

Hot Judder - An Investigation of the Thermo-Elastic and Thermo-Plastic Effects during Braking

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ABSTRACT

Thermo-elastic and thermo-plastic behaviour takes place with a disc brake during heavy braking and it is this aspect of braking that this paper considers. The work is concerned with working towards developing design advice that provides uniform heating of the disc, and equally important, even dissipation of heat from the disc blade.

The material presented emanates from a combination of modeling, on-vehicle testing but mainly laboratory observations and subsequent investigations. The experimental work makes use of a purpose built high speed brake dynamometer which incorporates the full vehicle suspension for controlled simulation of the brake and vehicle operating conditions. Advanced instrumentation allows dynamic measurement of brake pressure fluctuations, disc surface temperature and discrete vibration measurements. Disc run-out measurements using non-contacting displacement transducers show the disc taking up varying orders of deformation ranging from first to third order during high speed testing. This surface interrogation during braking identifies disc deformation including disc warping, “ripple” and the effects of “hot spotting”. The mechanical measurements are complemented by thermal imaging of the brake, these images showing the vane and vent patterns on the surface of the disc. The results also include static surface scanning, or topographical analysis, of the disc which is carried out at appropriate stages during testing. The work includes stress relieving of finished discs and subsequent dynamometer testing. This identifies that in-service stress

relieving, due to high heat input during braking, is a strong possibility for the cause of disc “warping”. It is also seen that an elastic wave is established during a braking event, the disc returning to its original form on release of the brake.

INTRODUCTION

Whole vehicle NVH refinement has been extremely successful over the past few years and as a result the re-emergence of effort towards finding a solution for problematic brake instabilities has again become the focus of increasing attention. Research towards understanding brake noise has never really remained static and so the advanced analytical techniques developed over the last 20 years, combined with the improved practical investigative skills and the sophisticated test facilities, have all enabled the mechanisms involved to be better understood. As such the technical competence in controlling dynamically induced vibrations, such as brake noise, has grown considerably so allowing this area to enjoy similar successes as general vehicle NVH improvements. As a result of the continuous efforts in the areas of brake noise there are some improved design guidelines available that allow new brake designs to be created with a reduced propensity to generate noise and so the effort is stabilising a little.

This success in one area of braking NVH, noise, is not reflected in the mechanically induced vibrations of brake judder and as such this has not advanced at the same rate. Judder in one form or another is now often seen to be more problematic than noise as shown in [Figure 1](#) where judder issues absorb 73% of new brake NVH research effort. Some

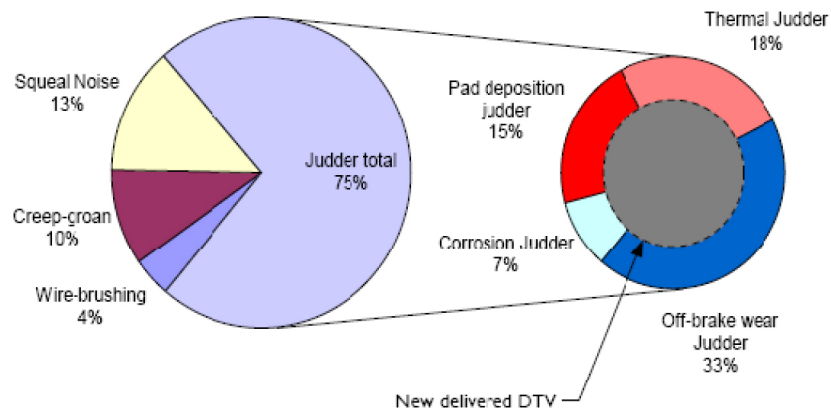


Figure 1. Distribution of dynamic instabilities. (Courtesy Bentley Motors Ltd)

of the fundamental mechanisms are well understood and the practical investigation methodologies are well established, but these remain primarily vehicle based. This is an expensive approach as much equipment must be dedicated and carried on-board the vehicle as indicated in [Figure 2](#) and even then the data that may be collected is restricted because of accessibility and the prevailing environment. In addition the available design guidelines remain restricted with manufacturing accuracy and brake materials forming part of the equation.

The proportion of noise to judder issues is not a constant and varies considerable from vehicle supplier to supplier. The heavier, high performance, vehicle manufacturers appear to suffer most from judder issues with the ratio being about 30% noise to 70% judder. Judder in this regard being as indicated in [Figure 1](#) - Pad deposition, corrosion, thermal and off brake wear. On the other hand the proportion may change for the lighter "town cars" to become 70% noise 30% judder. In the latter case the types of judder will be the same but the proportions will differ from that in [Figure 1](#). It is the demands for high speeds and braking performance on the edge of tyre friction limits that leads to such proportions and proportional changes. Off-brake wear and thermal judder will become more evident as speed increases and thus more prevalent with the higher performance cars. Clearly the speeds and energies involved are less for lighter cars and indeed the required braking forces are less. Brake judder, hot or cold, results from the degree of rotor distortion and the braking force applied. This combination results in a variable force being transmitted to the vehicle chassis and body - the heavier vehicle with the heavier braking being in a better position to generate these forces, hence judder.

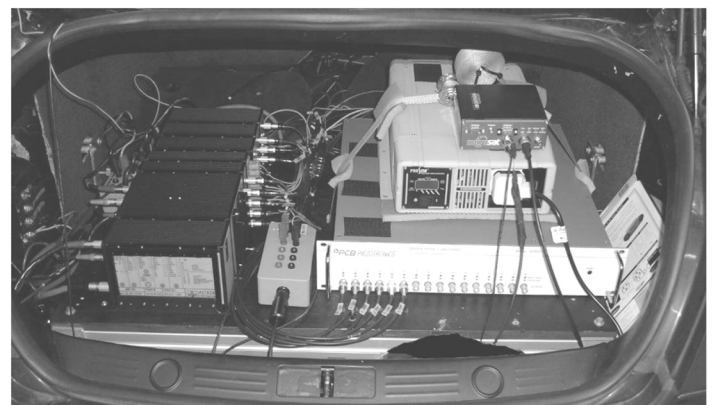


Figure 2. Typical equipment needed for on-board brake instability evaluation.

Judder is not a brake problem it is a vehicle problem and the front corner assembly design can significantly influence the degree of judder experienced by the driver. [Figure 3](#) [1] shows a typical front corner assembly where it is seen the knuckle holds the disc, calliper, suspension system and steering track rods; these therefore being mechanically linked to the vehicle, and through the tyre to the road. Under normal braking the knuckle will provide an appropriate reaction by transmitting the braking force to the vehicle body and road through any member attached to it and the vehicle. The braking torque would normally be steady so the reaction would be even. If there is any variation in braking torque the reaction force provided by the knuckle assembly will also vary and so the forces seen by the calliper, suspension, steering and tyre will also vary. The driver is also connected to the front corner assembly through the brake hydraulic system (foot pedal), the steering wheel (steering gear) and the cabin structure interface with the chassis. It is the interfaces that allows the driver to experience judder; through vibration of the foot pedal, vibration of the steering wheel and an audible noise. The frequency is not resonant but wheel speed related, similar to wheel imbalance, and in the region of around 100Hz. The effect of judder is not only an audible

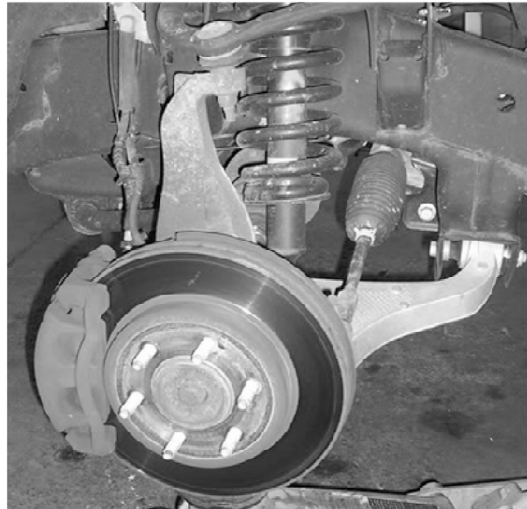


Figure 3. Typical front corner suspension showing knuckle fitted with caliper, disc, suspension and steering [1].

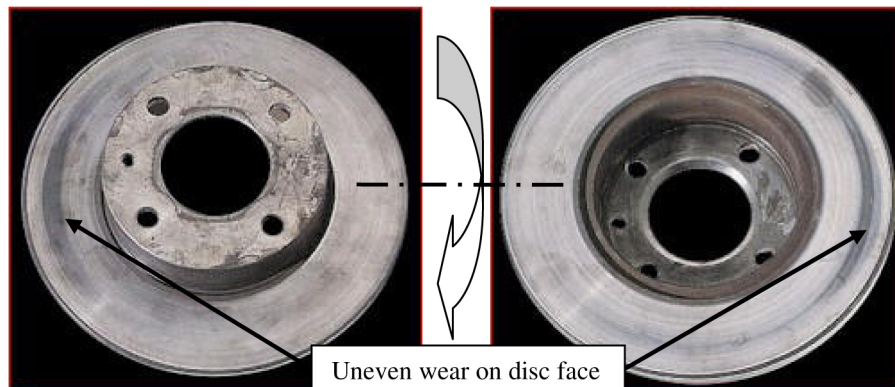


Figure 4. Disc showing runout wear which leads to disc thickness variation. The disc has been rotated about the horizontal axis to show wear diametrically opposite and on the reverse face of the disc.

experience; it is felt throughout the vehicle as whole body vibrations. This dynamic and often dramatic effect of vehicle vibration demands the focus to be moved from brake related noise problems towards brake judder - both hot and cold. It is the consideration of these two conditions that explain why brake torque may vary.

Cold judder is generally accepted to be all mechanically driven instabilities that are not thermally induced. These include off-brake wear, corrosion and uneven surface film transfer.

Off-brake wear is most obvious with discs having high disc runout or swash (when disc faces are not machined perpendicular to axis of shaft). A typical acceptable axial runout on a newly fitted disc may be in the region of 0.08 mm (80 micron). If the disc is fitted with a spec of rust or dirt in the region of 0.05mm (50 micron) then it is possible that the allowable runout will be exceeded. This swash allows the disc to make contact with the pads during normal running so

leading to uneven off-braking rotor wear or disc thickness variation (DTV). On braking this DTV leads to a brake torque variation (BTV) with consequential brake calliper, steering and body vibrations. Figure 4 shows typical wear pattern of a disc with runout [2].

There may also be inherent DTV as a result of machining inaccuracies. Clearly this may be resolved through improved quality control and effective calliper seal roll-back. The former solution may result in higher base costs whilst the latter will result in enhanced pad retraction and will inevitably affect pedal feel.

Corrosion judder results from disc corrosion because of extended vehicle parking in a mild corrosive environment (dockside storage) and is generally temporary and will eventually reduce during normal vehicle use. The exposed area of the disc experiences rust whereas the area under the pad does not. Removal of the rust during initial braking results in DTV. With DTV the disc experiences uneven

heating, the thicker area exhibiting the higher temperature and expands more than the thinner area -a self serving condition is created.

Surface film transfer, or pad deposition, may also cause judder if the film is not evenly distributed. This uneven distribution of surface film causes a variable disc/pad friction value and thus brake torque variation (BTV). The transfer of material from pad to disc and disc to pad is a fact of life and any instability investigation should only be undertaken following a degree of brake bedding or conditioning. This period of conditioning allows an even surface film transfer to be established and so a more stable system regarding the disc/pad friction coefficient. If this transfer is uneven then the interface friction characteristics will also vary and as such BTV will result, hence judder. Control of surface film transfer is difficult and related to pad formulation which has additional demands such as a predictable compressibility, good wear characteristics, stable friction level, good clean-up characteristics and yet not be excessively aggressive. It is an area that requires a careful study of compatible material characteristics and is not the purpose of this paper.

Hot (thermal) judder is probably the least understood of all judder experiences because it involves both low and high frequency judder (drone). It occurs during heavy braking and the resulting deformations and service data may reduce and even disappear once the brake cools. The demand for high performance cars will always exist but the high speeds, combined with high deceleration, means the need for the dissipation of high levels of energy. That energy is absorbed and rejected by the brake and as a result thermal effects become the focus of concern. If the brake absorbs energy significantly faster than it can dissipate it then the disc experiences high temperatures and as such thermal deformation. This deformation may be recoverable and as such judder may only be temporary. The issue becomes more serious if the deformation does not recover and so the disc will hold a permanent wavelike shape resulting in classical judder.

It will be shown later that during a heavy braking stop the disc can experience a high temperature rise, in the region of 270°C. Clearly if the driver brakes again before the disc cools then the disc temperature will rise until the “soaking” temperature is reached - when the disc loses heat as fast as it is generated due to braking and a steady state temperature is achieved. With the uneven temperature caused by DTV there is a possibility that the temperature can reach values in the region of 650-700°C. At these temperatures the cast iron changes structure and Cementite is formed. This Cementite is harder than the base cast iron and so wears less and the DTV becomes worse. In addition the Cementite will run hotter as it is not a good “heat sink” and so penetration into the disc surface increases. If the discs are relatively new then the Cementite may be removed by re-machining the discs but if

the penetration is too deep then the problem will quickly re-occur on refitting the discs.

It is common for high performance cars to use vented discs as these allow the heat to be dissipated more readily, but the overall purpose and effect is sometimes confused. Vented discs bring with them another form of thermal deformation in the form of “hot spotting” or “blue spotting” [3]. Such heating effects are localised and distributed about the disc in an apparent random manner but if left to multiply then the surface of the disc becomes covered in these “hot spots” as shown in [Figure 5](#). The hot spots may be localised regions of Cementite and as such the problems described above are equally relevant with these “hot spots”. The overall effect is high frequency judder leading to a droning sound caused by the multiple localised thermal deformations about the disc surface. It is tentatively believed that high frequency judder (drone) is caused by uneven temperature distribution on the disc surface, or within the brake rotor, causing both thermo elastic deformation and thermo elastic instabilities. Disc ripple also gives such effects. All these definitions and causes have been detailed in previous literature [4], [5], and [6] and therefore it is sufficient to only briefly mention them.



Figure 5. Extreme case of “hot spotting”. Often appears to be random but may be a function of rotor speed.

This paper reviews earlier work on the topic of thermal judder and focuses on establishing a disc design that avoids “heat sinks”, moving towards a more even heating and cooling of the disc surface and body. Such a design considers the geometry of the disc/pad interface and on the rib profiling. The purpose is not necessarily to increase the cooling capacity of the brake disc but to encourage a more temperature stable brake disc by adequate consideration of the heat distribution across, around and through the disc, in addition to overall even cooling of the disc body.

THERMAL ANALYSIS

To evaluate the thermal impact on a braking system it is possible to estimate the heat generated by a typical ABS stop for a typical vehicle. Consider values for the vehicle as indicated in Table 1:

Table 1. Characteristics of a typical high performance vehicle.

Car mass	(m)	2600kg
Rotational Inertia	(I_{eq})	126kgm ²
Tyre radius	(r)	320mm
Mass equivalent	(m_{eq})	1230kg
Initial speed	(u)	50m/s (180kph)
Final Speed	(v)	zero
Uniform deceleration to zero	(d)	-0.8g
Front disc mass	(m_d)	15kg

Where “mass equivalent” (m_{eq}) represents the rotational inertia of all the rotating parts within the transmission and also the non-driven wheels. These rotational inertias are referred to the wheels and represented as a mass that is added to the vehicle mass ($m_{eq} = I_{eq}/r^2$).

Ignoring drag and rolling resistance.

The Kinetic Energy (KE) = $\frac{1}{2} (m + m_{eq}) v^2 = \frac{1}{2} \times (2600 + 1230) 50^2$

$$KE = 4.79 \times 10^6 \text{ J}$$

$$v = u + dt \quad \text{where } t = \text{braking time (s).}$$

This is transposed to give $t = u/d$ resulting in $t = 50/(0.8 \times 9.81) = 6.37 \text{ s}$

$$\text{Power} = \text{Energy}/\text{time} = 4.79 \times 10^6 / 6.37 = 752 \text{ kW}$$

This power/energy is absorbed by the discs and is seen as heat.

Assuming proportion to front brakes during the stop 85% (not unreasonable).

From

$$Q = m_d C_p \Delta T$$

For front brakes this gives

$$\Delta T = Q_{\text{Front}} / (m_d C_p)$$

$$\Delta T = 0.85 \times 4.79 \times 10^6 / (2 \times 15 \times 502)$$

$$\Delta T = 270^\circ \text{C}$$

for a single ABS stop.

This assumes all the disc has time to absorb the heat which will not be the case and the disc will experience high thermal

gradients across its thickness with the surface temperature being well in excess of the 270°C. If the disc does “hold” all the heat uniformly then it will experience a thermal shock and will try to expand circumferentially. The time is insufficient and high mechanical stresses will be imposed on the disc. Consider the blade disc as a beam of section 97.5mm × 40mm thick. Let the disc be represented as a straight beam of a length equal to its effective circumference and constrained at its ends as shown in Figure 6.

The disc material characteristics are listed in Table 2.

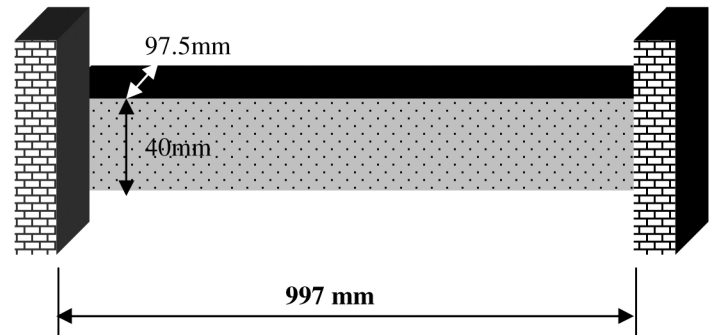


Figure 6. Disc blade represented as a beam constrained at its ends.

Table 2. Characteristics of beam (disc):

Parameter	Units	Value
Temperature rise (ΔT)	(°C)	228
Young's Modulus (E)	MPa	86300
Poisson's Ratio (ν)	-	0.25
Coefficient of Thermal expansion (γ)	1.00E-06/C	11.23
Specific Heat capacity (C_p)	J/kgK	502
Density (ρ)	Kg/m ³	7250

The temperature rises over a very short space of time.

$$\delta L = \gamma L \Delta T = 11.23 \times 10^{-6} \times 0.997 \times 270 = 3.027 \text{ mm}$$

Thermal expansion

Giving Strain

$$\epsilon = \frac{\delta L}{L} = \frac{3.027}{997} = 3036 \mu\text{strain}$$

$$\text{and induced thermal stress} = E\epsilon = 86300 \times 10^6 \times 3036 \times 10^{-6} = 262 \text{ MN/m}^2$$

$$\text{Axial mechanical load within disc to such cause stress} = \text{Stress} \times \text{Area} = 262 \times 10^6 \times 0.0975 \times 0.040 = 1.022 \text{ MN}$$

But buckling load of beam is given by Euler equation