

DEVELOPMENT OF AN AI-BASED MODEL TO DETERMINE VEHICLE TIRE DESIGN CONFIGURATION

¹ Olatunbosun, Oluremi, ¹ Yang, Xiaoguang, ¹ Behroozi, Mohammad*, ²Garcia-Pozuelo, Daniel

¹ School of Mechanical Engineering, University of Birmingham, B15 2TT, UK

² Departamento de Ingenieria Mecánica, Universidad Carols III de Madrid, Spain

KEYWORDS - artificial intelligence, design parameters, modelling, neural network, tire configuration.

ABSTRACT

The tire industry is moving away from the design and development of new tires by the process of trial and error, i.e. design, build, test and review. The ready availability of powerful computer hardware and software makes it possible to focus more on the design of the tire before a prototype is built. The ability to analyse the performance of the tire in a virtual environment can enable its design to be optimised to the product specification while achieving considerable savings in time and cost associated with the iterative process of building and testing prototypes.

Modelling the behaviour of tires in a virtual environment can be performed in different ways including mathematical modelling and finite element analysis. Conducting any of the aforementioned approaches requires the availability of a predefined and detailed configuration of the tire. It then requires that the modelling process for the new tire design be repeated iteratively until a design that satisfies the desired performance requirements is obtained. This process can be very time consuming and expensive.

To tackle this problem of high development cost, an Artificial Intelligence (AI) based method is introduced in this paper, which can lead to a quicker and logical achievement of the desired tire properties. In this method, several configurations of vehicle tire are first used to obtain tire performance characteristics using validated Finite Element models. The tire performance characteristics obtained in this stage along with the tire design input parameters enables a group of tire input and output data to be generated.

The next stage is based on utilizing artificial neural network (ANN) to learn the table of tire properties. The use of ANNs has been recognized as a powerful Artificial Intelligence method for modelling the nonlinear relations between the data which are captured from either natural or inanimate events. To use ANNs, there is a need to separate the data into inputs and outputs. Inputs are the *design parameters* of the tire which cause the differences in the performance characteristics of different tires. In this paper, some of the design parameters considered as ANN model input include *ply thickness, number of carcass plies, number of belt plies, cord end density, belt ply angle* etc. ANN

outputs are tire performance characteristics that may be of interest. These are mostly obtained from the FE analysis including radial stiffness, lateral stiffness, cornering stiffness etc.

The validity of this relation between input and output is examined with different tire configurations and it is shown to be a reliable and very fast approach to predicting the properties of new generated tire configurations without using FE analysis. Once a tire configuration which satisfies the desired performance requirements has been achieved, a full FE analysis can then be carried out to confirm the validity of the design. In this way, parametric studies are carried out using the ANN model and expensive FE analysis is only carried out once the appropriate tire design configuration that will produce the desired performance characteristics has been determined. The benefits of this technique are considerable savings in design cycle time and costs.

INTRODUCTION

Vehicle maneuvering behavior is predominantly controlled by tire dynamic characteristics through the forces and moments generated at the tire/road contact patch. The control of tire vertical force can improve the vehicle vertical vibration characteristics and ride behavior. The control of tire lateral force usually benefits the vehicle stability and cornering, and an optimized tire longitudinal force control can improve braking performance and reduce fuel consumption. Essentially, the aforementioned tire forces are generated by the tire deformation and contact patch friction. They are determined by tire characteristics, namely tire stiffness, damping and tire/road interface friction. As mentioned in [1], mechanical properties of a tire can be revealed by static stiffness testing through observing and measuring the tire elastic deformation and contact patch information. Alternatively, the variation of tire design configuration details is reflected in the measured test data as part of the conventional approach to the design and development of a new tire. However, this design, build, tests and review method is not suitable for modern tire development considering the considerable cost and time involved. As a virtual tool, the finite element tire model has the ability to analyze the performance of the tire in a virtual environment with respect to different tire design configurations. It can provide not only measurable test data but also data that is impractical to measure. It provides an alternative to the iterative process of building and testing prototypes. In order to further reduce the computational cost involved in tire development, an artificial intelligence (AI) based model is developed based on test data generated from a validated finite element tire model. It provides a quicker and logical prediction of the desired tire performance information. Although the AI based method has been used widely in different research fields in the past decades, its use as a design tool in the tire industry is only just developing. A fuzzy logic-based method was developed and applied for evaluating tire dynamic parameters such as tire contact area, cornering stiffness and tire-road friction coefficient for application in vehicle control systems [2]. Some ANN based methods were also proposed for tire applications, such as tire/road friction force estimation [3], tire handling performance prediction [4] and tire failure rate modelling [5].

In this paper, the FE tire virtual test environment and the AI technology are combined to investigate the parametric effect of tire design configuration, especially the belt ply design, on tire static stiffness

and tire/road contact characteristics. A detailed finite element tire model was built using the commercial software ABAQUS which provided the function for modeling the reinforcement cords details. A large number of samples with different tire design configuration were simulated using the validated finite element tire model. The inputs and outputs data from the above virtual tests were used to train an ANN model, with a view to providing a reliable and very fast approach to predicting the performance characteristics of new generated tire configurations without using FE analysis.

FINITE ELEMENT TYRE MODELING

The pneumatic tire has a complex structure consisting of reinforcement plies and rubber components. Reinforcement plies are made of nylon cords or steel wires as the frame of tire structure to support the load and control the overall performance characteristics of pneumatic tires. Covering the reinforcement plies are different rubber components allocated according to their varying functional requirements. In this study, a slick racing tire for Formula Student is used as the object to be modelled and generate data for the AI system.

In the cut tire cross-section view of Fig.1, the rubber is divided by reinforcement plies into different components such as tread, sidewall, undertread, apex and inner liner. In the bead region, the steel wire is embedded in rubber base in order to hold the tire to the wheel and prevent the air from escaping. The red curves are the reinforcement plies. Due to the diversity of functional requirements, the details of reinforcement plies also vary as shown in Fig.1.

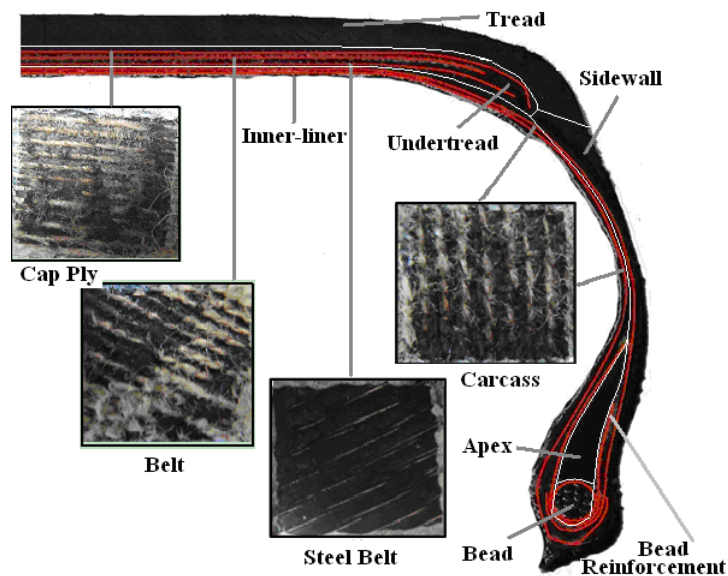


Fig.1 Cut tire cross-section view

As a powerful virtual simulation tool, finite element tire model is considered suitable to build the detailed structure of a pneumatic tire. The software package ABAQUS was used for the finite element tire modelling and simulation experiment. The finite element tire model features are described as follows:

A 2D tire model was generated based on the tire cross-section profile provided by the tire manufacturer. The rubber components were meshed using 2D axisymmetric hybrid elements. The reinforcement components were represented by rebar elements with 2 nodes, embedded in rubber elements. The rubber hyperelastic and viscoelastic material properties were obtained by tension test and modelled by Yeoh model and Prony series expansion respectively in ABAQUS [6]. The characteristics of reinforcement cords were defined in *REBAR LAYER card of ABAQUS [7] including the area per rebar, orientation angle of rebar, spacing distance, position of rebar and material property. The 2D axisymmetric model was then revolved around the axis to generate a 3D model using symmetric model generation approach provided by ABAQUS. During the revolution process, the angle can be controlled according to different requirements. In this case, 50x6.0° circumferential coarse sections and 20x3.0° refined sections for the contact patch respectively were created. Figure 2 shows the detailed view of 3D finite element tire model.

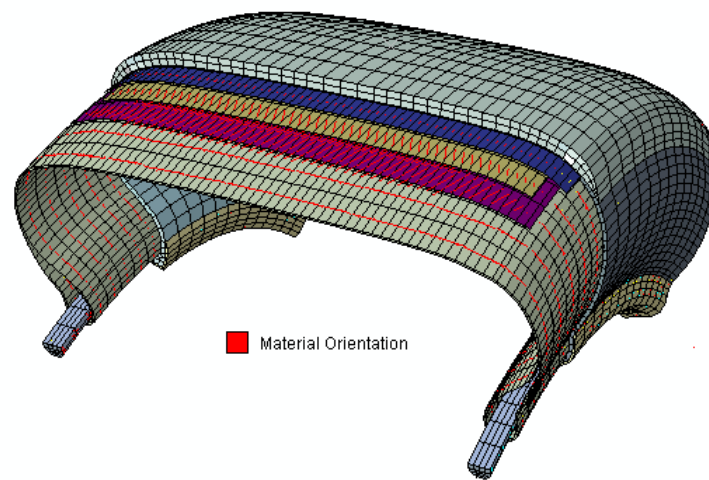


Fig.2. Detailed view of 3D finite element tire model

VIRTUAL TEST OF PNEUMATIC TIRE

Once the 3D finite element tire model was generated, different tire virtual tests were carried out on the tire. Static load-deflection tests in the vertical, lateral and longitudinal directions were performed with friction coefficient of 1.0 based on the 3D finite element tire model.

The *Vertical stiffness test*: Consisted of inflating the tire to the desired 80 kPa then the tire is loaded by giving the road reference node a displacement in the vertical direction, initially to make contact with the tire and then loading the tire through the road reference node. The ratio of applied load and the vertical deflection of centre node of tire contact patch is the tire static vertical stiffness. The lateral and longitudinal stiffness tests are carried out using the restart function in ABAQUS following the vertical test. This is done by giving the road surface a specified displacement in the lateral or longitudinal direction as required and recovering the corresponding force induced on the tire. Again the ratio of force and displacement is the stiffness. Apart from the stiffness information obtained from virtual test, the information of tire/road contact patch can also be recovered from ABAQUS

including contact area, maximum contact pressure, maximum longitudinal shear stress and maximum lateral shear stress, etc. The description about shear stress can be found in the literature [1].

Validation

In order to prove the validity of the finite element tire model, the tire radial load deflection results for different loads and inflation pressures were compared between finite element analysis and experiments. The vertical stiffness at normal inflation pressure 80 kPa as well as at $\pm 25\%$ and $\pm 50\%$ are listed in table 1 for the tire in its normal design configuration.

Table 1 the vertical stiffness validation

Inflation Pressure (kPa)	Vertical Stiffness Test (N/mm)	Vertical Stiffness Simulation (N/mm)	Absolute Difference (%)
40	51.181	51.439	0.50
60	68.898	67.419	2.15
80	84.786	82.813	2.33
100	96.457	97.249	0.82
120	112.02	112.34	0.29

It can be seen that the aforementioned tire finite element model gives good comparison with test results and is therefore capable of predicting tire performance. It thus provides a reliable platform for investigating the tire stiffness property. Considering the time consuming and numerical “noise” of explicit simulation in ABAQUS, the implicit analysis was used in this study [8].

METHODOLOGY AND IMPLEMENTATION

Artificial Neural Networks

Artificial neural network (ANN) is a tool which is used in modelling, time series processing, pattern recognition etc. and has its roots in neuro-science, mathematics and engineering. ANN consists of simple, adaptive processing units, often called neurons. A simple neuron is an information-processing unit that is fundamental to the operation of a neural network. Neurons are interconnected, forming a large network. The principle of neural modelling is that the inputs are known or they can be measured and the behaviour of outputs is investigated when the inputs vary. The manner in which the neurons of a neural network are structured is intimately linked with the learning algorithm used to train the network. Details of the operational principles and the design of artificial neural networks can be found in standard textbooks e.g. Hagan et al [9]. This study takes advantage of the important property of a neural network which its ability to learn complex relationships between the inputs and outputs of the network and to improve its performance through learning, just like the human brain. Here we make use of a certain ANN architecture known as the Multilayer Feed-forward Networks or Multilayer Perceptron (MLP). In the multilayer network, there are one or more hidden layers, whose nodes are correspondingly called hidden neurons.

In order to utilize artificial neural network techniques for predicting the effect of tire design configuration on tire static stiffness property, several independent tire configuration variables are chosen as the inputs to artificial neural network. They are tire belt cords orientation angle, spacing distance (cords end density), cross section area, material property and tire inflation pressure. To get a well-trained artificial neural network, 243 samples were created based on Table 1 using ABAQUS input files. In table 2, the independent input variables are brought with the ± 10 percentage variation for the cords orientation angle, end density, material property, and cross section area and ± 25 percentage change in inflation pressure in comparison with considered real tire.

Table 2 Inputs of ANNs in percentage order

Independent variables	low	normal	high
Orientation angle	-10%	0%	+10%
Cords end density	-10%	0%	+10%
Material property	-10%	0%	+10%
Cords cross section area	-10%	0%	+10%
Inflation pressure	-25%	0%	+25%

As a preliminary study, it can reflect the efficiency and effectiveness of AI technology on tire design configuration. In the following sections, model validation will be used to reflect the suitability of AI technology. It is performed by comparing the prediction of trained neural network with that generated by finite element tire model.

Since the neural network has to learn the complex relationship between inputs and outputs, the training phase is very important. The available data is normally split into two sets: one set for training and another for testing. After training the neural networks using the training set, the models become ready for validation [10]. To perform this, the test data is applied to the trained ANN and results are then analyzed.

In this work, a three-layer feed forward neural network was developed using the Matlab Neural Network Toolbox, with back-propagation training algorithm employed to learn the training set. The first and second hidden layers contain 10 and 25 nodes respectively. As discussed before, the ANN has 5 parameters as inputs and 7 as outputs. This configuration was obtained after a trial and error process in order to find the best configuration with least errors in the testing stage. The Tangent Hyperbolic activation function is utilized in all the layers and nodes.

RESULTS AND DISCUSSION

The training session was performed by using three quarters of the sample pool randomly selected and the remaining one quarter was used for testing. After successful training, the process was repeated for several times to check for network robustness. ANN output results have shown very close prediction of new samples. In this section, a number of results obtained from train and test procedures are illustrated in Fig.3-8. Each plot is combined of two sub-plots; upper one is the number of samples against specified property of tyre and the one in bottom shows correlation of ANN outputs and tyre virtual test samples. Figs.3-8 indicate values of vertical stiffness, Lateral stiffness, longitudinal stiffness, contact area, maximum contact pressure, maximum shear 1 respectively.

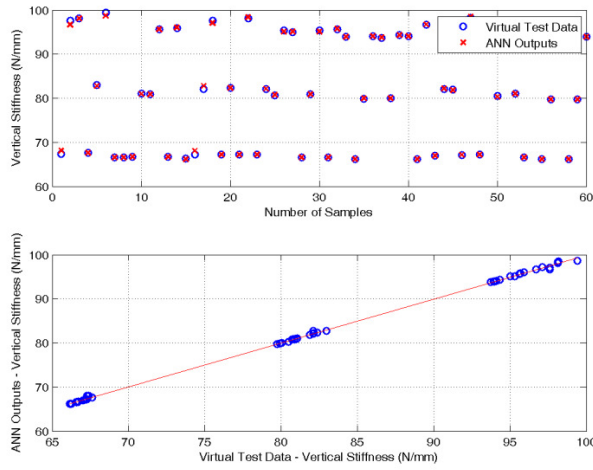


Fig.3: A comparison between vertical stiffness of ANN outputs and virtual test results

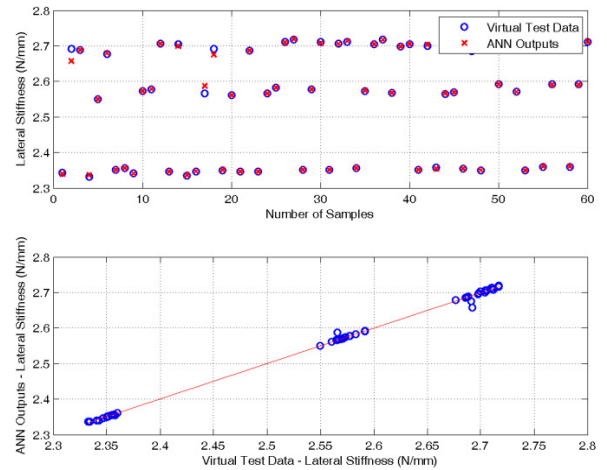


Fig.4: A comparison between Lateral stiffness of ANN outputs and virtual test results

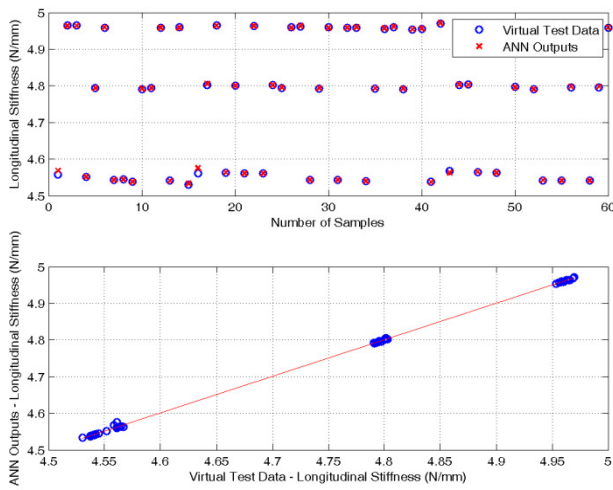


Fig.5: A comparison between longitudinal stiffness of ANN outputs and virtual test results

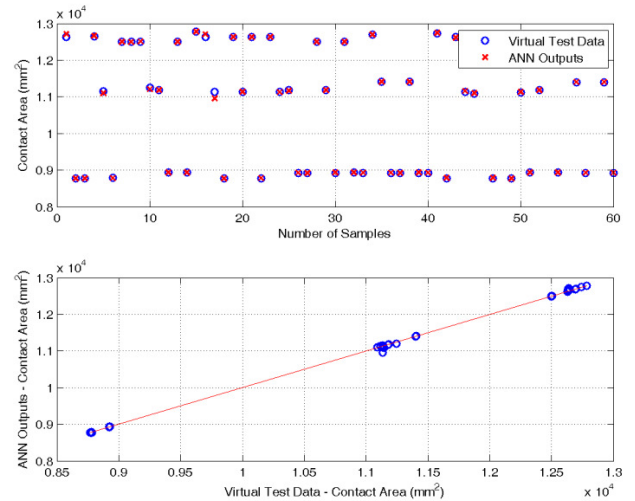


Fig.6: A comparison between contact area of ANN outputs and virtual test results

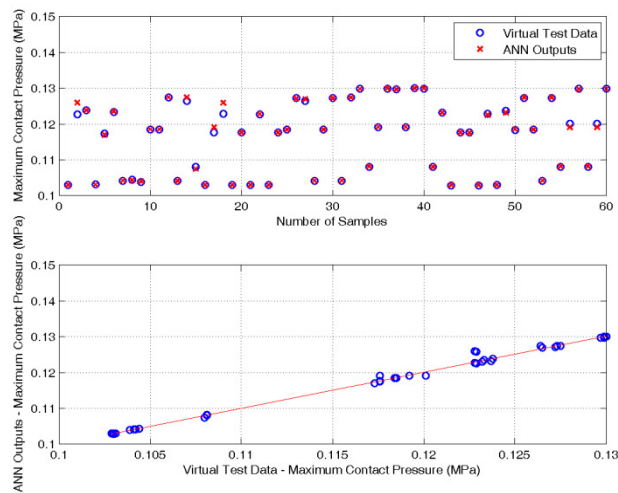


Fig.7: A comparison between maximum contact pressure of ANN outputs and virtual test results

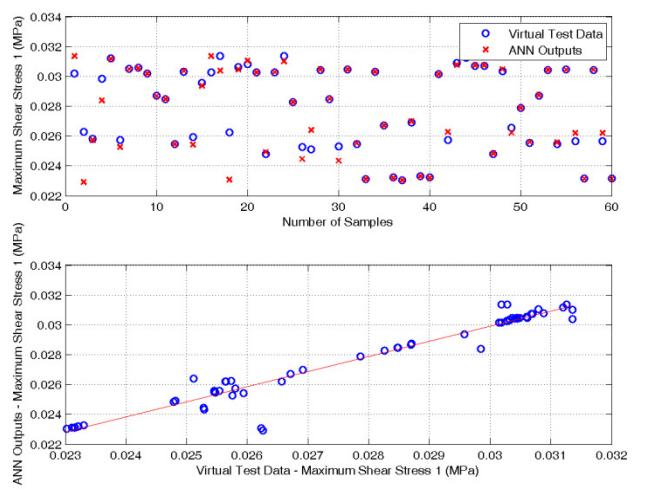


Fig.8: A comparison between maximum shear stress 1 of ANN outputs and virtual test results

CONCLUSION

In this study, an FE tire model was introduced to simulate tire behaviour. A validation was performed in order to confirm whether simulated results were matched properly to real-world test. Then, virtual tests were developed to generate a number of tire behaviours without having validation values of tire behaviour. Next, these results along with the input data were used in modelling an AI-based system to predict tire characteristics. The ANN using Matlab/NN Toolbox can find out the complex relationships between the geometrical and load parameters as input data and tire properties and stresses as outputs. This software can predict the output values such as stiffnesses, contact area etc. for new tire designs. This prediction can certainly help designers to have preliminary judgment about prospective products. This software also established that provided a suitable algorithm, data set, numbers of hidden layers, and number of nodes was selected properly; it could be employed in generating solutions for other tire and automotive problems such as computing burst inflation pressure, rolling resistance properties and modelling vehicle dynamics responses in certain situations. It is to be stressed that use of soft computing methods such as neural networks can be used as an alternative to analyses that are otherwise quite expensive and time consuming.

REFERENCES

- (1) P Gruber, R S Sharp, A D Crocombe. Friction and camber influences on the static stiffness properties of a racing tyre, Proc. IMechE Part D: J. Automobile Engineering, Vol. 222, pp1965-1976, 2008
- (2) Valentin Ivanov, Barys Shyrokau, Klaus Augsburg, Vladimir Algin. Fuzzy Applications to Tire Environment, FISITA 2008, F2008-12-001.
- (3) Jadranko Matusko, Ivan Petrovic, Nedjeljko Peric, Neural network based tire/road friction force estimation, Engineering Applications of Artificial Intelligence Volume 21, Issue 3, Pages 442-456, April 2008.
- (4) Andrew J. Barber, Thomas E. Renner, Shawn You, Gary S. Sandlass, Anders Maki, Predicting Tire Handling Performance Using Neural Network Models, SAE Paper No.2004-01-1574
- (5) Ahmed Z. Al-Garn, Ahmad Jamal, Artificial Neural Network Application of Modelling Failure Rate for Boeing 737 Tires. Applied Simulation and Modeling Conference 2008, Corfu, Greece, 23-25 June, 2008.
- (6) Yang, X, Olatunbosun, O.A., and Bolarinwa, E.O., "Materials Testing for Finite Element Model", SAE Paper No 2010-01-0418.
- (7) Abaqus user manual.
- (8) Ghosh, P., Saha, A., Mukhopadhyay, R., "Optimization of Tire Design Parameters through Finite Element Analysis and Correlation with Performance," SAE Paper No.2007-26-043.
- (9) Hagan, M. T., Demuth, H. B., & Beale, M. H. (1996). Neural Network Design. PWS Publishing Company.
- (10) N. Varotsis and V. Gaganis, "A novel non-iterative method for the prediction of the PVT behavior of reservoir fluids", SPE Annual Technical Conference and Exhibition, 3-6 October 1999, Houston Texas, Society of Petroleum Engineers.