Power distribution mechanisms with friction control in the transmission of a road train with an active trailer-dissolution

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Abstract. The article analyzes the experience of using gear controlled power distribution mechanisms in transport engineering as part of a dynamic stabilization system for high-speed ground vehicles. An overview of the sources on this issue is given. It is shown that the issue of increasing the lateral stability against skidding is relevant in modern conditions and has received a mathematical description mainly in the application to passenger cars. Attention is paid to theoretical studies of Russian scientists involved in the problem of power distribution control in transmissions of transport vehicles and tractors for various purposes. A solution to the problem of full control over the distribution of torques in a transmission containing several drive axles is proposed in the form of a structural diagram of a transmission based on the use of controlled gear power distribution mechanisms. The considered solutions are applicable for monohull vehicles and road trains with an active trailer link. Methods for determining external parameters (gamma of gear ratios) for interaxle and interwheel controlled power distribution mechanisms are proposed in the application to the case of turning a road train with an active trailer-dissolution having an electromechanical transmission.

1 Introduction

The issues of improving the transverse stability of transport and transport-technological machines in the entire range of operating conditions are relevant for transport engineering, despite the prevailing stereotypes in the design of mobile chassis. When considering lateral stability, rollover and skid resistance are distinguished, and skid, due to the layout features of modern cars, tractors, tracked vehicles, etc., usually precedes the threat of rollover (see works [1-8] and others).

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Mathematical models in assessing the lateral stability against skidding and overturning are built on the basis of an analysis of the forces acting on the transport schemes, and therefore are, as a rule, related. The fundamental provisions for these models are the questions of the influence of the chassis design on the lateral stability and the assessment of the distribution of normal reactions between the wheels (rollers) (see, for example, [9, 10]).

The current trend is the active control of skid resistance (see works [1-8,11] and others). Technically, the problem is solved by creating a stabilizing torque acting in the plan plane. Torque is generated by controlling the distribution of thrust forces along the sides. This moment can be used to stabilize the vehicle on the trajectory, and can be used to "turn" in order to more actively enter the turn.

Abroad, controlled cross-wheel controlled power distribution mechanisms (PDM) are mass-produced, as a rule, based on the design of a simple symmetrical gear differential. Known controlled PDM ZF Vector Drive, AYC, etc. Examples of such designs are described, for example, in the sources [12-14]. The inter-board steerable PDM maintains differential communication between the drive wheels when the controls are disabled. If it is necessary to create a difference in thrust forces along the sides, the controls are switched on for a short time.

Cross-wheel controlled PDM is currently working, as a rule, in the so-called dynamic stabilization system. The latter operates under digital control. Feedback is usually carried out according to the signals of the wheel speed sensors of the sides, or according to the signals from thermal accelerometers. In the Russian Federation, a number of technical solutions have been proposed to create alternative kinematic schemes and ensure the control of such controlled PDMs, and approaches to the design and production of such mechanisms have been described (works [15-18] and others).

Cross-wheel controlled PDMs are used mainly in transmissions of passenger cars, not necessarily all-wheel drive. There are works in which it is proposed to adapt a controlled PDM to work as part of the transmission of a tractor and other transport and traction machines, including skidders and forwarders, typical for the timber industry (see [15-18] and others).

In the domestic literature, despite the fundamental theoretical work in the field of the theory and design of differentials (see, for example, work [19]), the topic of controlled cross-wheel controlled PDMs is represented by a few publications ([15-18] and others).

On an all-wheel drive vehicle driven by a thermal engine or a series-type hybrid power plant, power distribution between the drive axles is carried out using an inter-axle power distribution mechanism. A simplified diagram of the distribution part of such a transmission is shown in Figure 1.

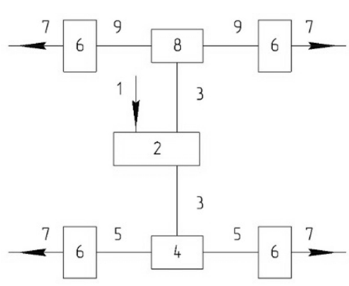

Fig. 1. The structure of the distributing part of the transmission of an all-wheel drive two-axle machine: 1 – power supply; 2 – interaxle controlled PDM; 3 – cardan gears; 4 – main gear and controlled PDM of the rear axle; 5 – axle shafts; 6 – onboard or wheel gear; 7 – power outlet to the drive wheels; 8 - main gear and controlled PDM of the front axle; 9 – half shafts with CV joints.

However, for the majority of transport and technological machines, as well as for special transport vehicles (less often for mass-produced passenger cars), the need to control the distribution of power between drive axles is typical. For example, for trucks, tractors as part of road trains, skidders, forwarders, at least 40% of the working time is occupied by self-movement, when a symmetrical distribution of the load over the drive axles is more beneficial. When such vehicles are fully loaded, it is advisable to transfer up to 2/3 of the power to the wheels of more loaded drive axles, which can realize a greater traction force. In the application to a monohull all-wheel drive vehicle, a similar problem is considered, for example, in [18].

Road trains and forwarders, as well as articulated vehicles with an active trailer link, differ from monohull transport and traction vehicles in a number of features of the kinematic and power characteristics of curvilinear motion. At the same time, the principle of an active trailer link with a mechanical transmission was developed in relation to military facilities and did not find wide practical application in "civilian" mechanical engineering (due to complexity, high cost, relatively low reliability), with the exception of tracked conveyors of the DT series. However, on a modern element base it is possible to return to the tasks of building active trailers with an electromechanical transmission.

Thus, the problem of distribution of power distribution control technologies in the transmission of all-wheel drive transport and transport-technological machines to road trains with an active trailer link is relevant.

The use of precisely gear-driven PDMs is determined by their high energy consumption, relative simplicity of design, the availability of proven manufacturing technologies, stable and sufficiently high efficiency, stable gear ratio in all operating modes, and other advantages compared to hydromechanical and electromechanical devices.

This study uses the methods of the theory of movement of transport vehicles, the synthesis and analysis of planetary gears, the theory of machines and mechanisms, etc.

2 Definition of external parameters controlled by PDM

An interwheel controlled PDM with the controls disabled must maintain a differential connection between the wheels of the axle, and with the friction controls fully engaged, the coordination of the kinematic (minimum specified for the steered wheels by the steering drive) and the calculated (fixed) power (obtained due to the difference in traction forces on the sides in the absence of slippage in the PDM controls) of the turning radii.

This principle is true for both a monohull car and a road train. On Figure 2, a design scheme for turning a road train with an active trailer-dissolution is proposed.

When constructing this design scheme, the following assumptions were made:

- a uniform turn on a horizontal surface with a constant radius and angular velocity is considered;
- tire deformation, skidding and slipping of wheels, displacement of the pole of rotation are not taken into account;
- the problem is considered as holonomic;
- the kinematic turning radius obtained by turning the steered wheels and the side turning radius due to the difference in traction forces are equal.

The external parameters that characterize the cross-wheel controlled PDM, regardless of its kinematic scheme, are a set of kinematic gear ratios for typical operating modes.

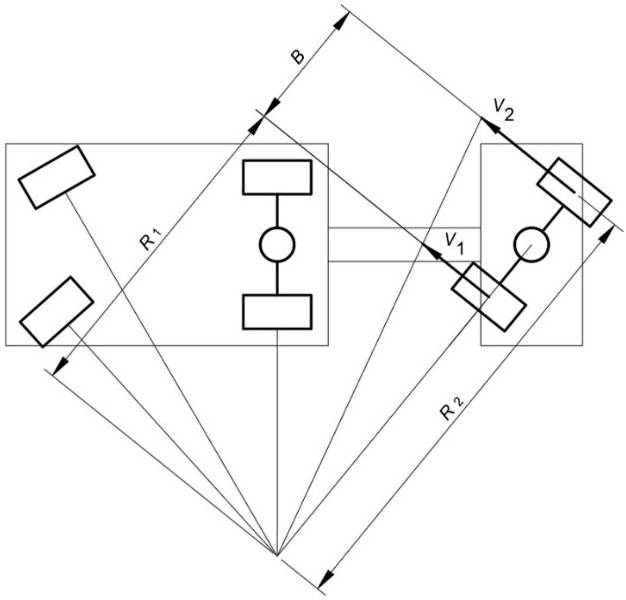

Fig. 2. Calculation scheme for determining the external parameters of an interwheel controlled PDM with friction control (the case of an active trailer-dissolution) of a road train with a single-axle active trailer-dissolution: B – trailer track width; $R_{1,2}$ and $V_{1,2}$ – turning radii and linear speeds of the inner and outer sides.

With rectilinear motion $u_0 = 1$ (as a result, the kinematic scheme of such an PDM is often based on a simple differential or a functionally replacing series with a kinematic parameter equal to (+2)).

It is possible to connect the inter-board gear ratio with the relative radius of the power turn using the dependencies obtained in [20]:

$$u = (\rho + 0,5)/(\rho - 0,5) \text{ and } \rho = 0,5(u+1)/(u-1) \ . \tag{1}$$

Using Figure 2, you can see:

$$\rho = R/B \text{ and } R = (R_2 + R_1)/2 \ , \tag{2}$$

where B is the track width in this case of the active trailer.

For most transport and technological machines, the value $\rho \in [3, 4]$ is in demand.

In accordance with Figure 2 can be organized mechanical, electromechanical and hydromechanical drive of the driving wheels of the active trailer. The hydromechanical drive is, due to the design features, expensive and massive, and also has a sufficiently high efficiency value only in a narrow range of operating loads. The current level of development of electric motors makes competitive options with a mechanical and electromechanical drive. In the latter case, the block concept of the drive, considered, for example, in [18], is of interest. However, in this case, the use of an interwheel controlled PDM is also implied.

The interaxle controlled PDM is characterized by two main external parameters - the values of the power gear ratios in the modes used. Typical modes of operation for the tractor in the considered in Figure 2 examples are self-movement (otherwise - “idling”) and movement with a full load. In the case of an active trailer, it will be necessary to take into account its traction and coupling capabilities.

A prerequisite is the preservation of the differential connection between mechanically connected axles: it is known that the circulation of power in the mechanical transmission of a heavy wheeled vehicle can lead to the destruction of the teeth of the main gears. In the case of using an active trailer, it is necessary to control the traction force on its wheels in such a way that the longitudinal force on the coupling device remains close to zero, but negative.

For an interaxle controlled PDM in a transmission built according to the scheme shown in Figure 1, in general, we can write:

$$\left|u_{\mathrm{I}}^{*}\right| = Z_{X\,\mathrm{I}} / Z_{Y\,\mathrm{I}} \text{ and } \left|u_{\mathrm{II}}^{*}\right| = Z_{X\,\mathrm{II}} / Z_{Y\,\mathrm{II}} \,. \quad (3)$$

Here $u_{\mathrm{I,II}}^{*}$ is the power transmission ratio between bridges X and Y in modes I and II in the absence of slippage in the MRM controls and the stopped drive link; and $Z_{X\,I,II}$ and $Z_{Y\,I,II}$ are normal responses for bridges X and Y in modes I and II.

For special machines, for example, intended for mountainous terrain, it may be advisable to obtain, due to the slipping of the used control element, a continuous range of gear ratios between the drive axles:

$$\left|u_{i}^{*}\right| = Z_{X\,i} / Z_{Y\,i} \;,\; u_{i}^{*} \in \left[u_{\mathrm{I}}^{*}, u_{\mathrm{II}}^{*}\right] . \quad (4)$$

It is obvious that such a mode of operation will be accompanied by power losses due to slipping of the control element (see similar calculations in [15,20]).

For most trucks, forwarders, road trains with an active trailer, you can focus on the values:

$$u_{I}^{*} = -1 \text{ and } u_{II}^{*} = -0.5 \,, \quad (5)$$

which corresponds to a symmetrical distribution of moments between the axles when driving without a load (1:1) and asymmetric - when driving with a load (1:2).

3 Cross-wheel controlled PDM

Since the external parameters of the controlled PDM do not depend on its structure, it is possible to offer various options for the kinematic schemes of mechanisms with desired properties. The synthesis of the kinematic scheme of a planetary controlled PDM with two degrees of freedom is based on recommendations from the sources [21,22,23]. In addition to using simple planetary mechanisms, in some cases it is possible to use a complex four-link mechanism. In many cases, it is not difficult to select the necessary kinematic parameters for well-known schemes (ZF Vector Drive, AYC). It is obvious that, in addition to patent purity, the key factors for rejecting possible solutions will be manufacturability (based on a technological base more accessible to the manufacturer), efficiency, expected resource, satisfaction with dimensional restrictions.

One of the compromise options is shown in Figure 3 is an example of a simplified kinematic diagram of an inter-wheel controlled PDM, which makes it possible to obtain the value of the minimum relative turning radius $\rho = 2.78$, which will correspond to the inter-board gear ratio $u(\rho) = 1.44$.

Planetary gears with an internal gear ratio of $k_3 = 2.05$ and $k_4 = 2.37$ are used to control the power distribution between the wheels of the drive axle. A positive value of the kinematic parameter is achieved through the use of a scheme with interlocked satellites (the satellite meshed with the sun gear interacts with another satellite meshed with the epicyclic gear; both satellites have a common carrier), which leads to a decrease in the efficiency of planetary mechanisms, complication and weighting of the structure and the gear part of the PDM as a whole.

As friction control elements, it is supposed to use disc brakes with a hydromechanical or electromechanical drive. Service brakes and wheel gears, the use of which is advisable in order to reduce the torque on the PDM, in Figure 3 are conventionally not shown.

The use of a hydraulic drive is justified if the machine has a high-pressure hydraulic system (the pressure in the brake booster can exceed 20 atm.). On lighter chassis, an electromechanical drive based on a tear mechanism can be used. The design and calculation method of the tear mechanism are described, for example, in the book [21]. An electric stepper motor can be used as an actuator. The disadvantage of the tear mechanism, as you might expect, will be speed-reducing gaps between the clips and the rolling elements. It is possible to reduce gaps by increasing the accuracy (and cost) of manufacturing and assembly, but in principle a gapless mechanism should be inoperable.

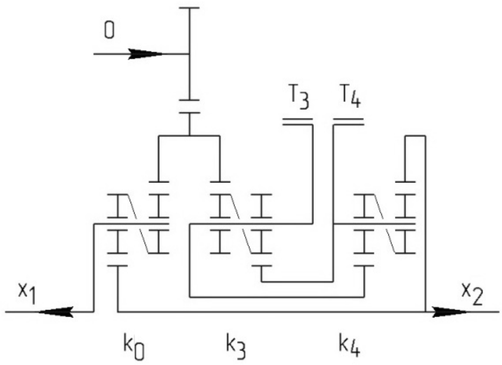

Fig. 3. Simplified kinematic diagram of an interwheel controlled PDM with friction control: 0, x_1 and x_2 – driving and driven links; $T_{3,4}$ – brakes; $k_{0,3,4}$ – kinematic parameters of planetary mechanisms (see source [5]).

The pneumatic drive used on some tractors to enable forced differential lock and switch modes in the gearbox is difficult to use to organize controlled slipping of the control element due to the high inertia of the working fluid and low energy consumption.

The specified minimum (calculated) value of the turning radius is realized in the absence of slippage in the disc pack of the used friction control element (brake T_1 or T_2, depending on the direction of turn). Since the inclusion of the control element reduces the number of degrees of freedom of the planetary mechanism by one, the curvilinear motion of the machine will be stable. The stability of the turning radius will remain even with controlled slipping of the control element.

Intermediate stable turning radii can be obtained using the principle of slip control in the control disc package. The angular speed of slipping of the package depends on the compression force of the disks. When using a hydraulic drive, the compression force is proportional to the pressure of the fluid in the control actuator hydraulic cylinder (booster). It is advisable to control the average value of the pressure in the booster by means of pulse-width modulation. In this case, the supply of pressure to the line is carried out by pulses with a constant amplitude, but with an adjustable duty cycle. The absence of gaps between pulses corresponds to the maximum pressure. As the duty cycle increases, the average pressure in the actuator decreases. Approved in SPbPU for disk friction control elements of heavily loaded transmissions of tracked vehicles, a closed (servo) system with analog control is operable in the pressure range of 5–15 Hz [24,25]. Feedback is carried out according to the angular velocity of the driven shaft of the disk pack, and when working on a running layout - according to the angular velocity of the tracked vehicle. To improve the quality of control, it is advisable to increase the frequency. At present, a closed-loop digital pressure control system in the control element drive booster has been tested in bench conditions, and the issue of its installation on a mass-produced chassis is being resolved.

4 Interaxle controlled PDM

The above principles for determining the external parameters of the PDM allow you to create mechanisms for specific transport and transport-technological machines.

However, there is reason to expect that the most popular option will be the one that allows you to switch between symmetrical torque distribution (1:1) and asymmetric 1:2. The controlled inter-axle PDM will be related to the inter-wheel, but there are significant differences. Due to the specifics described above, a controlled interaxle PDM must combine the capabilities of symmetrical and asymmetric differentials typical for transport engineering. It is also desirable to provide for the possibility of disabling one of the drive axles.

Since the vehicle is in the self-propelled mode for a smaller part of the working time, we choose a differential three-link mechanism with a kinematic parameter equal to (–2) as the basis of the PDM: the power is supplied to the carrier, and the sun and epicyclic gears are indirectly connected to the drive axles. A planetary gear is built into the branch of the rear axle, controlled by two controls - a locking clutch and a brake. The locking clutch should be permanently on, the brake - permanently off. When the clutch is forced off and the brake is applied, this mechanism implements a gear ratio (+0.5), which makes it possible to align the gear ratios from the input link to the output link and maintain the differential connection between the drive axles in both modes of operation.

On Figure 2 shows an example of a kinematic diagram of a controlled interaxle PDM built according to these principles.

Shown in Figure 2 scheme is based on a traditional asymmetric differential, providing the issuance of 1/3 of the torque to the front axle and 2/3 of the torque to the rear axle. The inclusion of the blocking clutch C_2 will allow you to use this mode of operation.

However, when the brake T_1 is turned on, a mechanism built on the scheme of a symmetrical cylindrical differential additionally operates in the kinematic chain of the rear axle drive. The kinematic and force analysis of the operation of the mechanism, performed according to traditional methods [21,22,23] will show that the distribution of angular velocities and torques between the driving axles in this case will be symmetrical.

Turning on the T_A brake will transfer all the power to the front drive axle.

Thus, a controlled PDM of this family, with the controls disabled, has three degrees of freedom, and two when the vehicle is moving.

The question of the expediency of controlling the distribution of power between axles (the implementation of controlled slipping in such a controlled PDM) requires additional research.

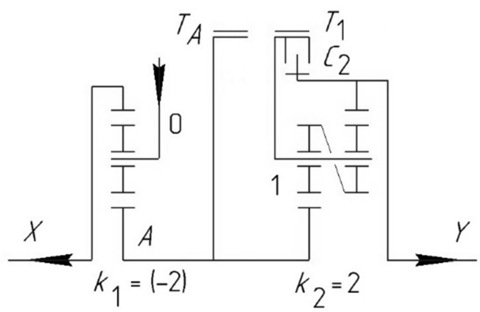

Fig. 4. Simplified kinematic diagram of an interaxle controlled PDM with friction control: 0, X and Y – driving and driven links; A and 1 – connecting and brake links; T_1, A and C_2 – controls; $k_{1,2}$ – kinematic parameters of planetary mechanisms.

Obviously, in order to simplify the design of the inter-axle controlled PDM, it is possible to replace the disc brakes and the clutch with gear clutches, which will be controlled while the vehicle is stopped, and the drive can be made completely mechanical.

Since the interaxle and interwheel controlled PDMs are based on a gear part based on planetary mechanisms, it is advisable to use the experience accumulated in domestic tank building and now mastered by the automotive industry in their design, manufacture and operation [19,24,25].

5 Conclusion

Based on the foregoing, the following main conclusions can be drawn.

The joint use of controlled interwheel and interaxle CPDM will improve the performance of wheeled and tracked vehicles and multi-link machines based on them.

The most compact and energy efficient are currently controlled MRM based on gear planetary gears, using electronic-hydraulic or electromechanical control; control system - closed, digital.

When designing, manufacturing, and operating controlled PDMs, it is advisable to use experience in the manufacture and use of planetary gearboxes for military tracked vehicles.

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