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

A I Fedotov[1], V G Zedgenizov[1], N I Ovchinnikova[2]

[1] Irkutsk National Research Technical University, 83 Lermontov St., Irkutsk, 664074, Russian Federation
[2] Department of Mathematics, Engineering Faculty, Department of Mathematics, Engineering Faculty, Irkutsk State Agrarian University. Molodezhny St., Irkutsk District, 664038, Russia

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 ΔR_z normal loads, measuring systems for the angular velocity of the wheel ω_k, angular acceleration of the wheel $\dot{\omega}_k$, angular velocity of chassis dynamometer ω_b, longitudinal reaction R_x, braking moment M_t.

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.

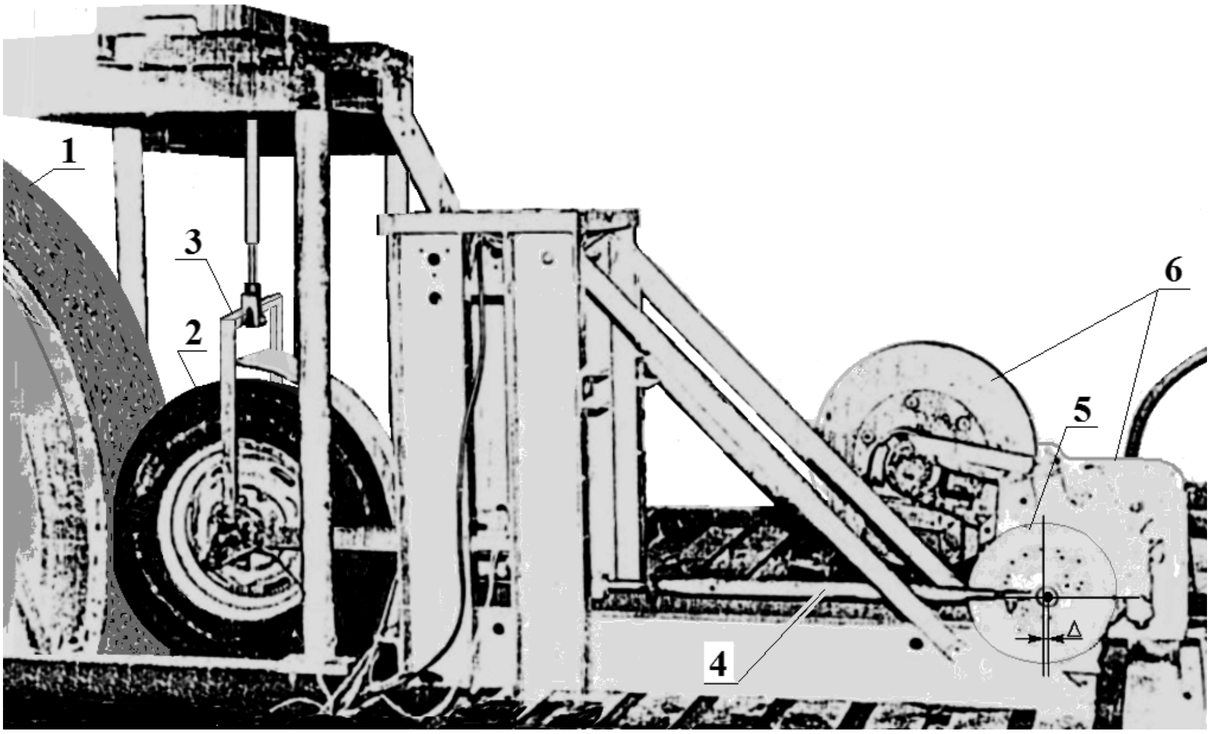


Figure 1. Layout of the test bench for studying elastic tired wheel braking under variable normal load: 1 – an asphalt-paved chassis dynamometer; 2 – an elastic tired wheel; 3 – a sensor's frame of longitudinal reaction R_x measurement; 4 – a gate of the loading system ensuring variable normal load R_z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

$$S = 1 - \frac{\omega_k \cdot r_{ko}}{\omega_b \cdot r_b} \quad (1)$$

R_{ko} is a rolling radius under driven mode;
r_b is a chassis dynamometer radius;
ω_k is an angular velocity of the wheel;
ω_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 ΔR_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 $\omega_к$ 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 $\omega_б$ 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 $\dot{\omega}_k$ 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 $r_{ko} = f(R_z)$ 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:

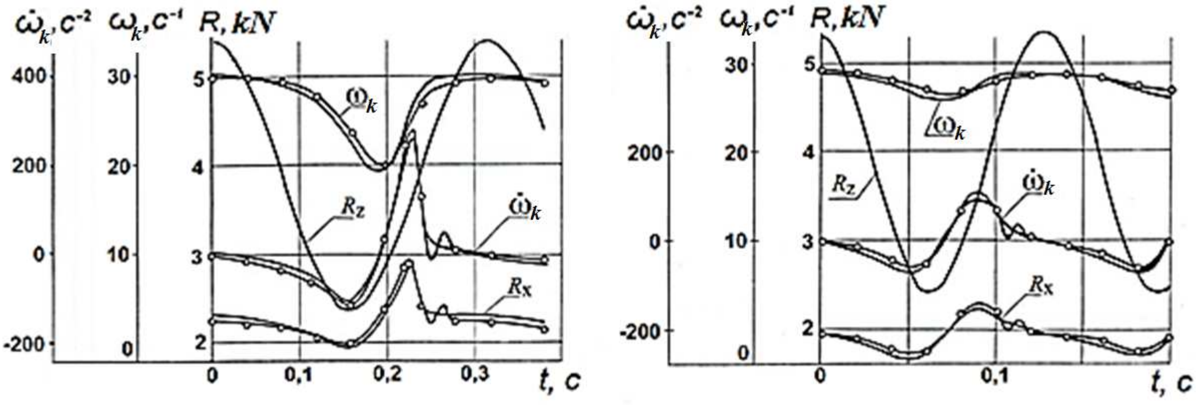
1. Air pressure in the warm tire was 170 kPa;
2. The minimum amplitude of normal load variations was set by changing the throw of a crack (see Table 1);

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

Sl.No	Under road conditions			On the test bench	
	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 ΔR_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				
5	Cobble-stone road	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 ΔR_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 ω_k; angular acceleration $\dot{\omega}_k$; braking moment M_t;
8. Normal load ΔR_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).



a) b)

Figure 2. Two oscillograms of wheel braking at normal load variation frequencies of 3 Hz and 7 Hz. ——— - calculation; —o—o— - experiment

The form of variations of the normal load on the wheel was close to sinusoidal, and the amplitude was ±1.5 kN. The value of the braking moment M_t was kept 0.63 kN·m, at a variation frequency R_z equal to ν = 3 Hz, and 0.54 kN·m at a variation frequency R_z, equal to ν = 7 Hz. It amounted to about 68 % and 56 % of the grip limit moment M_φ at the nominal normal load on the wheel R_z.

The comparison of experimental and calculation data [5] proved their qualitative and quantitative compliance for longitudinal reaction R_x, angular velocity ω_k and angular acceleration $\dot{\omega}_k$.

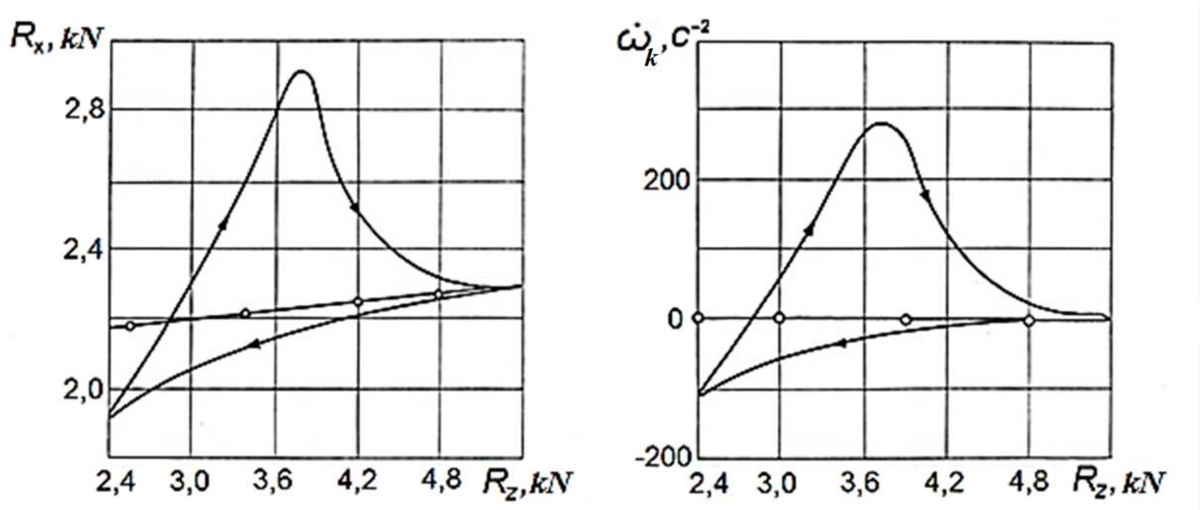
In particular, the maximum differences in slip values calculated with and without regard of contact area dislocation velocity for tested modes do no exceed 3 %. The maximum calculation error was obtained for angular wheel acceleration, and it does not exceed 5 %.

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 ν = 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 $R_x = f(R_z)$, $\omega_k = f(R_z)$, $\dot{\omega}_k = f(R_z)$ 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.



a) b)

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 ν = 3Hz);
—o—o— - stationary mode (ν = 0)

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

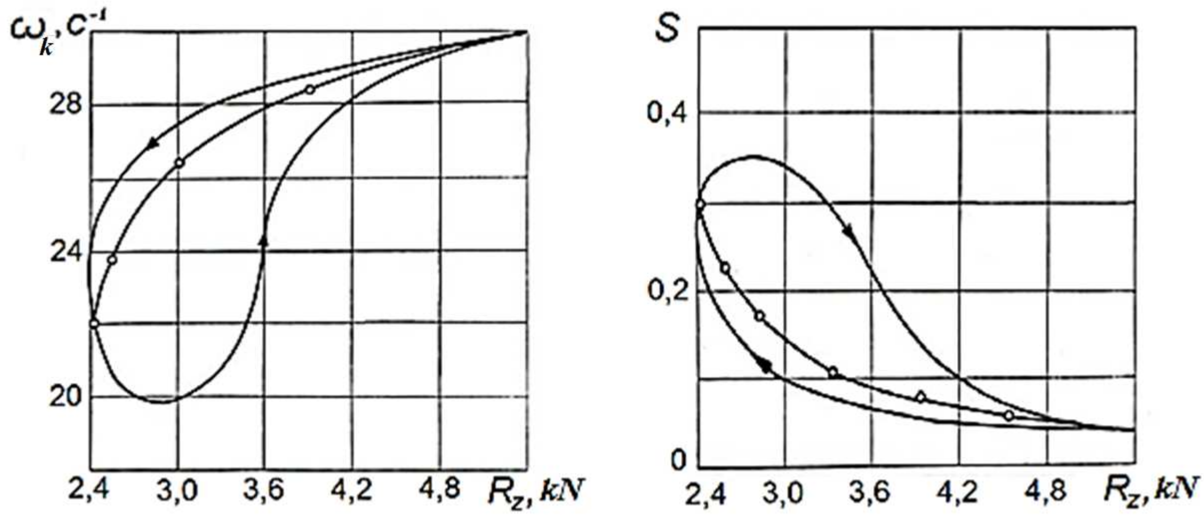
3. Results and discussion

In a stationary braking mode, the longitudinal reaction R_x (Fig. 3a) and angular acceleration $\dot{\omega}_k$ (Fig. 3b) depend almost not at all on R_z: the static (*stationary*) characteristics $\dot{\omega}_k = f(R_z)$ 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 ω_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_φ.

Dynamic components of the parameters ω_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.



a) b)

Figure 4. Phase dynamic characteristics of the angular velocity and slip of the Hankook 175/70R13 tired wheel:

——— - non-stabilized mode (ν = 3Hz);

—o—o— - stationary mode (ν = 0)

Thus, non-stabilized characteristics R_x, ω_k, $\dot{\omega}_k$ 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_φ (*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:

$$f_{t(\mathrm{s})} = \frac{M_t + M_{fc}}{r_{ko}} \cdot \frac{1}{R_z \cdot \varphi_{\max}} \tag{2}$$

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.

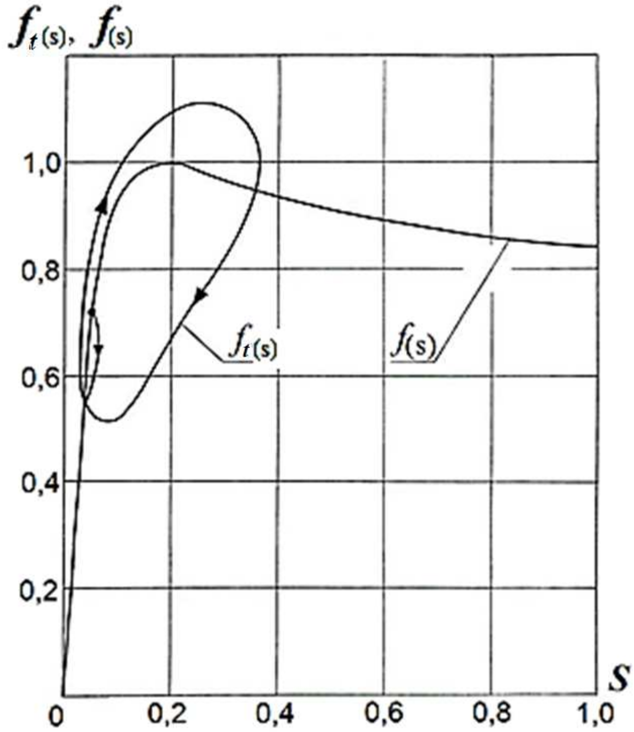


Figure 5. Normalized phase diagram of braking of Hankook 175/70R13 tired wheel at constant braking moment and variable normal load with frequency ν = 3Hz and amplitude $\Delta R_z = \pm 1.5$ kN

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.

References

[1] Fedotov A I 2015 *Dynamic method of diagnosing a pneumatic brake drive*. (Irkutsk IRNTU) p 512

[2] Fedotov A I 2016 Fundamentals of the theory of maintenance characteristics of motor transport vehicles. Manual for post-graduate students in the field 23.06.01 Technologies of road transport (Program “Motor Transport Maintenance”). (Irkutsk: IRNTU) p 254

[3] Zarshikov A M 1984 *Impact of the changes of basic loading of the wheel on the performance of an anti-blocking brake system.* (Extended abstract of Cand. Sc. Moscow MAMI) p 18

[4] Fedotov A I 2015 *Service control methods and diagnostics Manual* (Moscow Akademia) p 352

[5] Fedotov A I Boyko A V 2016 *Mathematical simulation of a car operation process. Manual*. (Irkutsk: ISTU) p 143

[6] Fedotov A I 1986 *Improving the efficiency of anti-lock systems with fluctuations of the normal loading on the wheels of the car. The dissertation on competition of a scientific degree of candidate of technical Sciences* (Moscow Moscow automotive Institute) p 187

[7] Pacejka H B 1996 PWA Zegelaar, The in-plane dynamics of tires on uneven roads Vehicle

System Dynamics, - ocp.tudelft.nl
[8] Pacejka H B 2002 *Tire and Vehicle Dynamics* (Butterworth-Heinemann, Oxford)
[9] Fedotov A I, Mlynczak M 2016 Simulation and Experimental Analysis of Quality Control of Vehicle Brake Systems Using Flat Plate Tester. Dependability Engineering and Complex Systems Proceedings of the Eleventh International Conference on Dependability and Complex Systems DepCoS-RELCOMEX (Brunów, Poland) pp. 135-146
[10] Fedotov A I, Mlynczak M 2016 Analytical Identification of Parameters Influencing Measurement Quality Using Flat Brake Tester. Dependability Engineering and Complex Systems Proceedings of the Eleventh International Conference on Dependability and Complex Systems DepCoS-RELCOMEX (Brunów, Poland) pp. 147-155