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DESIGN OF A NEW TYPE OF SELF-LOCKING AXLE DIFFERENTIAL INTENDED FOR INSTALLATION IN LIGHT ROAD VEHICLES, DESIGNED TO INCREASE THE RELIABILITY OF FUNCTION

Miroslav Blatnický, Ján Dižo, Ivana Domaniková, Kateryna Kravchenko
University of Žilina, Slovakia

Abstract

Modern torque transmission systems used in road vehicles ensure reliable driving performance under all weather conditions, which makes us benefit in reliability for vehicle, namely by increasing traction, stability, transmitting engine power to the wheels, which increases the safety on roads due to vehicle performance remaining consistent under varying road conditions. The differential is a key component of the vehicle drivetrain, enabling the wheels on the same axle to rotate at different angular velocities when negotiating a turn or a corner. In this manner, the differential distributes the engine torque between the wheels and enhances vehicle controllability. There are several types of differentials, which differ in their methods of torque transmission principles and in the methods used to limit wheel slipping. This research focuses on the design of a new type of automotive differential intended for installation as a part of the drivetrain of a passenger car or a light commercial vehicle. The proposed structural design represents an innovative technical solution in the field of self-locking differentials due to improving reliability of function and sustainability of a road vehicle due to reducing emissions and lower energy loses. Meanwhile other types of self-locking differentials currently used in vehicles incorporate electronic assistance and software-based control, the presented differential concept is capable of redirecting torque purely on mechanical principle with the aid of flowing lubricating oil. The proposed innovative differential then behaves as a hydrostatic converter, utilizing the pressure energy of the working medium, i.e. oil. The article presents schematic models of the differential as well as a 3D model of the most important structural assembly together with the main concept of its design solution and its operating principle. It is assumed that this innovative automotive differential may reduce the technical complexity of currently used self-locking differentials, improve reliability and contribute to the higher torque transmission efficiency which is beneficial for vehicle performance increasing, and leading to improved fuel economy.

Keywords: differential, vehicles, analysis, structural design

1 Introduction to problem statement

The conventional automotive differential was developed by the French mechanical engineer Onésiphore Pecqueur in 1827. It was initially applied in steam-powered vehicles, however, it became widely recognized primarily at the end of the 19th century, with the advent of the first internal combustion engines [1]. Since the introduction of the first differential, nearly two centuries have elapsed, during which these mechanisms have undergone various modifications, both in terms of materials and conceptual design. Nevertheless, there remains a scope for further technical optimization and innovation in their operating principles.

The automotive differential (figure 1) is a transmission mechanism whose primary function is to distribute torque between two driven wheels. At the same time, it allows each wheel to maintain its own angular velocity when negotiating corners and during changes in the vehicle´s direction of travel. In such situations, the inner wheel rolls along a shorter path than the outer wheel.

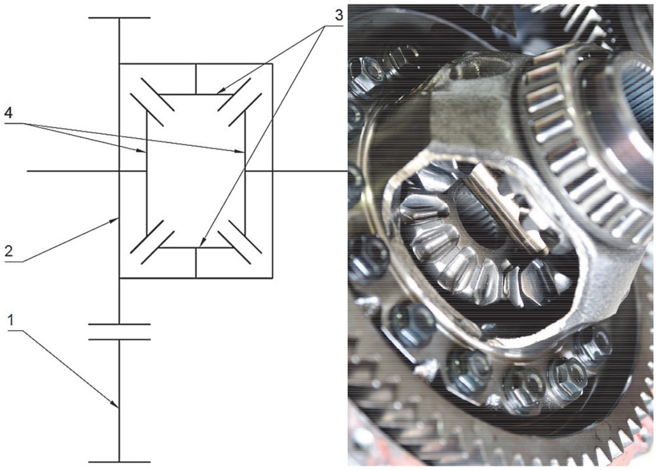

Figure 1 Schematic diagram of an automotive differential (on the left) and its documentation photograph (on the right), 1 – pinion gear, 2 – ring gear, 3 – satellite gears, 4 – planetary gears

By means of the differential, the drive shafts of both driven wheels are powered sequentially via the ring gear, the differential carrier, the satellite pinions, the satellite gears, and the planetary (side) gears. The satellite gears rotate together with the differential carrier, however, when cornering, they additionally rotate about their pins, thereby compensating for the different rotational speeds of the left and right wheels [2]. During straight-line driving, the rotational speeds of both drive shafts are identical. The satellite gears rotate together with the carrier but do not rotate about their pins. The planetary gears rotate at the same speed as the differential carrier, and the driving torque is evenly distributed between them. The ability of each wheel to maintain its own angular velocity is essential to prevent tire scrubbing against the road surface and therefore reducing the wearing of the road surface and improving its lifespan [3]. As a secondary effect, the differential prevents optimal distribution of the tractive force, since its maximum value is always limited by the minimum friction available at two wheels of the same axle. As a result, loss of traction leads to reduced vehicle controllability [4]. From a conceptual perspective, differentials can be classified as follows.

1.1 Open differential

The open differential is the most commonly used type of differential in motor vehicles. More complex solutions have subsequently evolved from this basic concept. It is mostly composed of a carrier rigidly connected to the differential case. Satellite gears with bevel gearing are mounted on the case by means of rotating pins and mesh with the planetary (side) gears. The differential case is driven by the input from the transmission, whereby the transmitted torque is evenly distributed to both outputs (driven wheels). The open differential delivers the same torque to both outputs regardless of differences in rotational speed, load, or wheel slip. If the adhesion of one wheel decreases to the level that it begins to slip, its resistance to rotation is reduced, and consequently, the transmitted torque decreases.

This results in an immediate reduction of torque by the same amount at the wheel with higher adhesion. As a result, the tractive force of both wheels is reduced; although one wheel slips (exhibiting a significantly higher angular velocity), the torques and tractive forces acting on both wheels remain equal. The reduction in the tractive force of one wheel is thus manifested twice, leading to a substantial decrease in the overall tractive force of the vehicle, which represents the principal disadvantage of the open differential [3]. This drawback can be mitigated by design modifications, either by incorporating a differential lock or by ensuring limited-slip functionality. The advantages of this type of differential include its simplicity, wide availability, and relatively low manufacturing and maintenance costs [5].

1.2 Locking differential

This type of differential is conceptually derived from the open differential. The difference lies in adding mechanism that enables the locking of the central (planetary/side) gears. This prevents the rotation of the satellite gears, forcing the differential to rotate as a single rigid unit. As a result, the entire torque is transmitted to the driven wheel with higher traction. This characteristic benefits in off-road vehicle operation. During normal driving conditions, the differential is used mainly in the unlocked state, functioning as an open differential. Driver-actuated locking of the differential is achieved by means of a sliding sleeve or a toothed clutch [6].

1.3 Self-locking differential

Self-locking differentials are used both in sports-oriented passenger vehicles and in motorsport applications mostly in performance-oriented driving condition surfaces. They are intended for driving conditions in which traction and stability are frequently compromised due to high accelerations and vehicle speeds [7]. Unlike open differentials, self-locking differentials are capable of transferring torque from the faster-rotating driven wheel to the slower one. The direction of torque transfer is determined by the difference in rotational speeds of the driven wheels, which is directly linked to the longitudinal traction available at each wheel thereby improving the vehicle traction and stability on the road surface. Self-locking differentials can be classified into limited-slip differentials (LSD), Torsen-type differentials, and self-locking differentials equipped with a viscous coupling [8].

2 Principle of operation of the new structural design

The construction of the axle-mounted self-locking differential (figure 2) for small road vehicles consists of four mutually meshing bevel gears. Specifically, it comprises two planetary (side) gears, which are connected via axle shafts to two satellite gears. This structural assembly is enclosed within a differential carrier equipped with a ring gear. The ring gear meshes with a pinion while maintaining the sphericity of the contact faces of the planetary and satellite bevel gears. The remaining free space between these contact surfaces is filled by two spherical plates featuring four specially shape-adapted surfaces. These plates are attached to an additional spherical hollow body (figure 3). One spherical plate fills the space between one set of opposing faces of the planetary and satellite gears. Second spherical plate fills the space between the opposite faces of these gears. At the corners of the spherical plates, eight flow channels with a defined diameter – depending on the vehicle type – are arranged radially through the wall of the spherical hollow body. Under normal operating conditions, i.e., during straight-line driving on a dry road surface, both planetary gears (to which the left and right vehicle wheels are connected) rotate at the same angular velocity as the differential carrier with the ring gear (figure 4 – straight-line driving).

If wheel slip occurs on one side (as illustrated in figure 4, center and right), a difference in rotational speed arises between the two planetary bevel gears. During their mutual relative motion with respect to the differential carrier with the ring gear, fluid flow occurs through eight flow channels in the spherical hollow body.

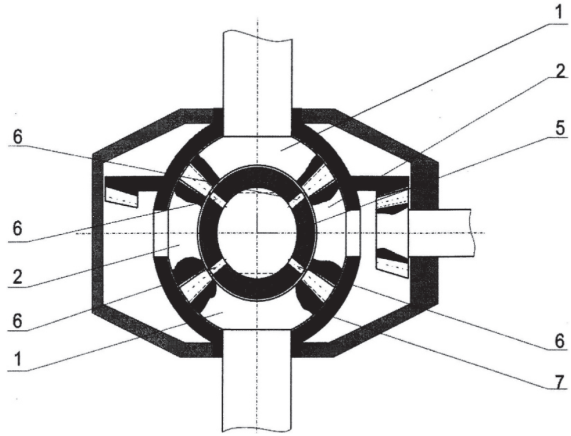

Figure 2 Schematic sectional view of the proposed self-locking axle differential, 1 – planetary bevel gear, 2 – satellite bevel gear, 5 – spherical hollow body, 6 – flow channel, 7 – ring gear

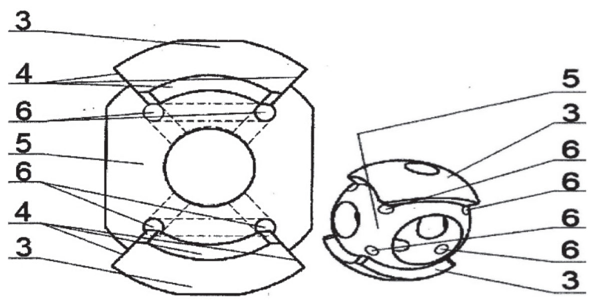

Figure 3 Front view of the spherical hollow body design (left) and an axonometric view (right), 3 – spherical plate, 4 – specially shaped surfaces of the spherical plates, 5 – spherical hollow body, 6 – flow channel

This effect occurs due to the presence of gear backlash between the planetary gears and the satellite gears. The result of this process is the self-locking effect of the differential, i.e., a larger portion of the torque is transferred to the wheel with more favorable adhesion conditions. The driving force is then rapidly and continuously redirected exclusively by mechanical means to where it is required, namely to the wheel with better adhesion conditions (figure 4 – denotes the input unit rotational speed of the pinion, represents the corresponding rotational speeds of the differential satellite gears, denotes the output wheel rotational speeds, represents the proportional distribution of torque to differently loaded wheels, and denotes the efficiency of the differential; for example, during straight-line driving the differential is inactive and the value of is therefore zero).

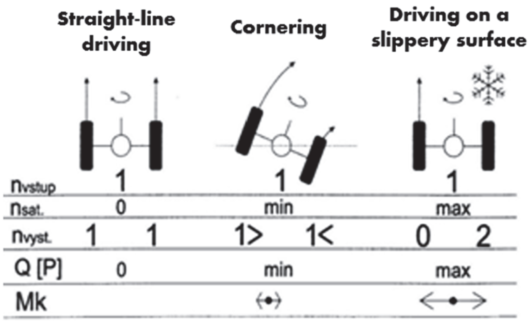

Figure 4 Operation of the proposed differential in off-road conditions

The operating principle of the differential is based on the pumping effect generated by the gear backlash of the meshing planetary and satellite gears. From the central cavity of the spherical body, the gear teeth draw in the working medium (e.g. lubricating oil) and force it into flow channels of a corresponding diameter. The differential subsequently behaves as a hydrostatic transmission, utilizing the pressure energy of the working medium, i.e., oil. The oil is forced into the flow channels by a pressure force whose magnitude depends on the ratio of the projected area of the gear tooth profiles in contact with the oil, projected onto a plane perpendicular to the direction of the flow streamlines of the working medium, to the diameter of the flow channels. Furthermore, the magnitude of this force is directly dependent on the dynamic viscosity coefficient of the working medium (characterized by the Reynolds number) and on the velocity of the oil flow through the channel. The differential operates under the physical constraint that only a quantity of working medium permitted by the continuity equation can enter the flow channel. As a result, a damping resistive force is generated, acting on the unloaded wheel, i.e. the faster-rotating wheel of the vehicle (the wheel undergoing slip). Consequently, torque and power are redistributed between both wheels. This effect persists until the rotational speeds of both wheels are equalized again. The same physical process occurs whenever wheel slip reappears on either side of the vehicle.

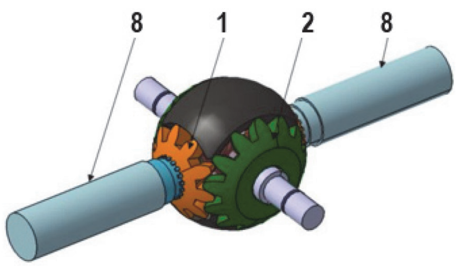

Figure 5 3D CAD model of the planetary and satellite gear assembly, 1 – planetary gear, 2 – satellite gear assembly, 8 – axle shaft

The advantages of the axle-mounted self-locking differential design for small road vehicles are evident from the effects it exhibits in operation. In general, it can be stated that the originality of the proposed device lies in the utilization of the pumping effect generated by the gear backlash of the meshing planetary and satellite gears, whereby the working medium—lubricating oil—is drawn from the central cavity of the spherical body and forced into flow channels of a corresponding diameter. The differential subsequently behaves as a hydrostatic transmission, utilizing the pressure energy of the working medium, i.e., oil.

3 Conclusion

For the purposes of dimensioning, material selection, and strength and dynamic analyses, it is essential to determine the maximum values that the device will be required to transmit. These include, for example, the maximum torque, power, and similar parameters. Correct identification of these differential parameters requires knowledge of the driving condition under which critical loading (stress) of the differential occurs. Therefore, future research will focus on the development of a case study aimed at describing such a critical scenario. As indicated in the schematic shown in figure 4, it is likely that the differential reaches its critical loading condition when one wheel exhibits maximum adhesion while the other has none. For clarification, one may consider a vehicle positioned on a lifting device, where one wheel is rigidly fixed. This wheel thus has its motion constrained and exhibits maximum adhesion. The second wheel is freely suspended, i.e., it offers negligible resistance. Under these conditions, the self-locking action of the differential attempts to transmit the maximum possible power to the fixed wheel. Consequently, the power flows from the engine through the transmission to the differential, where it is distributed in this case at a ratio of 100% to the fixed wheel and 0% to the free wheel. On the road surface, this device installed in a light vehicle is advantageous under conditions of reduced adhesion (for example mud, wet surfaces, snow, ice) improving adhesion between the vehicle and surface of the road. Transferring the torque power to the wheel with better contact with the road enables the vehicle to improve traction, maintain mobility, stability and controllability, which in the end reduces the risk of wheel slip or vehicle immobilization.

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References

[1] The Editors of Encyclopaedia Britannica: Differential gear, Encyclopedia Britannica, https://www.britannica.com/technology/differential-gear, 10.03.2021.

[2] Veeranjaneyulu, C., Hari Babu, U.: Design and Structural Analysis of Differential Gear Box at Different Loads, 2012.

[3] Cheli, F., Giaramita, M., Pedrinelli, M., Sandoni, G., Travaglio, G.C.: A New Control Strategy for a Semi-Active Differential (Part I), 16th IFAC World Congress, 2005.

[4] Vinattieri, F., Annicchiarico, C., Capitania, R.: A Study on the Influence of a Semi-Active Differential on the Vehicle Behaviour with a Software-in-the-Loop Approach, 44th Convegno Nazionale AIAS, Università di Messina, 2–5 September 2015.

[5] Resta, F., Teuschl, G., Zanchetta, M., Zorzutti, A.: A New Control Strategy for a Semi-Active Differential (Part II), 16th IFAC World Congress, 2005.

[6] Waghmare, A.S., Shinde, S.V., Kavale, A.S., Tathe, P.G.: Differential Locking System, 4 (2017) 12

[7] Tremlett, A.J., Massaro, M., Purdy, D.J., Velenis, E., Assadian, F., Moore, A.P., Halley, M.: Optimal control of motorsport differentials, Vehicle System Dynamics, 53 (2015) 12, pp. 1772–1794, DOI: 10.1080/00423114.2015.1093150

[8] Gadola, M., Chindamo, D.: The Mechanical Limited-Slip Differential Revisited: High-Performance and Racing Car Applications, International Journal of Applied Engineering Research, 13 (2018) 2