MACHINE DESIGN, VOL.9(2017) NO.1, ISSN 1821-1259 PP. 23-28

Research paper

DETERMINATION OF BASIC MECHANICAL PARAMETERS OF THE TRACTOR TYRE BY USING UNIVERSAL APPROACH

Boris STOJIĆ[1, *] - Aleksandar POZNIĆ[1]
[1] University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia

Received (25.05.2016); ***Revised*** (14.09.2016); ***Accepted*** (19.09.2016)

Abstract: *Tyre behaviour exerts crucial impact on every aspect of vehicle dynamics response. It is therefore of interest to have access to appropriate tyre model in order to address vehicle behaviour optimization by means of computer simulations. In this paper procedures for determination of some basic parameters of tractor tyre by using simple test facility and universal measuring techniques are described, including dependence between tyre vertical load, static radial deflection and contact length on the hard level ground, linearized radial stiffness and damping coefficients. Impact of tire pressure and vertical load on investigated quantities and relationships is also examined. Set of tyre parameters that can be used in simple tyre model was obtained. Linearized stiffness and damping coefficient values can be used in certain applications of tyre viscoelastic structure modelling. Relationships between tyre load, deflection and contact length can be useful when investigating tyre geometric or filtering properties such as enveloping behaviour.*

Key words: *tractor tyre. testing, model parameters*

1. INTRODUCTION

Tyre behaviour exerts crucial impact on every aspect of vehicle dynamics response. For the contemporary tractors, due to simultaneous increase of travelling speeds as well as trailing load capacity, issues of handling and stability of tractor itself or in combination with the trailer have become increasingly important for the public road safety [3]. At the same time optimization of tractor vibration behaviour always was and still is one of the most challenging task in tractor research and product development [2]. In order to be able to address such topics by means of computer aided vehicle dynamic simulations, proper model of tyre behaviour is of substantial significance for the validity of simulation results. For development, parameterization and/or validation of such tyre models, appropriate test facility is needed to investigate real tyre response. Such facilities are as a rule expensive due to high technical level, and this property is even more pronounced in the case of tractor tyres, due to large dimensions and much higher operational loads. For this reasons, tractor tyre test facilities are relatively rare and researchers who might want to explore vehicle dynamics of contemporary agricultural tractors by means of computer simulations have limited access to tyre data required for appropriate model.

The goal of this paper is to propose procedures to obtain at least basic tyre model parameters, by using simple test facility and universal measuring techniques and approaches, more accessible in usual budget-constrained university environment. The following features will be included:

- Dependence between tyre vertical load, static radial deflection and contact length on the hard level ground
- Linearized radial stiffness and damping coefficients
- Impact of tire pressure and load on investigated quantities and relationships.

2. TEST FACILITY

Experimental facility used in these investigations was described in more details in a number of previous papers (e.g. [4,6]) so that only the brief description will be presented herein. Facility is depicted in the Figure 1.

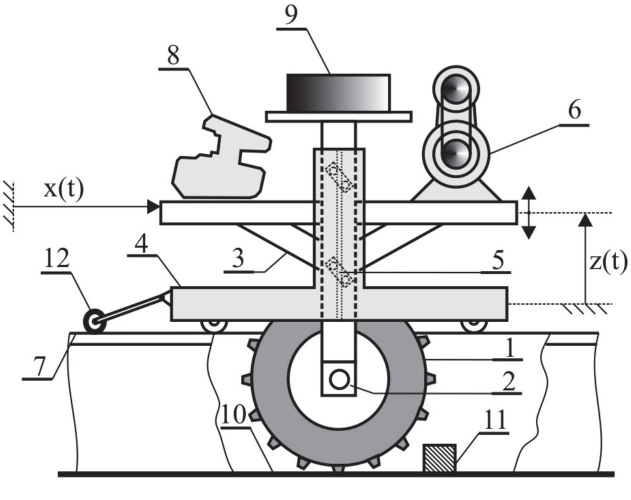

Fig.1. Composition of the test facility: 1-tested wheel, 2-wheel axle bearing, 3-wheel mounting frame, 4-wheel guiding cart, 5-vertical guide, 6-driving motor with reduction gearbox, 7-cart guiding rail, 8 and 9-changeable weights for vertical wheel load adjustment, 10-level ground, 11-road irregularity, 12- longitudinal travel sensor; x(t), z(t)-longitudinal and vertical travel of the wheel rim

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*Correspondence Author's Address: University of Novi sad, Faculty of Technical Sciences, Trg Dositeja Obradovica 6, 21000 Novi Sad, Serbia, bstojic@uns.ac.rs

Its mean features are as follows:

- Tested wheel (1) can roll freely along test ground (10), on which different forms of road profile (11) can be mounted to investigate tyre enveloping behaviour or vertical dynamics
- Longitudinal guidance for the facility is provided by the cart (4) and the rails (7)
- Wheel axle (2) is pivoted at the bottom of the carrying frame (3), which can move freely in vertical direction with regard to the cart, within the guides (5), providing the wheel with additional vertical degree of freedom
- Tyre vertical ground reaction is determined by the weight of the wheel itself, frame (3) with equipment (e.g. driving system (6)), and exchangeable weights (8 and 9)
- Induction displacement transducer is mounted between the frame (3) and the cart (4) to register change of the vertical position of the wheel with respect to the cart

3. DESCRIPTION OF MEASURING PROCEDURES

3.1. General Procedure and Equipment

For the measurements carried out in the scope of this work, the following equipment has been used, as depicted in Fig. 2: displacement transducer, force transducer, universal measuring amplifier and PC computer for data storage.

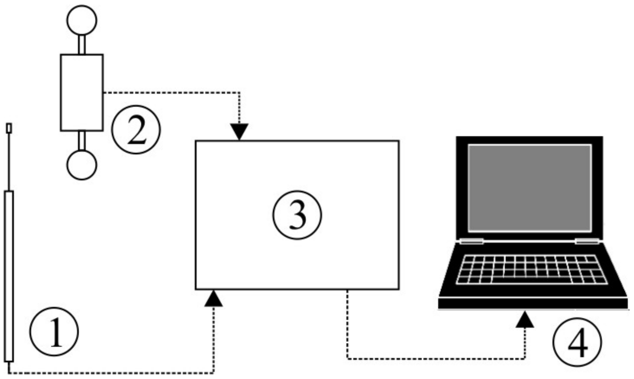

Fig.2. Measuring equipment: 1-displacement transducer, 2-force transducer, 3-measuring amplifier, 4-PC

Main components, and the basic measurement principles, which will be discussed subsequently, are presented in the Fig. 3. The upper end of the force transducer (2) is connected to the hook of the manually operated hydraulic crane (not presented in the Fig. 3), while the lower end is connected to the wheel carrying frame (4) by the mean of the lifting cable (3). Applying lifting force F_L, tyre ground reaction will change, together with tyre deflection and contact length. Since the force transducer is connected in series between the crane and wheel carrying frame, it is loaded by the lifting force F_L which enables its direct reading from the transducer signal.

Tyre deflection change is determined from the signal of the displacement transducer, which is located between the wheel guiding cart (4, Figure 1) and the wheel carrying frame (3, Figure 1), which moves in vertical direction together with the wheel rim. Finally, contact length is obtained by using two thin (<1mm thickness) rigid plates of rectangular shape, touching opposite edges of the tyre contact area, and measuring their longitudinal distance by using the measuring tape.

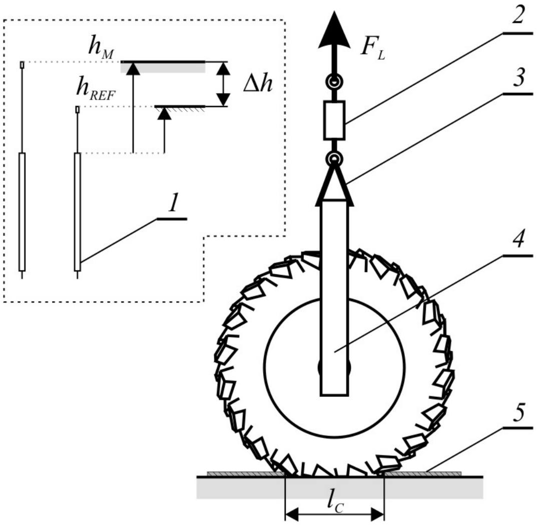

Fig.3. Measuring principle and main components: 1-displacement transducer, 2-force transducer, 3- lifting cable, 4-wheel carrying frame, 5-rigid plates of small thickness, F_L - lifting force exerted at the top, h - vertical tyre position, l_C - contact length

Values of measuring signals are recorded on a computer, and their instantaneous values can be read from the computer display using measuring software.

All measurements are carried out with 3 levels of system mass (i.e. total weight of the carrying frame together with the wheel and all mounted equipment and loads, determining tyre ground reaction), and 5 levels of tyre pressure, shown in the Table 1. Considerations about the choice of these values are discussed in [5].

Table 1. Operational conditions: system mass and tyre pressure

Mass values [kg]		
Level 1	Level 2	Level 3
660	960	1440

Tyre pressure values [bar]				
Level 1	Level 2	Level 3	Level 4	Level 5
0.8	1.1	1.4	1.7	2.0

All measurements were made using the test wheel of the size 12.4R28 ★121 A8 (8 P.R.)

3.2. Procedure for the Determination of Dependence Between Tyre Vertical Load, Static Radial Deflection and Contact Length

When the lifting force F_L (Fig. 3) is not applied, tyre ground reaction is equal to the weight of the carrying frame together with the wheel and all mounted equipment and loads. In this equilibrium position, tyre deflection and contact length have values that can be adopted as referent. Referent reading of the system height is obtained by the displacement transducer signal. It is not necessary to transform its signal to obtain zero value at this point, because the relative change of its value is compared to initial one, and the absolute signal values are not of importance. Applying some initial lifting force through the crane, a new static equilibrium position is obtained, for which it applies:

$$F_L + Z_G = W \qquad \Rightarrow \qquad Z_G = W - F_L \tag{1}$$

where:
F_L - lifting force
Z_G - vertical tyre ground reaction
W - weight of the carrying frame together with the wheel and all mounted equipment and loads

Using known value for W and force transducer signal value for F_L, the actual value of the ground reaction Z_G can be determined directly from the expression (1).

Ground reaction Z_G will change with the change of the force F_L. At the same time tyre deflection and the contact length will change accordingly. The following labels are now introduced (see also Fig. 3.):
$Z_{G0} = W$ - ground reaction in the absence of the lifting force ($F_L = 0$)
l_{C0} - tyre contact length when $Z_G = Z_{G0}$
f_0 - tyre radial deflection when $Z_G = Z_{G0}$
l_C and f - universal contact length and deflection values (for $F_L > 0$)
h_{REF} - displacement transducer signal value when the wheel is in the referent position ($F_L = 0$)
h_M - displacement transducer signal value for universal wheel position ($F_L > 0$)
h_0 - displacement transducer signal value exactly in the position when Z_G becomes zero ($F_L = W$)
$\Delta h = h_M - h_{REF}$ - difference between the instantaneous and the referent displacement transducer signal

By gradually increasing F_L, ground reaction will be decreasing according to (1). Exactly observing the instant when Z_G becomes zero (bottom part of the tyre circumference still just touching the ground but without producing any reaction force), value for deflection f_0 is obtained from the instantaneous value of the displacement transducer signal h_0:

$$f_0 = h_0 \tag{2}$$

Tyre deflection at arbitrary state (for the universal value of F_L) can then be calculated from:

$$f = f_0 - \Delta h \tag{3}$$

By using relationships (1), (2) and (3), by varying F_L, dependence between tyre load Z_G and the deflection f is obtained as a series of numerical values.

Varying of the lifting force F_L has to be done very gradually and in both directions (increase and decrease), in order to eliminate impact of tyre hysteresis. At the same time, after the force/deflection increment has reached a certain value, force variation is temporarily paused to carry out measurement of the tyre contact length, as shown in the Fig 3. and 4.

Measured value of the contact length is then recorded manually, together with the actual value of the lifting force. Series of values is then entered into computer memory for the storage and subsequent analysis and calculations. Establishing dependence between ground force and contact length, relationship between contact length and tyre deflection is also obtained, taking into account correspondence between the ground force and deflection. Described procedure for contact length measurements is technically simple to carry out, but it is also rather manual-labour intensive and time consuming.

The whole described procedure is repeated for different values of the tyre pressure and vertical load.

Fig.4. Measuring tyre contact length

3.3. Procedure for the Determination of Linearized Radial Stiffness and Damping Coefficients

Coefficient of stiffness can be determined in the following ways:

- statically, according to the slope of the curve of tyre deflection versus vertical load, and
- dynamically, according to the natural frequency of tyre vertical vibration.

Damping coefficient can be obtained through the time response of free vertical damped vibration by using logarithmic decrement method. Vibration is excited by the free fall of the tyre from the certain height level ("drop test"), which does not have to be much higher than the static equilibrium height.

Logarithmic decrement δ is used both in calculation of damping coefficient and dynamically determined stiffness coefficient:

$$\delta = \frac{1}{T_D} \cdot \ln \frac{z_i}{z_{i+1}} \tag{4}$$

where:
T_D - quasi-period of damped vibration
z_i, z_{i+1} - two adjacent amplitude peaks of the time response curve

Knowing vibrating system mass m, damping coefficient k can now be calculated:

$$k = 2 \cdot \delta \cdot m \tag{5}$$

Free natural frequency of the system ω_0 is:

$$\omega_0 = \sqrt{\left(\frac{2\pi}{T_D}\right)^2 + \delta^2} \tag{6}$$

Dynamically determined stiffness coefficient c is calculated from:

$$c = m \cdot \omega_0^2 \quad (7)$$

Finally, relationship for statically determined stiffness coefficient c is:

$$c = \frac{\Delta Z_G}{\Delta f} \quad (8)$$

where approximation of linear tyre response is adopted in the area of nominal vertical tyre load.

It is well known from the previous investigations (e.g. [1]) that both tyre stiffness and especially damping are dependent on both excitation frequency and the tyre rolling speed. Therefore, results obtained in this work should be viewed as more or less rough approximation. More broad set of test data in view of free damped vibration response with different mass values (meaning different natural frequencies of the system) would though enable empirical modelling of damping coefficient dependence on excitation frequency.

4. MEASUREMENTS RESULTS

4.1. Vertical load, Tyre Deflection and Contact Length

By using described procedure for the determination of dependence between tyre deflection and the vertical load, results were obtained that are presented in the Fig. 5.

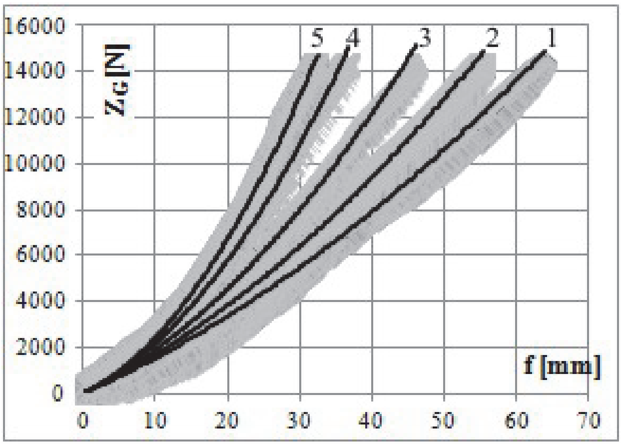

Fig.5. Dependence between tyre deflection f and the vertical load Z_G for different pressure values; 1-0,8 bar, 2-1,1 bar, 3-1,4 bar, 4-1,7 bar, 5-2,0 bar

Fig. 5. shows that, for full range of tyre loads, dependence between tyre load and the deflection is clearly non-linear. However, considering only limited load range in the area of tyre nominal load (i.e. taking very small loads and deflections out of consideration), Fig. 6. shows that linear dependence between load and deflection for this load range represents very acceptable approximation.

Dependence between contact length and tyre deflection is shown in the Fig. 7. Relationship can be well approximated by degressive power growth trendline. Results clearly show that this dependence is of pure geometrical nature, i.e. it is not affected by the tyre pressure or vertical load.

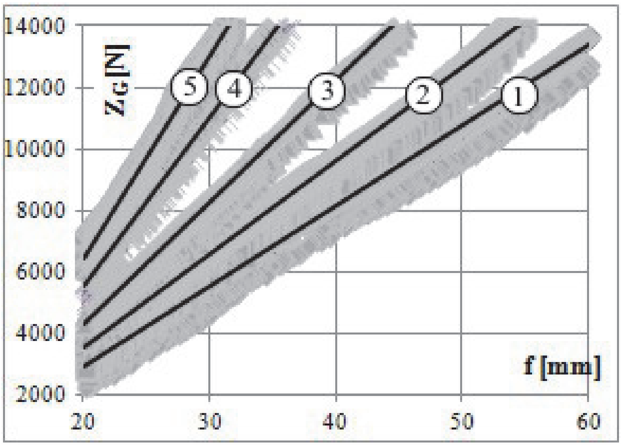

Fig.6. Linear approximation of dependence between tyre deflection f and the vertical load Z_G for limited load range (pressure values as in Fig. 5)

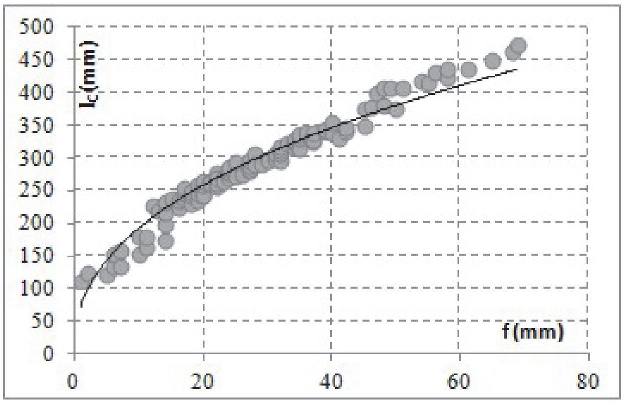

Fig.7. Dependence between contact length l_C and tyre deflection f

4.2. Tyre Radial Stiffness and Damping

Results for the statically determined stiffness coefficients for different tyre pressure values were obtained according to the relation (8), by using curves shown in the Fig. 6. For dynamically determined stiffness, relations (4), (6) and (7) were used. Parameters T_D and z_i (expression 4) were obtained from the oscillogramme, i.e. time history of tyre free response after the drop-test. An example of the oscillogramme is shown in the Fig. 9. Both statically and dynamically determined coefficient values for different pressure levels are presented in the Table 2., and their dependence on pressure is also shown graphically in the Fig. 8.

Table 2. Overall results of the stiffness coefficient calculations

Pressure level	Stiffness [N/m]	
	Static	**Dynamic**
1 (0,8 bar)	261088	377384
2 (1,1 bar)	304957	394732
3 (1,4 bar)	364064	461916
4 (1,7 bar)	520127	537827
5 (2,0 bar)	573638	585737

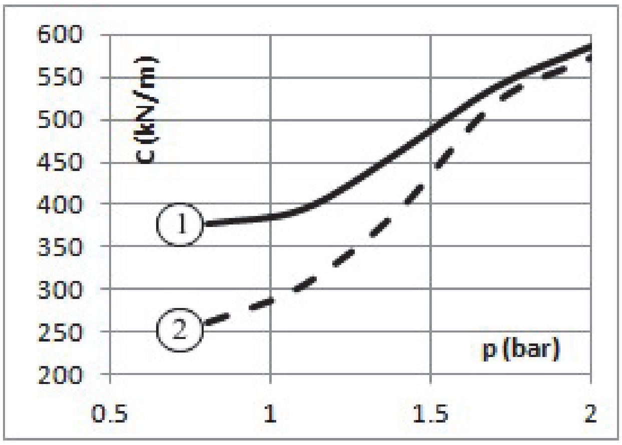

Fig.8. Dependence of statically and dynamically determined stiffness coefficients on pressure

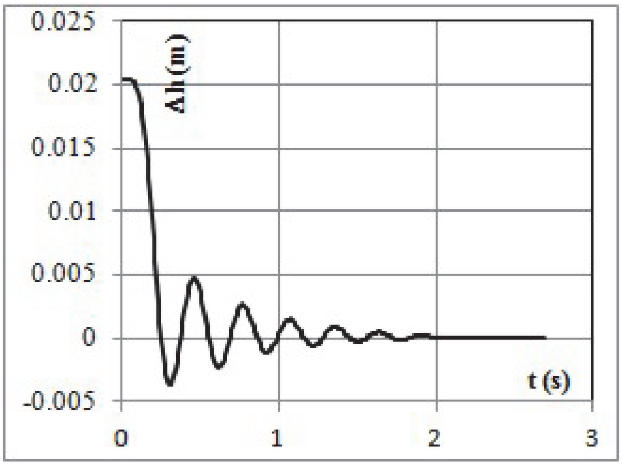

Fig.9. An example of the oscillogramme - time history of tyre free response after the drop-test; t- time, Δh- tyre height with respect to static equilibrium

Results presented in the Table 2 for dynamically determined stiffness coefficient values represent mean values of measurements for three different levels of tyre static load e.g. system mass/weight (according to Table 1). Results for individual values of tyre static load are shown in the Table 3.

Table 3. Results of dynamically determined stiffness coefficient calculations

Pressure level	Dynamic stiffness [kN/m]		
	m=660kg	m=960kg	m=1440kg
1	339,2	377,2	415,7
2	355,1	398,0	431,0
3	403,6	512,0	470,2
4	462,6	619,4	531,5
5	486,4	683,7	587,0

From the results in Table 3 a trend toward rise of the stiffness with higher tyre load can be noticed (though with certain deviations). This phenomenon could be attributed to nonlinearity of the dependence between tyre static load and radial deflection (Fig. 5). For higher loads, tyre vibrates about central position corresponding to greater static deflection, exhibiting greater slope of the load-vs.-deflection curve, which corresponds to higher value of linearized stiffness coefficient.

5. CONCLUSION

This paper describes procedures for determination of some basic tractor tyre parameters by using simple test facility and universal measuring techniques. Dependences between tyre vertical load, static radial deflection and contact length on the hard level ground, as well as stiffness and damping, were investigated.

All described measuring procedures were repeated for different values of tyre pressure and vertical load, which enabled investigation of impact of these two important tyre operational parameters on its behaviour from the observed points of view.

Measurement results shown acceptable level of deviation, so that they were easy for analysis and interpretation. Dependence between deflection and ground force shown non-linearity, although linear behaviour can be used as good approximation in the area of nominal tyre load. It was observed that the dependence between tyre deflection and contact length is of purely geometrical nature, i.e. it is not affected by the tyre pressure and vertical load. Some discrepancy was observed between statically and dynamically obtained results for linearized stiffness coefficient, which is ascribed to non-linear nature of tyre response.

Linearized stiffness and damping coefficient values can be used in certain applications of tyre viscoelastic structure modelling. Caution is though needed as real tyre exhibits dependence of these values on rolling speed and excitation frequencies. Relationships between tyre load, deflection and contact length can be useful when investigating tyre geometric or filtering properties such as enveloping behaviour.

ACKNOWLEDGEMENTS

This paper was done as a part of the researches on the project TR35041 – "Investigation of the safety of the vehicle as part of cybernetic system: Driver-Vehicle-Environment" and the project TR31046 " Improvement of the quality of tractors and mobile systems with the aim of increasing competitiveness and preserving soil and environment", supported by Serbian Ministry of Education, Science and Technological Development.

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