Introduction and guidelines for laboratory exercise:

Determination of the vehicle tire characteristics

1. Introduction

Wheels play important role in locomotion of vehicles. First of all, rotational motion of wheels is converted into linear motion of vehicle's chassis. Secondly, wheels are involved in transferring driving force to the road surface. While driving a vehicle over a bumpy road, dynamic forces and vibrations are induced on the vehicle. In order to reduce adverse effects of the forces and vibrations, wheels of modern vehicles are typically fitted with pneumatic tires.

Wheels of vehicles should meet multiple requirements to ensure safe ride. They have to withstand maximum loads and speed defined by vehicle operating conditions. Connection between tire and rim as well as rim and hub should be strong enough to prevent their relative motion. Moreover, connection between tire and rim should be tight enough to maintain air retention. Eventually, design of the whole wheel should allow for efficient cooling of brake disks and calipers.

Pneumatic tires are crucial parts of vehicles since they are the only ones that make contact with road surface. For this reason, they significantly influence vehicle's stability and response to control input. What is more, some properties of tires may badly affect fuel economy or cause excessive environmental pollution. For these reasons tires should ensure:

- safe and comfortable ride,
- durability and reliability,
- sufficient grip,
- low rolling resistance,
- reduced emissions of noise and tire wear particles.

2. Design of pneumatic tires

The internal structure of an exemplary modern pneumatic tire is presented in Fig. 1.

The main reinforcing plies of a tire are called the body plies. They wrap around bead bundle on the one side of the tire, pass across the tire and wrap around bead bundle on the opposite side. Mechanical properties, number of layers as well as orientation of body plies define strength and stiffness of the tire. Body plies are typically made from synthetic fibres, e.g. rayon, nylon or polyester. Steel cord plies are rarely used. Depending on the orientation of body plies with respect to the centerline of the tire two types of tires are distinguished: radial and diagonal ones (see Fig. 2.). Body plies of radial tires are laid parallel to each other at right angle with respect to the centerline of the tire. On the other hand, body plies of diagonal tires are laid at angle of 30^{O} … 40^{O} with respect to the tire centerline.

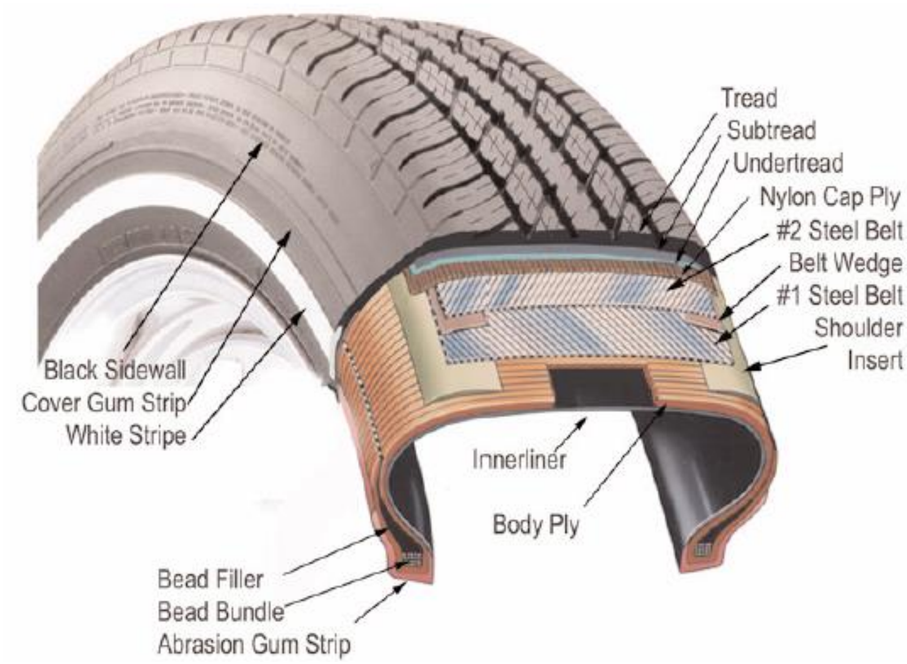

Fig. 1. Internal structure of an exemplary radial tire for passenger cars [3]

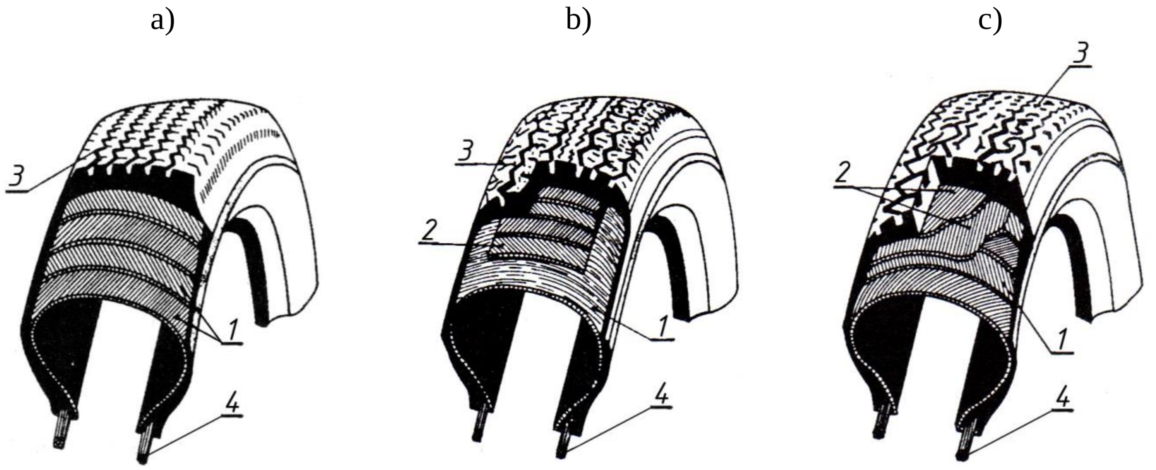

Fig. 2. Schematic view of various types of tires [4]: a) diagonal tire, b) radial tire, c) diagonal belted tire, 1 – body plies, 2 – belt, 3 – tread, 4 – bead bundle

Body plies of radial, and some types of diagonal tires, are wrapped with at least two belts made from steel or synthetic cords. The belts increase tire's vertical stiffness as well as improve impact resistance and stabilize the shape of tread area, preventing the tire from excessive expansion at high speed.

In order to insulate body plies from the edges of belts, shoulder inserts made from rubber compound are applied. On the other hand, belt wedges are placed near the edges of the belts in order to reduce interplay shear at the belt edges as the tire rolls and deflects.

The most inner layer of the tire is called the innerliner. It is made from rubber and its main role is to maintain air retention.

As it was mentioned, body plies are wrapped around bead bundles, i.e. two bundles of steel wires covered with rubber. Empty space between bead bundles and body plies is filled with rubber compound called bead filler or the apex. Bead bundles anchor the tire on a rim, so that they do not move with respect to each other. In order to avoid air leaks and prevent tire body plies from chafing against rim surface, body plies wrapped around bead bundles are covered with abrasion gum strip.

Crown, shoulder as well as sidewall of a tire are covered with layers of rubber. Layer of rubber covering the crown and the shoulder is called the tread, whose main role is to provide appropriate amount of grip. Hence, vast majority of tires has a pattern of grooves or blocks molded in the tread which channel water and loose particles out of the contact patch between tire and the ground. Depth of the grooves may differ depending on the tire's application. Grooves of passenger car tires are typically 6 … 10 mm deep, whereas, grooves of truck tires might be as deep as 16 mm. Layers of rubber covering sidewalls of tires improve tire stiffness and prevent sidewalls from chafing against curbs, road bumps and other obstacles.

3. Comparison of radial and diagonal tires

The main disadvantages of radial tires are complexity of manufacturing process and susceptibility of tire sidewall to damage. Moreover, vertical stiffness of radial tires is relatively high. Hence, elastic joints, i.e. rubber bushings, are typically embodied in suspension systems of vehicles fitted with radial tires. Nevertheless, vast majority of modern on-highway vehicles is fitted with radial tires due to their unquestionable advantages:

- low rolling resistance,
- high lateral stiffness, which improves handling performance,
- good overall durability,
- good grip in dry as well as wet road conditions,
- improved ride comfort on paved roads,

The advantages of diagonal tires over radial ones are simpler manufacturing process, improved durability of sidewalls and low moment of inertia. Thus, they are still used in some specific applications such as: off-road vehicles, agricultural and earthmoving mobile machinery as well as motorcycles and some specific race cars. However, disadvantages of diagonal tires are the following: relatively high rolling resistance and low maximum permissible operating speed.

4. Specifications of pneumatic tires

Size and other specifications of tires are typically molded in their sidewalls. Basic specifications of tires are represented with the following template standardized by ECE R 30 and ETRTO regulations:

195/60 R 15 85 H

where:

195 – width of the tire at inflation pressure of 0,18 MPa (expressed in millimeters)

60 – tire aspect ratio, i.e. ratio of tire height to width (expressed as a percent)

R – type of tire internal structure (R – radial, „-” – diagonal, D – spare wheel)

15 – rim diameter (expressed in inches)

85 – tire load index (see tab. 1)

H – speed rating (see tab. 2)

Tire load index defines the minimum load that particular tire is claimed to withstand at speed of 160 km/h and inflation pressure of 0,25 MPa. On the other hand, speed rating defines the maximum permissible speed at which the tire can be operated. While operating tires rated with Q and higher speed ratings at their maximum permissible speed, their actual load should be lower than the one defined by load index.

Tab. 1. List of tire load indexes (at 0,25 MPa tire inflation pressure)

Load index	**Load capacity (kg)**	**Load index**	**Load capacity (kg)**
80	450	100	800
81	462	101	825
82	475	102	850
83	487	103	875
84	500	104	900
85	515	105	925
86	530	106	950
87	545	107	975
88	560	108	1000
89	580	109	1030
90	600	110	1060
91	615	111	1090
92	630	112	1120
93	650	113	1150
94	670	114	1180
95	690	115	1215
96	710	116	1250
97	730	117	1285
98	750	118	1320
99	775	119	1360

Tab. 2. Exemplary speed ratings of radial passenger car tires

Speed rating	Permissible speed (km/h)	Speed rating	Permissible speed (km/h)
Y	300	M	130
W	270	L	120
V	240	K	110
H	210	J	100
U	200	G	90
T	190	F	80
S	180	E	70
R	170	D	65
Q	160	C	60
P	150	B	50
N	140	A8	40

Apart from the abovementioned basic tire specifications, some additional symbols and marks are usually molded in the outer surface (mainly in the tire sidewall) of tires:

M+S – „Mud and snow" symbol means that the tire is designed to be operated in mud and snow, however, its suitability for snowy conditions has not been confirmed by empirical tests.

3PMSF – Three Peaks Mountain Snow Flake – a symbol given to winter tires whose suitability for operation in snow has been confirmed by experiments. Generally, it is advisable to use the tires of this type if the temperature outdoors stays under 7^{O}C. According to regulations introduced in some European countries, on-road vehicles have to be equipped with tires of this type if road surface is covered with snow and ice.

2109 – a code representing tire production date. 2109 corresponds to week **21** in Year 20**09**. It helps to distinguish tires that do not ensure safe operation due to side effects of rubber compound ageing. According to tire manufacturers' guidelines, shelf life of tires should not be longer than 3 years, whereas tires older than 10 years should be treated as worn out regardless of tread grooves depth.

Max Inflation – maximum permissible inflation pressure of the tire.

TL – helps to distinguish tubeless tires.

TT – helps to distinguish tube type tires.

DSST, EMT, PAX, RFT – symbols given by various manufacturers to so called RunFlat tires, i.e. the tires capable of withstanding operation at zero inflation pressure and reduced speed for limited period of time.

TWI – Tread Wear Indicator – marks molded on the bottom surface of tread grooves, typically 60^{O} apart from each other. If height of tread blocks equals the height of TWI marks, tire is worn out and should be replaced with a new one.

5. Mechanical characteristics of pneumatic tires

Mechanical characteristics of pneumatic tires are usually determined by measuring:

- the amount of force acting on a wheel fitted with an investigated tire and
- deflection of the tire exerted by the force applied to the wheel.

They might be determined in laboratory or road tests. In both cases force applied to the wheel might be of deterministic or stochastic character. Figures 3a., 3b. and 3c. show the idea behind laboratory tests carried out in order to determine mechanical characteristics of pneumatic tires loaded in vertical, longitudinal and lateral direction. Exemplary results of these tests have been also shown.

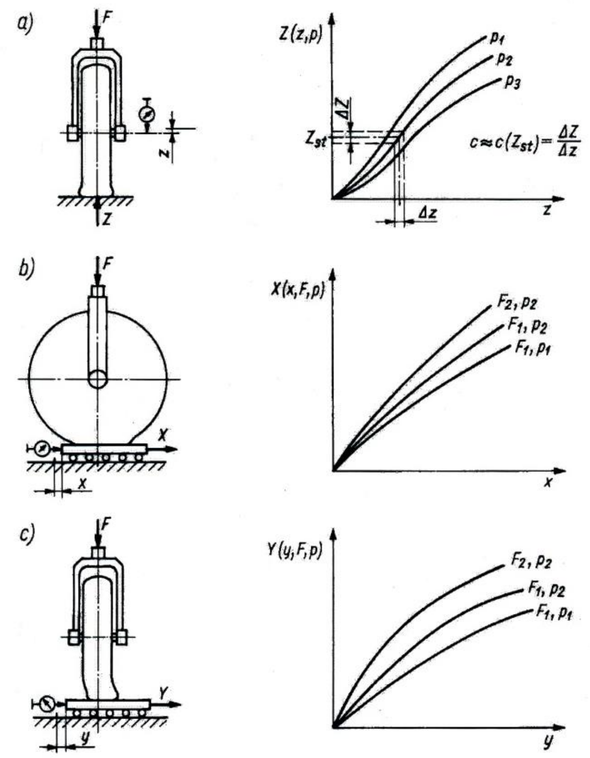

Fig. 3. The idea behind the tests conducted in order to determine mechanical characteristics of tires in vertical (a), longitudinal (b) and lateral (c) direction [2]

From the point of view of numerous engineering considerations, characteristics of very high importance are the relationship between vertical load and vertical deflection. The research on these characteristics might be carried out in various conditions.

- The most simple tests are conducted in quasi-static conditions, i.e. at low loading rate and zero angular velocity of wheel. They might be carried out on flat or uneven surface.
- More advanced tests are conducted in dynamic conditions, i.e.:
    - while rolling the wheel at non-zero angular velocity or
    - in the presence of vertical oscillations of the axis of the wheel.

Figure 4. presents relationships between vertical load and vertical deflection determined for an exemplary tire of an agricultural tractor. They were obtained at various values of inflation pressure as well as at zero and non-zero angular velocity of the wheel. According to Fig. 4. tests carried out in static and dynamic conditions bring slightly different results.

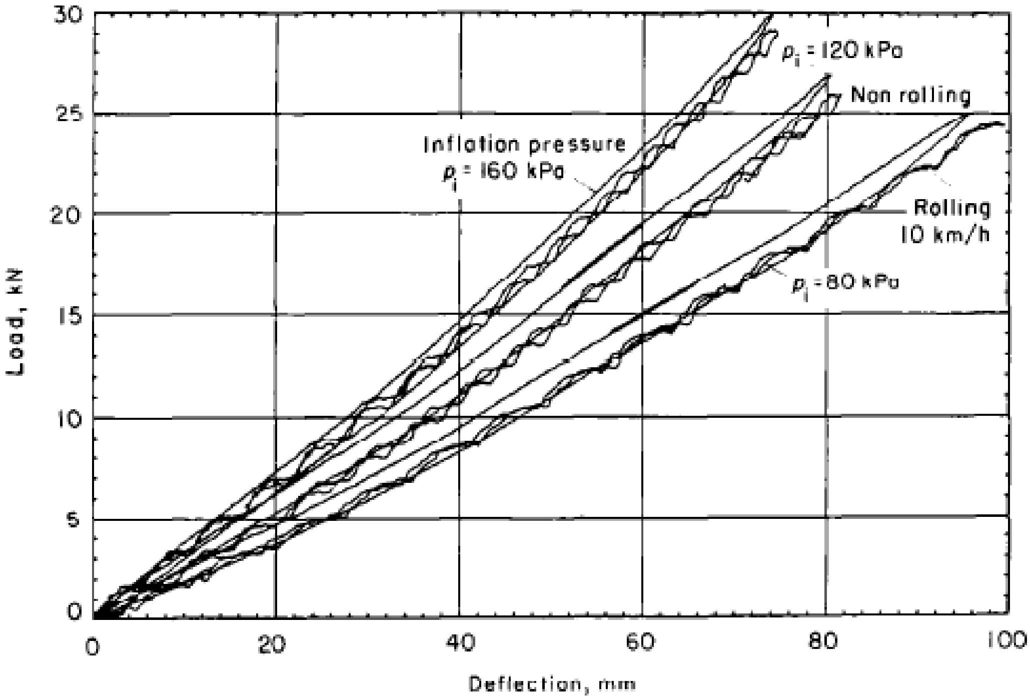

Fig. 4. Relationship between vertical deflection and load determined for an exemplary tire for an agricultural tractor – tire characteristics were determined at different values of tire inflation pressure and at angular velocity corresponding to tire circumferential velocity of 0 and 10 km/h [1]

As a consequence of relatively complex design of tires, depicted in Fig. 1 and 2., relationship between vertical load and deflection of tires is non-linear. Moreover, while tire is being repeatedly loaded and unloaded, some amount of energy delivered to exert tire deflection is lost due to mechanical hysteresis. The energy lost is converted into heat as a result of internal friction of rubber compound and friction between plies reinforcing the tire. As a consequence of mechanical hysteresis, the relationship between vertical load and vertical deflection of an arbitrary tire typically consists of two non-coinciding curves (see Fig. 4., 5. or 6.). The first curve represents tire mechanical characteristics at increasing load, whereas and the second one is valid at declining load.

Generally, stiffness of an arbitrary body is defined by a ratio of infinite small force to infinite small deflection that is exerted by the force (1).

$$\boldsymbol{k} = \frac{\boldsymbol{dF}}{\boldsymbol{dz}} \tag{1}$$

If the relationship between the force and the deflection is linear, stiffness may be simply calculated as a ratio of the overall force acting on the body to the overall deflection that corresponds to the force.

In practice, non-linearity of the relationship between vertical load and vertical deflection of tires is relatively small. Hence, in numerous engineering considerations it might be successfully approximated with linear function (see Fig. 5.). Consequently, it might be assumed that tire stiffness is represented by a constant value. In order to determine this value, firstly, an averaged curve, i.e. a curve lying right in the middle between the curves representing mechanical characteristics of the tire at increasing and declining load, needs to be found. The averaged curve is the most suitable one for the purpose of tire stiffness estimation since while the tire is rolling, it is being loaded as many times as it is being unloaded. Once the averaged curve is found, the line tangent to the averaged curve at the point representing tire nominal load should be determined. Slope of the line is the value of tire stiffness.

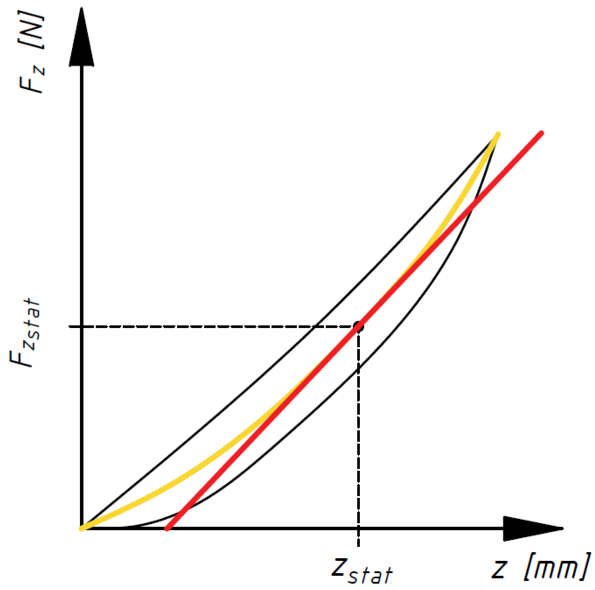

Fig. 5. A method for determination of vertical stiffness of an arbitrary tire; F_{zstat} – vertical force applied to the wheel fitted with a tire under investigation, z_{stat} – deflection of the tire under vertical load F_{zstat}

From the quantitative point of view, mechanical hysteresis of tires might by described by static damping factor ψ which is a ratio of the energy lost in a single loading/unloading cycle of a tire to the overall amount of energy delivered to the tire while increasing vertical load from zero to the maximum value. Referring to Fig. 6., energy delivered to the tire while increasing the load is represented by the area A1 highlighted with blue vertical lines. On the other hand, energy restored after unloading the tire is represented by the area A2 highlighted with the green lines. Thus, the energy lost in a single loading/unloading cycle is represented by the area of the hysteresis loop highlighted with red lines. Eventually, static damping factor ψ is calculated according to the equation (2):

$$\psi = \frac{A_1 - A_2}{A_1} \tag{2}$$

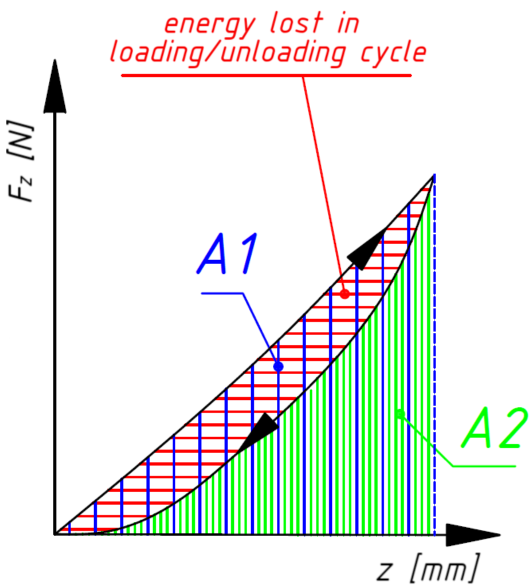

Fig. 6. A method for determination of static damping factor ψ

6. Course of the experiments

Fig. 7. A photography of a test stand involved in the experiments

As a result of the experiments carried out during the laboratory class, vertical stiffness k_z and damping factor ψ of an exemplary tire will be determined by the method explained in the previous section of the following instruction. Figure 7. presents the test stand involved in the experiments. The tests will be carried out in quasi-static conditions at 4 different values of tire inflation pressure. Every experiment will consist of 2 phases. In the first one vertical load of the tire F_z will be gradually increased from zero to the maximum permissible load of the tire. In the second one the tire will be unloaded. Vertical load F_z will be applied to the tire by means of a roman screw. Tire vertical load F_z will be measured by means of load cells embedded inside the plate placed underneath the investigated wheel. On the other hand, vertical deflection of the tire z will be determined using LVDT linear position sensor.

7. Exemplary test questions

- Draw the cross section of a radial tire. Highlight and name the main parts of the tire internal structure.
- Discuss the role played by: body plies, steel belts, tread, innerliner and bead bundles.
- Discuss the main difference in design of radial and diagonal tires.
- List the advantages and disadvantages of radial and diagonal tires.
- Which basic specifications of tires are typically molded in sidewalls of tires? Discuss the standardized template representing tire specifications.
- Which quantities are measured while determining mechanical characteristics of tires? Discuss the general idea behind the tests carried out in order to determine vertical, longitudinal and lateral tire stiffness.
- Describe the method for determination of vertical stiffness and static damping factor of an arbitrary tire.
- How do vertical stiffness and damping factor of a tire influence tire rolling resistance?

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The following instruction has been prepared using also the following references:

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