Quasi-static research of cornering stiffness for selected tires of UTV/ATV vehicles

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Abstract. The cornering stiffness is an important feature of the tire influences the dynamic behavior of the vehicle in curvilinear motion. The article presents results of quasi-static research of cornering stiffness. Two non-pneumatic tires (NPTs) of similar size and a pneumatic tire for utility terrain vehicles (UTVs) or all-terrain vehicles (ATVs) were selected for the research. The analysis of the research results showed a significant influence of the flexible structure of NPTs on the values of lateral forces.

Key words: pneumatic tire, vehicle, vehicle dynamics

1. Introduction
The tire is one of the most important elements of the vehicle. Its construction and the materials used affect, among others, traction and controllability of the vehicle, especially in critical conditions of its motion [1,2]). It is also an important, next to the suspension [3], an elastic-damping element that co-decides on the driving comfort and car movement of the car in various road conditions [4].

The pneumatic tire is the most common type of tire today. The performance of specific functions of a pneumatic tire is possible by appropriate materials selection of supporting structure and tread, as well as maintaining compressed air or gas under a certain pressure. Requirement to maintain compressed air (resilient factor) is unfortunately one of the major disadvantages of pneumatic tires. The air loss initially causes the deterioration of the tire's performance properties and, in the absence of any reaction from the driver, may lead to its irreversible damage [5]. An alternative solution to this problem are non-pneumatic tires (NPTs). Their modern construction correctly mimic the properties of compressed air thanks to the use of a supporting structure with often complex geometry [6-8]. In [6,8] detailed analysis of the normal load transfer mechanism depending on the supporting structure of NPTs are presented.

The structure of each NPT include the following common elements: rim, belt (shear beam/belt), tread, flexible structure (connecting the tread with the rim), e.g. single spokes or with a cell structure. The available test results for NPTs are mostly the results of numerical tests (finite element method). For example, [9] analyzed the effect of changes in the width and length of the spokes on the aerodynamic drag of the wheel based on numerical tests, supplemented by scaled model experimental tests in a wind tunnel. In [5], the NPT radial characteristics were analyzed using the finite element method for various geometries of the supporting structures, which were validated by a laboratory experiment. In [8] the influence of the NPTs spoke curvature on the radial characteristics of the wheel was analyzed. Increasing the spoke curvature resulted in an increased displacement of the NPTs center. The assessment of the
influence of wheels on the vehicle curvilinear motion (especially in transient non-steady-states) is always an important and carefully considered aspect. The vehicle course is determined by the cornering stiffness [10]. This parameter also provides information on the tire susceptibility to lateral deformation, which in dynamic conditions translates into a slower response of the vehicle to dynamic changes in the values of lateral forces transferred by the vehicle wheels. The lateral force loading affects the gradual increase in the deformation of the wheel resilient layer. The shape of the contact patch with the ground changes, while the lateral response increases until a certain constant value is reached, which is transmitted under the steady-state vehicle motion condition. This phenomenon is well described by the so-called tire relaxation length. Taking it into account is particularly important in the dynamic model of curvilinear vehicle motion. The purpose of this paper is to measure and analyze the cornering stiffness of NPTs and pneumatic tire used in utility terrain vehicles (UTVs) or all-terrain vehicles (ATVs).

2. Methodology and research conditions
The quasi-static research of cornering stiffness were carried out with use of the Universal quasi-static indoor tyre test bench (figure 1). A detailed description of the construction and measurement possibilities have been described earlier in [11, 12]. The authors are conducting comprehensive tests of NPTs. Therefore, the research of the cornering stiffness were carried out in the same conditions as those described earlier in [13] (the tests of the radial characteristics). The ATVs and the UTVs, during curvilinear motion, often move using large angles of wheels steering, which was taken into account in the selection of the cornering angles. The test conditions are presented in table 1.

Complementing the comprehensive research with the cornering stiffness was carried out for (figure 2):
- NPT_1 (non-pneumatic tire nr 1) - equipped with 24 pairs of spokes;
- NPT_2 (non-pneumatic tire nr 2) - equipped with a cellular (hexagonal – honey comb) flexible cell;
- PT (pneumatic tire) - diagonal tire.

Each measurement under specified conditions was repeated four times.

![Figure 1. The universal quasi-static indoor tyre test bench.](image)

| Research objects | Normal load [N] | Cornering angle [°] | Inflation pressure [MPa] |
|------------------|-----------------|---------------------|------------------------|
| NPT_1            | 1000            | 5                   | -                      |
| NPT_2            | 2000            | 10                  | -                      |
| PT               | 3000            | 15                  | 0.3                    |
The tire cornering stiffness contains the stable value of lateral force as a function of tire cornering angle. During the measurement, the wheel was positioned at a certain angle with respect to the direction of movement of the measuring surface. After applying the determined value of the normal force, the measuring (mimics road) surface was set in motion (figure 3). During the test, the value of the lateral reaction and the displacement of the measuring surface were recorded. The obtained measurements allow to determine the stable value of the lateral force as a function of cornering angle. The procedure for marking the cornering stiffness is shown in Figure 4.

![Figure 2. Badane kola: a) NPT_1, b) NPT_2, c) PT.](image)

![Figure 3. The method of measuring the cornering stiffness (top view).](image)
Figure 4. From left: example of trajectory of the lateral tire $F_Y$ as a function of measuring surface displacement $x$, characteristic of cornering stiffness.

3. Results
Research results were shown on figure 5. Measurement results are marked with gray pluses. Next, the mean values for each cornering angle are connected by a line. Green, orange and blue colors indicate the characteristics of the cornering stiffness, respectively for the normal force of 1000, 2000, 3000 N.

Figure 5. Characteristic of cornering stiffness: a) NPT_1, b) NPT_2, c) PT.

In general approach, the trajectory of the characteristics of the cornering stiffness for all research objects is similar. Increasing the cornering angle increases the lateral force, which stabilizes at the cornering angle of 15° or 20° (smaller value of angle for less load), depending on applied normal load. In the analysis, a pneumatic tire was used as a reference point, which can be replaced by NPTs. This comparison shows that the use of NPT_2 allows to achieve higher values of lateral force even at the smallest cornering angle (especially for applied normal load 3000 N). Probably the first cause of this phenomenon is the stiffer NPT_2 tire caps under tread area with a simultaneously larger radius of curvature of the cross-section. The effect of the above-mentioned is greater stability of the shape and contact path of the wheel. Another reason may be the high torsional stiffness of the with honeycomb structure. This inference can be confirmed by the results obtained in the research of the NPT_1. The measured values of lateral force are definitely greater than obtained for the other research objects. The reduction in the torsional stiffness of the "spoke" support structure is observed while maintaining the advantages of a stiff tread with belt. As a result, the tread protrusions are less deformed, which results
in an increase in the values of the lateral forces achieved (resulting from the adhesion force of the rubber forming the tread protrusions on the ground).

4. Conclusion

The quasi-static research of cornering stiffness were carried out for non-pneumatic tires and pneumatic tire used in UTVs/ATVs. During the research, the wheels were loaded with three different force values and were rolled at four cornering angles. NPT_1 (wheel equipped with single spokes) in each of the adopted test conditions was characterized by the highest value of lateral force. Obtaining higher values of the established lateral force may have an influence on the increase of the relaxation path compared to NPT_2 and PT. It may also have an impact on higher values of lateral deformation and a slower response of the vehicle to dynamic changes in the values of tire lateral force. Other research objects for normal loads of 1000 and 2000 N achieve similar cornering stiffness characteristics.

For the analyzed pair of wheels (NPT_2, PT) for the load of 3000 N, visible differences were obtained in the trajectory of cornering stiffness characteristics.

In the next stage of the research, it is planned to extend the test conditions with additional cornering angles and an additional value of inflation pressure of the pneumatic tire. The analysis of the test results will be enriched with the results of the relaxation path and the analysis aimed at explaining the observed results and the possible confirmation of the hypotheses formulated in the paper.

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