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Detailed vs. Simplified Tread Tire Model for Steady-State Rolling Analysis

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Analiza primjenom metode konačnih elemenata
Metoda konačnih elemenata
Kotrljanje u stacionarnom stanju

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This paper deals with the level of detail that is necessary for representation of tread pattern in finite element tire models. Different methods for creation of tire tread mesh are systematized by two different criteria: the most common approaches and the finite element analysis type. Some of the representative approaches found in literature are given in more detail and their advantages and disadvantages discussed. An example from author's experience, which describes the creation of finite element tire model with detailed tread for steady-state rolling analysis, is presented. The paper also brings a head-to-head comparison of the response of simplified and detailed tread tire models, subjected to a range of finite element analyses, from footprint analysis at static loading conditions to steady-state rolling cornering analysis.

Usporedba odziva modela pneumatika s detaljnim gaznim slojem i pojednostavljenog modela za analizu kotrljanja pneumatika u stacionarnom stanju

Izvornoznanstveni članak

Ovaj rad se bavi razinom detalja koja je potrebna za prikaz uzorka gaznoga sloja u modela pneumatika namjenjenih analizi primjenom metode konačnih elemenata. Različite metode za izradu mreže konačnih elemenata su sistematizirane po dva različita kriterija: najčešćih pristupa i tipa analize primjenom metode konačnih elemenata. Neki od tipičnih pristupa koji se mogu naći u literaturi opisani su u više detalja i navedene su njihove prednosti i nedostaci. U članku je dat primjer iz iskustva autora, koji opisuje stvaranje modela pneumatika s detaljnim gaznim slojem za analizu kotrljanja u stacionarnom stanju. U radu je također prikazana izravna usporedba odziva pojednostavljenog modela pneumatika i modela s detaljnim gaznim slojem, podvrgnutih nizu analiza, od analize kontakta između tla i pneumatika pod statičkim uvjetima opterećenja do skretanja pri kotrljanju u stacionarnom stanju.

1. Introduction

Finite element analysis (FEA) is often deployed in tire design to predict the behavior of the tire during its service life, as described in [1], [2] and [3]. Depending on tire response that is predicted, adequate level of simplification of finite element (FE) model is chosen. Probably the most important aspect of this simplification is the level of detail in which tire tread is modeled. It is addressed here through: a review of common tread modeling approaches, an example of building a FE tire model with detailed tread and response comparison of two tire models with same inner structure but different level of detail at tread area.

Tire tread provides the necessary grip or traction for driving, braking and cornering. Both tread pattern and tread compound must be designed to provide effective performance in various driving conditions, while also meeting customer expectations for acceptable wear resistance, low noise, and good ride quality. Tread pattern is designed to provide uniform wear, to channel water out of the footprint, and to minimize pattern noise on a variety of road surfaces [4].

Typical features of tread pattern design are described in [4]. They are combined in order to primarily satisfy the function of tire tread and also to conform to aesthetic trends, which form the customer's perception of product performance. Parametric and knowledge-based design systems may efficiently be used to streamline the process of tread design, as may be seen from [5], [6] and [7]. They help in merging the strict constrains, determined by tread function and manufacturability, with tacit knowledge of tire designer.

Depending on the type of results that tire FEA should yield tire tread is modeled in different level of detail, using different approaches, of which the most common ones are:

Symbols/Oznake

F_x	- Longitudinal force, N - Uzdužna sila	p	- pressure, $\mathrm{Nmm^{-2}}$ - tlak
F_y	- Lateral (cornering) force, N - Bočna sila (sila skretanja)		**Greek letters/Grčka slova**
F_z	- Normal force (vertical load), N - Normalna sila (vertikalno opterećenje)	α	- slip angle, ° - kut klizanja
v	- velocity, $\mathrm{ms^{-1}}$ - brzina	μ	- coefficient of friction - koeficijent trenja

1. **Simplified tread modeling**: the tire is modeled as a smooth one or only the circular channels are included in the FE model, while the other features of tire tread are omitted. If the goal of the analysis is to find the tire forces and moments during cornering or braking, or to find the first approximation of footprint shape, size and contact pressure distribution, such a model is often sufficient [1], [2], [3].
2. **Global-local approach**: at first a simplified (global) tire model is built and analyzed. Then the portion of the tire is modeled in detail (local model) and displacements and stresses are transferred from global to local model as boundary conditions [8], [9].
3. **Detailed tread modeling**: tire tread is modeled in detail and assigned a dense mesh of finite elements. The rest of the tire is modeled in less detail and assigned a relatively coarse mesh. Then the two meshes are tied along the contacting surface. If the contact pressure on tread surface is to be analyzed in detail, the FE model with detailed tread will produce the output which is closest to the experimental values [10], [12].

The level of detail in tire tread modeling is also determined by the type of FEA. If tire behavior on dry and stiff surface is considered, three different cases may be identified:

1. **Static FEA** - only the behavior of the tire subjected to static loads is considered [2]: finite element mesh on tire tread may be of arbitrary density; very large densities are possible; the most important consideration is how to merge the dense mesh in the vicinity of the footprint with the mesh on the rest of FE model [8], [10].
2. **Steady-state rolling analysis**: the behavior of steady-state rolling tire is analyzed using mixed Eularian-Lagrangian formulation [1], [3], [12], [13]; until recently only the circular channels could be modeled with the benefit of having the dense mesh only in the vicinity of the footprint; the method is now expanded to include detailed tread modeling where an identical tread segment is patterned and scaled in circular direction [11], [12], [13]; the approach of typical segment patterning necessarily implies the approximation of tread shape; mesh density is limited by model size, i.e. the time needed for the analysis to finish.
3. **Implicit FEA using purely Lagrangian approach or explicit FEA** [3]: tread pattern may be modeled without approximation of tread geometry; FE mesh may be of arbitrary density, which is limited by model size, nevertheless this limitation is very significant for those analysis types.

In this paper, the generation of finite element tire model with detailed tread is described trough literature review and an example from author's experience.

2. Tread modeling – examples from literature

This section does not present a detailed literature review of tire tread modeling, but rather presents some typical examples that illustrate the cases mentioned in the introduction.

In [14] an attempt is made to model the influence of tread pattern on the behavior of steady-state rolling tire by assigning orthotropic material properties to simplified tread tire model. Material properties are obtained by FEA of a flat portion of tire tread, containing several tread blocks. This approach had been introduced before the mixed Eularian-Lagrangian formulation was expanded to include detailed tread modeling. The analyses were performed on two FE tire models, with isotropic and orthotropic tread properties, and then compared to each other and to experimental results. The results showed that introduction of orthotropic tread properties brought the results closer to experimental ones.

A global-local approach is used in [8] and [9] to analyze the behavior of tire model with detailed tread pattern in the vicinity of footprint area. In order to transfer the solution results from global to local model, a tying algorithm for the linking of two originally geometrically incompatible finite element meshes with different degrees of refinement is proposed in [8], and applied to FEA of the model of an automobile tire with a simplified tread. Consideration of tread profile is restricted to the anticipated region of contact with the road surface and to its vicinity. For the remaining part of the analysis model a coarser finite element mesh is used.

Simplified and global-local tire models are roughly criticized in [10]. It is said that simplified tire models may produce poor numerical results because some of the major tire interactions, such as footprint shape and size, contact pressure distribution, frictional energy and rolling resistance are characterized by the deformation of tread blocks and the interaction between belts and adjacent parts of tire. Considering the global-local approach, it is claimed that even though the local model is able to provide the numerical results associated with tread block, its accuracy is strongly influenced by the reliability of simplified model. The reason for this claim is found in the fact that the local model uses the results obtained by the simplified model as boundary conditions and it also ignores any interaction between the tread blocks and the belts and the adjacent parts of tire.

The approach to detailed mesh generation described in [10] is based on a method for tying of two incompatible meshes: coarse regular mesh of tire body and dense tread pattern mesh, which is inserted either partially or fully, depending on analysis purpose. Tread mesh is constructed from 2D 1-pitch pattern, which is multiplied and transformed into 3D pattern by the subroutines coded in FORTRAN. When partial mesh is used, a transitional area must also be added, which serves to relax the abrupt density change in overall tread mesh and to avoid problems in assembling the tread mesh and body mesh. The paper also compares footprint stresses obtained numerically and experimentally, confirming the quality of proposed approach.

An example of detailed tread generation for use in steady-state rolling analysis is given in [12]. Similar to method described in [10], tread pattern mesh is created by multiplying and scaling of a repeating tread section and assembled to body mesh. The main difference between the two approaches is that the latter requires that the repeating section is bordered by two planar surfaces, which contain the tire axes. Such an approach is described in more detail in the next section.

3. An example of detailed tread modeling for FEA of steady-state rolling tire

In this section the finite element tire model with detailed tread, developed by the authors for steady-state rolling analysis, is described. The nature of mixed Eularian-Lagrangian formulation, which is used for tire FEA, implies that the mesh is composed of typical segments, ("slices") that are topologically equal. The segments have to be chosen in such way that by their multiplication and scaling in circular direction the best approximation of tire tread geometry is obtained. In this way a certain level of approximation of initial geometry is inevitably introduced, but it is a consequence of requirements dictated by the finite element formulation. The initial geometry of the tire which is modeled in this example is shown in Figure 1.

Figure 1. 3D parametric model of an existing tire type, dimensioned 165/70R13

Slika 1. 3D parametarski model postojećeg tipa pneumatika, dimenzija 165/70R13

It is obvious that a typical segment of tire geometry would be easily created if the tire was cut along the bottom of lateral grooves. However, the FE method requires that the slices are cut along the planes that contain the tire axes [11]. Thus, the tread geometry was idealized by removing of smaller features, sipes and kerfs, and then the optimal location of cutting planes was identified and typical segment produced (Figure 2).

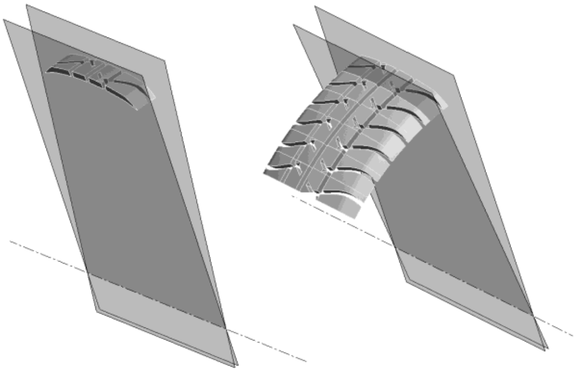

Figure 2. Identification of typical tread segment. The multiplication of the segment is shown for better visualization of resulting, approximated, tread geometry

Slika 2. Identifikacija tipičnog segmenta gaznoga sloja. Multiplikacija segmenta je prikazana radi bolje vizualizacije rezultirajuće, približne, geometrije gaznoga sloja

Independently from the tread segment, the typical segment of tire body (without tread) was created, which spanned the identical angle of 5.6° (the angle of intermediate pitch). The two segments were then assembled to form the complex typical segment of the tire (Figure 3).

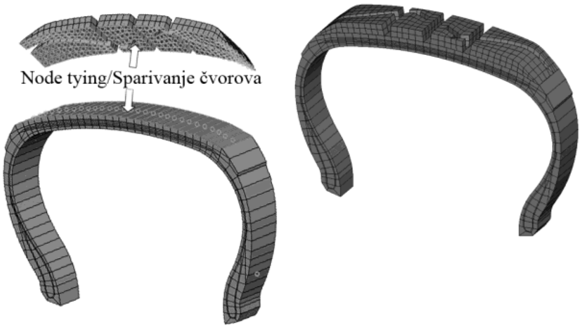

Figure 3. Typical mesh segment formed by assembling of body and tread segments. Nodes on contacting surface are tied by DOF coupling

Slika 3. Tipični segment mreže formiran sklapanjem segmenata tijela i gaznoga sloja. Čvorovi na površini kontakta odlikuju se sparenim stupnjevima slobode

Finally, the FE model of the tire was created by rotation of complex typical segment along circular direction (Figure 4). The segment was multiplied and scaled in such a way that a realistic disposition of tread blocks was achieved, which corresponds to a predefined pitch sequence (Figure 5).

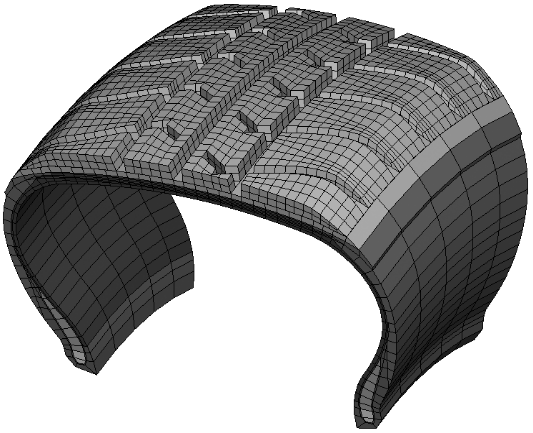

Figure 4. FE tire model creation by multiplication of complex typical segment

Slika 4. Kreiranje FE modela pneumatika umnožavanjem složenog tipičnog segmenta

Figure 5. Final 3D FE model of the tire

Slika 5. Finalni 3D model pneumatika za analizu primjenom metode konačnih elemenata

4. Comparison of numerical results obtained using simplified and detailed tread FE tire models

In order to illustrate the use of previously discussed FE tire models, the results of analyses performed on simplified and detailed tread model of the same tire are compared in this chapter. Detailed descriptions of simplified tire model, algorithm for FEA and analyses results, are given in [3]. The building of detailed tread model, which has the identical inner structure as simplified one, is described in previous chapter. Both tire models use the same material models and contain the same number of different materials, as does the model described in [3].

4.1. Static footprint analysis

Probably the most important advantage of detailed tread models in comparison to simplified ones is the accuracy of results on footprint stresses (Figure 6). If those stresses are well predicted, then the quality of tread pattern, in terms of grip and wear, may be assessed. Such results are often the ones that tire manufacturers are interested in the most.

Figure 7 presents the comparison of footprint contact pressure obtained by using simplified and detailed tread tire models. While the stress distribution is globally identical, there exists a significant difference in local stress values and peak locations on detailed tread model. The introduction of detailed tread generally yields the higher values of maximum contact pressure. The ratio of maximum contact pressure obtained by two FEA models equals 1.33.

Figure 6. Deformed shape of detailed tread model, inflated to 2 bars, under vertical load F_z = 3580 N, with footprint contact pressure shown

Slika 6. Deformirani oblik modela pneumatika s detaljnim gazećim slojem, napuhanog na tlak od 2 bara, pod vertikalnim opterećenjem F_z = 3580 N, sa prikazanim kontaktnim tlakom

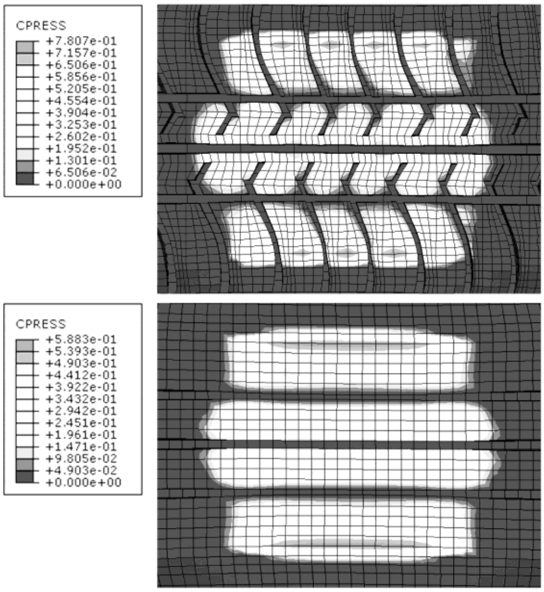

Figure 7. Comparison of footprint contact pressure obtained by FEA of simplified and detailed tread tire models

Slika 7. Usporedba kontaktnog tlaka dobivenog analizom pojednostavljenog MKE modela pneumatika i modela detaljnog gaznog sloja

The introduction of detailed tread also influences the vertical rigidity of FEA model, making it more flexible, as may be seen in Figure 8. The maximal difference between the deflections of two models at identical load equals to 3%.

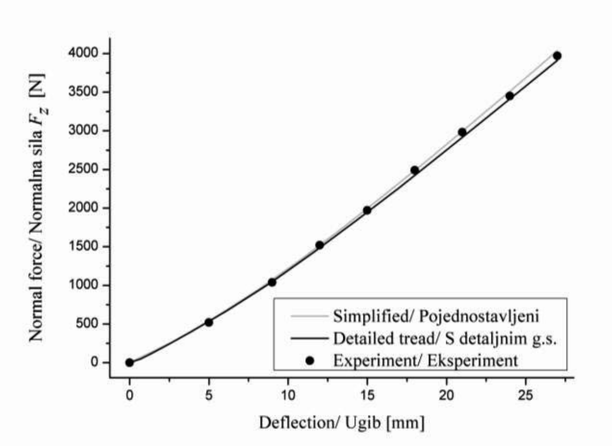

Figure 8. Load - deflection curves at vertical load of 3580N, obtained using simplified and detailed tread model, vs. experiment

Slika 8. Usporedba krivulja ugib - vertikalno opterećenje od 3580N dobivenih analizom modela sa i bez detaljnog gaznoga sloja i eksperimentalih rezultata

4.2. Braking and acceleration at straight-line rolling

Comparison of simplified and detailed tread model response in braking-to-acceleration analysis is given here through footprint stress and longitudinal force results. Both models have been inflated to 2 bars and loaded by vertical force of 3580 N. The coefficient of friction between the tread and the ground was set to 0.6. Horizontal speed of the road was set to 50 km/h and rotational speed of the tire was incrementally adjusted in order to obtain a number of steady state solutions that cover the range from full braking [15] to full acceleration.

In this case the difference between maximal stresses at the footprint gets much more significant than in the case of static analysis under vertical load, and equals 6.25, as may be seen from Figure 9. This difference is the consequence of localized deformations of tire tread, which occur when detailed tread model is used. Local deformations cause locally high stress values that the simplified tread model cannot capture. In order to find those values with greater accuracy a finer mesh should be used. Nevertheless, as may be seen from Figure 10., local differences in stress distribution do not have a significant influence on intensity of longitudinal tire force F_x. It may be seen that the model with detailed tread has a slightly lower rigidity at cornering and braking than simplified one.

Figure 9. Comparison of contact pressure obtained using simplified and detailed tread models, at full braking

Slika 9. Usporedba kontaktnog tlaka dobivenog upotrebom modela sa i bez detaljnog gaznoga sloja, pri punom kočenju

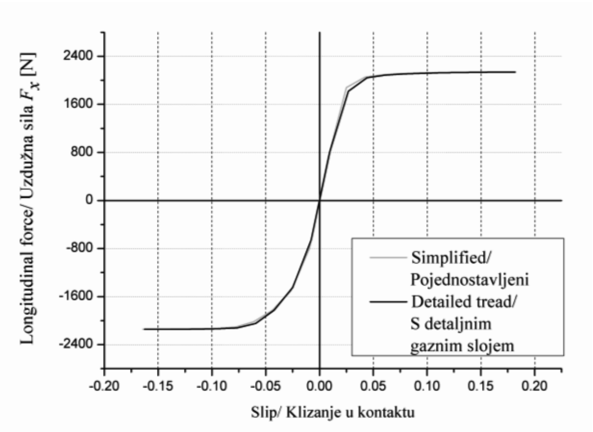

Figure 10. Longitudinal force vs. slip curves, obtained using simplified and detailed tread tire models

Slika 10. Krivulje uzdužna sila - klizanje u kontaktu, dobivene primjenom pojednostavljenog modela i modela s detaljnim gaznim slojem

4.3. Cornering analysis

Cornering analysis was also performed using the two described FE models. At inner pressure of 2 bars, vertical force of 3580 N and speed of 50 km/h, slip angle was changed from 0 to 8 ° and from 0 to - 8 °, in increments of 0.5 °, in order to obtain cornering results at series of steady states. The coefficient of friction between the tread and the ground was set to 0.6.

Figure 11 shows the distribution of contact pressure at the footprint of two compared models. If observed globally, both footprints have very similar, trapezoidal shape. Distribution of contact pressure is also globally similar, showing, as in earlier comparisons, significant local peaks when detailed tread model is used. The ratio of maximum contact pressure obtained by two models equals 1.3. Excluding the peaks, the distribution of contact pressure on detailed tread model is more even, which is the consequence of greater flexibility of smaller tread segments.

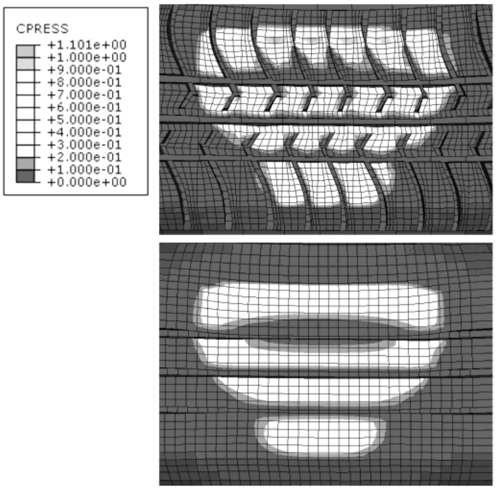

Figure 11. Distribution of contact pressure at the footprint of simplified and detailed tread tire models, at slip angle $\alpha = 8$ °, where $v = 50$ km/h, $F_z = 3580$ N, $p = 2$ bar and $\mu = 0.6$

Slika 11. Raspodjela kontaktnog tlaka na modelima sa i bez detaljnog gaznoga sloja, pri kutu klizanja $\alpha = 8$ °, gdje su $v = 50$ km/h, $F_z = 3580$ N, $p = 2$ bar i $\mu = 0.6$

In contrast to footprint stress distribution, cornering force curves obtained using the two models are very similar, as may be seen from Figure 12. The cornering stiffness of simplified model is slightly larger, as may be expected, concerning greater rigidity of its simplified tread pattern.

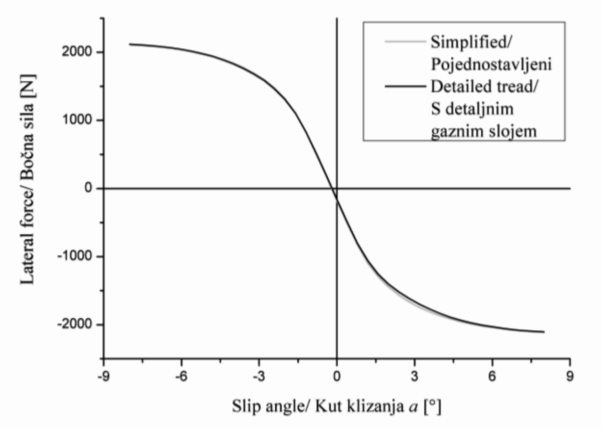

Figure 12. Cornering force F_y as a function of slip angle α, obtained using simplified and detailed tread model

Slika 12. Sila skretanja F_y kao funkcija kuta klizanja α, dobivena primjenom modela sa i bez detaljnog gaznoga sloja

The difference in the response of the two models is easier to observe in self-aligning torque vs. slip angle diagrams (Figure 13).

4.4. Discussion

Response comparison of simplified and detailed tread tire models under the action of vertical load as well as during acceleration, braking and cornering, shows that contact stress distribution at footprint, obtained by the two models, may be significantly different. Nevertheless, tire forces and moments produced by the two models do not differ substantially. Thus, it may be concluded that, in most cases, in order to predict tire behavior during service it may be sufficient to use simplified tread models, i.e. the models that contain only the circumferential grooves. In cases when the analysis and optimization of tread pattern design are needed, detailed tread models should be used. They can help in achieving a more even distribution of footprint contact pressure, and thus in lessening of the tire wear.

The size of the two models used throughout the comparison may be assessed from Table 1, while the differences in analyses times may be found in Table 2.

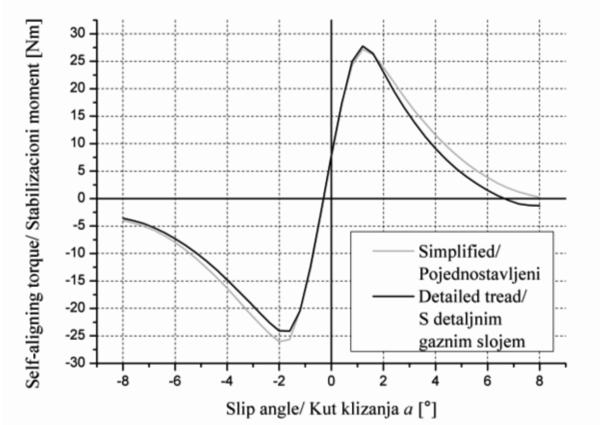

Figure 13. Longitudinal force vs. slip, obtained using simplified and detailed tread tire models

Slika 13. Uzdužna sila F_y kao funkcija kuta klizanja α, dobivena primjenom modela sa i bez detaljnog gaznoga sloja

Table 1. Data on size of FEM models

Tablica 1. Podaci o veličini MKE modela

FEM model/ MKE model	**Number of nodes/ Broj čvorova**	**Number of elements/ Broj elemenata**	**Number of active DOF/ Broj aktivnih stupnjeva slobode**
Simplified/ Pojednostavljeni	21712	18538	63480
Detailed tread/ S detaljnim gaznim slojem	76994	49217	229326

Table 2. Data on typical analyses times (in seconds), on a computer equipped with Intel Core 2 Quad processor Q9300 at 2.5GHz and 8GB RAM

Tablica 2. Podaci o tipičnim vremenima potrebnim za izvršenje analiza (u sekundama), na računalu opremljenom Intel Core 2 Quad procesorom Q9300 na 2.5GHz i sa 8GB RAM memorije

FEM model/ MKE model	**Inflation and vertical loading/ Napuhavanje i vertikalno opterećenje**	**Full braking to full acceleration/ Puno kočenje do punog ubrzavanja**	**Cornering/ Skretanje**	**Total/ Ukupno**
Simplified / Pojednostavljeni	524	1471	722	3002
Detailed tread / S detaljnim gaznim slojem	1088	3405	2939	8736

5. Concluding remarks

Various methods for creation of finite element tire models with detailed tread were systematized and discussed in the paper. Some of the most important meshing approaches found in literature were also described, along with the criticism of their quality. Detailed tread modeling approach with node tying between tread and body meshes was identified as the best one. Such a method, performed by the authors and adapted for steady-state rolling analysis was presented in more detail.

A comparison of simplified and detailed tread model response was performed in order to find and illustrate their advantages and disadvantages. It has been found that simplified model, which engages less computing resources, may readily replace the detailed tread one in analyses where tire forces and moments are sought as the results. On the other hand, detailed tread model is needed in situations when optimization of tire tread design is performed or detailed stresses near the footprint are needed.

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