

Drag Torque in Disk Brakes: Significance, Measurement and Challenges

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ABSTRACT

Drag torque is generated in disk brakes as a result of contact (dynamic friction) between brake disk and brake pads when the braking system is not actuated. Among the negative implications of drag torque are, notably, dispensable additional fuel consumption as well as increased pad wear, which can also unfold as uneven along the pads' surfaces. The paper is based on extensive knowledge acquired through several measurement-based studies and contains a comprehensive assessment of the main topics related to the subject.

Dedicated measurements illustrate the influence of different parameters on the level of drag torque and deliver a basis for a discussion about the conflict of objectives which may arise from the implementation of specific mitigation measures.

Further emphasis is laid on the presentation of the state of the art concerning the main direct and indirect methods to evaluate drag torque characteristics of brake systems. The particular advantages, disadvantages and limitations of the individual methods are discussed. The experiment-based comparison leads to the identification of distinguishing benefits arising from dynamometer testing. Moreover, the reasons leading to the high complexity linked to measuring drag torque reliably and representatively are presented and advancements reached in this field are pointed out.

Finally, key points for defining testing specifications, including important boundary conditions and evaluation methods are presented. Thus, it also represents a contribution for developing procedures which account for essential requisites to be integrated in the state-of-the-art of development of brake systems: Practicability, reliability, reproducibility and reference to real vehicle operational conditions.

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INTRODUCTION

Minimizing drag torque of vehicle brakes represents a task which has gained substantial importance due to increasingly stringent fuel economy and emissions standards. Whereas in the past a certain level of drag torque was yet desired (e.g. to keep the disk in a permanent dry and clean condition, the current demand is rather characterized as "low drag" and "zero drag", thus completely free of drag torque. Hence, the requirements for drag torque measurement have become substantially higher. This contribution addresses the influencing parameters on drag torque in brake systems, its measurement and an analysis on different approaches aiming to reduce drag torque.

INFLUENCING PARAMETERS

Several measurable properties of the brake system have a direct influence on the level of drag torque. A major effect is connected to the caliper properties determining the clearance gap. This is characterized by the default gap between pad and disk and its distribution regarding vehicle inner and outer sides (piston and fist sides of caliper, respectively) or by the residual clamping force after brake actuation. If there is contact between pad and disk, the

sliding force of the pads and / or the caliper has also a direct influence on the drag torque - as well as the coefficient of friction between disk and pads.

In addition, there are also indirect parameters which can exert influence on the drag torque, which are not caliper-related. These include lateral run out and axial thermal deformation. The thermally induced deformation of the brake disk leads to an increase in thickness of the friction ring as well as to radial growth and - in general - to a displacement of the friction ring towards the outer side of the vehicle through coning. When the brake actuation ceases, the axial alignment of the caliper is such as to match the current disk position. During the cooling process the disk returns technically to its original position. This reversal of the coning contributes significantly to increasing the clearance gap on the fist side. If the axial displacement is large enough, it leads to (intermittent) contact of piston-sided lining with the disk. Further effects can arise from rotor tilting under load, which depends chiefly on the wheel bearing stiffness and tolerances.

High caliper stiffness (subject to packaging and weight constraints) contributes to a steady behavior regarding the clearance gap as well as to avoiding uneven lining wear. In case of elevated radial or tangential taper wear, increased residual brake torque is to be expected. Thus, the

drag torque is also directly dependent on the imposed load spectrum, which is reflected also in the taper wear. High pad compressibility decreases the clearance, leading thus to higher drag torque. For reasons of comfort, however, pad compressibility cannot be arbitrarily minimized. Furthermore, compressibility values are subject to considerable mean variation in mass production.

Depending on particular design characteristics, brake systems are more or less susceptible to the effect of “pad suctioning”. With increasing speed a reduction of the air pressure between lining and disk can occur, which in turn leads to an additional force of the pad on the disk. In one particular case, an increase of drag torque of 4 Nm (at 20 km/h) to 40 Nm (at 120 km/h) was measured. Air pressure at the centre of the pad area was then at 0.7 bar below atmospheric.

Figure 1 shows an example of the dependence of the negative pressure on the speed and the direct connection between the reduced air pressure and drag torque.

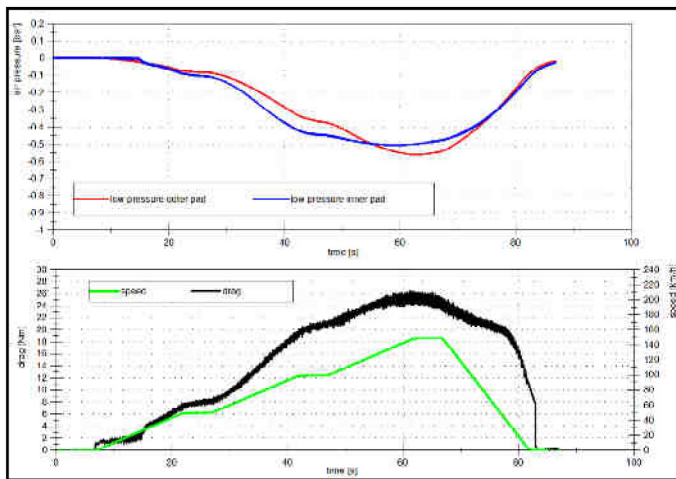


Figure 1. Effect of “pad suctioning” on drag torque

The aging of components represents an aspect which has not yet been thoroughly investigated. Yet it should be of undisputable relevance as regarding the influence on drag torque. Particularly to mention are the aging of the rubber elements and corrosion on components relevant to pad guiding.

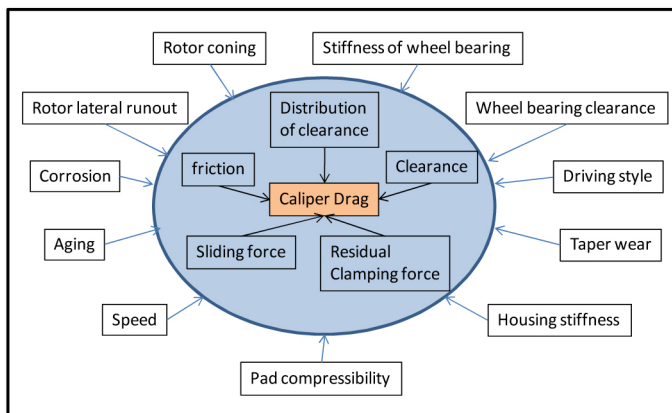


Figure 2. Overview of factors influencing drag torque

Figure 2 shows an overview of the factors influencing the drag torque. It must be remarked that there are also interdependencies between the factors themselves.

Adding to the factors shown above, several other vehicle-specific factors affect drag torque, such as knuckle and suspension stiffness, vehicle size, vehicle weight distribution and dynamic load transfer during braking and cornering, thermal expansion of corner components and assembly tolerance stack-up.

In assessing an appropriate test method for measuring residual brake torque, an evaluation of these factors is to be taken into account.

TEST METHODS AND INSTRUMENTATION

In principle, the drag torque can be determined directly or indirectly. Direct measurements are made in the static test field and on dynamometer by means of using rotating or stationary measuring shafts or lever/pendant mounts with load cells. In vehicle test, indirect methods of application are usual, such as evaluation of cooling curves, or coast down tests, consumption and emission measurements on the vehicle dynamometer.

The methods considered here to determine the drag torque are always composed of test setup (test assembly plus measuring device) and the respective test conduction. To evaluate the accuracy of a measurement method, the transferability and the analysis options are assessed. Accuracy includes both repeatability and measurement precision.

The ideal method is to have the highest transferability to the behavior in real driving conditions and must therefore take place in the vehicle. It should provide the possibility to measure drag torque, depending on the previous braking pressure at different speeds and at different disk temperatures with pinpoint accuracy. That is currently not possible, since such accuracy cannot be reached by means of employing state-of-the-art systems like measuring rims or strain gauges on the brake. Existing methods are thus a compromise intended to reflect on the ideal method.

A relatively simple method to measure drag torque directly in a static test field is shown in Figure 3. The caliper is mounted on an adapter plate over a brake disk. The disk is driven by an electric motor with a rotating measuring shaft. Its maximum measuring range is limited to ± 50 Nm, thus allowing an accuracy of ± 0.1 Nm. The drag torque can be determined over time in accordance to the hydraulic pressure of a static actuation. The transferability to real (vehicle) conditions is low. Dynamic braking measurements, as well as investigations of the influence of temperature or velocity, are not possible with this method.

A similar method for measurement of the drag torque can be realized in a vehicle on a car elevator. Also here the disk is driven by an electric motor with a rotating measuring shaft. The bearing torque must be deducted from the measured value, which is done by repeating the measurement after displacing the pads back to make sure that contact with the disk is avoided. The characteristics of bearing torque in such rebounded state must be questioned and interpreted critically, since it may well have an impact on the drag torque.

torque. The values obtained do not indicate the actual behavior during driving, but can be seen as a guide for monitoring drag torque without removing the brakes.



Figure 3. Drag torque measurement in the static test facility

Drag torque can also be evaluated in driving tests by means of analyzing the cooling characteristics of the disk. After continuous heating at a constant speed of 100 km/h for the duration of the cooling from $T_A = 200^\circ\text{C}$, down to $T_E = 50^\circ\text{C}$ for various braking pressures. This method is susceptible to disturbances such as ambient temperature, wind speed and direction and humidity, which restricts the reproducibility. An analysis of the dependency on the disk temperature and on the vehicle speed is not possible, nor is the assessment of the release behavior of the brake and drag torque over time. Another indirect method of determining the drag torque in vehicle test is the coasting test which is however rarely used in practice due to its high inaccuracy.

A further tool for determining and measuring the drag torque is the inertia dynamometer. With which it is possible to simulate the vehicle to be tested and to measure the drag torque indirectly or directly.

If there is no suitable measuring device for direct detection of the drag torque on a dynamometer, the indirect determination through a coasting test can be conducted. By differentiating the velocity over time the acceleration is obtained. Thus the torque leading to the acceleration value can be determined. However, the obtained value includes not only the drag torque from the brake, but also all torque values resulting from the other forces - in particular from friction in the bearings of the shafts of flywheels, engine and the vehicle knuckle. Such losses are dynamometer-specific and can be located in areas up to 20 Nm. The problem of the method is to determine the losses and then exactly hold them as constant as possible during the measurements. Sufficient long 'warming up of the dynamometer bearings' - for up to four hours was found to be necessary. During further testing procedure there must be no interruptions. A velocity dependence of the drag torque is not detected; an analysis of the releasing characteristics of the brake proves to be difficult. Due to varying bearing torques of different test rigs leading to different coasting times, the validity of a comparison of results between test rigs not reliably given.

Therefore, a direct measurement of drag torque by means of a suitable torque measuring device is to be favored.

Accurate measurement of the braking torques on dynamometers is derived from the following basic principles. The clamping force of the brake caliper generates the clamping force on the rotating disk, which in dependency on the coefficient of friction (μ) between the brake pad and the disk generates in turn the frictional force (F_{Friction}).

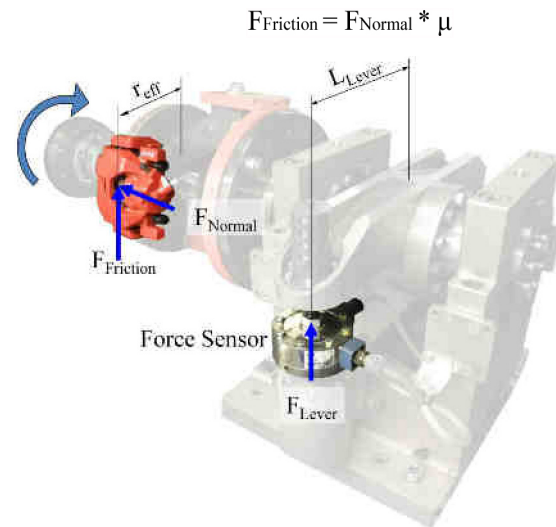


Figure 4. Principle of drag torque measurement on dynamometer

The braking torque is calculated from friction radius (r_{eff}) multiplied by the frictional force.

$$MB = F_{\text{Friction}} * r_{\text{eff}}$$

Since the friction radius and the friction force cannot be detected by measurement accurately, the braking torque is measured by a force sensor on a lever of a constant length (L_{Lever}).

$$MB = F_{\text{Lever}} * L_{\text{Lever}}$$

STATE OF THE ART

The force sensor is used for all functional tests in order to avoid conversions. In order to be suitable for hot judder analysis, the setup must not have natural resonances under 200 Hz. The braking torque for strength tests (up to 5000 Nm) must be measurable, but also the low values from drag torque (up to 0.5 Nm) must be detected when the brake is not actuated. This corresponds to a resolution of 0.01 %.

The zero point of the force-measuring sensor must not change due to the high loading or over time.

Figure 5 shows a measurement setup which fulfils the requirements described above.

The high-stiffness lever shifts the natural frequencies in a non-critical area for judder. In addition, the bearing has been optimized so that even after long usage no significant (rotation direction dependant) signs of wear are induced. This ensures that at varying torque (by rotation direction change) the zero point hysteresis does not increase.