2008-01-0818

Thermal Brake Judder Investigations Using a High Speed Dynamometer

David Bryant, John Fieldhouse, Andrew Crampton and Chris Talbot
University of Huddersfield

Jonathan Layfield
Bentley Motors Limited

ABSTRACT

This paper is concerned with addressing the problems experienced with the thermo-elastic behaviour of the disc - that of optimum heat dissipation, and equally important, even heating of the disc blade. The primary objective is to develop a more temperature-stable brake disc.

The work presented approaches the problems of thermal judder through benchmarking the current situation. This is approached by modelling the current brake and its validation by means of vehicle and laboratory testing. The empirical work is centred on a bespoke high speed brake dynamometer which incorporates the full vehicle suspension for an accurate yet controlled simulation of brake and vehicle operating conditions. The dynamometer is housed in a purpose built laboratory with both CCTV and direct visual access. It is capable of dynamic measurement of DTV, caliper pressure fluctuations, disc surface temperature and vibration measurements at discrete points about the rig. This information is presented and supported by thermal imaging of the brake during a heavy brake application and subsequent thermal judder. The results also include surface scanning of the disc which is carried out at appropriate stages during testing to identify disc deformation including disc warping, “ripple” and the effects of “hot spotting”.

Disc run-out measurements via non-contacting displacement transducers show the disc taking up varying orders of deformation ranging from first to third order during high speed testing. The state of cold deformation of the disc is also shown to vary with the disc returning to first or second order deformation upon cooling.

Thermal images of the brake disc have shown vane patterns to show through to the disc surface identifying uneven heat distribution.

INTRODUCTION

Brake judder still poses a serious design problem for the brake refinement engineer. It may take the form of cold or hot judder but in both cases it presents itself as a vibration directly related to wheel speed. Cold judder is typically manifested as a low-order vibration, whilst hot judder is typically associated with a higher-order vibration. Both types may be felt by the driver through the brake pedal, steering wheel or vehicle floor pan, with higher ‘drone’ frequencies becoming audible within the cabin. Cold judder tends to be caused by rotor geometry errors arising from off-brake wear. Hot judder is caused due to a short duration but high thermal input to the brake that results in a thermo elastic deformation, and eventual disc thickness variation (DTV), and thermo elastic instabilities in the form of hot spots. The problem is most prevalent on vehicles in the high performance luxury car market which must dissipate a significant amount of energy through the cast iron brake discs. It is therefore of great importance that research into brake judder on cast iron brake discs continues.

This paper details the in-house laboratory testing which has been carried out in an effort to further understand the judder phenomenon.

TEST EQUIPMENT

The brake dynamometer used for the purpose of this research is a bespoke design created especially for investigation into brake judder. The dynamometer comprises a brake ‘rig’ and motor. Briefly the design encompasses the following aspects:

A full quarter car suspension directly mounted to a rigid steel backplate to eliminate any unwanted vibrations and/or movements. The quarter car suspension allows investigations into the transmission path of brake judder from the brake assembly, through the suspension, to the vehicle structure. It also allows excitation frequencies of the various components to be analysed. The brake disc itself is directly coupled to a 110KW motor which can drive the discs at speeds of up to 2400rpm with a maximum brake torque of 700Nm. This brake torque is sufficient to replicate the typical high speed low deceleration braking which can cause brake judder. The brake is actuated via a pneumatic proportioning valve which controls hydraulic pressure in the brake master cylinder and allows for repeatable brake actuation.

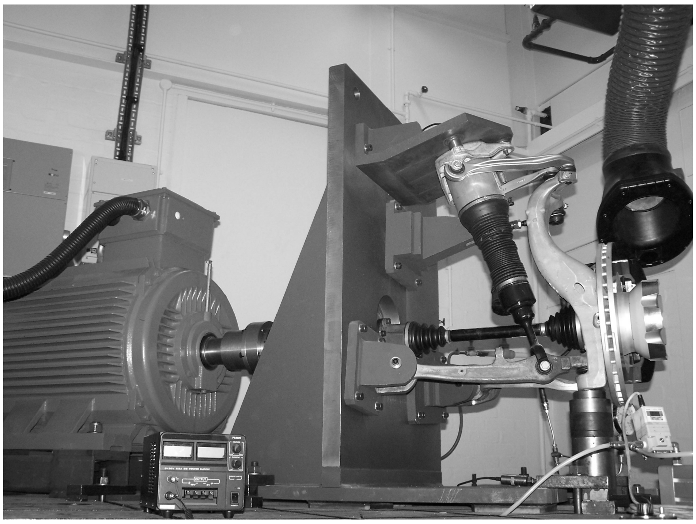

Figure 1 – General view of the dynamometer assembly showing motor, backplate, suspension assembly and brake disc.

The brake assembly used for the purposes of brake judder investigations comprises of a single piece cast iron vented brake disc and two piston sliding fist type caliper. The disc utilises straight vanes and is in the region of 400mm in diameter. The brake disc itself is mounted to the hub bearing using the centre section of the vehicle wheel. This allows identical mounting conditions, including clamping area, stress and torque, to be replicated. The mating faces of both the disc and hub are cleaned prior to mounting, and equal torque is applied to each of the mounting bolts. In doing this the installed run-out of the disc, and therefore the possibility of cold judder due to off brake wear, is minimised.

Measurement of the dynamic disc thickness variation and surface run-out is made possible by the use of non-contacting capacitive displacement transducers connected to a high speed data acquisition device. The transducers are rigidly mounted to a thick steel plate to eliminate any unwanted vibrations as shown in Figure 2. The steel plate forms an arc around the disc allowing measurements to be taken at different positions.

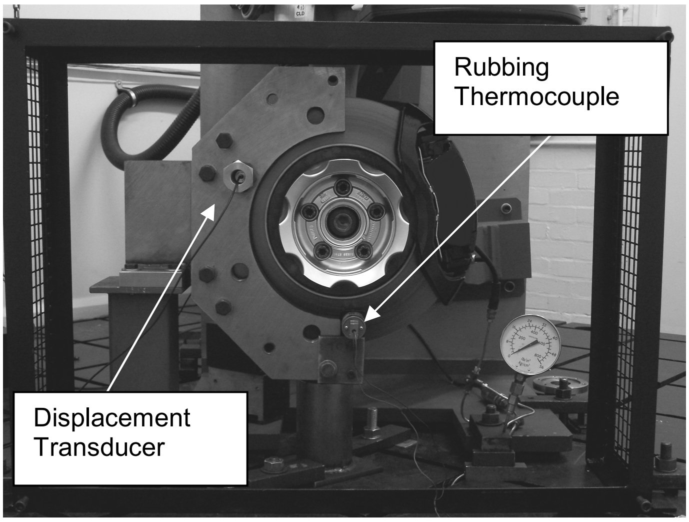

Figure 2 – Mounting arrangement of the displacement transducers

Rubbing thermocouples are mounted on the disc surface to give reference temperature measurements for both displacement and pressure measurements. The thermocouples also allow for accurate calibration of the thermal camera to take place by allowing for emissivity changes of the disc surface.

Test rig specifications:

- 110kW 400V 217amp 3 phase high performance flux vector inverter.
- 110kW 400V motor.
- Speed variable up to 2400rpm and down to 1 rpm
- Max. Torque 700NM
- Constant torque with speed reduction
- Full ¼ car suspension assembly
- 50mm thick steel fabrication provides rigid support for suspension assembly
- Tyre stiffness is replicated via rubber support beneath the suspension upright. The rubber mount was tested in compression and found to have a similar stiffness value to that of an inflated tyre.
- FLIR Thermal imaging camera capable of 50 frames per second.
- Spot, area or line thermal interrogation.
- High speed data acquisition cards capable of recording data at speeds of up to 500KHz simultaneously across 8 channels
- 2x pressure transducers
- Analogue pressure gauge (Visualisation purposes only)
- Bruel & Kjaer Non contacting displacement transducers
    - Dynamic DTV
    - Dynamic Run-out
- Sliding thermocouples
- Accelerometers
- CCTV cameras

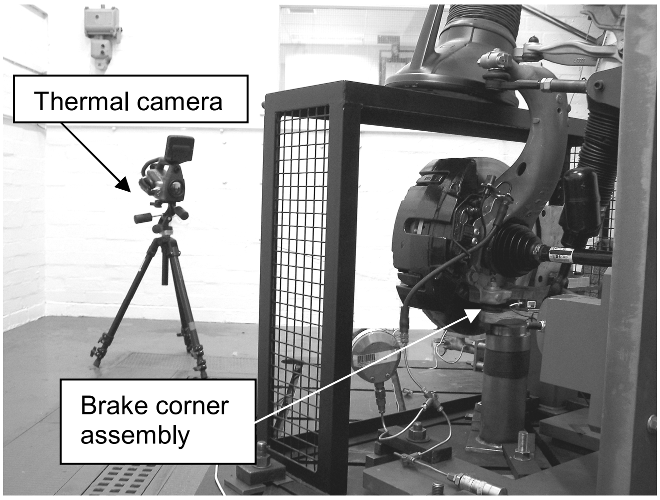

Figure 3 – Thermal camera arrangement

The thermal camera arrangement and location is shown in Figure 3. The camera looks directly at the disc face and can be given a clear unobstructed view. It is connected to an external PC for live recording purposes which enables remote use of the thermal imaging camera while the disc is in operation.

RESULTS

Shown in Figure 4 are surface scans of the outboard face of two similar brake discs measured on a Zeiss PRISMO Access CMM. Surface scans were recorded with over 16000 points on the disc surface to create a detailed surface map of the brake disc rubbing surfaces. The brake disc on the left is as received from the factory with only its protective paint coating removed. It can be seen that the disc exhibits first order run-out characterised by a single sine wave around the discs perimeter; this is a trait common with all 'new' brake discs. The peaks present on the left of the disc serve only as a reference feature for future measurements and are not part of the disc surface itself. The right hand image shows an identical disc after heavy on-vehicle testing [7]. Testing took place over thirty braking events; total heatflux into the rotor over the duration of each braking event was $16MW/m^2$. The disc has developed from first order run-out to permanent second order deformation during this testing. This is indicating that plastic deformation has occurred. The disc also shows a larger coning angle compared to the un-used disc.

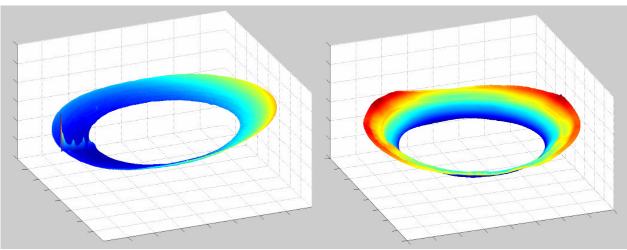

Figure 4 – CMM surface scan of new and used brake discs respectively

Figure 5 shows the surface run-out of this disc following vehicle testing. It is more apparent from this graph that there is dominant second order deformation. Additional peaks are also present in the plot, if large enough these will have the effect of increasing the order of vibration of the brake system.

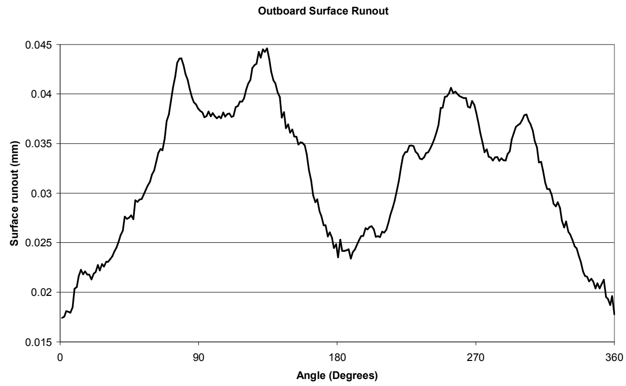

Figure 5 – Graph of outboard disc surface run-out measured manually on vehicle

Additional in-house dynamometer testing of this disc has shown further elastic deformation to take place. The dynamometer test procedure typically comprises ten short drag brake applications at a brake line pressure of 16bar; this is equivalent to a brake torque of approximately 600Nm. Each brake application is separated by four seconds. The speed of the disc throughout the test is 1200rpm and total heatflux dissipated through the disc per braking event is $8MW/m^2$, this is sufficient to generate heavy judder whilst minimising the effect of pad glazing. New brake pads are used to prevent any dampening out of the pressure signal which can occur with worn pads.

During testing the disc transforms from either first or second order run-out to third order as can be seen in Figure 6. It is believed that non-uniform expansion through the thickness of the disc may be the possible cause of this change in deformation. As the surface of the disc is heated it will expand at a greater rate than the inner vane surface exposed to air, this may cause disc buckling to occur which will have an influence on the order of deformation. Only relative dimensionless displacement is indicated on the graphs since focus is upon the shape and order of the waveform. It is believed that this is the most important aspect of the research as it can give more information on how the deformation, and therefore judder, is arising.

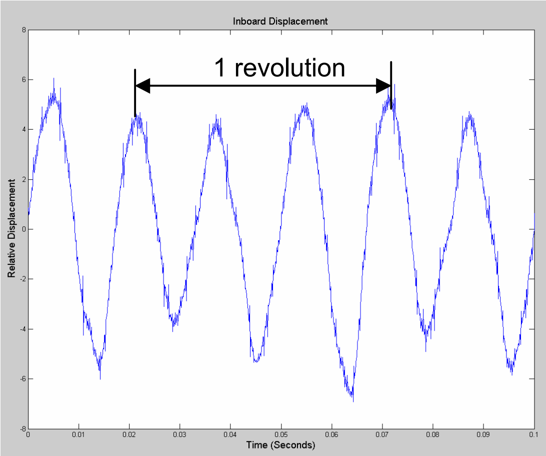

Figure 6 – Graph of disc surface run-out showing third order deformation – 300°C 1200r/min

The graph of disc thickness variation for the same time period also shows a third order component shown in Figure 7.

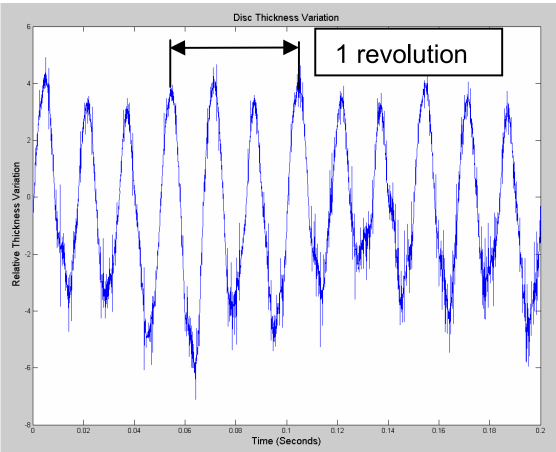

Figure 7 – Disc thickness variation showing third order component – 300°C, 1200r/min – heavy judder present

Judder was present audibly and visibly via the analogue pressure gauge during this test when the disc surface temperature reached approximately 150°C. Figure 8 shows the pressure fluctuation recorded at the caliper, this fluctuation would normally be transmitted back to the vehicle brake pedal. There is quite significant judder with a 2.49bar fluctuation.

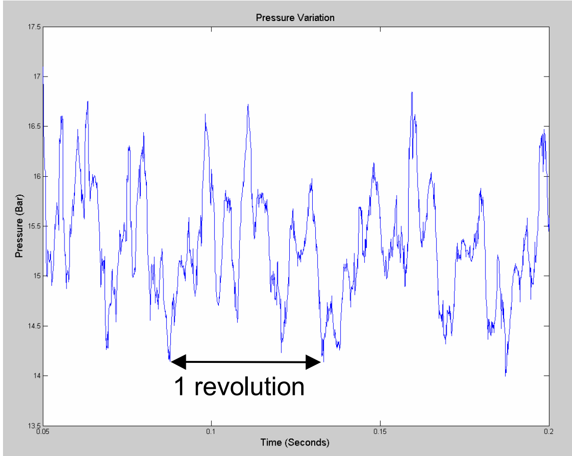

Figure 8 – Pressure variation – 2.49bar fluctuation, 1200r/min, 300°C **–** heavy judder present

Fourier analysis of the pressure fluctuation has identified first and third order deformation being dominant in the signal, with eighth and tenth order also being present. This is shown graphically in Figure 9 at a disc speed of 20Hz; all frequencies are a function of this disc speed. As can be seen from the graph in Figure 8 this builds up to form quite a complex signal. Repeat identical testing has shown the disc to consistently adopt third order deformation with the pressure response containing a third order component, whilst a tenth order component is also consistently apparent.

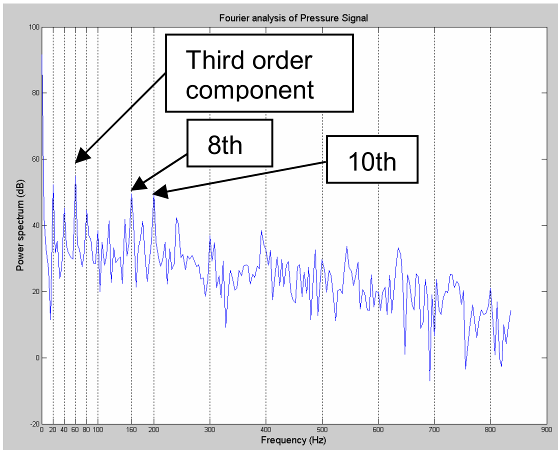

Figure 9 – Fourier analysis of pressure response to brake judder at a disc speed of 20Hz **–** 1200r/min 300°C – heavy judder present

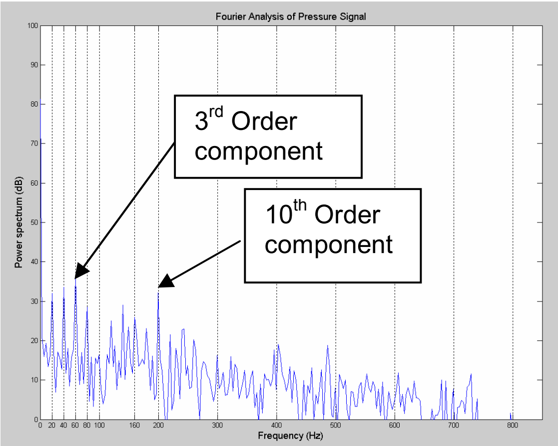

Figure 10 – Fourier analysis of pressure response to brake judder at a disc speed of 20Hz **–** 1200r/min 300°C – heavy judder present

Interestingly the disc appears to relax back to first or second order deformation when the disc is cold, with no apparent indicator as to which state it will return to. Figure 11 shows displacement measurements taken between high speed tests while the disc was cold. It shows second order deformation is present. However Figure 12 shows later testing where the disc has relaxed back to first order deformation. The possible cause of this phenomenon could be that the heating of the disc allows the removal of some of the plasticity which the disc previously experienced. It is important to note that if cold judder i.e. abrasive wear, were the cause of the third order wave, the disc would remain in this state upon cooling. It is therefore a clear case of hot judder occurring.

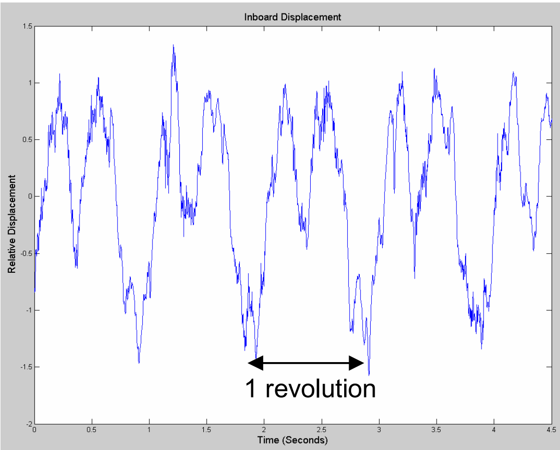

Figure 11 – Graph of disc run-out (cold) showing second order deformation

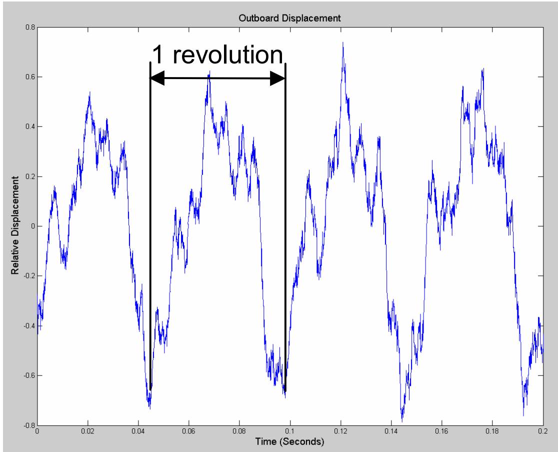

Figure 12 – Graph of disc run-out (cold) showing dominant first order run-out

THERMAL IMAGES

Thermal imaging has been used to analyse the heat distribution and build-up within the brake disc in an attempt to further understand what causes the disc to deform. Shown in Figure 13 is a thermal image of the brake disc after light brake application which has elevated the disc surface temperature to 100°C. The underlying vane pattern can be seen to influence the temperature distribution on the surface of the brake disc. It is believed that this vane pattern is due to the increased thermal mass available to the disc where there is a vane beneath the disc surface. This will allow the disc to conduct heat from the surface to a vane faster than surrounding areas. Note that the apparent hot ring around the wheel centre is due to the emissivity of the protective zinc paint.

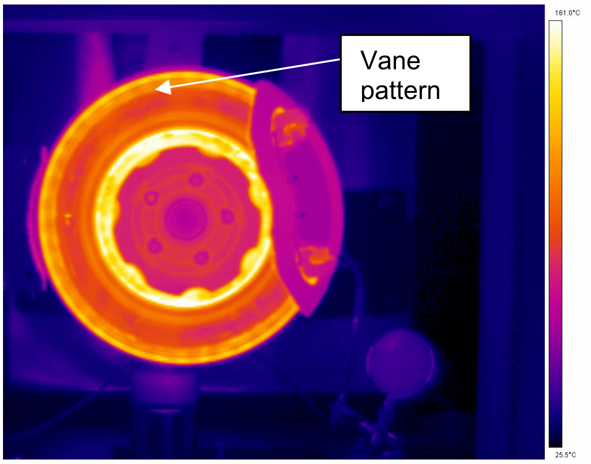

Figure 13 – Thermal image of brake disc showing the vane pattern

Shown in Figure 14 is the temperature profile around the disc at a radius of 187mm. The profile equates to an included disc angle of 262°, omitting the portion of disc obscured by the caliper. The number of peaks in the temperature profile correlates exactly with the number of disc vents in the included angle. It can clearly be seen that the vent profile is influencing the temperature on the surface of the disc, with a recorded temperature variation of 16.2°C. This variation is 21% of the average profile temperature and 19.7% of the maximum profile temperature recorded at this radius. It is temperature effects such as these which are believed to be the cause of disc hot spotting and possible higher order disc deformation.

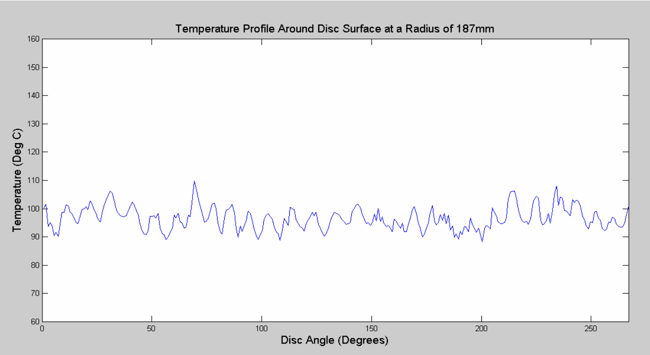

Figure 14 – Temperature profile around the disc surface at 187mm clearly showing the variation due to the disc vanes

Figure 15 shows a thermal image of a disc that has undergone repeat high speed testing on the brake dynamometer. The test involved eight repeat braking events at 100mph/160Kph with 16bar pressure application. The image is taken immediately after the final braking event. Thermal banding of the disc can be seen, but also apparent are hot regions associated with pad deposition. This has occurred where the disc has become hot enough to burnish pad material onto the surface. This condition will only get worse as the disc is repeatedly heated. The hot area will expand causing increased contact with the pad which results in increased heating and so on.

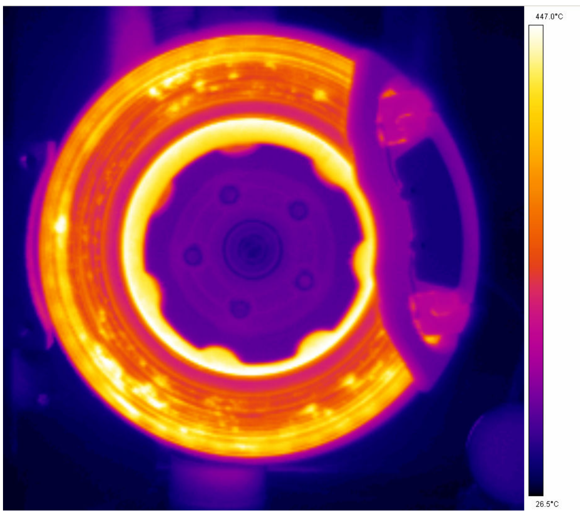

Figure 15 – Thermal image showing thermal banding and regions of pad deposition

CONCLUSION

- Judder is most apparent at temperatures of over 150°C.
- The deformation of the disc is shown to develop to third order deformation during high speed testing.
- The disc can relax back to differing orders of deformation upon cooling, usually first or second order. A disc which has previously taken up second order deformation upon cooling can relax back to first order deformation in follow up testing.
- The pressure response to brake judder has shown to have a component at the same frequency as the disc deformation or DTV. Higher frequency fluctuations are also consistently present within the signal namely tenth order.
- Thermal imaging has shown that the vane pattern of the disc can cause a corresponding temperature profile on the surface of the brake disc. This relates to uneven heat transfer from the disc surface; something which should be avoided to minimise thermal distortion.
- Future work aims to identify the source of the dominant frequencies present within the brake pressure variation signal. Correlation with accelerometer data will also be made possible.

REFERENCES

1. Bryant, D., Fieldhouse, J., Talbot, C., Crampton, A., Mishra, R., "The development of a Design Methodology to Reduce the Probability of Brake Judder and Drone due to Thermo-elastic Instabilities of the Brake Rotor", FISITA World Automotive Congress, 2006

CONTACT

David Bryant
The University of Huddersfield
School of Engineering
Queensgate
Huddersfield
HD1 3DH
England

Tel 01484 473531
e-mail d.bryant@hud.ac.uk

DEFINITIONS

DTV: Disc thickness variation

Run-out: Deviation between the disc surface and hub mounting face from parallel