Determination of geometric characteristics of friction areas in contact of the chassis wheel with a solid support

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Abstract. Elastic wheels contain the chassis of airplanes, automobiles and other vehicles. Their tires interact with a solid support surface – roads and airfields. As a result of this interaction, only static friction, only sliding friction or a combination of them, depending on the mode of the wheel movement, can be present in the contact patch. The geometric dimensions and relative position of the different friction areas determine the stable, unstable or boundary movement of the elastic wheel. Purpose of work: calculation and measurement of geometric characteristics of static and sliding friction areas in the wheel-to-road contact. Determined that: the slip area appears on the longitudinal axis of the contact patch, at a distance from the center of the contact patch equal to 1/4 of the length of the contact patch, then it increases due to a decrease in the static friction area; the center of the static friction area in the contact patch moves toward the current moment by an amount proportional to the moment; the maximum displacement of the center of the static friction area corresponds to the moment maximum in terms of adhesion, and is 1/3 of the length of the contact patch.

1. Introduction

Elastic wheels contain the chassis of airplanes, automobiles and other vehicles [1-6]. Their tires interact with a solid support surface – roads and airfields [7-10]. Since the phenomena occurring in contact of a moving tire with the support surface determine the movement stability properties, controllability and braking dynamics of the vehicle, when creating tires, their manufacturers strive to simultaneously provide a number of their important properties: friction, elastic at different coordinates, strength, weight, and reliability [11-15].

At the same time, most modern vehicles, including unmanned vehicles, are equipped with motion control and control systems, whose functioning algorithms provide for executive actions on the wheels and tires. Despite the fact that these systems are constantly being improved, their presence does not always contribute to maintaining safety, i.e., movement stability, controllability and brake dynamics [2, 3, 5, 7-9]. Moreover, it is known that in some driving modes, the activation of these systems leads to a loss of stability and controllability of the vehicle. These are modes associated with the presence of a side force of even a small value, amounting to 15...20% of the vehicle weight, while the presence of a brake mode further aggravates the situation [2, 3, 5]. The described phenomena are not related to malfunctions or defects in the design of the motion control and control system, which corresponds to the modern ideas of specialists-designers about the interaction of the wheel with the road [11, 16-20]. These modern concepts are not perfect due to the lack of knowledge of the phenomena that occur in the wheel-to-road contact patch, especially in the presence of lateral force. Accordingly, this lack of
knowledge is manifested in the problem of incorrect modeling of phenomena in the wheel-to-road contact patch (at the design stage of the vehicle), which determine the stability and controllability of the vehicle, and does not provide the basic possibility of creating motion control and control systems that can adequately perform their functions in all driving modes, including specific ones.

In this regard, despite the existence of significant basic research [11, 21-24], there is a need for further research of the interaction of an elastic wheel with a solid support, especially in the presence of lateral force. A number of problems appear, one of them is to calculate the changing geometric characteristics of areas with static and sliding friction in the contact patch of an elastic wheel with a solid support, which perceive external forces differently and create reactions to the wheel in different ways.

2. **Aim of work**
Calculation and measurement of geometric characteristics of areas with static and sliding friction in the contact patch of an elastic wheel with a solid support.

3. **Current state of the problem**
Previously, experiments were carried out on the experimental installation created at the Volgograd State Technical University to study the phenomena in the contact patch of an elastic wheel with a solid support surface, which allowed us to qualitatively identify the mutual location of areas with static and sliding friction in the contact patch [10]. They showed that:

1. In the contact patch of an elastic wheel with a solid support in the wheel braking mode, the static friction area is shifted back relative to the wheel speed vector, towards the rear of the contact patch;
2. In the contact patch of an elastic wheel with a solid support in the driving mode of the wheel, the static friction area is shifted forward relative to the wheel speed vector, towards the front of the contact patch;
3. When a side force is applied to the wheel, the static friction area is shifted in the direction opposite to the side force of the wheel (co-directed to the side reaction vector of the wheel).

These were qualitative studies, but not quantitative. At the same time, the result described in point 3 was new, and the results described in points 1 and 2 were confirmation of earlier studies by Knoroz V.I. and Balabin I.V.

4. **Methods and approaches**
As is known, the interaction of an elastic wheel with a solid support in the contact patch is characterized by diagrams of normal and tangential stresses. Using a plot of the normal stresses, it is possible to define a plot of permissible tangential stresses in the contact patch. Since the sliding area in the contact patch originates not where the tangent stresses are maximum, but where they begin to exceed the permissible ones, the condition for the appearance of sliding at the i-th point of the contact patch can be written as follows:

\[ \tau_{si} \geq \tau_{si} = f_{si} \cdot \sigma_{si} \]  

where \( \sigma_{si} \) – normal stresses at the i-th point of the wheel contact patch with the support; \( \tau_{si} \) – tangential stresses at the i-th point of the wheel contact patch with the support; \( f_{si} \) – static friction coefficient between the wheel and the support surface.

This method was implemented. The plots of normal and tangent stresses in the contact patch were analytically determined [3]:

\[ \sigma_{si} = \left( \frac{k \cdot R_d \cdot X_i}{I_c \cdot r^2} \cdot \varphi_{max} + \frac{1}{I_c} \right) \cdot P \cdot \frac{2}{(B_r/2)^2 \cdot \left( 1 - \frac{X_i}{(l/2)^2} \right)^{1/2}} \]  

\[ \tau_s = \tau_{si} - \Delta \tau_s \]
\[ \tau_{i0} = E \left( \frac{2 \cdot R_d}{l} \cdot \arcsin \left( \frac{l}{2 \cdot R_d} \right) - 1 \right) \cdot \sin \left( \frac{X_i}{l/2} \cdot \pi \right) \]  

(4)

\[ \Delta \tau_s = \left( k \cdot P_i \cdot \varphi_{\text{max}} \cdot R_d \cdot \frac{\sqrt{r^2 - X_i^2}}{S_c} \right) \]  

(5)

where \( R_d \) – free wheel radius; \( R_d \) – dynamic wheel radius; \( r \) – tire landing radius; \( l \) – length of the wheel contact patch with the support surface; \( B_e \) – width of the wheel contact patch with the support surface; \( S_c \) – the area of the wheel contact patch with the support surface; \( \varphi_{\text{max}} \) – maximum friction coefficient of the tire to dry asphalt; \( P_e \) – normal load on the wheel axle; \( X_i \) – longitudinal coordinate \( i \)-th point of the contact patch; \( k \) – dimensionless coefficient equal to the ratio of braking moments \((k = M_{\text{br}}/M_{\text{brmax}})\); \( E \) – elastic modulus of the tire material along the contact patch.

Then we compared the tangential stresses acting in the contact patch with the permissible ones and found the positions and sizes of static and sliding friction areas in the contact patch of an elastic wheel with a solid support at different values of the moment on the wheel.

Figure 1 shows the final schemes of the appearance and growth of the sliding area in the contact patch when the brake torque increases.

Thus, the plots of normal and tangential stresses in the contact patch of an elastic wheel with a solid support are obtained by calculation for different types of wheel loading, since it is possible to identify the place of sliding in the contact patch of an elastic wheel with a non-deformable flat base only on the basis of comparing the plots of tangential and normal stresses. The tangent stresses acting in the contact patch are compared with the permissible ones, and thus the geometric arrangement of the areas with static and sliding friction in the contact patch under different modes of wheel movement is analytically found.

For experimental confirmation of the obtained results, an experimental setup was created for quantitative detection of the relative location of areas with static and sliding friction in the contact patch, shown in figure 2.

The tire 4.10/3.50-5 (for an airfield cart) is diagonal, manufactured by Omega Company (Taiwan) has a pressure according to the passport – 2.5 ATM; the load – 1100 N. The pressure was created by a DC 12V 300 PSI compressor, designed for a maximum pressure of up to 3 ATM, and was controlled by a manometer of the type MTI GOST 2405-63.

The experimental setup consists of an elastic wheel pivotally mounted in a horizontal position, interacting with a solid flat support made of optically transparent material. It is a model of the road and provides the ability to visualize phenomena in the contact patch between the wheel and the road. The experimental setup allows the wheel to be loaded from the flat support side with a normal load and a longitudinal load until a complete sliding occurs in the wheel contact patch. For video shooting of the contact patch, a high-speed video camera with a shooting speed of 8 thousand FPS was used. The image was taken during longitudinal loading until complete sliding in the contact patch occurred, using 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 image analysis of the contact patch on a computer with visualization on a large monitor, as shown in figure 3. A large monitor and lens provide a hundredfold increase in the size of the contact patch. This eliminates the comparability of the measured values of the length parameters with the values of measurement error.

We considered those tire tread blocks that were completely located within the boundaries of the contact patch. Their characteristic parts were counted as points with numbers. Then, on the screen of the monitor, measurements were made of the geometric position of each characteristic point at each moment of time. From this data, the movements of each characteristic contact point at each moment of the process flow were calculated. The analysis of the forms of the obtained dependencies allows us to judge the location of each contact point at each moment of time in the area with static or sliding friction.
Preliminary processing of the experiment results confirmed the results of the calculations. The experimental research of pre-determined quantitative characteristics of static and sliding friction areas in the contact patch, namely, the coordinates of the location of the sliding phase relative to the center of the contact patch, the coordinates of the current location area with the sliding friction and end coordinates of this area at the time of full sliding. The coordinates are expressed in arbitrary units relative to the length of the contact patch. This allows to determine the location of the application of the lateral reaction of the support surface, implemented in the contact patch in response to external lateral force, since it is implemented only by the area with static friction in the contact patch and has the greatest effect on the deviation of the wheel from the specified trajectory.

**Figure 1.** Schemes for the appearance and growth of the sliding area in the contact patch of an elastic wheel with a solid support when the brake torque increases: O – the center of the contact patch; S – the place of occurrence of sliding area
Figure 2. Photo of the experimental setup: a – general view; b – contact patch view of the tire 4.10/3.50-5 (for an airfield cart)

Figure 3. Processing photo
5. Conclusion
1. In the contact patch of an elastic wheel with a solid support in the driving mode of the wheel, the static friction area is shifted forward relative to the direction of the translational speed vector of the wheel, towards the front of the contact patch.
2. In the contact patch of an elastic wheel with a solid support in the braking mode of the wheel, the static friction area is shifted backward relative to the direction of the translational speed vector of the wheel, towards the rear of the contact patch.
3. In the contact patch of an elastic wheel with a solid support, the sliding area appears on the longitudinal axis of the contact patch, at a distance from the center of the contact patch equal to 1/4 of the length of the contact patch. Then it increases by reducing the static friction area.
4. The center of the static friction area in the contact patch moves in the direction of the acting moment by an amount proportional to the moment.
5. The maximum displacement of the center of the static friction area corresponds to the moment that is maximum under the friction conditions, and is 1/3 of the contact patch length for all types and states of solid support. When this movement is achieved, there is a full sliding in the contact patch, when the sliding friction area occupies its entire space.

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