AN EXPERIMENTAL COMPARISON OF HOT JUDDER BEHAVIORS BETWEEN DYNAMOMETER TESTS AND VEHICLE TESTS
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KEYWORDS – hot judder, hot spots, brake torque variation, dynamometer, order analysis, thermal increase

ABSTRACT

Hot judder is a brake-induced vibration, which is mainly caused by thermal deformations of the brake disc. It is typically perceived by the driver as minor to severe steering wheel oscillation, brake pedal pulsation, whole car body vibrations, as well as low-frequency noises during braking. In the last decades, hot judder tests were predominantly carried out using flywheel brake dynamometers and manifold hot judder orders were observed. However, only a few vehicle tests were executed and there is no direct comparison with dynamometer tests up to now. Considering the different constraints of wheel brakes as well as the different hydraulic layouts of the braking systems, it is still unknown whether or not flywheel brake dynamometer tests can represent the real hot judder situation in a vehicle.

In order to investigate the potentially different hot judder behaviors between dynamometer tests and vehicle tests, one front brake and one rear brake with two different pads are separately tested with a brake dynamometer and through vehicle tests by means of road tests and chassis dynamometer tests. Hot judder behaviors during these tests are then compared with the following criteria: thermal increases of Brake Torque Variation (BTV) and Brake Pressure Variation (BPV), overall order behaviors, and dominant orders of BTV. Significant discrepancies are found in the different tests. However, hot judder seems to be generally more likely to occur in a brake dynamometer. Therefore, brake dynamometer tests are still appropriate for preventing the occurrence of hot judder in vehicles. This study provides a reference regarding hot judder detection for the brake manufacturers.

INTRODUCTION

During braking, a great deal of noises and vibrations could be produced by the braking system. Brake judder as one of the phenomena is normally perceived by the driver as low-frequency vibrations at the driving interfaces, such as seat and floor vibrations, brake pedal pulsation, and steering wheel oscillation. Sometimes a low frequency hum noise is audible [1]. Brake judder is mainly caused by Disc Thickness Variation (DTV) and disc waviness (in many literature references also called disc Lateral Run-Out, LRO). Due to different reasons for the occurrence of DTV and disc waviness, brake judder is traditionally divided into two categories: cold judder and hot judder.

DTV and disc waviness causing cold judder are induced by production tolerances, mechanical wear (cold washout), or the deviation of the disc axle resulting from assembly, which mainly happen in the off-brake status [2]. DTV and disc waviness causing hot judder are induced by thermomechanical effects in the wheel brakes during braking. It is normally combined with hot spots distributed in the circumferential direction of disc surfaces. Therefore, the vibration frequency of hot judder is an integer multiple of the disc’s rotational speed. The number of hot spots differs when comparing unalike brakes and sometimes also varies from different
braking conditions for the same brake [3] or even changes during one braking application [4].

Figure 1 shows some examples of the amounts of hot spots found by different authors.

Figure 1: Amounts of hot spots in literature [3]

It has already been testified by plenty of experiments [3-8] and simulations [9-10] that except for braking conditions, occurrence and development of hot judder are greatly dependent on the materials and structures of wheel brake components. Due to the difficulties of applying some sensors (e.g. displacement sensors and thermal camera) and controlling the braking conditions in vehicle tests, hot judder tests were almost exclusively carried out by brake dynamometers in the last decades. Only a few vehicle tests could be found in literature [11-13]. However, considering the different constraints of wheel brakes (e.g. supporting stiffness of the whole wheel brake, cooling rate of the brake disc, and possibly the retroactions of some resonance frequencies from either the vehicle or the dynamometer) and the different hydraulic layouts in the braking system as well as the different controlling methods of the brake fluid, it is still unknown whether or not dynamometer tests provide reasonable results that reflect the real hot judder situation in a vehicle.

The objective of this work is to investigate whether or not dynamometer tests represent the real hot judder situation in a vehicle by comparing the hot judder behaviors in dynamometer tests and in vehicle tests with identical wheel brakes.

METHODOLOGY

Test strategy

One front brake and one rear brake from two similar mid-size upper class cars are tested through dynamometer tests and vehicle tests. Only the original brake components are adopted for testing the front brake, while two sets of intentionally produced pads that have the same structure but different materials (one pair of NAO pads and one pair of ECE low-metallic pads) compared to the original pads are applied for testing the rear brake. Main specifications of the two brakes are shown in Table 1.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Front brake</th>
<th>Rear brake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caliper type</td>
<td>fist caliper</td>
<td>fist caliper</td>
</tr>
<tr>
<td>Disc type</td>
<td>ventilated</td>
<td>ventilated</td>
</tr>
<tr>
<td>Disc diameter</td>
<td>320 mm</td>
<td>320 mm</td>
</tr>
<tr>
<td>Disc thickness</td>
<td>32 mm</td>
<td>24 mm</td>
</tr>
<tr>
<td>Pad arc length</td>
<td>48°</td>
<td>42°</td>
</tr>
<tr>
<td>Number of piston</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Piston diameter</td>
<td>46 mm</td>
<td>42 mm</td>
</tr>
<tr>
<td>Effective (geometric) friction radius</td>
<td>133.5 mm</td>
<td>141.5 mm</td>
</tr>
</tbody>
</table>

In the first place, drag braking applications with constant velocity and constant braking pressure as well as stop braking applications with decreasing velocity and constant deceleration are carried out for both brakes by the brake dynamometer. In the second place, identical pads, caliper, caliper support brackets and knuckles used with the dynamometer are mounted onto the vehicles and tested through vehicle tests. In order to avoid the influence of different disc wear-out states after the dynamometer test, new discs are used in both types of tests.

It is found that the front brake is dominant with 1st to 4th lower orders in all the tests, whereas the rear brakes with both kinds of brake pads show 9th to 15th higher dominant orders in the drag braking applications at the dynamometer. Because thermal increases of lower orders could be found for every brake, comparing the behaviors of higher dominant orders is more meaningful. Hence in the third place, further vehicle tests are only carried out for the rear brakes at the chassis dynamometer, where testing of both stop braking and drag braking applications is possible.

As a results, for the front brake, hot judder behaviors in the road tests will be compared with those in the stop braking applications at the brake dynamometer; for the rear brake, hot judder behaviors during the three types of stop braking applications as well as during the two kinds of drag braking applications will be separately compared. The overall test strategy is shown in Figure 2.

![Figure 2: Test strategy of hot judder comparison tests](image)

Test designs for both brakes are listed in Table 2. With respect to all stop braking applications, four deceleration variations of 0.2 g, 0.3 g, 0.4 g, and 0.5 g are used; the initial disc surface temperature is always kept at 200 °C; three initial braking velocities of 175 km/h, 200 km/h, and 225 km/h are varied, except for the road test (from 175 km/h and 225 km/h) and the brake dynamometer test of the rear brake (only from 225 km/h).

Regarding the drag braking applications, three velocity variations and four variations of brake pressure are generally applied, and the testing duration is determined by the disc surface temperature ranging from 100 °C to 500 °C. However, for the brake dynamometer testing of the rear brake, in addition to the braking applications with constant pressures, one test program with constant brake torques of 100 Nm, 150 Nm, 200 Nm, and 300 Nm is also conducted, whose corresponding average braking pressures are approximately equivalent to the four varied pressures. For the chassis dynamometer tests of the front brake, although only brake pressure is used as control quantity, two different test programs are run: one from the lowest (175 km/h, 10 bar) to the highest velocity and braking pressure (225 km/h, 30 bar), the other in the opposite direction. Besides, in order to detect the hot judder behavior at lower velocities, braking from 125 km/h is taken in the testing of the front brake. Restricted by the
performance of the brake dynamometer, the maximum pressure is limited to 25 bar for the front brake and 30 bar for the rear brake.

Moreover, because new brake discs are used for each of the tests, a run-in program composed of 60 stop braking applications from 80 km/h to 30 km/h with a constant brake pressure of 30 bar and an initial disc surface temperature of 100 °C is executed before the dynamometer tests. Accordingly, a similar run-in program consisting of 30 stop braking applications from 80 km/h to standstill with a deceleration of about 0.4 g and the same initial disc surface temperature of 100 °C is also carried out before the road tests.

<table>
<thead>
<tr>
<th>Front brake</th>
<th>Brake Dyno Test</th>
<th>Road Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop braking</td>
<td>Drag braking</td>
<td>Stop braking</td>
</tr>
<tr>
<td>$v_0$ (km/h)</td>
<td>175, 200, 225</td>
<td>175, 175, 225</td>
</tr>
<tr>
<td>$a_0$ (g)</td>
<td>0.2, 0.3, 0.4, 0.5</td>
<td>0.2, 0.3, 0.4, 0.5</td>
</tr>
<tr>
<td>$T_0$ (°C)</td>
<td>From 200</td>
<td>From 200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rear brake</th>
<th>Brake Dyno and Chassis Dyno Test</th>
<th>Road Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop braking</td>
<td>Drag braking</td>
<td>Stop braking</td>
</tr>
<tr>
<td>$v_0$ (km/h)</td>
<td>225</td>
<td>175, 200, 225</td>
</tr>
<tr>
<td>$a_0$ (g)</td>
<td>0.2, 0.3, 0.4, 0.5</td>
<td>0.2, 0.3, 0.4, 0.5</td>
</tr>
<tr>
<td>$T_0$ (°C)</td>
<td>From 200</td>
<td>From 200</td>
</tr>
</tbody>
</table>

Test setups

The hydraulic control system and the test setup at the brake dynamometer are shown in Figure 3. This brake dynamometer can be conducted by brake torque, brake pressure, or brake deceleration. The controlling of these parameters is realized through the control valve labeled with the number 10 in Figure 3. Between the control valve and the caliper, one throttle valve (in the grey box labeled with the number 11) is mounted in the brake line in order to attenuate the transmission of the pressure variation from the caliper into the control valve. Otherwise, the dynamometer control system would try to compensate the BTV or the BPV, depending on the currently controlled parameter [5].

Both the layout of the hydraulic system and the control method are similar to those in the vehicle tests at the chassis dynamometer but different from those in the driving tests in which the driver is always trying to keep the brake pedal at a constant position during one braking application. This could be one main reason for different hot judder behaviors between the two types of dynamometer tests and the road test.

Quantities relevant to hot judder as well as their measuring sensors are listed in Table 3. Main working principles for measuring these quantities are the following:

- **DTV/Waviness**: 8 capacitive displacement sensors are applied, measuring the disc surface geometry at 4 different radii of friction rings.
- **Hotspots**: An infrared camera with a mirror system design makes it possible to measure the temperature distributions at both disc surfaces with only one camera. The temperature measurement is synchronized with the rotation speed, acquiring 125 samples per disc rotation.
• **BTV:** Brake torque is normally measured by a force transducer in the torque measuring shaft assembly of the brake dynamometer. However, there is a resonance frequency at about 180 Hz in the measuring shaft assembly by which the BTV measurement around this frequency is greatly amplified. In order to avoid this effect and to have the same BTV measuring equipment both at the brake dynamometer and in the vehicle, a new measuring method named “strain gauge caliper bracket” has been developed. Strain gauges are arranged at the most sensitive positions of the caliper bracket by using the full Wheatstone bridge configuration and are calibrated with the torque measuring shaft assembly of the brake dynamometer.

• **BPV:** Three pressure transducers are installed in order to measure the brake pressure: the first one directly at the vent hole of the caliper, the second one in the brake line near the caliper, and the last one near the control valve. By comparing the pressure variations before and after the throttle, the attenuating effect can be revealed.

• **Caliper vibration:** One 3-axis accelerometer is used to measure caliper vibrations in three directions and a single 1-axis accelerometer is mounted at the caliper bracket, gauging the circumferential vibration.

Besides the quantities above, disc surface temperature is also monitored by a sliding contact thermocouple and employed as the trigger signal. The rotational speed is determined by a Hall sensor, which gives one impulse per rotation.

In the vehicle tests, the identical strain gauge caliper bracket is used in order to measure BTV; the identical pressure transducer at the caliper vent hole is utilized to measure BPV; the two accelerometers are mounted at the same positions as in the brake dynamometer, measuring the vibrations of the caliper and the caliper bracket. In addition, disc surface temperature and rotational speed are also identified following the same principles as at the brake dynamometer.

![Figure 3: Test setup and control system of the brake dynamometer](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Measured quantity</th>
<th>Sensor (producer, type)</th>
<th>Effective range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Disc surface geometry (DTV and disc waviness)</td>
<td>Capacitive displacement sensors, (Capacitec, HPC-150-H)</td>
<td>0-250 µm, max. 400 °C</td>
</tr>
<tr>
<td>2</td>
<td>Hotspots</td>
<td>Infrared camera with mirror system, Infra Tec</td>
<td>125 per rotation</td>
</tr>
<tr>
<td>3</td>
<td>BTV</td>
<td>Strain gauges, HBM, 1-XY31-1.5/120.</td>
<td>-</td>
</tr>
</tbody>
</table>
RESULTS

Comparison criterion

Vibrations at the caliper and the caliper bracket are strongly influenced by some resonance frequencies in the three types of tests, especially in the vehicle tests. Amplitude, frequency and dominant order of the vibrations are not comparable. Therefore, only BTV and BPV are taken as comparison parameters. Specifically, order behaviors of BTV and BPV will be used as qualitative comparison criterion; BTV and BPV amplitudes of the “dominant orders” will be used as quantitative comparison criterion.

The dominant orders of BTV and BPV are not always clearly visible during the entire braking application. For example, Figure 4 shows a drag braking test result of the rear brake equipped with ECE pads. High amplitudes can be seen from the 10th to 14th order in BTV, BPV, DTV, and LRO. No single order is always bigger than the other orders. To have one unique dominant order for each signal, the one with the maximum amplitude during the whole braking time is defined as the dominant order. By this definition, the dominant order of BTV, BPV, and Waviness is the 11th order and the dominant order of DTV is the 12th order in the test. So as to explain the discrepancy of the dominant orders, or to clarify why there are some big adjacent orders, a thermal image of one disc-rotation at the braking time of 30 s is shown in Figure 5.

![Order analysis of the rear brake with ECE pads, drag braking with 225 km/h and 10 bar][1]

In this test, the temperature gradient is much bigger at the finger side friction ring than at the piston side friction ring. 12 hotspots are clearly to see at the finger-side friction ring, but the number of hot spots at the piston-side friction ring can be counted as 11 or 12. Besides, hot spots generally distributed at alternating positions on the two sides, which explains why the...
waviness of the high orders is bigger than DTV. But the distributions on both sides are not absolutely homogenous. In other words, the distances between two adjacent hot spots are not constant.

For the same rotation, temperature gradients at the same disc radius marked by the two black solid lines in Figure 5 are displayed in Figure 6. The antiphase effect can also be seen from the two temperature gradient curves. From the order analysis it can be seen that there are 11th and 12th big orders on the piston side and 10th to 14th big orders on the finger side. Uneven distribution of the hot spots explains the non-unique order of BTV, BPV, Waviness, and DTV signals.

Figure 5: Hot spots on the rear brake with ECE pads, drag braking with 225 km/h, 10 bar, 30 s

Figure 6: Temperature gradients at one disc radius and order analysis of the temperature difference

Moreover, brake judder is actually always a combination of cold judder and hot judder. In order to compare the behaviors of hot judder, cold judder effects need to be excluded. For this reason, evolutions of the first order and dominant orders of BTV, BPV, Waviness, and DTV during the whole braking time are displayed in Figure 7. The lower parts that appear immediately after braking begins are caused by cold judder. The higher parts are caused by
hot judder. Only the thermal increases from the cold judder to the maximum amplitude illustrated in Figure 7 are selected for the following amplitude comparison.

**Figure 7:** Thermal increase of brake judder, drag braking with 225 km/h, 10 bar

**Comparison of the front brake**

Figure 8 gives a test result of the front brake during drag braking with the dynamometer. In all the executed drag braking applications, high amplitudes are mainly found in the lower orders (e.g. 1st to 3rd orders for BPV and Waviness, 1st to 5th orders for BTV and DTV). Although a few big orders can be found in some signals (e.g. the 13th order of BTV, and the 10th and 15th orders of DTV in Figure 8), hot judder of the front brakes during drag braking is mainly indicated by thermal increases of lower orders, especially the 1st to 3rd orders.

**Figure 8:** Order analysis of the front brake, drag braking with 225 km/h and 10 bar, 100-500 °C

From the stop braking applications of both brake dynamometer tests and vehicle road tests shown in Figure 9, it can be seen that big judder orders are generally the 1st to 4th orders. However, the dominant order varies. Not only between brake dynamometer tests and road...
tests, but also among different dynamometer tests or among different road tests. Taking the tests in Figure 9 as an example, the dominant order of brake dynamometer tests is the first order, whereas the second order is the dominant order in the road vehicle tests, although both tests were executed with the same initial braking speed, deceleration, and initial disc surface temperature.

Figure 9: Comparison of BTV and BPV orders for the front brake, stop braking from 225 km/h to standstill, 0.3 g, from 200 °C

Because for both brake dynamometer tests and road tests thermal increases are very small, only the test results of stop braking with an initial braking speed of 225 km/h are used for the amplitude comparison. Figure 10 shows the comparison of thermal increases of BTV and BPV in the dominant orders. Tendencies of the thermal increases are comparable between the two types of tests, but hot judder intensity is generally much stronger in the brake dynamometer tests.

Figure 10: Comparison of BTV and BPV amplitudes, stop braking applications of the front brake

Comparison of the rear brake

The higher orders of hot judder found in brake dynamometer tests are reproduced in vehicle drag braking tests at the chassis dynamometer. Greater amplitudes of higher orders of BTV and BPV from order 9th to 15th are observed in all the drag braking applications of the rear brake with both types of brake pads. Hence, for the comparison of hot judder behaviors of the rear brakes in the drag braking applications, thermal increases of BTV and BPV amplitudes in the higher dominant order as well as the higher dominant order of BTV are taken into account. Testing results of the two types of brake dynamometer tests (with constant pressure or with constant torque) as well as the two test programs of the chassis dynamometer tests (in the
sequence of rising velocity and pressure, and in the adverse sequence) for the two pad sets are shown in Figure 11 and Figure 12 separately. The BPV measurements at the brake dynamometer for the tests with NAO pads are much smaller than the vehicle testing results, so they are not available in Figure 12. From the two figures, following conclusions can be drawn:

- Comparing the two different controlling methods at the brake dynamometer, BTV and BPV for the two kinds of pads show great discrepancies in many operating points, not only for the amplitudes but also for the dominant orders, especially for the tests with ECE pads. This means that hot judder behaviors at the brake dynamometer are strongly influenced by the control method: constant pressure or constant moment.

- Regarding the two test programs at the chassis dynamometer, thermal increases of BTV and BPV are basically reproducible. The amplitudes of BTV and BPV are comparable at most of the operating points for both pads.

- On the whole, hot judder intensity is much stronger at the brake dynamometer than in the chassis dynamometer vehicle tests when comparing the amplitudes of BTV and BPV. Considering the similar hydraulic systems in the two kinds of tests, this effect is most likely caused by the different disc cooling rates or the supporting stiffness of the wheel brakes at brake dynamometer and in the vehicle.

- The dominant order of BTV is not constant when using the two different brake pads on the rear brake. It varies not only at different operating points but also in different tests at the same operating point. Besides, the phenomenon of the unvarying judder frequency (the frequency keeps constant with changing velocity, e.g. 175 km/h with 14th order, 200 km/h with 12th or 13th order and 225 km/h with 11th order all happen at around 340 Hz, see the dotted line in the third plot of Figure 11) for the ECE pads in brake dynamometer tests with constant brake torque as well as the constant order phenomenon (hot judder order keeps constant with changing velocity, e.g. the dotted line in the third plot of Figure 12) for the NAO pads in brake dynamometer tests with constant brake torque are neither reproducible in the vehicle tests, nor reproducible in dynamometer tests with constant brake pressure.

Figure 11: Drag braking applications of rear brakes with ECE pads
In order to compare the hot judder behaviors in the three types of stop braking applications, one example of stop braking with rear brakes and ECE pads is shown in Figure 13. Generally, hot judder is more likely to be excited in drag braking applications because there is higher thermal energy input into the brake disc due to longer braking with a high constant rotational speed. Although they are all dominant with lower orders in the three kinds of stop braking applications, some higher orders which are mainly intensified at around the same frequency of 340 Hz can be seen clearly in the brake dynamometer tests. This frequency is deduced to be one resonance frequency of the rear brake. In addition, by further comparison of BTV and BPV amplitudes in Figure 14 it can be concluded that hot judder is most likely to occur during a brake dynamometer test and least likely to occur during road vehicle tests.
CONCLUSION

In this paper, hot judder behaviors of two brakes in dynamometer tests and vehicle tests are comprehensively compared based on an integrated test design and the correspondingly defined comparison criteria. On the one hand, it is found that there are great discrepancies in the amplitudes of BTV and BPV as well as in the dominant orders among different types of tests with identical brakes. Besides, the hot judder phenomena of constant frequency or constant order that were found in the brake dynamometer tests could not be reproduced in the chassis dynamometer vehicle tests. Hydraulic layouts of the braking systems as well as the control systems of the dynamometers should have remarkable impacts on both hot judder intensity and order behaviors. Generally, dynamometer testing results cannot exactly represent the real hot judder characteristics in a vehicle.

On the other hand, however, hot judder is generally more likely to occur during a brake dynamometer test than during vehicle tests. Still, the brake dynamometer test is a helpful tool for detecting the potential occurrence of hot judder in the early brake development phase, and therefore preventing hot judder in the finished vehicle. Although only two brakes have been compared in this investigation, it is the first direct comparison of hot judder behaviors in different tests and provides a reference regarding hot judder testing for the brake manufactures.

REFERENCES

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