

EXTRACTION OF HYBRID FRICTION LAWS WITHIN A MULTI-ASPERITY TRIBO-CONTACT

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INTRODUCTION

Knowing the continuous evolution of multi-scale friction laws over a wide range of displacements and velocities – *ie*, from $\mu\text{m/s}$ to m/s – is quite essential both : (i) at the fundamental level, for studying the *emergence* of new frictional physical laws from elemental asperity to the real contact area scale [1-3] and, (ii) for many industrial applications [eg.4], such as friction control in MEMS, robotics, additive manufacturing processes, or for the enhancement of tribological simulations. This paper describes a multiscale methodology combining experimental and simulations for extracting *hybrid* friction laws on a large range of sliding velocities.

METHODOLOGY & RESULTS

Experimentally, the multi-scale evolution of friction laws is studied as a function of sliding amplitude and velocity by using a AT-cut quartz crystal resonator (QCR, 6 MHz) which is in contact with a rough ball area at a constant normal load (8 mN). As shown in Fig. 1, the surface displacement amplitudes of the AT-cut QCR – *ie*, the sliding amplitude – is controlled by means of a Vector Network Analyzer (VNA R&S ZNC 3) [5]. Experiments have been performed over a wide amplitude range – from 0 to 40 nm – by changing the drive level provided by the VNA [6-8]. Thus, induced sliding velocity lies from several $\mu\text{m.s}^{-1}$ to m.s^{-1} . When the rough ball is applied at constant normal load on the QCR, the network analyzer sweeps the frequency across the resonance and measures the resonator's electrical admittance [8]. At the resonance frequency, the real part of the latter forms the well-known resonance curve, which is characterized by its quality factor Q . Hence, any variations of resonance frequency (dF) and dissipation factor ($dD = dQ^{-1}$) can be studied over time as function of the sliding amplitude or sliding velocity [6, 7]. From these experimental assessment, two main results can be exploited for extracting the evolution of the whole frictional behavior with respect to the imposed displacement U_0 : (i) the evolution of dF vs U_0 enables, in strong bonding conditions [9], the detection of the *sliding threshold* – *ie*, the moment the asperities leave off to stick and start to slip [7] ; and, (ii) the evolution of dD vs U_0 provides the evolution of the *additional energy dissipated per cycle* ($dW_{\text{loss/cycle}}$) averaged over millions cycles [10].

A numerical approach is then developed conjointly to the experimental one in order to extract the casually evolution of the coefficient of friction. It uses numerical simulations applied on the scaled real contact area assessed by AFM – by using a home-made BEM code ©ContactPlot [11] – where a classical Mindlin's fretting behavior is assumed at the asperity scale [3]. At first, the static real contact area is computed by mapping the elastic-plastic deformations due to the local contact pressure of the surface under the normal load. Dynamics of this real contact area due to the lateral displacement U_0 is then computed, for each asperity. Referring to [12], the percentage of the sliding area of each asperity is thus computed in order to assess to the energy dissipated (depending on μ and U_0) per cycle for each asperity submitted to fretting in either partial or gross slip, owing to its size. Summing and scaling all these energies E_d within the real contact area finally provides the *total dissipated energy* E_d . It can be compared to the experimental energy dissipated per cycle $dW_{\text{loss/cycle}}$ in order to extract the coefficient of friction μ by solving the relationship $[E_d - dW_{\text{loss/cycle}} = 0]$ using an iterative Newton method. Indeed, plotting the evolution of the E_d vs μ gives – for a normal force F_n and a displacement U_0 – a bell-shaped curve which provides two values of μ for the same $dW_{\text{loss/cycle}}$ value.

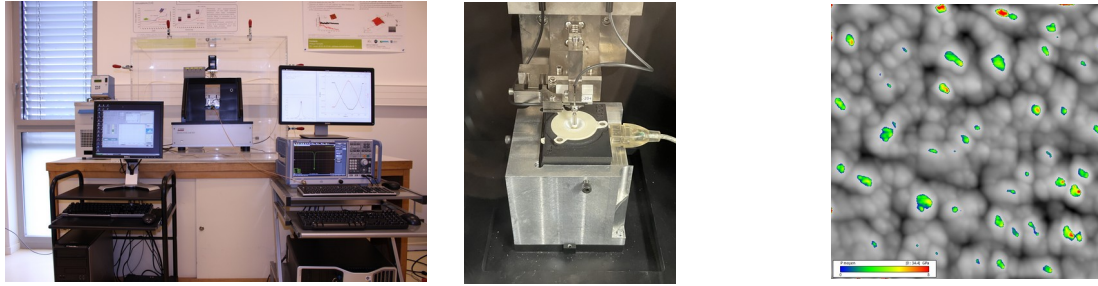


Figure 1: (left) Multi-asperity nanotribometer (NTR) working with an AT-cut Quartz Crystal Resonator (QCR) as a flat sample; NTR applies a constant normal load F_N in the range of the strong bonding conditions (8 mN) and QCR, driven by a VNA, simultaneously induces nanometric lateral displacements ; (right) Typical contact pressure map computed on the real contact area by means of a hand-made BEM code ©ContactPlot

The choice of the right value of μ is conditioned by the value of the *sliding threshold* extracted from the experimental curve dF vs. U_0 : (i) when U_0 is lower than the sliding threshold, the highest value of μ is chosen (ie, sticking area) whilst in contrast, (ii) the lowest one is chosen when U_0 is higher than the sliding threshold (ie, slipping area). Typical behavior of an aragonite ball (Φ 1.5 mm) rubbing on a 6 MHz-gold-coated quartz is plotted in Fig. 2 as a function of the sliding velocity (corresponding to a lateral displacement U_0 ranging from 0 to 40 nm). Surprisingly, the plot looks like a typical Stribeck's curve revealing an *emergence* of hybrid friction laws when the whole real contact area starts to slip, whereas only a solid friction has been assumed at the elemental asperity's scale. Solid and viscous frictional components can finally be extracted and studied separately. In addition, results reveal that this hybrid *emergent* behavior is not due to the presence of any lubricant-like organic components in the aragonite ball but instead to the out of sync tribological behaviors of the elemental asperities when the real contact area begins to slip as a whole.

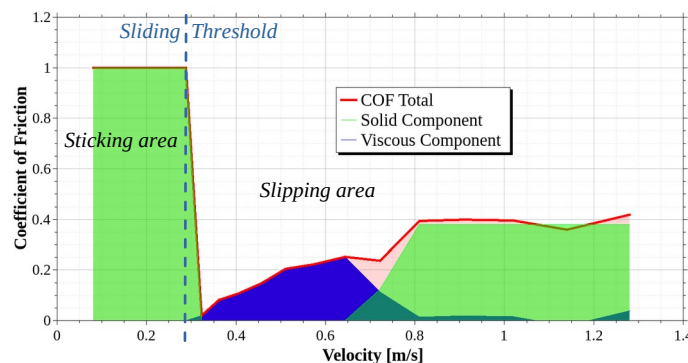


Figure 2 : Emergence of hybrid friction law vs. velocity when aragonite ball rubs on a gold-quartz resonator from 0 to 1.4 m/s corresponding to lateral displacement from 0 to 40 nm

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