New nano-measurements add spark to centuries-old theory of friction

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The phenomenon of friction, when studied on a nanoscale, is more complex than previously thought. When friction occurs, an object does not simply slide its surface over that of another, it also makes a slight up-and-down movement. This finding completes a centuries-old theory of friction dating to 1699 and uncovers a gap in contemporary thinking on friction. The phenomenon – termed lift-up hysteresis – was described in a recent study by researchers Farid Al-Bender, Kris De Moerlooze and Paul Vanherck of the Production Engineering, Machine Design and Automation Division at KU Leuven's Department of Mechanical Engineering.

Friction is the force that occurs when one surface slides over another, or when an object moves through a liquid or a gas. Until now, the theory explaining the phenomenon of friction was fragmented. French physicists Guillaume Amontons and Charles August Coulomb, working in the late-17th and mid-18th centuries, respectively, strove to find an explanation for frictional resistance. Frictional resistance explains, for instance, why gliding a heavy cabinet across a floor is much more difficult than gliding a chair. As the weight of an object increases, so too does the resistance. The floor and the bottom of the cabinet move against one another from left to right or vice versa. But at the same time the weight of the cabinet bears perpendicularly upon the bottom of the cabinet and the floor. This normal load – 'normal' in the sense of being perpendicular to the direction of shifting – pushes the two surfaces together and produces resistance as friction occurs. If we put the chair and the cabinet on wheels and push them uphill, more force is needed to move the cabinet than to move the chair.

Using this reasoning, Amontons and Coulomb explained friction by the roughness of both surfaces: the (sometimes microscopically small) nooks and crannies of one surface – asperities – which settle upon those of another when one object rests upon another. When friction occurs, these asperities play the role of slopes. They are made to climb, descend and deform so that movement can continue, similar to what happens when the bristles of two brushes rub together. This theory is sometimes called the 'bump hypothesis' because one surface grinds over the bumps of another with an up-and-down movement.

In the 20th century it became clear that the existing theory did not fully correspond with the laws of thermodynamics, the science that studies the conversion of heat into mechanical energy or vice versa. Specifically, Amontons and Coulomb's bump hypothesis failed to explain energy lost as a result of friction. In their theory, the sum of the energy needed to go 'uphill' and then 'downhill' is zero. At the same time, we know that pure surfaces have an electro-chemical tendency to stick to each other. This is caused by asperities being stuck to one another in a phenomenon called adhesion. A typical example is Scotch tape. When movement occurs, all the bonds between the asperities of the two surfaces are broken and reformed elsewhere. Consequently, factors such as speed and acceleration influence friction. With the rise of the newer adhesion theory, Amontons and Coulomb's theory gradually faded into oblivion. But the modern adhesion theory of friction was shown to have inconsistencies of its own.

Micro- and nano-scale measurement techniques now allow researchers to study friction at an atomic level. Professor Farid Al-Bender and his team conducted an experiment with extremely precise friction and displacement sensors and tested various materials (paper, plastic and brass) at different speeds of movement. The results map out frictional force measurements consistent with those predicted by adhesion theory. But until now, 'normal motion' – movement perpendicular to the rubbing movement – had not yet been measured. While normal motion amounts to a mere 5 – 50 nanometers – billionths of a meter – this systematic up-and-down motion had previously been overlooked. Measurements of this normal motion, say the KU Leuven researchers, confirms the centuries-old hypothesis of asperity deformation and slope pioneered by Amontons and Coulomb and paints a more complex picture of the phenomenon of friction because normal motion must now be taken into account when developing a comprehensive theory of friction. Al-Bender and his team's results suggest that friction is caused by an interaction of both adhesion on the one hand and asperity deformation and slope on the other.

Tribology – the science of friction, lubrication and wear – is an important area of mechanical engineering. Tribology research can help lower economic and environmental costs of production and usage. If the interaction between moving surfaces can be controlled, time and energy inputs can be optimised and wear-and-tear, malfunctions and waste can be reduced. Tribology research can also contribute to the miniaturisation of products, such as computer components. At KU Leuven, research in tribology is closely linked with research in mechanical engineering, machine design, materials science and robotics.

More information: Farid Al-Bender, Kris De Moerlooze and Paul Vanherck, Lift-up Hysteresis Butterflies in Friction, *Tribology Letters*, Volume 46, Number 1, 23-31, DOI: 10.1007/s11249-012-9914-y

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