MECA0063 : Driveline systems Part 3: Differentials

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DIFFERENTIAL



DIFFERENTIAL SYSTEM



r.>r; ; w.>w;

- The differential enables a different rotation speed at the two wheels of the axles as in turns!)
- The differential allows to deliver torques at left and right wheels even if they have different rotation speeds.
- The device enables to split the power and allocate it unevenly to the two wheels





TURNING A CORNER The planet pinions both circle around within the differential and spin. The half-

shafts now rotate at different speeds.

TRAVELING STRAIGHT The planet pinions circle around withir the differential without spinning. They drive both the half-shafts at the same speed.

In straight line, one has a rotation of the casing solely

In turns, the spinning of the planetary gears allows a different rotation speed of the sun and rings

THE DIFFERENTIAL

 For vehicles with multiple live axles, there is a differential systems to split the power and the torque between the different axles. The central differential is also often called transaxle.



- We distinguish different technologies for differential in automobiles:
 - Differential with helical gears
 - Differential with bevel and hypoid gears trains







- Differentials with bevel gears can be regarded as planetary gear whose sun and annulus have the same diameters.
- The only implementation possible is to have bevel gears between the sun and the planets and the planets and the annulus.
- The planet carrier is the input of the differential system.

- Differential is a particular planetary gear train in which sun and ring are replaced by bevel gears with equal diameters.
- In between, the planet gear are connected to the annulus of the differential that is a planet carrier.



Kinematic relations

$$i = \frac{Z_A}{Z_S} = 1$$

$$\omega_S = \omega_{LEFT} \qquad \omega_A = \omega_{RIGHT} \qquad \omega_{PC} = \omega_{CROWN}$$

$$\omega_A + i \, \omega_S = (1+i)\omega_{PS} \qquad \omega_R + \omega_L = 2 \, \omega_C$$

$$\omega_C = \frac{\omega_L + \omega_R}{2}$$

Torques

$$\frac{C_S}{1} = \frac{C_A}{i} = \frac{C_{PC}}{-(i+1)} \qquad C_L = C_R = -\frac{C_C}{2}$$

Locking of the differential

 $\omega_{S} = \omega_{LEFT} \qquad \omega_{A} = \omega_{RIGHT} \qquad \omega_{PC} = \omega_{CROWN}$ $\omega_{A} + i \, \omega_{S} = (1+i)\omega_{PS}$ $\omega_{S} = \omega_{PC} \qquad \Rightarrow \qquad \omega_{S} = \omega_{A}$ $\omega_{R} = \omega_{C} \qquad \Rightarrow \qquad \omega_{L} = \omega_{R}$

 Locking calls for synchronization of the crown speed with one of the output shafts

Differential with planetary gears



- The planetary gears can be used as differential systems to produce unequal torque/speed distribution at the output shafts (and axles or wheels).
- The input shaft is the planet carrier while the sun and the annulus are the output shafts.
- The ratio between the two output torques is given by the ratio between the diameter of the sun and the annulus.
- It is often the case for transfer boxes in all wheel drive vehicles.



Differential with planetary gears

Transfer box using a planetary gear





Velocities in points A and B

 $v_A = \omega_C R_C + \omega_P R_P = \omega_{LEFT} R_C$ $v_B = \omega_C R_C - \omega_P R_P = \omega_{RIGHT} R_C$

• It comes if $\omega_{LEFT} \neq \omega_{RIGHT}$ $2\omega_C R_C + 0 = (\omega_{LEFT} + \omega_{RIGHT}) R_C$

$$\omega_C = \frac{\omega_{LEFT} + \omega_{RIGHT}}{2}$$



• The equilibrium of torque gives:

 $C_{LEFT} + C_{RIGHT} = -C_C$







Operation of the differential

In straight line:

- The resistance torques left / right are equal
- There is no spinning of the (4) about their axis
- Same rotation speed of output shafts (5) and (6)

In turn:

- The rotation speeds of left and right axles are different
- Satellites (4) have to spin about their axis.
- Different rotation speed of the output axles left and right



Implementation of differential





- For front wheel driven vehicles, the gear box and the differential are integrated into the same unit
- The sole difference is the shape and the layout of the components
- Engine can be further mounted longitudinally or transversally

Slip control in differential

- With an open differential, the engine torques are characterized by an equal distribution of the torque but an uneven distribution of the power between the wheels.
- If one wheel is slipping (and spinning), the low µ slip wheel limits the power available at the high µ slip wheel and one observes a transfer of the power to the fast-spinning wheel.
- The same problem happens when one wheel lift off.
- To circumvent the problem, it is necessary to block the differential i.e. to clamp one of the planet gears to the differential casing.



- Devices to block differentials:
 - Self blocking differentials
 - Limited slip differential
 - Anti skid systems

- The maximum torque that can be transferred to the wheels is governed by the wheel with the smallest friction torque that can transmitted between the two wheels or the two axles.
- If the wheels were connected rigidly (at the price of a loss of a yaw torque) the maximum torque would be dictated by the maximum torque available at wheels.
- To maintain a high transmissible torque, one resorts to locking of the differential or better to a limited slip differential to maintain a better handling.
- The locking is characterized by the ratio between the difference between the two torques and the input torque

$$S = \frac{M_{max} - M_{min}}{M_e} \qquad \qquad M_e$$

 $M_e = M_{max} + M_{min}$

Limited slip differentials

- Limited slip differentials contains internal elements that can transfer the input torque to wheel shaft with the higher friction coefficient to the ground.
- Usually this is made by friction elements which react to different rotation speed conditions. Some of the systems use gears, worm gears or hydraulic clutches.



Limited slip differential

- One can distinguish three main categories of limited slip differential :
 - Differential with a manual engagement of the locking mechanism
 - Differential with a limiting systems based on friction elements that are sensitive to difference of rotation speed
 - Differential with friction regulated actively using electronic controller.



Fig. 7.11 - Blocage du différentiel : réalisation.

- 1. Denture à crabots solidaire du boîtier de différentiel.
- 2. Craboteur lié en rotation avec un des arbres de transmission, libre en translation.
- 3. Levier de commande du blocage.

Mémeteau Fig 7.11

- How to lock the differential?
 - A <u>dog teeth system is linked to one of the</u> <u>output wheel shaft</u> and that can be translated freely on a spline shaft
 - The <u>dog teeth mounted on the differential</u>
- When the driver operate the stick, a fork moves the dog teeth that mesh to the teeth made in the differential casing
- The maneuver must be realized at standstill because if the wheel is slipping the high difference of speed between the casing and the wheel forbids to realize the maneuver.



Manual locking of the differential using dogteeth

Such a locking mechanism can be operated manually whenever the speed is below 10 km/h

Above this critical speed, there is an automatic unlock automatically of the differential to avoid some bouncing behavior of the car while turning.



A gear pair of the planetary gear set is extended to allow for a synchronizing

A control fork to engage the dog teeth possibly using an actuator



- The locking of the differential can be realized using friction elements that limit the difference in torques or in rotation speed between the two output shafts.
- The most classical system is made of friction plates between the two output shafts
- The torque difference between the two output shafts is fixed and the rate S is reduced with the ratio. The rate S is also reduced with input torque.

Self-locking differentials

- The limited slip differential includes a locking system that becomes automatically active when the difference of rotation speeds between the two output shafts exceeds a threshold.
- The working principle that is the most usual is based on the action of centrifugal loads that act onto brake pads of clutches to lock parts using friction.
- The brake pads or clutch elements are linked to the wheel shafts while the brake drums are attached to the differential casing.
- Another working principle is to take advantage of axial loads generated by helical gears. These forces leads to axial displacements and later to contact between friction elements.



- The locking of the differential can be realized using a friction elements between the wheel shafts and the differential casing
- Types of limited slip differential:
 - Using clutch plates (Sure-Grip, Positraction, Traction Lok)
 - Using conical clutches (ex. Borg-Warmer system)
- The friction force is independent on the engine torque, but it depends on the effort generated on the gear teeth pushing the gear wheels against the casing surfaces







Eaton differential

Differential locking



- One of the most famous system is the TORSEN systems (for TORque SENsistive).
- It takes advantage of the friction developed between some helical gears
- It is made of several gear pairs similar to worm gears for which the helical angles has been optimized to have a self-locking effect.
- The helical angle is optimized to increase the friction in terms of different wheel torques.

Limited slip differential: TORSEN

TORSEN = TORque SENsitive



Limited slip differential: TORSEN



Typical Split Coefficient Performance Curve



SURFACE COEFFICIENT LOW TRACTION WHEEL VARYING HGH TRACTION WHEEL ON 1.0 µ
Limited slip differential: TORSEN



A famous application: the Torsen differential in the Audi Quattro



- The limited slip differential includes several locking elements based on the action of one or several clutch elements.
- In a purely passive version, the visco hydraulic coupling transfers the friction torque to the wall of the casing.
- The friction torque depends on the shear velocity of the fluid and so on the relative velocity of the plates.
- The set up of the systems depends on the experimental curves reporting the viscosity w.r.t. the temperature of the oil.









- The system can be further improved by including an active system able to modify the friction on demand.
- The HALDEX systems uses the pressure oil





TRANSMISSION SHAFTS

Transmission shaft: propulsion case

- The output shaft from the gear box is connected to the rear differential via a transmission shaft
- The transmission shaft is generally hollow and has to remain flexible
- To allow a certain relative motion, two universal (Hooke) joints are connected at both sides
- Homokinetic mounting requires to mount two Hooke's joint with a shift of 90° to prevent the fluctuation of the rotational speed.
- To enable a certain suspension vertical motion, the shaft must be able to extend thanks to a prismatic joint



Transmission shaft for rear live axles



Transmission shaft for rear live axles



Transmission shaft for rear live axles

- The transmission shaft creates some bending and torsion moments in the differential, the shafts, and the wheels
- The tractive forces developed at the contact patch flows to the body through the axle connection points. The forces are taken by the chassis via the leaf springs, the steering links
- In this case, one has not to account for the traction forces in the driveline.





Two implementation of the Hook / universal joint

- Universal joint or Hooke joint, it stems from the 16th century by Jérôme Cardan.
- The rotation motion is transmitted by the cross link that is free in rotation with respect to both input and output shafts (two hinge links concurrent in the intersection point of the two shafts).



• U-joints can cope with angles α rather important (up to 45°) between the input and the output shaft.

| Angles (α) possibles entre les deux arbres | | | | | |
|---|-------------|-----------|--------------|--|--|
| vitesses maximales admissibles | très lentes | 10 tr/min | > 600 tr/min | | |
| angles α possibles | 45° | 30° | 15 à 20° | | |

- U joint is not homokinetic since it does not preserve a constant ratio between the output and input speed. Even if the number of rotation is the same, the output speed (ω₂) fluctuates for a constant input rotation speed ω₁.
- The fluctuation is a function of the angle α between the two shafts.

If the shaft 1 has rotated by an angle θ from reference configuration sketched in figure 1 and the output shaft 2 has been rotated by an angle φ, one can write

$$\vec{OA} = \vec{r_1} = \vec{n}\cos\theta + \vec{i}\times\vec{n}\,\sin\theta$$
$$\vec{OB} = \vec{r_2} = \vec{m}\cos\phi + \vec{j}\times\vec{m}\,\sin\phi$$



 In all configurations, vectors OA and OB must remain perpendicular to each other

 $\vec{r_1} \cdot \vec{r_2} = (\vec{n}\cos\theta + \vec{i}\times\vec{n}\,\sin\theta) \cdot (\vec{m}\cos\phi + \vec{j}\times\vec{m}\,\sin\phi) = 0$

Given that

$$\vec{m} \times \vec{j} = \vec{n}$$
 $(\vec{i} \times \vec{n}).\vec{m} = \cos \alpha$

One obtains the geometrical relationship between the input and output rotation angles

 $\cos\theta\,\sin\phi = \cos\alpha\,\sin\theta\,\cos\phi$

 $\tan\phi = \cos\alpha \,\tan\theta$

• Differentiating the equation, one gets $\tan \phi = \cos \alpha \ \tan \theta$

$$\frac{1}{\cos^2\phi}\dot{\phi} = \frac{\cos\alpha}{\cos^2\theta}\,\dot{\theta}$$

Substituting, it follows

$$\frac{1}{\cos^2 \phi} = 1 + \tan^2 \phi = 1 + \cos^2 \beta \, \tan^2 \theta$$

And finally, it comes

$$\omega_2 = \frac{\cos\alpha}{1 - \sin^2\alpha\,\sin^2\theta}\,\omega_1$$

Differentiating once more, one gets the accelerations

$$\dot{\omega}_2 = \frac{\omega_1^2 \, \sin^2 \alpha \, \cos \alpha \, \sin 2\theta}{(1 - \sin^2 \alpha \, \sin^2 \theta)^2}$$

Fluctuation of the output speed is obtained by combining the equations

 $\tan\phi = \cos\alpha \, \tan\theta$

And

$$\omega_2 = \frac{\cos\alpha}{1 - \sin^2\alpha\,\sin^2\theta}\,\omega_1$$

$$\dot{\omega}_2 = \frac{\omega_1^2 \, \sin^2 \alpha \, \cos \alpha \, \sin 2\theta}{(1 - \sin^2 \alpha \, \sin^2 \theta)^2} \, \dot{\omega}_1$$

 Apart from situations where the angle α remains small, Hooke joints gives rise to variation of the output speed and thus angular accelerations that are detrimental for a power transmission with constant rotation speed.

 The non homokinetic nature of the Hooke joint is a source of vibrations which are more important for high angles and high rotation speeds.

| Fluctuation de la vitesse d'un cardan en fonction de l'angle des deux arbres | | | | | | | |
|--|-------------|-------------|-------------|-------------|-------------|--|--|
| α | 10° | 20° | 30° | 40° | 50° | | |
| $\frac{N_2}{N_1}$ | 0,98 à 1,02 | 0,94 à 1,06 | 0,87 à 1,15 | 0,76 à 1,30 | 0,64 à 1,55 | | |





Double Hooke joint

- To recover homokinetic properties, it is possible to combine two Hooke joints with a phase shift of 90° and to adopt kink angles a that have the same magnitude
- Let the function F_{α} that relates the engine speed to the output speed through the Hooke joints

$$\omega_2 = F_{\alpha}(\omega_1)$$

$$\omega_3 = F_{-\alpha}(F_{\alpha}(\omega_1)) = \omega_2$$

$$\omega_3 = F_{-\alpha}(\omega_2)$$



Homokinetic joints

- In automotive engineering, it was necessary to develop kinematic joints exhibiting homokinetic properties by construction (N₂ = N₁ at any time).
- **Tripod:** is based on three spheres articulated at 120° and able to slide in three cylindrical joints parallel to one of the shafts.
- In particular, it has an additional degrees of freedom in translation.



Homokinetic joints

 Four ball joints (Rzeppa): it is based on four balls at 90° which can roll in grooves (like in roller bearings) of toroidal shapes.







Homokinetic joints

 The two former homokinetic joints (Tripod and Rzeppa) are often coupled in transmission shafts connecting the differential and the wheel



Transmission shaft for front live axles



- Two kinds of homokinetic joints:
 - Tripod (Inner joint)
 - Rzeppa (Outer joint)

Transmission shaft for front live axles



Transmission shaft for front live axles



- In front driven vehicle, two homokinetic joints are used to cope with the suspension bounce/rebound and wheel steering leading to rotation speed fluctuation in the intermediate link and so vibration
- Shaft properties should be adjusted (diameter, inertia) to exhibits the same overall stiffness

Drive axle: solid shaft



Drive axle: hollow shaft



Wheel axles

- Keep the wheel in the right position, maintain the desired steering, and insure the transmission of propulsion torque
- It has to fix the wheels while enabling them to steer in turning conditions
- It serves as the load path from the contact patch to the chassis and body
- It is able to sustain the braking torques
- It is the supports to the shock absorber and damper
- The axle can be floating or semi floating



- Split types
- Banjo types
- Carrier types





Carrier type



Banjo type

Wheel axles: Full-floating axles

A full-floating axle shaft does not carry the vehicle's weight; it serves only to transmit torque from the differential to the wheels. It "floats" inside an assembly that carries the vehicle's weight. Thus, the only stress it must sustain is the torque (not lateral bending force). Full-floating axle shafts are retained by a flange bolted to the hub, while the hub and bearings are retained on the spindle by a large nut.



Wheel axles: Semi-floating axles

 A semi-floating design carries the weight of the vehicle on the axle shaft itself; there is a single bearing at the end of the axle housing that carries the load from the axle and that the axle rotates through.

SEMI FLOATING AXLE





Wheel axles: Three quarter-floating axles

In this axle bearing are on the outer side of casing between the wheel and the axle casing. The wheels are fitted at the end of the axle by means of a key, bolt or nut. The weight of the vehicle is supported partly by the axle casing and partly by the axle. The main advantage of this type of axle over the half floating axle is that the major part of the load is taken by the axle casing and not by axle. Axle only takes care of the rotating and transmits the power.



Wheel axles: Full-floating vs semi floating axles


Wheel axles



- Load and deformation of different types of rear axles
 - Semi floating
 - Three quarter floating
 - Full floating