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THERMO-STRUCTURAL BRAKE SQUEAL FEM ANALYSIS CONSIDERING TEMPERATURE DEPENDENT THERMAL EXPANSION

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Abstract: *During the process of evaluation of disk brake components for brake squeal occurrence using computational methods, invariance of material properties according to temperature is commonly considered. This approach is not usually in correlation with experiments and user experience. Paper focuses on study of thermal expansion coefficient variation of the friction material and its influence on brake squeal occurrence and propensity. Study has been done experimentally on simplified pin-on-disk system and also numerically using FEM procedures. Computational FEM model capable of time history thermo-structural evaluations and Complex Eigen Value calculation has been brought to study upper mentioned effects.*

Keywords: brake squeal, dynamic instability, FEM, thermal effect, thermal expansion

1. Introduction

In the analysis of brake squeal due to friction induced vibrations, particular emphasis has been dedicated to study of mechanisms and conditions leading to the unstable vibrations generation (Kinkaid et al., 2003). This well-studied phenomena leads to high amplitude of vibrations often associated with noisy sound emission occurring in friction based brake systems and other similar applications.

This possible instability is due to the collision of pairs of eigenvalues on the imaginary axis - Hamiltonian-Hopff bifurcation (Jan-Cees van der Meer, 1980) – which physically means a linking of the natural vibration modes of elastic structure. In this state, the braking vibration amplitudes increase far beyond audible levels.

Checking the quality of disc brakes for sound performance is currently being carried out according to standard (SAE J2521, 2001). The SAE Standard prescribes a Noise Vibration and Harshness (NVH) - based brake evaluation method accounting for also thermal load. Typical behavior of the tested brake shows a significant dependence of sound effects just from the thermal load (Suchal, 2013).

At present, there is no universal standard prescribing the NVH evaluation of the disc brake. Generally, computational FEM procedures using complex Eigen Value Analysis (CEVA) to identify unstable system modes are used. The brake disc design process consists of modifying natural modes by changing

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geometric or material parameters. However, CEVA leads to the prediction of a large number of possible unstable modes, not all of which are significant in the real system. This fact is due to the physical influences (damping, thermal load, contact inhomogeneities and others) being neglected.

Nowadays, producers of friction materials are becoming bounded by legislation to follow trends of environmental burdening and recyclability (Peciar et al., 2016) which leads to material with new temperature-sensitive properties.

In this paper the extended thermal – structural FEA model for brake squeal prediction is presented. This model includes experimentally obtained temperature dependent thermal expansion of friction material.

2. Experimental setup

Experimental results have been obtained using the experimental set-up depicted in Fig. 1. It is a simplified experimental set-up (pin-on-disc) of a braking system with reduced geometry (Úradníček et al., 2017). This experimental set up was designed for studies of influential parameters focusing on the influence of friction and contact parameters under the thermal loading in relation with the brake squeal phenomenon.

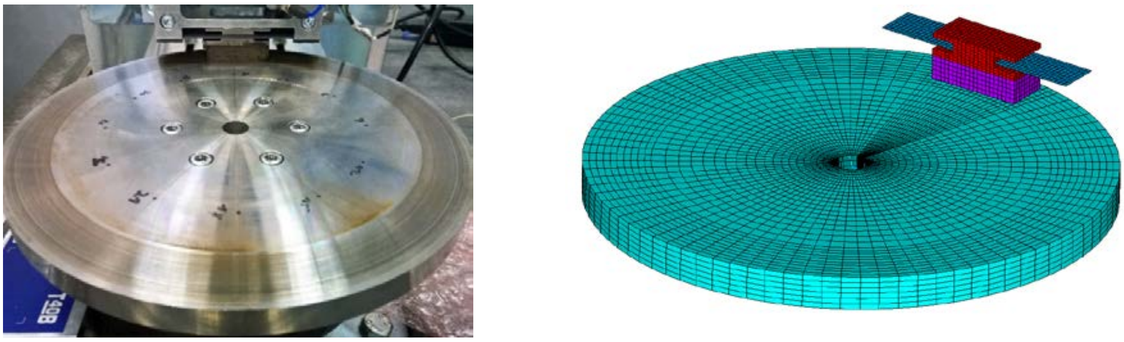

Fig. 1: Reduced pin-on-disc system, left - test bench, right - FEM model consisting of brake disc - pale blue, standard friction material FERODO - pink, back plate - red and thin plate - dark blue.

In experiments, various thermal loading has been considered. In general, results show increasing number of squealing frequencies and squeal propensity with increasing temperature, Fig. 2.

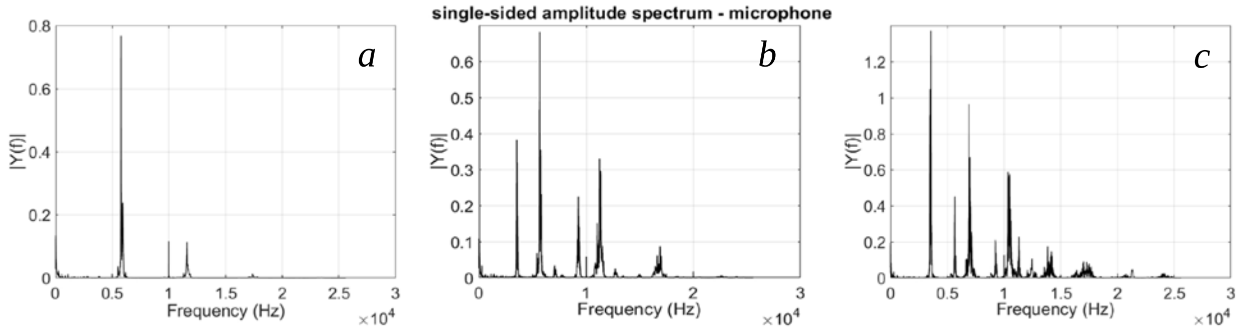

Fig. 2: Squeal noise instability occurrence and its propensity (Pa) along the temperature for a) cold, b) medium and c) fully heated system (disc contact area more than a) 20 °C, b) 50 °C, c) 80 °C).

In this work the emphasis has been placed on thermal expansion of friction material. This material parameter of friction material is markedly higher compared to standard steel. Frictional contact serves as interface between disc and friction material and its non-conservative nature can cause energy exchange between vibration modes of the system which leads to dynamical instability and squeal. Focusing on this fact, the behavior of the contact, its variation due to temperature loading and subsequently thermal expansion should be in the point of interest.

3. Measurement of thermal expansion

In this wok considered temperature dependent material parameter is the thermal expansion of friction material. This parameter was measured using Netzsch DIL 402C Piston Dilatometer. The obtained data can be seen in Fig. 3.

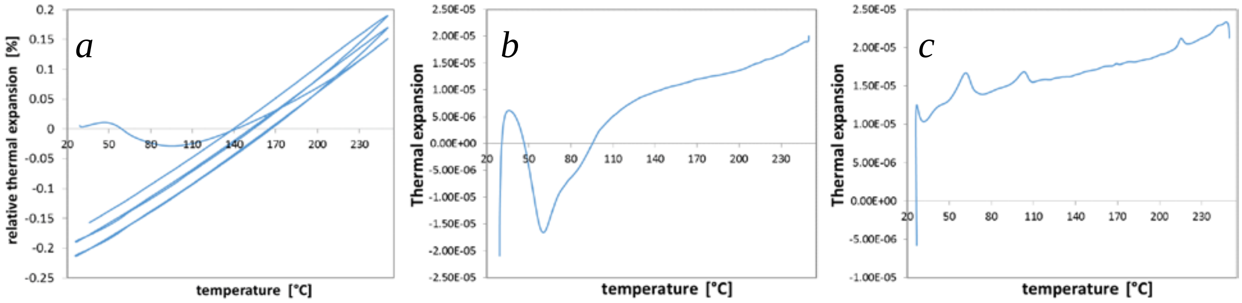

Fig. 3: a) relative thermal expansion (three heating-cooling cycles), b) thermal expansion in the first heating cycle and c) thermal expansion in the third heating cycle.

It can be seen that during the first heating the material is undergoing a material change and after this cycle is the thermal expansion quasi linear with respect to the temperature evolution.

4. Computational model

To introduce the thermal effects into the FEM analysis it is necessary to perform a transient analysis of the temperature field. One way is the coupled thermo-structural transient analysis, however it is very time consuming (Ouyang et al., 2009). Therefore, an uncoupled procedure was chosen, Fig. 4. The proposed solution is adopted from the work of (Majchercak and Dufrénoy, 2006), however the temperature field on the brake disc is calculated using the whole 3D model using the assumption of angularly homogeneous temperature distribution. In the paper, the temperature filed on the disc was calculated on a 2D cut and then transformed into 3D model using a special time to spatial frequency transformation method.

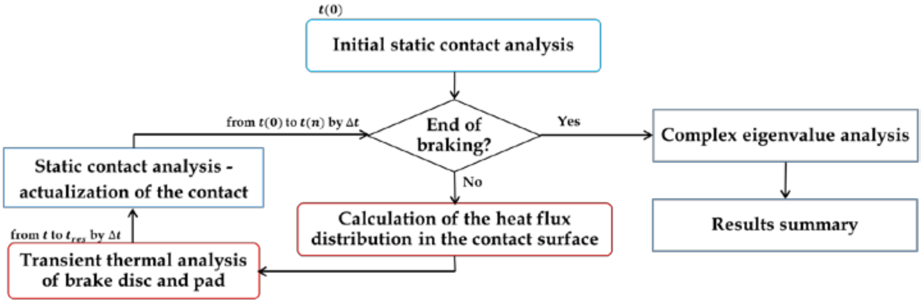

Fig. 4: Thermo-structural procedure.

Detailed description of proposed model, including the boundary condition can be seen in (Úradníček et al., 2016). In the used procedure, firstly the initial non-linear static analysis is performed. After this step, a loop of analyses is performed, containing of

- calculation of the heat flux according to contact forces, friction coefficient and disc angular velocity,
- thermal transient analysis, for which the input is the heat flux and
- static analysis, which works as actualization of the contact forces distribution with the consideration of the new temperature field.

When the cycle is finished a complex eigenvalue analysis is performed to obtain the unstable frequencies and shapes.

5. Results

Three simulations were performed: pure structural analysis and two thermo-structural analyses considering the temperature dependent thermal expansion of the friction material, one from the first heating and one from the third. The unstable complex frequencies, $\mathrm{Re}(\lambda_i) > 0$, of the structure can be seen in Tab. 1.

The change in the frequencies is caused by the consideration of thermal strain and due to it the change of the contact pressure between the pad and disc. The contact pressures can be seen on the Fig. 5. Fig. 5a displays the contact stresses without the thermal effect. Fig. 5b and Fig. 5c show the 60th and 120th second of the simulation when considering the first heating thermal expansion. Fig. 5d and Fig. 5e shows the 60th and 120th second of simulation when considering the third heating thermal expansion.

Tab. 1: Unstable complex frequencies.

Static		First heating				Third heating			
0 sec		60 sec		120 sec		60 sec		120 sec	
$Re(\lambda_i)$	$Im(\lambda_i)$	$Re(\lambda_i)$	$Im(\lambda_i)$	$Re(\lambda_i)$	$Im(\lambda_i)$	$Re(\lambda_i)$	$Im(\lambda_i)$	$Re(\lambda_i)$	$Im(\lambda_i)$
55.67	6021	0.51	6160	1.02	6160	50.38	6002	94.84	5948
0.32	6160					0.32	6160	615.81	6946
859.16	8028					841.63	7757		
						47.60	9383		

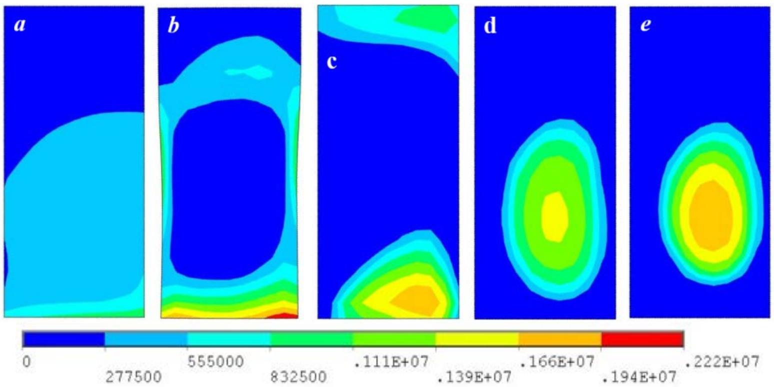

Fig. 5: Contact stresses [Pa] on the pad side.

6. Conclusion

This work deals with the influence of thermal effect on the brake squeal occurrence. The temperature dependent thermal expansion of friction material was measured and introduced into FEM analysis. The results of FEM simulation show the change of the unstable frequencies of the system and therefore the importance of this extension to simulation procedure.

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