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Methodology for the Composite Tire Numerical Simulation Based on the Frequency Response Analysis

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Highlights

- Research presents theoretical and experimental parts on composite pneumatic tire.
- The tire material have been tested by piezoelectric micro-vibration test and frequency analyses method.
- Obtained results indicate that offered methodology can be used in numerical simulation of composite tire.
- The research provide methodology for tire modelling avoiding problems of composite structure.

Abstract

Reliability and maintenance analysis in transport focus on the main objective of accident and incident investigations that benefit to better understanding of the causes of accidents and prevention of them in the future. The conducted research presents theoretical and experimental research on composite pneumatic tire used in transport engineering. The approach of the numerical simulation sequence which is offered in this research facilitates engineers in efficient determination of the dynamic properties and behaviour of vehicle tire at design stage. The tire materials have been tested by employing piezoelectric micro-vibration tests and frequency analyses. The Finite Element Method used for numerical simulation in combination with experimental measurements based on optimization by material frequency response, was applied in modelling tire material behaviour avoiding problems of composite structure modelling. The obtained results indicate that the offered methodology can be used in numerical simulation of composite tire investigation and considering material viscos-elastic properties.

Keywords

tire, composite, finite elements method, frequency analysis, numerical simulation, optimization

1. Introduction

With the development of automotive industry, the vehicles have gradually become the main means of transportation land goods or traveling. The expansion of road networks, low travel costs, comfortable and flexible travelling resulted in the increase of people travelling by private vehicles (cars, motorcycles, vans, etc.) and consequently in the annual increase of kilometres covered by these vehicles as well as in the numbers of registered vehicles. [2]. With the increase in the numbers of private vehicles on roads there were expectations that there would be a surge in road traffic accidents and fatalities. However, the statistics provided by United Nations Economic Commission (UNECE) [31] shows that the trend in road accidents has been slowly decreasing in almost all countries around the world (see Fig. 1a). Unfortunately, according to World Health Organization [34], the road traffic accidents make one of the major causes leading to death in all age groups of people. On the other hand, according to UNECE statistics on road traffic accidents in Europe and North America [31], in the period between 2009 and 2019 the Baltic States were among top ten countries which counted the largest decrease in road traffic fatalities.

One of the main aspects of all these statistics can be attributed to the information on the implementation of new

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technologies, methods and rules which could assist in the prevention of vehicle accidents, i.e., installing the lighting on the roads [11]. Therefore, the research on the implementation of different positive solutions in the transport area with reference to the safety of passengers, drivers and pedestrians is of key relevance and according to [10] is one of the decisive directions to be studied in the future road transport sector.

According to [35], approximately a half of traffic accidents on highways is related to tire problems many of which are provoked by blowout tires. Furthermore, since vehicle tires are the only contact point between a vehicle and road surface (contact patch problem) [14, 15, 29, 32], the tire condition has a crucial impact on a dynamic stability and safety of car movement, especially during winter and autumn season. Yet the investigation of accidents that are caused by tire-road interaction and depend on weather conditions or are caused by tire blowout are rather complicated [8, 27]. According to [26] the main causes of vehicle tire blowouts include severe surface wear and abnormal tire pressure which are most likely to occur in the case of high-speed driving or sudden breaking. The research provided in [9] sets forth the opinion that proper mathematical modelling of tire and numerical testing in different conditions can help to better understand road accidents resulting from tire blowout.

The pneumatic tire is made up of several structural components (see Fig. 1) which during the vulcanisation process are joined together and slightly overlap.

Fig. 1. Composite pneumatic tire construction (based on [6]).

The pneumatic tire is constructed using either rubber or rubber-based composites, as indicated by various sources [6, 24, 28]. Its design and construction underwent a series of experimental studies to ensure its stability and reliability. Utilizing numerical modelling techniques, such as the Finite Element Method, is a viable substitute for experimental testing due to its efficient use of time and economic resources, as evidenced by sources [5, 20]. However, to ensure accurate and effective analysis, it is imperative that the numerical model is developed with meticulous attention and care. The development of tires that would be most efficiently exploited relates to the factors which have influence on the friction contact mechanics of a tire with the road surface or tire local blast effect. These factors need to be well studied in the design stage. According to [23, 30, 33], the loads under operation and material behaviour should be considered while doing the proper modelling and researching vehicle tire behaviours. Therefore, the research of tire material behaviour should be investigated as well. According to [4, 16, 21], the investigation of tire material under the loading helps to improve blast resistance of a tire. According to [1], a tire can be optimized by material structure in combination with a finite element method approach and different algorithms, for example genetic algorithm. Additionally, according to [3, 22] there is a recommendation that a great care on materials numerical simulation by different methods should be considered with frequency response of the material. In this case experimental research in combination with numerical simulation have preference in similar studies.

In the finite elements analysis (FEA) of the composite tires, structural reinforcements can be modelled by using different methodologies, with two of them generally prevailing: the modelling based on composite materials theory [17] and the modelling of the rubber matrix and cords using “rebar” elements [13]. The precision of tire Finite Element Analysis (FEA) is heavily reliant on the accuracy of the material models employed in constructing the Finite Element (FE) model. The detailed review of the research referred to above shows that it has not considered a frequency response of vehicle wheel tire materials for a numerical modelling. Additionally, it is impossible to gain a deeper insight into material modelling of tire cord and its behaviour inside tire rubber. As a result, it is challenging to provide a comprehensive and precise description of tire behaviour and accurately predict the occurrence of blowouts under varying loads. This complexity arises from the viscoelastic properties of the rubber composite material used in tire manufacturing, which gives rise to intricate friction behaviour dependent on factors such as contact area between structural layers, sliding velocity, inflation pressure, ambient temperature, and environmental loads.

The current study's methodology centres on conducting experimental measurements in combination with numerical simulation sequence and facilitates in the efficient determination of the dynamic behaviour of vehicle tire composite based on a frequency analysis and without connection to complicated composite materials.

2. Tire numerical modelling by FEA

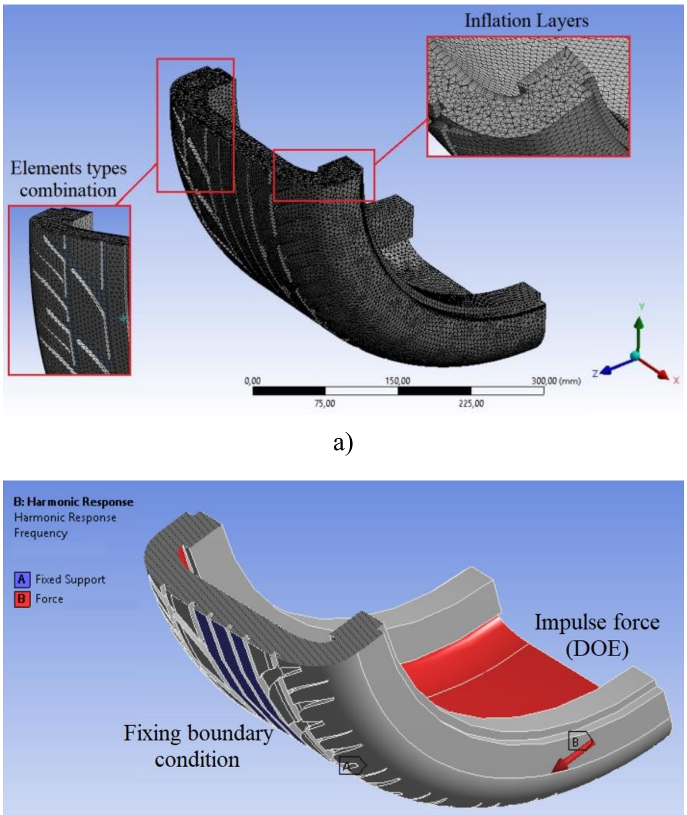
Numerical modelling based on FEA computational modelling was carried out by using the commercial software ANSYS®. Standard road vehicle tire with properties described in [7] and [20] was used for modelling. For comparison, we selected the tire non-linear models. The researchers incorporated an ideally elastic material, wherein the stress-strain correlation is derived from a function of strain energy density. The tire 3D model was created of which only a quarter part was used. This option was chosen since the objects were fully symmetrical and the use of only part of the object significantly decreased the time of simulation without changing the results of the experiment.

The investigation area of the tire model is a 3D volume, a mesh divided into hexahedral and tetrahedral hybrid elements. Up to seven Inflation Layers (IL) are created with an expansion factor of 1.2 – 1.6 near boundary layers where the impulse is generated. The mesh convergence study was performed by developing different grids. This promoted the determination of how the mesh quality affects simulation results (example of grids on Fig. 2a). The study results of mesh independence are given in Table 1. The study provides a summary of the primary features of the meshes, indicating that the simulation time is significantly influenced by the quantity of mesh nodes utilized. Fig. 2b shows boundary conditions for tire modelling.

Table 1. Physical and geometrical parameters of the research objects

Mesh parameters	Max elements size	№ of IL	Total № of elements	Total solution time
Grid 1 (G1)	Δ-5; □-6 (mm)	3	1,185,471	17 min. 31 s
Grid 2 (G2)	Δ-4; □-5 (mm)	4	1,879,598	29 min. 05 s
Grid 3 (G3)	Δ-3; □-4 (mm)	5	2,422,827	44 min. 28 s
Grid 4 (G4)	Δ-2; □-3 (mm)	6	3,101,437	1 h. 03 min. 47 s.
Grid 5 (G5)	Δ-2; □-2 (mm)	7	3,423,130	1 h. 22 min. 12 s.

Notably, the resolution of the mesh has a significant impact on the ultimate results of the simulation. The first results obtained during simulation tests with different mesh grid show that mesh independence study G3 and G5 account for nearly 2% of the difference. Nonetheless, the ultimate simulation time required for the two meshes to converge is the determining factor for the substantial discrepancy. The concluding simulation outcomes effectively illustrate that the simulation time is considerably impacted by the number of mesh nodes utilized. Due to the narrow difference between G5 and G3 and regarding the computational costs, it is more rational to further employ G3 and conduct numerical research analysis.



a)

b)

Fig. 2. View of numerical model parameters: a) example of grids in mesh independence study; b) view of the boundary conditions for numerical modelling.

The numerical code was based on the FEM (Newmark method) and performed in the dynamic simulation. The equilibrium equation can be expressed, according to [12 and 25], as:

$$[M]\{\ddot{x}\}_t + [C]\{\dot{x}\}_t + \{F\}_t^{int} = \{F\}_t^{ext}, \quad (1)$$

where $\{F\}_t^{int} = [K]\{x\}_t$ are vector of internal forces; $\{F\}_t^{ext}$ are vector of external forces (in current research – impulse from experimental part of research); $\{\ddot{x}\}_t$, $\{\dot{x}\}_t$, $\{x\}_t$ are the acceleration, velocity and displacement vector at solution time (t);. [M], [C] and [K] are matrices of masses, damping and stiffness, respectively.

Since, the variable vectors is assumed to be linear within the time step, the equations for acceleration, velocity and displacement will have a form:

$$\ddot{x}_t = b_1(x_t - x_{t-\Delta t}) + b_2\dot{x}_{t-\Delta t} + b_3\ddot{x}_{t-\Delta t}; \quad (2)$$

$$\dot{x}_t = b_4(x_t - x_{t-\Delta t}) + b_5\dot{x}_{t-\Delta t} + b_6\ddot{x}_{t-\Delta t}; \quad (3)$$

$$x_t = x_{t-\Delta t} + \Delta t\dot{x}_{t-\Delta t} + \left(1/_2 - \beta\right)\Delta t^2\ddot{x}_{t-\Delta t} + \beta\Delta t^2\ddot{x}_t. \quad (4)$$

The γ and β are dimensionless integration specifying parameters which varied. $b_1 \dots b_6$ are calculated integration constants in a simplified way. The extended view of these constants is shown in Table 2.

Table 2. Integration parameters of constants γ and β.

Constant	b_1	b_2	b_3	b_4	b_5	b_6
Parameters	$1/\beta\cdot\Delta t^2$	$1/\beta\cdot\Delta t$	$\beta - 1/2$	$\gamma\cdot\Delta t\cdot b_1$	$1+\gamma\cdot\Delta t\cdot b_2$	$\Delta t\cdot(1+\gamma\cdot b_3 - \gamma)$

The primary benefit of employing the Newmark method is the avoidance of time-intensive processes that necessitate stiffness matrix inversion. Instead, only the mass diagonal matrix is inverted. However, the method's principal drawback is its conditional stability, which necessitates limiting the time step according to the stability condition:

$$\gamma \geq 1/2\,; \beta \leq 1/2; \text{and } \Delta t \leq \frac{1}{\omega\sqrt{(\gamma/2)-\beta}_{max}}, \quad (5)$$

where $\omega_{\max}$ is the highest frequency element in the structural system mesh.

In modal analyses, a simplification is often made which means that the system is non-damped and without static loads. The damping matrix [C] and the extern load vector $\{F\}_t^{ext}$ in equation (1) are therefore omitted. In the undamped system, the displacement vector $\{x\}$ consists of nodal displacements $\{\bar{x}\}$ which vary sinusoidally with time, and displacements that occur due to an impulse loading and in a harmonic form (according to experimental test loading) have the view:

$$\{\bar{x}\} = \{F_i\}\, sin(\omega_i t), \quad (6)$$

where F_i is the amplitude of mode shape of the i^{th} natural frequency ω_i. However, in a linear problem, the natural frequencies are independent, and the vector therefore yields:

$$-\omega^2[M] + [K] = \{0\}. \quad (7)$$

The outcome from equation (7) provides Eigenvalues, representing the square root of the natural frequencies, and Eigenvectors, representing the amplitude of the corresponding natural frequencies. The natural frequencies obtained by the modal analysis can be used to provide information on tire deformation and validation with experimental measuring. Additionally, assuming that the metal base is not deformable, the contact between the metal base and a tire is based on the penalty method. To avoid a problem with composite structure modelling, the optimization task was proposed for numerical modelling. To obtain the results which are closer to the experimental part, the task of optimization based on material frequency response and partly based on [7], where minimization by objective function is used, was generated:

$$min\,\Phi = \sum_{i=1}^{NH}\left(\frac{A_i(\omega_i) - Aj_{iexp}(\omega_j)}{A_0}\right)^2 \quad (8)$$

where, NH refers to the number of frequencies where the amplitude difference is minimized. To establish the objective function, it is critical that each term of the objective function changes within a minimal range. Therefore, the amplitudes in the objective function are normalized, ensuring that the optimization problem is correctly formulated, resulting in a shorter solution time. Both the theoretical amplitude (A_i) and the experimental amplitude (A_{iexp}) are divided by a constant amplitude (A_0.).

It is essential to ensure that the frequency step used in both the experimental and simulation parts corresponds to each other. The experimental amplitude for equation (8) at frequency ω_i should be clarified by expression:

$$A_{iexp}(\omega_i) = \frac{\omega_{k+1} - \omega_i}{\omega_{k+1} - \omega_k}A_k(\omega_k) = \frac{\omega_i - \omega_k}{\omega_{k+1} - \omega_k}A_{k+1}(\omega_{k+1}) \quad (9)$$

During each iteration, a new spectrum of the velocity amplitude A_i is obtained. The frequency ω_i is determined in the interval between ω_k and ω_{k+1}. The specific process of designing the optimization task of composite tire material is illustrated in Fig. 3.By analysing the flowchart for successful optimization it is necessary to include several critical steps: The parameterization which means that the design optimization covers the choice of the variables and reduces the model complications structure; Design of experiment (DOE) which provides a reasonable and effective method for validation of the model and obtaining the information and data, which directly benefit in avoiding problems during simulation of extrude material structure; FE numerical test analysis which refers to a model database established in the end and based on DOE and simulation on each optimization step. Approximate model (AM) is a model that approximates a set of input variables (experimental frequency response) and output variables (simulation model frequency response) during optimization. The current research has chosen the Kriging model for building the Approximate model; Optimization calculation refers to reasonable algorithm used for solving objective function by minimization.

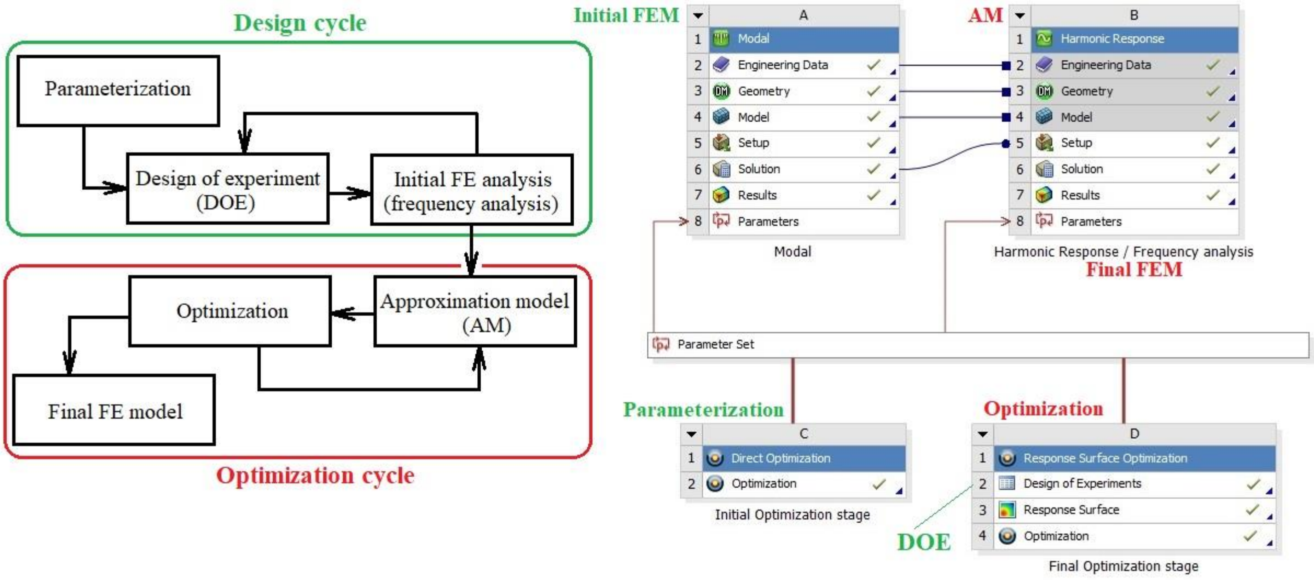
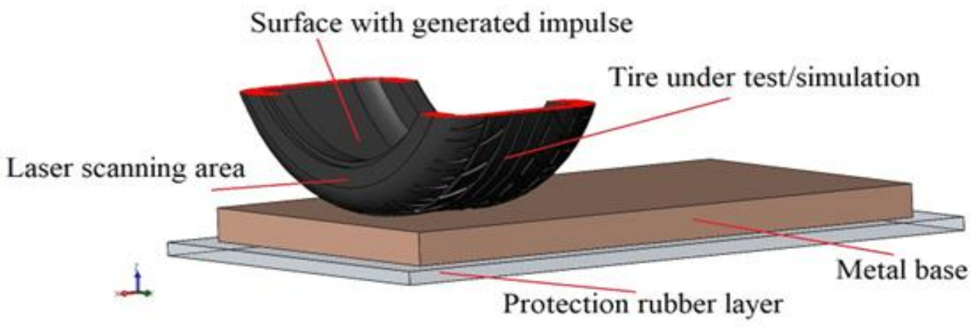


Fig. 3. Flowchart of the optimization task in ANSYS software.

3. Experimental part of the research (DOE)

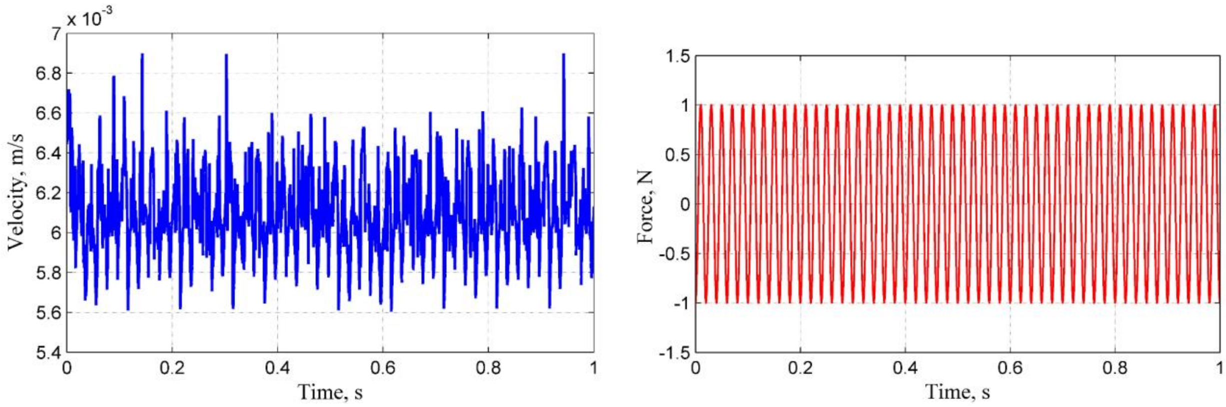
The current experimental part was conducted to evaluate tire damping properties, assessed during vibration and frequency analysis. The data was used in numerical modelling to avoid during the simulation a complicate composite material problem and obtain real object behaviour. The quarter of the tire was investigated using piezoelectric micro-vibration tests and modal analyses of structural constants: natural frequency and damping ratio were found. The tire was investigated using piezoelectric micro-vibration tests and frequency analyses. The piezoelectric micro-vibration technique was used to determine the vibration characteristics (natural frequencies and mode shapes) of a mechanical structure or composite tire structure, showing the movement of tire surface under dynamic loading conditions. Natural frequencies and mode shapes are significant parameters in designing a structure for dynamic loading circumstances. To perform the current modal analysis, the recorded vibration data is transformed using a Fast Fourier Transform (FFT) spectrum analysis. Experimental tests are conducted utilizing a two-sample measurement design, relying on a one-sample statistical method to estimate the uncertainty in the repeated measurement of data processing [23]. Test bench and measurement setups for the research include: a metal base with the environment low frequency influence protection rubber; research objects glued to metal base; scanning system for measuring a vibration from tire surface under piezoelectric micro-vibration element impact signal and FFT analyses (Fig. 4a). The measuring tests include several vibration tests of tire surface deformation (velocity/displacement) from micro-vibration impulse by piezoelectric element and double-sample measurement was utilized, employing a single-sample statistical method to estimate the uncertainty in the repeated measurements of data processing, according to [19]. During tests, the time of one point measured by PSV Sensor Head is 1 second. During this time a sinusoidal micro-impulse with frequency 50 Hz is generated on the research object tire by piezoelectric element. At the same time PSV Sensor Head measures the vibration velocity of the research object. The scheme of measuring is shown in Fig. 4b. The example of measuring data based on the test is presented in Fig. 5.

a)



b)

Fig. 4. The experimental details (the graphs from the measuring): a) test bench for measuring; b) scheme of measurement setup.



a) b)

Fig. 5. The example of measuring data from test: a) scanning signal by PSV-400 scanning head on tire surface; b) impulse generated by piezoelectric element on the inner surface of tire.

To mitigate the impact of measurement errors, the average results were employed. The primary outcome derived from the tests is the frequency response of composite materials, which is determined by performing spectrum analysis utilizing the Doppler Effect. The laser scans each point during a piezoelectric micro-vibration impulse and during the measuring time. A scan status was in optimal conditions, which means that a grid of points and focus of laser is optimal for reflection from tire rubber material. Furthermore, the frequency domain encompasses a bandwidth of 1 kHz with a step resolution of 0.25 Hz. The frequency response graphs are presented in the velocity domain because it allows for a more clear identification of resonance points in this spectrum analysis.

The results of obtained velocity amplitude on tire scanning surface in frequency response domain is shown in Fig. 6. The graph identifies three regions for analysing and characterizing the damping properties of materials: the low-frequency region (up to 200 Hz), mid-range frequency (from 200 Hz to 800 Hz) and high frequency (from 800 kHz). Furthermore, the main interest of the conducted analysis is a frequency range of up to 500 Hz as this frequency range exhibits the primary resonant modes, which are depicted by a reverse exponential curve, indicating their tendency. Firstly, all the picks on the frequency 50 Hz with its harmonic steps (50/100/150… etc. Hz) should be ignored during comparing process, since this frequency was generated by piezoelectric element micro-vibration impulse. Frequency analysis reveals that the main resonance frequency of tire composite structure is in the low frequency range and acts on the almost end of middle frequency range. Within this frequency range, the primary resonant modes are observed. Additionally, frequency analysis indicates that the investigated composite materials have a initial resonance frequency equal to 20 Hz and has a harmonic (20/40/60... etc. Hz). Frequencies in the low frequency range 62.5 Hz with a harmonic step should be pointed out as well, as they remain in midrange frequency (62.5/125/187.5... etc. Hz). The existing frequencies of the second resonance range are explained by the nature of the complicated composite structure of research object.

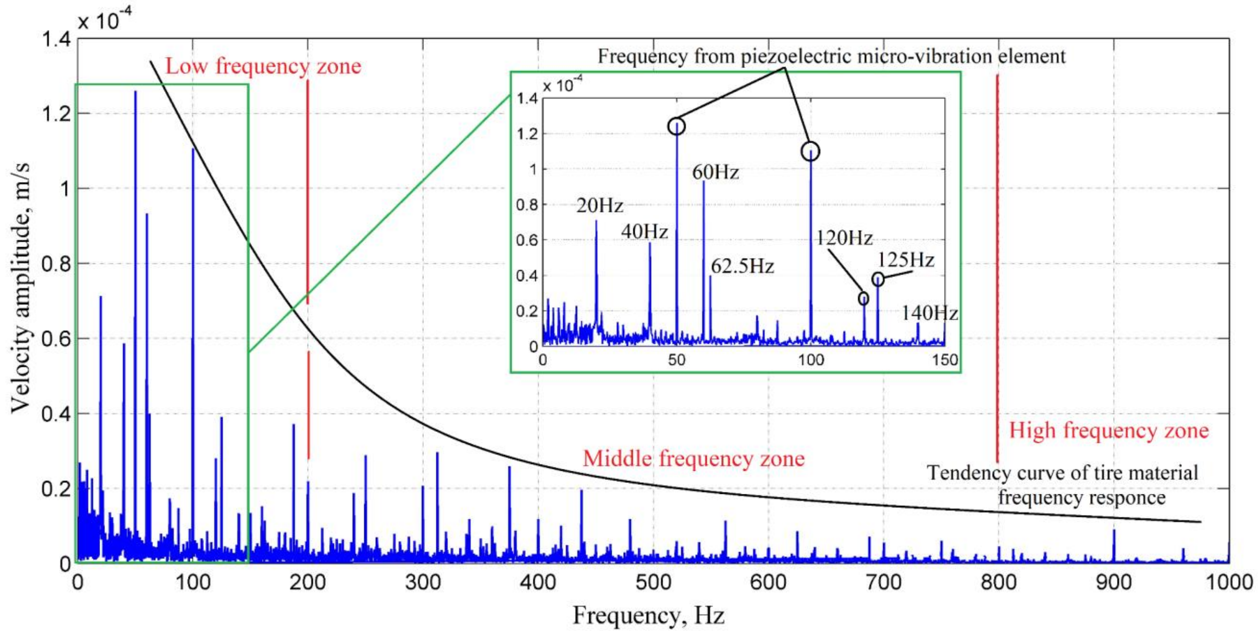
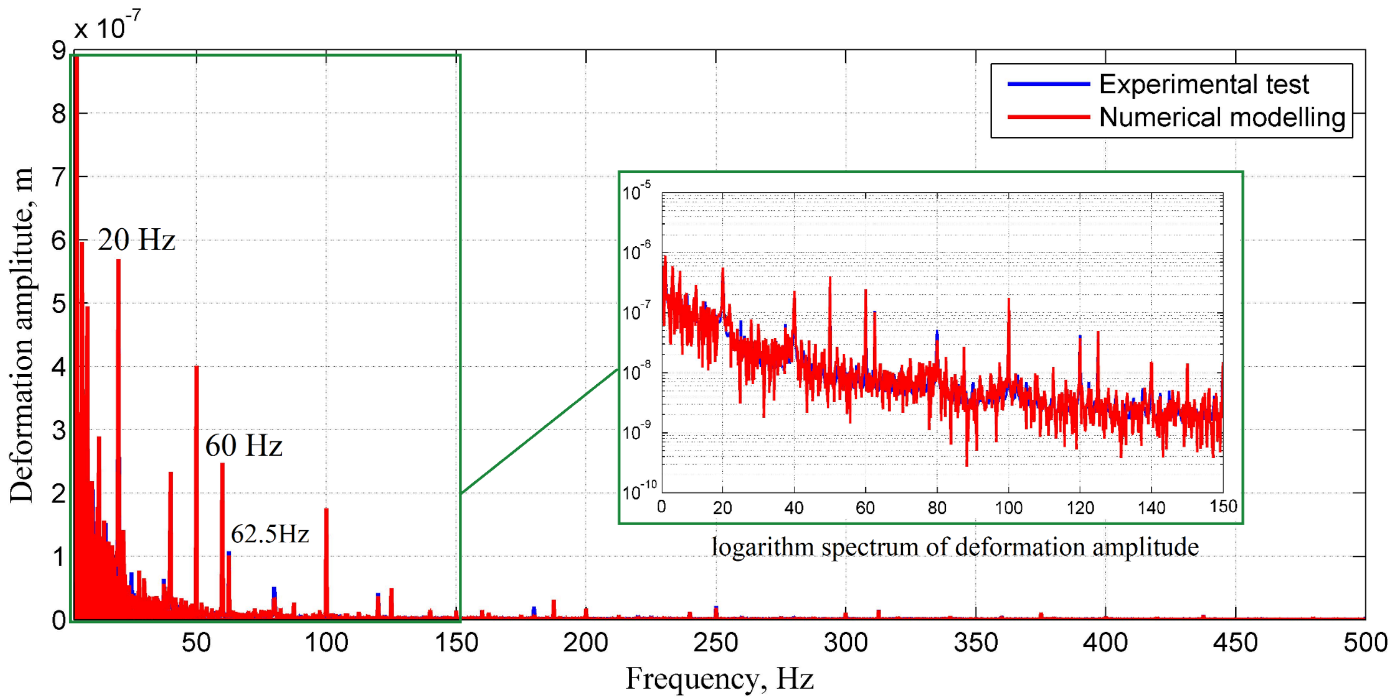


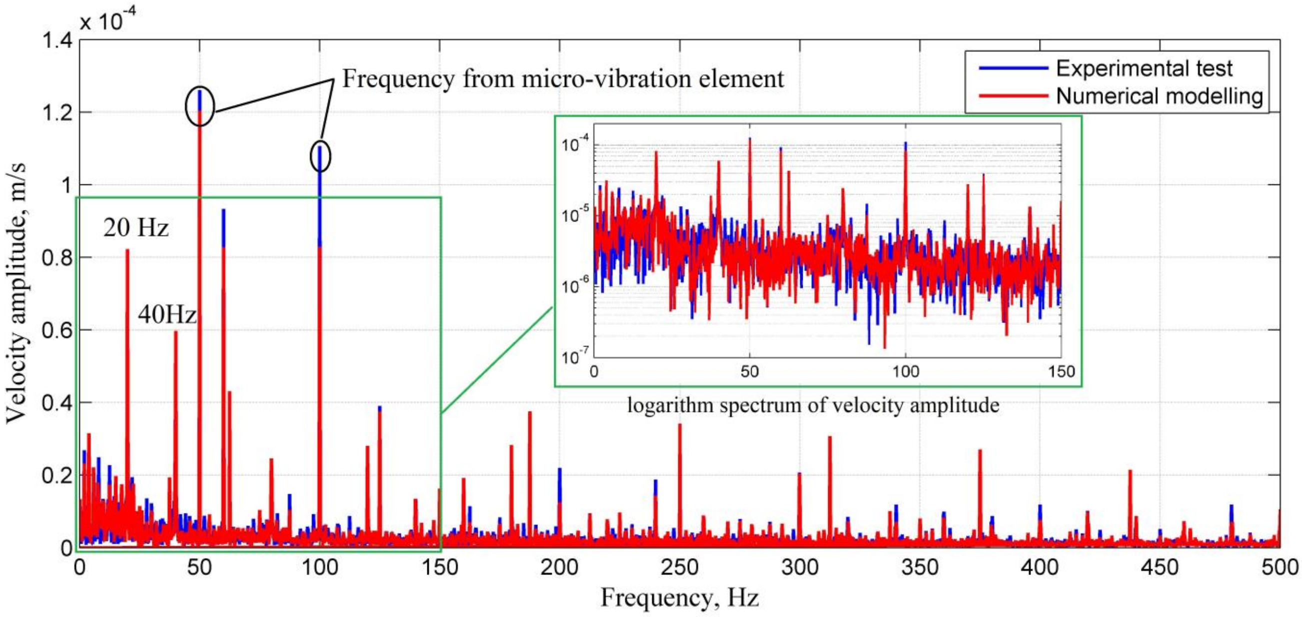
Fig. 6. The frequency response of composite tire surface from measurements.

4. Research results

Various types of results can be obtained from the current numerical modelling. Fig. 7 presents the comparison of the results obtained from tire frequency response performed experimentally and from numerical simulation after optimization (additionally shown in logarithm for better display of differences of obtained results). Obtained results can be used for validation of numerical model based on material frequency responses.



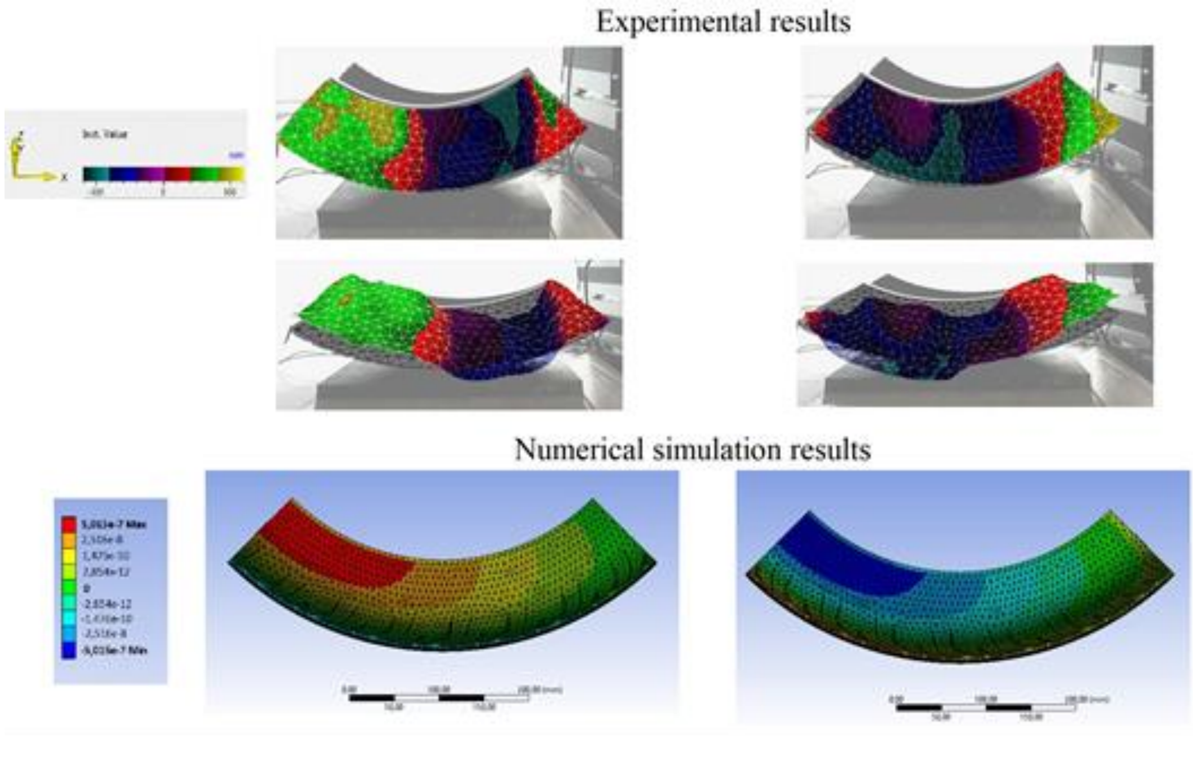
a)



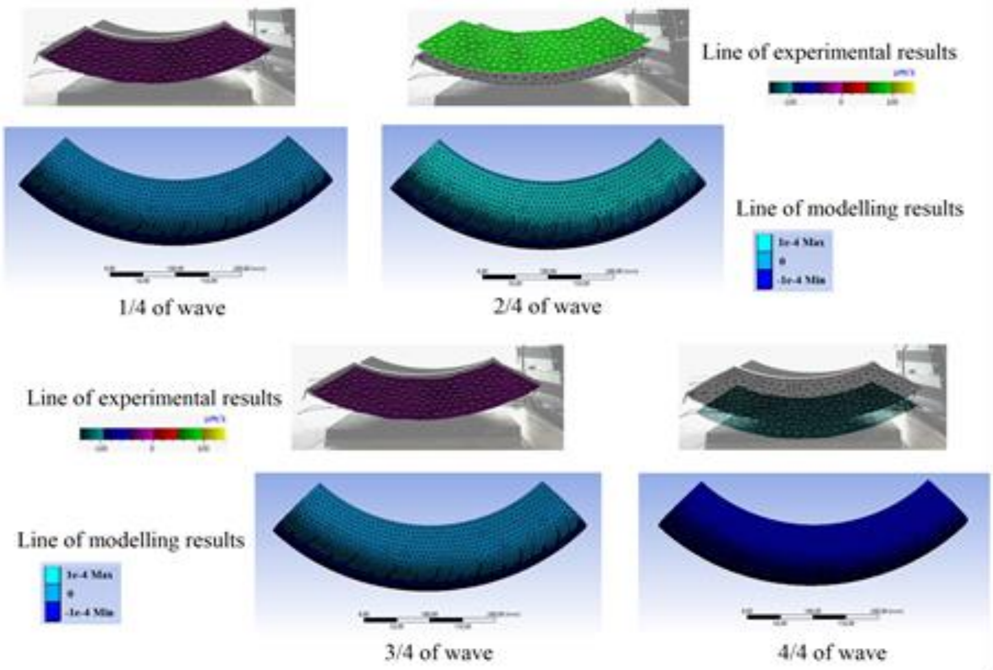
b)

Fig. 7. Comparison of frequency responses between experimental and numerical research: a) spectrum of deformation amplitude; b) spectrum of velocity amplitude.

The difference of the frequency response between experimental and numerical modelling is less than 6% at most frequency points (see Fig. 7). Also, it must be specified that the difference on resonance points does not exceed 5%. The logarithmic spectrum of the velocity amplitude suggests that, following optimization, there is a notable difference in the amplitude of certain frequencies. However, the number of such frequencies is limited and low. Fig. 8 presents the comparison of tire material front surface deformation in experimental measurement and in numerical modelling (after optimization) of the first resonance point and surface velocity deformation on generated impulse frequency.



a)



b)

Fig. 8. Front surface deformation of composite tire material from experimental and numerical results: a) deformation on first resonance frequency (20 Hz); b) velocity of deformation on frequency of generated impulse (50 Hz).

First, it must be pointed out that tire surface velocity of deformation and shape of deformation on the frequency of generated impulse (50 Hz) are almost the same. This leads to the conclusion that boundary loads were transferred correctly from experimental measuring to numerical model. The obtained results show that there is no significant difference between experimental measurement and numerical simulation. The maximum level of surface deformation in the experimental test and in the numerical simulation is $\pm 5.015\text{-}5.58 \cdot 10^{-7}$ m (the minus means that material deformation extends in the opposite directions in a wave form), and with a minimum difference. Additionally, the shape of the deformation wave (symmetrical sinusoid shape) is similar which demonstrates that proposed methodology of numerical simulation in combination with experimental measurements based on optimization of material frequency response can benefit in modelling tire materials behaviour to avoid the problems of composite structure modelling. The results obtained in the present research can be applied in future research in composite tire (airless and pneumatic) investigation and with reference to viscos-elastic properties of rubber material. The study aims to construct a realistic simulation model of the dynamic interactions between vehicle tires and road surfaces under varying loads.

5. Conclusion

The present study provides theoretical and experimental research on composite pneumatic tire used in transport engineering. The tire materials were tested employing the piezoelectric micro-vibration tests and frequency analyses methods. Frequency analysis reveals that the main resonance frequency of tire composite structure is in the low frequency range and acts on the almost end of middle frequency range. Thus, the primary resonant modes are observed within this frequency range. Furthermore, frequency analysis indicates that the principal and initial resonance frequency of the investigated composite materials is equal to 20 Hz and is characterized by regular increase. The existing frequencies of the second resonance type (62.5 Hz with a harmonic steps) are explained by the nature of the complicated composite structure of object.

The Finite Element Method (Newmark method in the dynamic simulation) used for numerical simulation combined with experimental measurements based on optimization by material frequency response, was used for tire material behaviour avoiding problems of complicate composite modelling. The difference on a frequency response between experimental and numerical modelling is less than 6% at most of the frequency points. Finally, deformation results of tire surface that depended on frequency response have been obtained. It has been established that there is an insignificant difference between experimental measurement and numerical simulation. The maximum level of tire surface deformation in the experimental test and the numerical simulation is ±5.015-5.58·10-7 m (the minus means that material deformation extends in the opposite directions in sinusoid wave form). Obtained results indicate that proposed methodology can be used in numerical simulation in composite tire investigation, with reference to the material with viscos-elastic properties.

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