FACULTY OF MECHANICAL ENGINEERING
UNIVERSITY OF WEST BOHEMIA

DEPARTMENT OF POWER SYSTEM ENGINEERING

Frictionally excited thermoelastic instability

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Проект „Развитие международного сотрудничества с украинскими ВУЗами в областях качества, энергетики и транспорта“
г. Харьков, 11/2018

Степан Прокопович Тимошенко

1878 - 1972

S. Timoshenko

Appeal for us:

Not to be afraid to use MATHEMATICS for solution of our mechanical problems.

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Introduction

● The heat generated in frictional organs like brakes and clutches induces thermal distortions which may lead to localized contact areas and hot spots developments.

● Hot-spots are high thermal gradients on the rubbing surface.

● They count among the most dangerous phenomena in frictional organs leading to damage and early failure.

● The thermomechanical solicitation due to these hot spots may induce a cycling of tensile and compressive stresses with plastic strain variations (i.e. TGV disks).

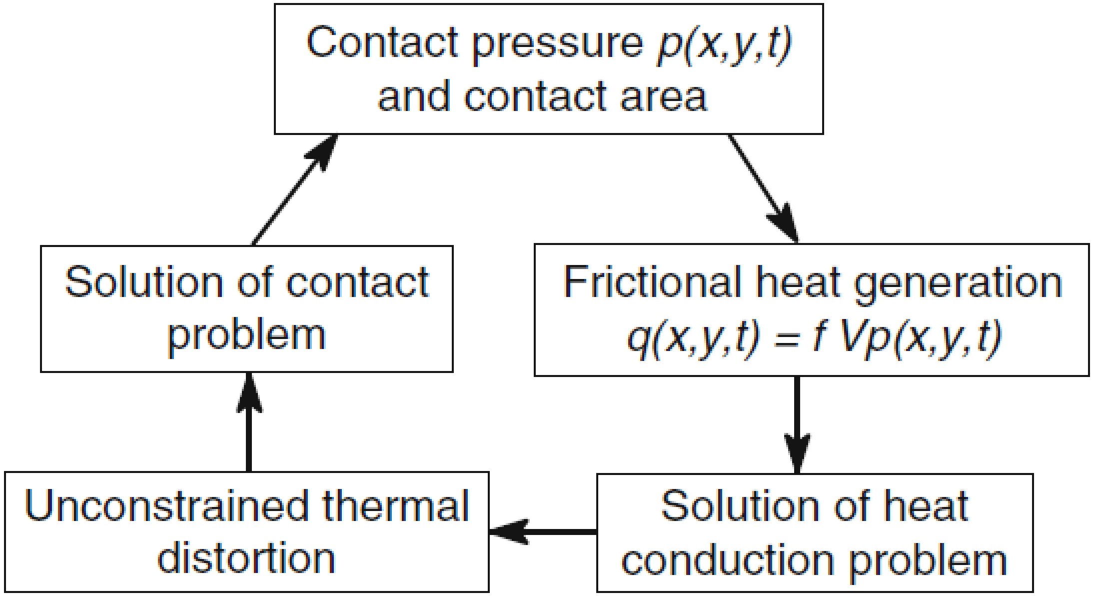
● Consequently, thermal low cycle fatigue may occur ... with the developments of cracks on the disk surface.

● These high local temperatures may also lead to unacceptable braking performance such as brake fade or undesirable low frequency vibrations called hot judder.

Introduction

- Parker and Marshall (1948) were the first to report evidence of hot spots in railway brakes.
- This phenomenon was first identified and explained by prof. Barber (1967, 1969) and was called "frictionally excited thermoelastic instability" or TEI.

The feedback process for TEI



Experiments

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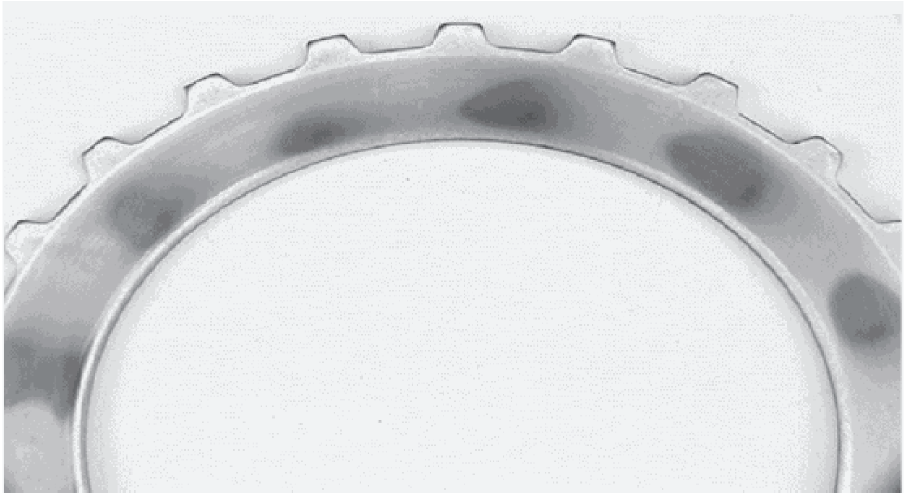
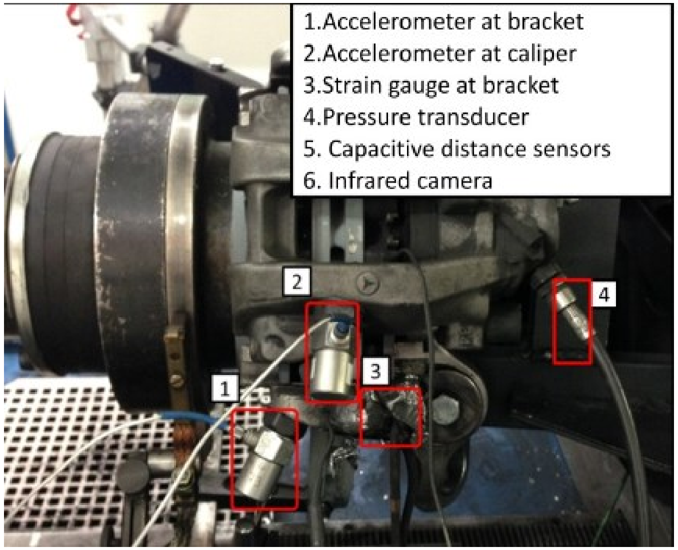
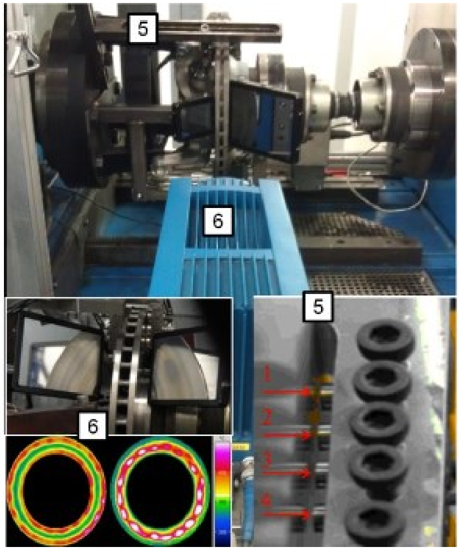


Hot spots as it appears on a clutch desk



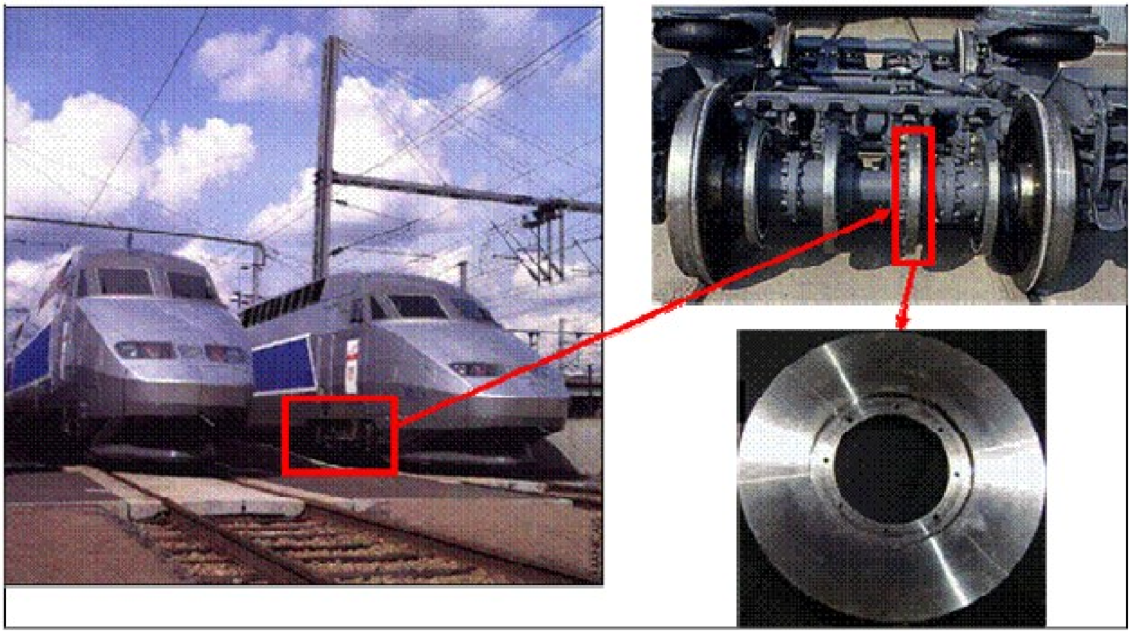


Automobile disk brake

Technical university Darmstadt, Germany

Experiments

TGV braking disk



The trailer bogies of the Thalys TGV include two axles equipped with four disk

outer diameter 640 mm

thickness 45 mm

made of 28CrMoV5-08 steel manufactured by a forging process

An emergency braking at 300 km/h

- the maximum stopping distance 3500m
- a braking time 80 s
- a dissipated energy of 14 MJ per braking disk

Experiments

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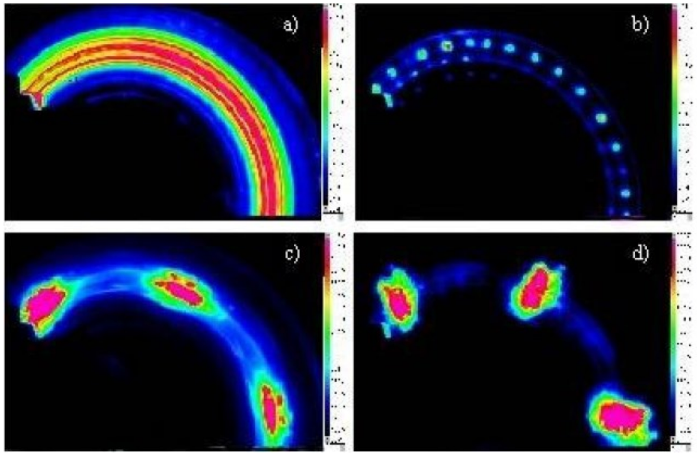
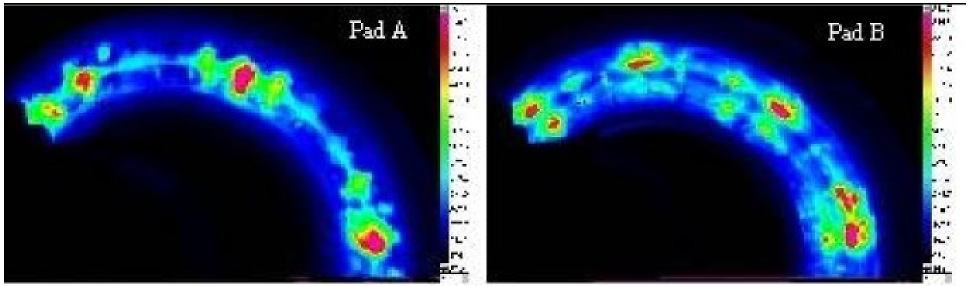
Full scale test bench for the TGV braking disk

Simultaneous thermographs of the 2 sides of the disk



Classical scenario of macroscopic hot spots development



Experiments

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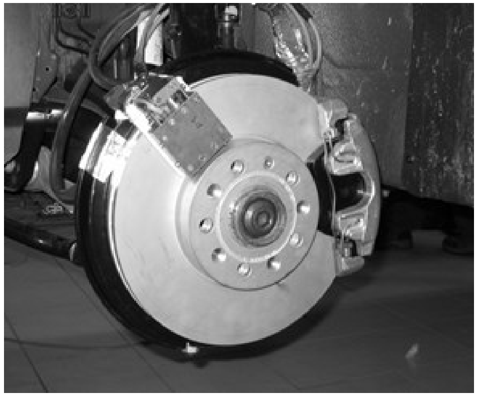
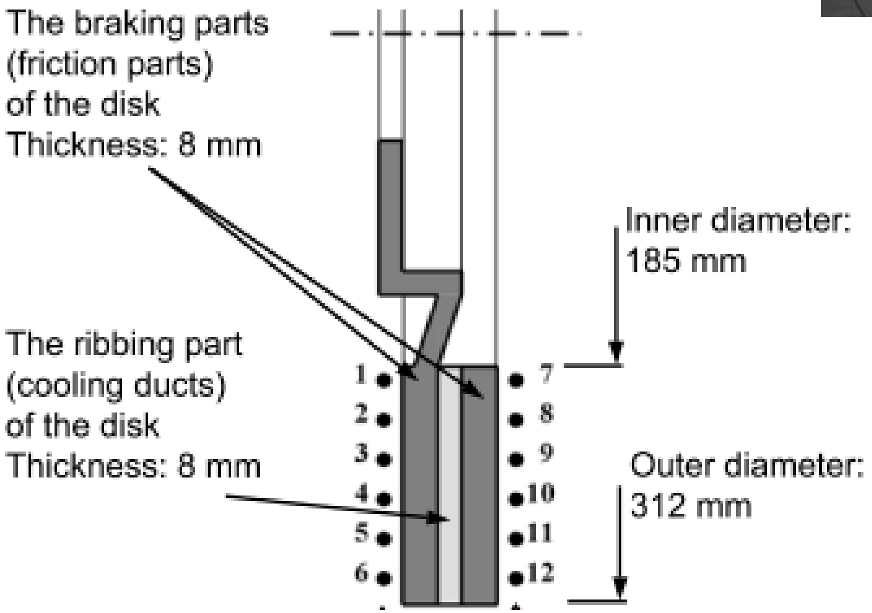
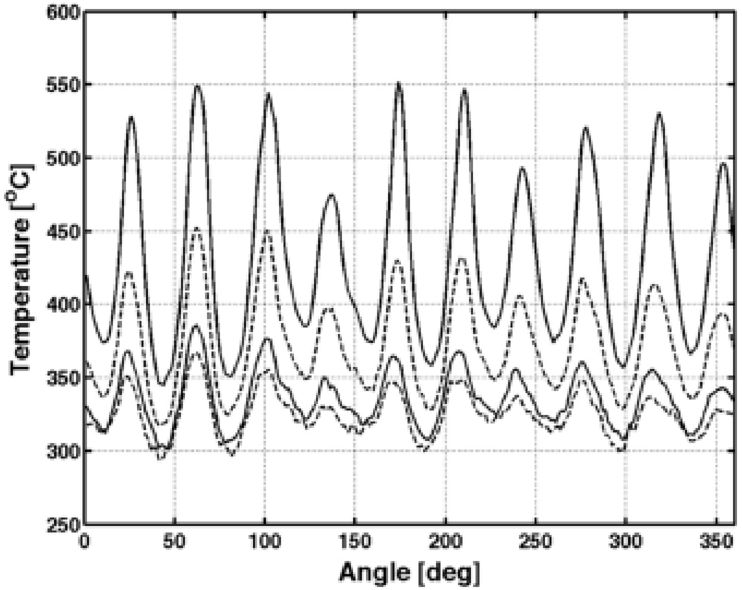


Tested brake disc:
cast iron (conductivity about 50 W/mK)



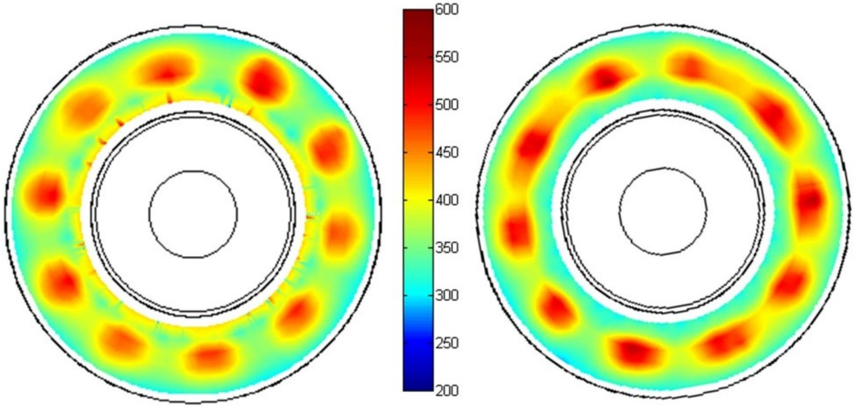


Increasing temperature amplitudes of hot spots under the sensor no. 3 at times 55 s, 60 s, 65 s and 70 s.

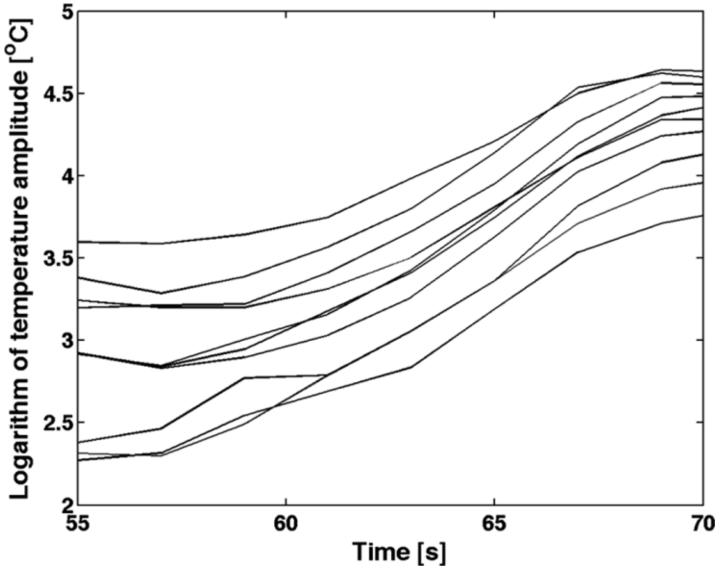
Experiments

University of West Bohemia

Results of the 2 sides of the disk



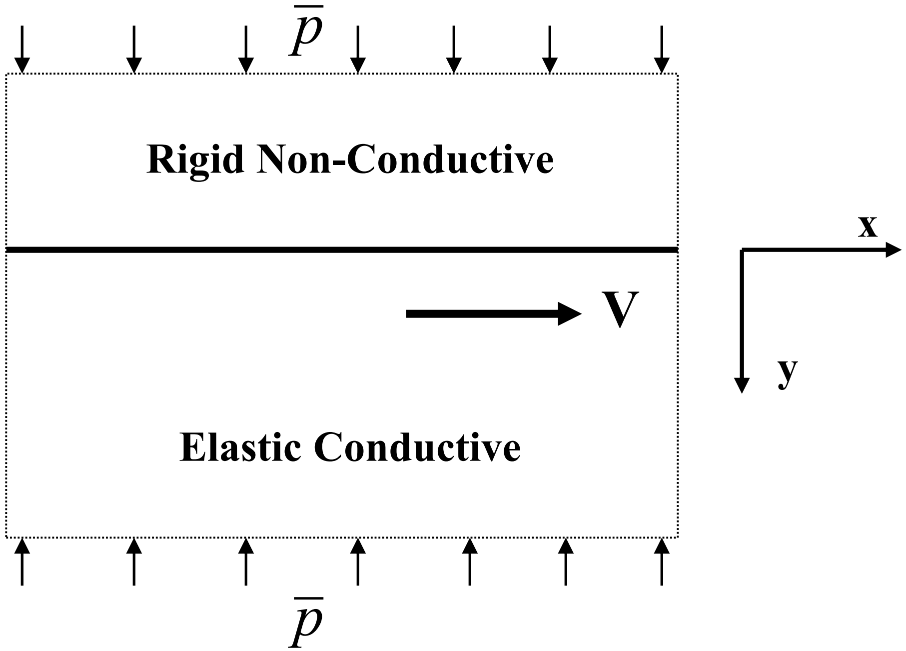
Time dependence of the logarithms of hot spot amplitudes



Burton's stability analysis

The most elementary situation that we can consider

Sliding contact of an elastic half-plane against a rigid plane surface



$$-K\frac{\partial T}{\partial y}(x,0,t)=f\,V\,p(x,t)$$

$$\frac{1}{k}\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}$$

$k = K/c\rho$

+ the problem of elastic stresses

(contact pressure *p* depends on *T*)

Following Burton at al., we consider

$$p(x,t)=\bar{p}(t)+p_0\,e^{bt}\cos(mx), \qquad T(x,y,t)=\bar{T}(y,t)+T_0\,e^{bt}\cos(mx)\Theta(y)$$

Burton's stability analysis

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b – exponential growth rate
m – wave number

V – sliding velocity
f – friction coefficient

b depends on V
$b > 0$ means instability

$$-K\frac{\partial T}{\partial y}(x,0,t) = f\,V\,p(x,t)$$

$$\frac{1}{k}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}$$

$k = K/c\rho$

+ the problem of elastic stresses
(contact pressure p depends on T)

5 2 1

$$p(x,t) = \overline{p}(t) + p_0\, e^{bt}\cos(mx), \qquad T(x,y,t) = \overline{T}(y,t) + T_0\, e^{bt}\cos(mx)\Theta(y)$$

4

$$\frac{d^2\Theta}{dy^2} - \lambda^2\Theta = 0 \quad \xrightarrow{3} \quad \lambda = \sqrt{m^2 + \frac{b}{k}}\ ,\ \Theta(\mathrm{y}) = \exp(-\lambda\, y)$$

Burton's stability analysis

The problem of elastic stresses

E – elastic modulus
α – coefficient of thermal expansion
ν – Poisson's ratio

6

$$p(x,t)=\bar{p}(t)+\frac{\alpha E m}{(1-\nu)(\lambda+m)}T_0 e^{bt}\cos(mx)$$

7

$$-K\frac{\partial T}{\partial y}(x,0,t)=f V p(x,t)$$

$$-K\frac{\partial \bar{T}}{\partial y}=f V \bar{p}$$

$$T_0 e^{-\lambda y+bt}\cos(mx)$$

8

$$K\lambda=\frac{\alpha E f V m}{(1-\nu)(\lambda+m)}$$

$$\lambda=\sqrt{m^2+\frac{b}{k}}$$

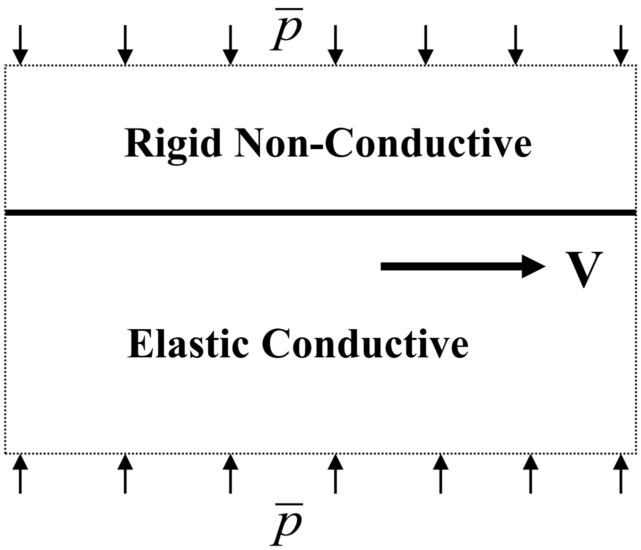
9

$$b=k\left(\frac{\alpha E f V m}{K(1-\nu)}-\frac{m^2}{2}-m\sqrt{\frac{m^2}{4}+\frac{\alpha E f V m}{K(1-\nu)}}\right)$$

$$V_{CR}=\frac{2Km(1-\nu)}{\alpha E f}$$

The critical sliding velocity V_{CR} for $b = 0$

Burton's stability analysis

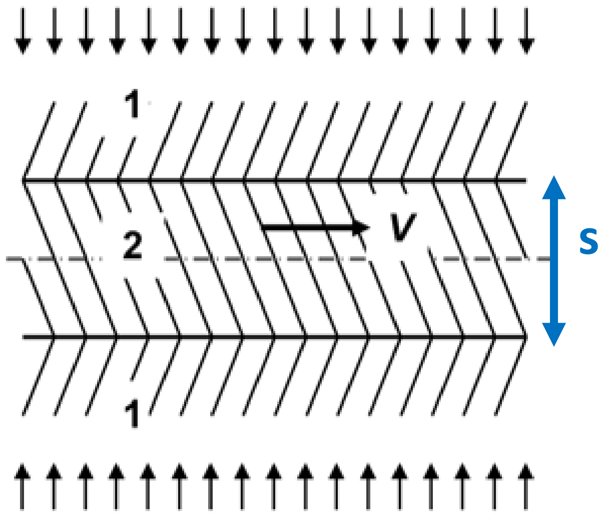


Too simplified, incorrect prediction for disk brakes

$$V_{CR} = \frac{2Km(1-\nu)}{\alpha E f}$$

$$V_{CR} = \frac{2Km(1-\nu)}{\alpha E f}$$

Lee and Barber 1993

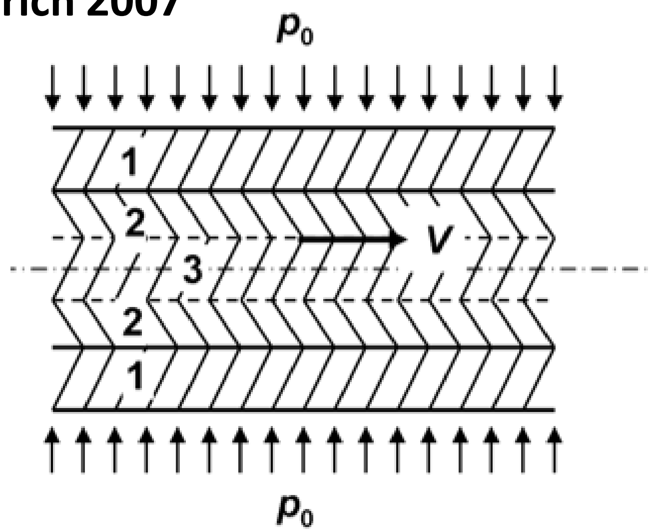


$$V_{CR} = C\frac{K}{\alpha E f s}$$

C **is a dimensionless constant that depends on other dimensionless features of the problem**

Burton's stability analysis

Voldřich 2007



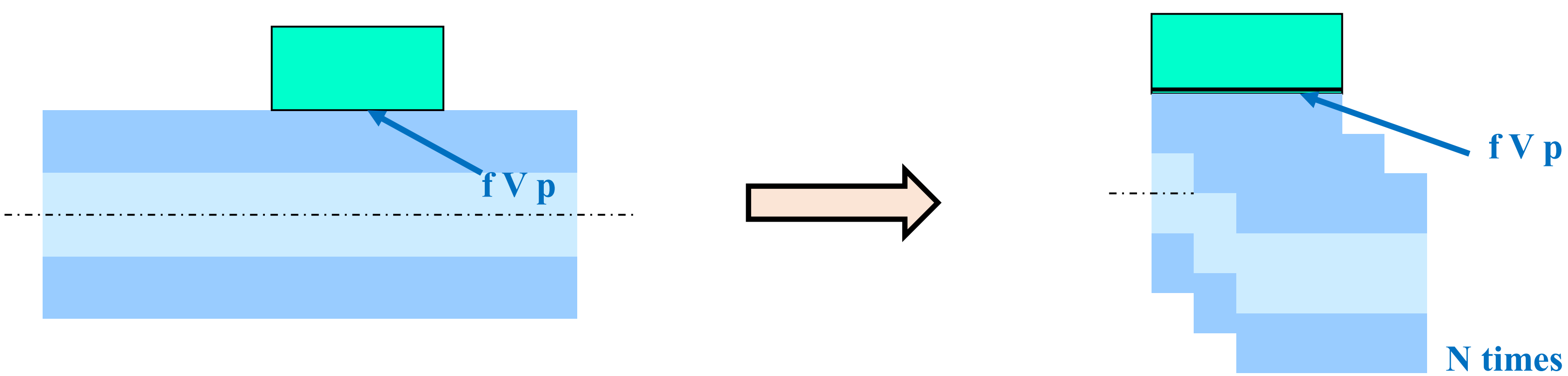
Intermittent contact – no analytical solution is possible to find.

Appropriate approximation:
- to enhance the disk thermal capacity N-fold
- to modificate the characteristic equation

$$N = \frac{\text{circumference of disk}}{\text{arc length of pad}}$$

Intermittent contact

Approximation



Parameters influencing TEI

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Usual automobile disk brake – dependance of the growth parametr *b* on the number of hot spots *H*

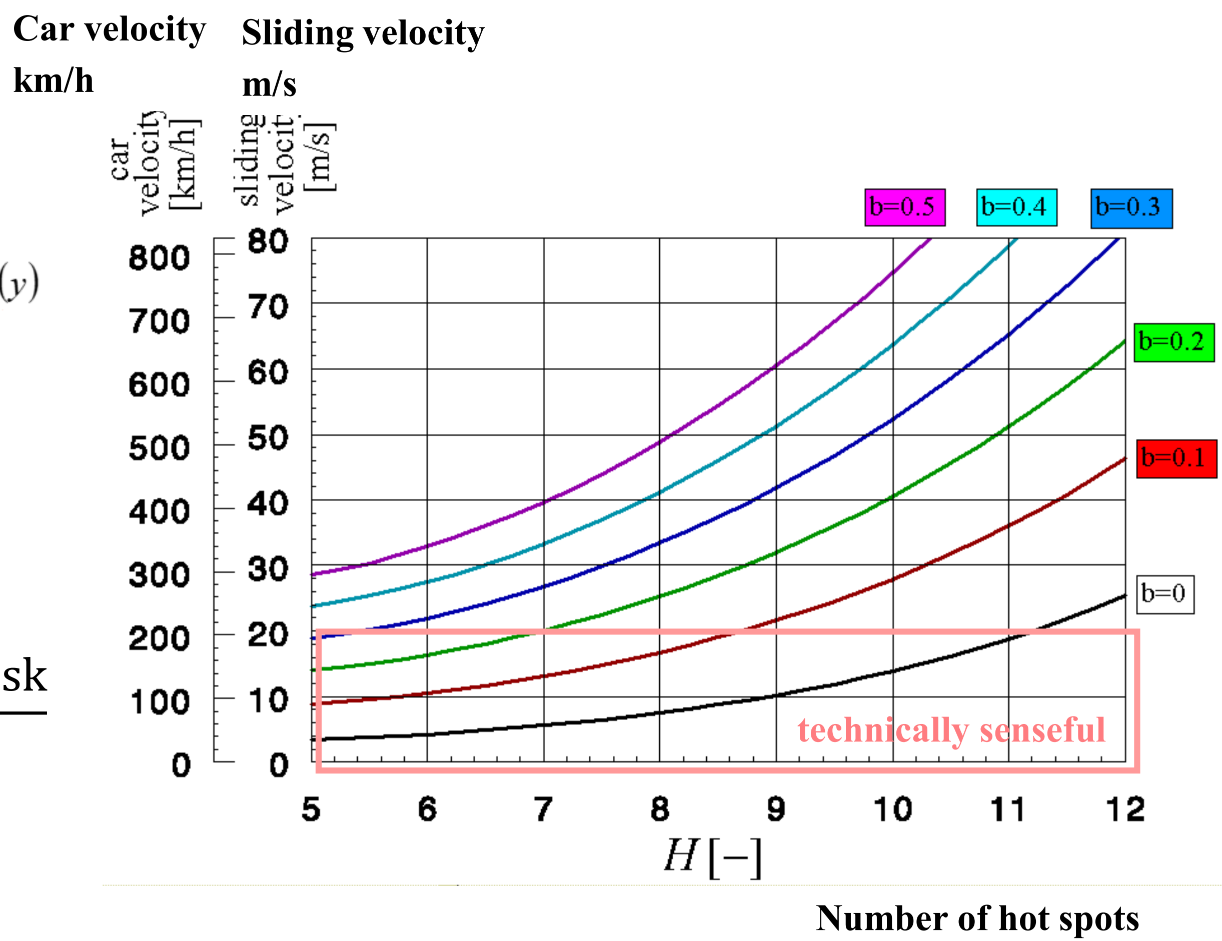
$$p(x,t) = \bar{p}(t) + p_0 e^{bt} \cos(mx)$$

$$T(x,y,t) = \bar{T}(y,t) + T_0 e^{bt} \cos(mx)\Theta(y)$$

$$H \approx N$$

and $H \geq 5$

$$N = \frac{\text{circumference of disk}}{\text{arc length of pad}}$$



Parameters influencing TEI

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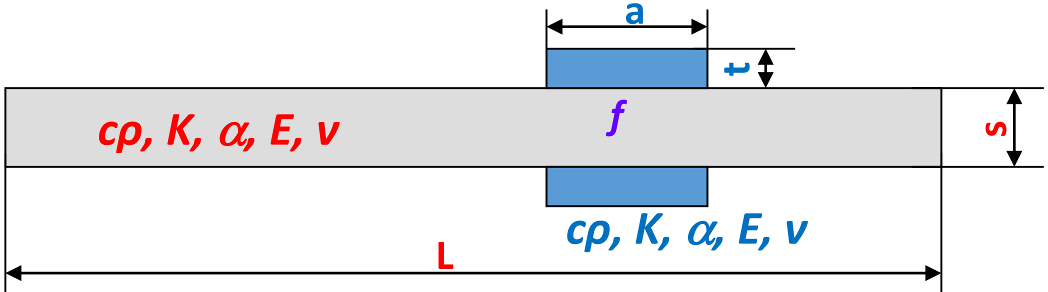
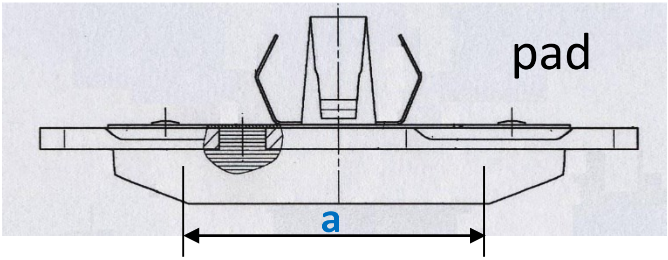
Influence of disk brake parameters on inclination to TEI





higher value – lower influence	lesser value – lower influence	low influence
- thickness of pads **t** - specific heat capacity of pads ***cp*** - thermal conductivity of pads ***K*** - specific heat capacity of the disk ***cp***	- friction coefficient ***f*** - elastic modulus of pads ***E*** - coefficient of thermal expansion of the disk material α - elastic modulus of the disk ***E*** - arc length of the pad **a, (a/L)**	- thickness of the disk **s** - Poisson's ratios **v**, v - coefficient of thermal expansion of pads α - thermal conductivity of the disk ***K***

Parameters influencing TEI

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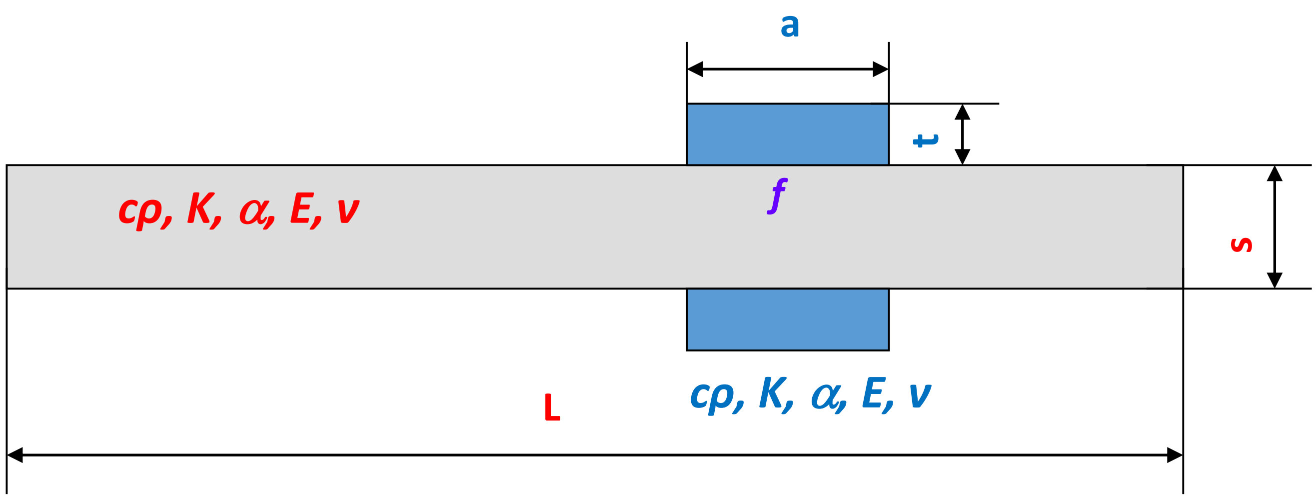
Advantage of TEI mathematical modeling

- too many parameters have to be experimentaly distinguished
- it is not possible to change only one parameter (material parameters depend on temperature)



Parameters influencing TEI

Suppression mechanisms of the exponential rise of instability

The exponential growth (≈ explosion growth) stops sooner or later. Mechanisms of the exponential growth interruption:

- **the friction coefficient *f* declines with increasing temperature, and so the friction heat source *fVp* declines as well**

- **the contact pressure amplitude p_{am} exp(bt) excceds the initial uniform pressure p_0 anyway. In such a case, the loss of contact under a part of the pads occurs. TEI comes into a second, strong nonlinear, mode of behavior.**

- **for disc of large diameter, used on railroads, the material yield strength is exceeded before the mentioned separation happens**

- **the wear of pads accompanies every real braking instance, and it depend above all on the local contact pressure**

Numerical approach

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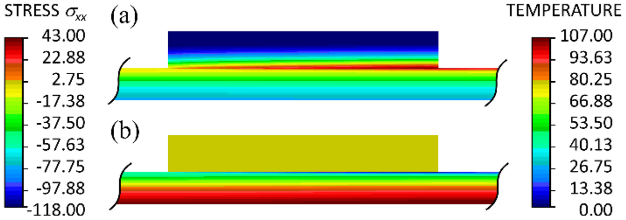
FEM – Petrov-Galerkin discretization

● The most direct numerical approach is to simulate the evolution of the instability in time.

The transient heat conduction problem necessitates a relatively small time step (Peclet numbers are generally large). Direct numerical simulation is very computer intensive even for 2D model.



FEM – eigenvalue problem

● An alternative approach is a finite element implementation of Burton's perturbation technique.

$$[(\boldsymbol{K} + \boldsymbol{C} + f(\boldsymbol{V\Phi})\boldsymbol{A} + b\boldsymbol{H}]\ \boldsymbol{\Theta} = \boldsymbol{0}$$

It is an eigenvalue problem for the growth paramegter b (Θ is an eigenvector here, sliding velocity V is given; *K, C, A, H* are suitable matrices).

Conclusion

● Processes of thermoelastic instability (TEI) occurring on brake systems become evident as non-uniform distribution of temperature with hot spots on contact surface.

● Their temperature amplitudes can increase exponentially in the first, initial, “linear”phase of TEI.

● Some experimental data show complex behavior of hot spots during braking.

● There are various mechanisms of the interruption of the exponential growth.

● Mathematical modeling is essential for understanding the phenomena TEI.

Thank You very much