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Research on a tubeless tire for a mobile robot

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Abstract. Airless tires are used not only in cars, but also in vehicles used in the construction, road, forestry, and robotics industries. In order to develop the construction of an airless tire, its optimization at the stage of their design, a comprehensive method of researching the operational properties of an airless tire is proposed. The methodology includes stress-strain analysis, modal and thermal analysis of an airless tire using three-dimensional modeling using the finite element method. The airless tire was studied in the following modes of uniform movement of the wheel on a solid base: driven wheel; driving wheel; free wheel; neutral wheel; brake wheel. An example of the study of an airless tire of a mobile robot is given.

1 Introduction

A wheel with a traditional pneumatic tire has a significant drawback: in case of loss of air pressure in the tire, the movement of the wheeled machine stops, and when the machine moves at high speed, a traffic accident with serious consequences is possible [1]. Other disadvantages of the pneumatic tire are the complexity of technological processes and high energy costs for its disposal, as a result of which the world has accumulated a huge number of used and substandard car tires. Modern achievements in the chemistry of polymers make it possible to create car tires of a new design, the performance of which is ensured not by the pressure of compressed air, but by the physical and mechanical properties of structural materials, for example, elastic polyurethanes.

Airless wheels are used not only in cars, but also in vehicles in the construction, road, forestry industry, and robotics [2]. The world's leading tire manufacturers, such as Michelin, Amerityre, Yokohama, Bridgestone, Hankook, Resilient Technologies, Polaris, are actively engaged in the creation of airless polyurethane wheels [3-6].

It should be noted that the main operational properties of most modern automotive airless wheels made of elastic polymer materials are practically no different from the operational properties of traditional rubber-cord pneumatic wheels. But in addition, their use makes it possible to increase the safety of civilian cars and the "survivability" of military vehicles, as well as to reduce the labor-intensiveness of servicing the chassis of wheeled vehicles.

2 Presenting main material

Airless wheels are a hollow structure, in which most often the function of air is taken over by rubber blocks. Today, there are two types of tires for such wheels: tires filled with fiberglass and tires with special polyurethane spokes.

In the table 1 presents the comparative characteristics of these types of tires.

Table 1. Comparative characteristics of types of airless tires

Criteria	Tire type	
	Tires filled with fiber	Tires with special polyurethane spokes
Repairability	Repaired	Repaired
Storage	Tire filled with fiberglass	Tire made in the form of honeycombs from recycled raw materials
External from minity	They are usually made closed and outwardly do not differ from tubeless wheels	The honeycombs are open for easy cleaning from dirt

Tires with special polyurethane spokes have gained great popularity due to the simplicity of the design, lower cost and weight, as well as ease of repair.

When introducing such airless wheels, it is necessary to conduct an analysis of two tires - tubeless and, accordingly, airless. This comparison is presented in Table 2.

Installing these tires solves several tasks:

- increase in tire life;

- reduction of tire damage at work sites;
- reduction of fuel consumption;
- increasing machine productivity;
- reduction of costs for the repair of wheeled motors.

We will conduct a comparative analysis of these types of wheels according to several criteria. These criteria are presented in the Technical Regulation of the Customs Union (TR MS 018/2011) "On the safety of wheeled vehicles". The results are presented in Table 3.

Table 2. Comparison of advantages and disadvantages of tubeless and airless wheels [7]

No. z/p	Criteria	Tubeless wheel	Airless wheel
1	The ability to maintain normal tire pressure in the event of a puncture	+	++
2	Little heating in case of fast and long movement	+	-
3	Ease of repair and maintenance	+	-
4	A long period of work for wear and tear	+	++
5	High speed of operation	+	+
6	Additional wheel cushioning _	+	++
7	A small mass	-	++

"-" - negative properties; "+" - positive properties, "++" - an efficiency indicator that is several times higher.

Table 3. Comparative table of wheels of tubeless and airless types according to the criteria of the Technical Regulations of the Customs Union [8]

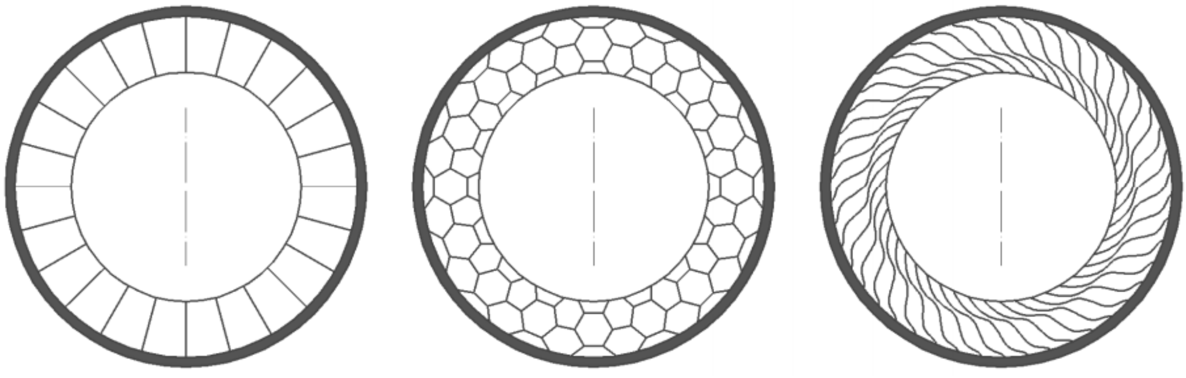
Criteria	Tubeless wheel	Airless wheel
Repairability	Any repair is possible at any point of tire installation	A special and well- known center for the repair of such tires with special equipment and trained personnel is needed
Damping properties	Appear only on a flat surface	It is an excellent view of all road irregularities
Installation and dismantling	Installation on the standard no bolts or nuts for water manufacturer	Installation on standard bolts or nuts of the manufacturer
Beating and imbalance	It is necessary to carry out an operation to balance the wheels	Balancing is not required
Speed of exploitation	Up to 150 km/h	There are no restrictions

The main criteria of existing airless tires are presented in the table 4.

Table 4. Airless tire criteria

Criteria	Michelin Tweel	Polaris	Bridgestone	Hankook I - Flex
Wheel construction	System of one-piece internal hubs, when folded to pi in the axis	Cell system under _ beehive	A system of hubs that can be twisted in both directions	Tire and rim one is whole
Maximum speed, km/h	64	80	64	130
Carrying capacity of one wheel, kg	900	200	150	375
Graduation year	2005			
Wheel material	Polyurethane	Polyurethane	About 60% is recycled old rubber	95.5 % are recycled materials

The main constructions of airless wheels are presented in Fig. 1.



а) б) в)

Fig. 1. Wheel designs: a – straight spokes; b – hexagonal cells (Resilient Technologies); c – curved spokes (Bridgestone AirFree)

The use of airless wheels is very effective and has a number of advantages compared to tubeless wheels: durability, fuel economy, reduction of damage. Airless wheels can be installed so far only on passenger cars and light types of construction, road vehicles and mobile works.

A wheel with hexagonal spokes of the Tweel type.

We will conduct research and analysis of an airless tire for cars using stress analysis in the Solidworks environment [9,10].

The design parameters of the airless tire elements are presented in Fig. 2.

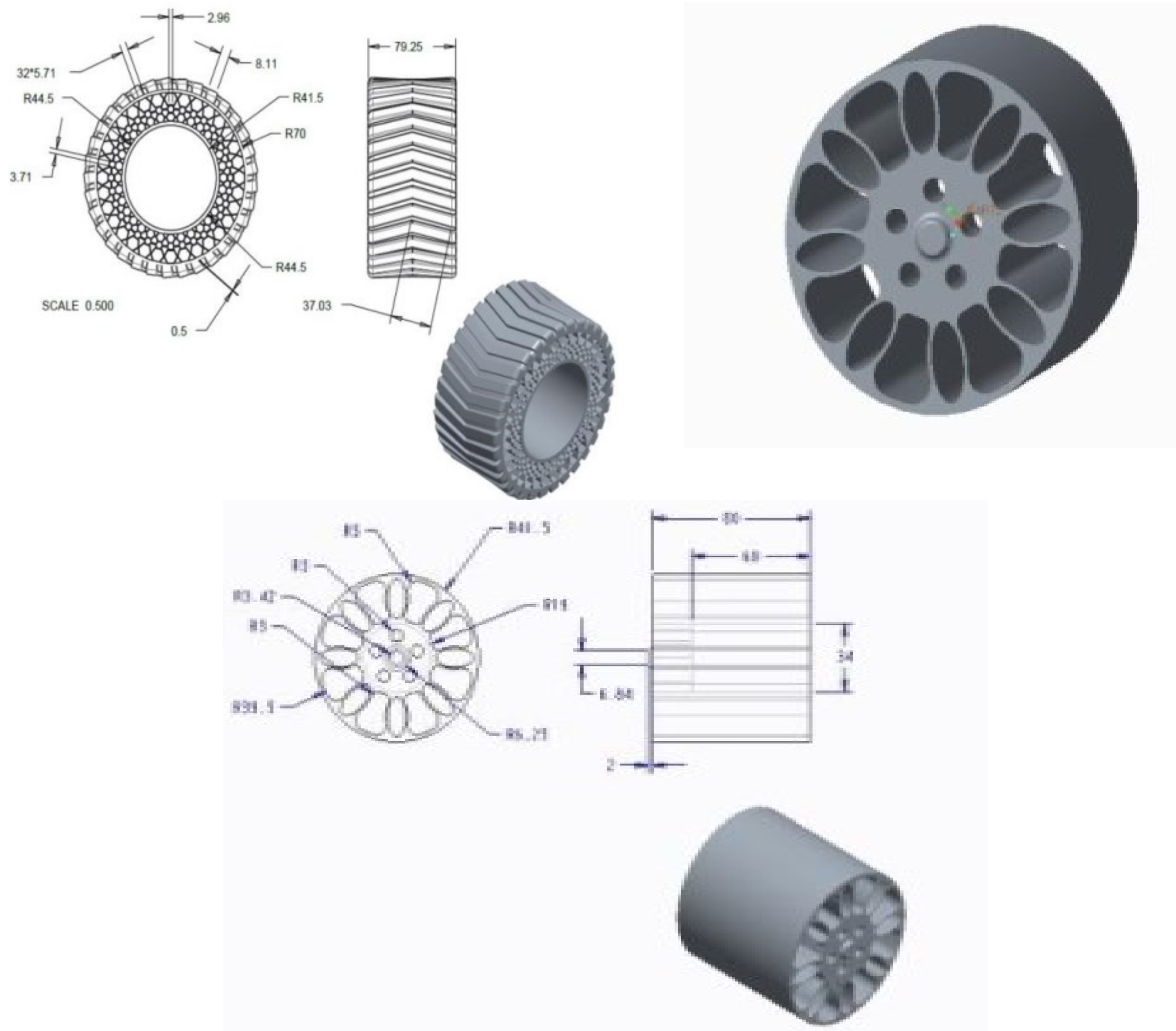
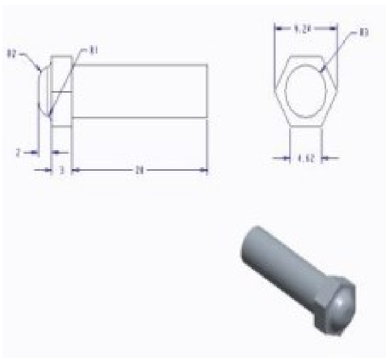


Fig. 2. The outer casing of the tire and the hub of the wheel

Material properties and experimental conditions are presented in Fig. 3.

Properties	Nylone4-6	Polyethylene
Young's Modulus (GPa)	4.8	2.7
Poisson's Ratio	0.4	0.4
Density (kg/m^3)	1150	1400



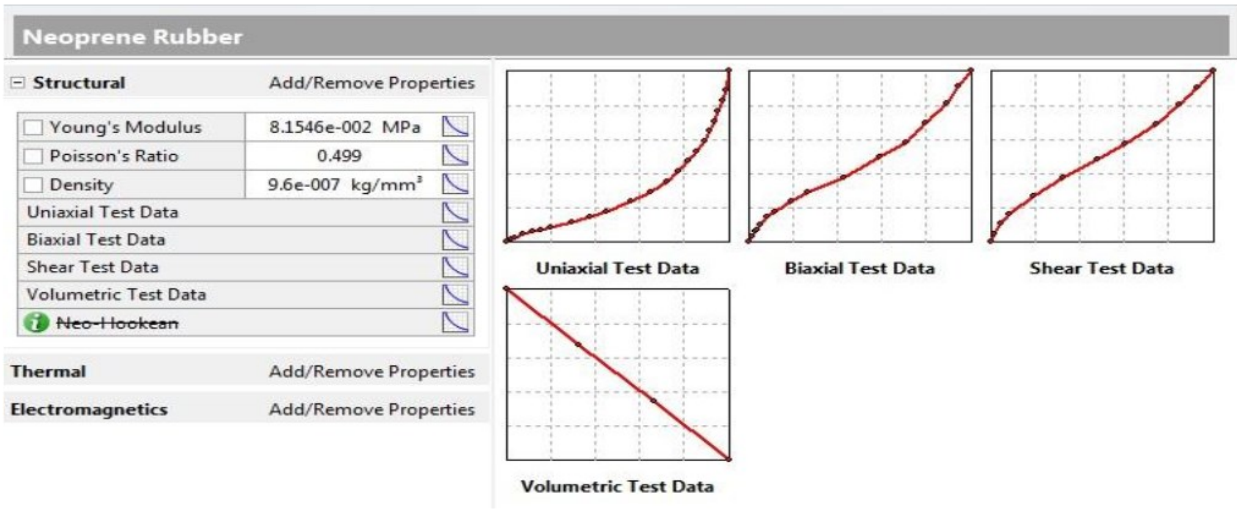
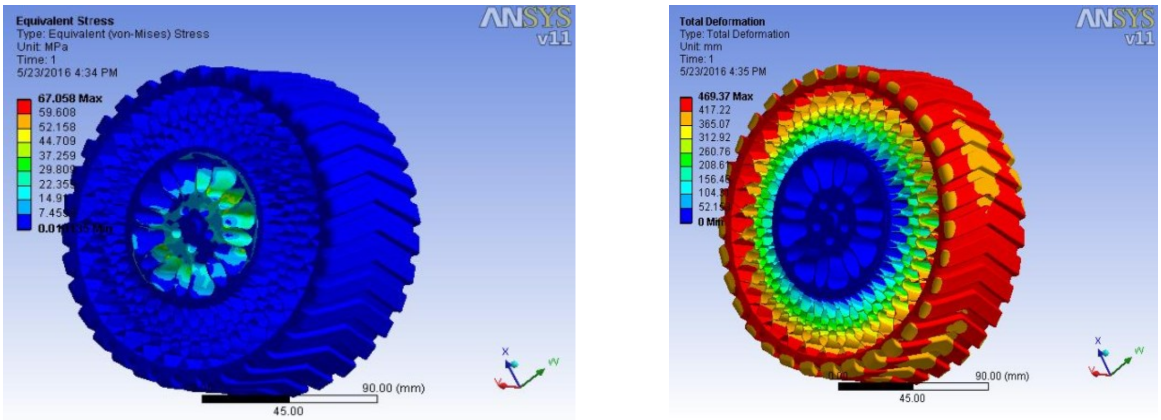


Fig. 3. Material properties and experimental conditions

Three-dimensional modeling using the finite element method (FEM) was used to study the stress-strain state in an airless tire. This approach makes it possible to determine the stress-strain state in all elements of the tire, taking into account its complex geometry, multi-element structure with different mechanical properties of individual elements, as well as the presence of essentially three-dimensional elements of the tread. In Fig. 4 presents the SE model built using three-dimensional 4-node isoparametric elements with three degrees of freedom at the node.

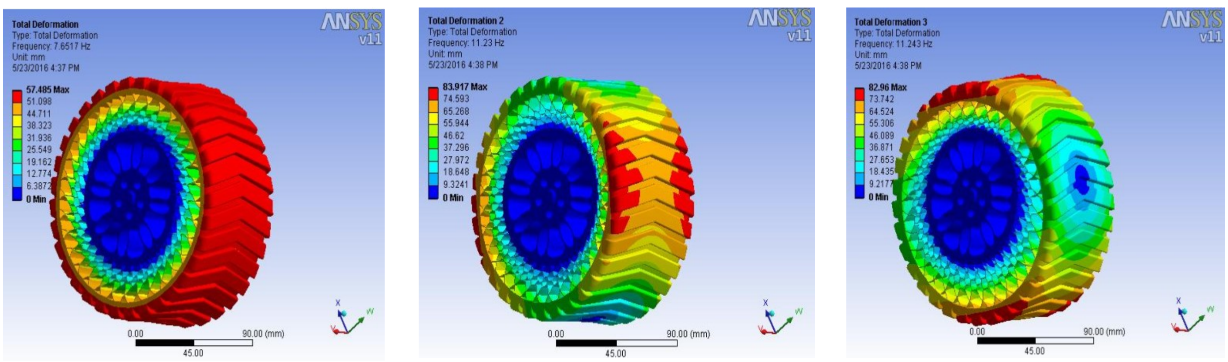


Distribution of equivalent stresses

Total deformation in the tire

Fig. 4. Static structural analysis

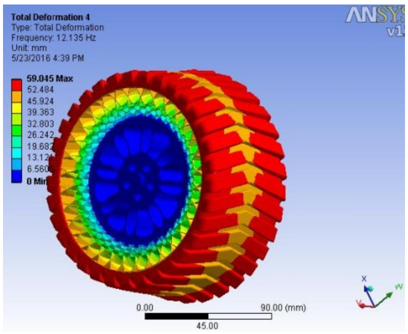
The use of modal analysis allows you to transform the coupled equations of motion of system elements into disconnected "modal" equations, each of which can be solved separately. The results of each of the modal equations are then added to obtain the complete result (Fig. 5). Modal analysis is most useful for linear systems with classical damping [11-13].



Mode 1

Mode 2

Mode 3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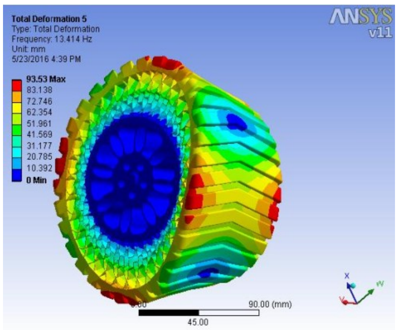
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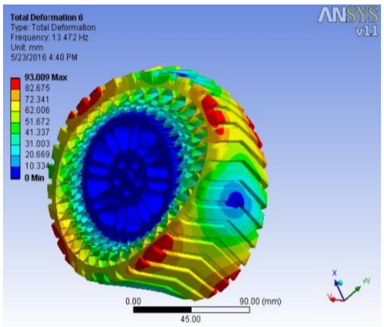
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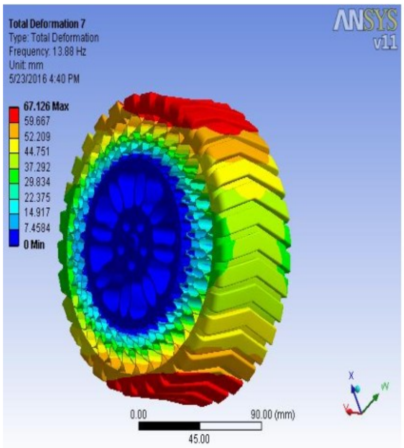
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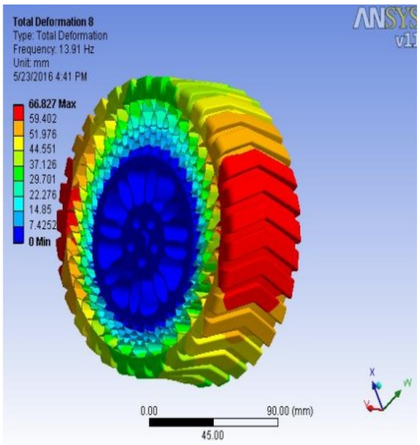
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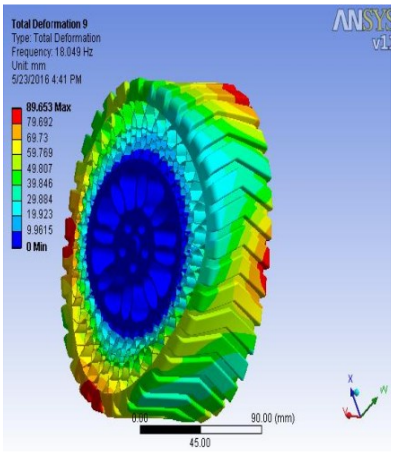
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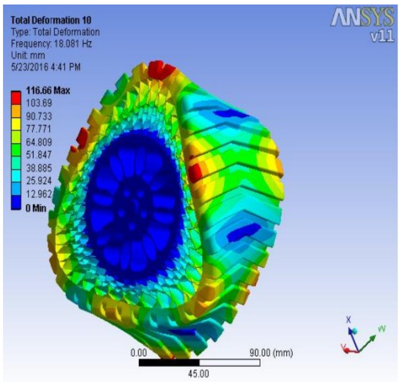
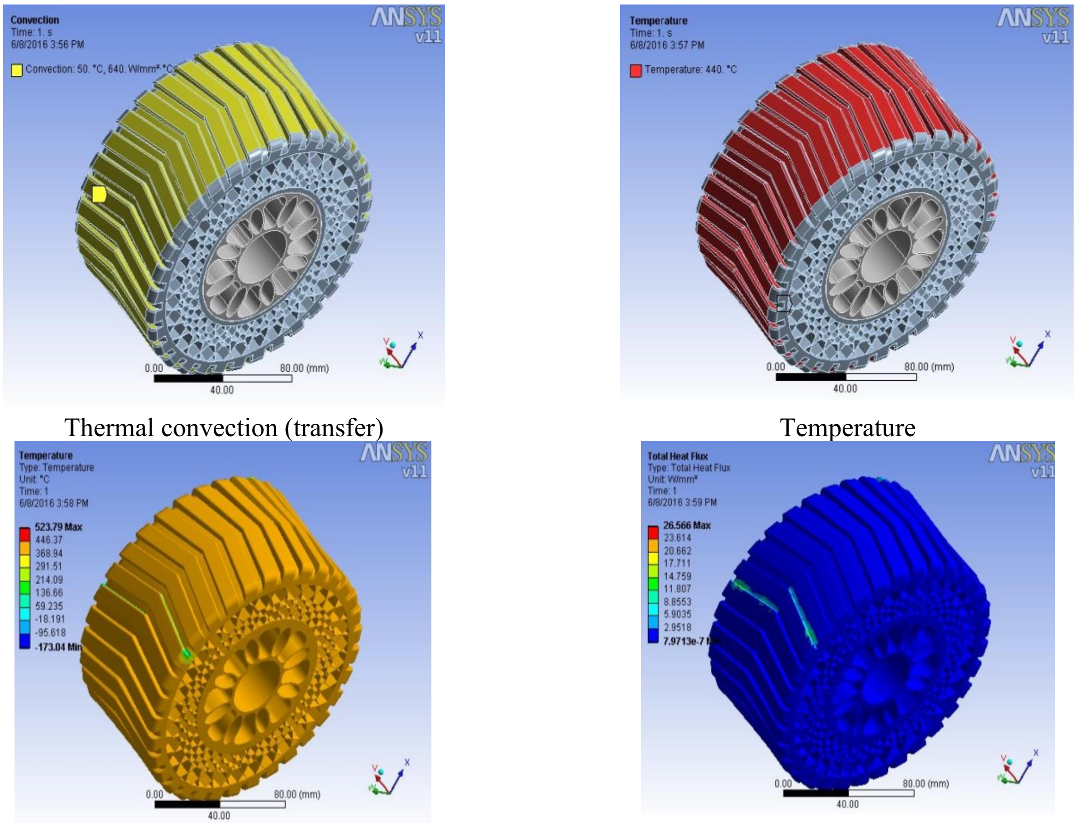

Mode 10

Fig. 5. Modal analysis

The heating of a car tire is formed as a result of hysteresis losses in the material, with variable mechanical deformation of the structure and friction against the road surface. At the same time, hysteresis losses make up 90-95% of total rolling resistance losses tires [14-16]. This occurs due to the presence of internal friction in the material, which absorbs part of the deformation energy, which depends on the properties of the materials used and their loading modes [17,18]. It should be noted that the rubber materials of pneumatic tires have low thermal conductivity, which leads to the appearance of local highly heated zones inside the tire [19]. The increased temperature of the wheel materials has a significant impact on its performance, as it reduces the mechanical properties of the materials, creates an additional thermal stress state and leads to the degradation of the material [17]. The use of modern polymer composite materials with low internal hysteresis damping opens up new possibilities for the use of airless tires. Determination of the temperature state of tires during operation can be carried out as an experimental test and calculation methods. The temperature of the tire surface is experimentally determined [20,21]. At the same time, the temperature of the inner layers of the tire elements remains unknown, or is determined at individual points, which is due to technical difficulties. Experimental methods do not allow us to build a complete picture of the thermal state of the tire and the airless tire. Most of the published works are devoted to calculation methods of thermal state assessment and analysis of viscoelastic properties of tire materials [22-25], but all of them differ in the formulation of the research problem and the scope of these studies.

An analysis of the thermal state of the airless wheel (tyre) during steady motion was carried out (Fig. 6). To estimate the absorbed energy, the visco-elastic characteristics of the polyurethane selected as a model wheel material were determined using dynamic mechanical analysis. The characteristics obtained and determined by the finite element deformation method were used to calculate the internal heating of the wheel elements when moving at two speeds of 5 and 90 km/h.

As a result of the simulation, it was established that in the first minutes of the car's movement, the tires are heated intensively. Gradually, the rate of tire heating decreases as their surface reaches a state of thermodynamic equilibrium with the environment.



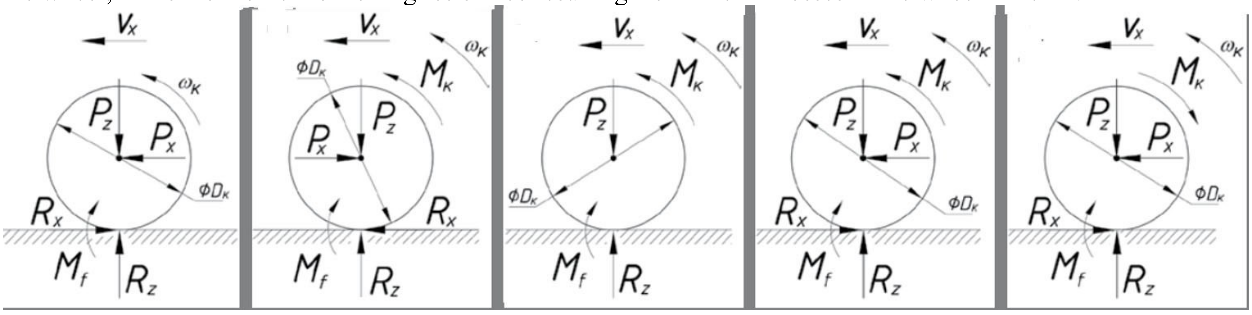
Thermal convection (transfer) — Temperature

Is the initial temperature — Total heat flow

Fig. 6. Thermal analysis

Further research consisted in determining the operational properties of the airless wheel, taking into account the modes of wheel movement. The following modes of uniform movement of a wheel on a solid base were studied [26]: driven wheel; driving wheel; free wheel; neutral wheel; brake wheel.

In the general case of rectilinear movement of the wheel, different forces and moments act on it (Fig. 7): Rx and Rz – respectively, the longitudinal and vertical reaction in the spot of contact of the wheel with the supporting base; Px and Pz – respectively, the longitudinal and vertical force applied to the wheel axis; Mk *is* the torque supplied to the wheel; Mf is the moment of rolling resistance resulting from internal losses in the wheel material.



a *b* *c* *d* *f*

Fig. 7. Modes of uniform movement of the wheel: a – driven wheel; b – driving wheel; c – free wheel; Mr – neutral wheel; d – brake wheel

1. Driven wheel (Fig. 7, a) – the wheel is driven into rotation by the longitudinal force Px applied to the axis of the wheel and coincident in direction with the speed Vx of its longitudinal movement. The torque of the wheel M is equal to zero.

2. Guide wheel (Fig. 7, b) – the wheel is driven into rotation by a torque Mk, the vector of which coincides with the vector of the angular velocity wk, and is loaded with a longitudinal force Px.

3. Free wheel (Fig. 7, c) – the wheel is rotated by the torque Mk, and the longitudinal force Px is zero.

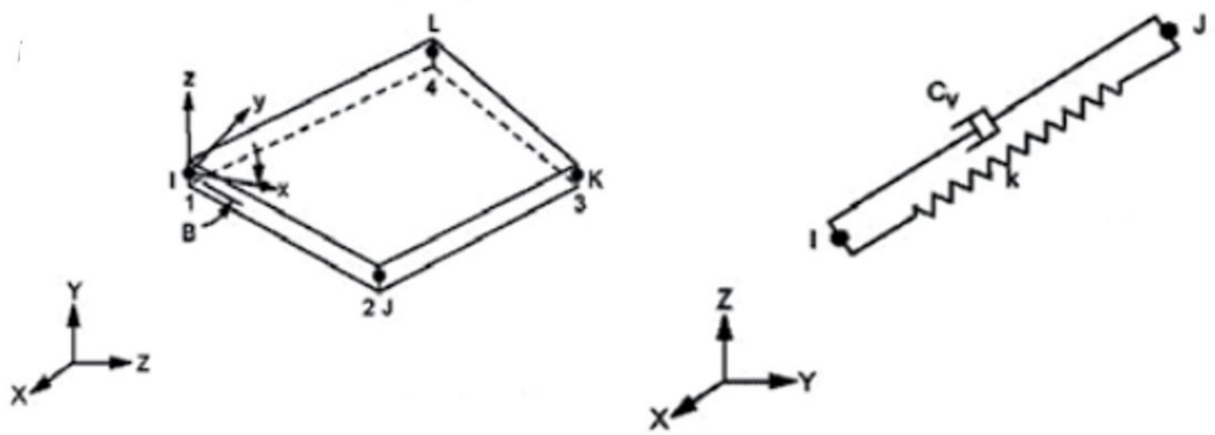
4. Neutral wheel (Fig. 7, d) – the wheel is driven into rotation simultaneously by the torque Mk and the pushing force Px.

5. Brake wheel (Fig. 7, e) – the wheel is driven into rotation by a pushing force Px and loaded with a torque Mk, the vector of which is opposite to the vector of the angular velocity ωk.

The following values are adopted as the main characteristics of the material of the elastic polyurethane wheel (PPK): modulus of elasticity of the first kind when bending E = 40,000 MPa; shear modulus G = 56000 MPa; material density ρ = 1900 kg/m ^{3} [27,28]. Energy losses in the wheel material are given by the logarithmic decrement of the attenuation δ. For the case when the internal friction is proportional to the displacement, δ = 0.41 (based on tests conducted at the Department of Machine and Tire Design and Automotive Engineering of the Lviv Polytechnic National University).

The process of movement of an elastic wheel on a solid support surface is modeled using the finite element method (FEM) in the SolidWorks software complex, designed for solving three-dimensional dynamic nonlinear problems of the mechanics of a deforming solid body, mechanics of liquids and gases, heat transfer, and related problems. You can find out more about the method of finite elements and SolidWorks in the available literature, only a brief description of the finite elements used in solving the given problem is given below [29,30].

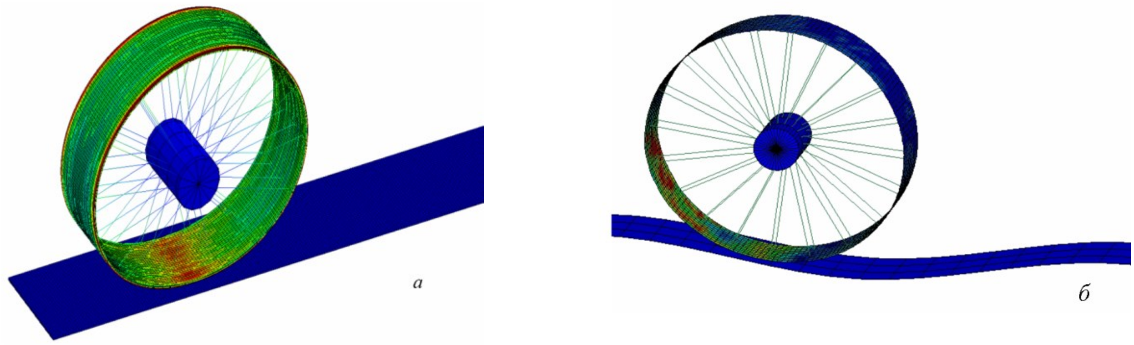
The Belichko-Tsai shell element is used to model the rim and the support surface (Fig. 8, a). Elastic spokes-springs are modeled by a two-node combined rod element (Fig. 8, b) [31,32].



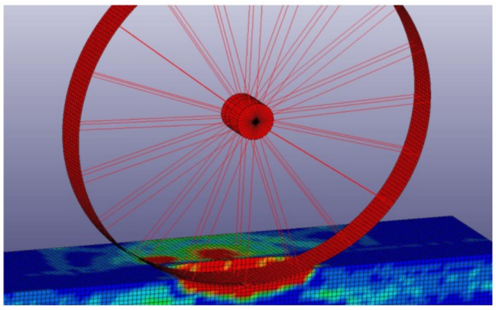
a b

Fig. 8. Types of used final elements: a – shell 4 isoparametric element with three degrees of freedom at the node ; b – 2-node combined rod element

In fig. 9 shows examples of simulation of various cases of motion of the PPC: driven wheel, leading wheel and free wheel.



a b



в

c

Fig. 9. Various cases of simulation of the movement of the PPK: a – on a solid basis; b – by inequalities; c – on a deformable support base

The coefficient of friction for each element of the PPK model that comes into contact with an element of the supporting surface is given using the definition of Coulomb friction [33]:

$$\mu = \mu d + (\mu s + \mu d) e — c | v| \quad (1)$$

where v – sliding speed, determined by the formula:

$$v = \Delta e / \Delta t \quad (2)$$

where μd – coefficient of friction of full sliding; μs – coefficient of rest friction; c – empirical coefficient; v – sliding speed at the node; Δ e is the displacement of the node that enters the contact.

To avoid shock loads and jerks, forces are applied gradually, as shown in Fig. 10 and Fig. 11.

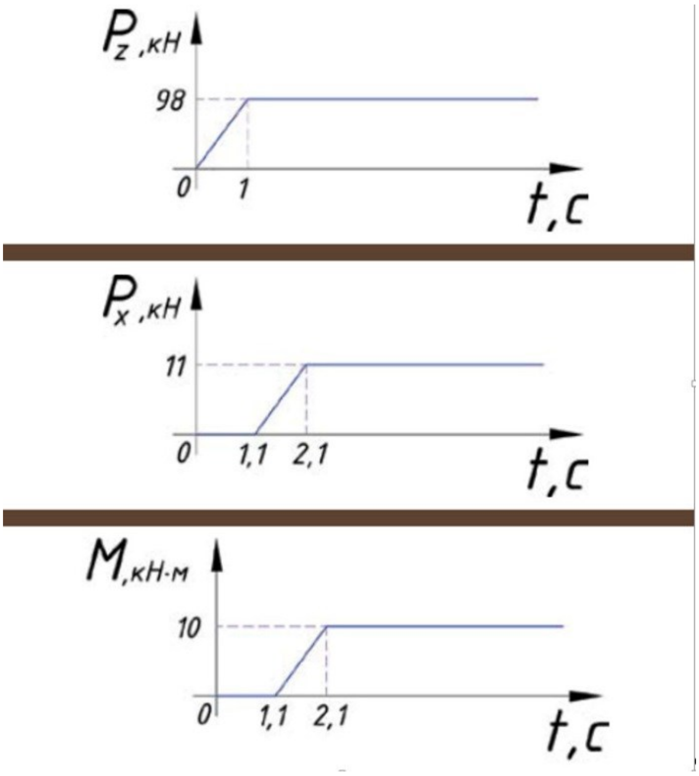


Fig. 10. Load application schedules: a – vertical force; b – longitudinal force; c *is* torque

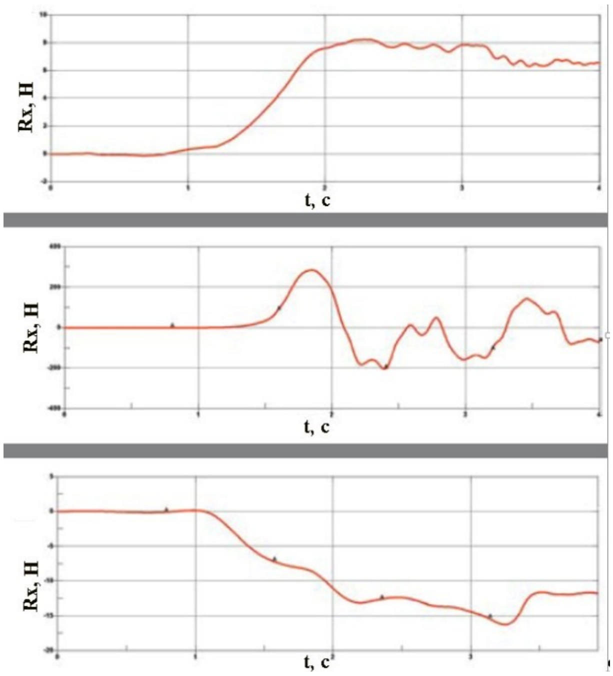


Fig. 11. Graphs of changes in the longitudinal reaction Rx in the contact spot: a – led mode; b – free mode; c - is the leading mode

In the first second, a vertical load is applied to the axis of the wheel drive. Then, in the second second, longitudinal force and torque are applied depending on the rolling mode.

The graphs obtained as a result of simulation of changes in time of longitudinal reactions in the contact spot Rx for three modes of wheel movement are presented in Fig. 12.

The obtained results do not contradict the modern ideas about the rolling of an elastic wheel. In the driven and leading modes, the longitudinal response Rx is directed in opposite directions, and in the free mode it is close to zero. The spread of values of the longitudinal response Rx in all modes is explained by torsional oscillations, the presence of which is a consequence of the absence of a damping link between the rim and the hub of the wheel. The general view of the contact spot of the PPK rim and the support surface for different modes is shown in Fig. 12.

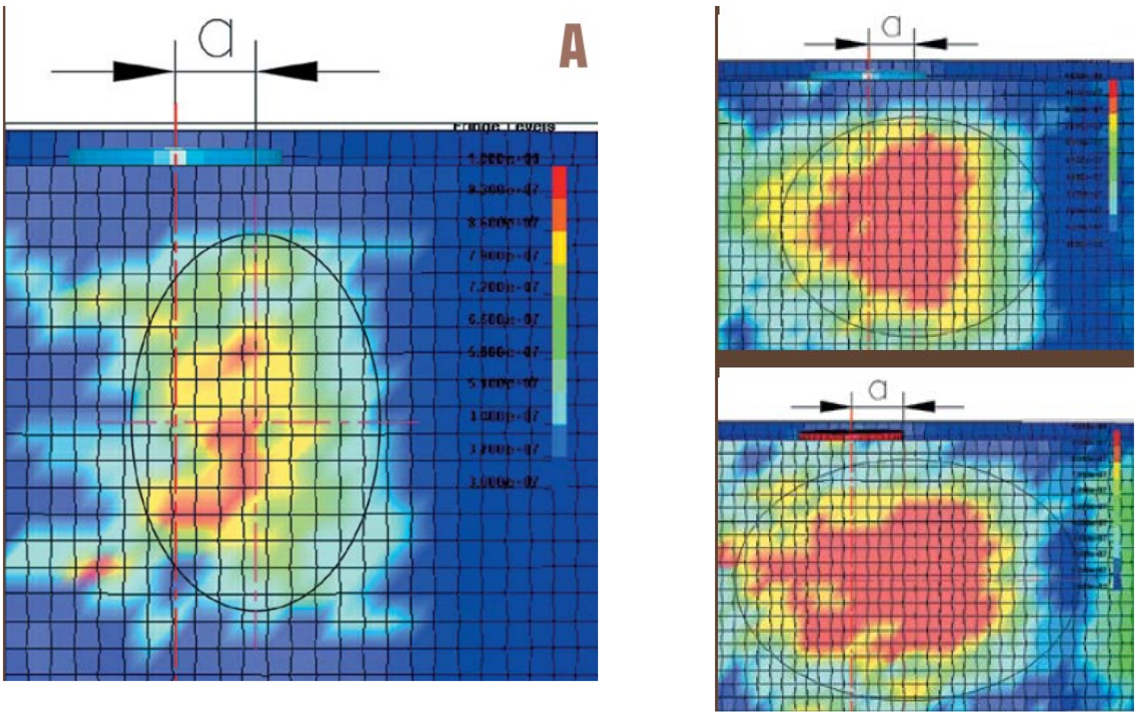


Fig. 12. General view of the contact patch in different rolling modes of the PPK: a – led mode; b – free mode; in - leading mode

It is worth noting the presence of a longitudinal displacement and an asymmetric contact spot relative to the PPK axis. As a result, the point of application of the total vertical reaction Rz will be located in front of the axis of rotation of the PPK. It is customary to divide this displacement a into the displacement that occurs due to the application of a longitudinal force to the wheel axis, and the displacement that occurs due to internal losses in the wheel material.

3 Conclusions

A comprehensive methodology for studying the operational characteristics of an airless tire is proposed, which includes stress-strain analysis, modal and thermal analysis of an airless tire using three-dimensional modeling using the finite element method. The airless tire was studied in the following modes of uniform movement of the wheel on a solid base: driven wheel; driving wheel; free wheel; neutral wheel; brake wheel

The conducted study of an airless tire with the help of the proposed methodology opens up new opportunities for the study of phenomena that occur during the interaction of the tire with the supporting surface, and makes it possible to optimize the designs of such engines at the stage of their design.

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