Dual characterization of boundary friction thanks to the harmonic tribometer:
Identification of viscous and solid friction contributions

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Abstract. All the usual characterization of an interface submitted to shear is generally achieved
thanks to an experiment using a pair of two loaded solids in continuous sliding. So, the friction
coefficient value can be determined. But, only this friction value is quite poor information and
is not able to reveal the complexity of the interfacial processes occurring in the sliding contact.
A novel method has been developed at LTDS, allowing us to identify both the velocity-
dependent and the solid friction contributions. It is based on a contact submitted to constant
normal load, one solid being supported by a 1D mechanical oscillator, under the form of an
elastic bi-blade, able to return to its equilibrium position through damped oscillations. The way
the amplitude is decaying during this elastic recovery is recorded. A mechanical model has
been developed, in order to fit experimental data, allowing us to identify two different
contributions: the velocity-dependent contribution (typically viscous damping), and the solid-
like contribution (typically solid friction). This technique has been applied here to a lubricated
sphere-on-plane contact. The contacting surfaces are made of AISI 52100 polished steel. Two
model products are tested: pure glycerol and 1,3-buthylene glycol. First results are presented,
showing the capabilities of this technique for giving a new insight on the mixed lubrication
regime description.

1. Introduction
The control of friction has been identified as a challenging topic for energy saving. Especially,
reducing friction is a goal for many systems involved in transportation: engines, gears and
transmissions. A good knowledge of phenomena occurring during friction is then needed. From a
classical approach, friction is measured thanks to tribometers, in which two solid surfaces are rubbed
together in given loaded conditions. The lateral force is measured and then the friction coefficient is
simply calculated by dividing the tangential force by the normal one. This classical approach is
extensively used in the different fields of tribology, for both fluid and solid lubrication. It gives overall
information relative to the interface under sliding but does not bring any detail concerning the intimate
processes involved into the velocity accommodation. In addition, different tribological systems have
been identified with low friction. Recent developments on so-called “Superlubricity” have been shown
[1]. In such cases, the value of classical friction coefficient can be as low as $10^{-3}$ to $10^{-4}$ or even less.
Some theoretical results have even predicted a total vanishing of friction force in particular conditions.
[2]. In such case, the determination of friction coefficient value with a sufficient precision is very difficult to obtain, due to limitations of the force transducers [3,4].

For these two reasons, a new technique has been developed. This paper presents some preliminary results obtained thanks to an original alternative way that allows to identify linear velocity-dependent and velocity-independent friction contributions, without measuring any tangential force. It is based on the development of a new instrument, and the analysis of the dynamic free response of a single degree-of-freedom mechanical oscillator.

2. Principle of the technique developed

2.1. Basic principle and apparatus
The basic principle of this method is based on the analysis of the dynamic free response of a single degree-of-freedom mechanical oscillator, to which a contact with friction is attached. The contact is a sphere-on-plane configuration. The initial situation to be considered is when the head is set out of equilibrium, with an initial deviation parallel to the sliding direction. When the head is released, relaxation process occurs, and the elastic energy accumulated in the elastic blades is progressively released. Position and speed of the head is then oscillating, and their amplitude is decreasing with time. The detailed analysis of the damped relaxation oscillations leads to qualitative and quantitative information on friction. This mechanical problem has been presented and solved in detail in literature [5,6]. We assume that friction at interface can have two origins: i/ a viscous-type component, depending on the sliding velocity, characterized by “zeta” value, ii/ and a solid-type friction component, characterized by “mu” value, Figures 1 and 2. A dedicated apparatus has been developed and presented previously in details [7].

2.2. Measurements and data processing
The relaxation process may have a total duration ranging from 20 sec (in case of low friction) down to less than 1 sec. Different signals are recorded during this phenomenon: i/ position and speed of the moving head, thanks to a laser velocimeter (POLYTEC OFV-5000), ii/ electrical contact resistance (ECR), thanks to a dedicated electronic device, described previously [7], iii/ the overall friction force, with a piezoelectric transducer, in order to have a qualitative approach of lateral force during relaxation. Identification is then processed on both position and speed, in order to get the final values of zeta and mu. Much care is needed in this data processing. Especially, It may happen that the first oscillations are deformed, due to some defect of positioning before relaxation. In such case, these oscillations are removed from the signal to be processed. No incidence on final values of zeta and mu is observed.

2.3. Precision and accuracy
The interest of this method is that identification process leads to a unique solution for both zeta and mu values. This technique gives good results for modeling both the number of oscillations and the amplitude decay evolution of position and speed of the moving head. Therefore, this method can be considered as very robust. The lower limit for the number of oscillations to be processed is 5 to 6, in order to have sufficient resolution. We consider that zeta becomes negligible when its calculated value is lower than 0.0001. The smaller the damping is, the better is the resolution for mu and zeta.

3. Experimental and results

3.1. Samples
We present here the results obtained with two different lubricants: glycerol C₃H₈O₃ (GL), with a dynamic viscosity of 0.72 Pa.s, and 1,3-buthylene glycol (13BG), with a dynamic viscosity of 0.09 Pa.s, as measured is a cone-plate rheometer at 25°C (ANTON PAAR MCR-300), with shear rate ranging typically between 10 and 1000 s⁻¹. The contacting surfaces are a ball, 3.0 mm diameter and a
flat, both made of 52100 AISI steel, polished by a series of diamond pastes: 3.0 then 1.0 µm, in order to obtain mirror-polish surfaces.

3.2. Natural self-damping of the system
Experiments without contact between the spherical pin and the flat have been performed, in order to identify dynamic and damping characteristics of the test apparatus by itself. Fig. 3 displays oscillations of the head with spherical pin in air. The number of oscillations observed before equilibrium is larger than 300 in this case, see Table 1. The dynamic response corresponds to purely velocity-dependent dissipation and equivalent viscous damping zeta, identified from the least mean square method. The zeta value is found in the millirange: zeta = 0.0013. Therefore, modeling the device by a single degree-of-freedom linear oscillator is validated. Apparatus dissipation can have different origins: inner damping inherent to the materials used, damping caused by micro-sliding in the connections between assembled mechanical parts, damping caused by air displacement and also the acoustic radiation of vibrating surfaces and vibrations transmitted to the flat. The relaxation behavior is linear as the amplitude of initial displacement remains small compared to the biblade length.

Table 1. Response of the steel-steel contact in different conditions: free response (no contact, no meniscus), meniscus response (no contact) and loaded contact lubricated with glycerol (GL) and 1,3-buthylene glycol (13BG), for a fixed normal load 50 mN.

| Normal load (mN) | Approx. number of oscillations | zeta   | mu     | ECR log(Ohm) |
|------------------|-------------------------------|--------|--------|--------------|
| No lubricant     | free relaxation               | >> 300 | 0.0013 | /            |
| GL lubricant     |                               |        |        |              |
| 0 (meniscus only)| ab. 100                       | 0.0108 | /      | /            |
| 50               | 16                            | 0.0186 | 0.037  | >4, stable   |
| 50 (repeated)    | 16                            | 0.0185 | 0.038  | >4, stable   |
| 13BG lubricant   |                               |        |        |              |
| 0 (meniscus only)| ab. 300                       | 0.0026 | /      | /            |
| 50               | 12                            | < 0.0001 | 0.179 | <1, fluctuations |
| 50 (repeated)    | 11                            | < 0.0001 | 0.192 | <1, fluctuations |

3.3. Effect of lubricant meniscus
In a lubricated contact, a meniscus of fluid is surrounding the real contact zone. The effect of meniscus is now under consideration. We have performed systematic experiments with a given quantity of lubricant, here 50 µl. As an example, we report the dynamic response of a sphere facing a plane sample, non-contacting and fed by GL lubricant. So a fluid meniscus is present in the gap (50 µm thickness) between solids. The time response is presented in Fig. 4. The number of oscillations before equilibrium is found close to 100, so much less than without lubricant, as expected. Identification of the time response leads to a centirange value: zeta = 0.0108. This value is one order of magnitude larger than without lubricant surrounding the contact. Therefore, we get evidence for the effect of the fluid meniscus in this technique. The same type of experiment is run for 13BG lubricant, having a lower viscosity. We can check that in this case, the damping is larger than without product, but much lower that in the more viscous case. Identification leads to a millirange zeta value: 0.0026.
From this section, we can understand that both the equipment itself and the fluid meniscus bring a viscous-type contribution to the harmonic relaxation of the moving head, after releasing out from its out-of-equilibrium initial position.

3.4. **Response of the lubricated contact with normal load**

We have performed experiments with lubricants at a given normal load of 50 mN. The corresponding maximum contact pressure is 245 MPa and the corresponding Hertzian diameter of 20 \( \mu \text{m} \). The results are presented in Table 1.

3.4.1. **Glycerol (GL)**

For glycerol, we can observe that the global damping of the lubricated loaded contact is larger than that for the non-contact situation (meniscus only), as expected, Figure 5.a. Damping is shown to increase when the normal load is applied, leading to a decrease of the number of oscillations before equilibrium. Identification of the position response leads to a centirange value of the solid-type friction: 0.037 and a millirange value of the viscous-type friction 0.0186. The results show that both the relaxation overall duration and the decay law of the oscillating amplitude is well fitted. We periodically checked the repeatability of the results. As an example, we show in Table 1 the results obtained in two different experiments for the normal load of 50 mN. The values of zeta and mu are found to be very close. ECR evolution shows that the measured value is set to more than \( 10^7 \) ohms Figure 5.b, showing that the contact is in full film conditions. For the last three oscillations, these conditions are changing and some metal junctions are appearing, giving some bumps on the ECR signal. The final value of ECR correspond to metal-metal contact.

3.4.2. **Buthylene glycol (13BG)**

We have also performed experiments with the lower viscous product, 1,3-buthylene glycol (13BG), Figure 6.a. We can observe that the damping is higher than in the previous case, leading a significant decrease of the oscillations. By identification, the two components are calculated. The solid-type contribution one found in the decirange: 0.179 and the viscous-type component is found negligible (<0.0001). Repeatability of results is shown in table 1. It seems that in mixed regime, dissipation can be influenced by some roughness effect. ECR signal shows clearly that mixed lubrication is occurring in the contact, Figure 6.b.

4. **Discussion**

4.1. **Fully fluid lubrication regime (GL case)**

The experiments achieved with GL lubricant show that the contact is operating with a fully fluid film in the contact, thanks to ECR measurement. ECR has a high value -close to \( 10^5 \) ohms- and stable with time. For this reason, in-situ electrical measurement is very useful and no doubt is possible on this point, Figure 5.b. It means that the contact is fed by a full film, whatever the speed value. In these experiments, the maximum sliding speed is 70 mm/s. In the classical EHL approach, the contact is assumed to operate in steady state conditions, with a constant value of sliding and rolling speed conditions. Then the fluid film thickness is strictly depending on the speed value. Therefore, if we consider that the film in the present contact is set due to combined effect of sliding speed, viscosity and piezo-viscous effect [8]. In this technique, the sliding speed at the contact is essentially varying, in a damped sine wave motion. Especially, when speed is passing by the null value (twice by each oscillation), a film of lubricant is remaining in between the two contacting bodies. In GL lubricated case, we can observe from measurement that ECR value is stable at the maximum value This phenomenon can be considered as an effect of squeeze film, as already described in literature [9]. This phenomenon can be quite important for applications, because we show that dynamic lubrication can be achieved even when the speed is zero.
When the relaxation comes to the end, in the last two oscillations, we observe that ECR value decreases drastically, showing that the complete fluid film is no longer operating between the surfaces. When checking the lateral force that is measured during relaxation, Figure 5.c, we can have a qualitative evolution of the total frictional force at the contact. The signal has not been calibrated here, so the evolution is only qualitative. We can observe that the extrema of the modulating lateral force \( F_t \) are slightly decreasing (viscous contribution decreasing due to the progressive velocity reduction), then the shape of oscillations becomes more square like. During the last oscillation, we notice that the friction signal increases, just before stop. This can be related to the end of the full fluid film regime.

stable, unless the speed reaches a low value. In this case, ECR is decreased. The lubrication regime is changed: from full film to mixed or boundary lubrication. This observation validates the mechanical model, in which we consider that the time response can be identified by a unique combination of both viscous-type and solid-type friction.

When considering the results of identification for the full film lubrication situation (GL), identification of the time response leads to a centirange value of both \( \zeta \) and \( \mu \). It means that the shearing cannot be considered only as viscous-type flow. This unexpected result brings a new description of sliding contacts. We can assume that it is related to the physical change of the lubricant under high pressure contact, when the lubricant is expected to change from viscous to solid-like material, as described extensively in EHL literature [8].

4.2. Mixed/boundary lubrication regime (13BG case)

The results obtained with the 13BG show that the contact is now operating in mixed or boundary lubrication regime. On ECR signal, we can observe low values, with many fluctuations, showing that the contact is mainly supported by solid-solid asperities in contact, without a continuous fluid film existing in the interface. In these conditions, the solid-type friction is found in the decirange, typically less than 0.2 and the viscous-type component is found very low, less than 0.0001, Figure 6.c. This value can be considered negligible compared to decirange solid-type friction, This case is found to be very different from the previous, obtained with GL lubricant, more viscous. We can deduce that this technique can be beneficially applied to the study of mixed lubricated contacts, in order to learn more about the limits between boundary and mixed regime. This topic is currently widely studied in literature [ref], and many authors are presenting data on the effect of roughness, texturing of surfaces, lambda ratio on the shape of the Stribeck curve. The practical applications of such developments are important in terms of minimizing friction, increasing durability of sliding contacts [10,11].

4.3. Additional friction measurements during relaxation

Basically, the new technique presented in this paper does not need any force measurement. The analysis is based on the study of the decay curves of both position and speed of the relaxing head with time. Then, the mechanical model allows us to identify viscous damping component and friction component generated by interfacial shearing. But in addition, a piezoelectric force transducer has been introduced in the sample holder, so that the measurement of the variation of tangential force is made possible. This measurement is still difficult, due to the low level of forces under consideration. The system has not been yet calibrated precisely and it gives only qualitative information, as presented in Figure 5.c and Figure 6.c. From variations of amplitude, phase and shape of these tangential force signals, we can think that precious information will be extracted in the future. This work is currently under progress. So, the complete experimental technique presented here is expected to bring a better understanding of complex friction phenomena, like pure viscous shearing, slip at wall interface [12], shearing of a solid-like interfacial media.

5. Conclusions

This paper presents a new method for evaluation of friction in a sliding contact. It is based on an experimental arrangement in which the sliding contact under load is supported by an elastic system. When the head is set out of equilibrium and relaxing, the study of damped oscillations process is
performed. A mechanical model based a 1D oscillator is used, and the main assumption consists on the possible contributions of both a viscous-type friction and a solid-like friction. Position and speed of the moving head is achieved by a laser velocimeter. In addition, electrical contact measurement and lateral force signal is recorded.

From the time response, we have been able to identify two components of the frictional dissipation: viscous-type friction and solid-like friction. The machine itself has been qualified. The results show that is behaves like a pure viscous damping system ($\zeta = 0.0013$). The technique has been applied to a steel on steel contact lubricated by 2 different products: pure glycerol (GL) and 1,3-buthylene glycol (13BG). For GL, the time response gives evidence for a fully fluid contact, thanks to ECR. Zeta and $\mu$ values are determined and both are found in the centirange. For 13BG: evidence is given for a boundary lubrication regime. The friction is mainly solid-type: $\mu$ in the decirange value and the viscous-type damping is found negligible in this case. The capabilities of this new technique are expected to bring a new insight in friction measurement and characterization.

The further steps in developments could concern the following items:

i/ Some improvements of the experimental rig, especially the calibration of lateral force signal, when measurable,

ii/ Application of this technique to different tribological systems operating in mixed and boundary lubrication regimes: effect of surface effective additives like adsorbed layers for example, effect of surface patterning for the case of controlled roughness. This technique could bring some new description of friction dissipation, for example the detection of viscous shearing, slip at solid surface, internal shearing, etc.

iii/ Application to superlow friction systems, when friction measurement is made difficult due to the low values of lateral force to detect. For that purpose, different tribological systems could be under consideration, both for fluid lubrication and solid lubricants, like MoS$_2$, DLC, ta-C for example. Let us remember that with this method, lower is friction -and damping, better is precision;

iv/ We can also propose that such an approach can be beneficially applied to a tip-probe based contact, like AFM-type equipments. In such case, the single asperity contact would make possible to elucidate the intimate processes occurring during friction.

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**Figure 1.** Schematic arrangement for the measurement with the harmonic tribometer. The contact is a sphere-on-plane configuration. The sphere is attached to the head, fixed at the end of an elastic arm that can oscillate. The speed and position of the head is measured by a laser velocimeter. In addition, electrical contact resistance ECR between sphere and plane and lateral signal force on the plane sample are measured during friction. Below, the schematic of the mechanical analysis.
Figure 2. Principle of the mechanical model. Friction is assumed to have two different contributions: i) a viscous-type one, velocity-dependent and characterized by zeta value. The amplitude of oscillations during relaxation is expected to be exponential, ii) a solid-type one, characterized by mu value. In this case, the decay of oscillations is expected to be linear.
Table 1. Response of the steel-steel contact in different conditions: free response (no contact, no meniscus), meniscus response (no contact) and loaded contact lubricated with glycerol (GL) and butylene glycol (13BG), for a fixed normal load 50 mN.

| Normal load (mN) | Approx. number of oscillations | zeta    | mu    | ECR log(Ohm) |
|------------------|-------------------------------|---------|-------|--------------|
| No lubricant     |                               |         |       |              |
| free relaxation  | >> 300                        | 0.0013  | /     | /            |
| GL lubricant     |                               |         |       |              |
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| 50               | 16                            | 0.0186  | 0.037 | >4, stable   |
| 50 (repeated)    | 16                            | 0.0185  | 0.038 | >4, stable   |
| 13BG lubricant   |                               |         |       |              |
| 0 (meniscus only)| ab. 300                       | 0.0026  | /     | /            |
| 50               | 12                            | < 0.0001| 0.179 | <1, fluctuations |
| 50 (repeated)    | 11                            | < 0.0001| 0.192 | <1, fluctuations |
Figure 3. Time response of the relaxing moving solid, after initial displacement. The evolution of position is plotted. We can observe the characteristic decay of amplitude over 10 sec. A detailed plot is given in the graph below, showing the oscillations, more than 300. The model is based on a single component behavior: \( \zeta = 0.0013 \).
Figure 4. Time response of the relaxing moving solid, fed by 50 µl of glycerol (GL), after initial displacement. The evolution of position is plotted. We can observe that the duration of relaxation process is shorter (about 3 sec.), showing that the damping is more intense. Identification leads to a single component behavior: \( \zeta = 0.0108 \).
Figure 5. Time response of a sphere-on-plane contact lubricated by pure glycerol: GL, $F_n=50$ mN, temp= 24°C, AISI 52100 steel against itself.

a/ Evolution of position: both experimental data for position (full line) and computed response (dotted line) are plotted. The model is based on a dual component behavior: $\zeta=0.0186$ and $\mu=0.037$.

b/ Evolution of electrical contact resistance ECR, showing the full fluid film lubrication regime.

c/ Evolution of the lateral force signal, giving qualitative evolution of the friction force during relaxation.
**Figure 6.** Time response of a sphere-on-plane contact lubricated by butylene glycol: 13BG, $F_n = 50\text{ mN}$, temp = 24°C, AISI 52100 steel against itself.

a/ Evolution of position: both experimental data for position (full line) and computed response (dotted line) are plotted. The model is based on a dual component behavior: $\zeta < 0.0001$ and $\mu = 0.179$.

b/ Evolution of electrical contact resistance $ECR$

c/ Evolution of the total force signal, giving qualitative evolution of the friction force during relaxation.