VPS VIBRATIONS IN PHYSICAL SYSTEMS
DOI: 10.21008/j.0860-6897.2022.1.05
Vibrations in Physical Systems, 2022, 33(1), 2022105

Experimental and Analytical Approaches to the Mechanical Resistance of Moped Tire Under Impact

Katarzyna SOBKOWICZ, Maciej OBST[1], Dariusz KURPISZ[1], Sebastian GLOWINSKI[2,3]

[1] Institute of Applied Mechanics, Poznan University of Technology, ul. Jana Pawła II 24, 60-965 Poznań, Poland; e-mail: maciej.obst@put.poznan.pl, dariusz.kurpisz@put.poznan.pl
[2] Department of Mechanical Engineering, Koszalin University of Technology, Sniadeckich 2, 75-453 Koszalin, Poland; e-mail: sebastian.glowinski@tu.koszalin.pl
3 Institute of Health Sciences, Slupsk Pomeranian Academy, Westerplatte 64, 76-200 Slupsk, Poland.

Corresponding author: Maciej OBST, email: maciej.obst@put.poznan.pl

Abstract The aspects related to the dynamic modeling of the mechanical properties of motorcycle tires following the practical application of research methods have been analyzed for many years. A test stand was constructed for the examination, and a mathematical model was proposed to calculate tire parameters. This study aims to develop the characteristics of the radial dynamic stiffness of a pneumatic tire depending on the pressure in the tire, speed of the beater simulating tire slipping onto a small obstacle lying on the road, and impact damping. The testing device was designed to simulate a sudden strike of a tire on a stiff foreign body lying on a road plane. The experiment was performed for three different values of air pressure in the tire, beater rate, and impact energy of the tested wheel. The dynamic radial stiffness of pneumatic tires decreased with increasing deformation speed and pressure. Presented in the paper research methodology can be an introduction to further, more complicated research, where will be taken into consideration factors such as wheel rotation, driving or breaking the wheel, friction, etc. The proposed methodology can be extended to assess the dynamic adhesion coefficient during tire impact loading.

Keywords: moped tire deflection, tire dynamic stiffness, tire radial deflection, tire impact loading, dynamic adhesion coefficient.

1. Introduction

Research on pneumatic tires research has been ongoing for many years. A rich body of literature presents various approaches to this problem. The authors focused on studying the dynamic properties of a moped tire when this type of component hits an object on the road. Critical situations in road traffic are so peculiar that the examination of various cases can contribute to the improvement of both road safety and support experts in explaining the circumstances of road accidents.

The front retreated part of vehicle tires is the only contact area with the road surface. For over 100 years, pneumatic tires have been successfully used on a large scale, and technological advances in design and material testing have contributed to the achievement of advanced operational capabilities.

Despite the continuous and noticeable development of a wide range of pneumatic tire designs, the area of research is still to understand the exact mechanism of interaction with the ground and deformation of pneumatic tires, also in connection with the impact of vehicle components, under several complex operational loads.

Industry literature is wealth in studies on the broadly understood research of pneumatic tires. Tire manufacturers apply procedures defined by standards and legal regulations to assess load capacity, service life, and safety of products in the market.

Tests of pneumatic tires are carried out at many levels, starting from issues related to materials science, through chemical and strength tests of fibres and rubber compounds, tests of interaction between the tire and the contact surface, tests of the relationship between the properties of the tire wheel and the vehicle suspension properties, and the behaviour of the entire vehicle in a variety of circumstances. Also noteworthy are the tests for tire life and user safety, which depend on many factors that are often difficult to define. The literature on the subject is rich in studies that over many years constitute valuable scientific achievements; however, dynamic research has been conducted intensively for a relatively short time. The continuous development of research methods, vehicles, and tires themselves requires systematic scientific work, also in the aspect of vehicle traffic safety. The response is the mechanical relationship between the vehicle and road surface. The operating conditions are so complex that it is impossible to predict all circumstances that affect the behaviour of the vehicle. In engineering practice, several peculiarities compel us to reflect on previously unknown cases and conduct further research.

Analytical methods for testing pneumatic tires in the context of stress and deformation states have been presented by Clark [1]. The authors characterized the materials used in the production of tires and their physical properties. He discussed the mechanics of cord, rubber, and steel fiber deformations. He focused on particular attention to the contact of tires with the road surface and presented test results related to tire slippage. However, data related to the dynamic stiffness of tires were not included.

Pacejka presented aspects related to the dynamic modelling of mechanical properties of motorcycles, focusing on the practical application of the research methods discussed [2]. The methods for measuring the mechanical properties of pneumatic tires, presenting the advantages and disadvantages of the analysed technical possibilities, were described by Wang [3]. Particular attention was paid to the rank of the coefficient of friction between the tire and road surface and the coefficient of lateral stiffness of the tires in the assessment of vehicle motion stability. The effectiveness of a vehicle traction assistance system strongly depends on the dynamic properties of pneumatic tires. The authors proposed a simulation method for estimating the friction and lateral stiffness coefficients of tires by focusing on the traction values of an electric car. The tests were carried out on a real vehicle using dedicated measurement systems, arguing the correctness of the methods used by the accuracy of the obtained characteristics.

The influence of vibrations on the radial stiffness of the tested tire at different filling pressures was presented by Taylor et. al [4]. The loaded tire was tested statically and dynamically, without and with a rolling wheel. It was observed that modelling the mechanical properties of a pneumatic tire as a viscoelastic body with damping did not yield the expected results. The results obtained from the elastic model with pneumatic tire damping were influenced by the tire pressure. Attention was drawn to the relationship between the load of the tested pneumatic tire with free vibrations and hysteresis loop was determined.

The analysis of nonlinear dynamic processes using ordinary differential equations was presented in [5,6]. The proposed theoretical, numerical, and experimental solutions for vehicle dynamics can be used in modern analyses and control of mechatronic systems of vehicles. The authors presented the relationship between the force acting on the tire and the coefficient of peripheral friction as well as the impact of the lateral force on the wheel and the angle of lateral friction, defining the slip angle. They drew attention to two models describing the properties of the tires that are used and popular: the Magnum model and the Wagner model.

The rigid-elastic model for describing the vibrations of a truck tire was characterized by Zhihao [7]. The stiffness of the tire sidewall is related to the geometry of the tire, and the adopted tire model is considered to interact with the ground with elastic beam properties. The deformable description of the ground was a tread model. Genetic algorithms were used to estimate the parameters. The tested linear and nonlinear models of the tire (sidewall) were verified experimentally by assessing the stiffness of the truck tire sidewall. The nonlinearity of the tire sidewall was modelled by geometry, whereas the radial stiffness changed in proportion to the changes in pressure inside the tire. The proposed methodology can be used to test other tires that are subjected to impulse loading. An experimental test was conducted by using a special measuring ram equipped with a force sensor. The vibrations were recorded using acceleration sensors placed at two different points on the tire. The signals recorded from both sensors constituted the data used to estimate the operational indicators.

The results of tests on a truck tire under loading conditions with a lateral force related to its operation (wheel sideslip) were presented by Luty [8]. It was observed that lateral deformation of the tire occurred intensively during the tire relaxation process. The IPG-TIRE model describes the cooperation between the tire and road surface. specialized experimental tests to determine the relaxation path length. The authors then determined the lateral elasticity function of the tire.

The proposed methodology for testing the tire relaxation parameters may be a reference point for further tests using simulation methods in which the interaction of the tire with the ground under transient conditions is of key importance. The results of experimental tests on a truck tire, reflecting the dynamic loads with the use of a dynamometric trailer and a two-drum device dedicated to dynamic tests of pneumatic tires, were presented in [9]. The tested pneumatic wheel was subjected to controlled twisting while rolling on the drum surface. In this study, the values of the reaction forces acting on tires were recorded at different wheel rolling speeds.

Interesting solutions for static and dynamic loading cases (driven wheels, brake wheels, curved driving, and complex load cases) were presented by Andrzejewski [10]. Various friction models were presented, and several tire models were characterized from the model described with radial springs through shell and crash models, reflecting the structure of the tire built using the finite element method. Andrzejewski proposed a methodology to conduct experimental tests on pneumatic wheels. Wang et. al. presented a method for estimating the tire stiffness of a four-wheel-drive vehicle in which each wheel is driven independently, as modern electric vehicles with motors are built into wheel hubs [11]. It was observed that the tested tire stiffness is particularly important when driving the curves. The authors used simulation and experimental methods to evaluate the tested indicators, using the difference in longitudinal forces between the wheels.

The experimental studies of the radial stiffness of tires were also conducted by Krmela et al. [12]. They consisted of the development of radial deformation characteristics using a dedicated test stand. The tested wheels were loaded with 1000 kg, and only the tire size was varied. A formula was proposed, based on which it was possible to estimate the radial stiffness of a pneumatic tire, assuming additional operating conditions. Tires of various sizes are used for the experiment. In addition to tire deformation, the authors also recorded the contact trace of the tire face (tread) with a flat surface, focusing on the results of simulation tests using the finite element method. The effect of different pressures on the static stiffness of pneumatic tires was analyzed by Sun et al. al [13]. A special testing device was used to record the stiffness of the tire and the contact pattern of the tread. Radial, longitudinal, lateral, and torsional stiffnesses were tested under various tire operating conditions. Luty et al. [14] experimentally determined the static radial elasticity of a pneumatic tire for a military APC with a "Run-Flat" insert for various pressures, including the case of a total drop in air pressure in the tire. The authors determined the radial elasticity characteristics using polynomial approximation. Moreover, they demonstrated the influence of the "Run-Flat" insert on the interaction between the tire and ground surface. Massaro et. al [15] developed an interesting research stand to analyze the influence of pressure inside a motorcycle tire on the stability of a two-track vehicle. The road was mirrored by a rotating disc with a large radius, and the special structure of the arm allowed for expected wheel guidance. The results of the experimental tests were used to further analyze the stability of the racing motorcycle by controlling the pressure on both wheels of the vehicle. Cossaler et. al conducted experimental tests on tires intended for scooters [16]. During the experiment, the wheel was tested in a strictly defined configuration (with the possibility of testing wheels inclined at large angles). This made it possible to distinguish the complex operating conditions of two-wheeled vehicle tires based on the operating conditions of car tires. The experimental results obtained were compared with those obtained from other research stands.

Despite many tests being conducted routinely for years in research and development centres, there is a need for continuous testing of pneumatic tires, with a particular emphasis on singular situations that are decisive when assessing road safety. There is still a lack of studies related to dynamic tests of the mechanical properties of pneumatic tires, which are needed in the design of vehicles and their suspensions and the circumstances of road accidents. Attention should also be paid to the necessity to conduct dynamic tests of tires due to unusual events that may have a decisive impact in critical situations that may end in a collision or a road accident.

The main aim of the study is to reflect, in laboratory conditions, a situation in which a pneumatic tire is in contact with a rigid obstacle due to impact. This situation may occur when a motorcyclist hits a stone or a wooden object. This is expected to simplify the test, ignore the rotation of the wheel as well as using, uncomplicated methodology that enables data capture in the engineering field

2. Materials and methods

Tests on the dynamic radial stiffness of a moped tire were conducted on an inertial test stand, where a freely falling mass was dropped on the retreated region of the tire (Fig. 1a). The test stand consisted of a rigid handle in which a wheel was mounted and a hammer was used to induce a dynamic impulse. The proposed research stand is the authors' original idea, and can be treated as a novel methodology for an experimental approach. Data were acquired using a high-speed Photron FASTCAM 1024 PCI camera. Photon FASTCAM Viewer was used to record images at a rate of 1000 fps. The moped wheel had a diameter of 504 mm. The wheel is equipped with a 2 1/4 - 19-inch Stomil Super Duet tire with an outer diameter of 614 mm (manufacturer: Stomil - Poland). The wheel was mounted on a rigid frame under a test stand. A specially constructed handle prevents rotation of the wheel while simultaneously distancing it 20 mm above the ground surface. A steel beater with a mass of 5 kg was used for the impact of the dome shape on the tire and contact surface (Fig. 1b). For rapid image recording using a camera (short exposure time), additional lamps were used to illuminate the test stand. The tire deflection was recorded using a camera with a resolution of

512 × 512, data recording rate 1 / frame, frame rate 1000 fps. Figure 2 shows the position of the beater, initial contact with the tire and its deformation under impact.

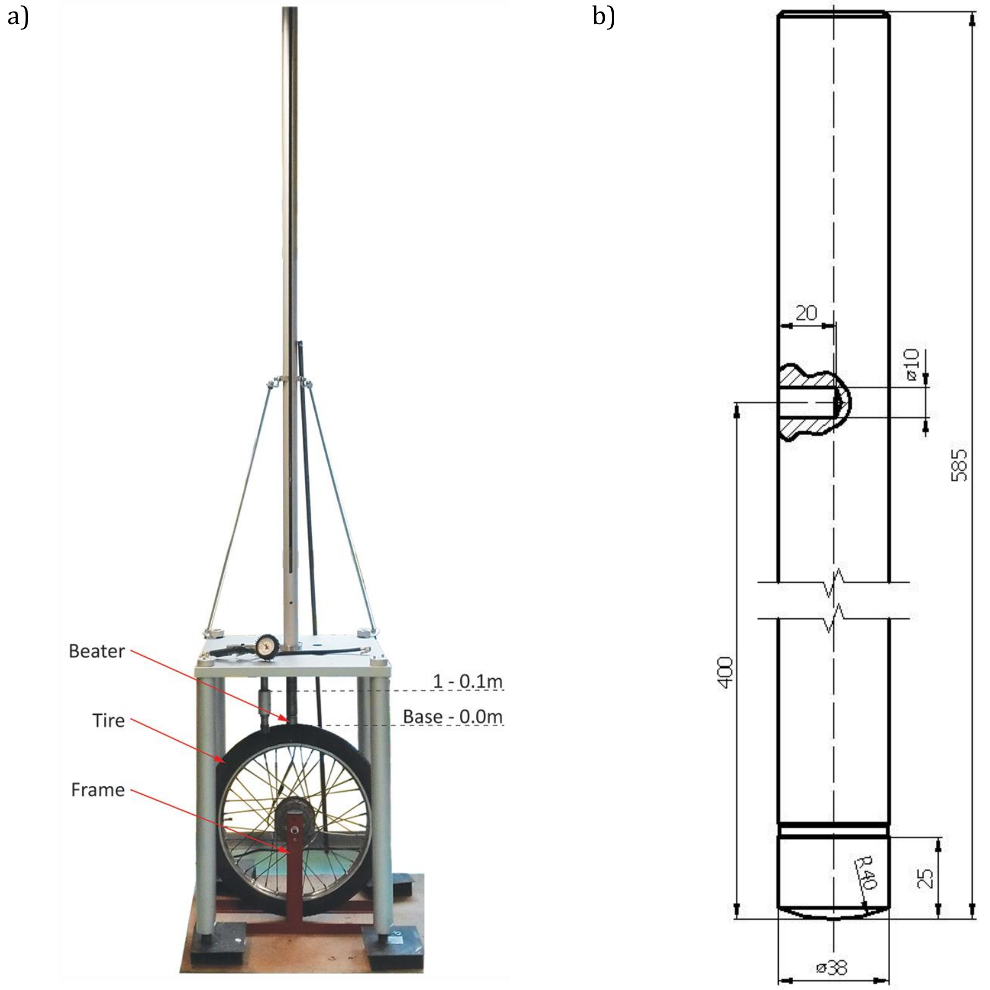

Figure 1. a) Inertial dynamic test stand, b) the beater drawing.

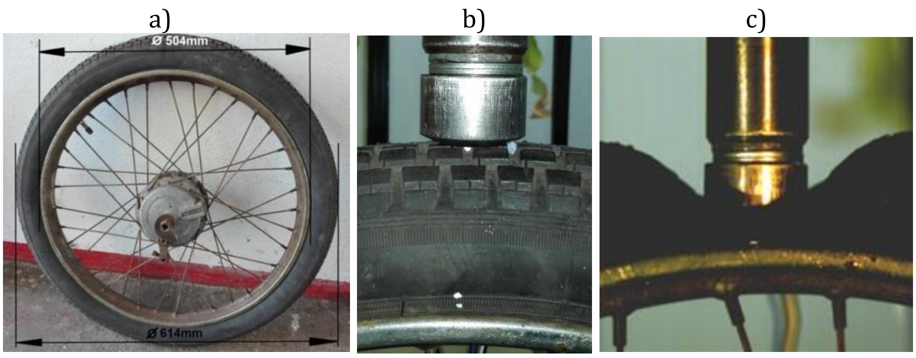

Figure 2. a) The wheel, b) the beater at the initial contact with the tyre tread, c) deformation of the tire under impact loading by means the beater.

The tests were conducted at three tire pressure levels (1.6, 1.8, and 2.0 bar) using an air compressor. The free-drop of the beater occurred at three levels (0.1, 0.6, and 0.8 m). In the movies, the deflection of the analysed fragment of the tire was determined. The results were approximated using a sine function with good fit agreement.

3. Results

The selected impact stages are shown in Figure 3.

Figure 3. The stages showing the reaction of the tire on impact at a pressure of 1.8 bar, drop height of 0.6 m.

As a result of the impact test, the following graphs on the dependence between the tire deflection arrow and time were obtained. An analytical model of the radial dynamic properties of a moped tire is proposed based on the experimental results. Additionally, their approximations were introduced using the selection of functions from a three-parameter family in the following form:

$$x(t) = a \cdot \sin\big(b(t - t_o)\big) \tag{1}$$

where a [mm], b [1/s], and t_o [s] are the parameters.

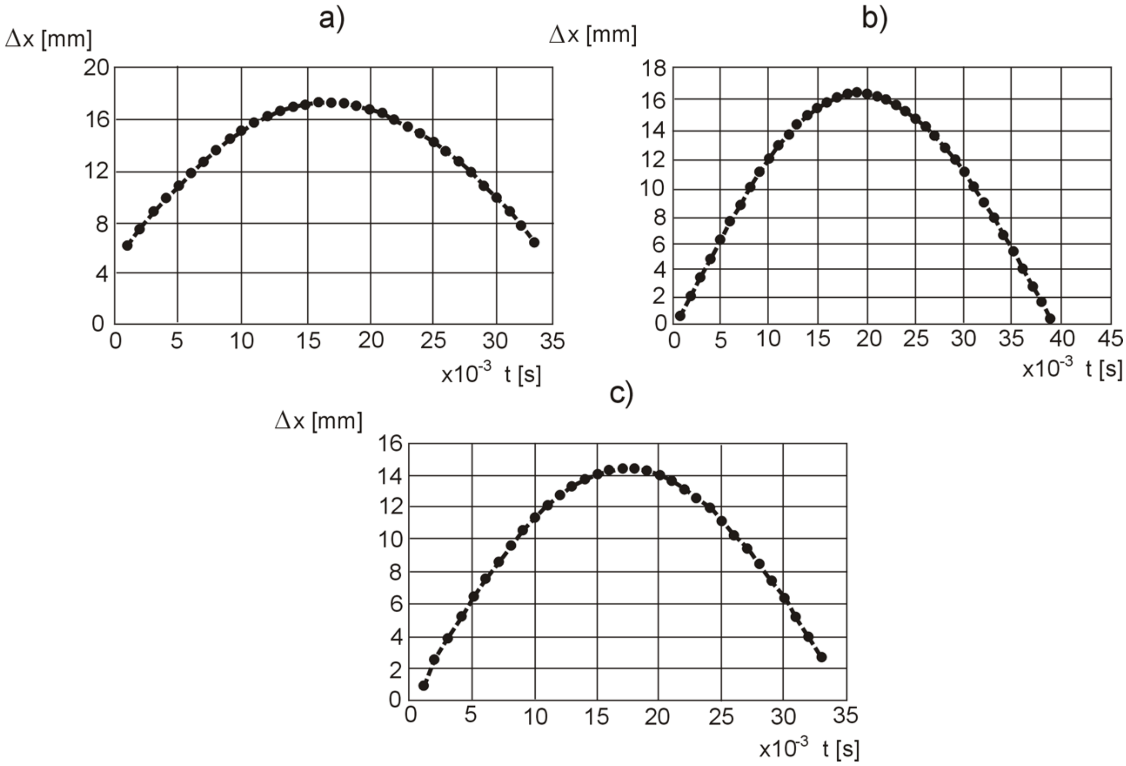

Figure 4. Dependence of the dynamic tire deflection arrow on time (with a beater-up with a mass of 5 kg, dropped from a height of 100 mm), and their approximations (dashed lines) at a) 1.6 bar, b) 1.8 bar, c) 2.0 bar.

Based on the approximations, the relation between force F and time t is as follows:

$$F(t) = m \cdot \ddot{x}(t) = -ab^2 \cdot \sin\big(b(t - t_o)\big). \tag{2}$$

The relationship between the radial force and tire deflection arrow was obtained by eliminating time from Equations (1) and (2). This relationship is linear and the slope of the regression line is a measure of the radial dynamic stiffness of the tire.

Selected approximations of the dependence of the force on the deflection arrow and stiffness are presented in Fig 5. The obtained stiffness values are summarized in diagrams Figs. 6-7:

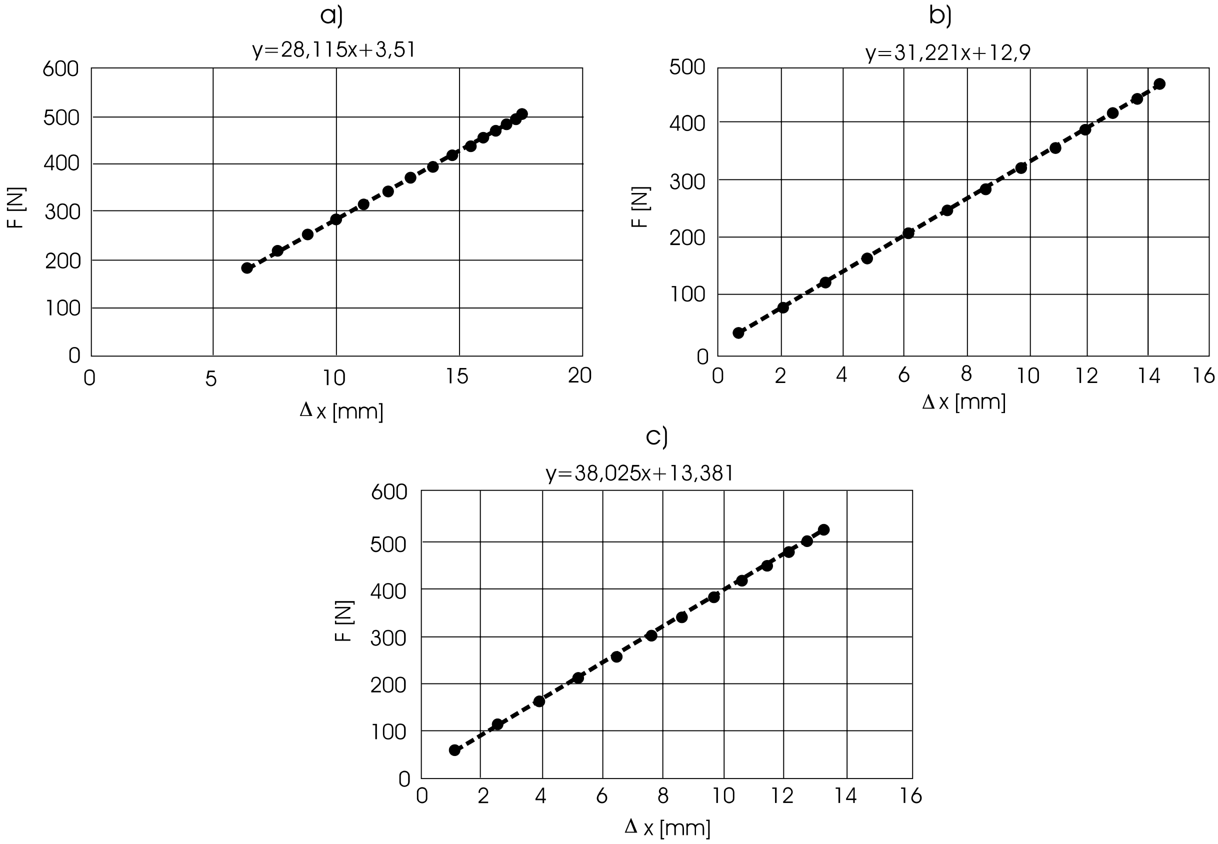

Figure 5. Relationship between the force and the dynamic tire deflection arrow (when ramping up with a mass of 5 kg, dropped from a height of 100 mm), and their approximations (simple regression) at a) 1.6 bar, b) 1.8 bar, c) 2.0 bar of air pressure filling the tire.

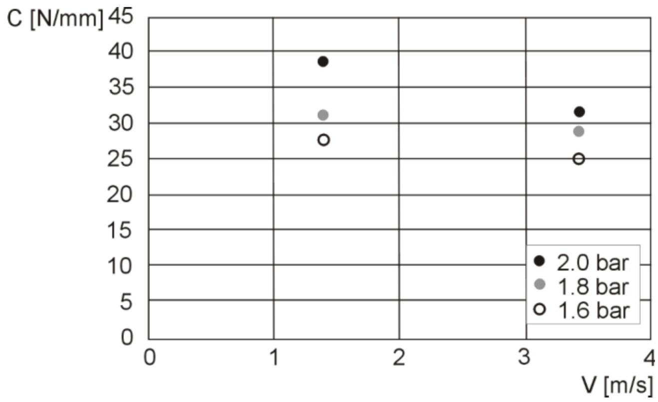

Figure 6. Radial dynamic stiffness of the tire in relation to the speed of impact with an obstacle.

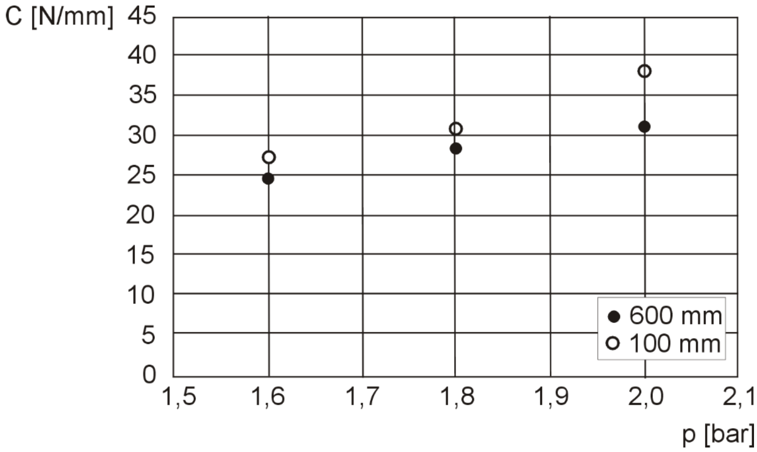

Figure 7. Radial dynamic stiffness of the tire depending on the pressure of the air filling it.

The charts developed above (Figs. 6, 7) allow us to conclude that the dynamic stiffness increases with an increase in the pressure in the tire and its decrease is related to an increase in the tire loading speed.

Analysing the time increase Δt [s] between the end of the first and the beginning of the second impact on the tire (a phenomenon related to the mass rebounding several times from the tire until it stops completely) and using the relationship

$$h_1 = \frac{1}{8} g \Delta t^2 \tag{3}$$

determined the height h_1 [mm] of hammer stroke achieved after the first impact.

The ratio of the hammer's potential gravity energy E_1 after impact to the energy E_o before impact defines the elastic coefficient S [%]:

$$S = \frac{E_1}{E_o} \cdot 100\% \, . \tag{4}$$

The inelastic coefficient related to damping can be calculated:

$$T = 100\% - S = \left(1 - \frac{E_1}{E_o}\right) \cdot 100\% \tag{5}$$

or equivalently:

$$T = 100\% - S = \left(1 - \frac{h_1}{h_o}\right) \cdot 100\%. \tag{6}$$

The experimentally determined values of the damping achieved during the impact with a mass falling from the height h_o=100 [mm] are presented in the diagram below.

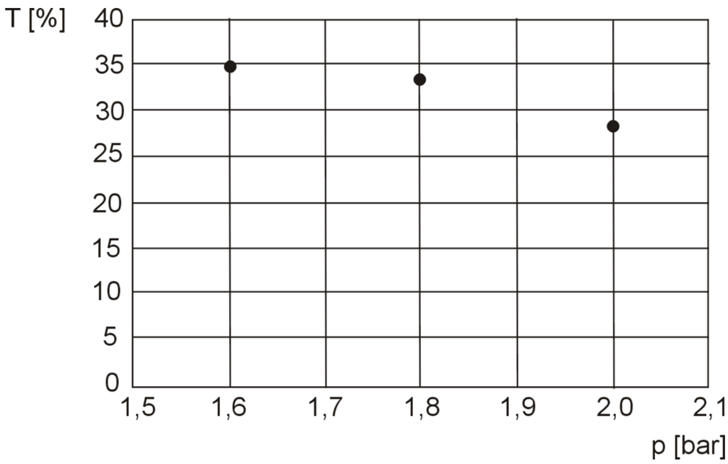

Figure 8. Dynamic damping of tire depending on wheel pressure.

The diagram in Figure 8 shows that the tire damping decreases with increasing air pressure, which is a direct consequence of an increase in its stiffness.

This results in an increase of the impact force caused by the wheel hitting the obstacle. This force, depending on the pressure value, is presented for two different values of the beater speed, as shown in Figure 9.

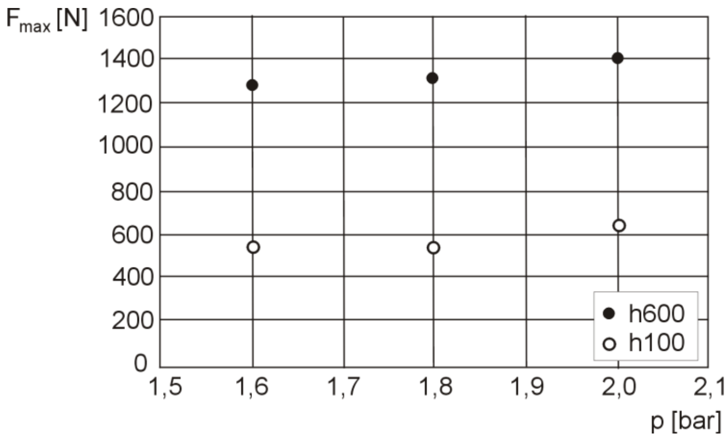

Figure 9. Dynamic loading on tires depending on air filling pressure.

The proposed analytical model, based on the experimental results collected using a propriety test stand, can be extended to further modify the research method. The dynamic properties of moped, motorcycle, and other vehicle pneumatic tires under typical road conditions are an important post-cognitive feature.

4. Discussion

The obtained results enabled the assessment of the radial stiffness and energy absorption of a wheel equipped with a moped pneumatic tire. Attempts were made to assess the tire response to impact loading by adopting changes in the radial dynamic stiffness and damping coefficient as criteria. The tire deformation was collected based on photographs. The analysis of the obtained relationship allowed us to formulate as following:

- the dynamic radial stiffness of a pneumatic tire decreases with increasing speed of impact,
- an increase of air pressure value in the tire slightly reduces it's dynamic radial stiffness,
- a lowering of the dynamic radial stiffness value was observed at an increasing impact energy,
- the damping abilities of the tested pneumatic tire were reduced with increasing air pressure and there is a non-linear relationship,
- an increase in tire pressure leads to an increase in the impact force at hitting an obstacle.

The dynamic tests performed on pneumatic tires require further investigation. The authors have drawn attention to an unusual issue related to the coaxing of a moped vehicle on a non-deformable small obstacle lying in a traffic lane. A single-track vehicle hitting a small, stiff foreign body was selected for a future study with respect to safety reasons and explanations of the circumstances of road accidents. It should also be noted that, at an appropriate speed of vehicle slamming onto a small foreign body, there is a high chance of exhausting the damping properties of the pneumatic tire and transferring the impact to the wheel rim structure. This case can radically change the characteristics of the suspension and mechanics of the rolling wheel movement.

Ethical Statement/Conflict of Interests

The authors declare that there is no conflict of interest

References

1. K.S. Clark; Mechanics of Pneumatic Tires; National Bureau of Standards Monograph 122, Michigan, 1971.
2. H. Pacejka; Tire and Vehicle Dynamics; Elsevier Ltd. Oxford 2012, ISBN 978-0-08-097016-5, Electronic ISBN 978-0-08-097017-2
3. R. Wang, J. Wang; Tire–road friction coefficient and tire cornering stiffness estimation base on longitudinal tire force difference generation; Control Engineering Practice, 2013, 21(1), 65–75.

4. R.K. Taylor, L.L. Bashford, M.D. Schrock; Methods for measuring vertical tire stiffness; American Society of Agricultural Engineers, 2000, 43(6):1415-1419, 0001-2351/00/4306-1415.
5. R. Andrzejewski, J. Awrejcewicz; Nonlinear dynamics of a wheeled vehicle; Springer Science+Business Media 2005, Inc. ISBN 0-387-24358-5
6. S. Glowinski, T. Krzyzynski; Modeling of the ejection process in a symmetrical flight; Journal of Theoretical and Applied Mechanics, 2013, 51(3),775–785.
7. L. Zhihao, G. Qinhe; Analytical investigation on tire dynamics by rigid–elastic coupled tire model with nonlinear sidewall stiffness; Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2018, 40(2), doi: 10.1007/s40430-018-1024-9.
8. W. Luty; Wyznaczanie parametrów modelu nabiegania ogumienia na podstawie wyników badań eksperymentalnych; Postępy Nauki i Techniki, 2012, 14, 307-316.
9. W. Luty; An analysis of tire relaxation process during dynamic changes of concerning angle; Journal of KONES Powertrain and Transport, 2009, 16(1).
10. R. Andrzejewski; Dynamika pneumatycznego koła jezdnego; Wydawnictwo Naukowe PWN 2020, ISBN: 9788320434347
11. R. Wang, J. Wang; Tire-road friction coefficient and tire cornering stiffness estimation base on longitudinal tire force difference generation; Control Engineering Practice, 2013, 21, 65–75.
12. J. Krmela, L. Beneš; Tire Experiments on Static Adhesor for Obtaining the Radial Stiffness Value; Periodica Polytechnica Transportation Engineering, 2014, 43(2), 125–129.
13. P.F. Sun, G.Y. Feng, S.T. Zhou, C.Z. Qiu, J.W. Fan; Experimental Analysis of Radial Tire Stiffness and Grounding Characteristics; Materials Science and Engineering, 2019, 677(2):022111, DOI: 10.1088/1757-899X/677/2/022111.
14. W. Luty, P. Simiński; Analiza sprężystości promieniowej ogumienia z wkładką "Run-Flat"; Journal of KONES Powertrain and Transport, 2007, 14(2), 131–138.
15. M. Massaro, V. Cossalter, G. Cusimano; The effect of inflation pressure on tire properties and motorcycle stability; Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering, 2013, 227(10), 1480–1488.
16. V. Cossalter, A. Doria, R. Lot, N. Ruffo, M. Salvador; Dynamic properties of motorcycle and scooter tires: measurement and comparison; Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility, 2003, 39:5, 329–352.