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Dependence of friction noise of rough surfaces with contact area

A. Le Bot, V.H. Dang and E. Bou Chakra

Laboratoire de Tribologie et Dynamique des Systèmes, 36 Avenue Guy de Collongue, 69134 Ecully Cedex
alain.le-bot@ec-lyon.fr

The noise emitted during the friction of rough surfaces is a wide band noise generated by the numerous impacts occuring between antagonist asperites of surfaces. This study presents an experiment which investigates the law between the acoustical power and a varying number of identical sliders i.e. the nominal contact area. It is found that in some cases, the acoustical power is proportional to the number of sliders while the sound is constant in some others. This result is explained by introducing a dissipation law of vibration at the interface of solids. In the regime where this dissipation process dominates, the sound is constant while in the regime where it is negligible compared with other dissipation processes, the sound is proportional to the number of sliders.

1 Introduction

The importance of surface roughness in macroscopic friction is recognized for a long time. As early as in the eighteenth century, Coulomb [1] claimed that the fundamental cause responsible of friction was the interlocking of antagonist asperities. The modern theory of the so-called *multi-contact interfaces* is due to Bowden and Tabor [2], Archard [3], Greenwood and Williamson [4]. From these studies, it appears that the proportionality between the actual contact area and the normal load, the key to explain Amontons-Coulomb's laws of friction, stems from a collective phenomenon of microscopic contacts.

But when the two solids are rubbed together, a sound is produced. Among all the consequences of friction, resistance to movement, wear and so on, the friction-induced vibration is certainly the one which has been the less studied. If the surfaces of solids are rough, and they are always rough, then the sound is wide-band with a low level [5]. This is for instance the sound which is produced by rubbing an hand on a table. Among several possible causes, it is clear that impacts between antagonist asperities is the main noise source [6, 7]. The noise results then from a collective phenomenon of multi-asperities and it is then reasonable to raise the question of the proportionality of radiated sound power with the surface of sliding solid. This question has been studied in Refs. [8, 9].

2 Existence of two regimes

When rubbing simultaneously several rigid and rough solids, some sugar lumps for instance, on a drum membrane, a sound is produced. The drum then plays the role of a resonator. It can be checked with a sonometer or more simply by hearing the noise, that *a larger number of solids does not produce a stronger sound.* Results of this experiment are shown in Fig. 1. The noise level remains constant up to fifty lumps.

This observation is rather paradoxical. The common sense tells us that the greater is the contact area the higher is the sound level. The difference of sound pressure level between a single source and n identical sources is $\Delta L_p = 10 \log_{10} n$ dB that is 10 dB per decade ($n = 10$). This law simply claims that the power being injected into vibration is proportional to the number of sources, or, in other words, that the sources are uncorrelated.

This law of additivity of sound sources applies in some cases. Let re-do the same experiment of sugar lumps on a thick wood table. Results are shown in Fig. 2. The noise level now increases with a slope near 9 dB per decade. These two simple experiments show that the link between friction-induced vibration and contact area is more complex that it could be at first sight.

Two regimes exist for roughness noise, a first regime where the constancy law applies and a second one where the additivity law applies. These regimes illustrated in these simple experiments, have also been explored on a single steel plate as well as all intermediate regimes [8].

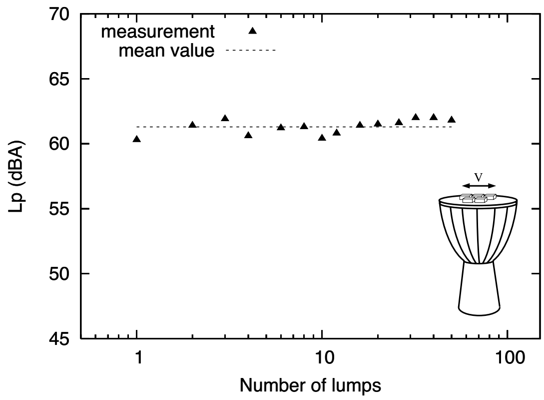

Figure 1: Evolution of SPL versus number of sugar lumps on a drum membrane.

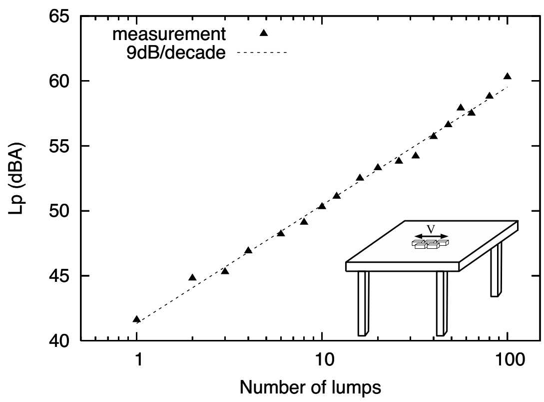

Figure 2: Evolution of SPL versus number of sugar lumps on a wood table.

3 Experiment

The experimental set-up is shown in Fig. 3. n rigid sliders of base area S_0 (total friction area $S = nS_0$) are pulled with a constant velocity V on an elastic resonator. The resonator is a steel plate where a damping layer may be added to increase the internal damping. The sliders are parallelepipedic solids (with very high natural frequencies). Two types of sliders thin and thick have been used. The base of sliders and the track on the resonator are rough. The RMS-value v of the vibrational velocity of the resonator is measured in the frequency band [10 Hz - 10 kHz] with an accelerometer.

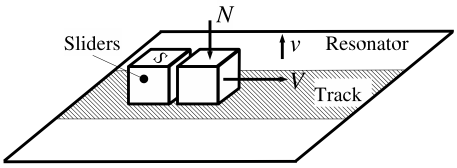

Figure 3: Principle of the experiment.

Four experiments have been done combining high and low internal damping with thin and thick sliders. The vibrational level evolution is measured when pulling from 1 to 8 sliders. In Fig. 4 is shown the vibrational velocity versus contact area curves for the four experiments.The slope of the curve v versus S has four different values. The lowest slope is encountered for low damped resonator and thick sliders while the greatest slope is when the damping is high and with thin sliders. The slope λ (dB/decade) as well as the mean vibrational energy $m\bar{v}^2$ are evaluated from Fig. 4. It is clear that λ can take small or high values always between 0 and 10 dB/decade.

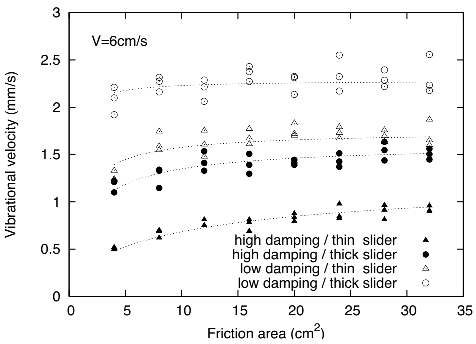

Figure 4: Evolution of vibrational energy versus contact area in four different experiments.

4 Dissipation law in rough contact

In order to explain the above results, we propose the following theoretical developements. The resonator behaves like a tank of vibrational energy. In steady-state regime, the energy is constant and results from the balance between the power being injected by sliding of solids and the power being dissipated natural mechanisms. We write,

$$P_{\text{inj}} = P_{\text{dis}}, \tag{1}$$

Concerning the excitation mechanism, the normal vibration stems from the numerous impacts occuring between antagonist asperities. Due to the random nature of surfaces, all these events are independent and the vibrational power being injected P_{inj} in the vibrating system is therefore proportional to the rate of impacts that is the contact area S,

$$P_{\text{inj}} = pS, \tag{2}$$

where p is the vibrational power being injected per unit area.

We now consider two mechanisms for the dissipation of vibration and write $P_{\text{dis}} = P_{\text{int}} + P_{\text{fric}}$ The first is the dissipation in the damping layer (or by the natural damping of the plate). In this type of dissipation, the power being dissipated P_{int} is proportional to the total vibrational energy in the resonator,

$$P_{\text{int}} = \eta_i \omega m v^2 A. \tag{3}$$

where A is the total area of the resonator and mv^2 the vibrational energy density. The internal damping loss factor η_i is an intrinsic property of the resonator. Its value just depend on the material (and the damping layer) but not on the contact area S.

But we also consider that the vibration can be dissipated in the contact zone itself. Then, we introduce the following assumption, *the vibrational power being dissipated in the contact is proportional to the contact area S and the square of the mean vibrational velocity* v^2. Let us introduce a "contact" damping loss factor η_c, the vibrational power being dissipated by friction is,

$$P_{\text{fric}} = \eta_c \omega m v^2 S, \tag{4}$$

where $\eta_c \omega$ is assumed to be a local quantity which depends on the roughness of surfaces in contact, the sliding velocity V and the mass per unit area m but not on the contact area S neither the resonator surface A.

The energy balance the reads,

$$pS = \eta_i \omega m v^2 A + \eta_c \omega m v^2 S \tag{5}$$

Or,

$$mv^2 = \frac{pS}{\eta_i \omega A + \eta_c \omega S} \tag{6}$$

Two special cases may be considered. When the internal damping dominates (wood table) then $\eta_i >> \eta_c$ and,

$$mv^2 = \frac{pS}{\eta_i \omega A} \tag{7}$$

The vibrational energy and therefore the radiated sound is found to be proportional to the contact area S. Now when dissipation by friction dominates $\eta_c >> \eta_i$ (drum membrane) then,

$$mv^2 = \frac{p}{\eta_c \omega} \tag{8}$$

And the sound no longer depends on the contact area that is the number of sliders!

Let us introduce the dimensionless quantity,

$$Y = \frac{\eta_c \omega m v^2}{p}, \tag{9}$$

as the ratio of vibrational power dissipated by friction and injected power. Clearly, $Y < 1$. With,

$$X = \frac{\eta_c \omega S}{\eta_i \omega A}, \tag{10}$$

being the ratio of powers dissipated by friction and by internal damping, Eq. (6) reads,

$$Y = \frac{X}{X + 1}. \tag{11}$$

The internal damping regime is found when $X < 1$ leading to the proportionality of friction sound with sources $Y = X$.

And the contact damping regime appears when $X > 1$, the constancy of friction noise versus sources then reads $Y = 1$.

In Fig. 5 are plotted all points of previous experiments in a dimensionless form. It then clear that the four experiments cover several regimes from the proportional regime (left part of the curve) to the contant regime (right part of the curve).

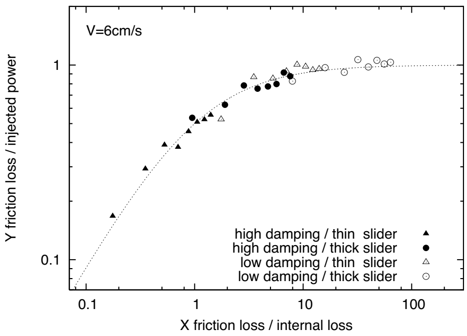

Figure 5: Evolution of Y versus X and results of previous experiments.

5 Conclusion

In this study, it has been shown that the level of normal vibration induced by mechanical impacts during the sliding of rough surfaces, may depend or not on the number of sliders. Two regimes exist for roughness noise. The regime where the contact damping dominates implies that roughness noise level does not depend on the number of sliders. It can be easily observed on drums and, more generally, on any structure highly reverberent. On the other hand, the regime of dominating internal damping implies that the noise level linearly increases with the number of sliders. It can be observed on highly damped resonators, a wood table for instance.

The underlying assumption that has been proposed in this study to explain the constant regime is that the damping of vibration in the interface is a local phenomenon governed by Eq. (4). This is a strong assumption. But this is the only assumption which leads to the energy balance where the contact area vanishes.

Acknowledgments

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