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PECULIARITIES OF DETERMINATION THE SELF-ALIGNING TORQUE OF THE TIRE DURING MOVEMENT WITH SIDE SLIP

The movement of an elastic wheel with a side slip, which is determined by the angle between the velocity vector and the wheel disk, causes a lateral displacement of the disk relative to the tire contact patch. The displacement is formed during the time the point of the tire comes into contact with the support surface until it leaves it. During such movement, longitudinal and lateral reactions occur in the contact patch and reduce to the self-aligning torque and resultant force, applied in the centre of the contact patch. The self-aligning torque is developed if there are reactions in the plane of the tire contact patch and the displacement of their resultant relative to contact patch centre. At the same time, the forces and moments that developed in the contact patch depend on the state of the contact patch, which is characterized by the ratio of the adhesion and sliding zones in it. This contact patch state is determined by the values of the turning angles of the locked steered wheel during its static turn and depends on the coefficient of road adhesion and the type of tire. Analytical dependencies were obtained for determining the self-aligning torque depending on the slip angle in the range of zero to the slip angle at which the traction properties of the tire with the support surface are fully realized. When the traction properties are fully realized in the tire contact patch during the movement of the wheel with side slip, the self-aligning torque of the tire reaches zero, since the displacement of the resultant reactions relative to the centre of the contact patch goes to zero. At the same time, under the effect of longitudinal reactions, the self-aligning torque can acquire negative values at large slip angles.

Keywords: vehicle, elastic wheel, slip, tire, self-aligning torque, support surface.

INTRODUCTION

Modern scientific research in the automotive industry is aimed at creating a safe and efficient vehicle that will meet modern environmental and technological requirements.

The elastic wheel of the vehicle is considered as a complete mechanism, which transforms the rotational movement of the wheel relative to the axis of rotation into its translational movement [1, 3, 6]. At the same time, the elastic wheel includes a hard disk, an elastic body of the tire (pneumatic) and a tire contact patch, which belongs to both the elastic wheel and the support surface simultaneously. At the same time, the input link of this mechanism is the hard disk, and the output link is the tire contact patch.

If there is adhesion of the tire to the supporting surface the forces and moments applied to the wheel disc from the car frame, transmission, braking and steering systems, etc., passing through the body of the tire, cause to occur reactions in contact between the tire and the support surface, which ensure the movement of the car [1, 2]. Thus, during the rectilinear movement of an elastic wheel, a moment of rolling resistance occurs due to the displacement of the resultant of any normal reactions relative to the center of the tire contact patch. At the same time, during curvilinear movement of a car, additional wheel movement resistance occurs due to the simultaneous turning of the wheel disk and its lateral displacement relative to the contact patch, which give rise to the tire body twisting torque and lateral force, respectively [3-6].

Rolling of the wheel with toe-in and the action of the lateral force on the wheel occurs the lateral displacement of the wheel disk relative to the tire contact patch during the time the point of the tire comes into contact with the support surface and until the moment it leaves the contact, which causes the wheel to move with side slip [3, 6]. At the same time, lateral reactions develop in the contact patch, the resultant of which is shifted relative to the geometric center of the tire contact patch. This resultant is reduced to the self-aligning torque and the force applied at the center of the tire contact patch. Longitudinal reactions in the tire contact during motion with side slip also give rise a tire self-aligning torque. Since the value of this torque is significantly smaller than the value of the self-aligning torque from lateral forces, and the effect of longitudinal reactions on its value is taken into account by the appropriate coefficient [1, 6].

This work is considered peculiarities of determining the self-aligning torque of the tire during the movement of an elastic wheel with a side slip.

The aim of the study. Determine the peculiarities of calculating the self-aligning torque of the tire during the movement of the wheel with a side slip.

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

The results of theoretical and experimental studies of the self-aligning torque of a wheel tire rolling with a side slip are given in the works of M. Keldysh [4], V. Knoroz [5], A. Lytvynov [7], R. Smiley and

V. Gornom [8], H. Frondenstein [9], H. Pacejka [10] and others. In works [11-14] the results of the study of the self-aligning torque using the simulation of the operation of the car tire by the method of finite elements are presented.

From the analysis of the above-mentioned works, it is known that during the rolling of a wheel with a side slip, the self-aligning torque Mt of the tire increases with an increase in the slip angle δ, reaches its maximum value, and then decreases when $\delta > \delta_{Mtmax}$ [7–14]. For some tires, at large slip angles, the value of the self-aligning torque can be significantly affected by longitudinal reactions, which causes a change in the sign of this torque [7, 10].

Increasing the inflation pressure in the tire reduces the self-aligning torque. However, this decrease is all the more remarkable, the greater the normal load [7].

The coefficient of road adhesion, which is one of the main physical and mechanical characteristics of the supporting surface, significantly affects the value of this torque. As the road adhesion coefficient increases, the maximum self-aligning torque increases [7–9].

The maximum self-aligning torque for tires under rated load and inflation pressure during wheel rolling with a side slip in [7] is recommended to be determined empirically:

$$M_{tmax} = (0{,}015...0{,}0225)G_w \;, \tag{1}$$

where M_{tmax} is the maximum self-aligning torque, N·m; G_w is the normal load on the tire, N.

This dependence is approximate and does not take into account the coefficient of road adhesion, inflation pressure, and design features of the tire.

Considering that the value of the self-aligning torque depends significantly on the slip angle, the self-aligning torque is determined as a function of the slip angle.

Analysis of the results of experimental studies of the dependence of self-aligning torque on slip angle for a tire size 6.45–13 mod. M130-A showed, that as the tire inflation pressure increases, both the current value of the tire self-aligning torque and their maximum values decrease [15].

Based on the analysis of experimental data on the dependence of tire self-aligning torque on slip angles, obtained by many researchers, in [15] an empirical dependence is proposed, which approximates the curve Mt = f(δ) in the slip angles range from zero to a value greater than 20–30 % of the slip angle corresponding to the maximum value of the self-aligning torque:

$$\frac{M_t}{M_{tmax}} = 2\frac{\delta}{\delta_{Mtmax}} - \left(\frac{\delta}{\delta_{Mtmax}}\right)^2, \tag{2}$$

where M_t is the self-aligning torque of the tire at the current value of the slip angle δ; M_{tmax} is the maximum value of the tire self-aligning torque; δ_{Mtmax} is the slip angle at which the self-aligning torque of the tire reaches its maximum value.

Values M_{tmax} and δ_{Mtmax} the author recommends to determine experimentally on the bench. However, during the research on the drum stand, the value of the torque Mt = f(δ) will be smaller than during determination on the plane [7, 15]. The difference between the experimental data will depend on the ratio of the drum and tire diameters. This is explained by the fact that as a result of testing tires on a drum, the pressure distribution over the contact area and its dimensions change. To obtain data on the self-aligning torque, it is necessary that the ratio of the drum diameter to the tire diameter should be at least 3.5.

In [8], it is recommended to determine the self-aligning torque of the tire according to empirical dependencies, dividing it into three zones, depending on the dimensionless value, which depends on the value of the road adhesion coefficient:

$$\text{at } \frac{k_{во}\delta}{\varphi R_N} \le 0{,}1 \quad M_ш = 0{,}4ak_{во}\delta \,, \tag{3}$$

$$\text{at } 0{,}1 \le \frac{k_{во}\delta}{\varphi R_N} \le 0{,}55 \quad M_ш = \frac{a}{2}\left[k_{во}\delta\left(1 - \frac{k_{во}\delta}{\varphi R_N}\right) - 0{,}01\varphi R_N\right], \tag{4}$$

$$\text{at } \frac{k_{во}\delta}{\varphi R_N} \ge 0{,}55 \quad M_ш = \frac{a}{2}\left[0{,}2925\varphi R_N - 0{,}1k_{во}\delta\right]. \tag{5}$$

where k_{s0} is the coefficient of lateral deflection at a small slip angle; R_N – vertical force acting on tire from ground; φ –coefficient of road adhesion; *a* is the contact patch length.

At the same time, in [8] recommend to determine the maximum value of the tire self-aligning torque by the expression:

$$M_{t\max} = 0{,}12a\varphi R_N. \quad (6)$$

In [11], a model of the Regional Haul Steer II, RHS 315/80 R22.5 truck tire was developed using the finite element method, and the Pam-Crash software, a study of the influence of some operating conditions on the characteristics of tires turning on a hard surface was carried out. The obtained dependences of the lateral force and the self-aligning torque of the tire on the slip angle for different values of the vertical load, inflation pressure, and speed of movement. It was concluded that the self-aligning torque of the tire increases parabolically at all values of the speed of movement, approaching the maximum at a slip angle of 4 degree, and then decreases at larger slip angles. In [12], [13], proposed several numerical methods for modeling the behavior of aircraft tires during cornering. The obtained dependences of the self-aligning torque on the slip angle, when the torque first increases, reaching the maximum value (at a slip angle of about 5 degree), then decreases. At the same time, the results of the simulation of the self-aligning torque of the tire and the coefficient of road adhesion sufficiently coincide with the experimental data, in particular, when the surface temperature changes.

Therefore, the self-aligning torque is formed by the displacement of the resultant of lateral and longitudinal reactions in the tire contact patch relative to the center of the contact patch during wheel rolling with side slip, and when the traction properties are fully realized in the tire contact patch during the movement of the wheel with side slip, the self-aligning torque of the tire approaches zero.

RESEARCH RESULT

The forces and moments acting on the elastic wheel when moving with side slip are determined by the reactions in the contact of the tire with the supporting surface and depend on the state of the contact patch. The state of the tire contact patch is characterized by the ratio of the adhesion and sliding zones. Depending on the ratio of the adhesion and sliding zones, three of its states are distinguished: in the contact patch there are only areas of adhesion, in the contact patch there are areas of adhesion and sliding; in the contact patch there are only sliding zones [1, 6, 15].

The state of the contact patch of the tire will be determined by the turning angle of the hard disk of the wheel relative to the tire contact patch during wheel static turn. The first state is possible at the turning angle of the disk $\theta \le \theta_A$, where θ_A is the maximum turning angle of the wheel disk during wheel static turn at which it is considered that there are only adhesion zones in the contact patch. The second state is possible at the turning angle $\theta_A<\theta<\theta_B$, where θ_B is the minimum turning angle of the wheel during wheel static turn where it is considered that there are only sliding zones in the tire contact patch. When the angle θ varies in the range from θ_A to θ_B, the area of the sliding zones increases, and the area of the adhesion zones decreases accordingly. The third state occurs at the rotation angle $\theta \ge \theta_B$. The values of the angles θ_A and θ_B for a specific tire depend on the value of the coefficient of road adhesion, the maximum adhesion of which is achieved on a dry asphalt concrete surface, and is in range 0.6-0.8 [1].

Considering the above, the dependence of the self-aligning torque can be described by analytical expressions as a function of the slip angle.

The results of experimental studies conducted with a wide-profile tire of size 1300x530–533 mod. ВИ-3 and radial tire of size 9.00-20Р mod. И-Н142Б in driven mode showed that the self-aligning torque of the tire acquires a maximum value during rolling with side slip angle $\delta_{Mt\max}$, which in absolute value is close to the angle of turning of the wheel during wheel static turn θ_A, in which conditionally linear dependence between the static tire steering resistance torque and the angle of turning of the wheel is maintained.

If we assume that the diagram of the distribution of lateral forces approaches a right triangle when $\delta \le \theta_A$, and their resultant is applied at its mass center, located at a distance of a/3 from its base, then the self-aligning torque of the tire Mt is determined by the expression:

$$M_t = P_s \frac{a}{6}, \quad (7)$$

where a is the length of the tire contact patch;$a/6$– the distance from the transverse axis of the tire contact patch to the mass center of the right-angled triangle of the side force plot P_s; P_s is the resultant of elementary lateral forces during wheel rolling with the slip angle $\delta \leq \theta_A$.

Expression (7) is valid if the diagram of lateral forces is a right triangle. Taking into account expression (7), the maximum self-aligning torque of the tire is determined as follows:

$$M_{t\max} = P_{M_{t\max}} \frac{a}{6}, \quad (8)$$

where M_{tmax} is the maximum tire self-aligning torque due to lateral force, N·m; P_{Mtmax} is the lateral force causing the maximum self-aligning torque, N.

If, with sufficient accuracy for practical calculations, it is considered that in the slip angles range $0<\delta\leq\theta_A$, the dependence between the lateral force and the slip angle is conditionally linear, then it is possible to write:

$$P_{M_{t\max}} = k_s \delta_{M_{t\max}}, \quad (9)$$

where k_s is the coefficient of lateral deflection, N/deg; $\delta_{M_{t\max}}$ is the slip angle, at which the self-aligning torque of the tire reaches its maximum, deg.

The cornering stiffness is determined under the condition [15] that the energy supplied to the wheel for the disk twisting and its lateral displacement during movement along a curved trajectory is distributed equally:

$$k_s = \frac{2C_\theta}{a}, \quad (10)$$

where C_θ – angular stiffness of the tire relative to the vertical axis, N·m/deg.

Taking into account dependencies (8)–(10) and the self-aligning torque of the tire reaches its maximum value at the slip angle $\delta_{M_{t\max}} = \theta_A$, the maximum self-aligning torque will be determined as follows:

$$M_{t\max} = \frac{C_\theta \theta_A}{3}. \quad (11)$$

Dependence (11) is obtained without taking into account the displacement of the resultant longitudinal reactions of the support surface relative to the longitudinal axis of the tire contact patch and under the condition that the specific pressure at each point of the contact patch and the road adhesion coefficient are the same. In real conditions, these parameters differ. At the same time, the value of this difference is significantly affected by the type of tire. The effect of the mentioned factors is recommended to be taken into account by the coefficient of proportionality of the self-aligning torque K_t. Then we have:

$$M_{t\max} = \frac{K_t C_\theta \theta_A}{3}, \quad (12)$$

where K_t. is the coefficient of proportionality of the self-aligning torque.

The value of K_t for high-pressure tires does not exceed 1.1, for low-pressure tires the value of this coefficient reaches 1.36. For any individual tire, the Kt coefficient must be determined experimentally.

The analysis of experimental data, obtained by many researchers using different methods, showed that under rated inflation pressures and loads, with a high coefficient of road adhesion for truck tires in the driven mode, the slip angle at which the self-aligning torque of the tire approaches zero is 13±2 degree.

The analysis of experimental data Mt = f(δ) showed that this dependence approaches a parabola, and therefore, in the slip angle range $0<\delta\leq\theta_B$, the self-aligning torque during rolling in the driven mode is determined by one of the dependencies:

at $0<\delta\leq\theta_A$
$$M_{ш} = \frac{K_ш C_\theta \theta_A}{3}\left[1-\left(\frac{\delta}{\theta_A}-1\right)^2\right], \quad (13)$$

when $\theta_A < \delta \leq \theta_B$ $$M_ш = \frac{K_ш C_\theta \theta_A}{3}\left[1-\left(\frac{\delta-\theta_A}{\theta_B-\theta_A}\right)^2\right], \quad (14)$$

Fig. 1 shows the effect of slip angle on the self-aligning torque for a wide-profile tire size 1300x530–533 mod. ВИ-3, calculated by expressions (2), (3)–(5) and (13), (14). Fig. 2 – the effect of slip angle on the self-aligning torque for the Regional Haul Steer II tire, RHS 315/80 R22.5, calculated by expressions (2), (13), (14) and obtained from the results of computer simulation using the finite element method [11]. Calculations by expressions were carried out with the coefficient of road adhesion φ = 0.7, coefficients proportionality of the self-aligning torque of the tire Kt = 1.1, angles θ_A = 5 degree, θ_B = 13 degree, in the slip angle range from 0 to 14 degrees. Other initial data for the calculation are given in the table. 1. The cornering stiffness was determined by expression (10). Calculations according to dependence (2) were carried out in the slip angle range from zero to a slip angle that is 20% greater than the angle δ_{Mtmax}. The results of the computer simulation are shown in slip angle the range from 0 to 6 degrees.

Table 1. Input Data Calculation

Indicator	1300x530–533 mod. ВИ-3	Regional Haul Steer II, RHS 315/80 R22.5 [11]
G_w, kN	27.0	53.4
r_t, MPa	0.4	0.4275
C_θ, N·m/deg	267.0	534.0

From the analysis of fig. 1, 2, it can be seen that the self-aligning torque of both tires increases with the increase in the slip angle, reaches its maximum value, and then decreases.

For tires 1300x530-533 mod. ВИ-3 calculations based on dependencies (2) and (13), (14) show that the self-aligning torque of the tire reaches its maximum value at the slip angle = 5 degree, which corresponds to the maximum angle at which only adhesion zones are present in the contact zone of the tire with the supporting surface. In the slip angle range from 0 to 5 degrees, the values of the self-aligning torque completely coincide. At δ =6 degree the difference is 2.4 %. According to dependencies (13), (14), the self-aligning torque of the tire approaches zero at the slip angle δ = 13 degree, which corresponds to the minimum angle at which the traction properties of the tire with the supporting surface are fully realized. Dependence (2) does not allow us to determine at what slip angle the self-aligning torque reaches zero.

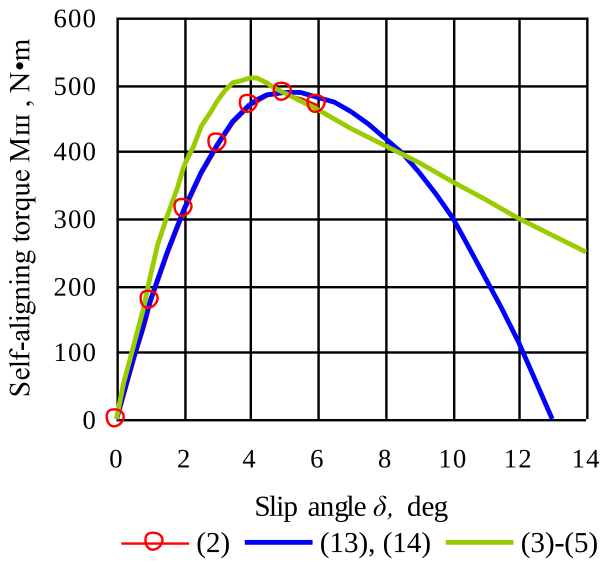

Fig1. Effect of slip angle on the self-aligning torque with 27 kN at 0.4 MPa

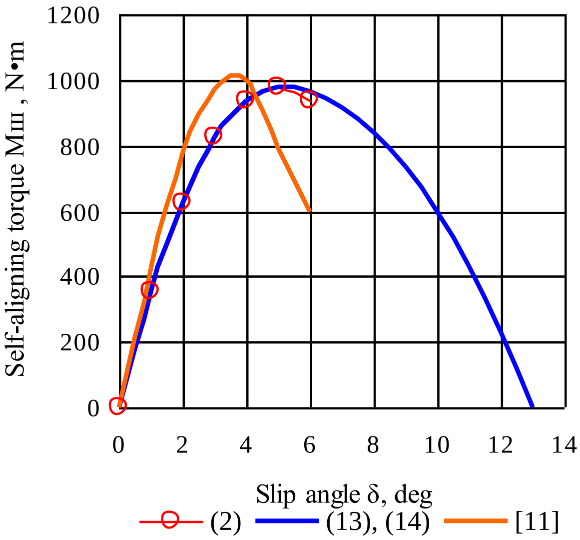

Fig2. Effect of slip angle on the self-aligning torque with 53.4 kN at 0.4275 Mpa

The results of calculations based on dependencies (6)–(8) show that the maximum value of the tire self-aligning torque is achieved at a smaller slip angle $\delta_{M_{t\max}}$ = 4 degree than determined by expressions (2) and (13), (14). In the slip angle range from 0 to 4 degrees, the difference in the values of the self-aligning torque does not exceed 8.5 %. In the case of a further increase in the slip angle δ>4 degree, the dependence $M_t = f(\delta)$ is almost linear. If the slip angles δ>9 degree, the calculation results differ significantly. The self-aligning torque of the tire reaches zero at the slip angle δ = 23.29 degree, which is significantly greater than according to dependencies (13), (14).

For the Regional Haul Steer II, RHS 315/80 R22.5 tire, calculated according to dependencies (2) and (13), (14), the values of the self-aligning torque of the tire when the slip angle changes from 0 to 5 degrees coincide. The maximum value of the self-aligning torque is reached at $\delta_{M_{t\max}}$ = 5 degree. At δ =6 degree the difference is 2.4 %. According to dependencies (13), (14), the self-aligning torque of the tire reaches zero at the slip angle δ = 13 degree.

The results of computer simulations in the slip angle range from 0 to 6 degrees show that the maximum value of the self-aligning torque is reached at a smaller slip angle = 3,8 degree than determined by expressions (2) and (13), (14). At a slip angle of 3.8 degree, the difference in the values of the self-aligning torque does not exceed 6.0 %. In the case of a further increase in the slip angle δ>4 degree, the calculation results differ significantly. At δ =6 degree the difference is 37.7 %.

Therefore, dependence (5) allows determining the self-aligning torque of the tire only in the slip angle range from zero to the slip angle at which the self-aligning torque reaches the maximum value, and dependencies (3)–(5), (13), (14) – from zero to the slip angle, at which traction properties are fully realized in the tire contact patch. At the same time, the analytically obtained dependencies (13), (14) with sufficient accuracy for practice reflect the physical phenomena that occur in the tire contact patch during wheel rolling with side slip, and allow determining the self-aligning torque of the tire in the slip angle range $0 \leq \delta \leq \theta_B$.

SUMMARY

1. The self-aligning torque of the tire occurs during the movement of the wheel with a side slip and is caused by lateral and longitudinal reactions, acting in the contact plane, and brought to the center of the contact patch of the tire. At the same time, the movement of the elastic wheel with side slip causes a lateral displacement of the disc relative to the tire contact patch, which is formed from the moment the point of the tire comes into contact with the support surface until the moment it leaves it.

2. Reactions that occur in the plane of the tire contact patch during the movement of the wheel with a side slip, depend on the state of the contact patch. This state of the contact patch is formed by the adhesion and sliding zones in it and is characterized by the values of the turning angles θ_A and θ_B of the locked steered wheel during wheel static turn. Their values depend on the coefficient of road adhesion and the type of tire. The obtained analytical dependences for determining the self-aligning torque of the tire during moving with side slip take into account the adhesion properties of the supporting surface and the tire.

3. When the traction properties are fully realized in the tire contact patch during the movement of the wheel with side slip, the self-aligning torque of the tire reaches zero, since the displacement of the resultant reactions relative to the center of the contact patch goes to zero. At the same time, under the effect of longitudinal reactions, the self-aligning torque can acquire negative values at large slip angles.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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