CAPABILITIES AND LIMITATIONS OF TORQUE VECTORING SYSTEMS (WHICH CORRECT THE DIRECTION OF MOVEMENT BY WHEEL DRIVING FORCES) IN MOTOR VEHICLES

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Summary

The presentation covers the idea and purpose of the systems that influence vehicle's drive direction by torque vectoring. Based on results of model simulations and experimental testing of existing systems, the effectiveness of such systems has been shown. The basic variants of Torque Vectoring systems, capable to fit in wheeled vehicle's single drive axle, have been presented and compared with each other. Particularly much attention has been dedicated to the description and analysis of the group of designs referred to as "active differential gears", featuring an additional inner kinematic bond. A few known designs of this kind, including those available in the market, have been described in detail. A comparison between them has highlighted significant differences in their kinematic layouts and control systems. The author has also tried to define directions of further development and standardization of the active differential gears. A particular design of such differential gears applied to electric and hybrid vehicles has been discussed and an author's own concept has been presented. In the final part, an attempt has been made to answer a question how the Torque Vectoring systems affect the active safety of motor vehicles, with highlighting the necessity of taking into account the capabilities of such systems in respect of the handling and transverse dynamics of a vehicle at post-accident simulations and analyses.

Keywords: power split devices, active differential gears, vehicle handling, transverse dynamics

1. Introduction

The impact of power split devices in wheeled vehicles on the direction of driving and the vehicle handling has been perceived for a very long time, or rather from the very outset of motorization. At first, it was found that two wheels of one axle, rigidly connected with each other by a shaft, caused significant difficulties in the vehicle turning and an increase in the resistance to motion when a vehicle moved along a curve. It was because of the necessity

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to eliminate this drawback that an inter-wheel differential gear was invented over 100 years ago. However, differential gears in their simplest form brought new problems, including the one considered as probably most important, that is the worsening of vehicle's driving properties. To improve the situation, different methods of restraining the operation of differential gears were introduced, from various kinds of solutions referred to as "differential locks" to an extremely wide range of differentials with increased inner friction. A final effect of this period of development efforts was a situation that, depending on the degree of improving the vehicle's traction, the differential gear more or less impaired the handling and turning radius of the vehicle. This may be concisely expressed in a statement that until quite recently, the more advanced construction of the vehicle's differential(s) was, the worse handling and transverse dynamics characteristics of the vehicle were. Only the present-day look at the motor vehicle and giving the prime importance to the safety requirements resulted in raising other expectations about differential gear components, including in particular power split devices. An idea emerged to drive vehicle wheels in a way influencing the direction of vehicle movement, most often referred to as "torque vectoring", with building special systems for active distribution of driving forces among vehicle wheels. Now it is known that the driving system can modify the direction of vehicle movement by changing the distribution of driving forces between front and rear axle wheels (in 4WD systems), by changing the distribution of driving forces between left and right wheels, or by employing both methods at the same time. In this presentation, most attention has been dedicated to the second method, which is implemented by applying solutions referred to as "active differential gears". Thanks to special design, such mechanisms make it possible to direct a higher driving force to the wheel that rotates with a higher speed and thus to assist in making a turn by the vehicle (Fig. 1).

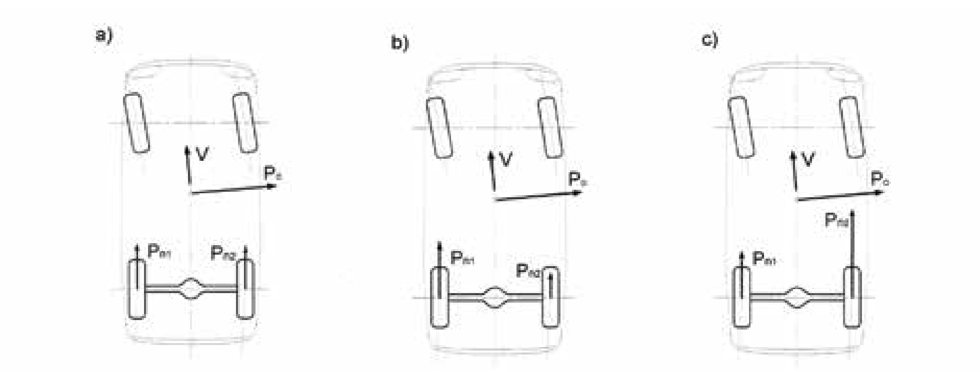

Fig. 1. Distribution of driving forces between wheels in a turning vehicle, in the case of various differential gears: a) simple (open) differential; b) limited slip differential; c) active differential gear performing the "torque vectoring" function

This means that the Torque Vectoring systems and their active differential gears can play an almost identical role as that played by the systems known previously, in most cases referred to as ESP (which stands for "electronic stability program"), where braking forces are used for this purpose. However, the basic difference and, simultaneously, the superiority of the torque vectoring lies in the fact that the driving forces are employed in this case, which results in a possibility of significant improvement in the longitudinal and transverse vehicle dynamics.

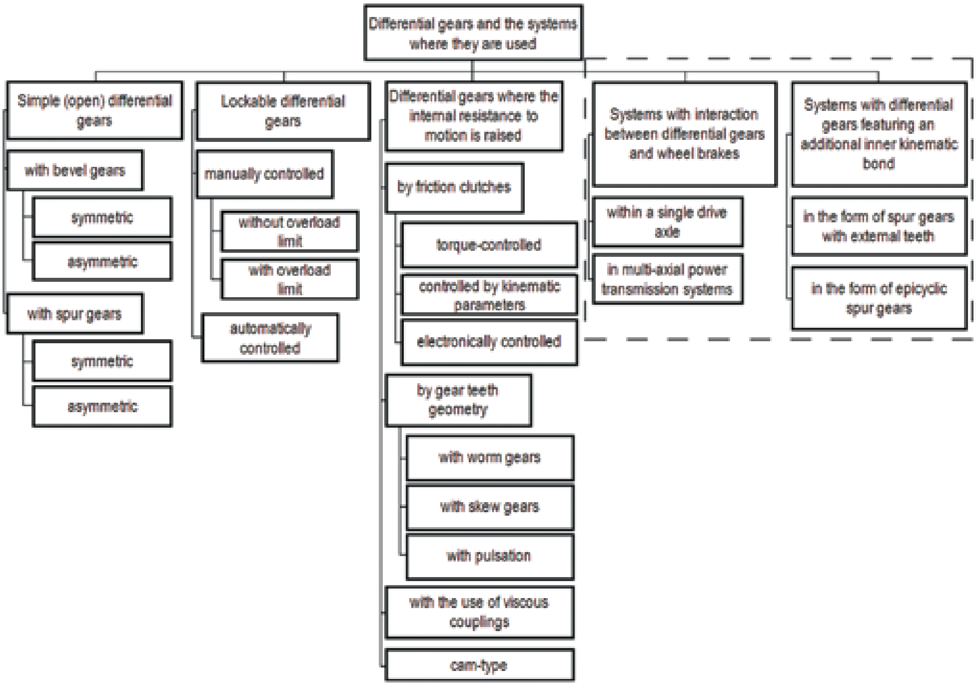

Fig. 2. The location of Torque Vectoring systems and their active differentials in the overview of power split devices

An overview [4] of the major types of differential gears developed in the recent several decades has been presented in Fig. 2. The two right columns comprise the most modern groups of designs, which may be classified as Torque Vectoring systems; the functioning of the types mentioned in the rightmost column is based on the operation of "active differential gears".

Basically, the idea of operation of the Torque Vectoring systems where active differential gears are employed draws on the functioning of the tracked vehicle turning gears. Based on [2], Fig. 3a represents a top view of a crawler tractor in curvilinear motion and one of its possible turning gears, comprising a "double differential gear", has been shown in Fig. 3b. In such a system, the tractor is caused to turn by applying a specific angular velocity to the planet wheel carrier in the drive axle differential gear, in result of which the tractor tracks move with different speeds.

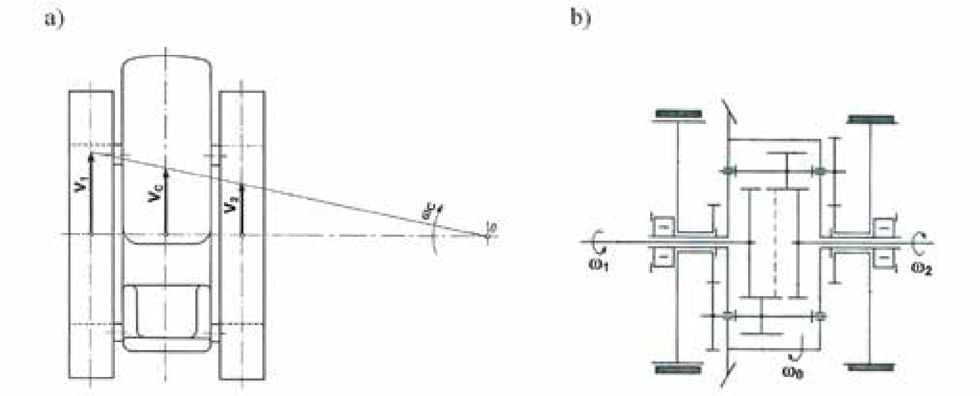

Fig. 3. Similarity of the Torque Vectoring systems to the tracked vehicle turning gears: a) tracked vehicle in curvilinear motion (V_1, V_2, and V_c – longitudinal velocities, ω_c – vehicle's angular velocity); b) an example of the turning gear with a double differential gear (ω_1, ω_2, and ω_0 – angular velocities of the output shafts and differential gear housing)

A similar process can be observed in motor vehicles. By imposing different driving forces on the road wheels of a single drive axle or by diversifying the angular velocities of the wheels, a vehicle yaw torque M_z is generated. Then, if such an input is consistent with the sign of the steering wheel turning angle, the tyre sideslip angle is changed and the vehicle turning effect is enhanced.

2. Influence of power split devices on the vehicle trajectory

The impact of road wheel driving forces, or rather of the relation between the forces, on the motion of vehicles with 4×4 and 4×2 wheel arrangement has been perceived from the very outset of the presence of vehicles driven by their own power sources. They were vehicle-turning difficulties that resulted in the devising of differential gears and in the extensive development in this field for the whole period of vehicle construction up to the present. Very much experimental and model research work on this issue was done [1, 3, 4, 6, 7, and 8]. Fig. 8 illustrates author's own experiments [4], carried out within research on the motion of a Honker 4×4 vehicle where a differential gear with stepwise-changing torque of inner friction was incorporated in the rear drive axle.

The tests carried out at a vehicle driving speed of 11 km/h for the differential operation modes where the inner friction torque was M_T = 0 and and M_T = 800 Nm showed that the vehicle path diameter increased by more than 11 % in the latter case.

Fig. 5a shows a prototype Cinquecento 4×4 car developed at OBR SM BOSMAL (Automotive Research and Development Centre BOSMAL) in Bielsko-Biała, during tests of its transverse dynamics; the vehicle paths obtained at the tests have been presented in Fig. 5b [4]. The power transmission system of that car was developed to a form that made it possible to

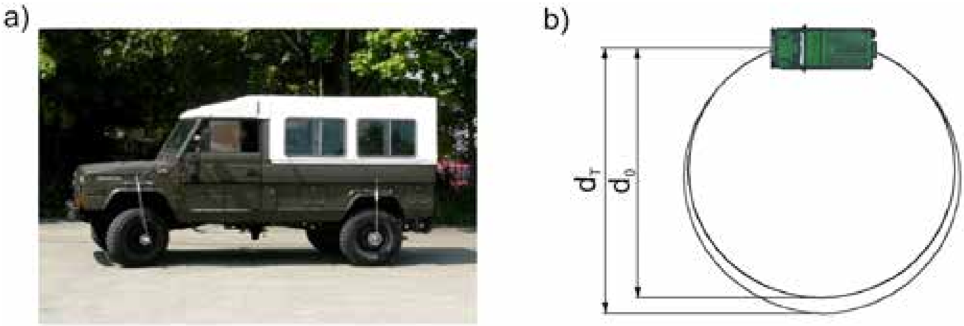

Fig. 4. The testing of a Honker 4×4 vehicle having a rear drive axle differential with variable inner friction torque M_T: vehicle path diameter d_0 = 10.25 m for M_T = 0 and d_T = 11.40 m for M_T = 800 Nm

test the car in three operation modes: front wheel drive (4×2) only, four-wheel drive with final drives of both axles being kinematically rigidly connected with each other (4×4), and four-wheel drive with an additional inner friction torque being applied in the differential gear of the rear drive axle (4×4+T). In this case, too, deterioration in the vehicle handling was observed in the system operation modes that raised the driving properties of the power transmission system (i.e. 4×4 and 4×4+T).

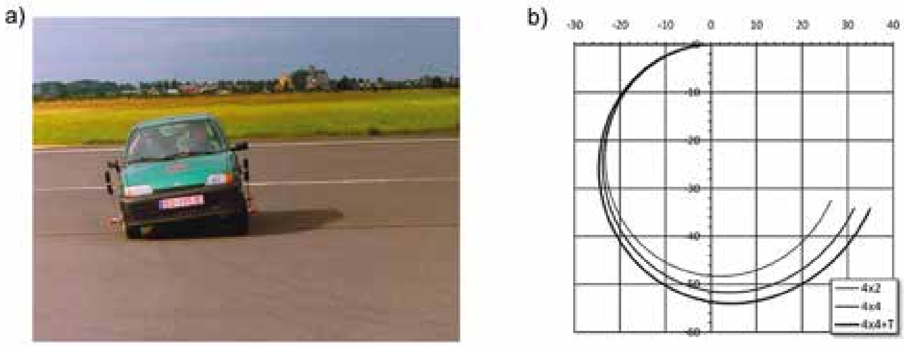

Fig. 5. A prototype Cinquecento 4×4 car during field tests (a) and the vehicle paths obtained for different modes of operation of the car's power transmission system, i.e. 4×2, 4×4, and 4×4+T (b)

Figs. 6 and 7, in turn, show the assumptions made at model simulation testing of a small urban vehicle electrically driven and some results of the tests, respectively [4]. The simulations of vehicle motion were carried out for different proportions between the the torques transmitted to the rear wheels. The indicator SEP = M_Z/M_W having been adopted was defined as the ratio of the torque applied to the outer wheel to the torque applied to the inner wheel when the vehicle moved along a circular path. An analysis of Fig. 7 shows that the smallest diameters of the vehicle path were obtained for the operation states with SEP = –3 and SEP = 2, which were only made possible by the Torque Vectoring systems.

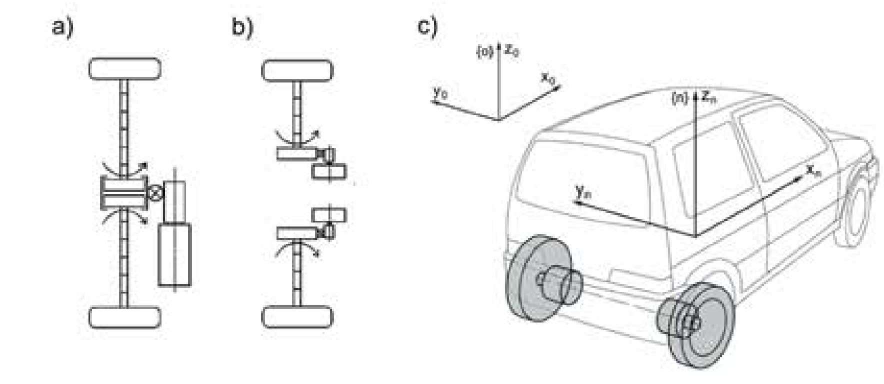

Fig. 6. Model simulation testing of an urban vehicle with two different rear wheel driving methods: a) wheels driven by an electric motor via a differential gear; b) wheels driven by two separate electric motors; c) vehicle model adopted

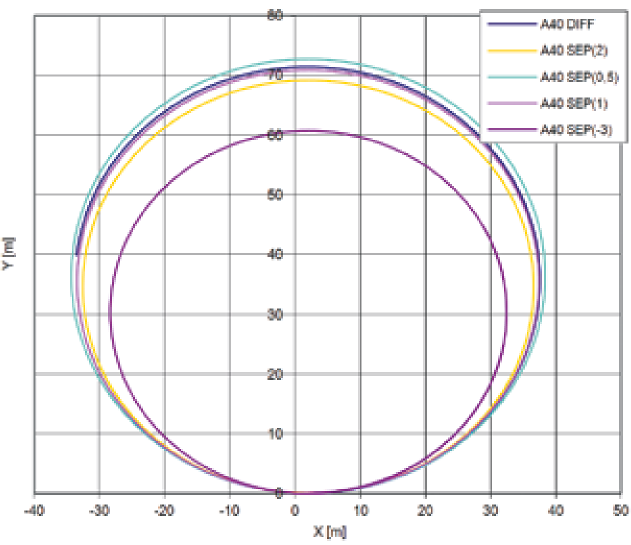

Fig. 7. Results of model simulation tests of a Cinquecento 4×4 vehicle at 40 km/h speed and various outer to inner wheel torque ratios SEP = M_z /M_w

The above examples of the influence of power split devices on the vehicle path and transverse dynamics may be supplemented with results of experimental testing of the active differential gears having already been launched. It can be seen in Fig. 8 [1] that the operation of such a differential gear may result in an increase in the centripetal acceleration by about 1.5 m/s^2, which means that a vehicle following a circular path with a radius of R_s = 40 m may be driven with a speed faster by about 10 % at the same turning angle of its steered wheels.

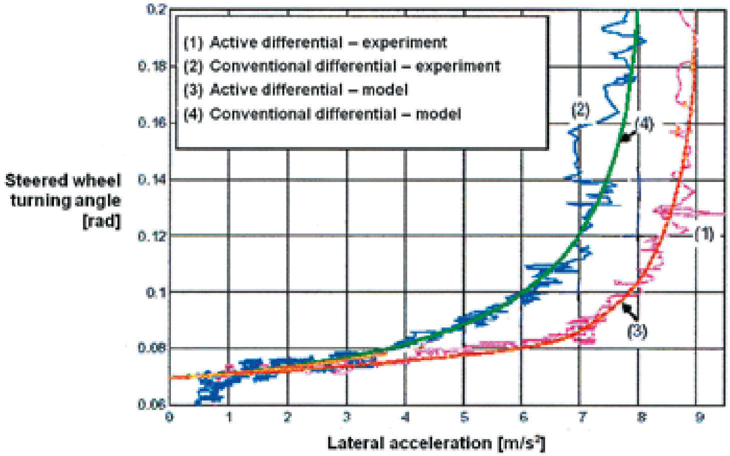

Fig. 8. Handling characteristics of a vehicle with an active differential gear fitted in its rear axle when driven on a circle with a radius of R_s = 40 m on a surface with good grip, according to [1]

The research results presented in Figs. 4b, 5b, and 7 show that the power split devices have a very significant impact on the vehicle trajectory and parameters of motion.

3. Possible methods of implementation of the function of an active differential gear

A problem to be solved is the question how to achieve the torque vectoring of a vehicle with the use of the simplest possible means and at the lowest possible cost. As it is known from textbook descriptions of the kinematics and dynamics of differential gears, increased driving forces cannot be achieved on the outer wheels of a vehicle driven on a curve if low wheel slip values are assumed. Such an effect cannot be achieved, either, by increasing the inner friction torque or by using special locking clutches in the differentials; basically, such methods even make the situation worse.

When the possible methods of solving the above problem are analysed, the four options described below seem to be possible.

a. Differential with variable internal gear ratio

A schematic diagram of such a system in the rear drive axle has been shown in Fig. 9. The features that may be considered good points of such a proposal include considerable freedom in setting the proportions between driving torques on vehicle wheels regardless of the vehicle path. However, the controlling of such a system might be very difficult because the value of the outer wheel torque M_z will depend not only on the value of the internal gear ratio having been set but also on the input torque controlled by the driver. A considerable drop in this input torque or even a transition to the engine braking mode may cause a change in the value or even sense of the torque and cause a hardly controllable change in the vehicle motion characteristics. An additional barrier is the lack of refined designs of continuously-variable intersecting-axis gears capable of transmitting sufficiently high torques at confined dimensions and fulfilling the function expected.

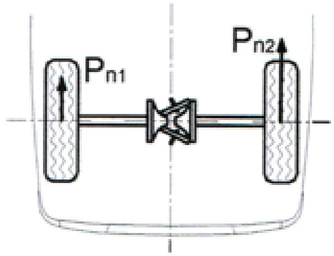

Fig. 9. Implementation of the function of an active differential by the application of a variable-ratio toroidal friction gear

b. Additional kinematic bond between axle shafts

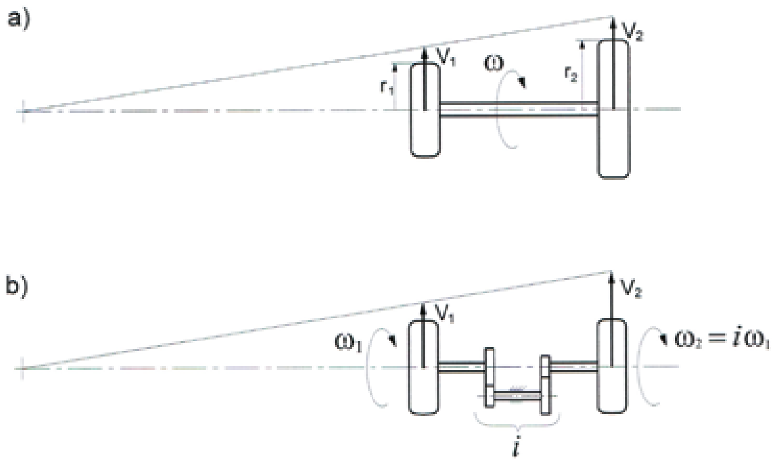

Fig. 10. Idea of an additional kinematic bond in the active differential gears: a) wheels of different radii coupled by a rigid shaft; b) wheels of equal radii kinematically coupled by a gear train

An idea of such a solution, corresponding with Fig. 3, where reference has been made to the example of a tracked vehicle, has been presented in Fig. 10. In the cases having been illustrated, the driving of one of the road wheels with a higher peripheral speed results in the operation of this wheel with a higher slip value and, in consequence, with a higher driving force. The schematic diagram shown in Fig. 10a is impracticable but the one in Fig. 10b is already realistic and used in modern designs. Undoubtedly, a good point of this option is the fact that it is relatively easy to be implemented with the use of known technologies (toothed gears); moreover, it always helps the vehicle to turn in the predetermined direction regardless of the current state of vehicle operation (i.e. whether the vehicle is being driven or braked by its engine). A problem associated with such designs lies in the fact that an additional gear train of this kind usually offers a single gear ratio, although the gear ratio should be variable and depend on the current radius of the vehicle trajectory. In practice, this problem is circumvented by applying a gear train with an optimum multiplying ratio, in most cases causing one road wheel to rotate with an angular velocity exceeding that of the differential gear housing by 10 %, and by using slip clutches whenever the ratio of the additional gear train should be different. Obviously, a solution like this causes some energy losses in the power transmission system. Besides, situations are also possible that for very small turning radii the differential gear may be incapable of generating wheel-driving torques in appropriate proportion. In addition to this, designs of this kind are always very complicated and, in consequence, relatively heavy and expensive.

c. Differential assisted by wheel brakes

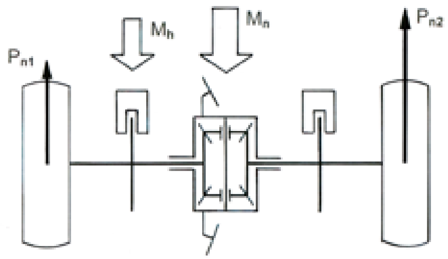

Fig. 11. Differentiation of wheel driving forces by means of a simple differential gear and separately controlled wheel brakes

This idea has been illustrated in Fig. 11. The state of differentiation of the driving forces on the road wheels of a drive axle, with the driving force on the faster wheel being higher than that on the other wheel, may be achieved by applying an input driving torque to the differential gear housing with simultaneously controlling the braking torque generated by one of the wheel brakes. The good points of such a solution include the fact that only the mechanical components that are present in a standard vehicle are employed and that the control system is similar to those used in the ESP systems in vehicles. On the other hand, power losses caused by the operation of brakes, thermal loads of the brakes, and difficulties in controlling the system that arise from the system susceptibility to the current state of operation of the vehicle driveline, or in other words to the value of the input driving torque applied to the differential gear housing and controlled by the vehicle driver, should be mentioned as bad points.

d. Driving of vehicle wheels by separate motors

This method of implementation of the torque vectoring idea seems to be obvious and the simplest to be applied in practice (Fig. 12).

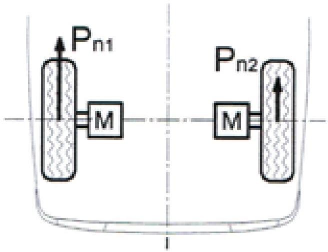

Fig. 12. Implementation of the active differential functions by using separate motors to drive the road wheels of the vehicle

Undoubtedly, a good point of the solutions of this kind is the freedom in generating the necessary wheel driving torques, which may differ from each other in both their values and senses. However, the driving of vehicle wheels with separate motors requires a complete change in the driving system concept, as electric or hydraulic motors must be installed at or in the wheels. Such designs are usually characterized by increased mass and lower efficiency. Hence, the systems of this kind are chiefly implemented in hybrid or electric vehicles, where electric motors are to be installed as standard, anyway.

4. Some designs of active differential gears

The earliest research works on Torque Vectoring systems include those carried out at Centro Ricerche FIAT [1] and Mitsubishi introduced its own designs as long ago as in its Lancer Evolution VII models in 2001. At present, active differential gears are offered in upper-class cars of several makes. Noteworthy is the fact that the existing designs, in their overwhelming majority, are based on the idea of controlled engaging of an additional kinematic bond between the differential gear housing and the left or right axle shaft. The most advanced solutions include those employed in BMW and Audi cars. In the design developed by ZF Friedrichshafen for BMW (Fig. 13) [3], planetary gears have been provided on both sides of a conventional bevel-gear differential, capable to speed up the left or right axle shaft by about 10 %. Each of the speeding-up gear trains is engaged by a multidisc friction brake, which immobilizes the planet wheel carrier. The brakes in turn are operated by a mechanical system driven by two separate electric motors. The system operation layout makes it possible to apply an additional torque of even up to 980 Nm to a selected axle shaft with the use of a relatively low controlling braking torque. As it can be seen in the illustration, the system is quite complicated and increases the vehicle mass, but it shows high effectiveness and strength even if it cooperates with the largest power sources (with an output torque of up to 680 Nm).

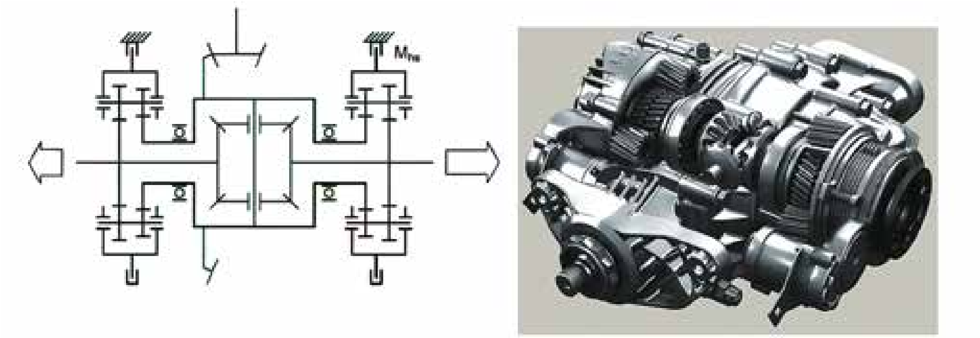

Fig. 13. Schematic diagram and view of the active differential gear applied to the rear drive axle of the BMW X6 car

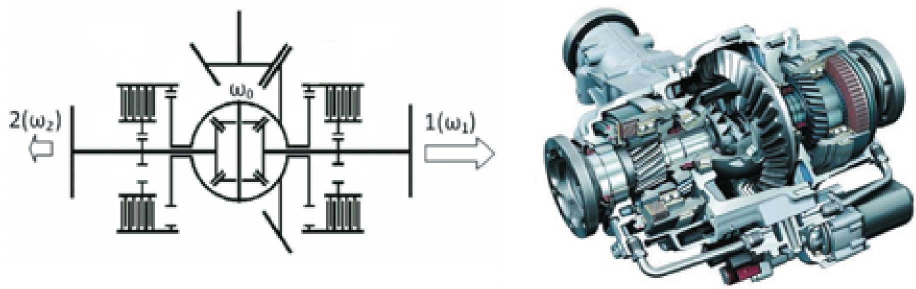

Fig. 14. Schematic diagram and view of the active differential gear developed by Audi

An active differential gear of somewhat different design (Fig. 14) has been applied to some Audi car models. In this case, single internal gear pairs and multidisc clutches to engage the gear pairs have been provided to speed up the outer wheel axle shafts. The clutch discs are clamped hydraulically and oil under an appropriate pressure is supplied by an external hydraulic pump driven by an electric motor. The whole unit is somewhat smaller and lighter than that used in the BMW cars; therefore, it is chiefly offered in sport car models. Other manufacturers' designs, e.g. those developed by GKN [14], Ricardo [11], Magna Steyr [10], or Getrag [7] may be mentioned here as well. Interest may also be aroused by the designs intended for hybrid and electric vehicles, such as those prepared by IAV [8, 15] or Schaeffler [13].

5. Searching for author's own concepts

The presented several manufacturers' achievements in the field of active differential gears cannot be considered completely satisfying. This is not because of their inadequate functioning; the reason is rather their complex design and high costs of production. It seems to be very advisable to continue studies and research and development work in order to develop simple solutions suitable for wide applications even in medium-class cars. The author is of the opinion that so far, too little attention was dedicated in the field of development of active differentials to the searching for multiplying transmissions other than conventional toothed gears. In 1980s, extended research and development works were carried out under author's management on differential gears having new operating characteristics and intended for off-road vehicles. Several dozen prototypes functioning on various principles were built, which were then tested at experimental departments of Polish automotive equipment manufacturing plants, technical universities, a military institute, and army units. Their designs were granted patent protection in more than ten countries, including the USA (patent No. 4 343 205) and Japan (patent No. 1 468 625). In the designs tested, unique methods were used to generate rotational speeds, which were then used as reference values in control systems. The concepts developed and the experimental tests carried out have been more comprehensively described in [4]. In author's opinion, the experience gathered indicates that there is a chance for the construction of much simpler active differentials, which should be based on mechanical transmissions other than gear trains. One of the possible concepts has been presented in Fig. 15.

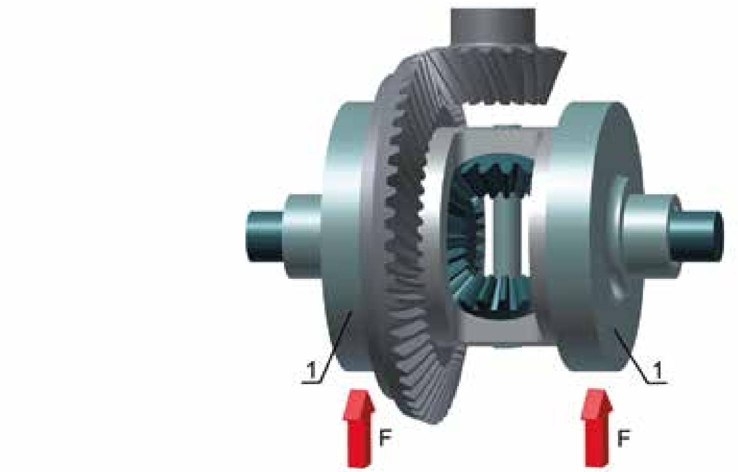

Fig. 15. General concept of an active differential gear of a new type: 1 – multiplying transmissions of a new type; F – radial forces to control the transmission ratios

An essence of this concept of an active differential gear lies in the mechanical transmissions of a new type (1) and the transmission engagement system; thanks to the new concept adopted, the transmissions are expected to be simpler and easier to be controlled in comparison with the transmissions previously used. Preliminary analyses have shown a possibility that they would be smaller and mounted directly in the differential gear housing. Development of this concept or of other related ideas will create chances for significant simplification and reduction of costs of such systems in comparison with those of the designs existing and known hitherto.

6. Final remarks

The presented analyses and brief review of the state of the art in this field provide grounds for the formulation of a few general remarks as specified below.

- The active differential gears available to date are very complicated, relatively heavy, and expensive, in result of which the range of their application is limited to upper-class vehicles.
- Further search for new design concepts of such systems is recommendable.
- The development works being in progress may be expected to result in the working out of such a design standard of active differential gears that will be suitable for wider application.
- Active differential gears improve the lateral stability and handling of a vehicle, which means that they increase the safety of driving. This, however, will only be true if the drivers abstain from raising the driving speeds to new safety limits.
- At the simulations of road traffic situations, the functioning of an active differential gear (if provided in any of the vehicles involved) should be taken into account in consideration of its significant impact on the direction of vehicle motion.

The author is convinced that in spite of problems in the spreading of drive systems with active differential gears, the development of differentials of this kind will be continued, because a vehicle provided with such a drive system is simply better.

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