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THE USE OF A MAGNETIC FIELD IN THE ASSESSMENT OF THE OPERATING LOADS OF PNEUMATIC TIRES

Summary. Steel is a typical construction material with ferromagnetic properties. This material is often used as a structural component of composites whose task is to transfer mechanical loads. This function is performed by the steel wires placed inside the tires. The aim of the preliminary tests was to determine the influence of air pressure changes in the pneumatic wheel on the distribution of the magnetic field observed outside the tire. The research used a magnetostrictive sensor that reacts to changes in magnetic induction. A sensor with three perpendicular measurement directions was used, and the components of the magnetic induction vector were measured at selected measurement points located in the space surrounding the tested tire. During the tests, measurements were made of the tire's magnetic field under various load conditions. The results confirmed the occurrence of measurable effects of changes in the magnetic field distribution of the tire depending on the pressure inside.

1. INTRODUCTION

Tires, which perform complex functions, are a key piece of equipment in any modern motor vehicle. On the one hand, their role is invaluable in terms of improving comfort, as their elastic damping properties ensure the mechanical filtration of vibration excitations coming from road unevenness. On the other hand, they are responsible for safety by transferring all forces and moments acting between the vehicle and the road surface. Such complex tasks set for car tires indirectly influence the complexity of their structure, which, on the one hand, should ensure adequate compliance and, on the other hand, ensure the maintenance of high stiffness when transferring shock loads. An additional important feature of the use of tires in vehicles is the generation of an appropriate operating pressure inside them, which prevails in the pneumatic wheel [1, 2].

The cross-section of a car tire is presented in Fig. 1. Such tires (especially those used in passenger cars and trucks) consist of many components with different utility functions. Some parts of the tire, such as the tread, shoulder, and side, are used to ensure flexibility, grip and damping properties, while others, such as belts and cords, provide shape stiffness under the influence of both constant and variable operational loads [3, 4].

Mass production uses a wide range of available materials to produce tire components while maintaining the required parameters. This also applies to strapping, which often consists of elements (wires) made of iron alloys, among other elements. The belt often consists of several layers of hypereutectic steel wires with a diameter of 0.1 mm to 0.5 mm. In each layer, the wires are arranged

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parallel to each other and embedded in the rubber mixture. Typically, the construction of tires uses two such layers placed one above the other (but there may be more). The wires in the layer are at an angle to the other. This creates a mesh-like structure when viewed from above from the tread side. The belt holds the elements of the tire together and keeps them in the correct shape. Tire deflection during car movement depends mainly on the static and dynamic load, as well as the radial stiffness of the tire. This is related to, inter alia, tire pressure, temperature, and the physical properties of the materials used for its construction, as well as the arrangement and dimensions of the tire components [1, 5-7].

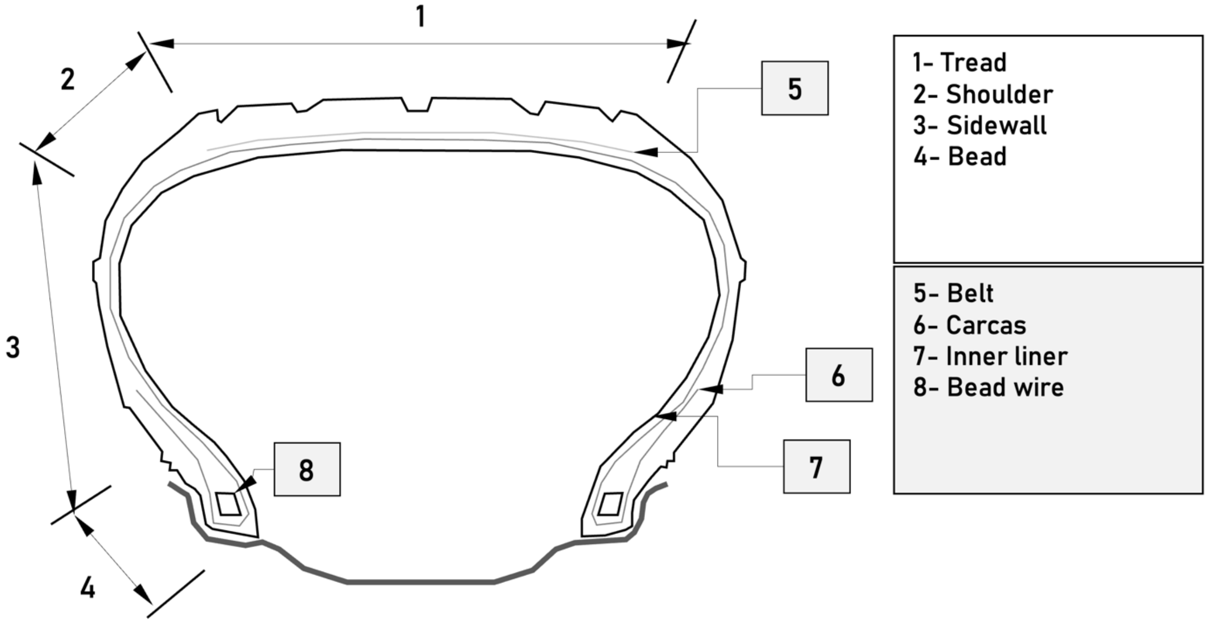


Fig. 1. Cross-section of a tire

The belt flexes when pivoted, similarly to (but not exactly the same as) the tread. Belt deflection is caused by many factors, such as actual pressure; inflation pressure; wheel speed; car speed; and forces that occur when cornering, accelerating, braking, and negotiating obstacles. All of these factors constantly change with time, mileage, and wear. According to the latest research, the distribution of the magnetic field of a belt and its intensity change with time during normal operation. Therefore, it can be assumed that the process of magnetizing the wires in the belt is due to the phenomenon of reverse magnetostriction caused by stresses.

The briefly described reasons for magnetizing the tire belt related to the manufacturing process are the primary cause of the tire's magnetic field. It is impossible to draw conclusions about the tire directly from the results of measurements of the magnetic field distribution. Valuable information contained in the magnetic field distribution can be extracted from the results using signal analysis techniques, which will be presented in a manner beyond the scope of this article. To take a measurement, one must first select the appropriate measurement technique, as well as the measurement approach and equipment. This task is quite demanding because the steel belt tire rotates (together with the rim) in the Earth's magnetic field during normal use. Therefore, it can be assumed that the induction of the Earth is homogeneous and that its intensity ranges from 25 μT to 60 μT [7, 8].

The variable rotational speed of the road wheels during operation affects the frequency of the tread passing through the load zone from 0 Hz to as much as 50 Hz in the case of sports cars [9, 10]. The influence of the above-mentioned factors and the fact that the deflection of the tire belt occurs at each revolution allows us to assume the existence of the Vilary effect. This causes changes in both the magnetic field's strength [12] and distribution [11]. The changes in the magnetic field presented in [8, 12-14] are significant. Therefore, it is necessary to ensure repeatable measurement conditions.

As mentioned earlier, measuring techniques must be consciously selected for the measuring device. Earlier work by researchers has documented a fairly ingenious and effective approach to this topic.

Stankowski [12], Jacobs et al. [15], and Kawase et al. [16, 17] used only hand instruments or instruments connected with special or improvised grips for fixing and turning the whole wheel (rim + tire). The results of such measurements give knowledge about the distribution of the magnetic profile, but results obtained in this way (circumferential magnetic profile) are poorly reproducible. The results of magnetic field measurements are their time distributions, which were analyzed as time signals [18, 19].

Previously, scientists used wooden handles to rotate the wheel. Standard wheel balancers were often used in such tests. The disadvantage of this solution was that the balancers were made of ferromagnetic materials (a large number of steel structural elements), which caused interference in the measurement results. The authors of these studies were aware of this, and they treated the obtained results as preliminary research material. It was often (and rightly) assumed that the influence of magnetic materials of the accessories was negligible, as it results, inter alia [20, 21], but only when the sensor is very close to the tire tread.

Brol et al. [11] used a device with controlled kinematics (angular velocity) to measure magnetic induction. Unfortunately, errors caused by the human factor were not avoided, which affected the deterioration of the repeatability of the obtained results due to the influence of the sensor position adjustment in the direction of the width of the tire tread. This inconvenience was removed in the second version of the instrument by introducing the computer control of the sensor shift in the direction parallel to the axis of rotation and the automation of the measurement process [12].

The aim of the present research was to assess the possibility of using the tire's magnetic field to test its operational loads. The results confirming the hypothesis are presented in the following chapters.

2. RESEARCH METHOD AND RESULTS

There are currently two main methods of measuring the magnetic field of a complete wheel over the tread, as shown in Fig. 2. The first is to measure the magnetic profile along the circumference of the tread. This is a measurement (1D) that results in a circumferential magnetic induction profile B. The second method is to measure the spatial distribution of the magnetic induction around the tire. The method of operation of the scanning device is described in [12]. Magnetic surface $B_k(\varphi, w)|_h$ is measured for $\varphi \in (0..2\pi)$ and $w \in (wmin..wmax)$ at a fixed increment of w, denoted as Δw and fixed h. In reality, the magnetic surface consists of several circumferential profiles $B_k(\varphi, w = const)|_h$, and every element of the profile (i.e., B vector consisting of three projections of B_x, B_y, and B_z) is measured at the same φ. This allows the extraction of a cross profile $B_k(\varphi = const, w)|_h$ from a magnetic surface. Two details are essential in determining the measurement process. The magnetic circumferential profile consists of a vector of B, which, in these investigations, has Cartesian 3 projections. Therefore, "circumferential profile" can refer to a profile consisting of scalar values of B projections, such as $B_x(\varphi, w = const)|_h$, $B_y(\varphi, w = const)\big|_h$, and $B_z(\varphi, w = const)|_h$, or to the resultant value $|B|(\varphi, w = const)|_h$ (in short, B_x, B_y, B_z and generally B_k). There is also profile B, which is the resultant profile of three components. The h value represents the distance between the B sensor's surface and the lower part of the tread's groove as close to the middle of the tread as it is marked in detail in the rectangle in Fig. 2.

Measurements according to the method described above are made on the device (a diagram of which is shown in Fig. 3a). In Fig. 3b, its photo is shown. Technical parameters of the test stand are included in Table 1.

Examples of circumferential tire magnetic induction profiles measured on a test bench for various tire pressures are shown in Fig. 4.

Figs. 4a and 4b look very similar. However, even at this magnification, some subtle differences in signal amplitude can be seen, especially when comparing the B values with the sample numbers of 100, 500, or 1500. Attention was also paid to the different values of the signal amplitude differences depending on the pressure. Therefore, we decided to introduce the so-called differential peripheral profile, which is the difference between two signals (profiles), the first of which always refers to the lowest pressure in tests.

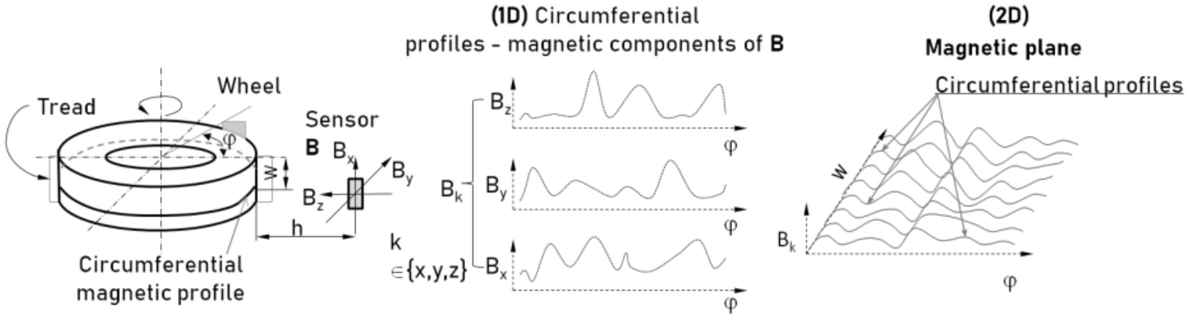


Fig. 2. Schematic of the magnetic scan and cross profile extraction

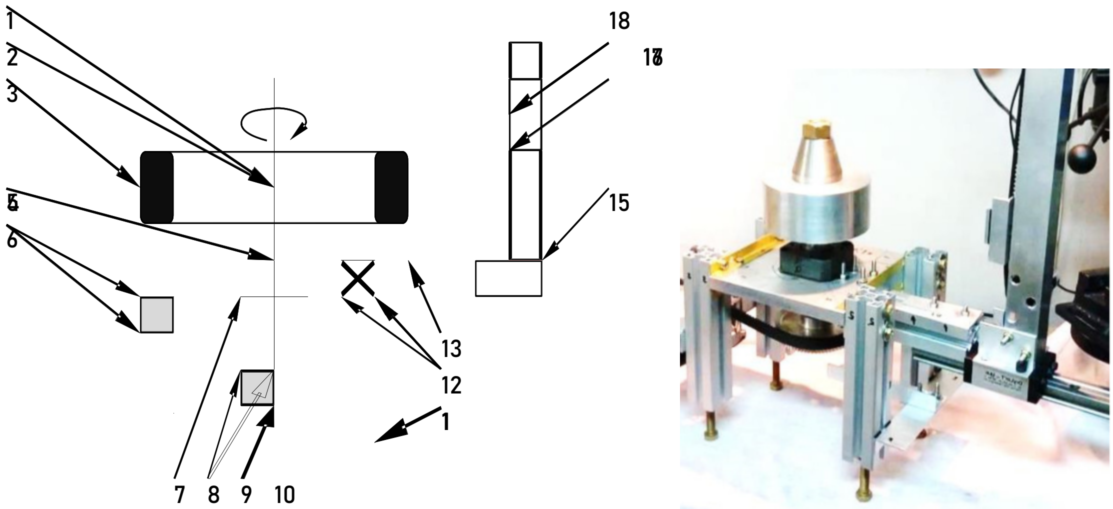


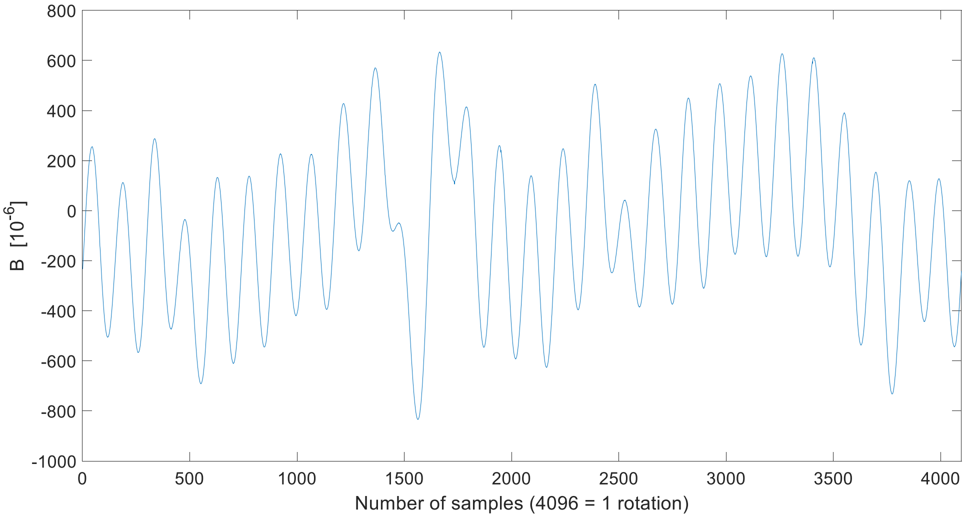
Fig. 3. Scheme and view of the measuring device: (a) 1 − vertical main shaft, 2 − wheel fixing nut, 3 − tested wheel, 4 − bearing seat, 5,7 − toothed belt transmission, 6 − electric motor, 8 − rotary encoder, 9 − encoder mounting plate, 10 − horizontal beam, 11 − adjustable support points on the ground, 12 − slide securing lock, 13 − vertical beam, 14 − horizontal guide, 15 − electric drive, 16 − magnetic induction sensor, 17 – slider, 18 − pol; and (b) photo of the measuring device

Table 1

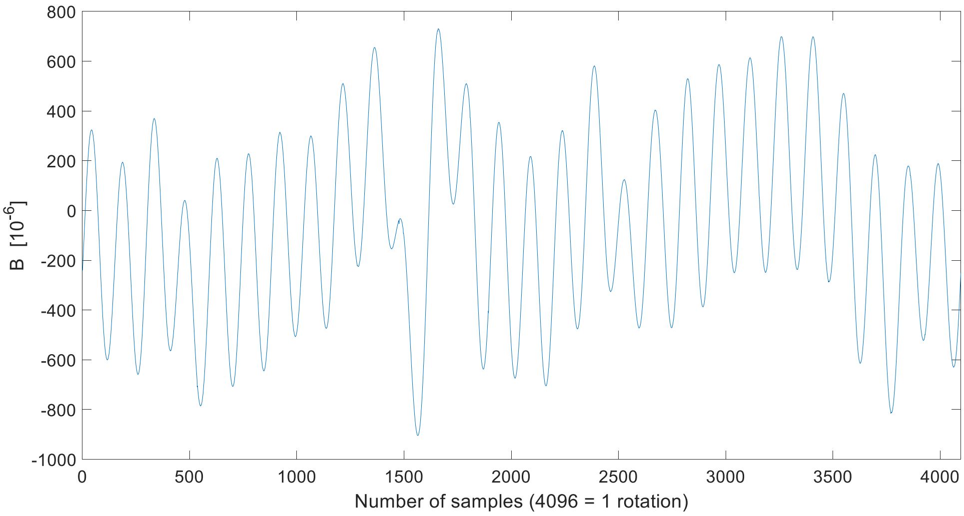
Measuring parameters used in investigations

No of tires	**Tire dimensions**	**Wheel's rims**	**w** $[w_{min}..\Delta w..w_{max}]$ **[mm]**	**h [mm]**	**Measurement mean radius** r_m **[mm]**
4 winter	195/65R15	Steel rims	[1..4.8..195]	15	317
Constant measuring device parameters					
Shaft rotational speed of shaft (with fixed wheel): 1.05 rpm Magnetic sensor type: HMC5883L Range of magnetic sensor: $\pm 8 \cdot 10^{-4}$ T Digital Resolution:12 bit Angular resolution: 12 bit for 2π rad Circumferential uncertainty: $(r_m\ \pi)/2^{12}$ mm					

As can be seen in Fig. 5, the difference profile carries information about the change in the value of the increment measured by *B* on the circumference of the wheel (above the tread) for different pressures. For this reason, these types of profiles will be discussed later in this paper, as they provide information about the effects of changing the tire pressure.



a)



b)

Fig. 4. Circumferential profiles measured in the radial direction for (a) 0.5 bar and (b) 3.0 bar of tire pressure

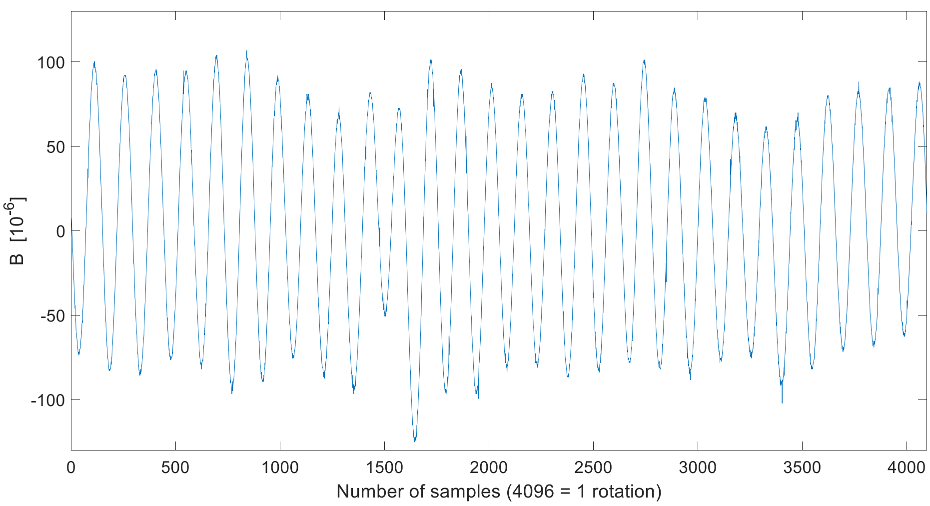


Fig. 5. Differential profile of the circumferential profiles presented in Figs. 4a and 4b

All tests used the same winter tires (produced by the same manufacturer) mounted on 15-inch steel rims. As previously described, their width and height were 195 and 123 mm, respectively. The carcass was made of polyamide, and the belt consisted of two layers of steel rods. The tested tires were used in the car for two years under constant mounting conditions (i.e., the same axle and side of the vehicle) throughout the test.

The complete wheel was mounted on a prototype measuring device shown in Fig. 3. The pressure in the tire was lowered to 0 bar, and the magnetic surface above the tread was scanned. For analysis and further activities, nine profiles (middle) from the scan were selected. Further, however, the procedure was repeated by previously increasing the tire pressure by 0.5 bar until it reached 2.5 bar. After collecting the profiles, they were subtracted from the profile ordinates from the first measured profile with the same angular arguments.

3. THE METHOD OF PROCESSING THE MEASUREMENT RESULTS

The measurable effects of “programming” the mechanical stresses in the values of the magnetic induction of steel bars inside the tire make it possible to make an assumption about the possibility of using this effect to determine tire loads. The main exploitation factor in tires is the pressure inside them, which may increase during the drive as a result of work done in the pneumatic wheel in terms of damping. Similarly, when tires are used in winter conditions, a decrease in the average pressure value can be observed. While driving in dynamic conditions, it can be assumed that the instantaneous pressure values change and that these changes occur around the average pressure value. In the conducted tests, the results were presented in the form of peripheral scans of the distribution of the magnetic field around the tire. The profile of such a distribution for a given tire is qualitatively constant (Figs. 4a and 4b), while the values of the magnetic field strength at selected points depend on the pressure inside the tire. It is advisable to assume the necessity to identify selected areas (points) on the circumference of the tire for which the observation of changes in the magnetic induction will enable the evaluation of the operational load of the pneumatic wheel.

3.1. Resolution of peripheral measurements

The prototype device used for measuring magnetic profiles, among other properties, allowed us to obtain up to 4096 samples of B on the circumference. The device is characterized by a constant angular resolution, but it also has a variable circumferential resolution because it depends on the free wheel diameter in this measurement method. In the tested tires, all the differential profiles obtained for different pressures were periodic and in phase with each other. Differential peripheral profiles were counted from 28 to 32 local induction maxima per circuit. Moreover, the amplitudes were different for different pressures and changed according to the increase in pressure. According to the Nyquist frequency, the profile, which is initially measured excessively (as much as 4096 samples per revolution), can be reproduced by adopting a resolution equal to two samples per period (i.e., 256 samples per revolution). However, it is recommended that the real resolution is many times higher to avoid hitting the wave node (i.e., zero crossing in this case). Therefore, this criterion can be used successfully only with regular differential profiles, such as the one shown in Fig. 6, to establish the measurement sites so that they are close to the maximum and minimum.

The tire test results presented here do not exhaust all possible types of induction changes on the circumference of the circle (profile shapes). However, it should be emphasized that previous studies on other wheels revealed circumferential profiles that were characterized by complex spectral characteristics [11, 12]. However, the profile elements (i.e., elevations or valleys) were much wider than in the cases described here. Thus, based on the collected data, it can be assumed that the mapping of the perimeter profile can be performed with more than 256 samples per perimeter.

The problem of searching for a local maximum or minimum in the profile in a place considered representative should be considered somewhat differently. On the basis of the above considerations, the global extremum of the profile can be taken as such because the increments of B resulting from increasing the tire pressure are the largest in the local maxima or minima, although one of them may be (and most often is) the global extremum.

3.2. Location of the measurement site

The variability of the distribution of the magnetic induction value in the circumference of the tire means that its use to determine the operational load provides an answer to the following question: Is point measurement or the value of the selected statistical parameter a better measure of the load condition? The answer is not clear without specifying the measurement conditions. In laboratory conditions on a measuring stand or during tests carried out on tires of a non-moving vehicle, it is more expedient to use the measurement results obtained in one specific place around the circumference of the tire. Thus, the selection of the measurement site must be preceded by a preliminary perimeter scan, which will allow us to determine the angular position of the local maximums of the induction value (Fig. 6). The selection of one of the local maxima makes it possible to present the changes in B as a function of changes in tire pressure (Fig. 7).

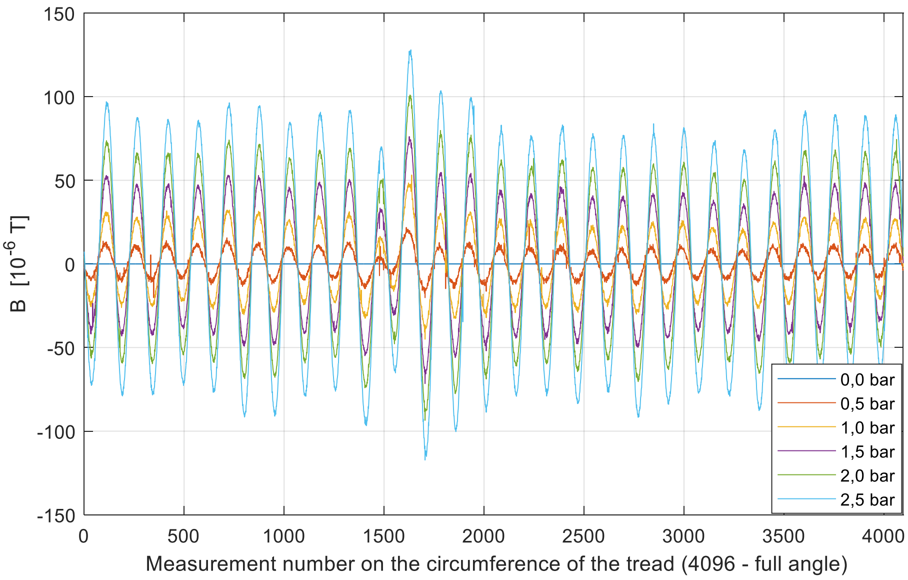


Fig. 6. Differential profiles for different tire pressures

In the conditions in which the operational tests were carried out (e.g., while driving), the global assessment of the proposed measure should be used instead of focusing on specific induction values (i.e., for the recorded profiles of magnetic induction changes, an amplitude measure can be indicated). The selected measure should not be very sensitive to the maximum values of induction. The distribution of magnetic induction circuits is random. For this reason, the authors propose a measure based on the definition of the variance of the magnetic field distribution to assess the changes in tire load caused by pressure fluctuations inside the tire.

3.3. A proposal for a global measure based on circumferential measurements of the magnetic induction of the tire

The registered circumferential profiles of the magnetic induction distribution resulting from changes in pressure inside the tire can be treated as distributions of a random variable. The values of the magnetic field strength measured in a given radial direction assumed values from the range of real numbers. For this reason, their use in the assessment of the operational load of the tire requires the use of angular positioning when selecting the location at which information about the magnetic field is collected. A better practical solution is to use the global measure of magnetic induction distribution in the form of an amplitude discriminant defined as the effective value of the magnetic induction B_{RMS} measured on the circumference of the circle according to Equation (1).

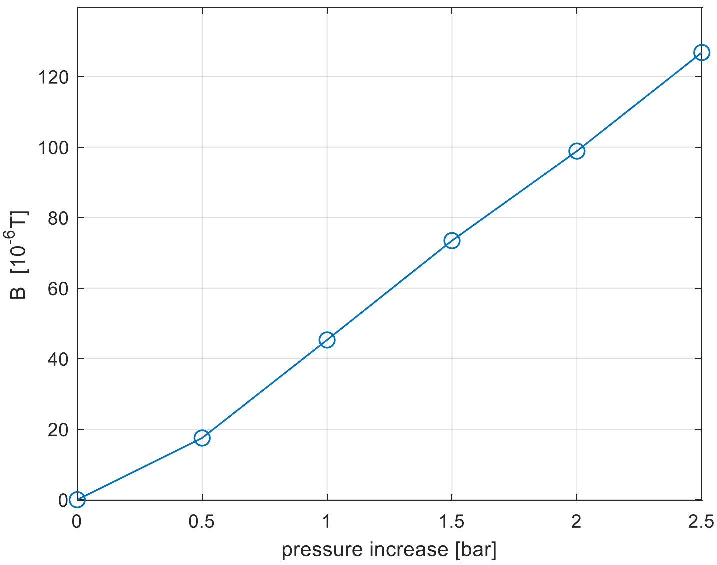


Fig. 7. The presented relationship was determined in the tested tire for 1632 of the sample corresponding to the value of the angular position of the tire $(143^0 35^{'})$

$$B_{RMS} = \sqrt{\frac{1}{N}\int_{i=1}^{N} B_i^2} \quad [T] \tag{1}$$

where: i is the indexed values of consecutive samples corresponding to angular positions on the circumference of the circle, and the value of N results from the angular resolution of the scan (Fig. 6).

The results of the survival of induction distributions obtained for various increases in pressure inside the tire are shown in Fig. 8.

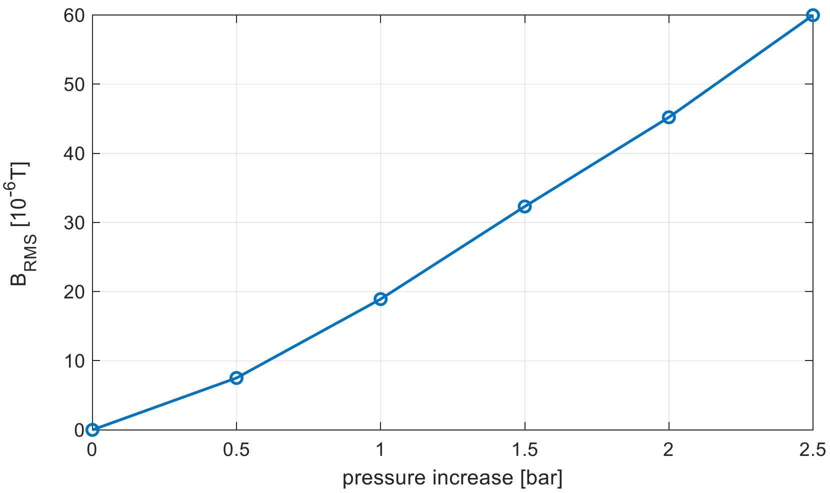


Fig. 8. The root mean square values of the magnetic induction of differential profiles

The nature of changes in the value of magnetic induction with changes in pressure determined for the local maximum of the distribution (Fig. 7) is very similar to the curve describing the studied phenomenon globally. Therefore, it can be assumed that the use of a global measure that is insensitive to the positioning parameter gives similar information that can be used in the assessment of the operational load of a tire.

4. CONCLUSIONS

In the preliminary research presented in this work, the main goal was to demonstrate the possibility of using the magnetic field around a car tire to assess its operational loads. The operating loads of a pneumatic wheel contribute directly to changes in driving safety. One of the indirect effects of changes in tire loads in a wheel is fluctuations in the pressure inside the tire. There are methods for measuring and monitoring tire pressure that are commonly used in motor vehicles. Tire pressure is measured either directly by a pressure sensor or indirectly by the variation in the radius of the dynamic wheel causing the change in rotational speed. Pressure change, understood as the change in the operational load of a tire, affects the magnetic field around the tire. The method proposed by the authors allows for direct measurement of the impact of operational loads resulting from changes in tire pressure on the distribution of the magnetic field. A close correlation was shown between the magnetic field and the pressure inside the tested tire (Fig. 8). The present results should be treated as an introduction to a more extensive study of magnetic fields generated by pneumatic road wheels of vehicles. On the basis of the conducted preliminary tests, the usefulness of the described method was also confirmed in the study of structural changes inside the material. Higher internal pressure increases the magnetic field's strength around a tire, which is associated with an increase in the forces acting on the structural component of the tire (steel belt). Further research will be conducted to confirm the usefulness of the proposed method in tests of tires used in normal conditions. At this stage, the described method concerns testing in laboratory conditions (without external interference from other vehicle systems). Future research on real objects is planned.

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