Modelling of quasistatic rolling of pneumatic tyre in Abaqus program complex

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Abstract. In the last ten years enterprises producing tyres for cars have had a tendency to the full automation that includes not only development of an independent line on tyre production, but also digital design based on the creation of a whole set of pneumatic tyre computer models with a series of calculations of their main characteristics at the car movement. Special attention is paid to the influence of the protector geometry, as well as the structure and properties of the materials of the tyre basic elements on its stress-strain state in the course of stationary rolling. To define these characteristics within the conditions of quasistatic rolling, the Abaqus program complex is used. The finite element modelling of a car tyre is carried out in the three-dimensional statement. The analysis of inflation and pressing is made both in the static state and during dynamic rolling. The results of modelling are epures of contact pressure distribution on the tyre surface.

1. Introduction

Tyres play an important role in running of vehicles. The controllability of cars and the safety of road users largely depend on the tyres quality and operating parameters. The tyre worn-out state has a considerable impact on the reliability of the tyre-road adhesion.

The tyre wear is a complex process that depends on various factors, such as material, design, bad alignment of wheels etc. “Bald” tyres increase fuel consumption and noises of the car at its high speed, they cannot provide a smooth ride, etc. All of this raises the emergency risk. One of the possible solutions of the problem is the development of new composite materials that have all the characteristics necessary for trouble-free operation. However, due to the growing number of new composite materials (including rubber-based) the benchmark tests requirements are considerably raised. One of the important mechanical characteristics of tyre operation is fatigue endurance. Though its value can be estimated by physical tests, they can last for months [1]. The finite element modelling and visualization program complexes are a convenient and effective tool for a theoretical research of tyres characteristics as well as tyres digital design.

The object of the present research is a radial pneumatic tyre, where the framework threads are located in the direction of the tire profile radius from one board to the other so that the threads in all the layers are parallel to each other. Only the breaker has a diagonal design. Such an arrangement of the framework threads does not allow the rubber to stretch strongly in the crosswise direction; the breaker holds the framework threads from the longitudinal movement. At the above-described arrangement of the
framework threads the emerging tensions are approximately twice as low as those at the diagonal arrangement. This gives an opportunity to reduce the number of the cord layers; hence the weight of radial tyres is less than that of diagonal ones. Since the framework of radial tyres is less thick it is more elastic and has smaller internal friction. Consequently, there is a smaller amount of heat during its work which allows to increase the thickness of the tyre tread and the depth of its drawing thus extending the service life of the tyres.

The breaker, on the contrary, is very rigid and almost inextensible in the radial direction. Radial tyres have a greater stability of the form of the spot of contact with the road paving and create a lower rolling resistance thus providing a lower fuel consumption [2].

The present work sets the task to carry out finite and element modelling of a car tyre in three-dimensional statement, to investigate the tyre mechanical behavior at inflation and pressing in the static state as well as during stationary rolling.

2. Materials and methods

Due to the peculiarities of the material of the research object, the program complex of finite and element modelling Simulia Abaqus made by the Dassault Systems was chosen as the instrument of modelling. The main reasons for choosing this product are ample opportunities of the nonlinear analysis, the possibility to use an independent library of materials and elements and also special opportunities to solve the problem of tyre stationary rolling in the quasistatic statement.

The example of the tyre studied in the present work as well as its basic elements are given in figure 1.

![Tyre structure](image1)

**Figure 1.** Tyre structure: 1) innerliner; 2) tyre tread; 3) steel board; 4) framework; 5) breaker

The following assumptions were accepted for the development of the finite element model of the radial pneumatic tyre. The tyre radius is 305 mm, the width is 187 mm, the profile height is 116 mm. The value of the wheel load was varied discretely: 300, 350 and 400 kg respectively. The load was applied from top downward to the tyre axis of symmetry. The tyre consists of five separate parts: a rubber tyre tread, metal rings, a nylon two-layer cord, a two-layer breaker and an innerliner. The properties of the materials according to the chosen rheological model are presented in Table 1.

The equation of the material of Neo-Hookean model is presented in (1):
where $U$ is the density of deformation energy per unit of volume; $C$ and $D$ are the material parameters depending on the temperature; $I$ is the first invariant of the deformation tensor.

Table 1. Properties of the pneumatic tyre components

| Structural elements of the pneumatic tyre | Density, model of material, dimensions | value of the parameters |
|------------------------------------------|--------------------------------------|-------------------------|
| framework                                | density, kg/m$^3$; Marlow hyper elastic model | 1500                    |
| innerliner                               | density, kg/m$^3$; Neo-Hookean model coefficients: $C_{10}$, MPa, $D_{1}$, MPa$^{-1}$ | 1100 $0,6$ $0,03$      |
| tyre tread                                | density, kg/m$^3$; Neo-Hookean model coefficients: $C_{10}$, MPa, $D_{1}$, MPa$^{-1}$ | 1100 $0,5$ $0,04$      |
| metal rim                                 | density, kg/m$^3$; Young modulus, MPa, Poisson coefficient | 7500 $207000$ $0,3$    |
| metal-clad breaker threads                | density, kg/m$^3$; Young modulus, MPa, Poisson coefficient | 7500 $207000$ $0,3$    |

The nylon threads of the framework cord are perpendicular to each other in the two composite reinforcing tyre layers: along and across the rotation axes of the tyre. The metal threads of the breaker are laid diagonally at the angle of 65 and -65 degrees to the rotation axis of the tyre in the rubber filler. As a whole it forms metal cord composite material.

The properties of the nylon threads and the rubber were set by the hyper elastic model of the material. The materials of the rings of the rim and the metal threads of the breaker layers were defined by the linear function. The determination of the supporting cords properties was simplified due to the assumption about the independence of supporting cords geometry on the material surrounding them. Thus, the creation of the grid for the cords was carried out without regard to the layers of the rubber components of the tyre. For this purpose, the program complex ABAQUS offers a possibility to use superficial elements describing the supporting cords properties. The superficial elements are used to define the cords geometry only. They are “cut into” the three-dimensional Solid elements and applied in order to model the rubber components of the tyre by introduction of the kinematic connections between the knots of the grid of the rubber material matrix and the knots of the superficial elements of the supporting cords.

Using the basic data we constructed a finite element model of the pneumatic tyre in the axisymmetric and three-dimensional statements (fig. 2) in order to study the influence of the axial vertical load value on the contact spot form and the stress-strain state of the tread material.
Figure 2. Geometrical model of the complicated tyre tread

Figure 3 presents the dependence $\sigma = \sigma(\epsilon)$ of normal tension on relative lengthening. The maximum lengthening was 50%.

Figure 3. Dependence of normal tension on relative lengthening $\sigma = \sigma(\epsilon)$. $\epsilon = 50\%$

Comparing the experimental results with the data obtained from the models we should mention that at such lengthening all the material models work identically. However, some of the material models stop working when we increase relative lengthening (fig. 4). While modelling the pneumatic tyre three models, namely Mooney-Rivlin, Neo-Hookean and Yeoh models, describe the stress-strain state of the tread material most adequately.
3. Numerical approaches to the problem solution

The numerical experiment represented dynamic rolling of the model of the pneumatic tyre with a simplified drawing of the tread on the rigid level surface. All the model parts were joined into a single entity by imposing additional connections.

Modelling of the tyre static load was conducted in three stages:
1 stage – tyre inflation up to the operating pressure;
2 stage – initial pressing of the tyre to the rigid level surface described by the analytic plane. The initial pressing was set up by an artificial vertical shift of the analytic plane against the tire to provide tyre-surface interaction in the contact zone;
3 stage – after a steady tyre-surface contact is achieved, release of the tyre from the movement set at the second stage and application of the weight load to the tyre center.

A universal direct approach is creation of the tyre model in the three-dimensional statement ready to all types of computing experiments and adapted for a rapid change of boundary and initial conditions, geometry and properties. The limitation of this method is a considerable time span necessary to solve the dynamic problems of the tyre rolling, which is connected with a large number of the model degrees of freedom, as well as with the need to use a short lead time and a long period of time before the system gets into the stationary mode. Such method to solve the problems of stationary rolling is the most widespread in the tyre industry to assess the efficiency of the product. Unfortunately, it cannot be used for a digital design of tyres. So we developed a method to solve the problem of rolling at the constant speed based on the decomposition of the stress-strain state and the use of the independent Lagrange-Euler approach well-known in the continuum mechanics.

This method of calculation of the tyre stationary rolling was realized in the Abaqus Standard and consists of several stages:
1 stage – creation of the model of cross section of the pneumatic tyre with regard to its internal structure and solution of the problem of inflation in the axisymmetric statement;
2 stage – transformation of the constructed section into the three-dimensional model with the help of the Abaqus Standard. The Abaqus program complex makes it possible to pull the model from the section around the circumference with the preset number and type of final elements and to impose kinematic conditions to ensure the tyre surface pressing.
3 stage – using the elaborated three-dimensional finite element model of the tyre, imposing of power conditions in the form of weight and calculation of the stress-strain state of the tyre under the influence of weight;
4 stage – calculation of the dependence of the tyre stress-strain state in the conditions of the established rolling at the preset load on the car weight.

Figure 4. Dependence of normal tension on relative lengthening $\sigma = \sigma(\varepsilon)$. $\varepsilon = 100\%$
The established rolling of the tyre was studied at the wheel speed equal to 80 km/h and the coefficient of friction between the road and the tire equal to 0.5.

4. Results and their discussion

Computer modelling was carried out in two stages: static and dynamic. The static test modelling was carried out using two techniques with the invariable sizes and properties of the materials. The pressure in the tire was equal to 0.245 MPas, the normal load was equal to 3.3 kN. The results of the calculations are given in table 2.

Table 2. Calculation results for the tyre contact spot

| Problem definition / model                  | Contact pressure, MPa | Print sizes, mm×mm |
|--------------------------------------------|-----------------------|--------------------|
| Static pressing of the tyre to the rigid surface | A full three-dimensional model of the tyre | 0.72                | 141×132             |
|                                            | A simplified model without a rim           | 0.57                | 127×125             |
| Stationary rolling of the tyre on the rigid surface | A full three-dimensional model of the tyre | 0.77                | 126×123             |

The analysis of the results of the experiment showed the existence of an insignificant deviation of the contact pressure value for the tyre model in the full three-dimensional statement and that in the axisymmetric statement. It allows to state the expediency of the use of all the three ways of making a wheel. However, due to a great time expenditure on the numerical calculation of the tyre model in the three-dimensional statement the priority is given to the tyre model in the axisymmetric statement. But the use of the simplified model does not allow to take into account the geometrical features of the tread (fig. 4). That is why to create a complicated asymmetrical geometry of the tread it is necessary to use the tyre model in the three-dimensional statement.

The analysis of the results showed an increase of the contact pressure in the contact zone which can be explained by the increase of the tyre volume and the centrifugal effect. Fig. 5 shows the forms of the print of the tyre in contact with the road depending on the size of the imposed load and the material model.

5. Conclusion

Thus, the present research includes:
- numerical modelling of tyres with account of nonlinear analysis;
- calculation of tyres behavior at static and dynamic loads with account of the material models;
- creation of our own models of materials;
- modelling of a complex structure of the tyre;
- optimization of the tyre structure, for example, of the tread drawing or the cord characteristics.

The analysis of the results of the pneumatic tyre modelling in different statements and with variation of external and internal conditions showed that there are several solutions to the given task: in the axisymmetric statement and in the full three-dimensional statement. To describe the material properties we chose Yeoh material model as the one that describes the stress-strain state of the material most adequately. It is possible to use the received results in future in calculations of the tread rubber wear [3].
Figure 5. The form of the print of the tyre in contact with the road depending on the load and the material model (from top to down Mooney-Rivlin model, Neo-Hookean model, Yeoh model)

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