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TORQUE VECTORING DIFFERENTIAL

Maja Čavić, Marko Penčić, Miodrag Zlokolica
Faculty of Technical Sciences
Trg Dositeja Obradovića 5, 21000 Novi Sad,
Serbia

ABSTRACT

A differential is a particular type of gear set which is widely used in automotive applications. Due to the differential the two driving wheels of a car can rotate at different speeds as they follow different ways around a corner. Conventional differentials usually split the torque symmetrically to both driving wheels. The drawback of this property is, that if just little torque can be transmitted by one wheel, the torque at the other wheel is reduced too. In order to improve the traction it is necessary to block the differential and retransfer the torque to the wheel with the better friction conditions. Such simple blocking of the differential can lead to significant problems in handling of the vehicle. In order to solve the problem the differentials have to be designed to actively distribute (vector) the driving torque among vehicle wheels and, in this way, to improve the vehicle movement.A torque vectoring differential is presented in this paper. Torque vectoring function is achieved through an additional assembly comprising of the differential gear set and motor. Since this solution does not use friction components it is efficient and durable.

Keywords: differential, torque vectoring, dynamics

1. INTRODUCTION

When cornering, vehicle wheels have to rotate with different angular velocities because they have to travel different distances in the same time interval. The same situation occurs when the radii of vehicle wheels differ (due to a difference in tire pressure or tire ware), in this case the wheels traverse the same distance but have different radii. The differential is a mechanism that facilitates torque transmission to the left and right wheels while they rotate with different angular velocities. In a conventional - open differential the torque distribution is constant and equal, even if the angular velocities of the two output shafts differ. Maximal torque that can transferred with the differential is [1]:

$$T = \min(T_e, T_{w1}, T_{w2}) \tag{1}$$

where:

T_e – torque generated by the engine,

$T_{w1} = \mu_1 F_{N1}$ – resistance torque on the wheel 1,

$T_{w2} = \mu_2 F_{N2}$ – resistance torque on the wheel 2,

F_{N1}, F_{N2} – normal reactions between wheel 1 and 2 and the road, and

μ_1, μ_2 – coefficient of friction between wheel 1 and 2 and the road.

When one of the driving wheels encounters a surface with a low coefficient of friction, it will start to spin because all power is diverted to that wheel. The other wheel becomes stationary and the vehicle tends to stop. In order to move the vehicle it is necessary to block the differential i.e. to kinematicaly join the two half shafts. This way, the engine power will be retransferred to the wheel with better friction conditions thus enabling movement of the vehicle. These differentials can lead to significant difficulties in handling and transverse dynamics characteristics of the vehicle. New types of differentials are developed to solve those problems. They have special mechanisms for active distribution (vectoring) of driving torques among vehicle wheels ant they drive wheels in such a way to influence the direction of vehicle movement thus improving the steering.

Modeling of the torque vectoring mechanism with the aspect on the of power transmission is presented in this paper. Analysis of the torque vector function is performed and possibilities of the optimization are investigated.

2. STATE OF THE ART

Lockable differentials are presented in [2]. Working principle is based on the locking i.e. kinematic joining of the half shafts which forces both wheels to turn in unison. Locking can be done manually or automatically. Because they do not operate as smoothly as standard differentials, locking differentials are often responsible for increased tire wear. Also, automatic locking differentials significantly affect the vehicle steering.

Limited slip differentials (LSD) tend to eliminate the difference between angular velocities of the vehicle wheels. They transfer torque to the slower wheel i.e. a redistribution of the torque from wheel with less traction to the wheel with better traction, is done. This comes handy in a situation when one of the wheels is on the surface with the small coefficient of friction and is spinning – torque is transferred to the other wheel and a vehicle can move. Limited–slip differentials can either be simply mechanical (passive) [3] or electronically controlled (active) [4]. Their main characteristics is that they allow magnitude but not direction of torque transfer to be controlled. Both types are usually based on clutches or other friction elements to alter the torque distribution. Problem arises during vehicle cornering in normal road conditions. More torque is transferred to the inner wheel and less to the outer one. This difference invokes the difference between tractative forces which, further, generates moment around the vertical axis of the vehicle. The moment acts in the direction opposite of the direction of the vehicle rotation thus making the steering difficult [5].

Torque vectoring differential can actively transfer torque to the half shafts regardless to the angular velocities of the wheels i.e. it is possible to direct a higher torque to the wheel that rotates with a higher speed. These differentials can, not only, provide significantly larger tractative forces but improve dynamic behavior of the vehicle as well so they stand up as good solutions. Developed designs are based on automatically controlled brakes or clutches for torque generation [6], [7]. Nevertheless, thermal capacity and durability of the clutches present a significant issue in a differential and have a major impact on its performance.

A solution to perform torque vectoring without clutch technology is presented in [8]. Continuously variable transmission with torque transfer shaft is used and, in comparison with solutions with clutches, significant energy saving is obtained.

In this paper, a conception of the torque vectoring differential which use electric motor and a gear set for moment generation is presented. Considering the fact that electric motors already exist in contemporary differential designs, this solution has same level of complexity and price in comparison with other designs. Because it does not have friction elements losses are diminished making it very efficient.

3. DIFFERENTIAL – DESIGN AND FUNCTIONING

Kinematic scheme of the torque vectoring differential is presented in Figure 1. It has two main assemblies:

1. standard open differential (gears 1,2,3,4 and 5) which realizes main torque transfer
2. differential gear set (gears 6,7,8,9,10,11 and 12 and carriers k_1 and k_2) with electro motor which provides (adds or subtracts) additional torque. In order to provide additional torques of the equal intensities but opposite directions to the wheels, gears 6, 7, 8, and 9, 10, and 11a have the same dimensions respectively. Gear 11 has both inner 11a and outer 11b. Carrier k_1 is rigidly connected to the link 2 (housing of the open differential assembly). Carrier k_2 is rigidly connected to the right half shaft. For simplicity only one planetary gear 10 is presented in Fig.1. Motor is automatically controlled.

3.1. Power transmission analysis

When vehicle moves in a straight line in normal road conditions there is no need for torque vectoring and differential performs as standard open differential. Motor is stationary and so are gears 11 and 12. Thanks to the gear dimensions, angular velocities of the carriers k_1 and k_2 are equal so angular velocities of the wheels and the housing 2 are equal too.

When a need for torque transfer arises (loss of traction, dynamic cornering) motor starts and transfers torque to the gear 12. This torque is then transferred, through differential gear set, to the housing 2 and right half shaft. Kinetostatic analysis of the differential is presented in Figure 2. Since inertial moments of the gears have small values in comparison with the active loads they can be omitted from the analysis.

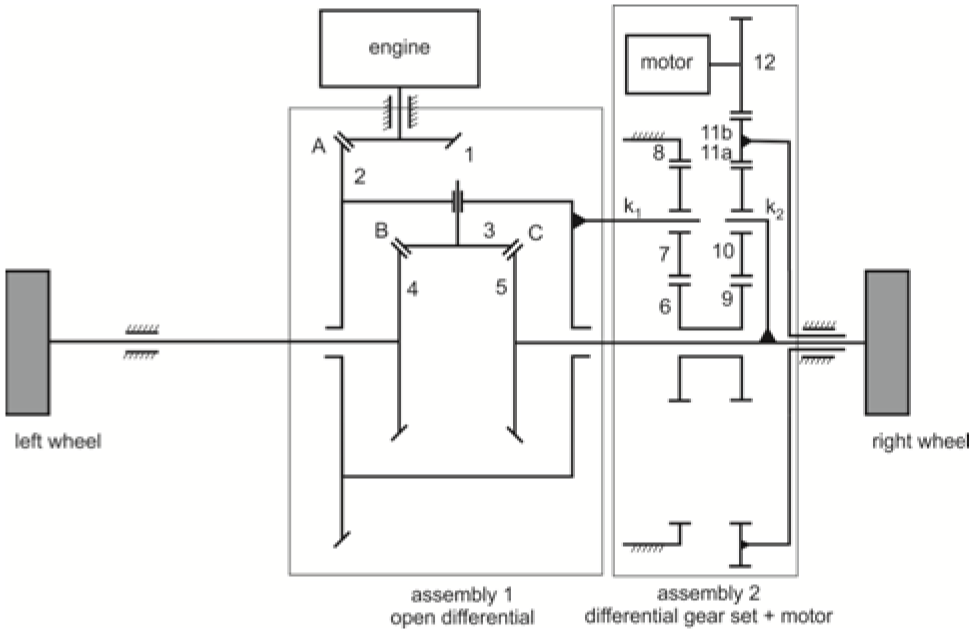
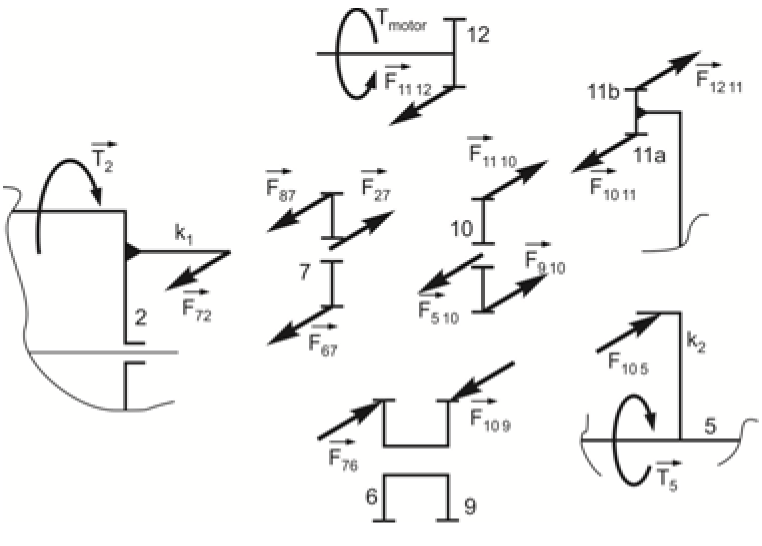


Fig. 1. Kinematic scheme of the torque vectoring differential, 1-12 gears, k_1 and k_2 - carriers

Following equations are derived from Fig. 2. Symbol F_{ij} is used to denote force with which link i acts upon link j and r_i is radius of the link i. Only tangential forces in the meshing points of the gears are considered since radial forces do not influence power transfer.



$$T_{motor} = F_{11\,12} r_{12} \quad (2)$$

$$F_{12\,11} = F_{11\,12} \quad (3)$$

$$F_{12\,11} r_{11b} = F_{10\,11} r_{11a} \quad (4)$$

$$F_{11\,10} = F_{10\,11} \quad (5)$$

$$F_{11\,10} = F_{9\,10} = F_{5\,10} / 2 \quad (6)$$

$$F_{10\,5} = F_{5\,10} \quad (7)$$

$$F_{10\,9} = F_{9\,10} \quad (8)$$

$$F_{10\,9} = F_{76} \quad (9)$$

$$F_{67} = F_{76} \quad (10)$$

$$F_{67} = F_{87} = F_{27} / 2 \quad (11)$$

$$F_{7\,2} = F_{27} \quad (12)$$

Fig. 2. Kinetostatic analysis of the torque vectoring differential

$$T_{\Delta 2} = F_{7\,2} r_{k1} = F_{10\,5} r_{k2} = T_{\Delta 5} = T_{\Delta} \quad (13)$$

From equation (12) and Figure 2. it can be concluded that the additional torques T_{Δ} of the same intensities but opposite directions are transfered to the right wheel and housing 2. Overall torques on the right wheel and the housing in the torque vectoring regime are (T_2 and T_5 are torqueson the right wheel and the housing generated form the vehicle engine):

$$T_{2active} = T_2 - T_\Delta \tag{14}$$

$$T_{5active} = T_5 + T_\Delta \tag{15}$$

Having in mind equation of moment equilibrium for the differential with three coaxilal elements [9] it can be written:

When there is no torque vectoring – torques on the wheels are generatd only by vehicle engine:

$$T_2 - T_4 - T_5 = 0 \tag{16}$$

When ther is torque vectoring – torques on the wheels are generated by vehicle engine and motor:

$$T_{2active} - T_{4active} - T_{5active} = 0 \tag{17}$$

From equations (14) - (17) following is obtained:

$$T_{4active} = T_4 - T_\Delta \tag{18}$$

Same amount of the torque T_Δ that is added to the right wheel is subtracted from the left wheel.

By changing the direction of the motor rotation, sign of the additional torque is changed, so now torque is subtracted from the right wheel and added to the left one:

$$T'_{5active} = T_5 - T_\Delta \tag{19}$$

$$T'_{4active} = T_4 + T_\Delta \tag{20}$$

Amount of the additional torque depends on the power of the electromotor and the transmission ratio of the gear pair. If there are difficulties concerning the motor adoption one can intervene by modifying transmission ratio (11b,12). Whereas there are several (3-6) planetary gears 7 and 10, differential gear set has high load capacity and, accordingly, can have relatively small overall dimensions.

4. CONCLUSION

In this paper a concept of the torque vectornig differential is presented. It has two main assemblies: standard open differential which realizes main torque transfer and a torque vectoring assembly which consists of differential gear set with electro motor and provides (adds or subtracts) additional torque. Assembly for the torque vectoring enables transfer of the additional torques of the same intensity and opposite direction to vehicle wheels. Amount of the additional torque is determined by automatic regulation of the motor. Direction of the additional torque is changed by altering the direction of the motor rotation. Because of the high load capacity due to the number of the planetary gears, differential gear set can have small overall dimensions. Since this differential does not have friction elements, its efficiency is better in comparison with current designs which are traditionally oriented to the clutch technology. In further work an accurate mechanical model of the differential including the tire model and complete vehicle dynamics will to be developed in order to design control strategy and investigate the behavior and stability of the whole system.

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