Aerospace & Mechanical Engineering

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Simulation of Differentials in Four-Wheel Drive Vehicles Using Multibody Dynamics

Virlez Geoffrey
PhD student – Research Fellow FRIA

University of Liège, Belgium
Automotive Engineering Department

SAMTECH

JTEKT

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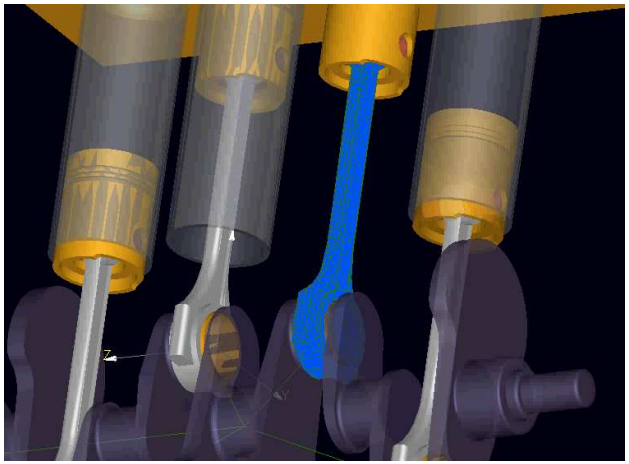
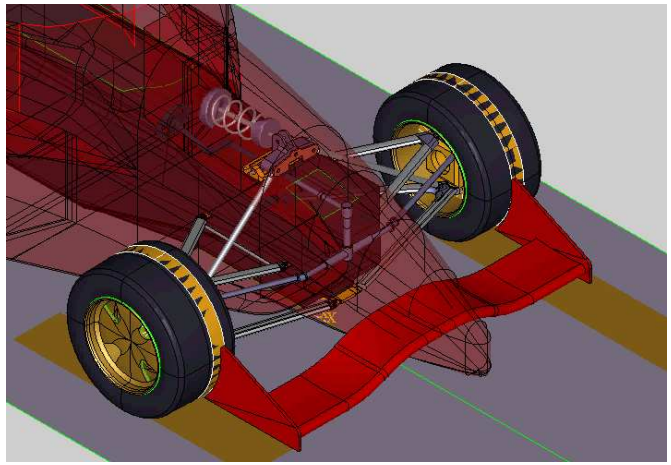
Driveline modeling



(Courtesy: SAMTECH)

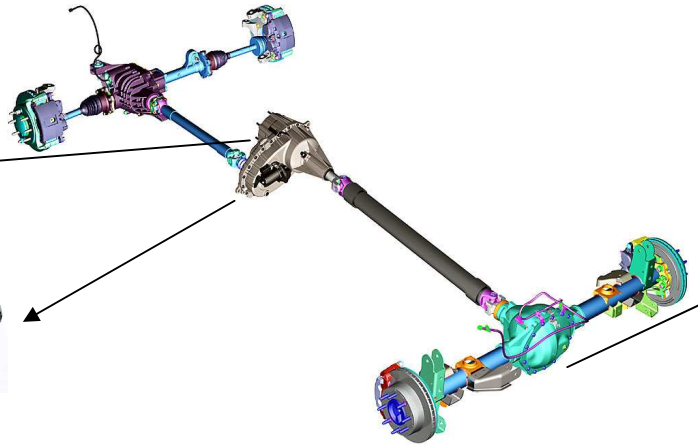


Motor

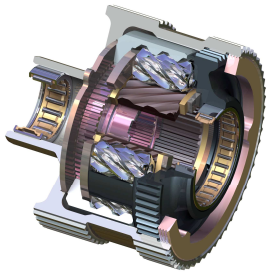
Vehicle dynamics

Transmission line

Gear box



Clutch



Differential

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

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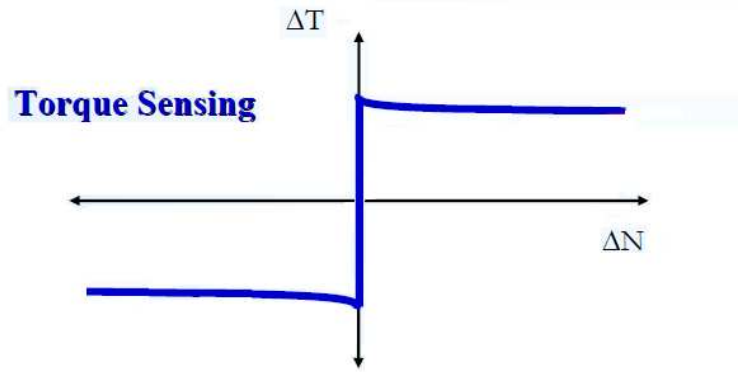
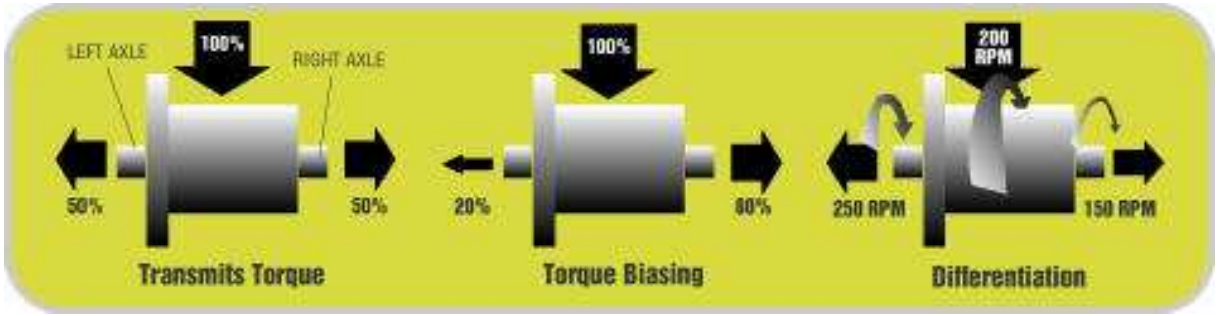
Outline

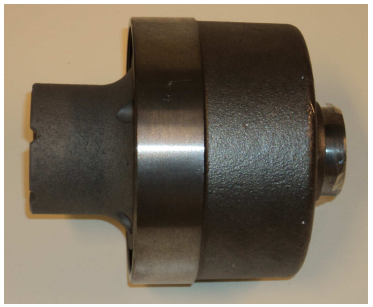
- Description of the application: TORSEN differentials
- Gear pair and contact element modeling
- Model description
- Numerical results
- Academic four-wheel drive vehicle
- Conclusion

TORSEN differential

- Limited slip differential
  - Allow a variable torque distribution between the output shafts ➔ avoid spinning when ground adherence not sufficient on one driving wheel
  - Torque biaising before differentiation

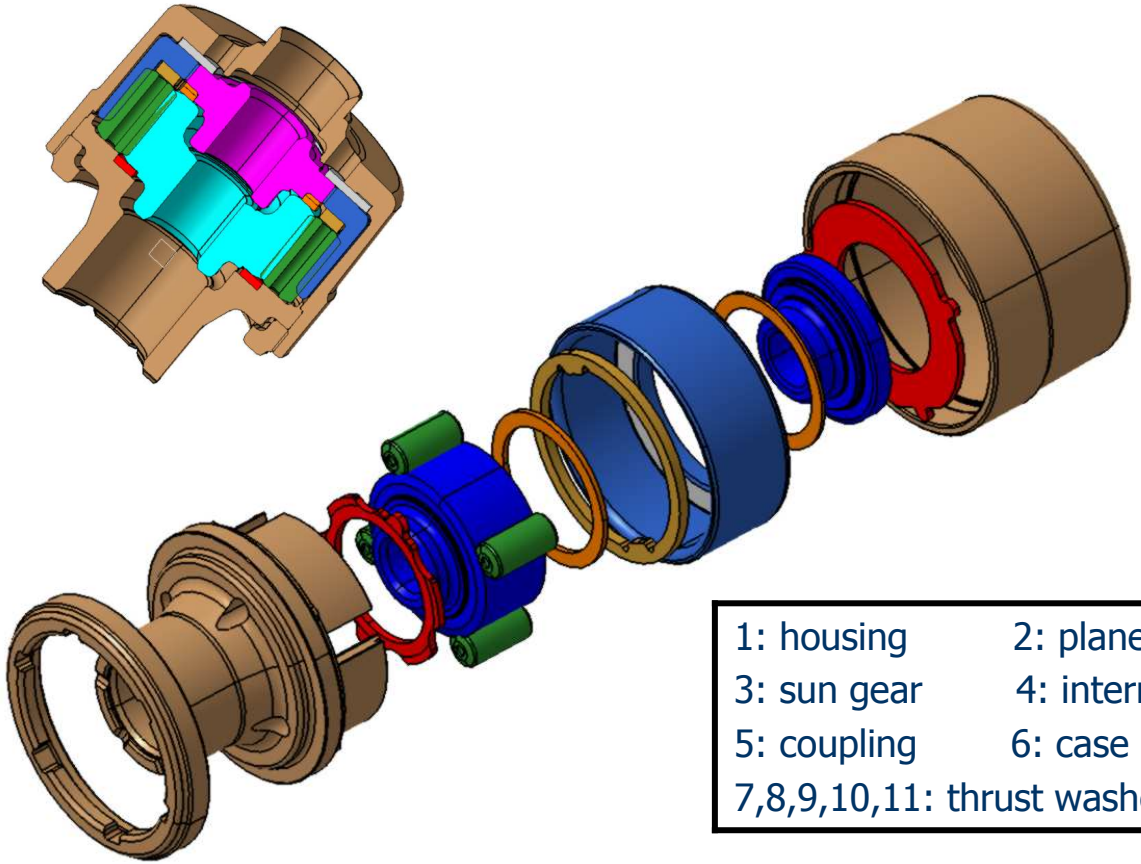


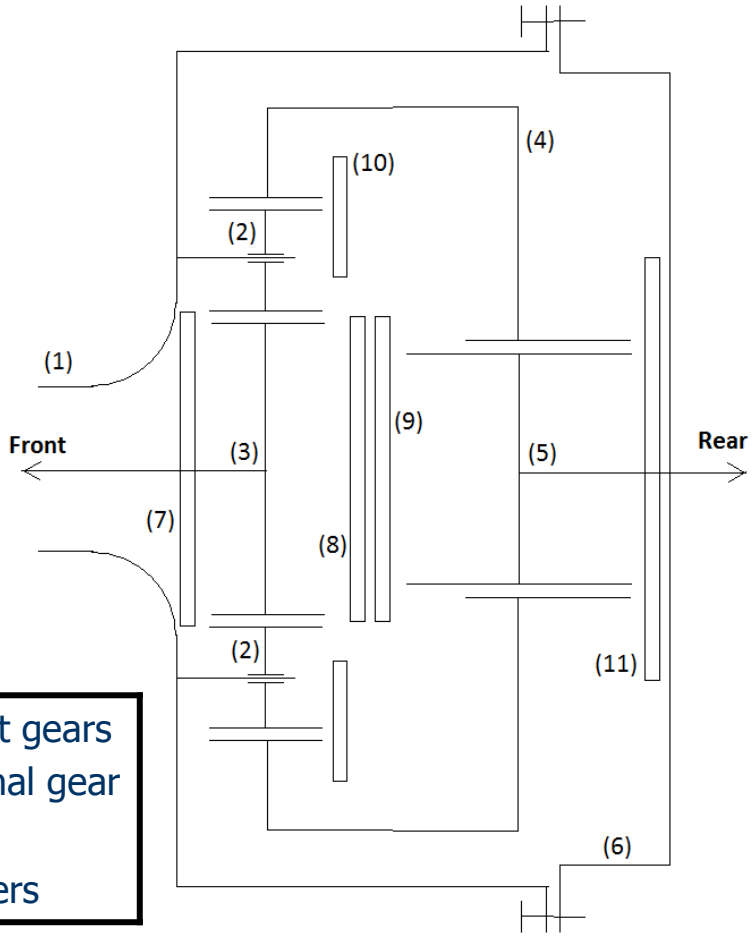




Type C Torsen

- Central differential
- Composed of gear pairs and thrust washers
- Locking due to relative friction between gears & washers
- 4 working modes





1: housing 2: planet gears
3: sun gear 4: internal gear
5: coupling 6: case
7,8,9,10,11: thrust washers

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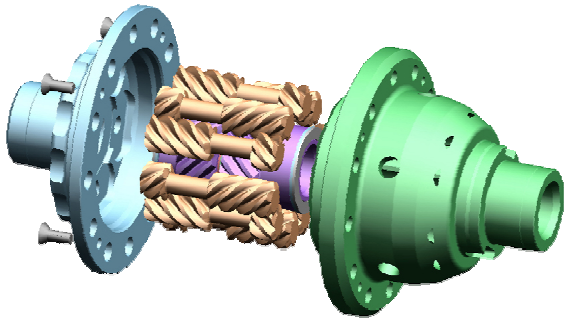
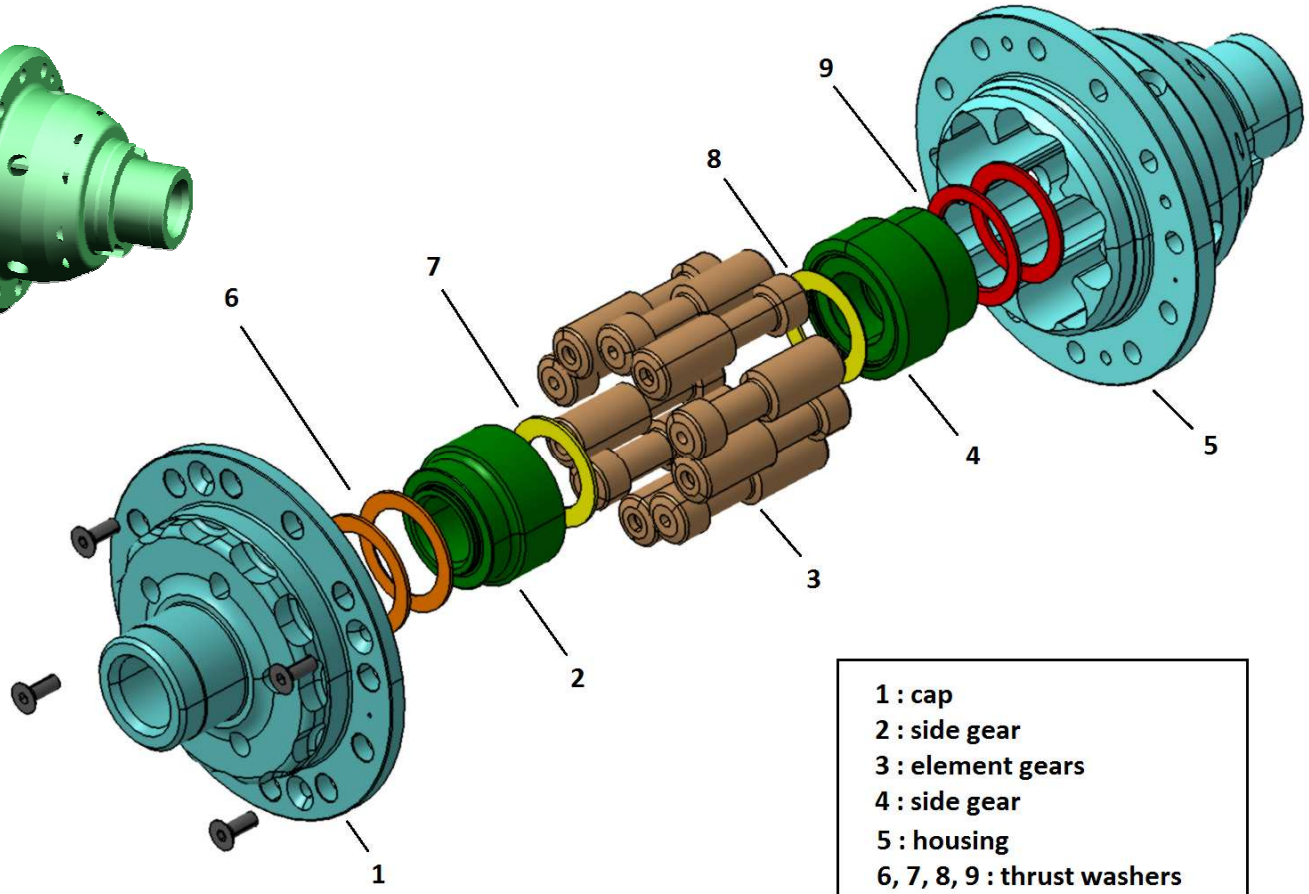
Type B Torsen

- Front or rear differential
- Thrust washers and gear pairs (without ring gear)
- 4 working modes

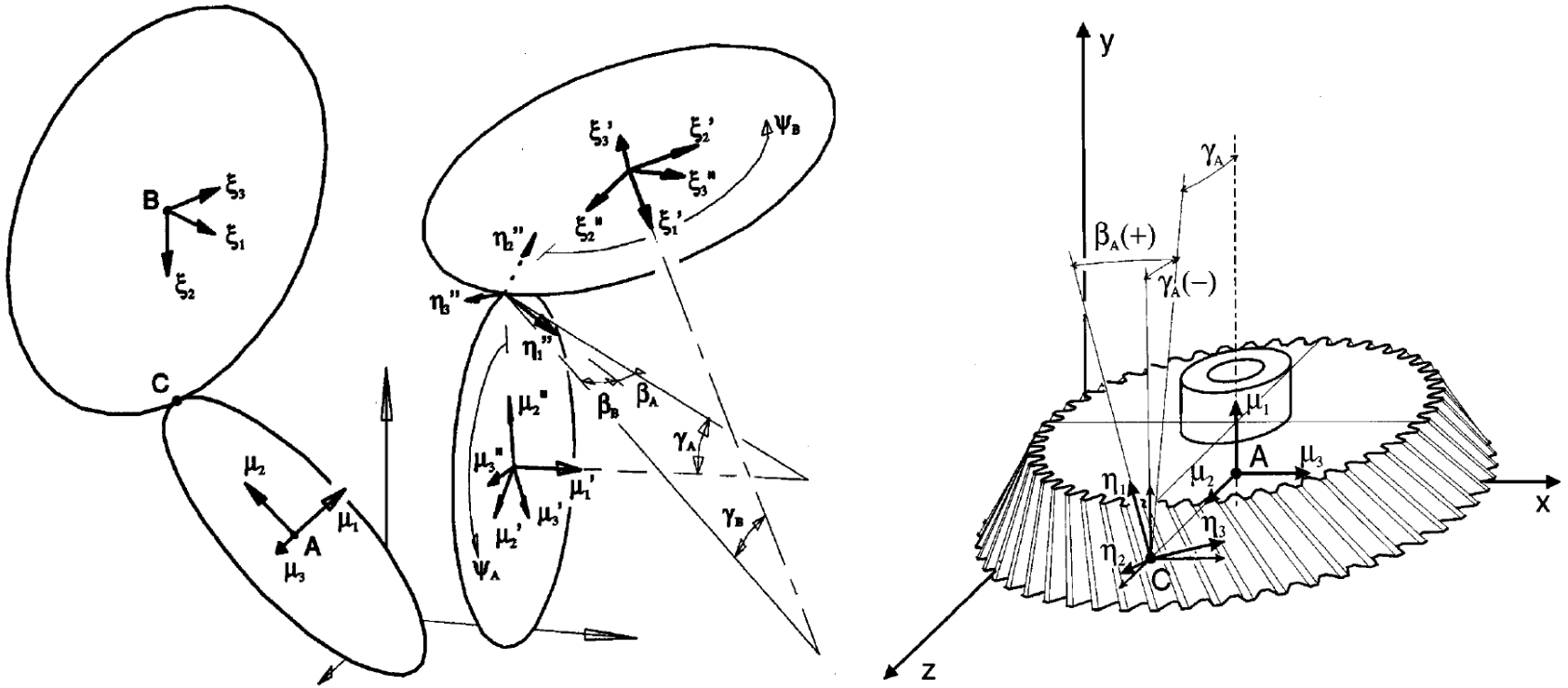




1 : cap
2 : side gear
3 : element gears
4 : side gear
5 : housing
6, 7, 8, 9 : thrust washers

Gear pair element

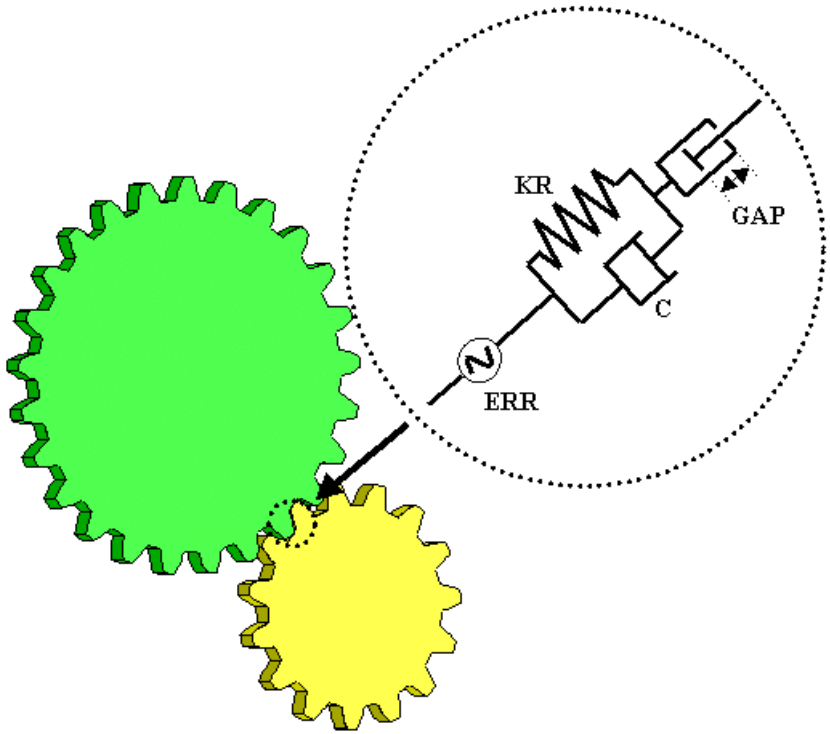
- Flexible joint between two physical nodes: one at the center of each wheel (rigid body).
- Any kind of gear pairs : spur gear, bevel gear, helical gear, worm gears…



(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



Gear pair element

- 15 variables

Deformation of the gear mesh in the hoop direction

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

12 dof

3 redundant coordinates

3 constraints

$$\phi_1 = (-\psi_A \, z_A + \psi_B \, z_B)\frac{m_n \, \cos\alpha_n}{2} + u_m \, \cos\alpha_n = 0$$

$$\phi_2 = (x_C^A - x_C^B).\eta_3''^A = 0$$

$$\phi_3 = \eta_2''^A.\eta_3''^B = 0$$

$$\mathcal{F} = k\lambda_1$$

Normal contact force

Teeth flexibility, clearance and mesh stiffness fluctuation are introduced in the model by relating deformation along the normal pressure line to normal forces acting on teeth.

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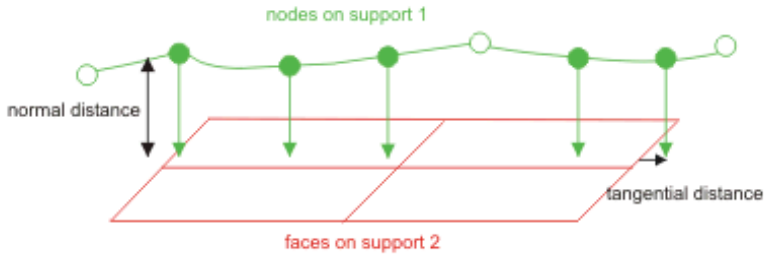
Contact condition

- SAMCEF/MECANO : flexible/rigid or flexible/flexible contact
- 2 steps : - projection of slave nodes on master surface(s)



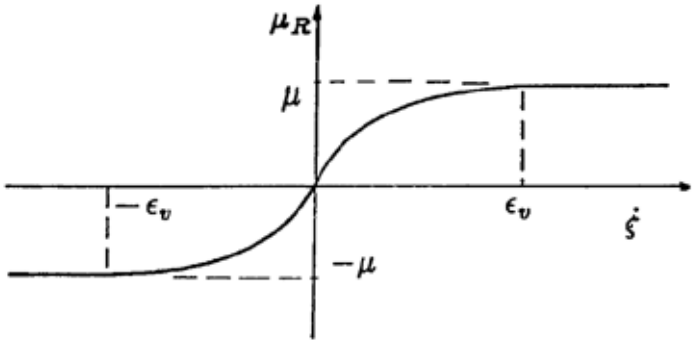
$$\delta d_n = \underline{n}^T \; B \; \delta \underline{q}$$
$$\delta \Delta u_1 = \underline{t_1}^T \; B \; \delta \underline{q}$$
$$\delta \Delta u_2 = \underline{t_2}^T \; B \; \delta \underline{q}$$

- definition of the contact condition

➔ Penalty method (spring only active in compression)

- Friction

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

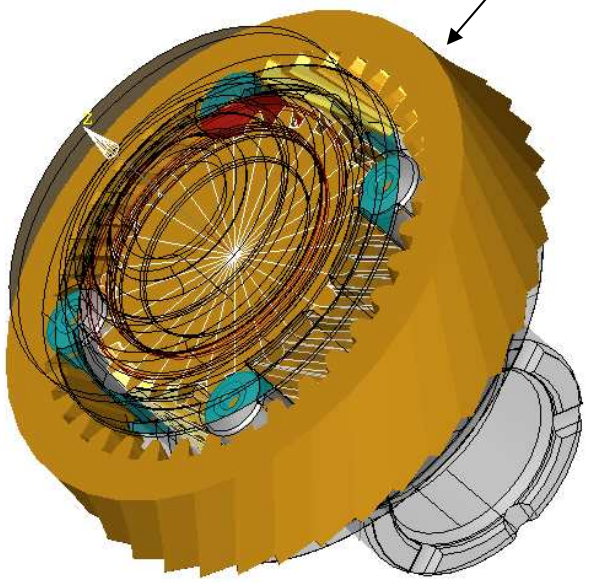


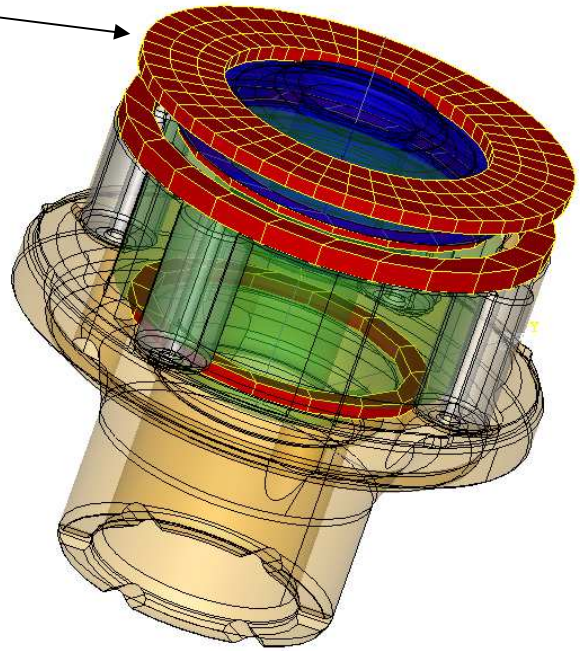
Regularization to avoid discontinuities

Model description

Assumptions: - joints between Planet gears and housing modeled as hinges
- contact SG/washer 3 and CPL/washer 4 neglected
- lubricating oil not modeled

- 15 bodies (*10 rigid, 5 flexible washers*), ≈ 8000 dof
- Constraints : - 8 gear elements
  - 5 contact conditions
  - 4 hinges
  - 1 screw joint

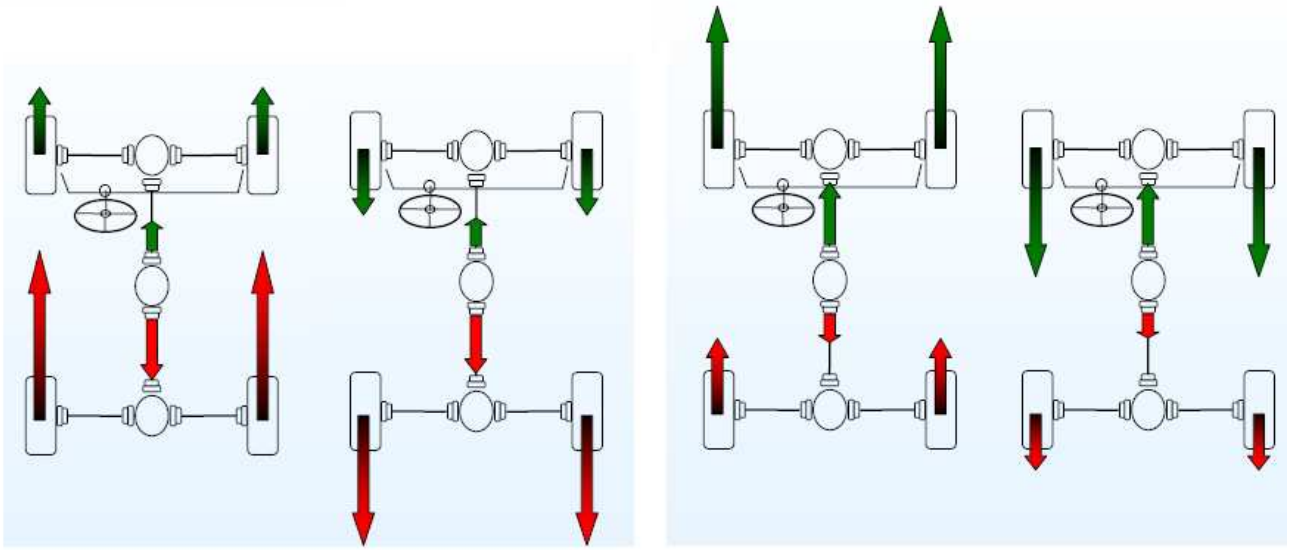


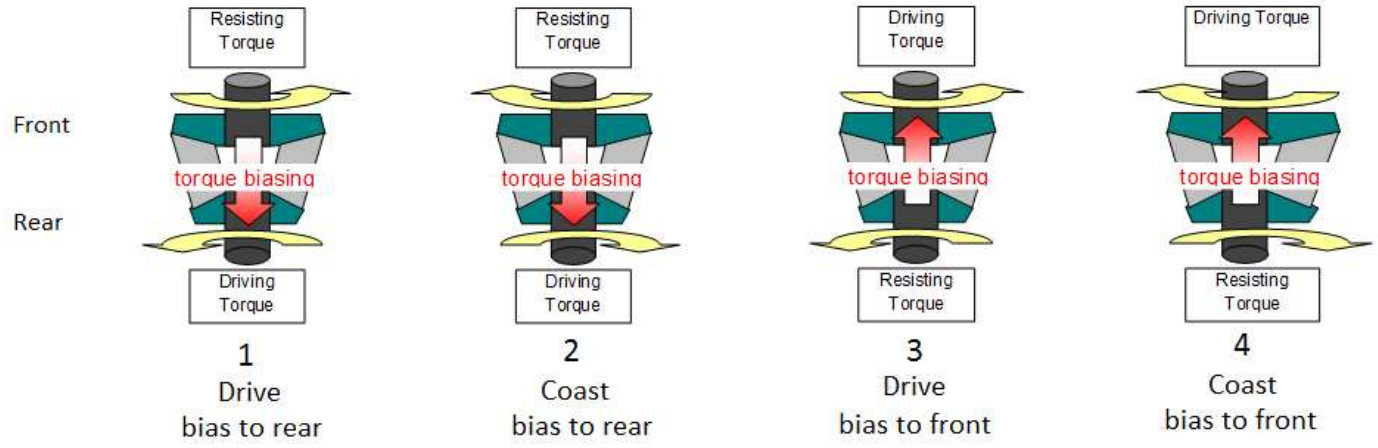


TDR computation for the 4 locking modes

- TDR : Torque Distribution Ratio

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





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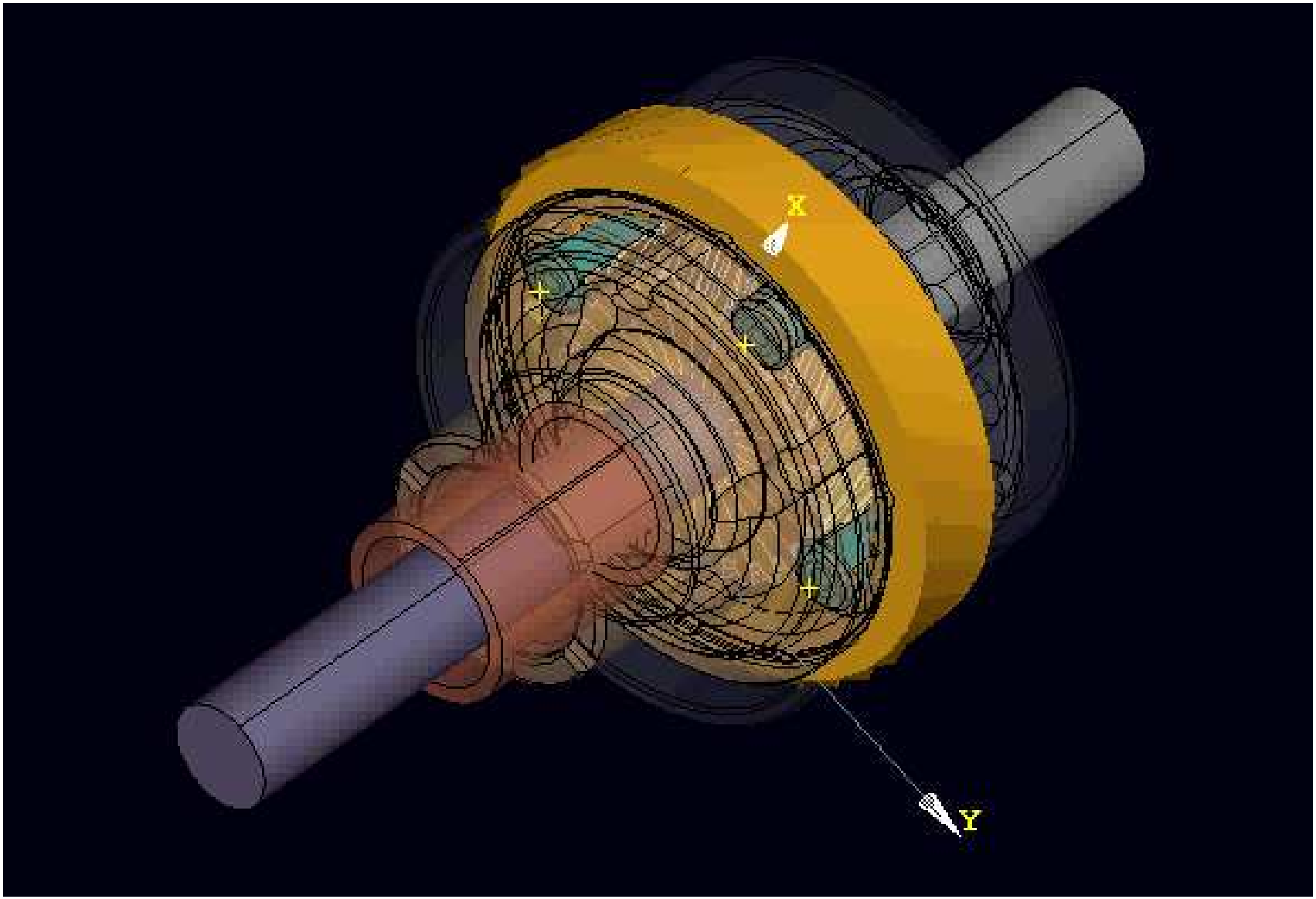
Configuration on vehicle



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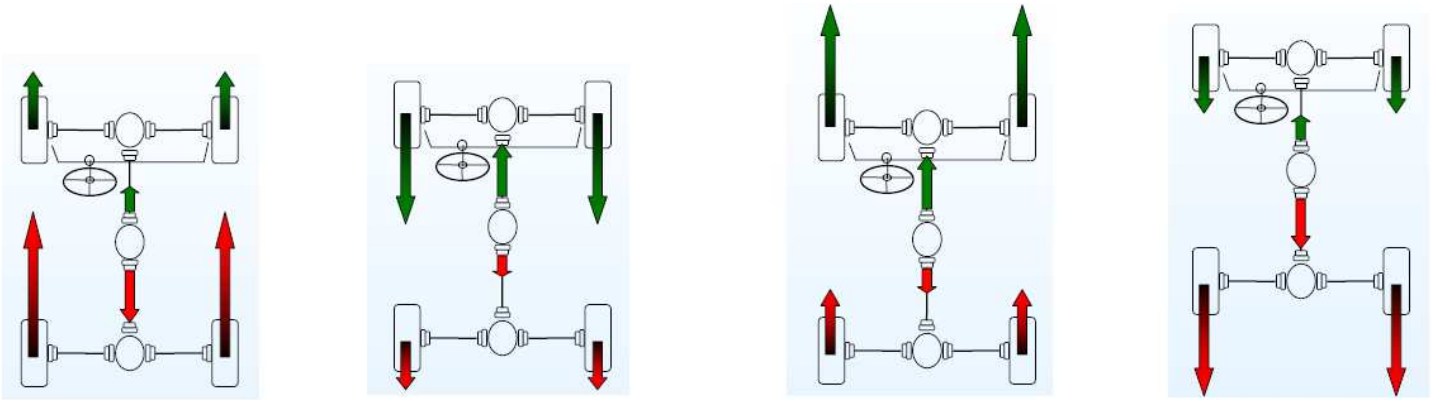

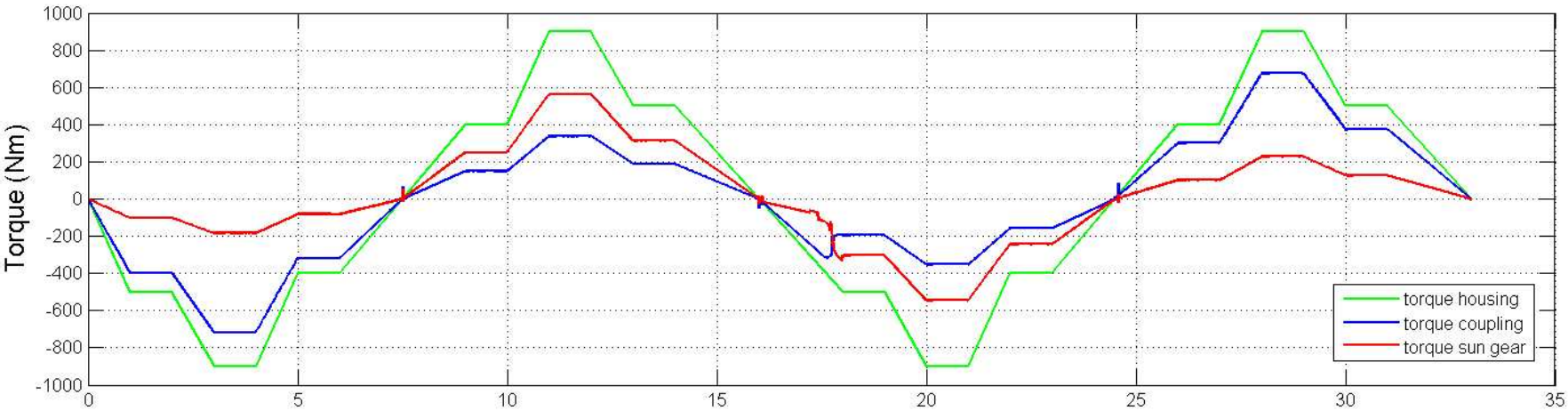

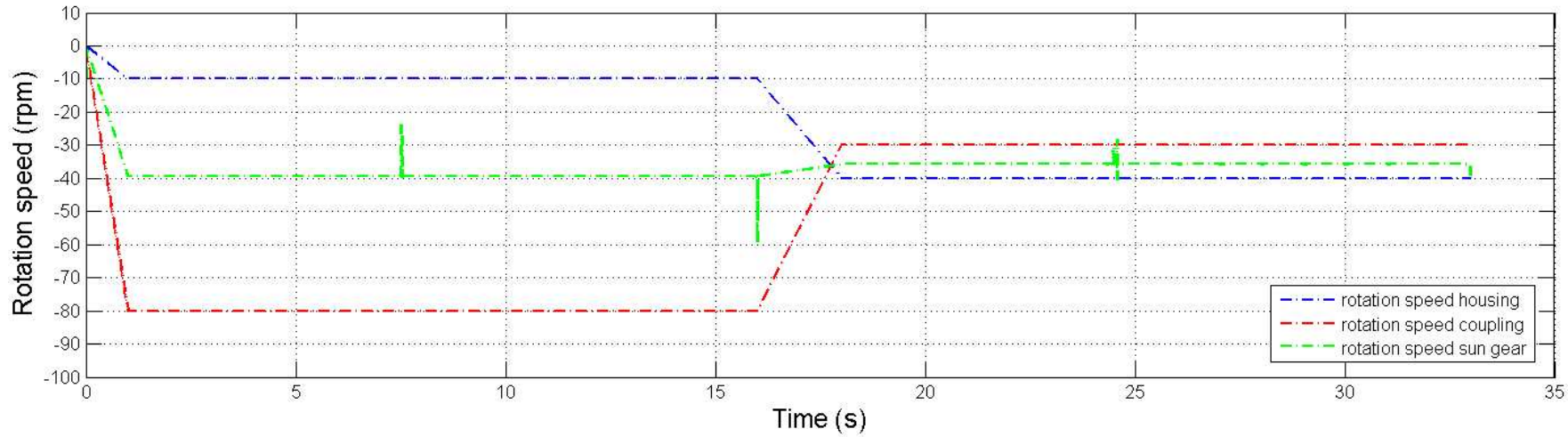

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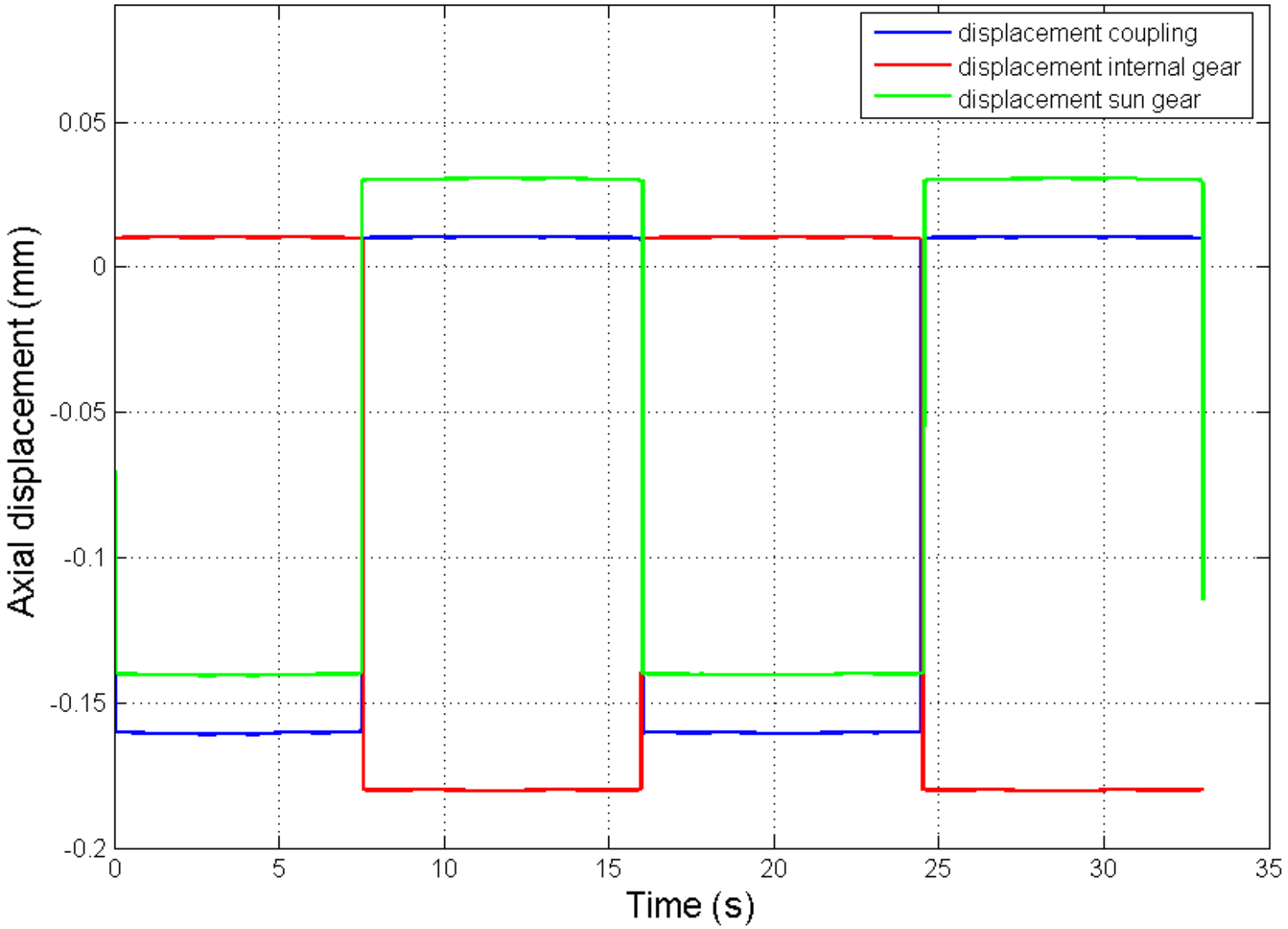
Axial displacements of gear wheels



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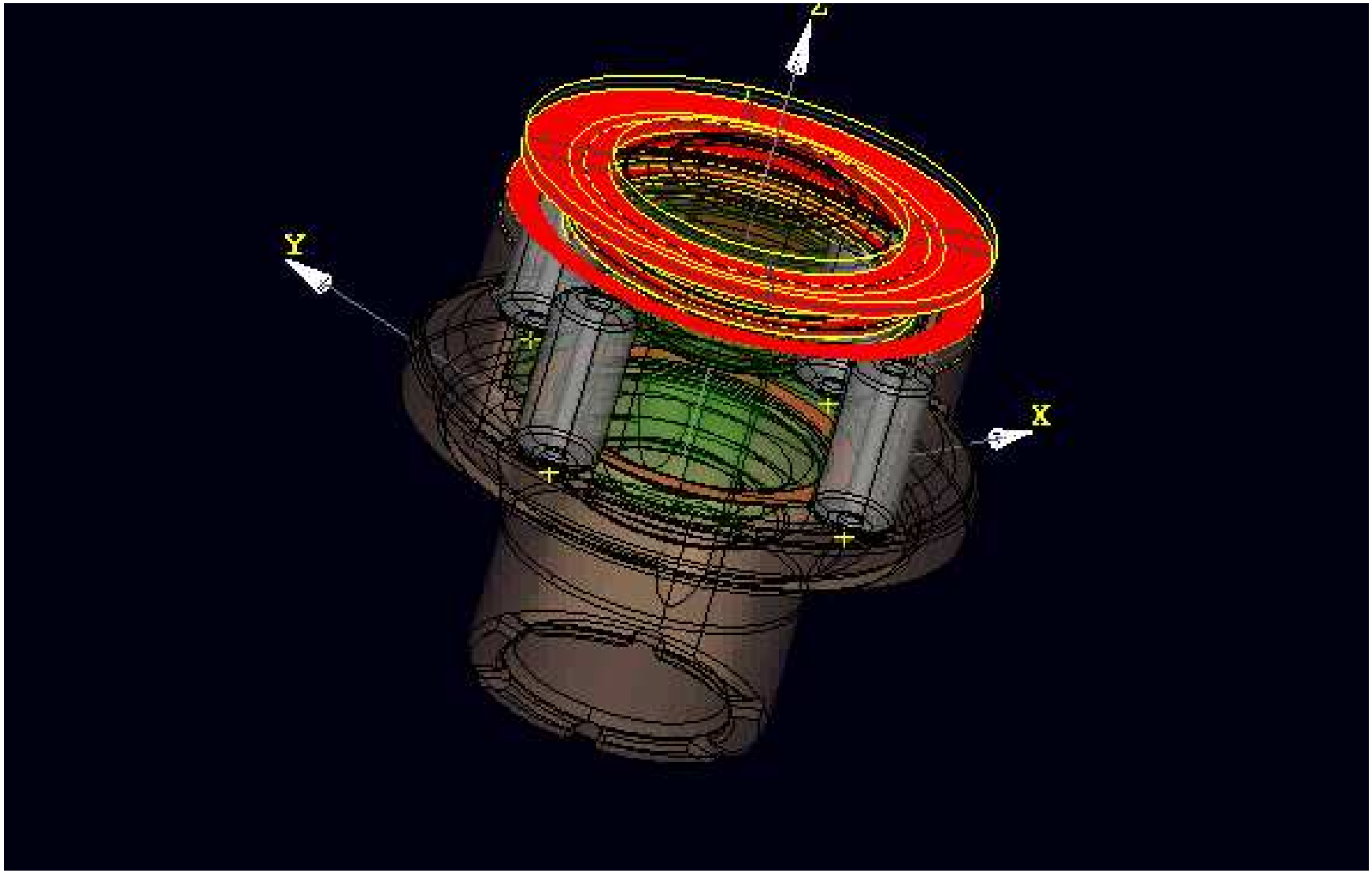
Contact pressure



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Model validation

- Comparison of TDR for each mode with experimental data

Type C (center diff)

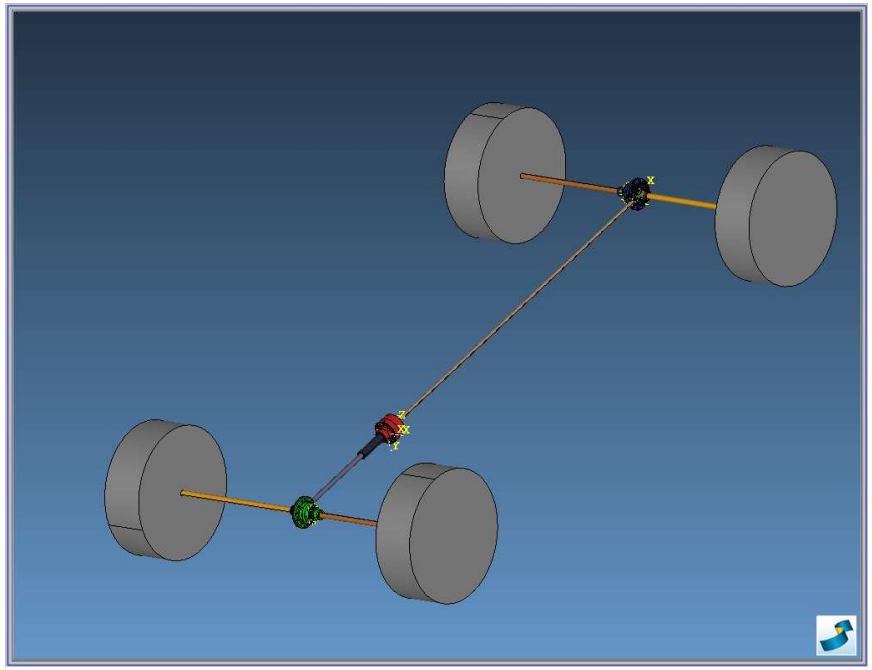
TDR	Mode 1 Drive bias to rear	Mode 2 Coast bias to rear	Mode 3 Drive bias to front	Mode 4 Coast bias to front
experimental	4,02	2,82	1,57	1,62
simulation	3,9	2,94	1,56	1,65
error (%)	2,98	4,25	0,64	1,85

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

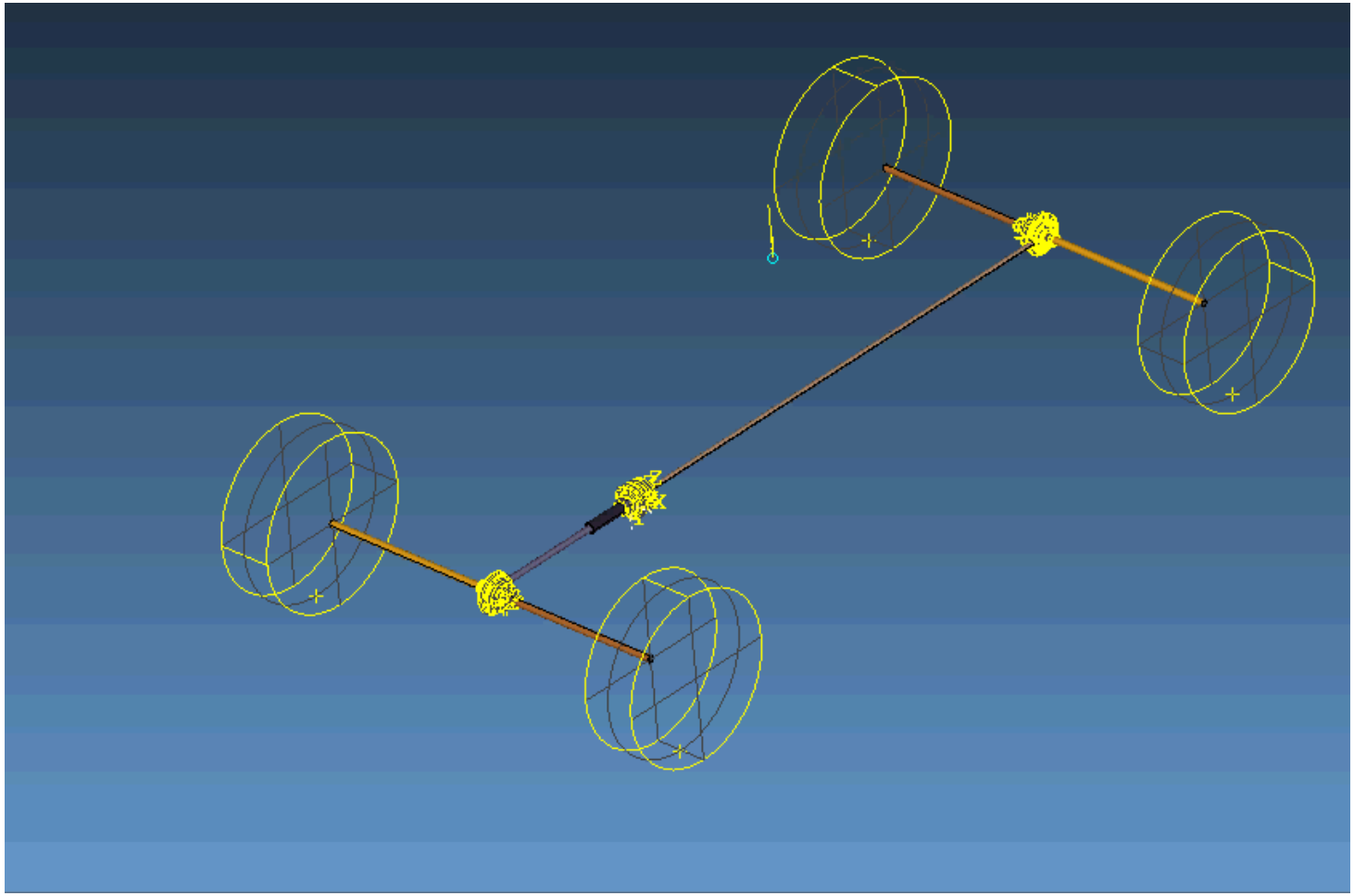
Four-Wheel Drive Vehicle

- Very simple four-wheel drive vehicle model with 3 TORSEN differentials (B – C – B)
  - No suspensions nor steering system
  - Car body = lumped mass
  - rigid driveshafts
  - simple tire model



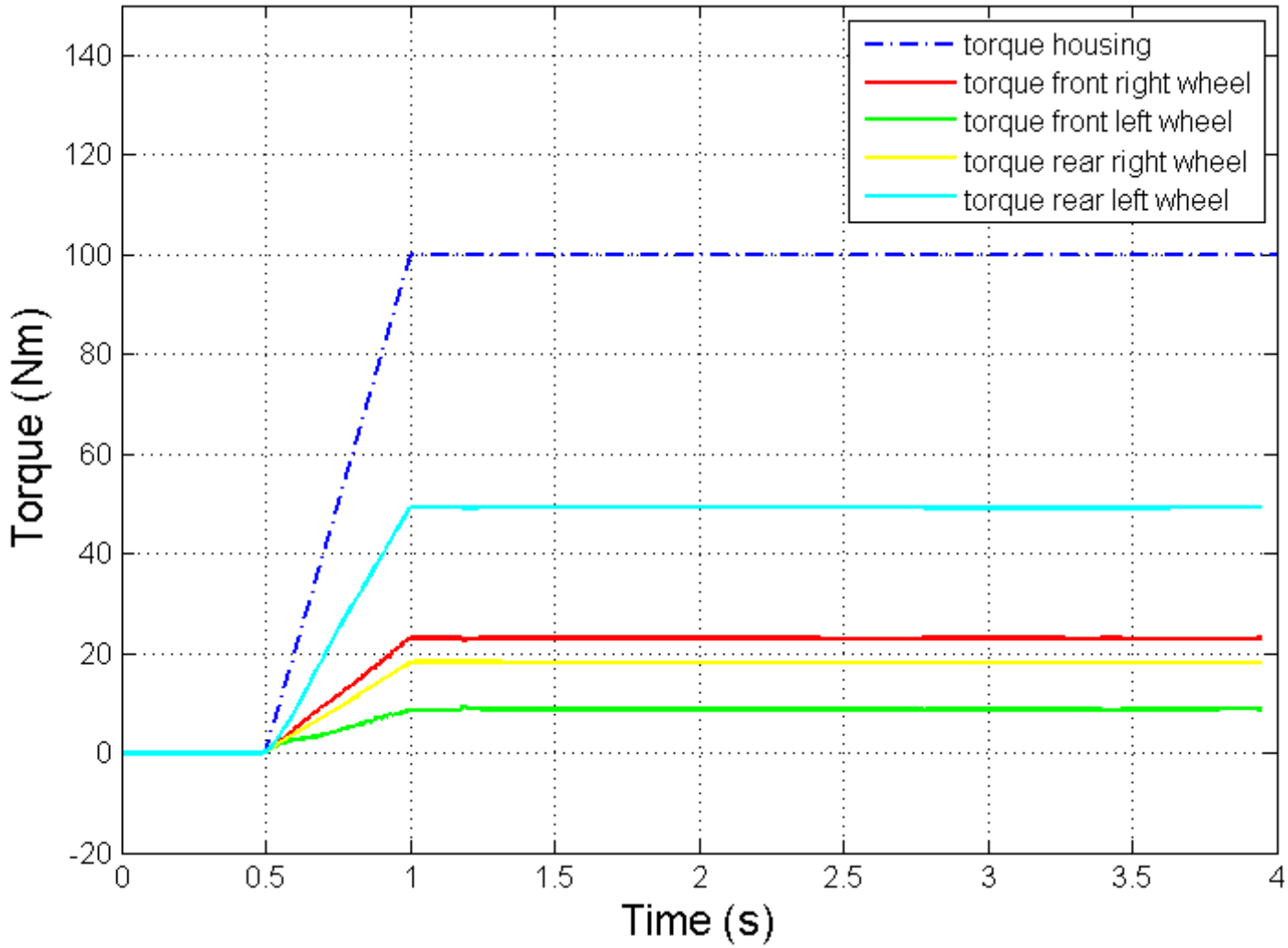
Four-Wheel Drive Vehicle

- Loading : torque applied on housing of central differential



Four-Wheel Drive Vehicle

- Straight line motion with a different friction coefficient for each ground-wheel contact



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Conclusion

- Dynamic TORSEN differentials modeling:
  - Gear pairs and contact condition
  - Global validation :comparison with experimental data (TDR)
  - Assembled in a academic four-wheel drive vehicle model
- Outlook:
  - Development of rigid/rigid contact model
  - More complex vehicle model : flexible chassis, suspensions, Pacejka tire models
  - Flexible driveshafts : study interactions with differentials

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Questions / Answers

Thank you for your attention !