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Simulation of Contact Dynamics in Automotive Brakes with an Abstract Cellular Automaton

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In loving memory of
Ruth Watnick and Jack Merlis

Foreword

The present work was carried out during my tenure at the Institute of Dynamics and Vibrations at the Technische Universität Braunschweig.

Firstly, I extend my deepest gratitude to the director of the institute, Prof. Dr.-Ing. habil. Georg-Peter Ostermeyer. Through his enduring support, he provided numerous opportunities for me to learn and grow. He has always motivated me and often made himself available for interesting discussions, offering many helpful suggestions and ideas along the way. His support and encouragement have shaped this work decisively, as well as his valuable advice and constant readiness for scientific exchange. I am very thankful that he consistently put his trust in me, opening many doors for me to develop and reach my goals.

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Braunschweig, August, 2019 *Joshua Merlis*

Zusammenfassung

Tribologische Hochlastkontakte sind wesentliche Elemente verschiedener mechanischer Systeme. Obwohl sie in den letzten Jahren intensiv erforscht wurden, sind die zugrunde liegenden Phänomene noch nicht vollständig verstanden. Ein prominentes Beispiel dafür ist der Reibkontakt von Fahrzeugbremsen.

Die tribologische Kontaktdynamik zwischen dem Bremsbelag und der Bremsscheibe wurde am Institut für Dynamik und Schwingungen an der Technischen Universität Braunschweig in unterschiedlichen Arbeiten beispielsweise mit dynamischen Reibmodellen oder klassischen Zellulären Automaten modelliert. Dabei konnten bereits unterschiedliche Phänomene der Reib- und Verschleißdynamik erfolgreich abgebildet werden. Die dabei eingesetzten Zellulären Automaten waren aber nicht in der Lage, den gesamten Reibkontakt der Bremse zu beschreiben. Somit waren insbesondere Aussagen zu makroskopischen Schwingungen nur sehr eingeschränkt möglich.

Ein neues multiphysikalisches Simulationsprogramm, ein „Abstrakter Zellulärer Automat“ (Abstract Cellular Automaton), wird in dieser Arbeit eingeführt, um den gesamten makroskopischen tribologischen Kontakt zwischen Bremsbelag und Scheibe zu simulieren. Detaillierte Analysen von besonders einflussreichen mikro- und mesoskopischen Kontaktflächen werden durchgeführt und die umliegenden Kontaktflächen werden mit niedrigerer Auflösung analysiert. Dies wird durch eine neuartige Kombination von spezialisierten Zellulären Automaten erreicht.

Die Simulationen werden auf mehreren Zeitskalen durchgeführt. Auf der „langen“ Zeitskala wird der Abstrakte Zelluläre Automat durch tribologische Messungen validiert. Bekannte Bremsphänomene werden reproduziert und neue Perspektiven auf etablierte dynamische Zusammenhänge aufgezeigt. Auf der „kurzen“ Zeitskala ist die Schwingungsbewegung der Kontaktstrukturen mit Schwankungen der entscheidenden globalen tribologischen Dynamik verbunden. Theoretische Bremsszenarien werden implementiert, um grundlegende Phänomene und Abhängigkeiten abzubilden. Anschließend wird eine realistische Studie durchgeführt, in der die natürliche Entwicklung der Kontakttopographie auf der langen Zeitskala simuliert und direkt in einer Schwingungsanalyse auf der kurzen Zeitskala verwendet wird. Dabei wird der Einfluss der Lasthistorie untersucht.

Synchronisierte Schwingungen im Reibkontakt können Vibrationen in den Reibkörpern anregen und dadurch störende Geräusche und Schwingungen verursachen. Um das relevante Synchronisationsverhalten zu identifizieren und zu charakterisieren, werden die Analyse „Frequenzdekomponierte Metagruppenanalyse“ (Frequency-Decomposed Meta Group) und ein Synchronisationsmaß (das „Synchronization Index“) entwickelt. Gemeinsam helfen sie, dem Verständnis für Auslösemechanismen des Bremsenquietschens näher zu kommen.

Abstract

High-load tribological contacts are crucial elements of various mechanical systems. Although they have been the subject of much research in recent years, the underlying phenomena are not yet fully understood. A prominent example of this is the friction contact of automotive brakes.

The tribological contact dynamics between a brake pad and disc have been modeled in various works from the Institute of Dynamics and Vibrations (Institut für Dynamik und Schwingungen) at the Technische Universität Braunschweig. Various phenomena pertaining to the friction and wear dynamics were successfully modeled and simulated using, for example, dynamic friction models and classical cellular automata. These cellular automata were, however, incapable of simulating the entire friction contact of a brake system, offering limited insights into macroscopic vibrational phenomena.

A new multiphysics simulation program, the *Abstract Cellular Automaton*, is introduced in this work towards simulating the entire macroscopic tribological contact between a brake pad and disc. Detailed analyses of highly influential micro- and mesoscopic contact areas are carried out, and the surrounding contact areas are analyzed with lower resolution. This is achieved through a novel combination of specialized cellular automata.

Simulations are carried out on multiple timescales. On the long timescale, the Abstract Cellular Automaton is validated through tribological measurements. Known braking phenomena are then reproduced, and new perspectives on established dynamic interdependencies are revealed. On the short timescale, the vibrational motion of the contact structures is related to fluctuations of crucial global tribological dynamics. Theoretical braking scenarios are implemented to depict fundamental phenomena and dependencies. A realistic multi-timescale study is then carried out, in which the natural development of the contact topography is simulated and directly used in a vibration analysis. The influence of load history is thus investigated.

Synchronized vibrations in the friction contact can excite vibrations of the bulk friction materials, resulting in disruptive noise and vibrations. To identify and

characterize the relevant synchronization behaviors, the *Frequency-Decomposed Meta Group* analysis and the *Synchronization Index* are developed. Together, they provide an aid towards understanding the triggering mechanisms of brake squeal.

Contents

Nomenclature

Abbreviations and Acronyms

ACA	Abstract Cellular Automaton
AUT	Automated Universal Tribotester
Cov	Patch Coverage State
CWT	Continuous Wavelet Transform
DoF	Degree(s) of Freedom
FDMG	Frequency-Decomposed Meta Group
FEM	Finite Element Method
FIV	Friction-Induced Vibrations
HF	High-Frequency
LF	Low-Frequency
NVH	Noise, Vibration, and Harshness
Par	Braking Parameters
SI	Synchronization Index
STFT	Short-Time Fourier Transform
TEI	Thermoelastic Instabilities

Notation Conventions and Operators

$x \propto y$	x is proportional to y
$x \sim y$	x is on the order of magnitude of y
$\lfloor x \rfloor$	*Floor*: Value of the greatest integer less than or equal to x
$\lceil x \rceil$	*Ceiling*: Value of the least integer greater than or equal to x
$x \mathrel{+}= y$	*Compound assignment*: overwrite x with $x + y$
$x \mathrel{-}= y$	*Compound assignment*: overwrite x with $x - y$
$x \mathrel{*}= y$	*Compound assignment*: overwrite x with $x \cdot y$
$\min(x, y)$	Equals x if $x \leq y$, equals y otherwise
$\max(x, y)$	Equals x if $x \geq y$, equals y otherwise
$\dot{x}$	First derivative of x with respect to time
$\ddot{x}$	Second derivative of x with respect to time

x'	Linear density of x
$\overline{x}$	Arithmetic mean value of x
$\tilde{x}$	Alternate value of x for the ABC analysis with element precision rather than bin precision
$\mathrm{sgn}(x)$	*signum function*: sign of x
x_{reg}	Value of parameter x of a given pad region
$x_{reg}(p)$	Value of parameter x of the pad region on which the patch p is located
$x_{I,J}$	Value of parameter x of the pad region at $[r_I, \theta_J]$
x_{p_i}	Value of parameter x of the patch p_i
$x_{i,j}$	Value of parameter x relating the patches p_i and p_j

Latin In-Line Notation

Symbol	Description	Unit
A	(Surface) Area	m^2
a	Age	s
B	Contacting Body, Thermal Body	1
Bi	Biot number	1
C, G, n	Simulation Factor or Variable, Constants	1
c	Viscous Damping Coefficient	$\mathrm{kg/s}$
c_P	Specific Heat Capacity	$\mathrm{J/(kg \cdot K)}$
D	Thickness	m
d	Distance	m
F	Force	N
f	Frequency	Hz
H	Indentation Hardness	$\mathrm{N/m}^2$
h	Height	m
h_{rad}	Radiative Heat Transfer Coefficient	$\mathrm{W/K}^4$
h_T	Convective Heat Transfer Coefficient	$\mathrm{W/(m^2 \cdot K)}$
$I,\ J$	Pad Region Indices in the r and θ directions, respectively	1
K	Spring Stiffness Estimation Constant	$\mathrm{N/m}^2$
k	Spring Stiffness	$\mathrm{N/m}$
k_T	Thermal Conductivity	$\mathrm{W/(m \cdot K)}$
l	Length	m
m	Mass	kg
N	Total Number (of Patches, Pad Regions, Bodies, Bins)	1
P	Power	watt
p	Patch	1

Q	Array of Patch's Neighbors	1
$\overline{R}$	Local Region (Cell) of the Brake Pad	1
r	Radius (from the Central Axis of the Rotor)	m
S	Synchronization Index	1
s	Study	1
T	Temperature	°C
T_K	Temperature	K
t	Time	s
U	Weighting Factor	1
V	Volume	m^3
v	Velocity	m/s
W	Work	J
w	Thickness Loss Due to Wear	m
X	Magnitude of Oscillation	m
x, y	Cartesian Position	m

Greek In-Line Notation

Symbol	Description	Unit
α	Thermal Expansion Coefficient	K^{-1}
Γ	Discrete Filter Element	1
Δ	Change, Variation	1
Δt	Simulation Time Step	s
ζ	Damping Ratio	1
θ	Angle	°, rad
κ	Contamination	1
Λ	Lifetime	s
μ	Coefficient of Friction	1
ξ	Analysis Constant	1
π	Archimedes' Constant ≈ 3.14159	1
ρ	Density	kg/m^3
σ_{ABC}	Stoicism Limit	elements
σ_y	Compressive Yield Strength	Pa
τ	Tangential Displacement	m
Υ	Torque	$N \cdot m$
Φ	Total Number of Elements in ABC Analysis	elements
ϕ	Phase Angle	rad
ω_0	Natural Angular Frequency	rad/s

Subscripts

Symbol	Description
A	Area
ABC	ABC Analysis
air	Air
app	Applied
B	Contacting Body, Thermal Body
bin	Bin
$birth$	Patch Birth
C	Coupling
$cell$	Pad Matrix Cell
ch	Characteristic
col	Patch Collapse
$conv$	Thermal Convection
$disc$	Brake Disc (Rotor)
eff	Effective
esc	Escape to the Surroundings
f	Friction
$gain$	Contributing to Gain, Amount Gained or Increased
$glob$	Global
$growth$	Patch Growth
hf	High-Frequency
hg	Heat Generation
I, J	Pad Region Indices in the r and θ directions, respectively
i, j	Indices
ic	Intermediate Case
in	Inner
k	Kinetic
L	Linear
lat	Lateral
ll	Lower Limit
$loss$	Contributing to Loss, Amount Lost or Decreased
max	Maximum Value, Maximum Permitted, Maximum Possible
min	Minimum Value, Minimum Permitted, Minimum Possible
N	Normal to the Contact Surface of the Brake Pad
$noise$	Noise
out	Outer
p	Patch

pad	Brake Pad, Brake Pad Matrix Material
r	Radius (from The Central Axis of the Rotor), Radial
rad	Thermal Radiation
Rand	Random
ref	Reference Value
reg	Local Region (Cell) of the Brake Pad
rel	Relative
rep	Representative
s	Static
scale	Scaling
SI	Synchronization Index
T	Temperature, Thermal Effects
t	Time
Δt	Time Step
th	Threshold Value
total	Total
V	Volume
veh	Vehicle
wear	Wear
wp	Wear Particles
α	Thermal Expansion
θ	Angle, Angular
λ	Thermal Conduction
τ	Tangential, Parallel to Friction Forces
0	Original, Initial, Lowest, Least
1, 2, 3, ...	First, Second, Third, ... Indices
∞	Ambient, Surroundings