Development of the scheme and method for measuring the characteristics of the friction areas in the car wheel contact

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Abstract. The aim of the research is to develop and implement a scheme and method for measuring the characteristics of static and sliding friction areas in the contact patch of an elastic wheel with a solid support when they appear, exist and disappear. The characteristics are understood as: the relative location of static and sliding friction in relation to the vector of the translational speed of the wheel axis; their size and location in the contact patch when they appear, spread and disappear; the values of the moments on the wheel, corresponding to the appearance, spread and disappearance of static and sliding friction. A scheme and a method for measuring these characteristics have been developed and implemented. The measurements are indirect. It has been experimentally established that, in the general case, the geometric center of static friction in the contact patch moves towards the moment acting in the plane of the wheel rotation relative to the rotation axis by an amount proportional to the moment. The maximum value of this displacement according to the moment that is maximum in terms of sliding conditions, and is one third of the contact patch length for all types and conditions of a solid support. The research results are valid for elastic wheels with a radial stiffness not exceeding 1200000 N/m, the main plane of which is perpendicular to the reference plane. The research results can find application in design modeling of stability and controllability of vehicles.

1. Introduction

The interaction of an elastic car wheel with a solid support surface has a significant impact on the properties of its active safety: stability, controllability and braking dynamics. This influence is caused by the presence of static and sliding friction areas in the contact patch. The longitudinal and lateral reaction of the support surface is realized by areas of different friction with different characteristics. It is known about the presence of these areas and their relative position relative to the translational speed vector of the wheel. These are quality characteristics. To determine quantitative characteristics, it is necessary to create a special measurement scheme. The aim of the research is to develop and implement a scheme and method for measuring the characteristics of static and sliding friction areas in the contact patch of an elastic wheel with a solid support when they appear, exist and disappear.

Under the elastic wheel, we will understand a solid deformable wheel that has a radial stiffness of no more than 1200000 N/m. Such wheels are now supplied to the following vehicles: cars, trucks and trailers, buses, airplanes, helicopters, motorcycles, etc. We will consider such an interaction of an elastic with a solid flat support, in which the main plane of the wheel is perpendicular to the reference plane.

It is known that in the contact between a moving elastic wheel with a solid support surface in the...
braking mode and in the driving mode there is static and sliding friction [1-4]. Knowledge of the parameters of frictions in contact is required to solve problems related to the design prediction of stability, controllability and braking dynamics of vehicles [2], as well as problems related to the performance of road and airfield surfaces.

The sizes and location of static and sliding friction areas in the front or rear parts of the contact patch relative to the direction of the translational velocity vector of the wheel axle affect different properties of the wheel, especially in the presence of a lateral force. If there is already full longitudinal and (or) lateral sliding of the wheel, then the sliding friction area extends over the entire contact area, and the wheel ceases to be stable and steerable. If there is still no full sliding of the wheel, then in the contact patch there are static and sliding friction areas.

One of the differences in the manifestation of static and sliding friction forces is that the vector direction of the static friction forces is opposite to the vector direction of the total forces sum acting on the body, and the vector direction of the sliding resistance forces is opposite to the direction of the body velocity vector relative to the motionless surface. In this regard, until the sliding moment of the entire surface of the contact patch comes, the static friction area in the contact patch can perceive a part or all of the longitudinal and all transverse forces, and the sliding friction area – only a part of the longitudinal force directed opposite to the motion speed.

Therefore, the sliding friction area only perceives the longitudinal load and implements part of the longitudinal reaction of the support surface. In this case, the static friction area perceives longitudinal and lateral loads and implements part of the longitudinal and all lateral reactions of the support surface. This determines the friction coefficient of the wheel to the support and parts of the friction coefficient realized by static and sliding friction areas in the contact patch [2]. The location and sizes of different friction areas in contact determine the points position of the reactions application of the support surface. In particular, the lateral reaction is applied in the middle of static friction area at the contact patch, as shown in Figure 1.

![Figure 1. Arrangement of reactions in the contact patch in the wheel braking mode](image)

In this regard, it becomes necessary to further study the processes of interaction of an elastic wheel with a solid support, especially in the presence of a lateral force. A number of problems appear, one of which is to determine the changing characteristics of static and sliding friction areas in contact of an elastic wheel with a solid support, which perceive external forces in different ways and create reactions to the wheel in different ways.
2. Measurement method

The scheme and method of measuring these characteristics developed by the authors are presented. The characteristics are understood as: the relative location of static and sliding friction in relation to the vector of the translational speed of the wheel axis; their size and location in the contact patch when they appear, spread and disappear; the values of the moments on the wheel, according to the appearance, spread and disappearance of static and sliding friction.

Determination of the characteristics of static and sliding friction areas in the contact of an elastic wheel with a solid support will improve the accuracy of predicting the stability and controllability of vehicles in design modeling.

A lot of works has been devoted to the interaction of an elastic wheel with a solid support surface. The geometrical characteristics of the contact patch have been investigated and determined [5-12]. The change in the geometric parameters of the contact patch (shape and sizes of the common contact surface) is analyzed depending on the wheel load and the air pressure in the tire.

We studied the friction properties of a solid and elastic wheel in the absence and presence of lateral forces on surfaces of different types and conditions [2, 13-17].

Models for describing tire deformations and their radii [19, 20] have been created [18]. Theoretical and experimental methods have been developed to determine the forces and stresses in the contact between an elastic wheel with a solid flat support.

Recently, attempts have been made to approximate the mechanism of formation of different friction areas in contact [4]. These were qualitative studies, but not quantitative ones. The principle of formation of static and sliding friction areas was explained and only their relative location to the vector of the wheel translational speed was proved. In this work, the characteristics of static and sliding friction areas in the contact patch of an elastic wheel with a solid support are determined when they exist from appearance to disappearance.

To achieve the aim of the research, the authors created a measuring scheme and implemented it on an experimental setup for studying the phenomena in the contact patch of an elastic wheel with a solid support surface made of optically transparent material. Figure 2 shows the kinematic diagram of the experimental setup, and Figure 3 – its photograph.
Figure 2. The kinematic scheme of the experimental setup for measuring the characteristics of static and sliding friction areas in the contact patch of an elastic wheel with a solid support: a – front view; b – view from above

The hub 1 with the rim 2 of the wheel 3 is pivotally mounted on a fixed frame 4. On the fixed frame 4, a rotary measuring support platform is hingedly mounted with the possibility of adjusting its spatial position 5. The rotary measuring support platform 5 has the ability to move longitudinally along its guides 6. It constantly interacts with tire 7 of the wheel 3 to create a contact patch centered at the contact point A, lying on the radius of the circle with the center coinciding with the geometric center of the wheel 3, to provide the possibility of acting on the wheel 3 with a radial loading force factor to create a radial load \( P_r \) in the rotation plane of the wheel 3, causing the appearance of a normal reaction of the support surface \( R_z \), proportional to the radial loading force factor. The radial load factor is used as the primary loading force factor. To create a radial loading force factor, a radial loading device 8 of the wheel 3 is provided, equipped with a radial force sensor 9 to determine the normal reaction of the support surface. From the readings of the radial force sensor 9, the normal reaction of the support surface at the contact point A is calculated from the relation:

\[
R_z = P_{sz} \cdot \frac{b}{a}
\]

where \( P_{sz} \) – radial force sensor readings; \( a, b \) – arms.

The radial force effects on the wheel 3 are directly proportional to the radial deformation of the tire 7, to determine which a radial displacement sensor 10 is provided, from the readings of which the radial deformation at the contact point A is calculated from the relation:

\[
Z = Z_{sz} \cdot \frac{a}{b}
\]

where \( Z_{sz} \) – radial displacement sensor readings; \( a, b \) – arms.

The obtained values of the normal reaction of the support surface and the radial deformation of the tire at the contact point A make it possible to calculate normal (radial) stiffness coefficient of the tire by one of the known methods. The axle 11 of the wheel 3 is fixed in the vertical swivel bush 12 to enable it to change its position in the longitudinal vertical plane and to implement the required inclination of the wheel 3. The longitudinal one is used as a secondary loading force factor. On the hub 1 of the wheel 3, a rotary beam 13 is rigidly fixed, abutting against a fixed limiting support 14, to
exclude the possibility of turning the wheel 3 from the influence of the longitudinal loading force factor.

To create a longitudinal loading force factor, a longitudinal loading device 15 of the wheel 3 is provided, equipped with a longitudinal force action sensor 16 to determine the longitudinal reaction of the support surface. From the readings of the longitudinal force sensor 16, the longitudinal reaction of the support surface at the contact point A is calculated from the relation:

$$ R_x = P_{sx} - R_{fr} $$

(3)

where $P_{sx}$ – longitudinal force sensor readings; $R_{fr}$ – friction losses in guides 6.

The longitudinal force effects on the wheel 3 are directly proportional to the longitudinal deformation of the tire 7 at the contact point A, to determine which a longitudinal displacement sensor 17 is provided.

The obtained values of the longitudinal reaction of the support surface and the longitudinal deformation of the tire at the contact point A make it possible to calculate the longitudinal stiffness coefficient of the tire by one of the known methods.

The rotary measuring support platform 5 is a road model. It is made of optically transparent material to ensure the possibility of registering the size, shape of the contact patch, as well as the qualitative and quantitative characteristics of the position of static and sliding friction areas in it.
3. Results and Discussion
The experiments were carried out with a tire model 4.10/3.50-5 (for an airfield cart). It is diagonal, manufactured by Omega (Taiwan), has a pressure according to the passport – 2.5 atmospheres; load – 1100 N. The pressure was created by a DC 12V 300 PSL compressor, designed for a maximum pressure of up to 3 atmospheres, and was controlled by a pressure gauge of the type MTI GOST 2405-63. The combined loading of the tire was carried out: first, radial (passport load), then longitudinal.

A high-speed video camera VS-FAST with a shooting speed of 8000 FPS was used for video recording of the contact patch. The record was carried out in the process of longitudinal loading until complete sliding in the contact patch, through an optical lens with a focal length of 0.2 m to visually increase the size of the contact patch. The video recording was processed using the analysis of contact patch images on a computer with visualization on a large monitor. The large monitor and lens provided 80x larger contact patch. This excludes the comparability of the measured values of the length parameters with the values of the measurement error.

To process the results, we considered those tire tread blocks that were completely located within the boundaries of the contact patch. Their characteristic parts were indicated by points with numbers. On the monitor screen, measurements were made of the geometric position of each characteristic point at each time moment. Namely, the distances of the characteristic points of the contact patch from the measuring base were measured. A fixed vertical element of the stand structure located in the same plane with the movable supporting surface of the wheel is taken as the measuring base. The analysis of the forms of the obtained dependencies makes it possible to judge the location of each contact point at each time moment in the area with static or sliding friction.

Three experiments were carried out with a passport load on the tire of 1100 N. Distance measurements were carried out according to the schemes shown in Figure 4 and Figure 5 for three points of the three sections 1, 2, 3 of blocks A and B, i.e. for 18 points during the time periods of the process. The average of three measurements for each point was calculated.

Due to the fact that the studied tire has a rounded transverse profile shape, and the dimensions of the blocks are comparable to the dimensions of the width of the contact patch, it is logical to assume that the normal stresses of the extreme points (1, 1', 1'', 3, 3', 3'') the outer sections of the studied blocks are smaller compared to the points of the middle section, where the calculated normal stresses act.
In the absence of braking moment \( M_b \) on the wheel, the friction coefficient \( \phi_x = 0 \), and therefore, the friction force \( R_x \) are also absent. When the moment \( M_b \) reaches \( 0.4 M_{b \text{max}} \) (the same as the friction force of \( 0.4 R_{x \text{max}} \)), sliding friction is generated in section 2 of the block B. In this case, the deformations of the points of section 2 are close to zero. Its primary position according to a point (2'' of block B) is located at a distance \( l_x / 4 \) from the front of the contact patch. This is confirmed by the smallest total displacements (3 mm) of this point 2''. At point 2', the total deformation during the loading time is greater and amounts to 4 mm, and at point 2 it is even greater and amounts to 5 mm. At this time, there are no sliding elements in block A, since the displacements are \( X_i > 0 \) for all points.

Sliding elements appear in block A at approximately \( R_x > 0.6 R_{x \text{max}} \), as evidenced by the appearance of «horizontal tops». When \( R_x \approx R_{x \text{max}} \) a «break» occurs, i.e. full sliding in contact. Before the moment of «break» the boundaries of the sliding area spread from point \( S_0 \) (2'' blocks B) to point \( S \) (2' block A). This is evidenced by the oscillatory process in contact at these points when the value of \( R_x \) approaches \( R_{x \text{max}} \). The point \( S_0 \) is located at a distance \( l_x / 4 \) in front of the center of the contact patch, and the point \( S \) is located at a distance \( l_x / 6 \) behind the center of the contact patch relative to the wheel speed vector.

![Contact patch scheme](image)

**Figure 4.** Contact patch scheme
4. Conclusion

1. We developed and implemented a scheme and a method for measuring the characteristics of static and sliding friction areas in the contact patch of a car wheel with a solid support when they appear, exist and disappear. Measurements are indirect.

2. It was experimentally confirmed that in the driving mode of the wheel, the static friction area is displaced forward relative to the direction of the translational speed vector of the wheel axis, that is, towards the front of the contact patch.

3. It was found experimentally in the braking mode of the wheel that the static friction area is displaced backwards relative to the direction of the translational speed vector of the wheel axis, that is, towards the rear part of the contact patch.

4. It was experimentally determined that in the braking mode of the wheel, the sliding friction initially appears at a moment on the wheel of \( \approx 0.4 \) of the maximum allowable range for sliding conditions, in the front part of the contact patch, at a distance from the center approximately \( \approx 1/4 \) of the contact patch length. Then it spreads in both directions, and at a moment of \( \approx 0.65 \) of the maximum allowable for sliding conditions, it occupies approximately half of the contact patch in area. The sliding area has the maximum possible area when the moment on the wheel is equal to the maximum allowable for sliding conditions. Its extreme border is located at the rear of the contact patch at a distance from the center approximately \( \approx 1/6 \) of the contact patch length. When the moment on the wheel reaches the value that is maximum permissible under the sliding conditions, full sliding begins in contact, at which the sliding occupies the entire contact.

5. It was found experimentally that, in the general case, the geometric center of static friction in the contact patch moves towards the moment acting in the plane of the wheel rotation relative to the rotation axis by an amount proportional to the moment. The maximum value of this displacement according to the moment is maximum in terms of sliding conditions, and is one third of the contact patch length for all types and conditions of a solid support.

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