Aspects regarding the disc brake's thermal stress simulation by using Infrared Thermography

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Abstract. The paper proposes a new simulation method of a disc brake thermal stress resistance, for different temperatures, by interactive processing of images obtained by thermography. Temperature evaluation for different working regimes can be made by recording and processing thermograms of a disc brake heated inside the laboratory by an external heating source. Taken pictures along the temperature variation, from the ambient value to a value close to real one obtained on the usual experiments, are processed using image analyse softwares.This way can be simulated different working regimes (temperature, humidity etc.) without the need of experimental determination on the road or on a test bench.

Keywords: driverless, disc brake, modelling and simulation, thermography, thermal stress

1. Introduction

Thermal stress is a result of exterior constrains during temperature variation ΔT inside the disc brake, having no possibility to expand or constrict. It can be expressed as [1]:

$$\sigma = -\frac{E}{1-\nu} \cdot \alpha \cdot \Delta T \tag{1}$$

where α – the linear thermal expansion coefficient of the brake disc material; $\Delta T = T - T_a$, T – local disc temperature, T_a – ambient temperature, E – Young modulus, ν – Poisson coefficient.

While braking heat is generated by the friction between disc and pads and dissipated by convection and radiation. The surfaces of disc which remains in contact with pads will have higher values of temperature, which can cause, in time, thermal stress inside disc brake. The stresses are amplified in some cases by the pressure between pads and disc (fig. 1). While pads press the disc during braking, the heat generated will make both of them to expand.

If ν coefficient is considered negligible from figure 1 result:

$$\sigma_1 = E_1(\alpha_2 - \alpha_1)\Delta T \text{ and } \sigma_2 = E_2(\alpha_1 - \alpha_2)\Delta T \tag{2}$$

Total heat flux accumulated Q is obtained by dividing the brake power by swept area of the disc brake $Q(t) = kma(V_1 - at)/S_1$; S_1 – swept area of the disc brake by brake pads; $Q(t)$ – time varying heat flux [2].

The stress σ from the S_1 area can be written as:

$$\sigma = \frac{2\pi \cdot Q}{\phi_0 \cdot \mu \cdot p \cdot r \cdot \omega} \tag{3}$$

where $p = p_{max} \cdot \dfrac{r_2}{r}$; p_{max} – maximum pressure distributed on pad; p – radial pressure on the disc brake;

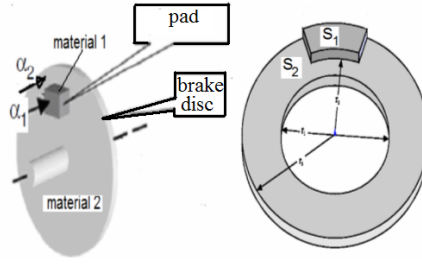μ – friction coefficient, which varies with temperature for different materials [3].

Fig. 1: Schematic disc brake mechanism

A part of the heat flux Q is dissipated by radiation [3]:

$$Q_{rad} = \sigma_0 \cdot \varepsilon \cdot A(T^4 - T_a^4) \tag{4}$$

where A - area of the disc radiation heat, and σ_0 - Boltzamn constant;

The time variation of stress from equation (3) can be written as:

$$\sigma(t) = \frac{2\pi \cdot Q(t)}{\phi_0 \cdot \mu \cdot p \cdot r \cdot \omega} \tag{5}$$

From two values of temperature T_1 and T_2 of brake disc, obtained for two values of radial speed ω_1 and ω_2, the thermal stress ratio can be written from equation (5) as follows:

$$\frac{\sigma_1(T_1)}{\sigma_2(T_2)} = \frac{(T_1^4 - T_a^4) \cdot \varepsilon(T_1) \cdot \omega_2}{(T_2^4 - T_a^4) \cdot \varepsilon(T_2) \cdot \omega_1} \tag{6}$$

Infrared thermography is a powerful, full field non contact, technique of measure thermal stress [4]. The temperature distributions measured with the infrared system give information about gradients in material properties [5]. The stress generated by repeated expands or contractions of disc material can be simulated in two parts:

-1st determine the temperature distribution;

- 2nd determine the effects caused by temperature variations (expands, contractions etc.)

2. Phenomenological and analytical considerations

2.1 Short description of the idea

An important part of driverless car is the brake disc from the brake system, which is exposed to high thermal stresses during and after high speed intensive braking. It's difficult to obtain, by radiation, the real values of temperature. For this reason, the authors propose a method of thermal behavior simulation by processing the obtained thermograms [6], which are obtained in the laboratory by heating the disc brake from an external heat source (fig. 2).
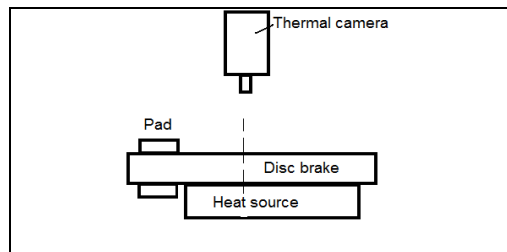

Fig. 2: Position of thermal camera

This method can permit a thermal analysis of disc brake for braking in different conditions of environment. The main reason is the extreme conditions like temperature and humidity – where the driverless cars can be used.

The method consists in placing the disc brake on a heat source, in laboratory conditions, having the possibility of generating different climate conditions. The disc is gradually heated (at an adjustable

temperature due to a thermocouple) and frames are taken and recorded by a thermal camera. Every thermogram (corresponding to different climate conditions) can be processed by software, modifying the contrast and brightness. This way, at a point, for a thermal and humidity regime can appear concentrated color spots, emphasizing areas with possible thermal stresses.

The emissivity variation follows the thermal stress variation, as shown in relation (5). All of these variations can be highlighted and followed by establishing the pixel intensity and the contrast obtained on that thermogram.

2.2 Approaching the idea

The ambient temperature over the termographic images' quality

A thermal camera can display thermograms in two ways:

In thermographic regime, by displaying temperature values $T \in [T_{min}, T_{max}]$, case where the temperature is calculated inside the camera by its processor, with the relation of calibration [7]:

$$T = T_{min} + \sum_{0}^{C_T - 1} \frac{abs(T_{max} - T_{min})}{C_T - 1} \tag{6}$$

where T_{max} and T_{min} are the high and, respectively, the low temperature levels detected by thermal camera; on display they correspond to pixel intensity I_{max} and I_{min}.

By taking account of thermal energy taken by thermal camera, based on Plank law, which permits to highlight the contribution of emissivity and spectral working domain. In this case, the first step consists in assure a prime conversion of radiation R in pixel intensity coefficient with relation [8]:

$$R_i = c_i \cdot p_i \tag{7}$$

where C_i – calibration coefficient; p_i – pixel intensity.

$$R(\lambda, T) = \frac{K}{\lambda^5 \cdot \left(e^{\frac{A}{\lambda T - 1}} \right)} \tag{8}$$

The result is:

$$T(\lambda, R) = \frac{A}{\lambda \cdot \ln\left(\frac{K}{\lambda^5 \cdot R} + 1 \right)} \tag{9}$$

For a taken frame "i", temperature T_i can be written as: [9]

$$T_i = T_a + \frac{C_T}{255}(T_i - T_a) \tag{10}$$

The intensity C_T is the mean of the intensities of these pixels. Note that the camera was set to have a linear relationship between intensity and temperature, and relating intensity to temperature is the reason why equation (10) is linear [9].

The most disadvantageous situations (when the shown image on display has a lower contrast) are met when the target and the background temperatures are closer or when the environment is a powerful heat irradiated. Planck's theory may plausible explain the resolution's variance that results by the temperature growth. Thus, for a better understanding, the distance between two maximum of existence given by Planck's law for two closed lines of a heated pattern is drawn for 3 temperatures in figure 3.

Taking into account the Stefan-Boltzman relation:

$$R = \sigma_0 \cdot \varepsilon \cdot T^4 \tag{11}$$

Three characteristics are important in analysing and characterization of a thermal image for a taken frame: the geometrical resolution, the contrast and the brightness (which are associated directly to the gray level intensity value of the image pixels). More on the contrast depends on geometrical resolution (figures 4,

and 5). It is obvious (figure 4) as the temperature (respectively the corresponding brightness on display) between two pattern's lines increase, the direction of the bars appears more distinctly emphasized, meaning a higher obtained resolution. A high brightness on a thermal camera display corresponds to a high temperature, so, a high clarity of picture is obtained. On the other way, the contrast on display is defined by the highest and the lowest brightness displayed [10].
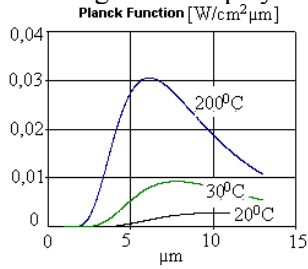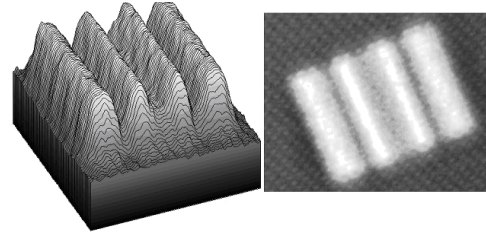

Fig.3: Exitance distribution shape

for three different temperatures:T=200C; 300C;2000C

Fig.4: 3D Exitance distribution shape and its

corresponding pattern image; it may be seen that

temperature and resolution depends on contrast
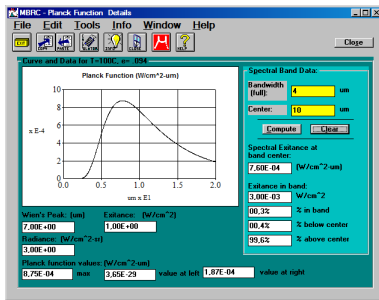
Fig.5: Calculation of a black body emitted radiance, by MBRC program at temperature of 1000C and emissivity 0.094
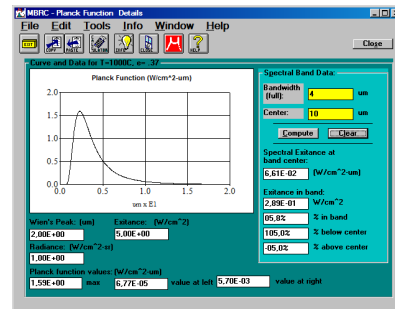
Fig.6: Calculation of a black body emitted radiance, by MBRC program at temperature of 1000C and emissivity 0.37
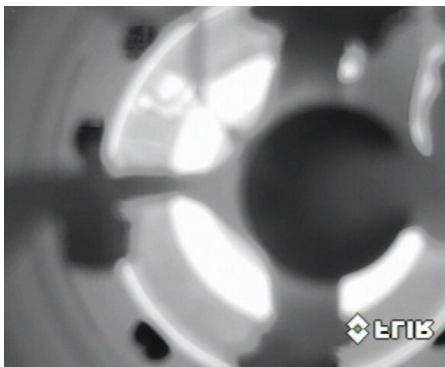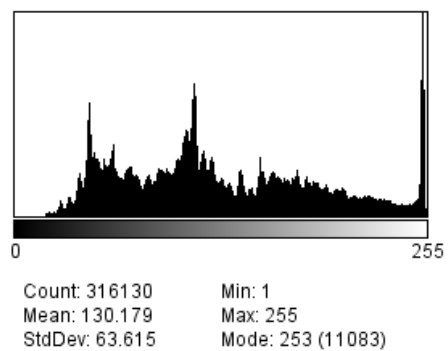

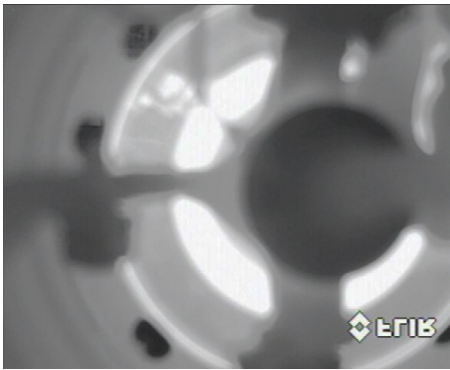Fig.7: Image of gray scale thermograms of a disc brake

Fig.8: Histogram of figure 7

Fig.9: Image of gray scale thermograms of a disc brake for a contrast decrease of 40%

Count: 313872   Min: 1
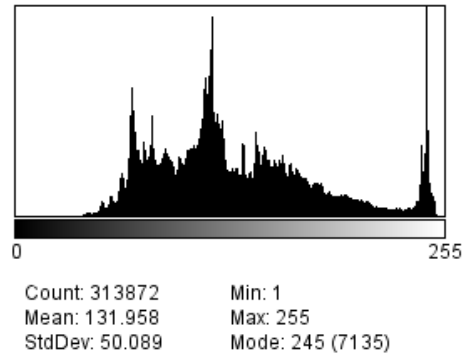Mean: 131.958   Max: 255
StdDev: 50.089   Mode: 245 (7135)

Fig.10: Histogram of figure 9

The histograms shown in figures 8 and 10 illustrates that images utilize the full range of gray levels of an 8-bit image from 0 to 255.

2.3 Theoretical justification of image degradation

The contrast of an image is the range of gray levels used to represent the scene. There are a possible 256 shades of gray for an 8-bit imaging system. Typically, the more gray levels an imaging system uses the higher contrast is. For a thermographic image, a lower contrast means less gray levels so the object image resolution decreases. This way it seems to have an appropriate emissivity.

## 3. Experiments, results and discussions

The deterioration of the thermal contrast has been simulated with software of image processing. By a controlled degradation of image contrast, the emissivity can be estimated for different environmental temperatures. At experiments were used a thermal camera, a contact thermometer and a disc brake (fig. 11). Thermal camera's technical characteristics were as follows: working spectral range between 8…12 μm, detection matrix with micro-bolometers and resolution of N_C=320 x 240 pixels, size of the detection item d_p=45 μm, objective focal distance f_{ob}=19 mm.

a) Temperature of brake disc in real tests

b) Measuring temperature inside the laboratory
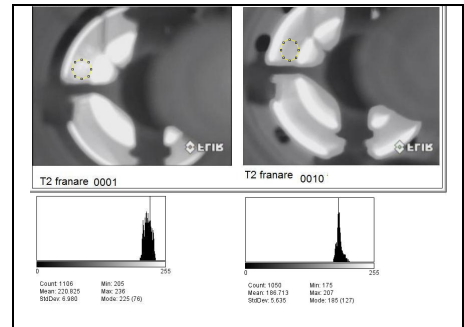
c) Thermal images and histograms at the beginning and the end of braking tests (intensive braking from 100 to 0 km/h)

Fig.11: Tests inside and outside the laboratory and their results

Furthermore, starting from one of the images taken by thermal camera, in laboratory conditions, a degradation of its contrast (C_T) was simulated, through software of image processing. It was followed by the image degradation to obtain a contrast limit, barely perceptible to the eye (fig. 12).

So between the contrast variation made by software and the one obtained in laboratory by decreasing the thermal contrast between pattern and the black body is in quite good similarity (fig.13). This means that an image acquired on-site may be shading by soft to simulate an environment with a lower IR transmittance.

The contrast value thus obtained was compared with the real value obtained in laboratory conditions and during braking (fig. 14-19).
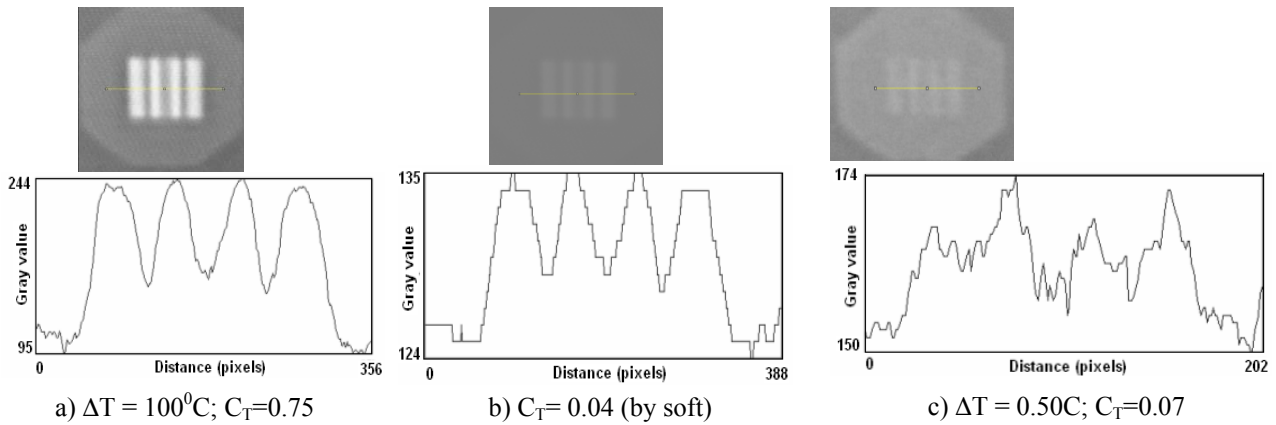

a) $\Delta T = 100^0 C$; C_T=0.75   b) C_T= 0.04 (by soft)   c) $\Delta T = 0.50 C$; C_T=0.07

Fig. 12: Pattern image that was seen with a thermal contrast of $\Delta T = 100 C$ (a) and then it was degraded to a limit barely perceptible by the eye (b)
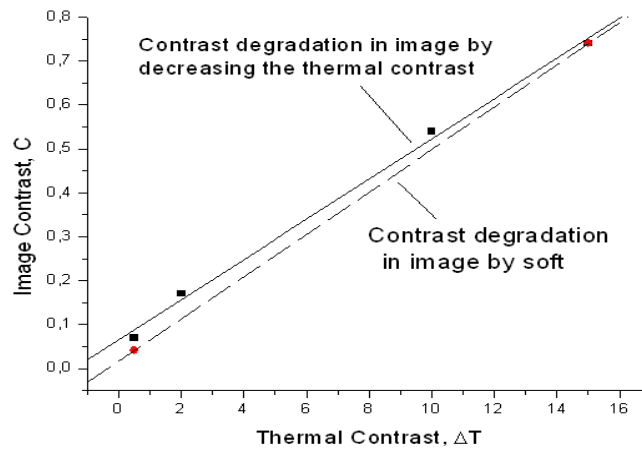

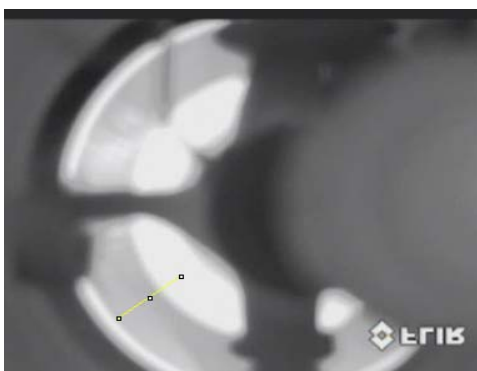Fig.13: Image contrasts obtained by software (from fig. 12 b) and in laboratory (fig. 12 c)

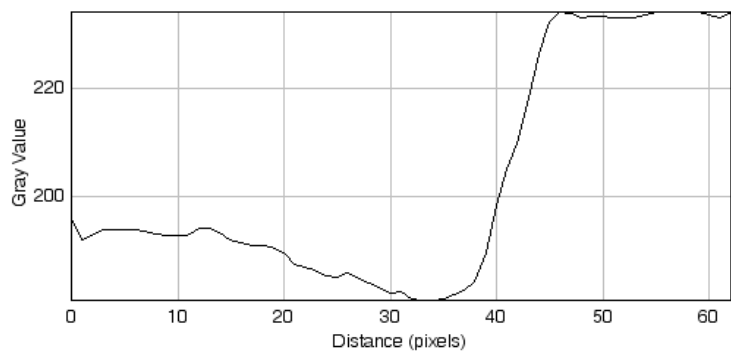Fig. 14: Thermogram of a disc brake at the beginning of braking, at 100 km/h)

Fig.15: Contrast of the line selected from the thermogram of figure 14. The calculated contrast is (230-190)/(230)=17.4%
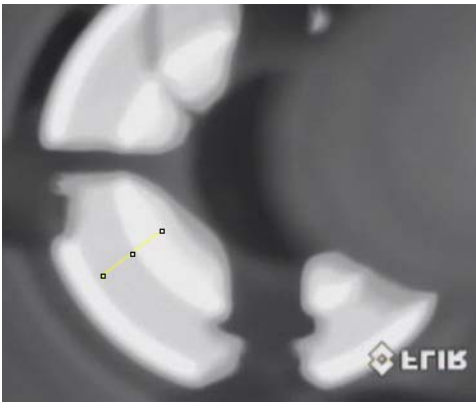
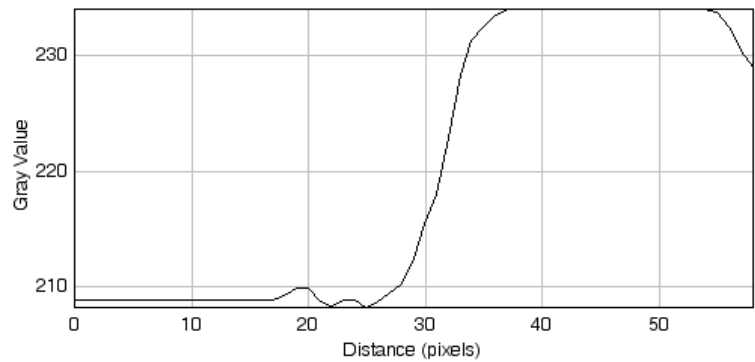Fig.16: Thermogram of a disc brake during braking, at 70 km/h)

Fig.17: Contrast of the line selected from the thermogram of figure 16. The calculated contrast is (235-208)/(235)=11.4%
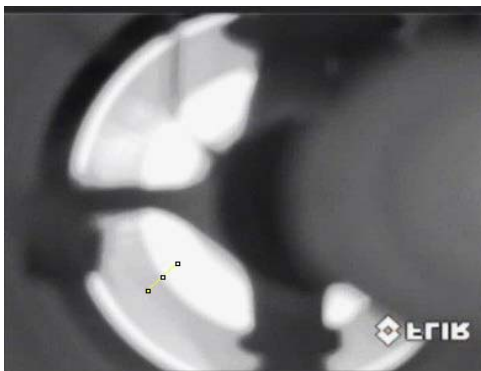

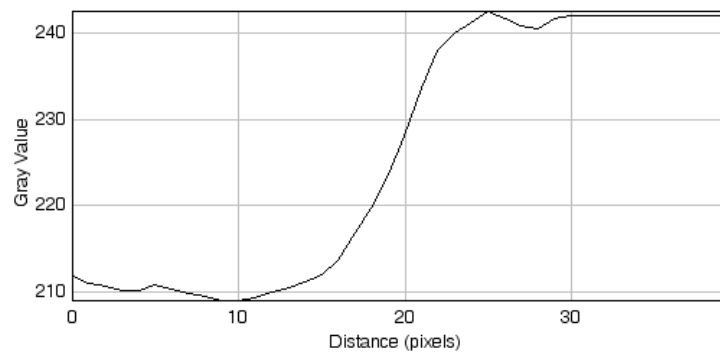Fig.18: Thermogram of a depreciated image of brake disc at the beginning of brake (100km/h)

Fig.19: Contrast of the line selected from the thermogram of figure 18. The calculated contrast is (242-210)/(242)=13.2%

4. Conclusions

1. To estimate the thermal stress for different temperatures, the deterioration of the thermal contrast can be simulated with software of image processing, by a controlled contrast degradation of image;

2. The contrast variation by software and that one obtained in laboratory by decreasing the thermal contrast between pattern and the black body is in a quite good similarity.

3. The material emissivity is a major problem of temperature IR measuring for a disc brake. If the emissivity of a disc brake material has a low value (in case of low temperature) it acts as a mirror and distorts the right determinations because it reflects of appropriate worm bodies.

5. References

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