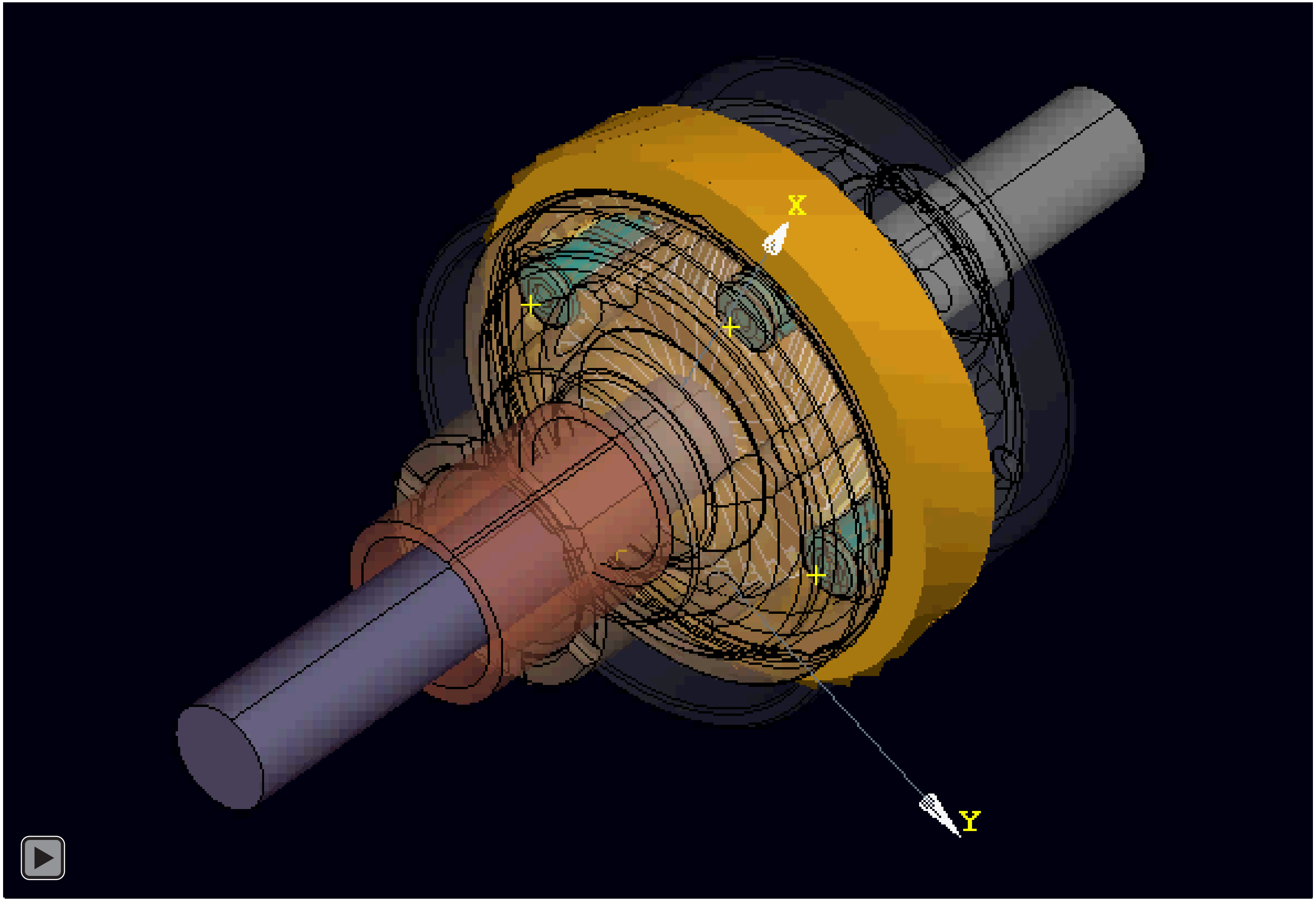
TDR computation for the 4 locking modes

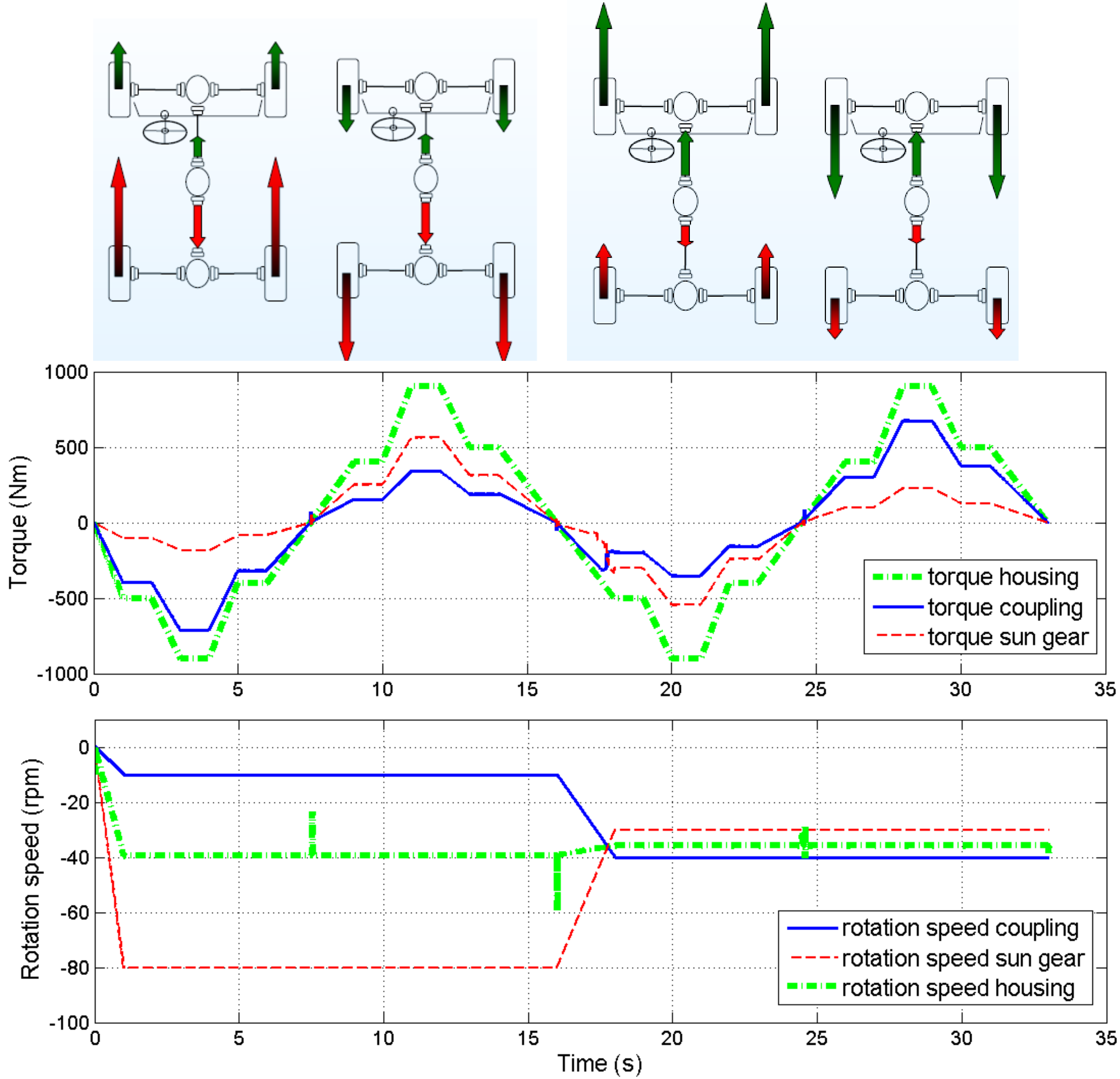
- TDR : Torque Distribution Ratio

$$TDR = \frac{T_1}{T_2}$$



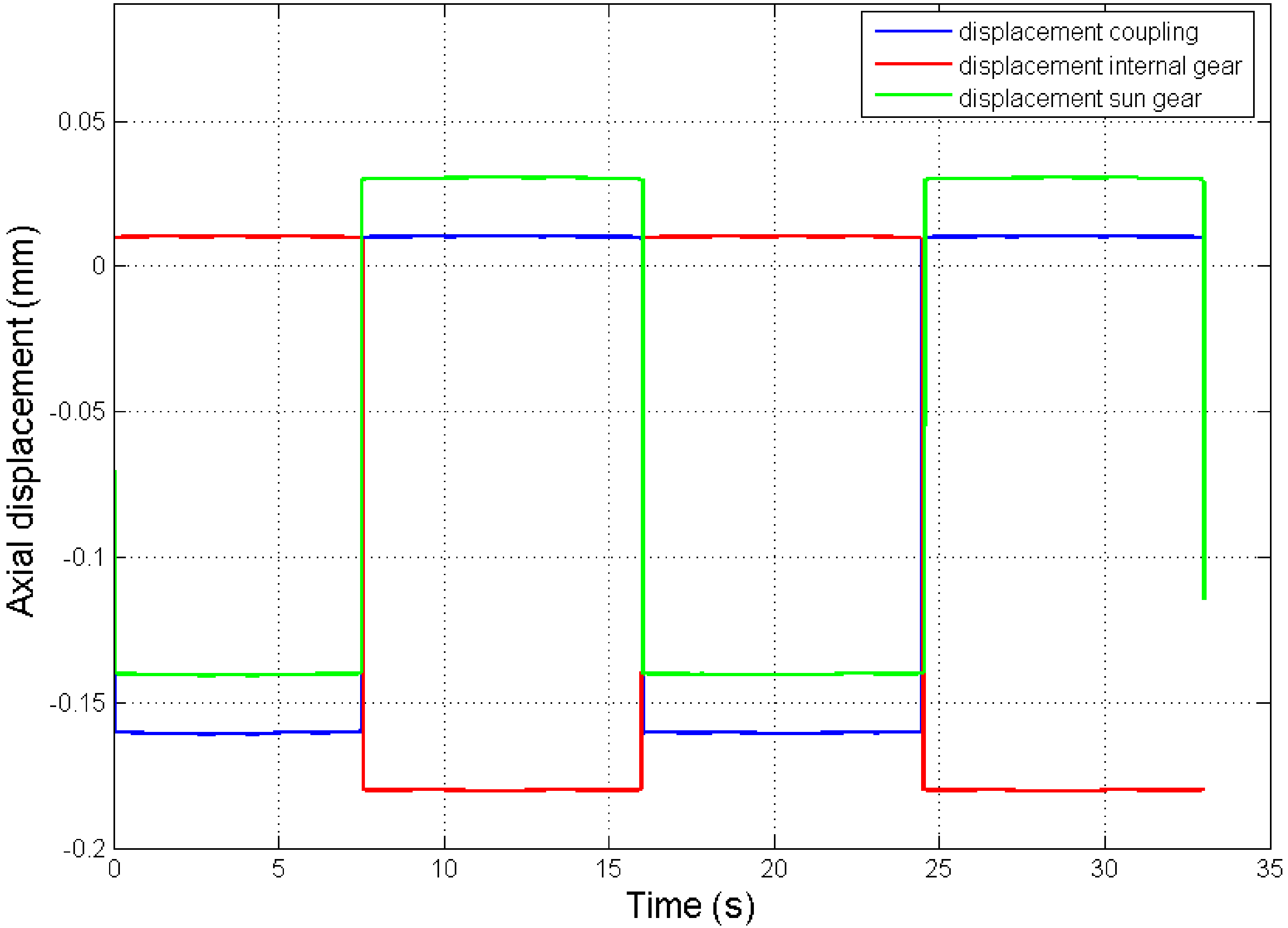
Configuration on vehicle



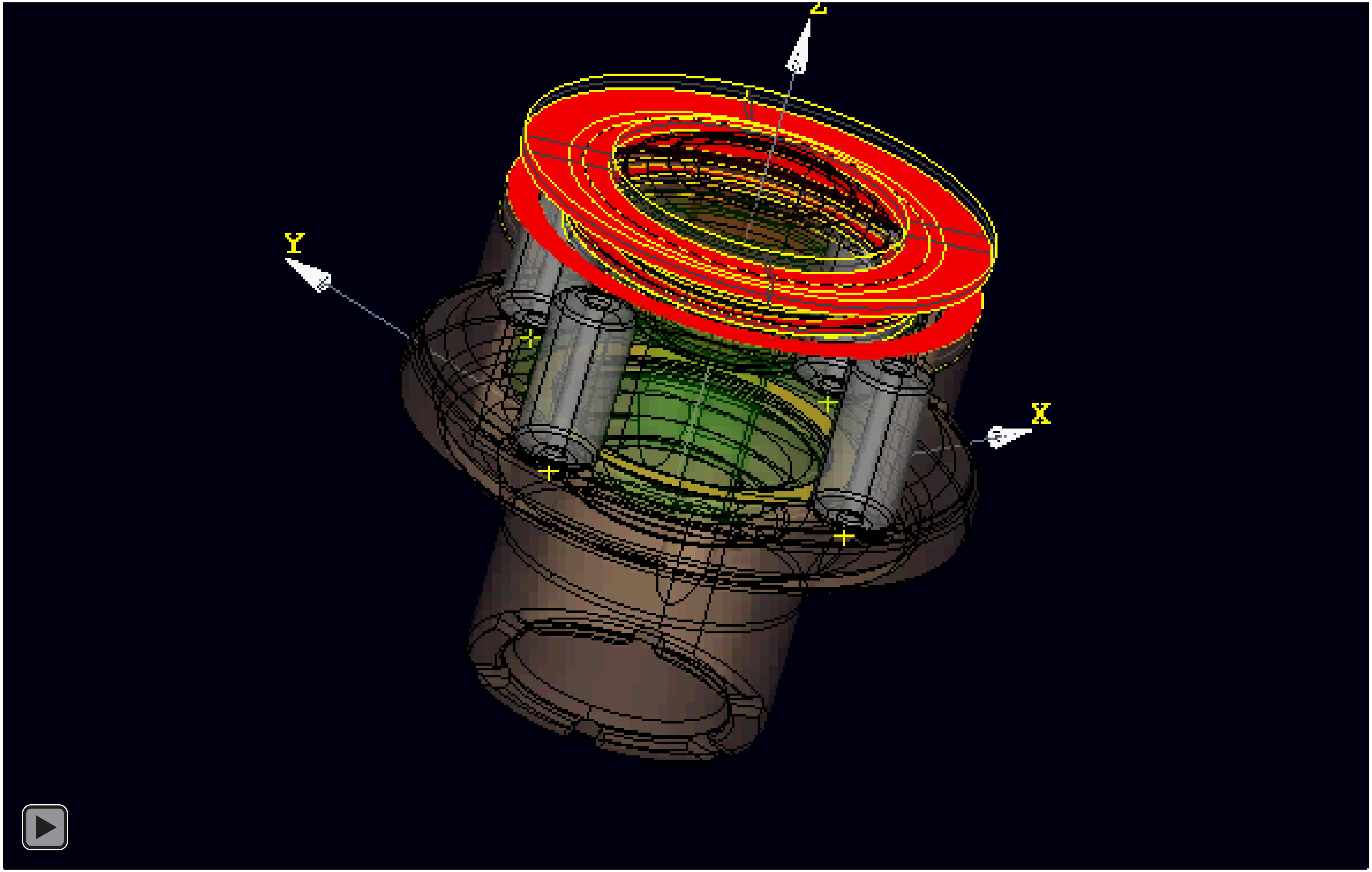


1000
500
0
-500
-1000
Torque (Nm)
0
5
10
15
20
25
30
35
torque housing
torque coupling
torque sun gear
0
-20
-40
-60
-80
-100
Rotation speed (rpm)
Time (s)
rotation speed coupling
rotation speed sun gear
rotation speed housing

Axial displacements of gear wheels



Contact pressure



Model validation

- TDR comparison for each mode with experimental data

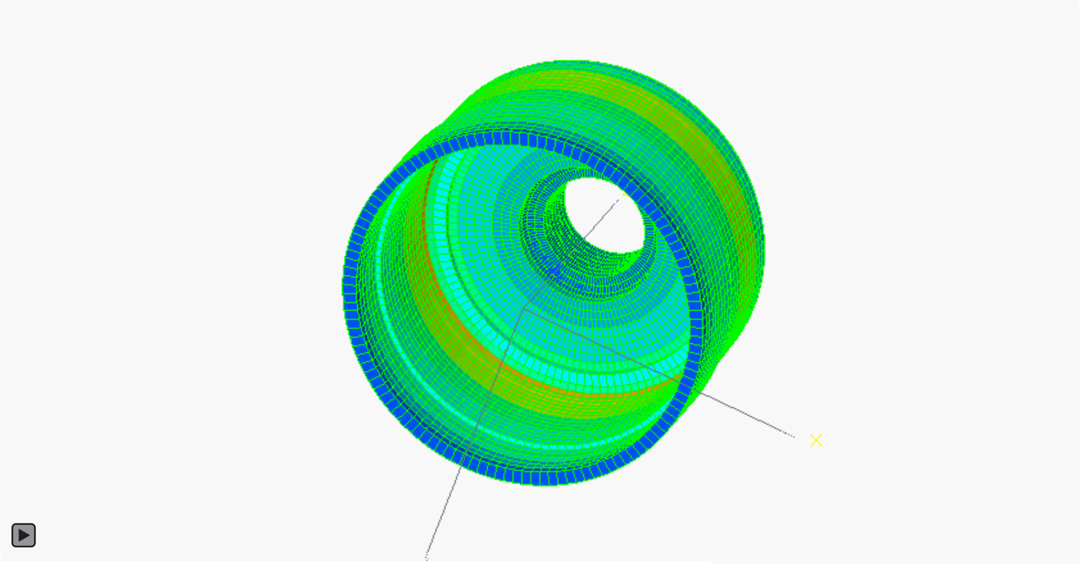
Type C
(center diff)

TDR	Mode 1 Drive bias to rear	Mode 2 Coast bias to rear	Mode 3 Drive bias to front	Mode 4 Coast bias to front
experimental	4,02	2,82	1,57	1,62
simulation	3,9	2,94	1,56	1,65
error (%)	2,98	4,25	0,64	1,85

Type B
(front diff)

TDR	Mode 1 Drive bias to right	Mode 2 Coast bias to right	Mode 3 Drive bias to left	Mode 4 Coast bias to left
experimental	1,6	1,7	1,6	1,7
simulation	1,58	1,66	1,61	1,64
error (%)	3,20	2,35	0,62	3,53

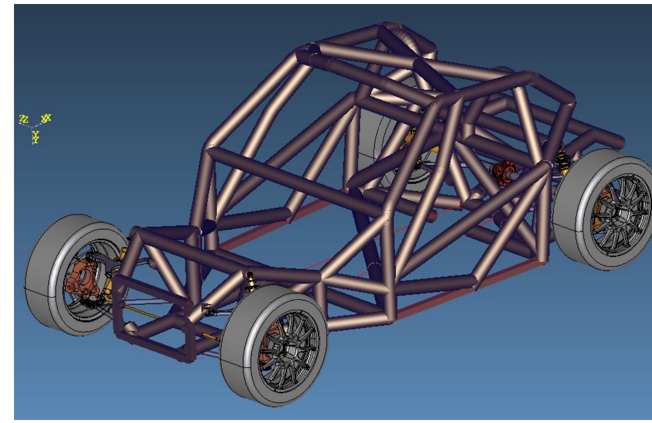
Flexibility of driveshafts and case



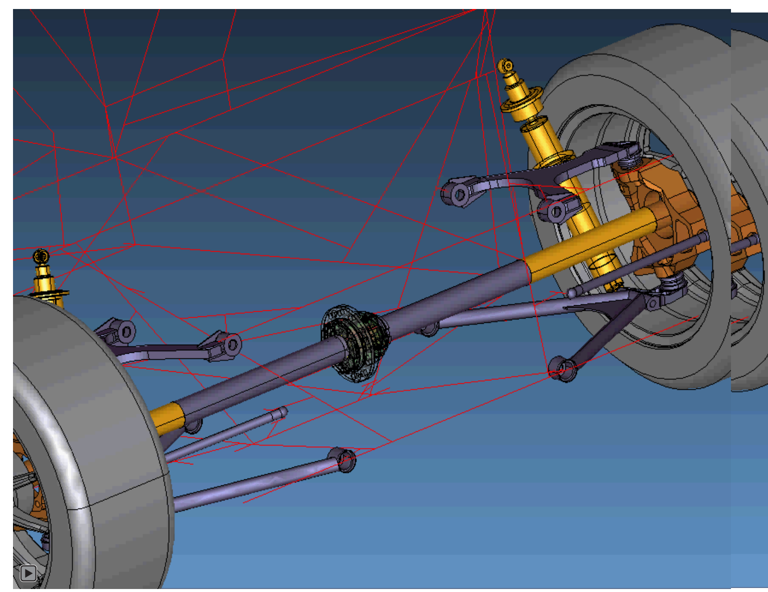
Time evolution of deformations (highly amplified) and equivalent stresses in the case and driveshafts

Differential in vehicle model

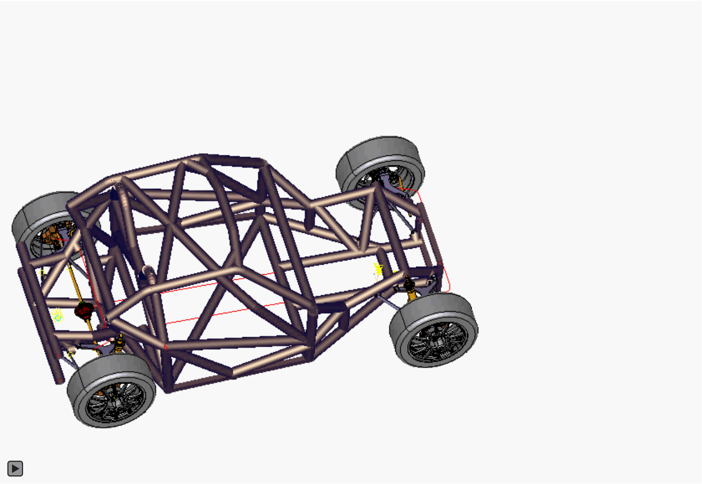
- Rear differential included in full vehicle model with:
  - Rigid driveshafts
  - Flexible chassi (beams)
  - Suspensions fixed on chassi with bushings
  - Tyre models (Pacejka)



- TORSEN Type B
  - 20 rigid bodies
  - 20 gear pairs
  - 26 contacts
  - 10 cylindric joints
- 12730 generalized coordinates

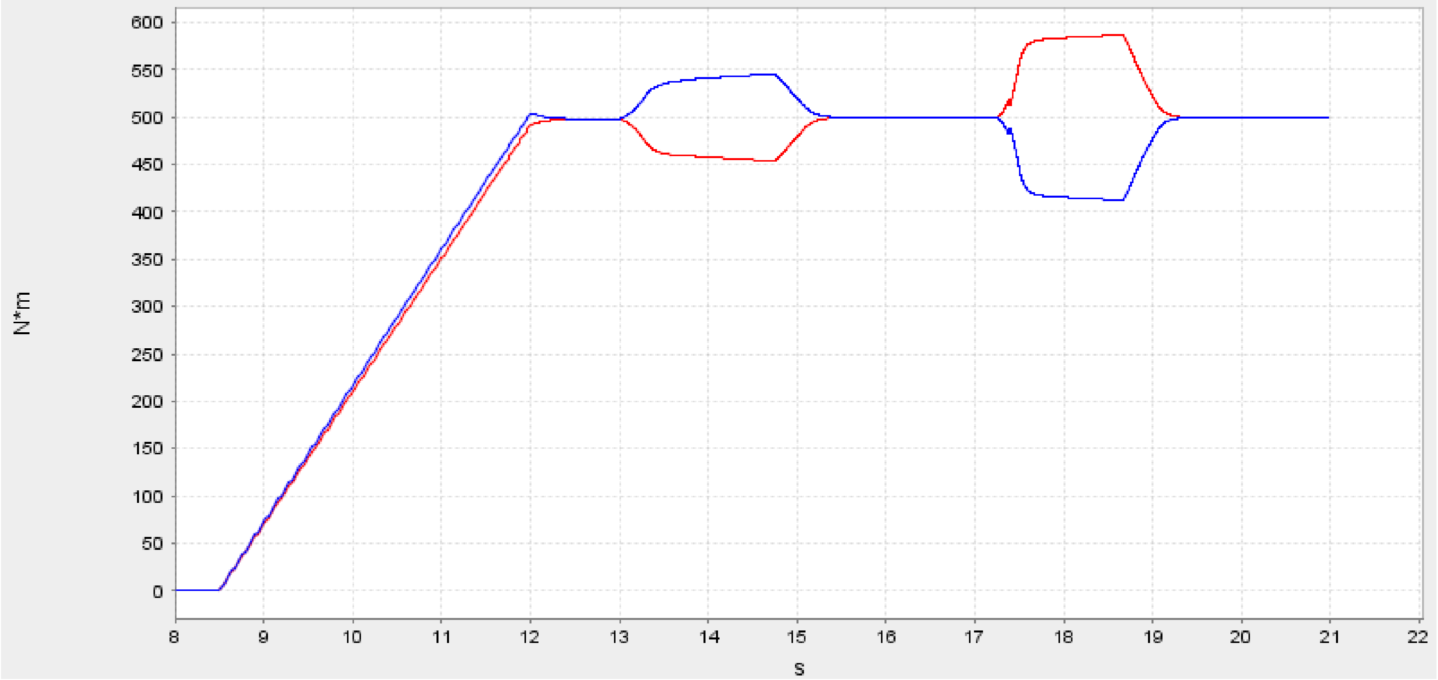


Vehicle model



- Torque transfer of TORSEN differential when a vehicle accelerates on a slippery surface

Torque on right and left rear wheel



Conclusion & outlook

- Dynamic TORSEN differentials modelling:
  - Gear pairs and contact condition (+ squeeze film model)
  - Global validation :comparison with experimental data (TDR)
  - Included in a full protype vehicule model (RWD)

- Specific kinematic joint to model the link between planet gears and housing
- Optimisation of differential case to reduce the weight:

Topology Optimization of Flexible Components in Multibody Systems: Application to the Housing of an Automotive Differential, **Emmanuel Tromme**

Session MS-34,2: Optimisation in Nonlinear Solid Mechanics, Wednesday, 10:49 room K6

Thank you for your attention !

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