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Research Article

Transient Thermo Elastic Analysis of Disk Brake

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Abstract

Thermo elastic instability is caused by frictional heating and thermal deformation of the surfaces when two bodies slide against each other, and alters the original contact configuration. Even if the surfaces are perfectly flat at the outset, instability will lead to a departure from flatness. Above a certain critical speed, a nominally uniform pressure distribution is unstable, giving way to localization of load, excessive heat generation and hence to hot spots at the sliding interface (Barber, 1969), (Kennedy and Ling, 1974), (Floquet and Dubourg, 1994), (Bryant, et al, 1995), (Kao et al., 2000). The problem is particularly prevalent in energy dissipation systems such as brakes and clutches. Hot spots can cause material damage (i.e. wear) and undesirable frictional vibrations, known as ``hot roughness'' or ``hot judder'' (Kreitlow, et al, 1985), (Inoue, 1986), (Zagrodzki, 1990), (Anderson, 1990), (Lee, 1998).The present paper describes the use of ANSYS simulation software to perform a transient analysis of the thermo elastic contact problem for disk brakes. The numerical simulation for the thermo elastic behavior of disk brake is obtained in the repeated brake testing carried out on a dynamometer. The computational results are presented for the distribution of heat flux and temperature on each friction surface between the contacting bodies.. In addition, comparisons of the thermal behavior of the different brake pad materials with respect to disk materials have been discussed.

Keywords:*Volvo Disk Brake, Finite Element Analysis, Thermo Elastic Instability.*

1. Introduction

Magnetorheological (MR) brake (Sarkar and Hirani, 2015), (Sarkar and Hirani, 2013), (Gupta and Hirani, 2011), (Sukhwani, *et al*, 2009), (Sukhwani and Hirani, 2008), (Sukhwani and Hirani, 2008), (Hirani and Manjunatha, 2007), (Sukhwani, *et al*, 2007), (Sukhwani, *et al*, 2006), (Huang, et al, 2002), (Li and Du, 2003) is a device, where MR fluids are used as brake friction materials. During braking, kinetic energy of machines gets converted into heat and shear thinning of MR fluid due to increase in temperature occurs which in turn reduces the braking effect. Similarly, in conventional disk brake during the braking action, the kinetic energy produced at the wheel is transformed into heat energy, which doesn't dissipate fast enough into the air stream from the brake and the brake disk, as a result, one of the disk brake material properties; the thermal conductivity plays a critical role in handling such friction heat generated. Thermal judder occurs as a result of non-uniform contact cycles between the pad and the disk brake rotor, which is primarily an effect of the localized Thermo-Elastic Instabilities (TEI) at the disk brake rotor surface. Localized TEI act at the friction ring surface generating intermittent hot bands around the rubbing path which may in turn leads to the development of so-called hot spots (Eggleston, 2000).

The mechanism of the TEI phenomena taking place during the braking process has been of interest to many researchers (Lee, 2000), (Jang and Khonsari, 2003), (Lee and Brooks, 2003), (Dufrenoy, 2004). However, in this paper an assumption has been made that the thermo mechanical phenomenon of each disk is symmetrical about the disk's mid-plane. Also, the wear action taking place during the braking process, resulting from the friction between the disk brake and the pad, is assumed to be so small and thus to be neglected in the analysis. A FEA model has been suggested to simulate the braking action by investigating both the thermal and elastic actions occurring during the friction between the two sliding surfaces (the disk brake and the pad).The results obtained from the suggested model are compared with actualmeasurements performed by Kumar,*et al, 2009*.

2. Methodology

The FEA simulation was performed into two stages: thermal and elastic. During the analysis, the braking parameters,such as rotational speed of the disk brake, the cycle of the pressure applied and the time period

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(shown in Fig. 1) of the different phases: braking, dragging, and release, were set to the values, extracted from the literature.

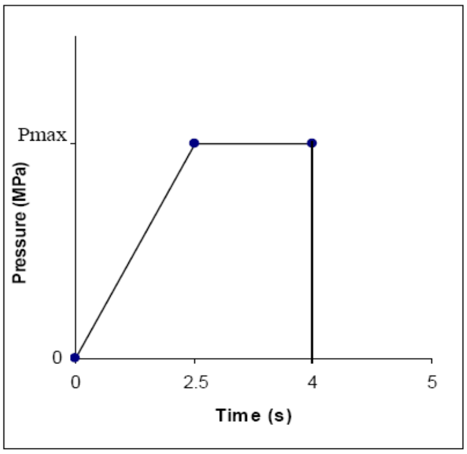


Fig.1 The change in applied pressure during breaking process

As shown in figure 1, during the braking process, it is assumed that the pressure will first increase linearly until it reaches the maximum value P_{max} within 2.5 s, then the pressure remains constant for another 1.5 s, then it dropsto zero.

The governing equation for the transient heat transfer problem is:

$$\rho C * \frac{\partial T}{\partial t} + \nabla(-k\nabla T) = Q - \rho.Cp.u.\nabla T \quad (1)$$

Where, ρ is density, C is heat capacity, T is temperature, k is thermal conductivity, Q is heat source or heat sink, $Cp$is the specific heat capacity and u is the velocity.

The governing equation for the elastic problem is:

$$\rho * \frac{\partial^2 u}{\partial t^2} - \nabla c \nabla u = K \quad (2)$$

where, K is the force vector.

Figure 2 shows the boundary conditions assumed during the simulation of the heat transfer problem.

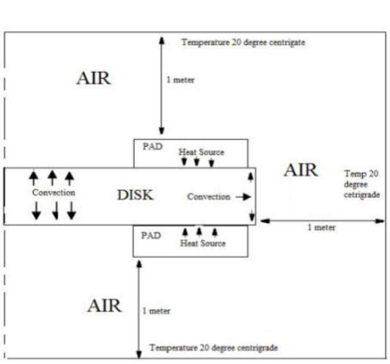


Fig.2 Heat Transfer Boundary Condition

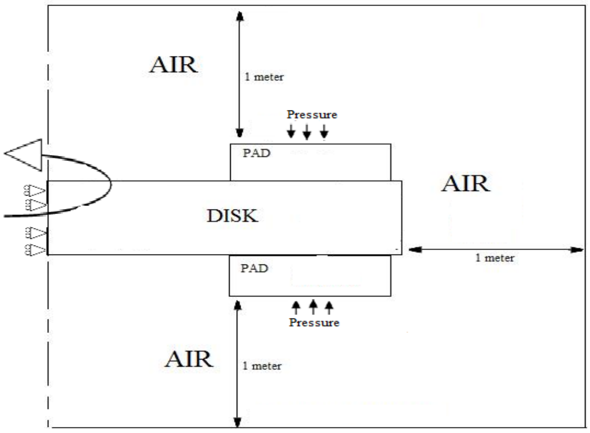


Fig.3 Elastic Problem Boundary condition

The boundary conditions stated for the elastic problem are represented in figure 3.

The objective of the study presented in this paper is to simulate the thermo elastic phenomenon taking place during the braking process. In addition, comparisons of the thermal behavior of the different brake pad materials with respect to disk materials have been discussed. Table1 shows the disk material's properties and Table2 shows the brake pad material's properties. The coefficient of friction values varies from 0.35 to 0.45 for these materials.

Table 1 Disk Material properties

Material	Grey Cast Iron
Density, ρ(Kg/m^3)	7031
Specific Heat, C (J/Kg K)	495
Thermal Conductivity, K (W/m/k)	56.72
Elastic Modulus, E (Pa)	1.50E+11
Poisson's Ratio	0.265
Thermal Expansion Coefficient, α (/k)	1.30E-07

Table 2 Physical, chemical and mechanical properties of VOLVO brake pads series

Parameters	P	A
Density (g/cc)	2.24	2.21
Acetone extraction (%)	1.25	1.35
Hardness ® (ASTM D 785)	95-102	89
Th. Conductivity (W/mK) (ASTM-E1461-01)	2.03	1.97

Table 3 shows the material properties of P series of composites.Table 4 shows the other mechanical properties of composites. Table 5 shows the operating conditions.

The elastic problem was simulated in order to investigate the mechanical action taking place at the disk's contact surface during the braking process. The deformation obtained from the elastic problem was approximately 200 μm.

Table 3 Physical and mechanical properties of the Series P composites (4th series)

Properties	BP Series	CP Series	IP Series
	BP_1	CP_1	IP_1
Density (g/cc)	2.30	2.31	2.29
Porosity (%)	4.33	4.30	4.10
Acetone extraction (%)	1.38	1.18	1.28
Tensile strength (MPa)	12.37	12.65	14.56
Young's modulus (GPa))	2.28	2.30	2.16
Flexural strength (MPa)	24.15	23.89	30.43
Flexural modulus (GPa)	4.33	4.80	5.70
Rockwell Hardness (S-scale)	78-88	88-93	85-95
Compressibility (%)	1.07	1.02	1.26
Thermal Conductivity (W $m^{-1}K^{-1}$)	2.22	2.41	2.11
Thermal diffusivity x10^{-4}(cm^2s^{-1})	80	97	71
Specific heat (J $kg^{-1}K^{-1}$)	1207	1076	1298
Effusivity (J $m^{-2}K^{-1}s^{-1/2}$)	2482	2447	2504

Table 4 Other Mechanical Properties of Composites

Material	Specific Heat, C (J/Kg K)	Elastic Modulus, E (Pa)	Poisson's Ratio, γ	Thermal Expansion Coefficient, α (/K)
Composites	800	4e11	0.25	6e-6

Table 5 Operating conditions.

Operating Conditions	Brake	Disk
Hydraulic pressure, P (MPa)	1	
Angular velocity, w (R.P.M)		150

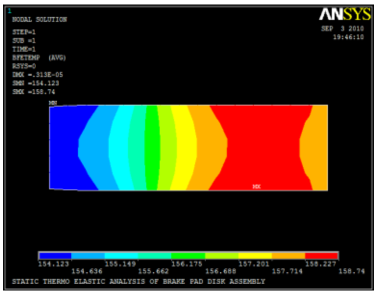
3. Results and Discussions

The developed finite element analysis model contains a total of 32242 elements and 23 degrees of freedom, while the time step used during thenumerical computation was 0.01s. The initial temperature used during the simulation was set as 20 ºC.

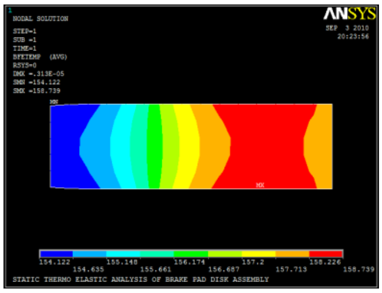
As mentioned before, the suggested model was applied to the stated materials in order toinvestigate which of these materials possess better temperature distribution as well as themaximum temperature produced when subjected to the same braking conditions.

Figure 4 depicts one of the typical temperature distributions developed under the mentioned braking conditions using the suggested finite element analysis model. It's shown how the temperature increases further from the center of the brake disk to the point of the maximum temperature within the contact area between the disk and the pad, and then it decreases.

Figure 5 shows the Von misses stress distribution and average displacements of the disk brake.

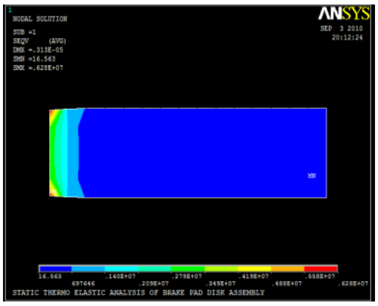


(a) Pad P: Maximum temperature: 158.74º C

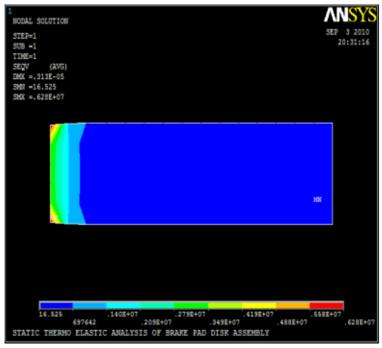


(b) Pad A: Maximum temperature 158.739º C

Fig .4 Temperature distributionat Pad A and Pad B



(a) Pad P: Von misses stress: 0.628 e7 Pa

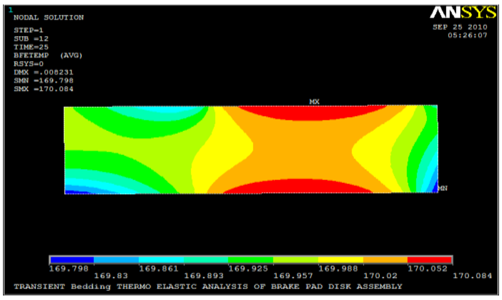


(b) Pad A: Von misses stress: 0.628e7

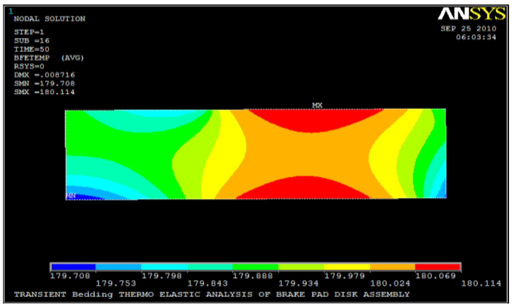
Fig .5 Von misses stress at Pad P and Pad A

From the above results, it can be observed that temperature distributions and generated Von-misses stresses for both pads are same.

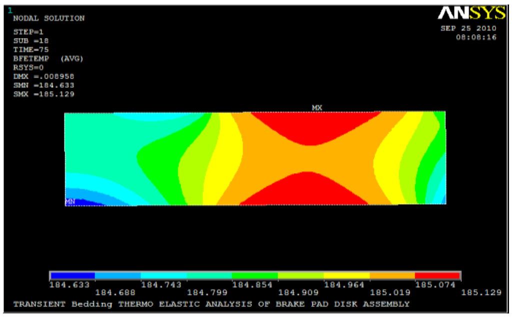
The temperature distribution during the braking process at different application is shown in Figure 6, in which the temperature distribution of the brake disk is presented at 1, 2, 3, 4, 5, 6, 7 and 8 no of application.



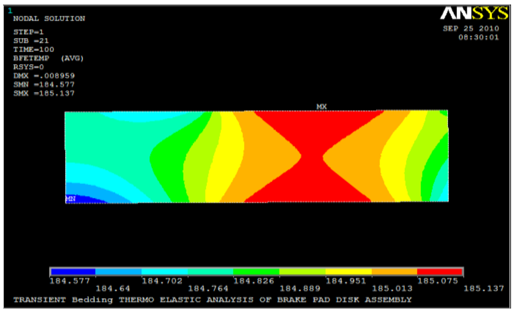
Brake Application No. 1



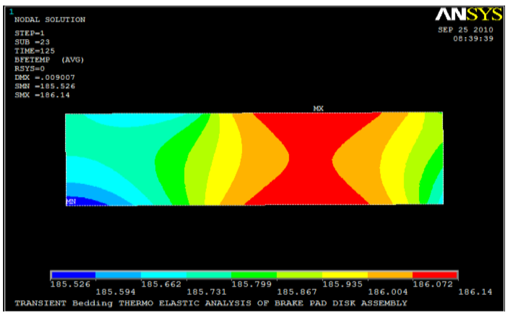
Brake Application No 2



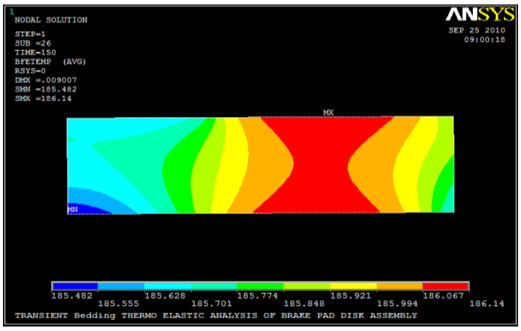
Brake Application No 3



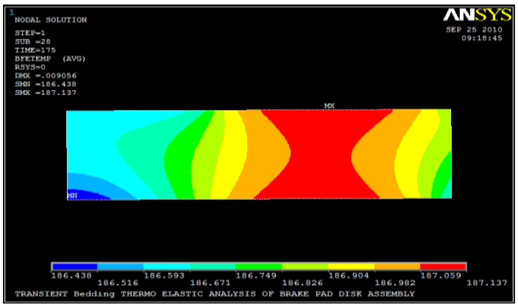
Brake Application No 4



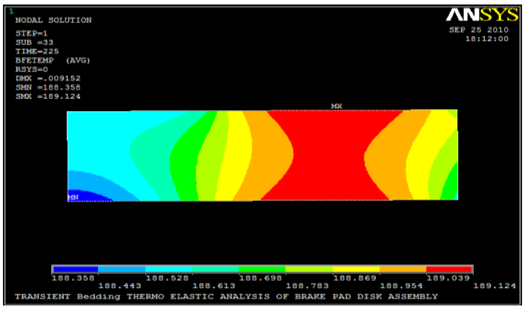
Brake Application No 5



Brake Application No 6



Brake Application No 7



Brake Application No 8

Fig. 6 Temperature distribution of the brake disk

In order to validate the proposed model, the maximum temperatures obtained from the proposed model were compared to the actual measurement performed (Kumar, *et al*, 2009). The results are listed in Table 6.

Table 6 Comparison between the actual temperatures measured (Kumar, *et al*, 2009) and the simulated values obtained from the suggested finite element analysis model

No of Appl.	Actual temperature measured (° C) at **5.8 Bar**	Simulated temperature (°C)	Difference (%)
1	165	147	11
2	173	170	1.7
3	183	180	1.6
4	187	185	1.1
5	185	185	0
6	186	186	0
7	187	186	0.5
8	188	187	0.5
9	190	189	0.5

From the Table 6, it can be concluded that the suggested model produced a maximum difference of 11% at initial conditions, but subsequent to that difference between the calculated temperature and the measured temperature decreases. This comparison provides confidence in finite element model used to simulate the braking cycles.

The comparison of the maximum is also plotted in the Figure 7, which shows a very close fit between the proposed model and the experimental results Kumar, *et al* (2009).

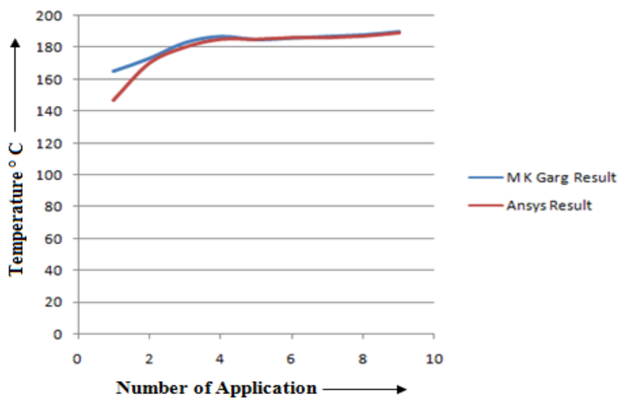


Fig.7 Comparison of Temperature Distribution

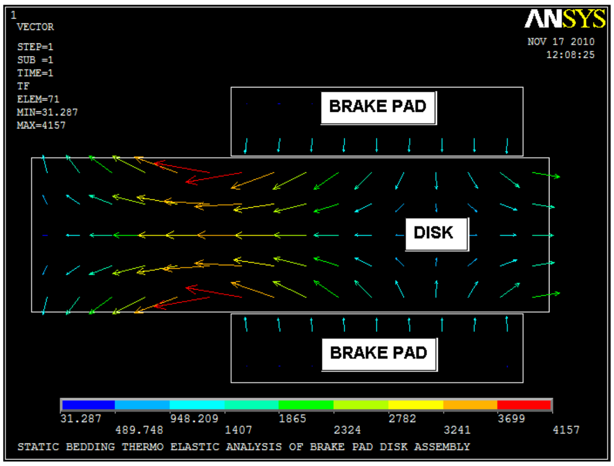


Fig. 8 ANSYS graphics shows the direction of heat flux

The vector plot showing the heat flow from the brake pad to the disk has been presented in Figure8. The red arrow is for high value of the heat flux.

Conclusions

A finite element analysis model was developed in order to investigate both the thermal and mechanical behaviors taking place between the disk brake and the pad, during the braking process. The developed model was compared with actual measurements performed (Kumar, et al, 2009) in order to validate the proposed model. The simulated results match very close to the experimental results.

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