COMPARISON OF THE PHYSICAL AND EMPIRICAL APPROACH TO MODELLING OF QUASISTATIC ENVELOPING PROPERTIES OF THE TRACTOR TIRE

Boris Stojić, Ph. D, Assistant professor

UDC: 629.113;631.374; 631.565

INTRODUCTION

Tractor tire vibration characteristics are an important indicator of their overall performance. Tractors mostly travel off-road with the presence of shock barriers and short-wavelength unevenness what emphasise the ability of tires to deform locally and envelope the obstacle – ‘enveloping behaviour’. As a result, vibration excitation transmitted to the tractor does not match the actual surface profile but occurs as a result of geometric filtering of the actual profile. In spatial domain, this excitation is represented by the trajectory of tire’s centre point and it is called the effective profile of the surface or enveloping curve. Therefore, the enveloping curve is defined by dependence between the ordinate height of the effective profile and longitudinal position of the tire. In the study of vibration behavior of the tractor using the computer aided simulation it is necessary to have available the tire model that is able to cover the above phenomenon. Possible approach is to use an analytical model of the tire structure which, taking into account geometrical and physical properties of the actual tire, can predict local deformities of the short-wavelength unevenness and therefore, the effective micro profile. Having in mind that such models are based on the real structure of the tire they are usually characterized by a high degree of complexity. This complexity can have a negative impact on the speed of simulation what can be seen as a disadvantage. This problem can be eliminated by using an alternative approach. This paper discusses the concept of dividing an integral tire model into two basic components:

- model of elastic structure
- enveloping model.

This approach allows the development of a simpler model, and hence shorter execution time. In order to circumvent the difficulties in analytical modeling of the contact that tires have with uneven terrain a semi-empirical or empirical approach can be used for an enveloping model [9][13].

The aim of this paper is development and application of two different enveloping models and their comparative analysis. One model is empirical in nature, based on artificial neural network and the other analytical, based on a simplified tire structure (radial and interradial springs).

TIRE ENVELOPING BEHAVIOR

Rolling over short-wavelength unevenness ie. those with length less than the tire contact length, the tire performs low-pass geometric filtering of the ground profile. According to [13], the effect of filtering is based on the following mechanisms:

1.When the tire rolls over the short wave-length unevenness its front segment will, based on geometric conditions, come into contact with an uneven terrain before the central area of the tire comes over that edge. Because of the tire symmetry the same conclusion (but in reverse) applies to the completion of the tire contact and an uneven terrain after the posterior segment of the tire crosses over. Accordingly, the length of a particular segment of the effective profile is greater than the length of its corresponding unevenness.

2.When the tire crosses over a discreet unevenness, whose length is less than the tire contact length due to the effects of vertical force and thanks to tire structure compliance, the contact surface is locally deformed partially or completely enveloping the uneven terrain. As a result, the maximum height reached by the tire center when overcoming unevenness remains less than the height of the unevenness.

3.The third mechanism, based on both geometry and the effect of local deformities, is the transformation of sharp, singular edges of the observed unevenness into smooth segments of the enveloping curve.

There have been numerous research of pneumatic tire behaviour on uneven terrain carried out by a number of authors, for example [1][4][8][9][13] etc. Typical form of response to an obstacle of a rectangular cross-section with a vertical wheel load as a parameter is shown in Figure 1.

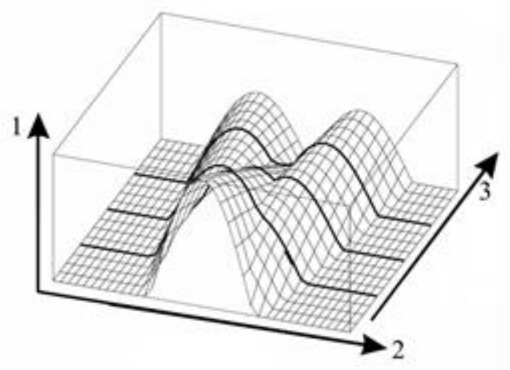


Figure 1 Typical response of pneumatic tire on rectangular obstacle with vertical wheel load as parameter [13]:

1 – effective road profile height, 2 – longitudinal displacement, 3 – vertical wheel load direction

EXPERIMENTAL FACILITY

Experimental research necessary to gather empirical data was carried out by experimental facility whose simplified scheme is shown in Figure 2. The facility is based on a rail guided cart which rolls a vertically movable frame with a tire to be tested. That way the tire can also move in the vertical direction while rolling over uneven terrain and generating effective profile. Thus, in the case of quasistatic conditions, the vertical ground reaction remains constant during the motion. Record of effective surface profile is obtained by simultaneous measurement of longitudinal and vertical coordinates of the tire center. Such experimental facility was described in more detail in previous publications, eg. [10], [11].

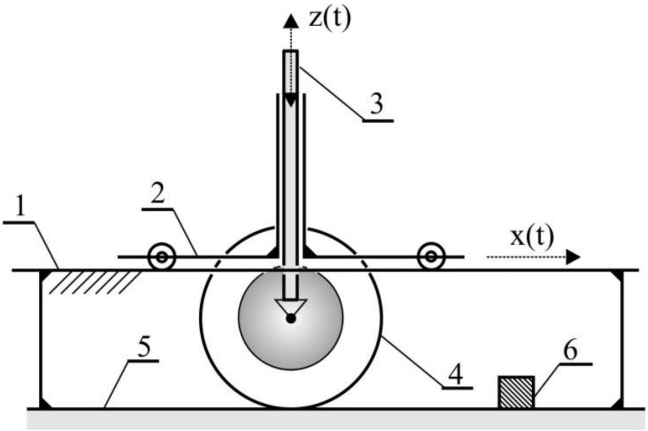


Figure 2 Simplified schematics of experimental facility: 1-rails, 2-cart guiding the tire, 3-vertical tire guide, 4-testing tire, 5-flat surface, 6-obstacle (uneven terrain); x(t), z(t)-longitudinal and vertical movement of tire, respectively

A rectangular cross-section obstacle was used in experimental research and the results obtained using these obstacles are proportionally easy to interpret and compare. Rectangular cross-section obstacles are greatly used in the studies of other authors (eg. [8], [9], [13], etc.) since they are well suited for standardization and their relatively easy application in the real and virtual tests.

NEURAL NETWORK-BASED TIRE ENVELOPING MODEL

Effective profile is based on local deformations of tires in contact with the short-wavelength unevenness. This occurrence s accompanied by a variety of mechanisms and phenomena of a complex nature. There are the following phenomena: nonlinearity of geometry, nonlinearity of material behavior, anisotropy of composite structure, viscoelasticity of rubber compound etc. Because of all this, the analytical modeling of the observed phenomena leads to various problems. An alternative approach is the adoption of empirical modeling approach, thus forming a suitable mathematical relationship that connects the input to the output data, without taking into account the physical nature of the observed system or phenomenon. Neural networks are structures of artificial intelligence capable that through training and iterative application of an appropriate optimization algorithm, establish the required input-output relation. Among other things, their use is especially expedient in the case of empirical modeling of phenomena which exhibit a high degree of complexity and nonlinearity [3].

To form a model a feed-forward, back propagation neural network was chosen as a form of neural network suitable for establishing an empirical input-output relation. Since the enveloping curve defines dependence between the tire longitudinal position as input and height ordinate of effective profile as the output values, thus partially defining input and completely defining output from a neural network. Input data must be completed by the tire longitudinal coordinate and the obstacle geometry parameters, if the neural network is to be trained for obstacles of various dimensions.

In order to find optimal parameters for a neural network and its training process there are no unambiguously defined criteria. Therefore, it is necessary to apply an experimental approach which means parameters have to be varied until reaching an optimal solution. In order to achieve that it is necessary to define:

- optimal network structure ie number of hidden layers and number of neurons in them
- optimal training data set
- optimal number of learning cycles

Due to all of the above the training process can be lengthy and complex. On the other hand, in the stage of application, a model based on neural network is characterized by a relatively high speed of execution. Adopted structure and characteristics of the neural network, with structure schematic in Figure 3, is shown in Table 1. Basic characteristics of the training process are given in Table 2. In addition, each of the data sets listed in Table 2 consist of a set of discrete, associated values of input and output vectors at quasistatic tire roll over obstacles, starting with the establishment of the initial contact to the position in which the vertical axis of symmetry of the tire and an obstacle are congruent. Such choice of length was made on the basis of symmetry of enveloping curve compared to vertical axis.

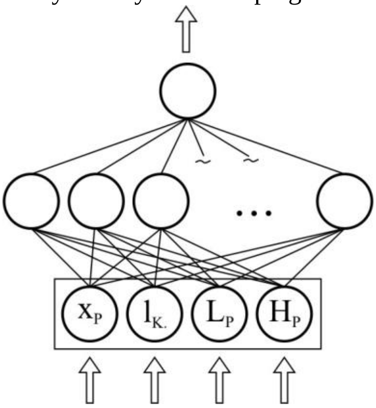


Figure 3 Feed-forward neural network schematic

Table 1 Basic characteristics of neural network

Type of network	Feed-forward, backpropagation
Number of input neurons	4 (normal longitudinal movement, tire working regime parameter, obstacle height, obstacle length)
Number of hidden layers	1
Number of neurons in a hidden layer	8
Number of output neurons	1 (effective road profile height)
Connectivity	Complete forward directed connectivity of adjacent layers
Training algorithm	Standard Backpropagation algorithm
Activating function	Logistic function, $f(x) = 1/(1+e^{-x})$
Exit function	Identity, $f(x) = x$

Table 2 Basic characteristics of training process

Number of available training sets (number of different obstacles)	28
Number of data sets used for training	19 (≈68%)
Number of data sets used for control of generalisation ability during training	5 (≈18%)
Number of data sets used for validation	4 (≈14%)
Number of training cycles	$\approx 2 \cdot 10^5$

TIRE ENVELOPING MODEL WITH RADIAL AND INTERRADIAL SPRINGS

Tire model with a system of radial springs, to which interradial ones can be added, is an analytical (physical) model based on the simplification and discretization of tire elastic structure. In this model radial springs present radial structure elasticity while interradial springs mould bending stiffness of a tire tread. This concept has been previously known and used in literature, for example [1], [12] and others. In this paper, model application was adapted to the quasistatic conditions ie. tire rolling is modeled over an obstacle at a constant intensity of a vertical ground force.

The model is based on a curved segment with a number of radial and interradial springs, according to Figure 4 (a).

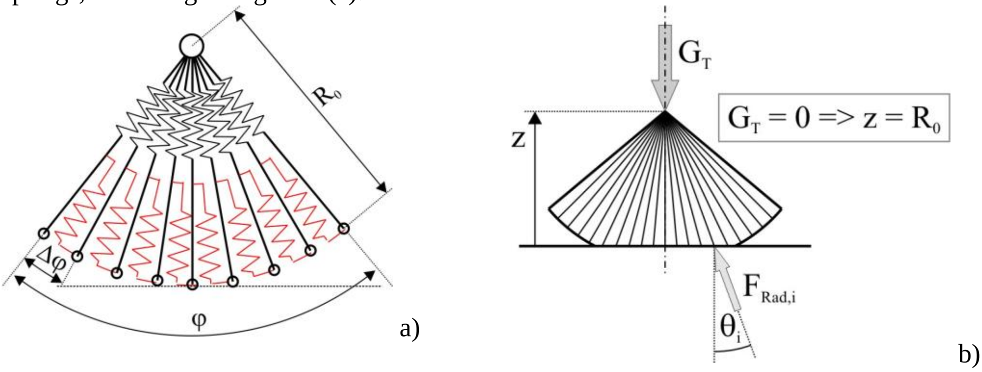


Figure 4 a) Geometric form of a model with radial and interradial springs: R_0 – free tire radius, φ - angular segment width, $\Delta\varphi$ - angle between adjacent radial elements

b) The effect of vertical load GT on a model: FRad,i – force in the i^{th} radial element; θ_i – angle between the vertical axis and force line of application FRad,i; z – coordinate defining the position of the system relative to vertical axis

Vertical load pressures tire tread segment causing deflection of some radial elements and the formation of radial forces. Static equilibrium in the vertical direction is of importance in this case and its equation is:

$$G_T = \sum F_{Rad,i} \cdot \cos\theta_i \,, \tag{1}$$

Sum in (1) applies to all elements whose deflection is greater than zero or who were deformed under the influence of load GT. When communicating or changing the vertical load, the position of the system changes due to the response of radial and interradial elements. As elements are subjected to deflection ie with the increase in vertical load, they successively come into contact with the surface, it is not possible to analytically solve a system of constitutive equations since there is no advance knowledge of the number of elements, realizing static equilibrium, that will tread the surface. Therefore, it is necessary to use an iterative approach in order to find an approximate balance position.

For each longitudinal position through which the system passes during the simulation iterative calculation of static equilibrium position is carried out. Iterative procedure starts from the coordinate z guess value and the current value of the longitudinal position x. For these values of x and z deflection of radial elements is calculated and memorized from geometrical conditions providing radial force values. By summing up the vertical components of certain forces a total surface reaction for a given system position is calculated. If there is a deviation between the calculated and the given value of the surface response (which, due to static equilibrium must be equal to GT) that is greater than a preset permitted tolerance □, then a new value of coordinate z is calculated in accordance with secant method for iterative solution of the nonlinear equations [6]:

$$\left|G_T - F_{Z,sum}\right| > \varepsilon \Rightarrow z_{(j+1)} = z_{(j)} - \frac{\left(F_{Z,sum(j)} - G_T\right)\left(z(j) - z(j-1)\right)}{F_{Z,sum(j)} - F_{Z,sum_{j-1}}}, \tag{2}$$

where:

- j – serial number of iteration steps

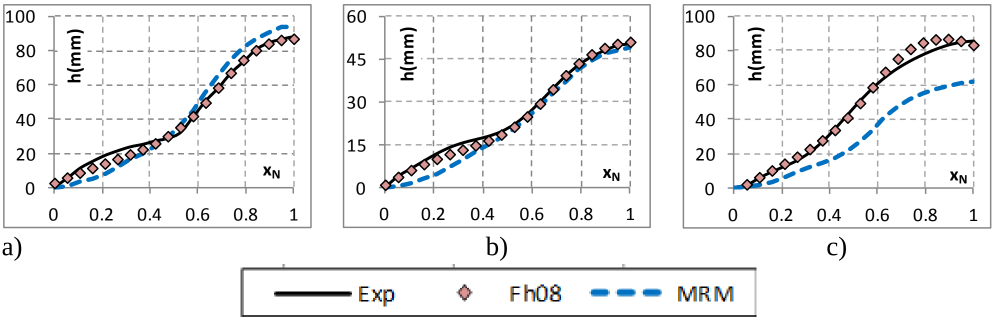
Model parameters are stiffness coefficients of radial and interradial springs, as well as the number of radial elements. The optimal parameter values are determined by experiments, by variations in certain number of iterations.

MODELS COMPARISSON

Performance analysis of the models and their comparison was made on the basis of model prediction review together with the review of certain measurement results, Figure 5. The covered cases (in terms of various obstacle dimensions and tire working regime) are shown in Table 3.

Table 3 Results used for comparison and performance analysis of the models

Serial number	Label (internal)	Tire working regime indicator – contact length (mm)	Obstacle dimensions(length × height, mm)
1	"F"	380	300 × 100
2	"J"	330	300 × 50
3	"R"	280	100 × 100



a) b) c)

Figure 5 Simulation results comparison of empirical and physical model with measuring results according to Table 3 a) case 1, b) case 2, c) case 3h(mm) – effective surface profile height, xN – normalized longitudinal displacement

Figure 5 shows that the empirical model qualitatively provides a satisfactory description of the real system behaviour, while the physical model exhibits some discrepancies in the initial part of the curve (near the origin). These deviations, however, occur in the area of small amplitudes and therefore, can be expected not to impair the overall prediction accuracy of the model significantly.

Regarding the quantitative accuracy of the predictions, Figure 5 a) and b) (cases 1 and 2 of Table 3, respectively) show that in these cases, with the approximate degree of accuracy, both models describe the enveloping curve but the empirical model achieves slightly better results. In case c) in Figure 5 (case 3 in Table 3) for both models the results are worse than in the previous cases and the physical model prediction totally deviates from the measurement results. The results suggest that the assumption regarding the physical model degree of discretization should be adapted to the geometry of the surface profile. Also, it can be concluded that both models have difficulties with modeling tire response to obstacles with height and length ratio above a certain threshold..

CONCLUSIONS

In this paper two models of quasistatic enveloping curve of tractor tires were developed. The empirical model, based on artificial neural network, is an original solution to the problem in a way that it has not been applied in previous research. The physical model is based on discretization and simplification of the tire physical structure by representing it as a system of springs. This model, used by other authors (eg. [1], [12] and others.), was suited for quasistatic enveloping curve modeling in this study.

The empirical model is characterized by high-speed execution in the application stage and that is its most important asset. Since this is a model based on artificial neural networks in the stage of model generating it was not necessary to perform parameterization procedure. The main disadvantages of the model are the need for intensive work on experimental measurements and time-consuming, experimentally based, parameter optimization process of neural network as well as its training. Also, the model does not have the flexibility to adapt to change the structural parameters of the tire. The model is suitable for application within the simulation of vertical dynamics of the tractor when traveling over uneven terrain.

Carrying out a physical model involves an iterative process causing its significantly lower speed of performance. One of the model’s advantages is the possibility to change the numerical values of parameters for tire modeling of different structural characteristics. Also, model parameterization requires a relatively small number of experimental measurements.

On the other hand, parameterization is based on an experimental approach and that makes the whole process lengthy and complex. The structure of the model developed in this study cannot be directly applied in a vehicle dynamics environment since it is a quasistatic model. The purpose of this model is to use its results in the empirical model training and thus save labour and time for experimental testing.

As far as the accuracy issue is concerned, to some extent exhibited by both models, especially the physical one, it should be noted that this study carried out a preliminary model development. It can be expected that the accuracy will be improved by further development of both models. Further study will include, in addition to model training, the application of the empirical model within the vehicle dynamics simulation and its integration with the model of the elastic tire structure.

ACKNOWLEDGMENTS

This research was done as a part of project TR35041 "Investigation of the safety of the vehicle as part of cybernetic system: Driver-Vehicle-Environment", supported by Serbian Ministry of Science and Technological Development.

REFERENCES

[1] Badalamenti J. M., Doyle G. R.: Radial-Interradial Spring Tire Models, Journal of Vibration, Acoustics, Stress and Reliability in Design, 110(1988)1, 70-75

[2] Herkt S.: "Towards a Finite Element Tyre Model for Multibody Simulation", Dissertation, Universität Kaiserslautern, 2008, Kaiserslautern, D

[3] Kinnebrock, W.: Neuronale Netze – Grundlagen, Anwendungen, Beispile, R. Oldenbourg Verlag München Wien, 1992.

[4] Maurice, J.P.: "Short Wavelength and Dynamic Tyre Behaviour under Lateral and Combined Slip Conditions", PhD Thesis, Technical University of Delft, Netherlands, 2000, Delft, NL,

[5] Oueslati F.: "An Analytical Investigation of Passive and Active Suspension Systems for Articulated Freight Vehicles", PhD thesis, Concordia University Montreal, Quebec, 1995.

[6] Petković Lj.: Numerička matematika sa programiranjem, Gradina, Niš, 1994.

[7] Scarlett, A.J. et al: "Whole-body vibration on agricultural vehicles", Research report, Silsoe Research Institute and RMS Vibration Test Laboratory for the Health and Safety Executive, 2005, Silsoe, GB,

[8] Schlotter V.: Einfluss dynamischer Radlastschwankungen und Schräglaufwinkeländerungen auf die horizontale Kraftübertragung von Ackerschlepperreifen, Dissertation, Universität Stuttgart, 2005.

[9] Schmeitz, A.J.C.: "A Semi-Empirical Three-Dimensional Model of the Pneumatic Tyre Rolling over Arbitrarily Uneven Road Surfaces", PhD Thesis, Technical University of Delft, Netherlands, 2004, Delft, NL,

[10] Stojić B., Poznić A., Časnji F.: "Test Facility for Investigations of Tractor Tire Dynamic Behavior on Hard Surfaces", 39th International Symposium: "Actual Tasks on Agricultural Engineering", 2011, Opatija, HR, 119-127

[11] Stojić B., Poznanović N., Poznić A.: "Test Facility for Investigations of Quasistatic Enveloping Behavior of Tractor Tire", 8th International Symposium "Machine and Industrial Design in Mechanical Engineering", 2014, Balatonfüred, HU, 89-92

[12] Witzel,P., Böttinger,S.: Upgrading of the Hohenheim Tyre Model to a radial approach for the simulation of obstacle passages, VDI Berichte Nr. 2124, VDI-Verlag, Düsseldorf, 2011, 431-437

[13] Zegelaar, P.W.A.: "The Dynamic Response of Tyres to Brake Torque Variations and Road Unevennesses", PhD Thesis, Technical University of Delft, Netherlands, 1998, Delft, NL.At annual and total level in production processes of the new fabrics for vehicle production.