

FEM MODELLING OF CONTACT INTERACTION BETWEEN WHEEL AND SUPPORTING

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Abstract: Modelling of contact interaction of wheel and the supporting surface is an important problem for the vehicle design. Paper considers the option of modelling the wheel, as well as methods of processing the calculation results of the dynamic contact interaction for the main evaluation parameters. A version of simulation cord and breaker of the shell element is proposed. The adequacy and effectiveness of the proposed method of processing the results of contact interaction of the wheel and the bearing surface are shown.

Keywords: *car, wheel, tire, contact, modelling of contact interaction, CAD, FEM, ANSYS, LS-DYNA*

1. Introduction

As part of his thesis on the topic of choosing the optimal parameters of suspension system, depending on the operating conditions faced with the task of processing the results of modelling of contact interaction of the wheel and the supporting surface. From the perspective of permeability, the most important parameters are the contact interaction are peak pressure at the contact patch, the average pressure at the contact patch, the coefficient of rolling resistance, width and depth track.

The software package ANSYS LS-DYNA was chosen to model the contact interaction between the wheel and the bearing surface because it is one of the most advanced tools for solving problems of this kind, well in the work of the leading manufacturers of wheel tire companies (including Michelin, Goodyear). This program is designed to simulate nonlinear problems involving large deformations.

2. Simulation of finite-element model

The system contains two parts: tire (p. 1, Figure 1) and supporting surface (p. 2, Figure 1). In this case it is not attempt to obtain quantitative results, a qualitative assessment only and analysis of it. That is why the supporting surface is represented by the height of one parallelepiped element and superior in size to the dimensions of the wheels 50%.

As the material of the supporting surface (p. 2, Figure 1) is selected concrete with following characteristics: elasticity modulus $2 \cdot 10^{10} Pa$, Poisson ratio 0.2, density 2500 kg/m³. Modell were performed by volume elements solid164 type.

Wheel modelled from several parts: belt (p. 1, Figure 2), cord (p. 2, Figure 2), rubber part of tyre (p. 3, Figure 2), bead (p. 4, Figure 2), rim (p. 5, Figure 2), disk (p. 6, Figure 2).

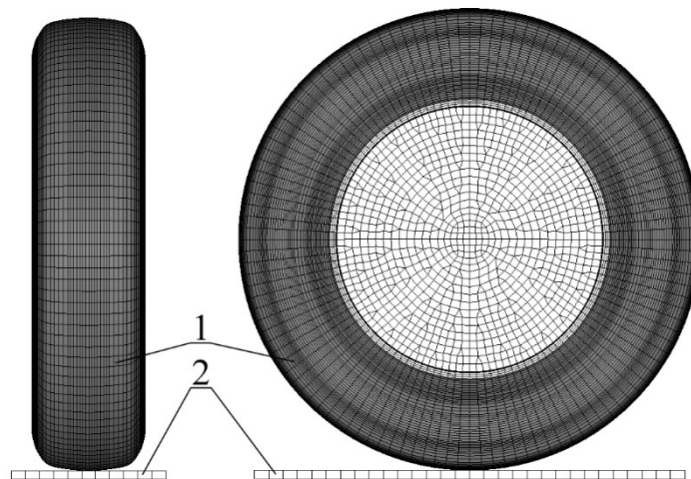


Figure 1. Finite-element model of the system
1 – tyre; 2 –supporting surface

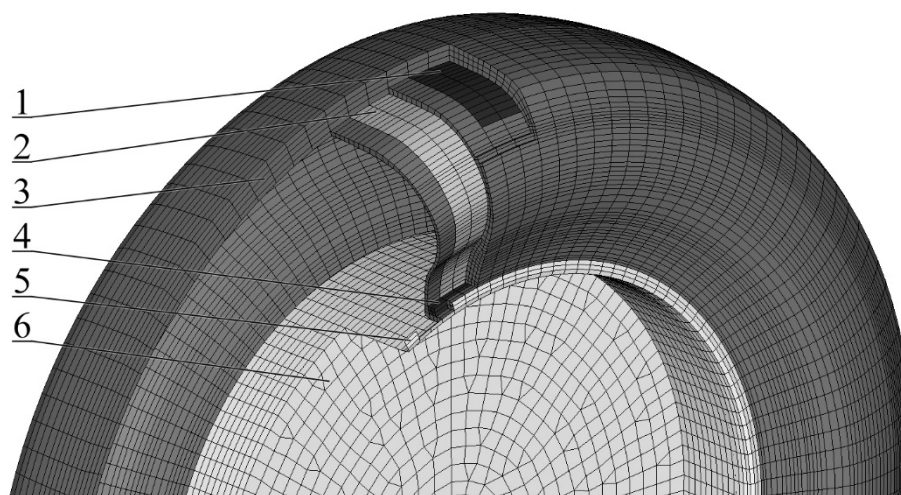


Figure 2. Finite-element model of tyre
1 – belt; 2 – cord; 3 – rubber part of tyre; 4 – bead; 5 –rim; 6 – disk

Belt (p. 1, Figure 2) and cord (p. 2, Figure 2) were performed by shell elements shell163 by orthotropic material (carbon steel) with following characteristics by main direction: elasticity modulus $2.1 \cdot 10^{11} Pa$, Poisson ratio 0.28, density 7800 kg/m^3 . In two other directions of the modulus of elasticity is $9.3 \cdot 10^{10} Pa$. The thickness of the elements is 0,025 mm.

Thickness and elasticity modulus elements on secondary directions chosen so to ensure the rigidity and weight [1] equivalent to the corresponding parameters of the cord and the belt composed of steel filaments (Figure 3).

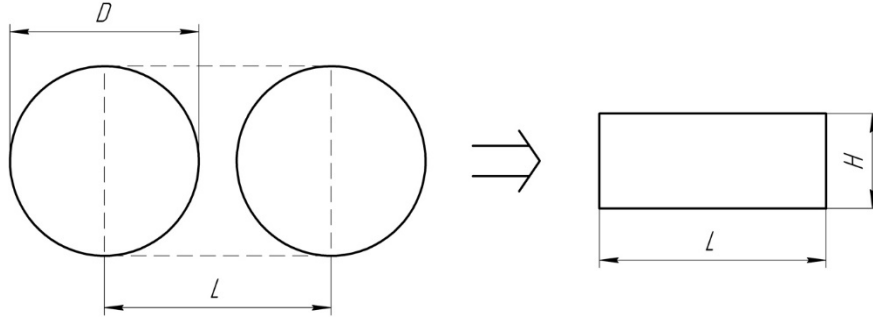


Figure 3. Converting square of cord to equivalent to the area of a rectangle

In the case of small dimensional deformations (within the elastic zone, where in Hooke's law is valid), the stiffness can be defined as the product of modulus of elasticity (in tension, compression and bending) or the shear modulus (shear and torsion) to the relevant geometrical characteristics of the element cross section. In the case of bending it is the axial moment of inertia. Belt and cord works on bending and stretching in this task [0]. The equivalence of the tensile stiffness is provided by the equality of cord steel filaments area and the equivalent rectangle:

$$H = \frac{\pi D^2}{4L} \quad (1)$$

The equivalence of the bending stiffness is determined by the product of the modulus of elasticity to the polar moment of inertia for both sections. This means that:

$$E_{eq} = \frac{12L^2}{\pi^3 d^2} E_{steel} \quad (2)$$

The flexural rigidity of belt and cord in the transverse direction is much less than in a longitudinal because weaving structure where rigid steel filaments in this direction are connected kapron flexible filaments.

Since the thickness of the equivalent cross-section has been determined previously, the equivalent modulus of elasticity in the transverse direction define equal to experimentally obtained.

Rubber part of tire (p. 3, Figure 2) was performed by solid elements solid164 type by Mooney–Rivlin model (used to modelling hyper elastic elastomeric materials such as rubber). Material characteristics: Poisson ratio 0.499, density 1200 kg/m³. Size and load curve of the sample correspond to the experimentally obtained data.

Bead (p. 4, Figure 2) was performed by solid elements solid164 type from carbon steel material. It has the following characteristics: elasticity modulus $2.1 \cdot 10^{11} Pa$, Poisson ratio 0.28, density 7800 kg/m³.

Rim and disk (p. 5 and p. 6, Figure 2) were performed by shell element shell163 from carbon steel material with following characteristics: elasticity modulus $2.1 \cdot 10^{11} Pa$, Poisson ratio 0.28, density 7800 kg/m³. In this task the solution accuracy is not required. Therefore, to simplify model the thickness of the element is set to 5 mm in all sections.

Assumptions: this model is intended for the qualitative assessment of contact interaction of the wheel and the bearing surface, so all the elements that do not affect the stiffness of the tire were modelled with simplifications and their mechanical properties are set to the

reserve. The bead is made of steel and considerably larger than the prototype. It has no effect on the stiffness of the tire because of the distance from the contact patch. But this simplification reduces the complexity of the simulation.

Rim and disk executed by the simplified geometry, so that loads are applied to node in the geometric centre of the wheel assembly. The thickness of the elements was chosen higher than necessary to eliminate the influence of the rigidity of the disk on the interactions of tire and supporting surface. In this model they perform an auxiliary function.

Consolidations and loads: the support surface mounted on axes X, Y and Z in the lower part. Disk nodes have restrictions on lateral movements.

To the inner surface of the rubber part of the tire pressure of 200 kPa is applied. To the central disk node attached downward direction vertical force 1750 N. The same node attached torque 100 Nm in the direction of the wheel rolling. To all nodes of the model applied acceleration of gravity g .

Due to the fact that a model created for the qualitative analysis of the interaction and does not require the precise values the tread pattern is absent.

3. Method of results calculation process

To determine the width and depth of the track is required to obtain data on the movement of the reference points of the surface. It will be enough to get the data from all three points – vertical movement of the node in the centre of track and coordinates of nodes on opposite edges of the gauge (the track width is absolute value of their difference).

To obtain the desired peak value of pressure at the contact patch, the average pressure at the contact patch, the coefficient of rolling resistance is required to convert data received from the pattern of pressure distribution in the contact patch.

This picture is available in ANSYS and LS-DYNA postprocessor: Plot > Results > Contour plot > Element solution > Stress > Y-Component of stress.

For the convenience of processing the results should make the colour scale legend in the form of shades of grey from black (zero pressure) to white (maximum pressure). To do this, create a new scale: PlotCtrls > Style > Colours > Create Colour Map. The preferred will create 16 shades of grey and even pitch in brightness. If possible, one must create 256 levels.

For ease of processing it is recommended to set a scale so that the minimum value is negative, so that:

$$\min = -\frac{\max}{n-1} \quad (3)$$

where max is the maximum value of the study, n is the number of grey levels.

In this case, it turns out that each gradation (except the first one corresponding to zero and negative values) corresponds to the value:

$$p_i = \frac{\max}{n-1}(i+1) \quad (4)$$

where i is number of level.

Then one can bring a picture of the pressure distribution on the screen and save the image: PlotCtrls > Capture Image > File > Save as > select the file name and format bmp (bitmap – no compression). It is recommended to use the maximum resolution of the monitor ANSYS expands the window to full screen and hide all the tool windows.

Next, in a graphics editor (e.g.: GIMP 2.8) one must clear the corresponding section of the wheel is not involved in the contact (make them black tool brush, which corresponds to zero pressure) and save the file in PBM p2 (portable bitmap encoded in ASCII [3]): File > Export > Drawing PGM > Export > Text (ASCII) > Ok.

At this stage it is possible to reduce the size of an image without carrying the information about voltages (black squares), to reduce the size of the matrix and increase the rate of calculating (Part II, Figure 4).

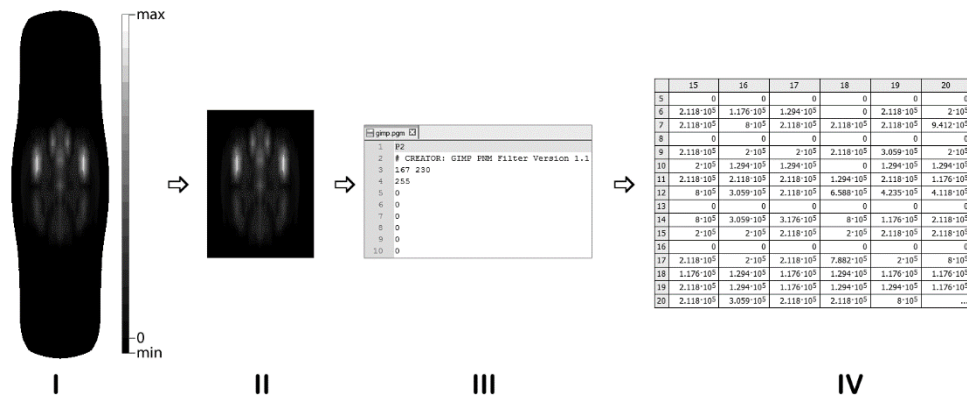


Figure 4. The processing steps of calculation results

1 – original picture of the stress distribution; 2 – treated pattern of stress distribution; 3 – vector format data PGM; 4 – matrix stress distribution

The resulting file should be opened in a text editor (e.g.: Notepad++). Figure 5 shows a sample file PGM. In it, the first line p2 represents the version of the format (in this case, grayscale, recorded in the encoding ASCII), the third row contains information about image size (number of columns {col} and row {row}, respectively), and the fourth – the depth of colour {depth} [0] (255 means that each pixel can have a brightness of 0 to 255). The fifth and next to the end of file – brightness {data}.

```
gimp.pgm
1 P2
2 # CREATOR: GIMP PNM Filter Version 1.1
3 13 5
4 255
5 247
6 240
7 246
```

Figure 5. Listing of the PGM file

The resulting data can be transferred into the program, which make calculation (MathCAD, Excel etc.).

The variable data contains a column of data (Part III, Figure 5), which should be transformed into a matrix of brightness:

$$lightness_{i,j} = \frac{data_{i(row-1)+j}}{depth} \quad (5)$$

where j varies from 1 to row, i varies from 1 to col.

Now lightness is a matrix of relative brightness. Multiplying it by the maximum pressure {max} of the legends of the initial picture of the stress distribution (Part I, Figure 5) we obtain the matrix of the pressure distribution in the contact patch (Part IV, Figure 5).

In the event of a major partitioning into finite elements model the pressures can be calculated manually using the colour picker tool in your photo editor and putting it into line value from the legend of the original image.

Define the contact area:

$$S = \sum_1^n \sum_1^m p_{Heaviside} l^2 \quad (6)$$

where n , m are the number of rows and columns in the matrix of pressure values, $p_{Heaviside}$ is the matrix of pressure values, each element of which is equal to one if the corresponding element of a non-zero pressure (using the Heaviside step function [0]), l is the length corresponding to one pixel of the image pattern pressure distribution in the contact patch.

This length is determined by the ratio of the size of the model in millimetres corresponding to the size of the image in pixels. For this purpose it is convenient to create a finite element model of three-element beam length of 0.1 m (or any other comparable with the characteristic dimensions of the model) in the direction of the principal coordinate and consolidate all of their components from moving. They are conveniently situated away from the main model, so they do not overlay on the deformed model after calculation but were visible. The size of the image in pixels can be defined in a graphics editor.

Defining the total vertical force exerted by the wheels on the supporting surface:

$$F_{\Sigma} = \sum_1^n \sum_1^m p l^2 \quad (7)$$

where p is the pressure of the matrix (obtained by the mapping results to calculate pressure LS-DYNA). In the stabilized mode, this force must be equal to the sum of the vertical forces acting on the centre of the wheel and the mass of the wheel.

Then the average pressure in the contact patch will be determined by dividing the total force to the area of the contact:

$$p_{avg} = \frac{F_{\Sigma}}{S} \quad (8)$$

Peak pressure in the contact spots will be determined as a function of the maximum:

$$p_{max} = \max(p) \quad (9)$$

The coefficient of rolling resistance is determined by the formula:

$$f = \frac{M(r_K - r_{dyn})}{F_{\Sigma} r_K r_{dyn}} + \frac{a}{r_{dyn}} \quad (10)$$

where M is the torque, r_K is the free wheel radius (defined geometry), r_{dyn} is the dynamic wheel radius (calculated as the difference between the vertical coordinates of the central disk node (O) and a node located in the contact), a is the longitudinal displacement of the centre of pressure relative to the projection in the centre of the wheel contact patch.

Calculate longitudinal displacement of the centre of pressure as the difference of the distance between the longitudinal coordinates of the centre of the wheel (O) and the farthest node of the contact (L_1) and the distance from the node to the centre of pressure (O_p) of the contact (L_2). L_1 value is determined in ANSYS: TimeHistPostpo >AddData > Nodal

Solution > DOF Solution > X-Component of displacement > one need to choose the node > List Data > after this, select the value corresponding to the time when the oscillations died down and the wheel moves in steady mode. L_2 value is determined from the pressure distribution matrix according to:

$$L_2 = \frac{M_p}{F_\Sigma} \quad (11)$$

where M_p is the moment created by the pressure relative to the farthest node of the contact:

$$M_p = l^2 \sum_1^n \sum_1^m \left[p_{i,j} \left(il + \frac{l}{2} \right) \right] \quad (12)$$

4. Results

Processing of the results gave the following values (Figure 6): col = 167 is the number of columns in the contact patch pattern; row = 230 is the number of rows in the contact patch pattern; depth = 255 is the brightness depth; max = $3 \cdot 10^6$ Pa is the maximum pressure in the contact patch (in legend); $l = 0.59$ mm is the length corresponding to one pixel; $S = 66.9$ cm² is the contact patch area [62]; $F_\Sigma = 2580$ N is the integrated force in contact patch [2450]; $p_{avg} = 386$ kPa is the average pressure at the contact patch [395]; $p_{max} = 2860$ kPa is the peak pressure in contact patch; $f = 0.016$ is the coefficient of rolling resistance [0.015–0.018].

The numbers in square brackets are the theoretical values. As you can see, all the values are relatively minor error theoretical except peak pressure. Lots of peak pressures under the edge of the belt, at the transition to the sidewall of the tire tread. This corresponds to the observed picture of the stress distribution in the contact patch.

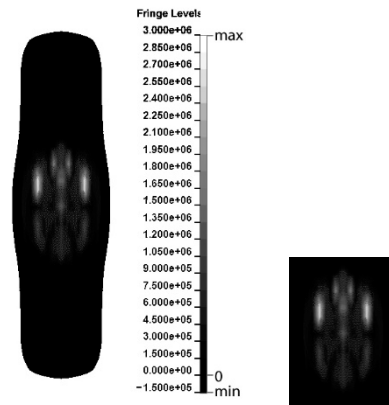


Figure 6. The results of the calculation. contact pressure

5. Conclusion

The calculation results show that the proposed finite-element model of the wheel and the method of processing the results of the calculation are adequate and can be applied in the

future. The error in the estimated parameters of the contact interaction of the wheel and the bearing surface does not exceed 10%.

The calculation showed that the main novelty of the model (modelling cord and breaker of the shell element) is admissible and can reduce the dimensionality of the model, thereby increasing the speed of calculation, by reducing the number of beam elements.

Evaluation of contact interaction parameters were calculated by hand and by the proposed method. The parameters obtained by the proposed method have a smaller error relative to the experimental data.

6. References

- [1] *Stiffness*, <http://en.wikipedia.org/wiki/Stiffness>.
- [2] *Heaviside step function*, http://en.wikipedia.org/wiki/Heaviside_step_function.
- [3] *Portable anymap*, http://en.wikipedia.org/wiki/Portable_anymap.