Observations of a new dissipation regime in metals.

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We have observed a low frequency transition, in metal flexures, from viscous-like dissipation, dominated by individual dislocations at high frequency, to a less predictable dissipation mode at low frequency, dominated by collective dislocation effects, governed by Self Organized Criticality statistics. The threshold frequency is determined by the material characteristics, but likely also by the dimension of the flexures. In the newly observed mode sudden instabilities are observed, including spontaneous change of the filter equilibrium point, collapse in mechanical oscillators, hysteresis and anomalous 1/f transfer functions. The evidence is that a non-negligible fraction of a metal's Young's modulus is contributed by entangled dislocations. Dislocation disentanglement leads to avalanches, during which the material Young's modulus is reduced and the viscous-like dissipation is enhanced. The observed results will influence the design of the seismic isolation chains of third generation Gravitational Wave Detectors, and likely affect the operation of the second generation ones, presently under construction.

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The measurements presented here were performed using a Geometric Anti Spring (GAS) filter, illustrated in Fig. 1 [1, 2]. The Maraging[1] blades of the filter are the same used in Seismic Attenuation Systems like TAMA [3], a LIGO HAM chamber [4], as well as other sites around the world [5]. The GAS and the Electro Magnetic Anti Spring [6] mechanisms were used to reduce the filter resonant frequency and to expose the underlying Self Organized Criticality (SOC) controlled dissipation.

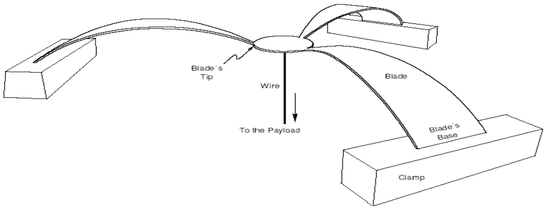

Fig. 1: Schematics of a GAS filter; applying a radial compression to the blade's clamps the resonant frequency can be lowered.

Line dislocations are pervasive in metal grains, they can move more or less freely across the crystal under stress gradients and, responding sluggishly to varying stress fields, are responsible for viscous-like dissipation in metals. Being energetically expensive crystal defects, line dislocations mostly repel at short range and entangle easily, so much that in heavily work-hardened metals they permanently entangle with a noticeable stiffening of the material and reduction of the dissipation factor. Theory of SOC [7] of dislocations [8] predicts that in normal metals entanglement is only a metastable situation, and slowly varying stresses can result in temporary disentanglement and re-entanglement of dislocations in different configuration, with a consequent change of the equilibrium point, or even run-off.

Effects connected to SOC should appear for changes of conditions slower than the characteristic dislocation's avalanche growing time, which is function of the material characteristics, but also on the size of the flexure undergoing stress changes.

A series of equilibrium point variations, each with amplitude obeying to the 1/f SOC statistics [9] (like those caused by a thermal drift, or by the forced oscillations used to probe the

[1] Marval-18, X2NiCoMo18-8-5, produced by Aubert Duval, Gennevilliers, FR, hardened for 100 hours at 435ºC.

filter's performance) can be expected to produce 1/f filter transfer function.

Stress fields oscillating faster then the characteristic avalanche growing times can be expected to quench the avalanche growth, thus strongly depressing this kind of dissipation, and mask the effects of SOC statistics, but were still observed to affect the material Young's modulus and its viscous-like dissipation.

We experimentally observed all these effects in our GAS filter with a transition frequency of 200 mHz (1.25 $^{s-1}$ pulsation).

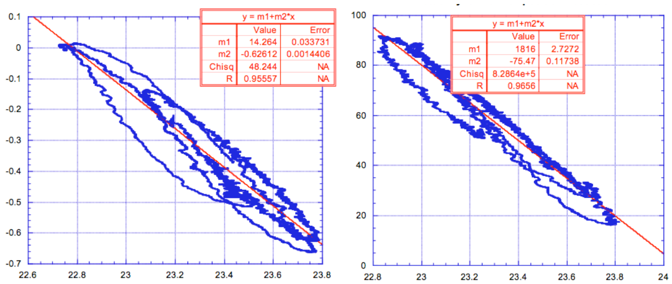

Fig. 2 Thermal hysteresis of the equilibrium point in free running, and of the correction force when the equilibrium point if fixed by a slow integrating feedback. Horizontal scale [ºC], Left panel vertical scale [mm], Right panel vertical scale [mN].

Static hysteresis [10, 11] is probably the first manifestation of dislocation entanglement. The observation that the filter's hysteresis is not eliminated by position feedback (Fig. 2) shows that hysteresis does not derive from physical motion, but is generated from the varying internal stresses in the material, which in this case are thermally driven.

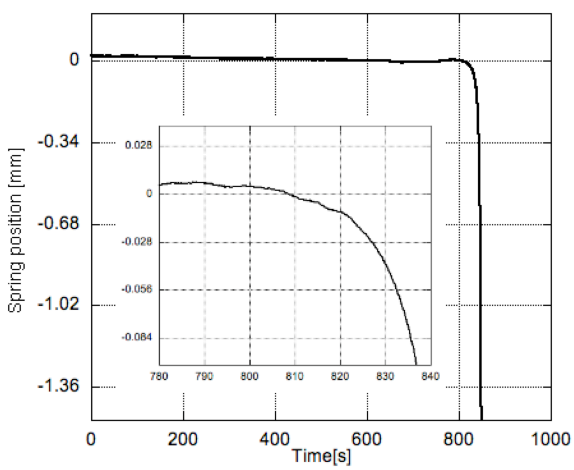

Fig. 3 Run-off of the filter tuned at fixed resonant frequency. The zoomed insert illustrates the slow and irregular start of the event due to individual avalanches, followed by a progressive acceleration as many avalanches spread around the flexure in a sort of domino effect.

The filter, tuned by the GAS and/or EMAS mechanism to an effective restoring force of 2-3% of the original one, kept to its equilibrium position by a slow integrative feedback, and exposed to prolonged thermal drift, is observed to sudden run-off (Fig 3); this anomalous collapse had already been observed in Inverted Pendulums (IP) [12]. This collapse observation shows that at least 2-3% of the material's Young's modulus is contributed by entangled dislocations in a metastable situation.

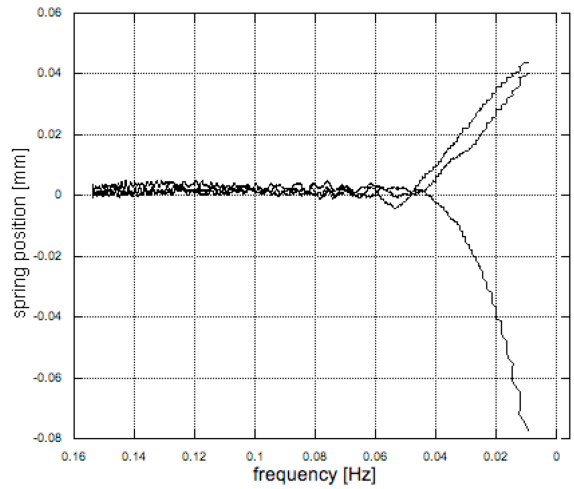

Fig. 4 The EMAS gain is run up to progressively weaken the spring. The 65 kg payload falls, indifferently up or down, well before the oscillator's mathematical instability (frequency equal to zero).

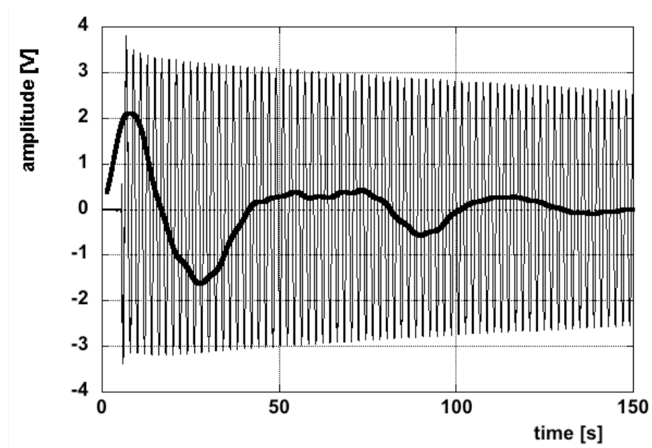

Fig. 5 Oscillation of an IP at different frequency tunes.

At high frequency the quality factor is very high and the motion is predictable. Below a certain frequency threshold the damping grows rapidly and the movement predictability is severely reduced, reflecting the action of dislocation avalanches.

The fact that run-off happens indifferently up or down (Fig 4) and that the system is easily restorable by simply forcing it to the previous equilibrium position eliminate any hypothesis of creep or material failure driven events.

The onset of dislocation avalanches happens at different frequencies depending on the flexure's geometry. The transition is observed at about 200 mHz for the GAS filters of this experiment and below 50 mHz for inverted pendulums (Fig. 5) [10].

Above the transition the Quality factor was observed to grow very rapidly with frequency, while below the transition it changes according to the expected quadratic behavior of purely hysteretic losses. We observed the same deviation from a quadratic function for different mechanical tunes: it assures that the effect is material and not tune dependent. The frequency of the transition measures the time necessary for dislocation avalanches to spread across the entire flexure. Above the transition frequency the exponential growth of avalanches are interrupted by the reversing of the stress field and the dissipation rapidly turns to be viscous-like and predictable.

Below the transition the SOC statistics limits the predictability of the motion (fig.5).

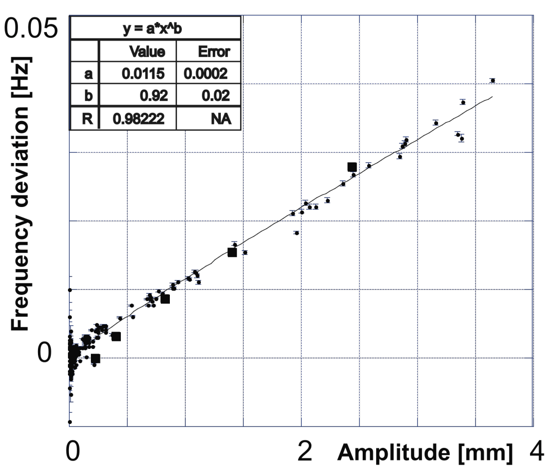

Fig. 6 Frequency deficit versus oscillation amplitude; the dots evaluated in ringdown measurements, the squares with swept sine.

It was also observed that forced oscillations, either ringdown, or swept sine excitations, cause a reduction of the Young's modulus roughly proportional to the square of the amplitude. In Fig. 6 a Frequency deficit (reduction of resonant frequency with respect to the expected increase) of 19% is observed for oscillation amplitude of 4 mm corresponding to a 34% reduction in elastic constant. At the same time (Fig. 7) the disentangled dislocations become available for an excess of viscous-like dissipation, which more than doubles for amplitude oscillations of 4 mm. Both measurements were taken at 0.21 Hz, without EMAS.

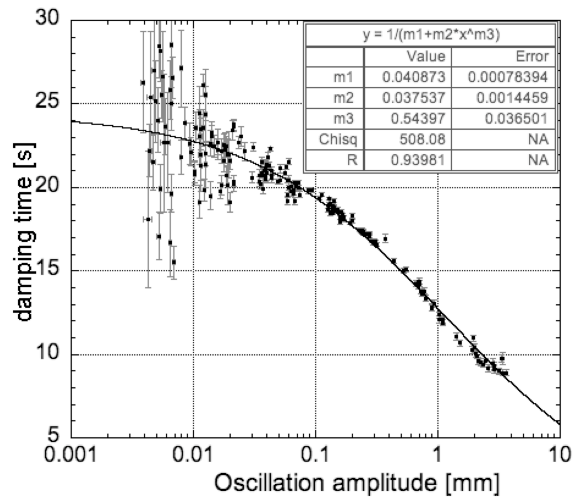

Fig. 7 Change of damping constant versus oscillation amplitude.

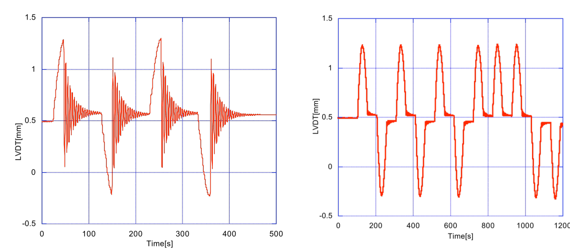

Fig. 8 Hysteresis study for different types of excitation for filter's tune of 0.21 Hz.

At 0.21 Hz tune there is sufficient restoring force from the crystal to generate oscillations. If the excitation force is suddenly cut and the filter is allowed to oscillate, no hysteresis is observed (Fig 8-left). If the excitation force is slowly reduced to zero, some hysteresis is observed (Fig 8-right).

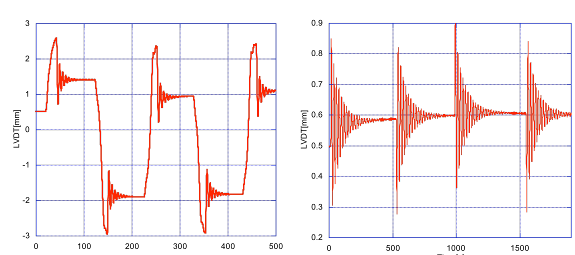

Fig. 9 Hysteresis study for filter's tune of 0.15 Hz.

With filter tuned to 0.15 Hz (half the elastic constant) the restoring forces are dominated by the fraction of elasticity contributed by entangled dislocations, which are only metastable. The excitation causes the entanglement to shift the equilibrium point to a different location, much less oscillation is observed, and substantial hysteresis ensues (Fig. 9-left). If a damped sine excitation force is used, forcing the system through the same trajectory of Fig. 8-left, no hysteresis is observed (Fig. 9-right).

We think that we have observed a transition from viscous-like to SOC-controlled dissipation in Maraging steel flexures. Similar hysteresis behavior has been observed in piano wire [13] and other flexures, which indicates that SOC generated, low frequency 1/f noise, may be a common occurrence in metals, at least when dislocations can move sufficiently to generate metastable entanglement. SOC statistics may explain the anomalous 1/f transfer function behavior observed by Stochino [14]. The slow excitations used to measure the transfer function may be generating avalanches, whose noise would then extend to higher frequency with a 1/f power law, as prescribed in an avalanche dominated regime.

This kind of noise may disappear in absence of slowly changing excitations (mechanical, thermal or other).

Although not all aspects of SOC of dislocations are yet clear, and it is not understood to which extent the noise contributions from dislocation avalanches can extend to the frequency range of the present GW detectors, the observed phenomena will likely affect their operation modes, and certainly affect the engineering, and choice of materials for the seismic attenuators for the third generation, lower frequency GW interferometers.

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