Acoustic emission in sliding friction

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Abstract: Acoustic emission associated with friction between two materials is studied. In particular we focus on the acoustic emission signals generated when sliding an aluminium block on sand paper. We show that energy and amplitude of the individual signals (hits) are distributed according to a combined probability law. Most energies and amplitudes are power-law distributed and fewer are Gaussian distributed. It has also been found that decreasing the roughness of the sand paper displaces the Gaussian distribution to larger energies and amplitudes. The overall scenario can be explained in the framework of the Dragon King Theory, that suggests that extreme events follow a different physical law than those in the main distribution.

I. INTRODUCTION

Tribology is the discipline that studies the contact of two surfaces that are in relative movement. In particular, it focuses on the study of three phenomena: the friction between two materials, the wear of the surfaces and the lubrication to reduce that wear [1]. Friction can be defined as the resistance to the movement of one body to another body while they are in contact [2]. Classical studies show that friction follows the three Amontons-Coloumb's laws: i) the frictional force (F_f) is directly proportional to the normal force between the surfaces (Amontons' 1st law), ii) the frictional force is independent from the apparent area of contact (Amontons' 2nd law) and iii) kinetic friction is independent from the sliding velocity (Coulomb's law) [3]. These three laws only apply to dry friction, which is the case of the present work.

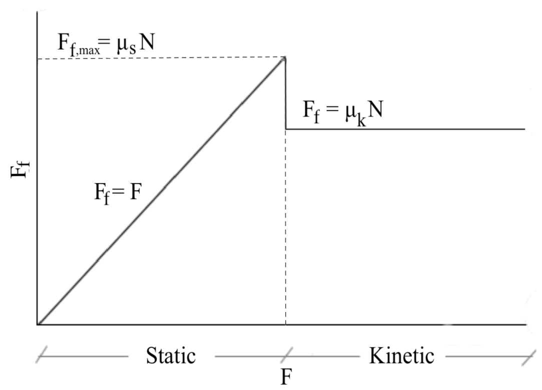

FIG. 1: Schematic graphic of the relation between frictional force and applied force (F).

Fig.1 shows a typical example of F_f vs F described by classical theories. When a force is applied, the object will be initially at rest. During this regime, there will be a static frictional force equal to the applied force, given by:

$$F_f = F \quad (F_f < \mu_s N), \tag{1}$$

where μ_s is the static friction coefficient and N is the normal force acting between the two objects. The object will start moving when the applied force exceeds its maximum, and the frictional force then becomes kinetic:

$$F_f = \mu_k N, \tag{2}$$

where μ_k is the kinetic friction coefficient. This force is constant and below the maximum value of the static frictional force. All frictional forces oppose to the applied force. Classical theories give a general idea about frictional force, but reality is more complex, as we will show further in this work.

Our aim is to monitor friction at a microscopic scale during the process of sliding a block on a rough surface. This will be done by recording Acoustic Emission (AE) at ultrasonic frequencies. All kinetic friction processes generate quasi-continuous AE signals, produced by the stick-slip motion of two contact in materials [4]. Signal intensity depends on many different factors such as block velocity, contact force, material type [5] and surface properties as roughness, hardness or the use of lubrication.

Fig.2 shows an example of an AE signal obtained experimentally. The top panel shows the continuous AE signal with numbered hits. The precise definition of an AE hit starts when the pre-amplified signal crosses a threshold, and finishes when the signal remains below the threshold for more than a predefined time, the HDT (Hit Definition Time). The bottom panel displays a close up of a hit, showing some of its properties such as its duration and its amplitude [6].

In the present work we will focus on the analysis of different properties of AE hits, such as its duration (D), its amplitude (A) and its energy (E). Amplitude is defined as through a logarithm:

$$A(dB) = 20\log(\frac{V_{max}}{1\mu V}) - G, \tag{3}$$

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where G is the gain of the pre-amplifier and V_{max} is the maximum voltage of the hit. Energy is computed as:

$$E = \frac{1}{R}\int_0^D V^2(t)dt, \tag{4}$$

where R is a reference resistance ($R = 10$ kΩ).

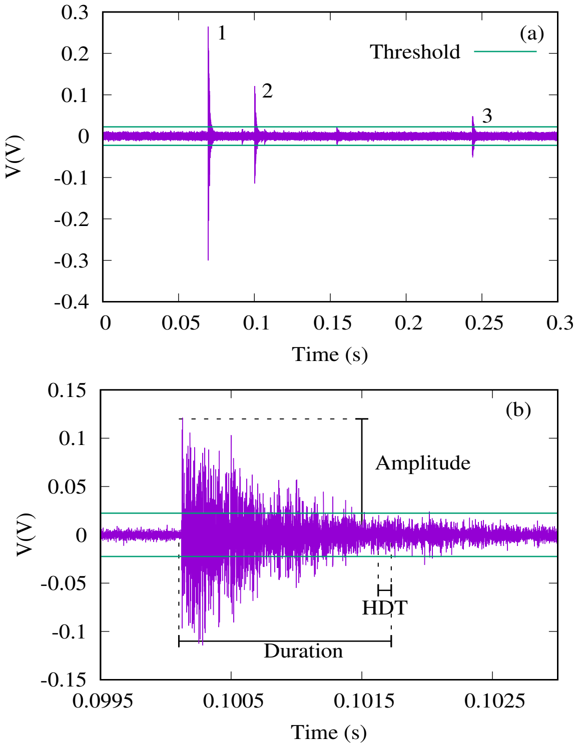

FIG. 2: (a) AE signal acquired experimentally. Hits are numbered. (b) Zoom of hit number 2 with its properties. Threshold is at 27dB and HDT is 100 μs. For this particular case $A = 45$ dB and $D = 1626$ μs.

To study the AE signal we performed two different measurements: i) we recorded the acoustic activity (number of hits per time unit) and ii) we studied the statistics of the properties E, A, D of the individual hits.

In the past there have been many studies of AE associated with friction, but mainly from an engineering point of view (earthquakes, bridges, bio-medical application, etc) [7][8]. Our goal is to study AE signals from a more out-of-equilibrium statistical-mechanics point of view with the aim of finding possible critical phenomena.

II. EXPERIMENTAL SETUP

AE signals will be recorded while sliding an aluminium block (size 1,26 x 9,92 x 4,95 cm; mass 161,54 g) on an abrasive paper (size 22,8 x 28 cm).

The AE sensor is placed on the block to collect the ultrasonic signals. The voltage signal from the transducer is pre-amplified and sent to a computer, where data is analyzed with a PCI-2 acquisition system from Euro Physical Acoustics (Mistras Group), working at 40 MHz. Software AEWIN is used for data processing.

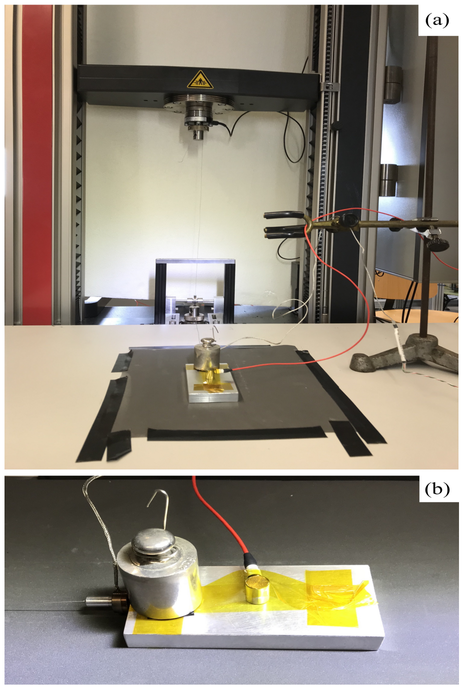

FIG. 3: (a) Image of the experimental setup. (b) Close up of the aluminium block, with the AE transducer and a load.

The block is moved by an inextensible fluorocarbon thread connected to a Z005 Zwick/Roell testing machine, at very slow and constant velocity, so the displacement of the block is proportional to time. The testing machine incorporates a load cell to measure the force applied to the block. The experimental setup can be seen in Fig.3.

The experiment was repeated with different parameters such as AE channel setup parameters and timing parameters: threshold, HDT, filters, etc., and also varying other external parameters such as the roughness of the abrasive paper (grit 80, 800, 1000), the weight above the aluminium block, the velocity, etc. We also studied some force driven experiments (force proportional to time), using a hanging dead load.

The results presented here correspond to experiments done with a weight of 200 g above the aluminium block, with a pre-amplified factor $G = 60$ dB, band-filtered between 100 kHz and 2 MHz, with data recorded at 2 million samples per second. The threshold is fixed at 27 dB and the HDT is 100 μs. The total duration of the experiment is approximately 100 min and the velocity of the block is 1 mm/min. The following results correspond to two different abrasive papers: sand paper P800 grit (Norton Saint-Gobain, T489 series), and silicon carbide paper of 1000 grit.

III. RESULTS

Two kinds of analyses of the results have been made. The first one is focused on the comparison of the AE activity with the frictional force behaviour and the second one is the statistical analysis of A, E and D properties of the AE hits.

With the purpose of eliminating electrical noise, all individual hits with $D < 1$ μs and $E < 5$ aJ have been removed.

A. Signal analysis

Fig.4 shows the results for the experiment with an 800 grit paper. The force during time progress is shown on the top panel. At the beginning of the experiment while the block is static, the force has a linear behavior corresponding to a static friction regime. During that time interval the acquisition system has not collected any AE signal, as we can see on the bottom panel. AE signals appear at a certain time ($t = 110$ s) corresponding to the change from static to kinetic friction, represented on the graph by a discontinuous line. During kinetic friction the force is approximately constant, but clear fluctuations not described by the Amontons-Coulomb's model are observed.

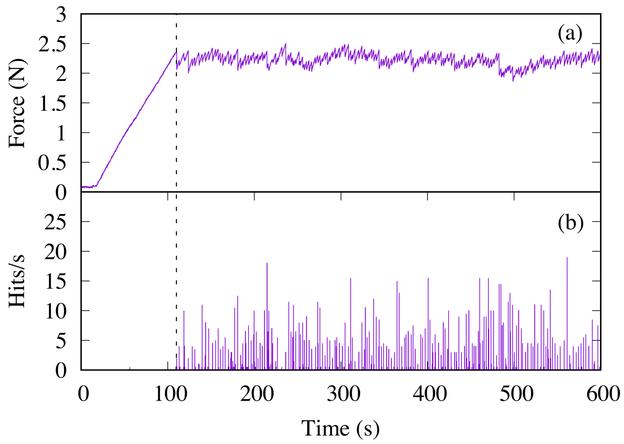

FIG. 4: (a) Force during time progress on the block. (b) AE activity: histogram of hits/s. Each bin has a width of 0.5 s and a total number of hits $N = 10458$. The vertical dash line shows the change from static to kinetic regime.

Fig.5 shows a zoom of Fig.4 in the kinetic frictional regime. On the bottom panel it can be seen that on a small scale the AE hits are generated when the system changes from stick to slip [9][10], coinciding with the movement of the block, as indicated by the dash lines in the graph. On the top panel it can be appreciated that on a small scale the behaviour is similar to the general Amontons-Coloumb model, with static and kinetic regimes.

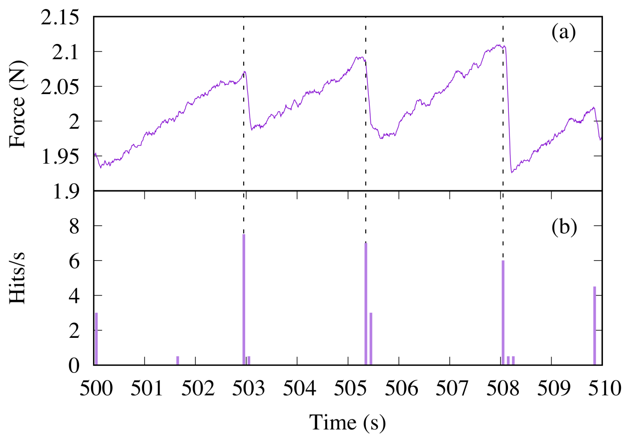

FIG. 5: Close up graphic of Fig.2. (a) Frictional force of the block force during time progress of the friction force. (b) Activity: histogram of hits/s. Each bin has a width of 0.1 s.

B. Statistical analysis

Fig.6 shows a histogram representing the number of hits of each A. The observed decrease in hits for $A < 35$ dB is due to the filtering of the data and is called 'the window effect'. The green and purple lines correspond to the same histogram but with hits separated depending on of their duration; they will be discussed later. Focusing on the orange line, for $A < 60$ dB, the relation between hits and amplitude is linear (note that the histogram is shifted upwards 10 times). Since hits are in a logarithmic scale, and amplitude is related to the maximum voltage also through a logarithm, this means that V_{max} is power-law distributed (Pareto) with the following relation:

$$P(V_{max}) \sim V_{max}^{-\alpha} \tag{5}$$

The dash line in the graph indicates the $\alpha = 1.8$ exponent. A different behaviour appears for $A > 60$ dB, where a maximum can be observed.

Fig.7 shows a histogram representing the number of hits at different energies. Purple and green lines will be discussed later. Hits with $E < 10000$ aJ have a power-law distribution, with the following relation:

$$P(E) \sim E^{-\epsilon}, \tag{6}$$

with the exponent $\epsilon = 1.5$ as indicated with the dashed line in the graph. For $E > 10000$ aJ energies exhibit a clear different behaviour, the histogram shows a maximum.

The occurrence of the different behaviours suggests that two different kind of hits could coexist. We will refer to the power-law distributed hits as Type I, while the hits in the different distribution will be called Type II.

Fig.8 shows the relation between the amplitude and duration of the recorded hits. The color scale indicates

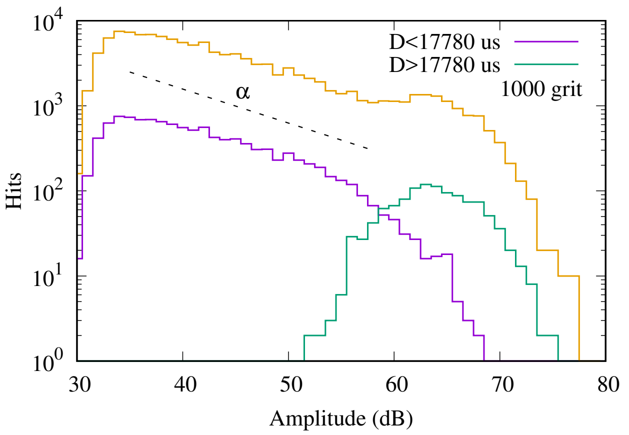

FIG. 6: Histogram of hits vs A. Each bin has a width of 1 dB. In orange, the histogram is shifted up 10 times to avoid overlapping. The total number of hits is $N = 12204$. The dash line shows a power-law behaviour with $\alpha = 1.8$. In green ($N = 1127$) and purple ($N = 11077$), hits are separated by its duration.

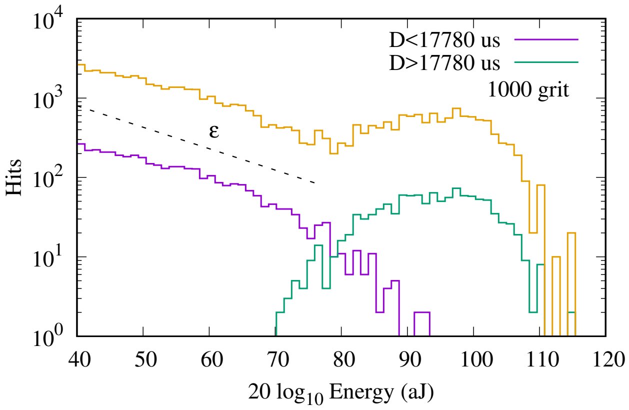

FIG. 7: Histogram of hits vs E. Each bin has a width of 0.058 aJ. In orange, histogram is shifted up 10 times. The total number of hits is $N = 12204$. The dash line shows a power-law behaviour with $\epsilon = 1.5$. In green ($N = 1127$) and purple ($N = 11077$), hits are separated by its duration.

the height of a 2D histogram. The top panel shows results for the paper of small roughness (1000 grit), and the bottom panel shows the results for the paper of larger roughness (800 grit). It can be seen that in these maps Type I and Type II signals are easier to separate, specially in the top panel for the 1000 grit paper. Moreover, one observes that the peak corresponding to the Type II signal shift to larger amplitudes and duration when the sand paper is smoother. We have approximately located the peak corresponding to the Type II signals at $D = 22,4$ ms, $A = 57$ dB for the 800 grit paper, and at $D = 50,1$ ms, $A = 65$ dB for the 1000 grit paper.

Similarly Fig.9 shows the relation between the energy and the duration of the recorded hits. The Type II signal also shifts to larger energies when the sand paper is smoother. The peak corresponding to Type II signals is approximately located at $E = 3981$ aJ in the 800 grit paper and at $E = 50118$ aJ in the 1000 paper. On the

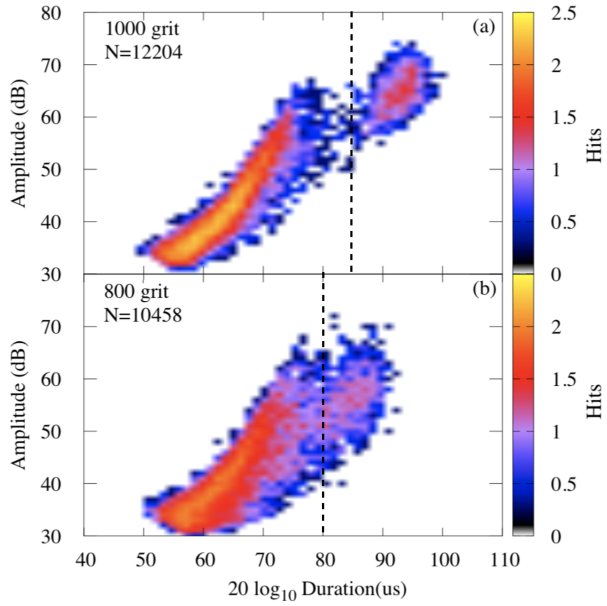

FIG. 8: Amplitude in function of the duration for abrasive papers of different roughness. The color shows the number of hits in logarithmic scale. Dash line shows separation between signals Type I and signals Type II. (a) 1000 grit paper. (b) 800 grit paper.

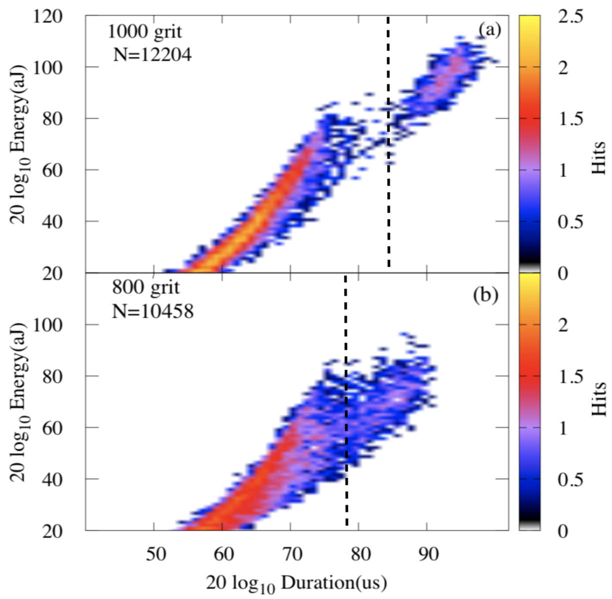

FIG. 9: Energy in function of the duration for abrasive papers of different roughness. The color shows the number of hits in logarithmic scale. Dash line shows separation between signals Type I and signals type II. (a) 1000 grit paper. (b) 800 grit paper.

top panel we can see that the two types of signals can be separated using a threshold of $D = 17780\ \mu$s indicated with the dashed line for the 1000 grit paper. With this separation the histograms in Fig.6 and Fig.7 can be split into two separated distributions of amplitude and energy for Type I and Type II hits.

The separation confirms that Type I signals are power-law distributed thus they have no characteristic energy or amplitude scale. On the contrary, Type II signals are described by a different distribution with a clear peak. Note that since vertical and horizontal scales are logarithmic this peaks can be well described by a Gaussian distribution.

The results observed so far allows us to propose the following hypothesis: AE hits during dry friction are basically power-law distributed, as corresponding to a self-organized critical phenomenon (absence of characteristic scales)[8]. Nevertheless a certain amount of hits (typically less than 10%) become outliers (Type II signals). This kind of scenario is often observed when dealing with critical phenomena in natural science [11].

It seems like Type II distribution is an outlier of the power-law and may be defined by the Dragon King (DK) theory [12]. The name of the theory is a metaphor. The term 'dragon' refers to the mythological animal with mystical powers above the rest of the animal kingdom. The term 'king' refers to the fact that usually kings are richer than most of the richest inhabitants of the country, so while the wealth of the population (excluding the king and his family) describes a power-law distribution (Pareto), the king and his family are an outlier with a wealth larger than the predicted with a Pareto power-law extrapolation. The 'king' regime may be the result of specific historical events that have accumulated richness to the kingdom. The main idea of the DK theory is that in power-law distributions the outlier is due to the fact that extreme events follow different physical mechanics than normal events. DK theory has been used to study financial drawdowns, earthquakes, etc. [12].

IV. CONCLUSIONS

We have built an experimental setup for the acquisition of AE signals during sliding friction of an aluminium block on sand paper. From the registered signal we have defined and separated AE hits by using an appropriate threshold.

We have shown that AE signals generate when the block changes from stick to slip. This occurs successively during the kinetic regime.

Two different kinds of AE signals are observed. Type I signals are power-law distributed, which is followed for most of the hits (90%). Type II signals (10%) are Gaussian distributed and are only visible with large amounts of data. These observations can be understood as a self-organized critical phenomenon [8] with power-law distribution of system response coexisting with outliers according to the DK theory.

The Gaussian distribution describing Type II signals shift to larger values when the roughness of the abrasive paper decreases.

A complete understanding of AE during sliding friction will require further analysis, in particular studying the influence of the velocity, the load on the block, the different materials, the possibles influence of aging [13] or uncycling, etc.

Acknowledgments

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