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Experimental research in automobile non-pneumatic tire force heterogeneity

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Abstract. Simplicity and high efficiency of a wheeled mover as a mechanism for converting rotational motion into a translatory one have conditioned its wide application in overland machines including motor vehicles. However a wheel with a non-pneumatic tyre (NPT) has a sufficient drawback lying in termination of a wheeled machine movement at the excess air pressure loss. Moreover, the loss of excess air pressure in a pneumatic tyre of traditional design at high speed of movement of a motor vehicle can lead to a traffic accident with heavy consequences. The stop of a motor vehicle to change a wheel on a heavy traffic roadway or roadside also poses a threat. These reasons determine the necessity of both well-known design improvements and search for the new wheeled mover design solutions to enhance a motor vehicle safety, the use of wheels with non-pneumatic tyres of elastic polymeric materials being one of them. Safety enhancement by means of non-pneumatic tyre use along with keeping the high performance of wheeled machine operational properties, is an important scientific and technical task that determines the research urgency.

Non-pneumatic tyres of elastic polymeric materials were first applied in 1991 to wheeled armored machinery by South African company Allthane Technologies International SA (Pty) Ltd. A significant contribution to creation and improvement of non-pneumatic tyres was made by such companies as Uniroyal [1], Michelin [2-4], Resilient Technologies [5] in common with the University of Wisconsin-Madison's Polymer Engineering Center, Polaris [6], Yokohama [7], Bridgestone [8], Hankook [9], Toyo [10], Boeing [11], Amerityre [12], Sumitomo [13], Britek [14] and others. Russia's research on non-pneumatic wheeled movers are conducted by Vescom Research Centre for Tire Industry LLC, Bauman Moscow State Technical University, South Ural State University, Alekseyev Nizhny Novgorod State Technical University and others.

The Department of Automobile Transport (Department of Machine Building and Transport since May 2018) at Bratsk State University has experience in development and research on automobile non-pneumatic tyres of elastic polymeric materials.

The implemented design analysis and patent search allowed to find new technical solutions aimed at the perfection of automobile non-pneumatic tyre design, develop and engineer scientifically based modulus and, enjoying the financial backing of Ministry of

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Education and Science of Russian Federation, manufacture full-scale models of wheels with automobile non-pneumatic tyres.

As a general case, a full-scale model of the wheel represents (figure 1) a non-separable modulus consisting of a non-pneumatic polyurethane tyre with flexible spokes and standard steel stamped VAZ 5JX13H2 wheel with a deep edge-free band. The removal of band edges provided close equivalence of profile widths for a non-pneumatic tyre and a tread cap of a standard pneumatic tyre protector that makes up a set for VAZ 5JX13H2 disk wheels which in the long run allowed reducing the mass of a full-scale model.

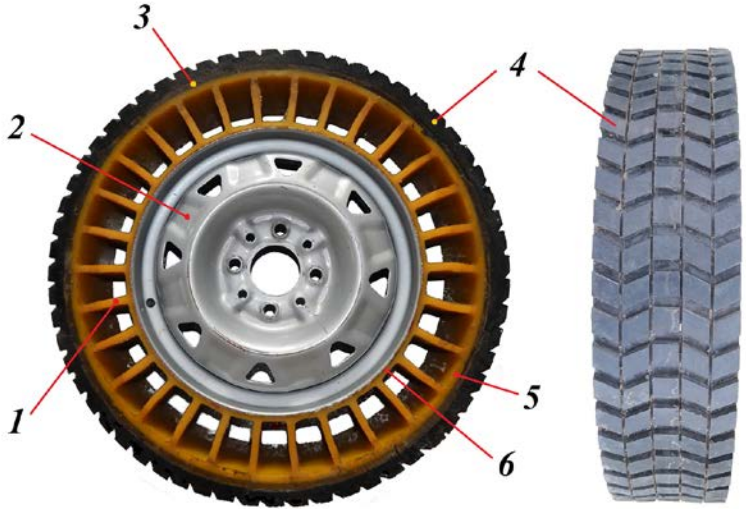

Fig. 1. Automobile wheel with non-pneumatic tyre of elastic polymeric materials: *1* - flexible spokes; *2* - standard 5JX13H2 disk wheel with a deep edge-free band; *3* - supporting ring; *4* - protector ; *5* - fitting ring; *6* - mounting ring.

Strong and reliable joint of a disk wheel and a non-pneumatic tyre are ensured by elastic polyurethane high adhesiveness to specially prepared band metal surfaces.

Elastic properties and bearing capacity of a non-pneumatic tyre are provided by flexible spokes and a supporting ring. At that under the influence of weight load in the contact zone of the wheel and the road surface the flexible polyurethane spokes experience buckling and loose stability, and, being affected by stretching forces, they get in a strained condition in the upper semi-circle of a non-pneumatic tyre.

To manufacture full-scale non-pneumatic tyre models double-base molded elastic polyurethanes of hot curing produced by research and production enterprise Surel LLC (Saint-Petersburg) on basis of prepolymers SUREL TF-228, SUREL TF-235, SUREL TF-682 and SKU- PFL-100 were used.

Table 1 shows engineering factors of full-scale non-pneumatic tyre models manufactured in BrSU laboratories, the elastic property specifications and bearing capacity of which are most similar to pneumatic tyres of the same size.

One of the important parameters specifying the elastic properties of an automobile tyre is its force heterogeneity causing normal (radial) force buckling at the wheel contact zone even during its rolling on a plane road surface. Considerable force heterogeneity of automobile tyres notably worsens the majority of operational property factors and, above all, a wheeled vehicle smooth run. Intensive buckling leads to the enhancement of vibration load level for a driver, passengers and cargo transported by a motor vehicle, as well as to the decrease of hauling and speed properties, fuel saving, stability and motor vehicle controllability.

Table 1. Engineering factors of full-scale non-pneumatic tyre models

Factor name	NPT models	
	№ 1	№ 2
1. Prepolymer of flexible spokes and a fitting ring	SUREL TF-228	SUREL TF-228
2. Prepolymer of a supporting ring	SUREL TF-682	SUREL TF-682
3. Protector prepolymer	SUREL TF-228	
4. Number of flexible spokes	30	
5. Thickness of flexible spokes, mm	8	
6. Length of flexible spokes, mm	55	
7. Width of tyre profile, mm	120	
8. Height of tyre profile, mm	100	
9. Load-free ring radius, mm	265	
10. Thickness of supporting ring, mm	8	20
11. Height of protector, mm	25	
including height of protector pattern, mm	5	
12. Mass, kg	14	

Force heterogeneity of automobile tyres can be conditioned by production, technological and operational factors, and for non-pneumatic tyres also by design peculiarities connected with flexible spokes discrete arrangement.

Force heterogeneity estimation is carried out with the help of heterogeneity coefficient (coefficient of variation) including:

$$K_v = \frac{100}{\overline{P}_z}\sqrt{\frac{\sum_{i=1}^{n}\left(P_z(t_i)-\overline{P}_z\right)^2}{n-1}},$$

$P_z(t_i)$ - normal force at the contact of an automobile tyre with supporting surface in the *i*-point of a buckling curve, N; $\overline{P}_z$ - mean arithmetic value of normal force at the wheel rolling, N; n - number of points at the curve of normal force buckling.

Registration of normal force buckling of non-pneumatic tyre full-scale models at the contact with supporting surface was carried out in the process of the wheel "forward-backward" rolling on a traveling platform of SHS-77 tyre test rack (figure 2) by means of a strain-gage sensor [15] in complete with a DN-10W amplifier, analog-to-digital LA-20USB converter and computer.

Normal force buckling curves at the contact of non-pneumatic tyre full-scale models with supporting surface of traveling platform on SHS-77 tyre test rack are represented in figure 3, and table 2 shows radial force heterogeneity coefficients received by processing of these curves.

Significant deviations of radial force values from static preloading by rolling of test model № 1 are conditioned by relaxation processes taking place in elastic polyurethane of which a non-pneumatic tyre is manufactured. At that in the steady-state mode of rolling during several cycles of "forward-backward" the creep of automobile tyre constructional materials does not have time for development. In its turn the decrease of creep and enhancement of resistance to wearing out can be provided by non-pneumatic tyre reinforcement, the ways of which are also being developed by the Department of Automobile Transport of BrSU.

It was stated that radial force heterogeneity of tested experimental models in controlled steady-state mode rolling makes up 1,19 to 5,43 % and is not connected with modulus peculiarities of new type wheeled movers but depends on the terms of their manufacturing.

By the results of numerous rack and road tests [16, 17] one may say that new wheel designs with non-pneumatic tyres can be in demand by producers of civil and military motor vehicles, wheeled armored machinery [18] and tractors, road-building machines, special motor transport and wheeled planet rovers [19]. However their large scale production and wide application requires further deep theoretical and experimental research and testing in different modes and conditions of service, as well as upgrading of physical and chemical properties of elastic polymer materials aimed at decreasing of hysteresis losses.

Fig. 2. An automobile wheel with a non-pneumatic tyre in the process of force heterogeneity experimental research at SHS-77 tyre test rack with a traveling platform

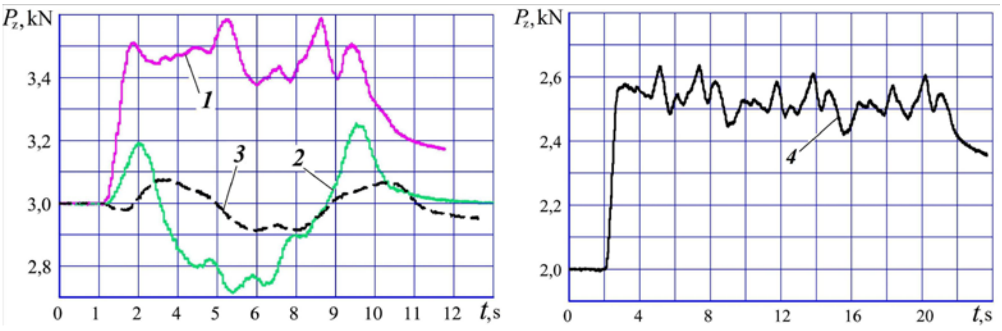

Fig. 3. Normal force buckling at the contact of automobile tyres with the surface of traveling platform at SHS-77 tyre test rack in the process of rolling: *1* is for model № 1; *2* is for model № 2; *3* is for BL-85 175/70R13 pneumatic tyre; *4* is for specimen № 1 in three "forward-backward" rolling cycles.

Table 2. Results of processing of radial force buckling curves at the contact of automobile tyres with supporting surface in controlled steady-state mode of rolling

Parameters	Tested automobile tyre		
	Model № 1	Model № 2	Pneumatic tyre BL-85 175/70R13
1. Coefficient of force heterogeneity, %	1,19	5,43	1,75
2. Amplitude of radial force buckling, N	218,3	539,5	82,4

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