Experimental studies of breaking of elastic tired wheel under variable normal load

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Abstract. The paper analyzes the braking of a vehicle wheel subjected to disturbances of normal load variations. Experimental tests and methods for developing test modes as sinusoidal force disturbances of the normal wheel load were used. Measuring methods for digital and analogue signals were used as well. Stabilization of vehicle wheel braking subjected to disturbances of normal load variations is a topical issue. The paper suggests a method for analyzing wheel braking processes under disturbances of normal load variations. A method to control wheel baking processes subjected to disturbances of normal load variations was developed.

1. Introduction
Automobile remains the most dangerous mode of transportation. Travelling at a high rate of speed, having a large mass and kinetic energy, cars have only one possibility to reduce speed or change a direction of travel – to use forces of the grip of tyres on the road.

Car braking is closely related to the characteristics of tyre grip on the road. To increase braking efficiency, cars are equipped with automated systems. But the quality of these systems decreases if road irregularities impact the wheels of a braking car. For example, variations of normal load $R_z$ on the wheels increase the length of the brake path by 37-40% [3].

So, more research on this timely topic is urgently needed. The authors believe that both theoretical and experimental studies can be used [4].

2. Materials and methods
Figure 1 shows a layout of the test bench created for the experiment. Test bench structure allows analyzing the wheel braking under normal load $R_z$, disturbances and enables:

– experimental studies of tire grip characteristics on the chassis dynamometer surface in steady-state;
– experimental studies of the wheel braking under both constant and variable normal load $R_z$;
– change in harmonic normal wheel loading $R_z$ providing the ability to vary its frequency and amplitude;
– controlling the braking of the wheel.

The test bench is equipped with a chassis dynamometer drive system, system loading the wheel with both constant $R_z$, and variable $\Delta R_z$ normal loads, measuring systems for the angular velocity of the
wheel $\omega_k$, angular acceleration of the wheel $\dot{\omega}_k$, angular velocity of chassis dynamometer $\omega_b$, longitudinal reaction $R$, braking moment $M$.

Asphalt-paved chassis dynamometer 1 with an outside diameter of 1770 mm rotates an electric hydrodrive (not shown in Fig. 1). It enables one to smoothly handle the rotation velocity of the chassis dynamometer in the range of 0 to 22.6 rad/sec. The circular velocity of the chassis dynamometer surface can amount to 20 m/sec.

Figure 1. Layout of the test bench for studying elastic tired wheel braking under variable normal load:
1 – an asphalt-paved chassis dynamometer; 2 – an elastic tired wheel; 3 – a sensor’s frame of longitudinal reaction $R_x$ measurement; 4 – a gate of the loading system ensuring variable normal load $R_z$ on the wheel; 5 – a crank ensuring impact of a variable component $\Delta R_z$ of the normal load on the wheel; 6 – an electric hydrodrive of the loading system ensuring variable normal load on the wheel.

Wheel slip $S$ with respect to the chassis dynamometer surface can be determined by formula:

$$S = 1 - \frac{\omega_k \cdot r_k}{\omega_b \cdot r_b} \tag{1}$$

$R_k$ is a rolling radius under driven mode;
$r_b$ is a chassis dynamometer radius;
$\omega_k$ is an angular velocity of the wheel;
$\omega_b$ is an angular velocity of the chassis dynamometer.

Braking drive consists of a disc brake of GAZ-3110 connected to wheel 2 with a cardan shaft and hydraulic disc brakes (not shown in Fig.1).

The loading system ensuring variable normal loads on the wheel consists of electric hydrodrive 6 (consisting of an electric engine and a hydrostatic drive) rotating a crank with controlled gate 4 and
loading the wheel through frame 3. The static component of the normal load \( R_z \) on the wheel is assigned by changing the length of controlled gate 4. The frame connected to the gate through bearing units and a shaft provides normal load \( R_z \) on wheel 2.

The static value of the target normal load \( R_z \) on the wheel is 0 -7.2 kN; the dynamic one is 8.5%-52% of the static load value.

The dynamic component of the normal load \( \Delta R_z \) is produced as a result of the impact of rotating crank 5 on gate 4. The crank is rotated by an electric hydrodrive consisting of an electric engine and a controlled hydro pump. The amplitude of the dynamic component of the normal load varies distinctly by changing the throw of crank 5. Amplitude values are shown in Figure 1.

Measuring system for the longitudinal reaction \( R_x \) consists of frame 3 connected with wheel spindle 1 and a tenso-beam (not shown in Fig.1). The longitudinal reaction ranges from 0 to 7.2 kN with an accuracy of ±3.1%.

Angular velocity \( \omega_k \) measuring system has an electromagnetic pulse sensor which produces 120 sinusoidal pulses in one full revolution. Electronic converter converts sinusoidal pulses into standard pulses “1” – “0” which are fed to the computer for recording, processing and storage.

The system measuring the angular velocity of the chassis dynamometer \( \omega_b \) operates in the same way as the angular wheel velocity measuring system.

The values of the angular velocity range from 0 to 50.0 rad/sec. with an accuracy of ±1.7%.

Angular acceleration of the wheel \( \ddot{\omega}_k \) is determined by computing the first derivative of an angular wheel velocity signal.

Experiments were carried out to analyze the braking of the elastic tired wheel under variable normal load \( R_z \). The relations between force and kinematic parameters of the braking wheel under variable normal load \( R_z \) were identified.

The experiments were carried out on the tests benches using Hankook 175/70R13 tires for which one determined dependences of a rolling radius \( r_k \text{o} = f(R_z) \) on the normal load. Normal load variation frequency was 1, 3, 5, 7 and 10 Hz. It complied with variation frequencies for sprung and unsprung masses. The amplitude of normal load variations for the braking wheel \( R_z \) was selected according to wheel rolling along roads under operating conditions (Table 1) [3].

The average value of the normal load was selected according to the Government Standard 4754-97 and amounted to 3.9 kN.

Methods of the experiment were as follows:
1. Air pressure in the warm tire was 170 kPa;
2. The minimum amplitude of normal load variations was set by changing the throw of a crack (see Table 1);

Table 1. Changes in normal load on car wheel under road and test bench conditions [3]

| Sl.No | Type and condition of a road surface | Car velocity, [km/h] | Change in load \( R_z \) with respect to the static one, [%] | Change in load \( \Delta R_z \) with respect to the static one, [%] | Amplitude of changes in a dynamic wheel radius, [mm] |
|-------|-----------------------------------|----------------------|-------------------------------------------------|-------------------------------------------------|----------------------------------|
| 1     | Good highway                      | 32 70                | from ± 2 to ± 5 from ± 4 to ± 11                | ±8.5 3.5                                        |                                  |
| 2     | Good asphalt-paved road           | 28 70                | from ± 10 to ± 15 from ± 15 to ± 25             | ±22 9.0                                        |                                  |
| 3     | Satisfactory asphalt-paved road   | 34 77                | from ± 16 to ± 33 from ± 20 to ± 55             | ±38 15.5                                       |                                  |
| 4     | Asphalt-paved road               | 57                   | from ± 10 to ± 75                               | ±52 25.4                                       |                                  |
with a lot of irregularities

|   | Cobble-stone road |   |   |
|---|------------------|---|---|
| 5 | 51               | 71 | more than 100 |

3. The average value of the normal load $R_z$ on the wheel was set at 3.9 kN by changing the length of a loading gate;
4. Chassis dynamometer was accelerated to the target velocity;
5. Mechanism ensuring normal load $\Delta R_z$ variation was started.
6. Wheel loading was ensured by constant braking moment $M_t$ increased distinctly up to the wheel module;
7. By varying the braking moment $M_t$ we recorded changing characteristics of longitudinal reaction $R_x$, normal load $R_z$, angular velocity $\omega_k$, angular acceleration $\omega_k^\prime$; braking moment $M_t$;
8. Normal load $\Delta R_z$ variation frequency was equal to 1, 3, 5, 7 and 10 Hz;
9. The amplitude of normal load $R_z$ variations increased (see Table 1).

![Figure 2. Two oscillograms of wheel braking at normal load variation frequencies of 3 Hz and 7 Hz.](image)

The comparison of experimental and calculation data [5] proved their qualitative and quantitative compliance for longitudinal reaction $R_x$, angular velocity $\omega_k$ and angular acceleration $\omega_k^\prime$.

In particular, the maximum differences in slip values calculated with and without regard of contact area dislocation velocity for tested modes do no exceed 3 %. The maximum calculation error was obtained for angular wheel acceleration, and it does not exceed 5 %.

The experiments show that normal load variations impact force and kinematic parameters of the braking wheel, particularly at a high rate of the braking moment.

For example, when the braking moment $M_t = 0.63$ kN·m and normal load variation frequency $\nu = 3$ Hz, minimum and maximum values of the angular wheel acceleration are $-120$ rad/sec$^2$ and $+270$ rad/sec$^2$ correspondingly. Threshold limit values of the circumferential delay when the existing ABS signals releasing brakes are $(0.8...2.5)$ g [2].

For absolute values of the angular wheel acceleration, they are $- 2.6...82$ rad/sec$^2$. It means that the impact of variations of the normal load on the ABS is significant and should be taken into account when designing and operating a vehicle.
Dependences $R_x = f(R_z)$, $\omega_k = f(R_z)$, $\omega_\ell = f(R_z)$ and $S = f(R_z)$ illustrate the impact of normal load variations on force and kinematic wheel parameters. They are shown in Figures 3 and 4.

**Figure 3.** Phase dynamic and static characteristics of the longitudinal reaction and angular acceleration of the Hankook 175/70R13 tired wheel braking at average normal load $R_z = 3.9$ kN:

- non-stabilized mode ($\Delta R_z = \pm 1.5$ kN with frequency $\nu = 3$Hz);
- stationary mode ($\nu = 0$)

They are constructed using the above-mentioned data (see Fig. 1a).

3. Results and discussion

In a stationary braking mode, the longitudinal reaction $R_x$ (Fig. 3a) and angular acceleration $\omega_\ell$ (Fig. 3b) depend almost not at all on $R_z$: the static (stationary) characteristics $\omega_\ell = f(R_z)$ is in the zero line, and $R_x$ rises slightly with increasing $R_z$, due to decrease in the force arm $r_ko$.

These parameters mainly respond to the rate of normal load $R_z$ variations. The dynamic components of these parameters reach a peak when variation rates $R_z$ are maximum.

In a stationary mode, angular velocity of the wheel $\omega_k$ and slip $S$ depend on $R_z$ (see Figures 4a and 4b). It is due to the dislocation of braking mode along $f(S)$ diagram when changing the wheel grip $R_\varphi$.

Dynamic components of the parameters $\omega_k$ and $S$ reach a peak in the area of small values of $R_z$, when the static characteristics $R_x = f(S)$ varies significantly, and increase or decrease in $R_z$ is still significant.
Figure 4. Phase dynamic characteristics of the angular velocity and slip of the Hankook 175/70R13 tired wheel:

- non-stabilized mode (v = 3Hz);
- stationary mode (v = 0)

Thus, non-stabilized characteristics $R_z$, $\omega_k$, $\omega_k$ and $S$ at a constant braking moment and a variable normal load depend on both the rate of changes in $R_z$, and wheel rolling mode determined as a correlation of the braking moment $M_t$ and grip moment $M_g$ (*expression of potential grip characteristics of tires and support surfaces*). With an increasing degree of grip characteristics, the impact of non-stabilized normal load $R_z$ on the force and kinematic parameters of elastic tired wheel increases.

To analyze the ABS performance, phase characteristics (dependences of the values of the braking moment $M_t$ and longitudinal reaction on the slip $S$) can be used. Use of these characteristics at the variable normal load $R_z$ is impossible, as the wheel braking mode depends on the correlation of the braking moment and grip limit moment. The relative ratio (*a normalized braking function*) can be used instead:

$$f_{t(s)} = \frac{M_t + M_{fc}}{r_o} \cdot \frac{1}{R_z \cdot \varphi_{max}} \quad (2)$$

It is a relation of the braking force determined by moment $M_t$ to the maximum longitudinal reaction under that load.

If one adds a normalized braking function $f(S)$ in the diagram (Fig.5), one can obtain a chart of the normalized phase diagram of the wheel braking which is equivalent to phase characteristics of ABS controlling [2].

When the wheel is loaded with constant braking moment $M_t$, $f_t$ changes due to a decrease or increase in normal load $R_z$. In a traditional phase characteristics, only changes in braking moment are taken into account.
Figure 5. Normalized phase diagram of braking of Hankook 175/70R13 tired wheel at constant braking moment and variable normal load with frequency $\nu = 3\text{Hz}$ and amplitude $\Delta R_z = \pm 1.5 \text{kN}$

4. Conclusion

Variable normal load on the wheels of a braking vehicle is a significant interference which can affect the braking of the wheel.

Braking of the wheel subjected to interference can vary between complete blocking and deep brake releasing. It is equally true for the braking system as a part of the ABS and apart from it.

The normalized phase diagram of the braking is the most relevant for analysis of the braking process subjected to interferences under variable normal load $R_z$, with regard to the variable braking moment $M_t$. It enables us to analyze the process with regard to variable normal load $R_z$, and variable braking moment $M_t$.

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