

Amontons-Coulomb Friction Laws, A Review of the Original Manuscript

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ABSTRACT

The ratio of two forces acting respectively perpendicular and normal to a contact surface of two bodies, the coefficient of friction, is widely used in engineering and science depicting the friction resistance of materials sliding over one another. Ruled by the so-called Amontons-Coulomb friction laws (independence from the load, the contact area and the sliding speed), this dimensionless quantity appears to be convenient for engineering and relatively easy to determine. Nevertheless, the use of tabulated friction coefficients becomes somewhat an issue to predict friction behavior of mechanical systems. The system dependence of friction is sometimes ignored, leading to misapplication. Moreover, the fundamental origins of sliding resistance are not as clear and care should be taken when attributing a fundamental significance to the friction coefficient. This paper aims to clarify findings on friction Charles Augustin Coulomb did and that have been used for hundred of years. At the demand of the French *Académie Royale des Sciences* calling for rules and accurate data to design machines, Coulomb developed an experimental study of friction of woods and metals used for rubbing parts in machinery. Alongside his findings, he was aware of limitations of Amontons' findings. He demonstrated by experimentation the dependence of friction on the normal load, on the area of contact or on the sliding speed. In his day, he proposed some physical interpretations in agreement with his findings. He explained friction was originating from a variety of sources which led to various friction behaviors.

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INTRODUCTION

Firstly enunciated in Leonardo da Vinci manuscripts [1], the proportionality of the friction force to the applied load and its independency of the apparent area of contact were shown from experiments and proposed for generalization by Guillaume Amontons in 1699, known as the two-first friction laws [2]: "the resistance due to friction rises or falls proportionately with the amount of normal load whatever plane size or shape". Amontons studied the friction of various plane sizes and shapes submitted to various loadings applied by a spring (Fig. 1). He measured the amount of force that was necessary to move specimens towards each other. Amontons studied wood, iron, copper, lead in many combinations and smeared with rendered-pork fat, a lubricant used at this time to reduce friction and wear. He found that the resistance due to friction is the same whatever the materials when the contacting surfaces are smeared with rendered pork fat. He proposed friction resistance is roughly equal to a third of normal load.

At this time, Amontons defined friction as anything else than the action by which a part pressed on an other is moving on the surface to that which it touches. He was considering that

friction is the force that is necessary to overcome surface inequalities. In the case of overcoming rigid surface inequalities, he explained the proportionality of the friction force with load by analogy with the amount of force necessary to lift a load, which is proportional to the weight. In the case of non-rigid surface inequalities, he attributed the proportionality of friction with load to the linearity of the load-displacement relationship for springs (Fig 2).

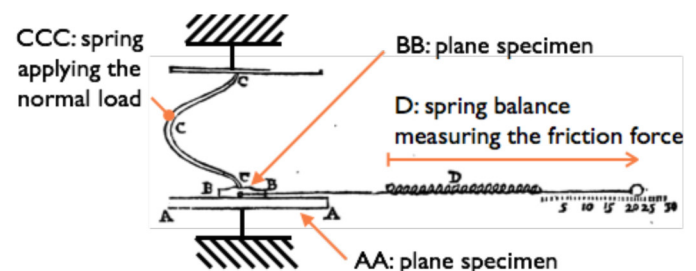


Figure 1. Set up used by Amontons.



Figure 2. Modelling proposed by Amontons of non-rigid surface inequalities capable of springs.

COULOMB'S EXPERIMENT

Charles Augustin Coulomb [3] developed experiments of friction in the latter half of the XVIII century at the request of the French *Académie Royale des Sciences* calling for practical rules and data on friction to design machines. Coulomb was also motivated by misapplications for use in marine machinery, controversy and disputed findings [4, 5, 6]. Coulomb considered Amontons carried out experiences "in small", in a physic laboratory, allowing friction conditions too far from actual situations inside machines in use.

Coulomb built various devices taking care of large friction surfaces matching the usage and carried out numerous experiments, allowing to study precisely in various conditions the dependency of friction on the nature of materials in contact, the extent of the surfaces, the load that the surfaces bear. The main setup was composed of a large table made of oak equipped with various devices, a load plate above a well allowing to apply traction loads during long travels, an arm balance to apply a given traction load in a short time. Normal load applied to a sleigh was varying from dozen to thousands of French pounds, while the extent of surfaces was adjusted using planes and sliders from dozens to hundreds of inches square. Coulomb used rounded sliders to reduce the contact area as much as possible, the sliders being used along or across the sliding direction. Materials he studied were those of contacting parts used in machinery at this time: wood on wood (oak, pine, elm) taking care of the wood-grain direction, metal on metal (iron and copper), and heterogeneous contact wood on metal. He considered dry friction and friction of surfaces smeared with mutton suet or rendered pork fat, or with oil in the case of metal on metal. In addition to the nature of materials, the surface extent and the load, Coulomb focused on the effects of a large panel of contact conditions: time that has past since the surfaces have been in contact, sliding speed, history effect, bedding-in, ageing of lubricant, sliders or/ and wood grains orientation along or across the sliding direction, etc.

Coulomb carried out more than hundreds of experiments that correspond to thousands of tests, sometimes waiting hours, in some cases up to a week, to obtain results. He determined numerous values of friction ratio for bodies under relative motion or impending relative motion. Depending on the testing conditions, his findings were in agreement with the friction laws proposed by Amontons, he also found the friction ratio to be independent of the sliding velocity in a large range of sliding conditions. Alongside these results, he was aware of limitations of those friction laws. In his day, he proposed some physical interpretations such as the dependency of friction to the cohesion of surface, surface deformation, or entanglement of wood fibers to explain various contact behaviors. Depending on the contacting conditions, he found that friction was dependent on a lot of factors, for example, the dependency of friction on the sliding velocity in the particular case of heterogeneous contact involving wood rubbing on metal. The three following case studies aim at highlighting how Coulomb conducted his experiments and interpreted the related findings.

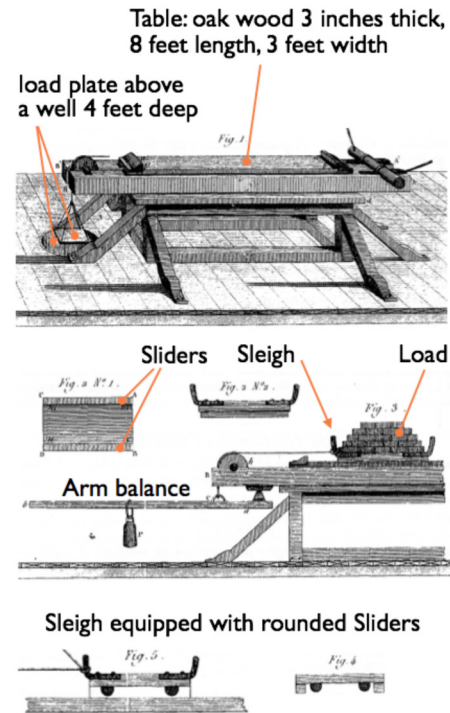


Figure 3. Coulomb's set up.

DRY SLIDING FRICTION OF WOODS

Experiments

For these experiments, table and sleigh were made from oak and polished by 20 preliminary slidings, three sleigh contact-surface sizes were tested: a large plane of 3 feet square, two sliders providing a friction area of 36 inches square, and two rounded sliders to reduce as much as possible the contacting surface. Sliders were used along and against the wood grains and various loads weighted down the sleigh from 74 to 2474 pounds. Coulomb studied a four-feet travel considering 2 tests for each experiment to determine the minimal traction load:

- first test to maintain a very low initial speed;
- second test to obtain movement continuation when the sleigh is initially gently shaken.

Observations and Results

1st-test movements were more or less uniform, like quasi-static equilibrium, while 2nd-test movements were uniformly accelerated, indicating for each case a constant friction force. The friction force could then be deduced from equilibrium of the sleigh. The following results relate to the second test of experiments conducted with the sleigh sliding along the wood grains (Figure 4). 3 experiments were carried out for each extent of surface, increasing the load. The first column ($A-F=$) gives the resulting force applied to the sleigh deduced from the uniformly accelerated movement of the sleigh, allowing to determine the friction force F knowing the traction force A applied to the sleigh. The second column gives the friction ratio which is defined by the normal load divided by the friction