Contact Mechanics and Elements of Tribology Lecture 1. Motivation: Industrial Applications

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Creative Commons BY Vladislav A. Yastrebov A lot of relevant applications (really many [©])
Short summary

Tire/road

- Composite material: cords and elastomer
- Cords: fiber, steel
- Cords ensure strength (internal pressure ≈ 2.1 bar)
- Elastomer: Styrene-butadiene rubber (SBR) with glass transition $T_g \approx -60$ °C
- Rolling resistance VS wear resistance and grip
- Decrease rolling friction and increase sliding friction
- Tread role: avoid hydroplaning, reduce noise (play with eigen frequencies) and wear
- Bicycles, vehicles, aircrafts
- Wheel-surface contact: on the Moon and Mars (granular bed)



www.motortrend.com

Rubber charged with nano-particles



Rubber charged with nano-particles



Rubber charged with nano-particles



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www.motortrend.com

Tires are of critical importance in F1



Photo of ©Formula 1

Tires are of critical importance in F1



Photo of ©Formula 1

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Photo of ©Formula 1

Tire/road



Photo of ©Formula 1

Tire/road



Photo of ©Formula 1



Video of ©Formula 1

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www.motortrend.com

- Metal-to-metal contact
- Wheel + rail tire (bandage)
- Special conical form
- Decrease rolling resistance
- Traction can be reduced by water, grease, oil
- Steel-steel friction *f* ≈ 0.75, in service *f* ≈ 0.4, it determines the maximal tractive torque
- To increase traction at starting a heavy train, sand is distributed in front of driving wheels
- Curved paths: use cant (*dévers*) to increase the speed
- On wheel: wear, fatigue cracks, oxide delamination, noise, martensite formation
- On rail: corrugation, cracking



Railway wheel www.railway-wheel-axle.com



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Slight hollow wear and some fatigue cracking from KTH Royal Institute of Technology www.kth.se



Sections parallel to the rolling direction through the wheel disc run at 3% slip^[1]

[1] Lewisa R. and R. S. Dwyer-Joyce. Wear mechanisms and transitions in railway wheel steels. Proc Instit Mech Engin J: J Engin Trib 218 (2004)

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Sections parallel to the rolling direction through the wheel disc run at 5% slip^[1]

[1] Lewisa R. and R. S. Dwyer-Joyce. Wear mechanisms and transitions in railway wheel steels. Proc Instit Mech Engin J: J Engin Trib 218 (2004)



Video of ©RWTH Aachen University

- Metal-to-metal sliding contact seal
- Piston ring (segmentation) mounted on the cylinder
- 3 rings for 4 stroke and 2 rings for 2 stroke engines
- Cast iron or steel + coating (chromium, or plasma sprayed (also PVD) ceramic)
- Objective: avoid gas from escaping to use entirely the gas work
- Good sealing VS high friction
- Responsible for ≈ 25% of engine friction
- Lubricated contact: difficult conditions, permanent sliding direction reversion





Four-stroke cycle in cylinder (moteur à quatre temps) from Wikipedia

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Cylinder with grooves for piston rings from Wikipedia

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• Relatively high temperature



Piston rings from Wikipedia

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Relatively high temperature V.A. Yastreboy



Zoom on grooves and the drain system for oil from www.enginelabs.com

Bearings

- Reduce friction between moving parts
- Constraint motion of machine elements
- Rolling bearing
- Fluid bearing (liquid or gas)
- Magnetic bearing (no contact)
- To reduce friction and wear: use balls or rollers and lubricant (liquid or solid)
- Loads: radial, axial, bending
- Speed: rolling < fluid < magnetic</p>
- Failure analysis: pressure-induced welding, fatigue, abrasion



A cylindrical roller bearing from Wikipedia

Gears

- From wrist watches to ship gear boxes
- Impact contact, vibration
- Friction, lubrication
- Material: non-ferrous alloys, cast iron, powder metallurgy, plastics
- Failure reasons^[1]:
 - Lubrication:
 - rubbing wear (slow),
 - fatigue cracking (pitting),
 - scoring (thermally triggered rapidly evolving wear)
 - Strength:
 - plastic flow,
 - breakage

[1] Ku P.M. Gear failure modes - importance of lubrication and mechanics. ASLe Trans. 19 (1976)

[2] Burrows M., Sutton G. Interacting gears synchronize propulsive leg movements in a jumping insect. Science 341 (2013)



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Interior of Rolex watches www.rolex.com



Ship reduction gearbox 14 MW (e.g. Renault Mégane $1.4 \approx 60$ KW) www.renk.eu

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Lecture 1

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"Functional gears in the ballistic jumping of the flightless planthopper insect Issus" (only in nymphs, not in adults)^[2]

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Renault Mégane at 130 km/h

Boeing 747 at landing



Renault Mégane Renault



Boeing 747-400 www.airplane-pictures.net



TGV Eurostar www.lepoint.fr

TGV Eurostar at 300 km/h

- Renault Mégane at 130 km/h $E_{kin} \approx \frac{1}{2}960 \text{ kg } 36^2 \frac{\text{m}^2}{s^2} = 622 \text{ kJ}$ Would melt 0.7 kg of steel* To stop in 5 seconds $P \approx 124 \text{ kW}$
- Boeing 747 at landing



Renault Mégane Renault



Boeing 747-400 www.airplane-pictures.net



TGV Eurostar www.lepoint.fr

TGV Eurostar at 300 km/h

*Steel $C_p = 0.49$ KJ/(kg· T), $T_m \approx 1300$ °C, $\Delta H_f = 270$ kJ/kg

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- Boeing 747 at landing $E_{\rm kin} \approx \frac{1}{2} 3 \cdot 10^5 \text{ kg } 72^2 \frac{\text{m}^2}{s^2} = 777 \text{ MJ}$ Would melt 857 kg of steel To stop in 1 minute $P \approx 13 \text{ MW}$
- TGV Eurostar at 300 km/h



Renault Mégane Renault



Boeing 747-400 www.airplane-pictures.net



TGV Eurostar www.lepoint.fr

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- TGV Eurostar at 300 km/h $E_{\text{kin}} \approx \frac{1}{2}713 \cdot 10^3 \text{ kg } 83^2 \frac{\text{m}^2}{\text{s}^2} = 2.5 \text{ GJ}$ Would melt 2756 kg of steel To stop in 2 minutes $P \approx 21 \text{ MW}$

*Steel
$$C_p = 0.49 \text{ KJ/(kg· T)}$$
, $T_m \approx 1300 \text{ °C}$, $\Delta H_f = 270 \text{ kJ/kg}$



Renault Mégane Renault



Boeing 747-400 www.airplane-pictures.net



TGV Eurostar www.lepoint.fr

- Vehicle, aircraft, locomotive
- Disk-pad vehicle/aircraft
- Clasp brake for trains they wear the wheel tire and thus increase the noise or rolling
- Disk: steel/ceramic/carbon
- Pad (*plaquette*): ceramics/Kevlar
- Strong thermo-mechanical coupling
- Thermal instabilities
- Brake squeal
- Particle emission
- Performance VS longevity
- Wear, friction, water lubrication



Reinforced carbon brake disc on a Ferrari F430 Wikipedia



New LL brake blocks aimed to reduce noise from rail sector photo: UIC/EuropeTrain

Lecture 1

- Disk-blade assembly in turbines wear, friction, fretting, crack initiation
- Rivets
- Bolts
- Screws (vis)
- Nails (clou)
- Nontrivial mechanical problems involving fracture and frictional contact
- Vibrational nut removal (video)
- Stress relaxation



Modern steam turbine Wikipedia



GE J47 turbojet, youtube channel AgentJayZ, Canada

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Fuselage of modern aircraft contains ≈100 000 rivets www.news.cn



Bolt vibration, youtube channel Nord-Lock Group
- Aircraft impact Nuclear reactor containment building has to be designed to sustain it
- Bird on aircraft impact Bird/engine, bird/fuselage
- Vehicle crash tests *Plasticity, contact, self-contact, friction*
- Plasma deposition of powder
- Drop tests
- Traumatic injury (brain, organs)
- Meteorite impact a part of Canyon Diablo meteorite is stored in Musée de Minéralogie de l'Ecole des Mines $E_{kin} = \frac{1}{2}3 \cdot 10^5 \text{ kg} \cdot 13.9^2 \cdot 10^6 \text{ m}^2/\text{s}^2 \approx 29 \text{ TJ}$



Crash test of supersonic jet fighter McDonnell Douglas F-4 against a reinforced concrete target Sandia National Lab

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Bird impact traces on aircraft's nose/wing

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Mercedes crash test Insurance Institute for Highway Safety

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Crater of the Canyon Diablo meteorite Barringer Crater, Arizona, USA bp.blogspot.com

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Part of the Canyon Diablo meteorite (226 kg) http://www.musee.mines-paristech.fr

Penetration and perforation

- Military applications
- High velocity impact
- Energy dissipating materials
- Problematics:
 - attack: increase penetration VS
 - defense: decrease penetration



Handgun Self-Defense Ammunition Ballistics Test (bullet penetration in synthetic silicon) www.luckygunner.com



Sherman Firefly armor piercing shell on Tiger tank armor, Bovington Tank Museum Andy's photo www.flickr.com

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Fruit perforation lunabeteluna.wordpress.com

Drilling

- Home/industrial/geological
- Percussive, rotary, etc.
- Ductile/brittle materials
- Rocks: hard/soft
- High temperature, high pressure
- Wear vs rate of penetration (RoP)
- Stability of the column in the borehole
- Diamond coatings/hardmetals (WC)
- Industry: oil/gas, thermal energy



Drill crown and a single drill-bit button WC-Co



Varel's drill crowns www.varelint.com

Lecture 1

Haptic perception

- Shape and roughness
- Temperature and heat capacity
- Braille is a tactile writing system
- Touch user interfaces (TUI)
- Touchscreens
 - capacitive (performance)
 - resistive (robustness)
 - surface acoustic waves
- + Haptic response



Sensory interacting system V. Hayward, ISIR UPMC, CNRS International Magazine 34 (2014)



Braille page www.todayifoundout.com



Touch screen from "Minority Report"

 Ice skating Nontrivial physical question: why ice is slippery?



The skating minister by Henry Raeburn, National Gallery of Scotland in Edinburgh

- Ice skating Nontrivial physical question: why ice is slippery?
- Because skate exerts locally a high pressure which melts the ice?
 JJoly (1886), O. Reynolds (1899)
- Because friction-generated heat melts the ice?
 F.P. Bowden, T.P. Hughes (1939), S. Colbeck (1988-1997)



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- Correct answer: Because the one-molecular surface layer cannot bond properly to the bulk forming a "water-like" film, which lubricates the contact!^[1]

 R. Rosenberg. Why is ice slippery? Physics Today (Dec'2005)



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Molecular dynamics simulation of ice surface^[2]

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Ski

Footwear contact

- Footwear
 Wooden boots vs modern shoes
- Adhesion and wear-resistance properties
- Water resistance vs air circulation
- Rock climbing: adhesion ≫ wear-resistance
- Other sports: football, tennis, basketball, etc.



Holland wooden shoes www.rubylane.com/

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Sport shoes (Rafael Nadal VS Quentin Halys, RG 2015) www.zimbio.com



Climbing shoes www.alp.org.ua

Atomic force microscopy (AFM)

- Oscillating cantilever beam
- Atomically sharp tip
- Measures:
 - topography at atomic scale
 - rigidity
 - adhesion
 - electric resistance
- Wear of the tip affects the precision
- Studies in nano-tribology: friction, indentation, wear



Atomic force microscope (www.brucker.com)



Height and adhesion measurements of Sn-Pb alloy surface (AFM) www.brucker.com

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Atomic force microscope (www.brucker.com)



Virgin and worn AFM tip National Institute of Standards and Technology www.nist.gov

Mining industry

- Mines digging
- Producing of gravel concrete and roadways
- Mineral crushers
- Excavator/bulldozer bucket/blade
- Transportation of gravel
- Charge and discharge results in impact and abrasive wear
- Thermo-mechano-metallurgical coupling



Crack interfaces

- Mode II and III cracks in monotonic loading
- All cracks in cycling loading
- Fatigue crack propagation
- Cracks in contact interfaces (pitting, fretting cracks)
- Plasticity in rocks
- Rapid cracks in composites (elastodynamic frictional phenomenon)
- Analogy between fracture mechanics and friction phenomenon



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Fiber-matrix interface^[1]

 D. Blaese et al. ZrO₂ fiber-matrix interfaces in alumina fiber-reinforced model composites, J Eur Ceramic Soc 35 (2015)

V.A. Yastrebov

Lecture 1

Electrical contact

- Switches
- Micro-Electro Mechanical Systems (MEMS)
- Electric brushes
- Electrical contactors
- Electrical brushing trains, trams, metro
- Coupled thermo-mechanoelectro-magneto-metallurgical problem

■ Complex interplay of involved phenomena: mechanical contact → current intensity → Joule heating → temperature rise → material properties → mechanical contact → etc.



Siemens Switch www.siemens.com



Rouen's tram brush Wikipedia

Sealing engineering

- Contact/non-contact seals
- Static/dynamic seals
- Liquid/gas sealing
- Topic:
 - cylinder/liner, bearings
 - gaskets, o-rings
 - rock permeability
 - shale gas/oil extraction
 - water circuits (civil, nuclear power plants)
- Polymers/metals
- Pressure/capillary action driven
- Interface geometry/roughness
- Permeability (e.g., tennis balls)
 VS transmissivity (seals)

Space shuttle Challenger disaster January 28, 1986: A rubber o-ring failed because of usage "well below its glass transition on an unusually cold Florida morning" "Challenger, The Final Flight" (2020) Netflix



O-rings www.powersportsnetwork.com



Space shuttle Challenger disaster www.time.com

- Contact and friction determines their mechanical behavior
- Coupling with liquid (beach sand)
- Granulometry
- Carrier engineering critical slope
- Earth-slides
- Gauge (granular layer) in geological faults
- Third body (wear particles and contaminates in contact)
- Brazil nut effect (granular convection)



Dunes by Declan McCullagh www.mccullagh.org/

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DEM simulation of a soil slope (particles)



DEM simulation of a soil slope (chain forces) Fabio Gabrieli (University of Padova) geotechlab.wordpress.com

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Video: soil liquefaction: ANIM/Liquefaction

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Animation: Granular convection simulation Dynaflow Research Group www.dynaflow.com

Human joints and implants

- Lubrication/lack of lubrication
- Vertebral column (≈ 24 joints)
- Knees/shoulders/elbows
- Artificial joints
- Bio compatible materials
- Wear particle contamination
- Teeth/bone implants
- Stents



Human joints

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Teeth implant www.michaelsinkindds.com



Self-expanding Nitinol stent endotek.merit.com

Bowed string instruments & sound

- Specific friction
- Material: natural fibers catgut string vs horse hair in bow
- Stick-slip phenomenon
- Brake squeal
- Grasshoppers
- Crickets
- In general, sound producing is related to mechanical contact



Violin and bow www.walmart.com



Grasshopper's leg by Nico Angleys on www.flickr.com

Bowed string instruments & sound



Someone's video

Metal forming and machining

- Deep drawing
- Huge pressure
- Severe plastic deformations
- Specific friction laws friction is no longer proportional to contact pressure
- Dies should be properly lubricated to avoid braking
- Machining (usinage)
- Wear of the cutting tool
- Friction between the tool and swarf (copeaux)



Metal forming www.thomasnet.com



Metal cutting (machining) www.hurco.com

Hard disk drive

- Hard disk drive
- Air lubrication is used to avoid direct contact between the disk and the head *linear velocity 35 m/s*
- Soon (≈2020-2025) will be replaced by SSD



Hard disk drive (HDD) www.ssd-hdd.info
Hard disk drive

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Zoom on the head of Seagate HDD Wikipedia

Geological faults

- Slip in faults (faille)
- Dominant mechanism of earthquakes
- Elastic energy stored in the crust can be liberated by local slip
- Stick-slip phenomenon
- Partly dissipated in friction
- Partly removed by elastic-waves
- Huge pressure intermediate-depth earthquake 70-300 km
- Presence of fluid pressure
- Non-trivial friction law slip and velocity dependent
- Thermo-mechanical coupling





0.1-100 km

Geophysical scale slip - basal glacial slip on the bedrock - rock-rock slip in faults

Hardness testing

- Non-destructive material test
- Can be tested with portable equipment
- Material parameters at small scales: specific phase, thin film, etc.
- Various macroscopic tests:
 - Vickers (HV)
 - Brinell (HB)
 - Rockwell (HR)
 - etc
- Elastic/plastic properties



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- Wetting (mouillage)
- Surface energy and surface tension
- Contact angle θ : balance of forces $\gamma_{sg} = \gamma_{lg} + \gamma_{sl} \cos(\theta)$
- Roughness of solids VS surface tension
- Apparent contact angle: Wenzel VS Cassie-Baxter models
- Self-cleaning surfaces (lotus)
- Super-hydrophobic surfaces
- Wet adhesion (meniscus) Sand castles



Equilibrium of interface forces (adapted from Wikipedia)

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Wenzel model (Wikipedia)



Cassie-Baxter model (Wikipedia)

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H.J. Ensikat et al. Superhydrophobicity in perfection: the outstanding properties of the lotus leaf. Beilstein J Nanotech (2011)

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G. McHale, M.I. Newton, N.J. Shirtcliffe. Immersed superhydrophobic surfaces: Gas exchange, slip and drag reduction properties. Soft Matter (2010)

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Adhesion

- Biology
- Bio-inspired devices
- Inspiring gecko's ability to climb on flat surface
- Van der Waals forces based adhesion^[1]

K. Autumn et al. Evidence for van der Waals adhesion in gecko setae. Proc Nat Acad Sci (2002)



Gecko's feet (adapted from photos of Central Michigan university, Biology department)

- Stiff/stiff
- Soft/stiff
- Soft/soft

In terms of interface properties

- Frictionless
- Dry friction
- Adhesive
- Lubricated

In terms of inertia

- Quasi-statics
- Dynamics
- Vibration

- Solid mechanics
- Thermomechanics
- Solid+fluid
- Thermo-electro-mechanics

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- Application-wise objective: increase/reduce friction *rolling bearing vs tyre grip*
- Application-wise objective: increase/reduce wear *polishing* VS *cylinder-liner*
- Type of contact: normal/partial-sliding/sliding/rolling contact *touch interface* VS *rock shoes*
- Interface type: dry/lubricated contact brake system VS cylinder-liner
- Lubrication type: boundary, hydro-static/dynamic, elasto-hydrodynamic, mixed cylinder-liner at middle path VS at extreme points
- Range of applied pressure matters touch interface VS metal forming
- Involved temperatures (melting point of contactors)
- Phase changes (metalurgical aspects, glass transition)
- Other involved phenomena (electricity, material inter-diffusion, etc.)

Thank you for your attention!