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AN ANALYSIS OF TIRE RELAXATION IN CONDITIONS OF THE WHEEL SIDE CORNERING AGLE OSCILATIONS

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Abstract

Results of laboratory experimental research of a truck tire, in conditions of side cornering angle dynamic changes are presented in this work. As research objects, there were 2 truck tires. These tires had different construction and as an effect they had different properties, including cornering resistance and relaxation length. Tires tests have been performed using the dynamometric trailer, fixed on the drum facility. During testing, the wheel side cornering angle oscillatory changes have been forcing, with frequency of 2 and 4Hz, in wide scope of the wheel rolling velocity. Chosen measurement results of lateral reaction force have been presented in time domain. Values of the lateral force oscillations amplitude and lateral force time lag have been observed. Amplitude and phase dynamic characteristics of tires, using FFT transformation, have been determined. A decrease of the lateral force oscillations amplitude and an increase of the lateral force phase shift with increasing input signal frequency, as the wheel cornering angle oscillations, have been shown. Conclusions about influence of the wheel rolling speed on tire relaxation effects in dynamic conditions have been formulated. There have been revealed that different properties of different tires types, described in quasistatic conditions have an influence on their behaviour also in dynamic conditions. Lower tire cornering resistance can decrease an amplitude of lateral force oscillations whilst greater tire relaxation length can decrease an amplitude and also can increase phase shift of lateral force oscillations.

Keywords: *pneumatic tire, tire relaxation, tire cornering stiffness*

1. Introduction

In recent years, the interest has been focused on the tire characteristics that determine its behaviour during a dynamic change of wheel motion conditions. In the curvilinear vehicle motion, a dynamic variation of driving wheel motion conditions leads to a phenomenon called a relaxation. The relaxation, as unsteady state process of tire-road interaction, occurs for example during cornering angle fast changing. In such conditions, the change of a lateral reaction force value up to value, related to new motion condition, needs a certain distance to travel by the wheel.

Tire relaxation can be the most easily observed in the laboratory conditions. There are many tire relaxation test methods [1,2,3]. The most of them are dynamic test methods. Although within a cope of the author’s work, a new tire relaxation test method, during wheel cornering using in quasistatic conditions have been developed [4,5,6]. Research results of tires tests, performed in quasistatic conditions allow to determine the tire relaxation length L_n - a parameter which is often used when modelling a tire unsteady state side cornering [6,7,8].

It’s well known that the relaxation length value L_n depends on a cornering angle and wheel normal load, as well [4,6,8]. It’s also known that in dynamic conditions a wheel rolling speed and a wheel cornering angle change rate influence on change rate of lateral reaction force, transmitted by a tire during relaxation process, as a result of forcing a cornering angle step input. [7].

In case of dynamic tires properties analysis, a special importance have tire research results, performed in conditions of wheel cornering angle oscillatory changes. Results of such tests allow describe the tire properties in time and frequency domain, as amplitude and phase dynamic characteristics. Research results, presented in literature, show amplitude decrease and phase shift of lateral reaction force changes, as a result of increasing frequency of the wheel cornering angle changes [9,10]. So it can be supposed that tire relaxation can really change impacts of lateral reaction force on vehicle chassis in conditions of wheel fast turning steering angle, so typical for dynamic drive style or machine controlled steering system. Description of such impacts requires the implementation of experimental research results.

In this work experimental research of truck tires in conditions of cornering angle oscillatory changes, during straight wheel rolling, have been performed. The main aim of research was to describe dynamic characteristics of tires, taking into account the influence of wheel rolling speed and tire type on research results.

2. Research object, conditions and method

The research object were a truck tired wheel, equipped with 2 types of tires:

- all-steel tire of size 275R22.5, marked as „tire 1”,
- nylon-steel tire of size 9.00R20, marked as „tire 2”.

The tires are chosen to realize planned research because of earlier revealed differences between their properties, including cornering stiffness and relaxation length (Fig. 1). The tire 2 has lower cornering stiffness and greater relaxation length. Both of these properties can influence the tire characteristics in conditions of oscillatory cornering angle changes.

The research have been performed in conditions as follows:

- wheel normal load - F_z=1500daN,
- changes frequency of wheel cornering angle values, forced as an input signal - f=2 Hz, f=4 Hz,
- amplitude of wheel cornering angle oscillations, as forced an input signal - $A_\delta \approx 1^O$,
- wheel rolling speed - v=30, 60, 90km/h,
- tire inflation pressure - p_k=650kPa.

A dynamometric trailer have been used in the dynamic tests. Its wheels are rolled on a surface of the steel drums of double-drum facility (Fig. 2) [11].

The trailer force measurement system allows indirect measure of tangential reaction forces (F_x and F_y) transmitted by tested wheel. There are force transducers installed in trailer chassis (Fig. 3.) [12]. So values of lateral reaction force F_y, measured indirectly during research actually characterize the tired wheel impact on the trailer chassis.

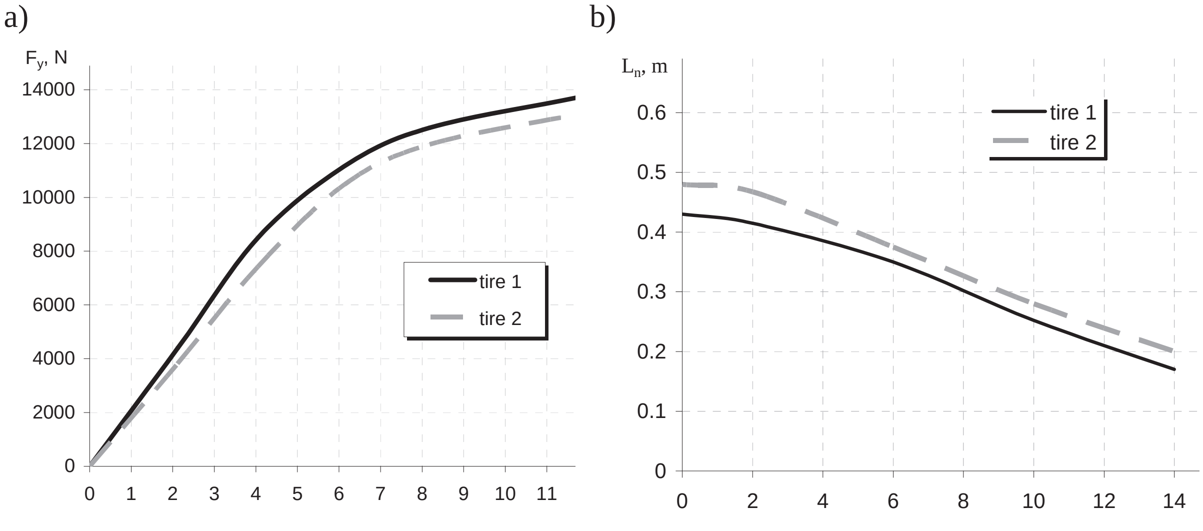

Fig. 1. A comparison of tires selected properties, determined in quasistatic wheel motion conditions; a) cornering resistance characteristics of tires; b) tires relaxation length characteristics of tires

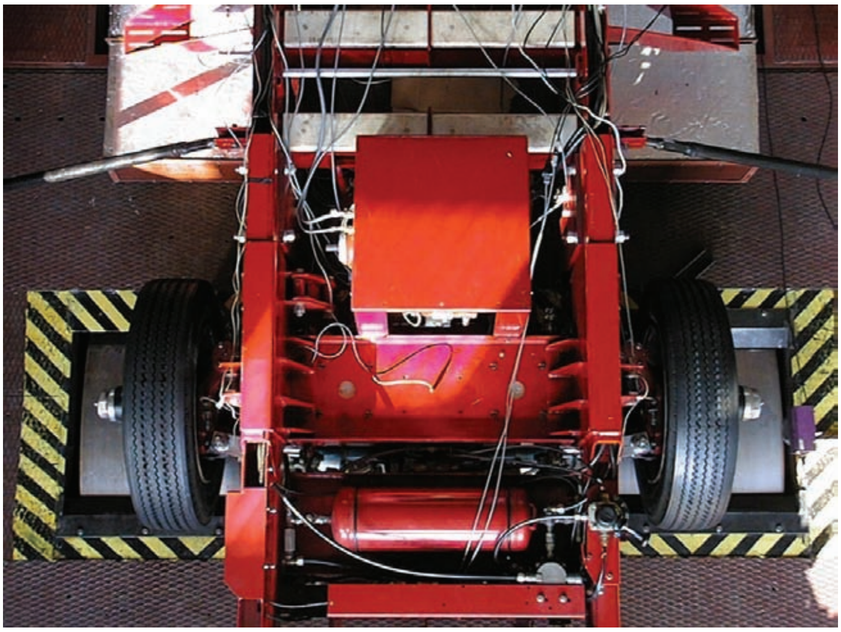

Fig. 2. The dynamometric trailer during the tire testing at the double-drum facility - top view

The trailer is equipped with hydraulic system of the wheel turning, controlled by the programmable D/A converter card. This is an important advantage of steering method. The control of tested wheel turning by the machine ensures a repeatability of research conditions, especially important in scope of frequency and amplitude of wheel cornering angle changes, as an input signal.

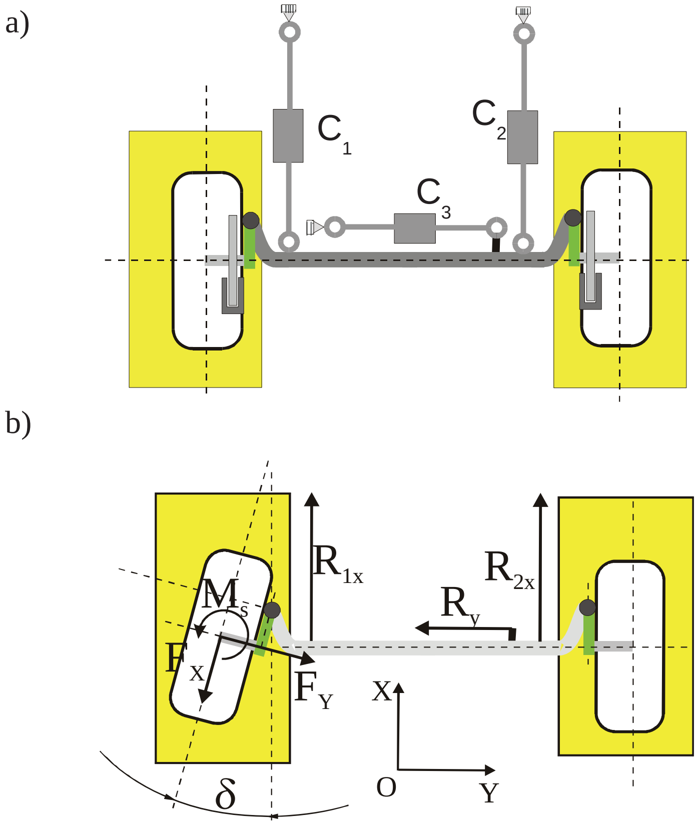

Fig. 3. A scheme of dynamometric trailer axle suspension (a) and system of forces acting on the trailer axle during tested wheel turning (b); R_{1x}, R_{2x}, R_y - forces in reaction rods, F_x – longitudinal reaction force, F_y – lateral reaction force, M_s – stabilizing moment, δ -wheel cornering angle (turn angle)

3. Research results analysis

Example measurement results, obtained during wheel rolling with speed 30 km/h, are presented on Figure 4. As an input signal are oscillatory changes of cornering angle values δ (Fig. 4a). The response for input signal is values oscillations of lateral force F_y, transmitted into trailer chassis (Fig. 4b).

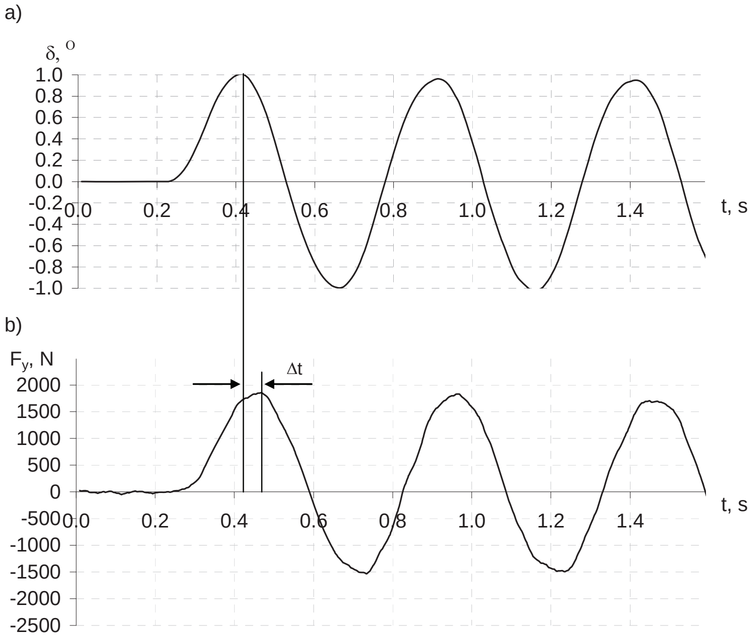

Fig. 4. Changes of lateral reaction force F_y, transmitted by wheel, as a response for the wheel cornering angle δ oscillatory changes (tire 1, v=30km/h, f=2Hz); a) changes of the wheel cornering angle δ - input signal; b) changes of lateral force reaction F_y, transmitted by wheel - output signal

Lateral force F_y values oscillate with certain amplitude and frequency due to input signal frequency, but with clear time lag Δt of these oscillations relatively to input signal. On the next Figure You can see that the same input signal causes an increase of lateral force F_y oscillations amplitude with increasing the wheel rolling speed (Fig. 5).

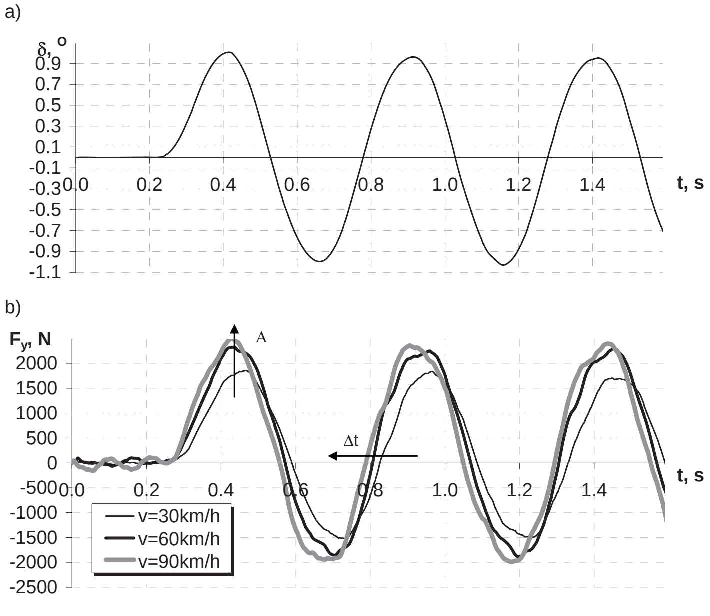

Fig. 5. Changes of lateral reaction force F_y, transmitted by wheel, as a response for cornering angle δ oscillatory changes of wheel, rolled with different speeds (tire 1, f=2Hz); a) changes of the wheel cornering angle δ - input signal; b) changes of lateral force reaction F_y, transmitted by wheel - output signal

Simultaneously, with increasing the wheel rolling speed a time lag Δt of lateral force F_y decreases, so its values changes occur faster. Also an increase of input signal frequency (cornering angle oscillations), while maintaining the same amplitude, causes clear changes of response signal. On the Figure 6, You can see a clear decrease of lateral force F_y oscillations amplitude as an effect of wheel cornering angle δ oscillations frequency.

Observed phenomena are an effect of the tire relaxation in unsteady state side cornering process. Established forcing method of the wheel cornering angle changes enables to conduct an analysis of tested wheel impact on vehicle chassis in frequency domain. Forced input signal (the wheel cornering angle δ oscillations) and obtained output signal (lateral force F_y values oscillations) have been processed with Fourier's transformation. Obtained spectrum signals are presented on Figure 7.

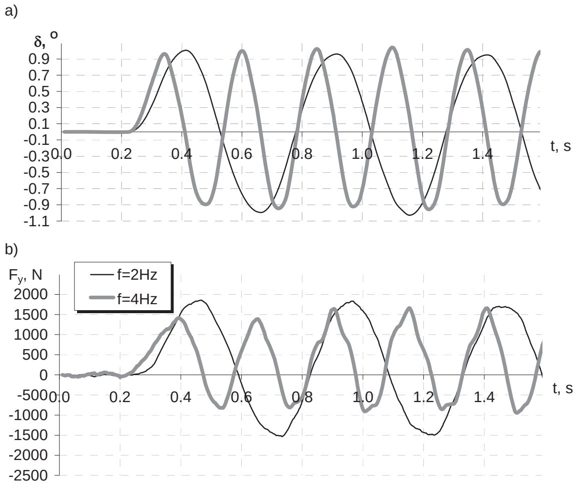

Fig. 6. Changes of lateral reaction force F_y, transmitted by wheel, as a response for the wheel cornering angle δ changes with different oscillation frequency (tire 1; v=30km/h); a) changes of the wheel cornering angle δ - input signal; b) changes of lateral force reaction F_y, transmitted by wheel - output signal

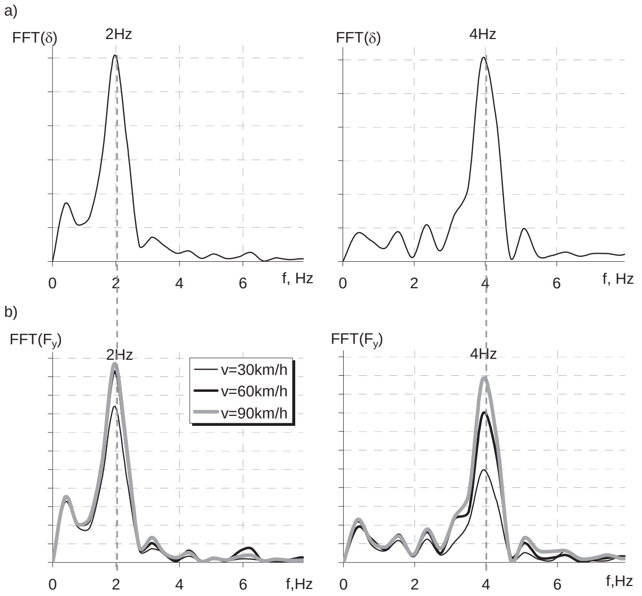

Fig. 7. Magnitude of measured signals Fourier transformations (tire 1); a- spectrum of input signal forced as oscillations of the wheel cornering angle δ; b - spectrum of output signal obtained as oscillations of lateral reaction force values F_y

The tire behavior observed before in time domain is also visible in frequency domain. For similar, repetitive spectrum of input signal FFT(δ), for fixed forced input signal frequency, there are visible (Fig. 7):

- increasing values of lateral force spectrum FFT(F_y) with increasing wheel rolling speed,
- much decreased values of lateral force spectrum FFT(F_y) for higher values of input frequency (4 Hz), for every wheel rolling speed.

Obtained spectrum signals allows calculating of the transmittance module and the phase shift of the lateral reaction force F_y signal in relation to input signal, forced as the wheel cornering angle δ, in certain motion conditions. For both certain values of input signal frequency and at particular wheel speed, there have been calculated:

- transmittance module for lateral reaction force, dividing the value of lateral force signal spectrum magnitude by the wheel cornering angle signal spectrum magnitude

$$G(F_y) = \frac{A(F_y)}{A(\delta)}, \tag{1}$$

- pahse shift of lateral force, substracting a phase angle of cornering angle signal from phase angle of lateral force signal

$$\phi = \phi(F_y) - \phi(\delta). \tag{2}$$

For input frequency f=0 Hz, there have been settled:

- transmitantce module $G(F_y)$, basing on the tire cornering resistance characteristics, obtained in steady state wheel motion conditions (Fig. 1)

$$G(F_y) = \frac{F_y(\delta = 1^O)}{1^O}, \tag{3}$$

- phase shift for steady state wheel motion conditions ϕ=0.

Calculation results are presented as amplitude and phase dynamic characteristics (Fig. 8).

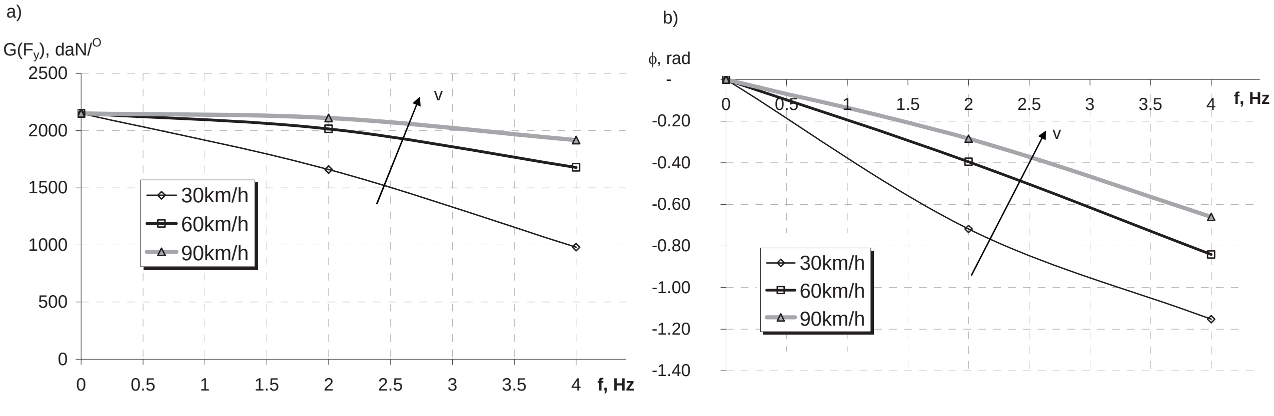

Fig. 8. Dynamic characteristics of tire 1, determined in frequency domain, for different wheel rolling speed, in conditions of the wheel cornering angle oscillatory changes; a) amplitude characteristics; b) phase characteristics

Assuming that transmittance module characterizes a possibility of lateral force F_y transmitting with certain oscillation amplitude and that phase shift characterizes a tire response time lag in relation to changes of the wheel motion conditions, it can be said that:

- a possibility of transmitting lateral force oscillations with certain amplitude, during dynamic changes of the wheel motion conditions, decreases with increasing these changes frequency, but increase with increasing the wheel rolling speed.
- a time lag of tire response for dynamic wheel motion conditions changes increases with increasing these changes frequency, but decreases with increasing wheel rolling speed.

Example measurement results of two tire of different construction (tire 1 and tire 2) during oscillatory changes of wheel cornering angle are presented on Figure 9. As it’s visible, with similar input signal, as cornering angle oscillations δ, the tire 2 shows clearly lower values of lateral force F_y oscillation amplitude and greater time lag of lateral force oscillation, comparing to tire 1. These are effects of as well lower cornering stiffness as higher values of relaxation length of tire 2 comparing to tire 1, which are well visible on Figure 1.

Research results of the tire 2 have been processed with Fourier's transformation similarly to tire 1, so its dynamic characteristics have been also obtained. Characteristics of both types of tires are presented on Figure 10. As it is visible both tires respond similarly to the wheel motion conditions, but the tire 2 shows clearly a greater time lag relatively to input dynamic changes of the wheel motion conditions, throughout the range of forced frequency and the wheel rolling speed, compared to the tire 1 (Fig. 10b). In this case it is a result of higher values of tire's 2 relaxation length L_n. Basing on amplitude dynamic characteristics (Fig. 10a) it's difficult to say, if the tire 2 responses to dynamic changes of motion conditions different than the tire 1. Although values of transmittance module of the tire 2 are lower compared to the tire 1, throughout the range of motion conditions changes but it can be only an effect of the tire 2 lower cornering stiffness. That's why tires dynamic amplitude characteristics transformed to dimensionless characteristics, which are presented on Figure 11. In this case it's revealed, that the tire 2 shows stronger relative decrease of transmittance module compared to the tire 1 with increasing forced input signal frequency, especially for lower wheel rolling speed. This is the prove that it's a relaxation effect of the tire, which has higher values of relaxation length L_n (the tire 2).

So higher relaxation length values L_n of the tire 2 are also a reason why its possibility of a lateral force transmitting with possible amplitude, during dynamic changes of the wheel motion conditions, decreases more than the tire 1 shows.

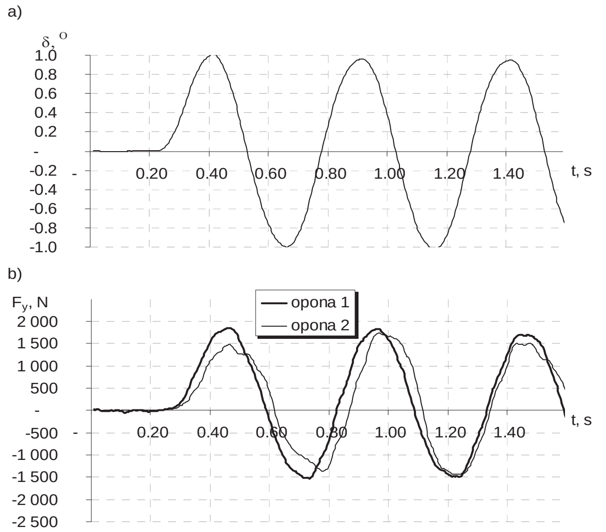

Fig. 9. Changes of lateral reaction force F_y, transmitted by wheel equipped with different tire types, as a response for the wheel cornering angle δ oscillatory changes (v=30km/h, f=2Hz); a) changes of the wheel cornering angle δ - input signal; b) changes of lateral force reaction F_y, transmitted by wheel – output signal

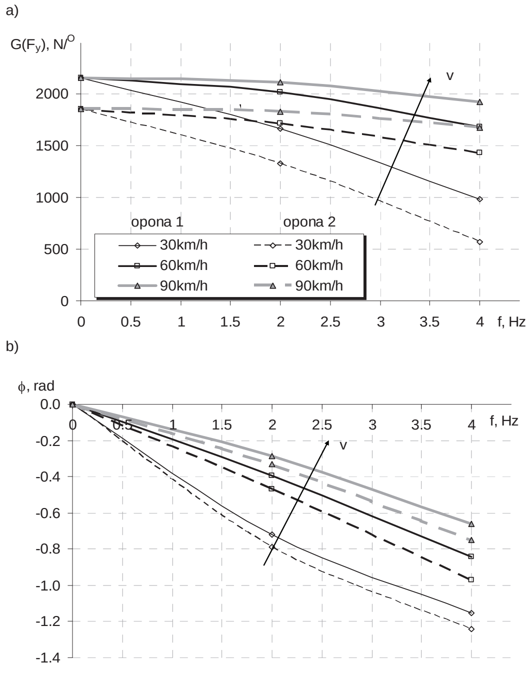

Fig. 10. Dynamic characteristics of tires 1 and 2, determined in frequency domain, for different wheel rolling speed, in conditions of the wheel cornering angle oscillatory changes; a) amplitude characteristics; b) phase characteristics

4. Summary

Basing on presented experimental research results, it's possible to say, that tire properties in transient conditions of a wheel motion, described during quasistatic research have an influence on tire behaviour in dynamic conditions. An increase of the wheel cornering angle oscillations frequency causes lower values of lateral reaction force oscillations amplitude and also causes longer time lag in relation to forced input signal.

A change of the tire properties, causing elongation of its relaxation length, can decrease the amplitude and increase the phase shift of the tire lateral reaction force oscillations.

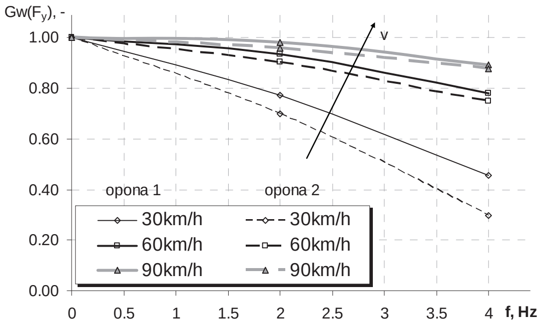

Fig. 11. Dimensionless amplitude characteristics of tires 1 and 2, determined in frequency domain, for different wheel rolling speed, in conditions of the wheel cornering angle oscillatory changes;

There have been shown, that increase of the wheel rolling speed causes clear decrease of a tire relaxation weight, from the viewpoint of amplitude and time shift of later force oscillations transmitted by the tire to the vehicle chassis. With the wheel rolling speed increase, differences between transient properties of different construction tires become blurred.

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