Seismic attenuation, problems for Low Frequency underground Gravitational Wave Observatories

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Seismic attenuation LF problem

- Inconsistencies observed in Inverted Pendula and Geometric Anti Spring filters
- Hysteresis, Random walk of equilibrium point, even Instability.
- Manifested only at lower frequency

- Not compatible with the commonly accepted viscous or loss angle description of dissipation

What happens at low frequency

- Dislocations start acting collectively
- Dissipation observed to switch
- from "viscous"
- to "fractal" Self Organized Criticality (avalanches)

- Unexpected NEW physics

- Excess LF noise
- Reduced attenuation power
- Is F-D theorem in trouble ?

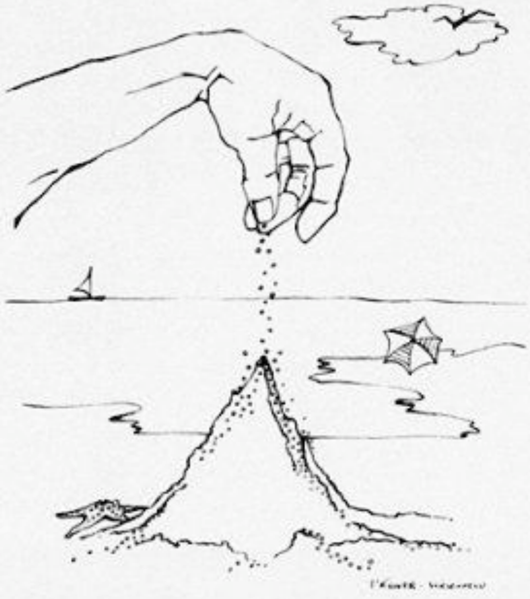
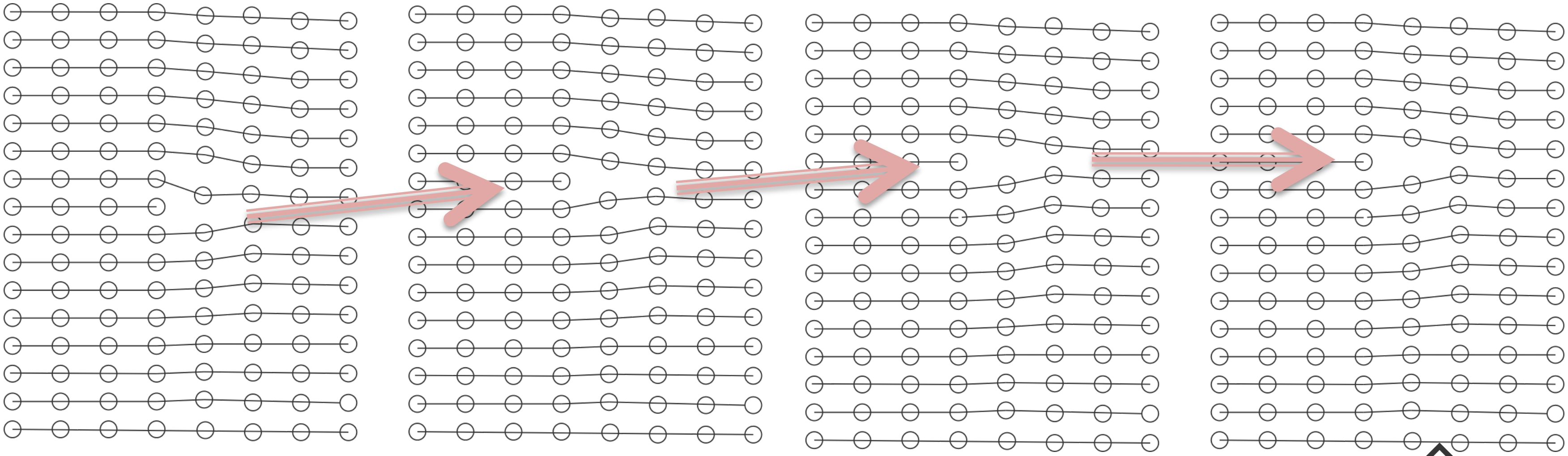
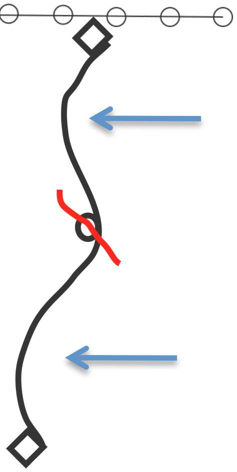


Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

Dislocation movements

- Zipping happens plane by plane
- An atom switches bond in a plane
- The corresponding atom in the next plane responds with a delay





- Dislocations form loose strings pushed and

  tensioned by stress gradients
- The strings glides zipping after zipping
- Their motion is locally impeded (pinning)
- by defects or by other dislocations

Self Organized Criticality

(SOC)

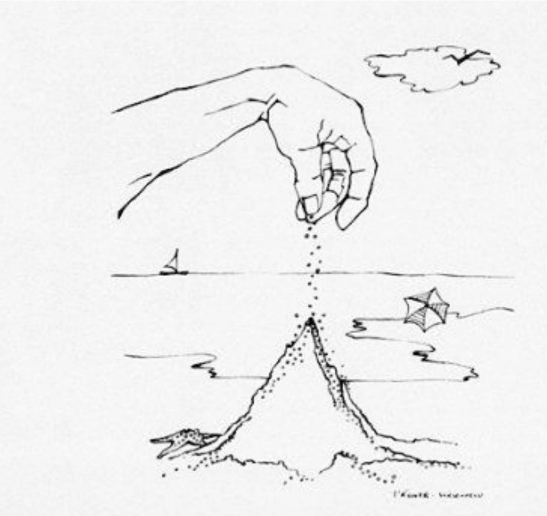


Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

- The dislocation form a network that can shift and rearrange in a self-organized pattern, scale-free in space and time

- Entangled dislocation contribute to elasticity (work hardening)

=> Disentangling dislocations subtract elasticity from the lattice

- Disentangled dislocations generate viscous-like dissipation

- Dislocations carry stress (plasticity)

=> Eventual re-entanglement of different patterns of dislocations generates static hysteresis

Per Bak 1996
How nature works: The Science of Self-Organized Criticality

Self Organized Criticality

(SOC)

- Movement of entangling dislocations is intrinsically

Fractal

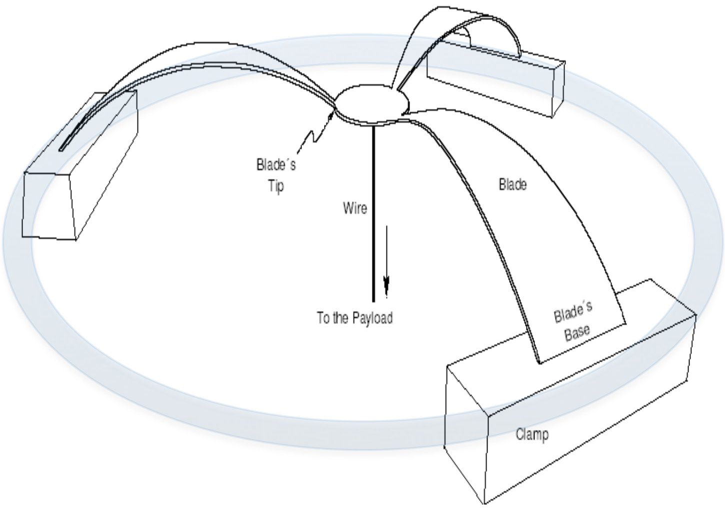
- => Does not follow our beloved linear rules ! !
- => Avalanches and random motion

Per Bak 1996
How nature works:
The Science of Self-Organized Criticality

The observational tool

The GAS mechanism

(Geometric Anti Spring)



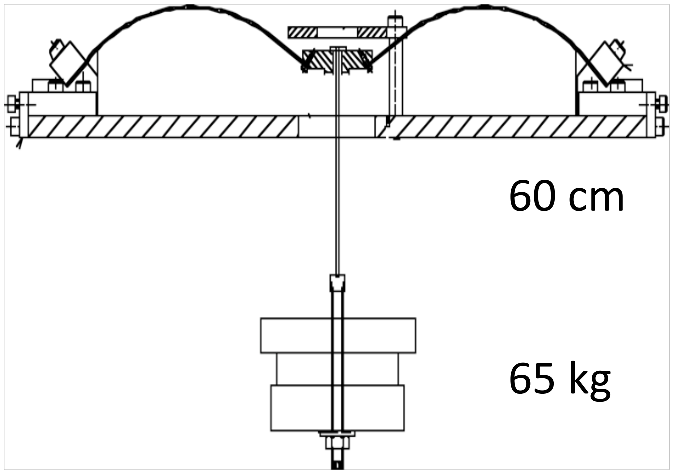
Radially-arranged Maraging blades clamped to a frame ring.

Radial compression produce the Anti-Spring effect

(Vertical motion produces a vertical component of the compression force proportional to the displacement)

The GAS mechanism nulls up to 95% of the spring restoring force
EMAS mechanism do the last 5%
(Electro Magnetic Anti Springs)

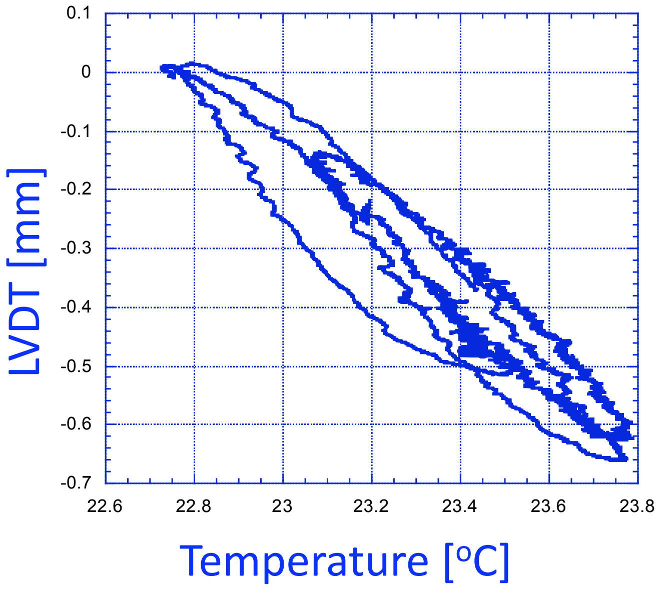
Our "microscope" to observe
Low frequency effects



The evidence

Hysteresis without actual movement

- Overnight lab thermal variations
- No feedback, free movement
- Thermal hysteresis of equilibrium point



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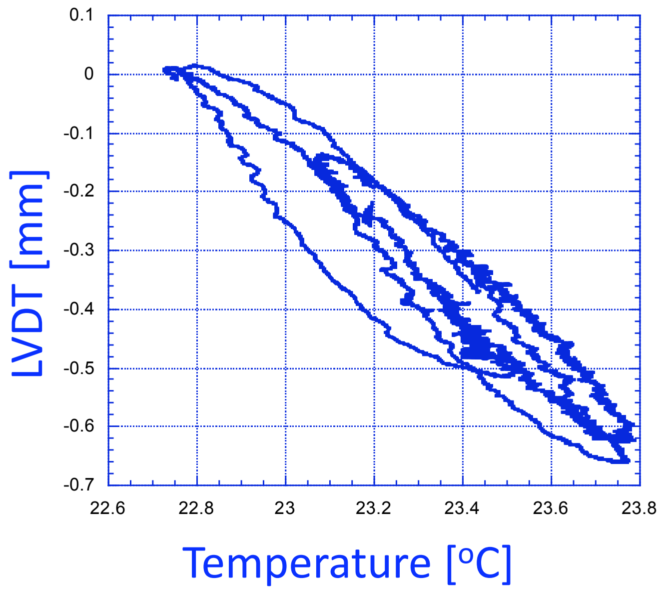
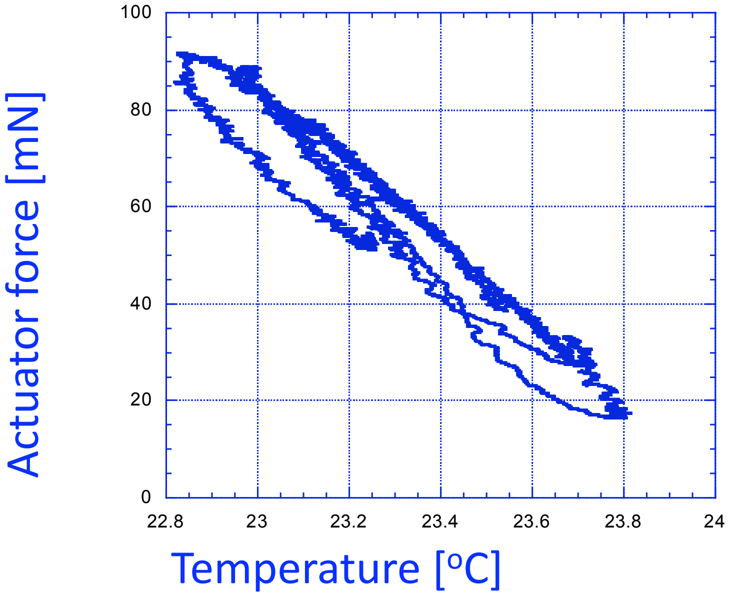


- Position feedback on
- No actual movement, expect no hysteresis
- Hysteresis shifts to the control current ! !



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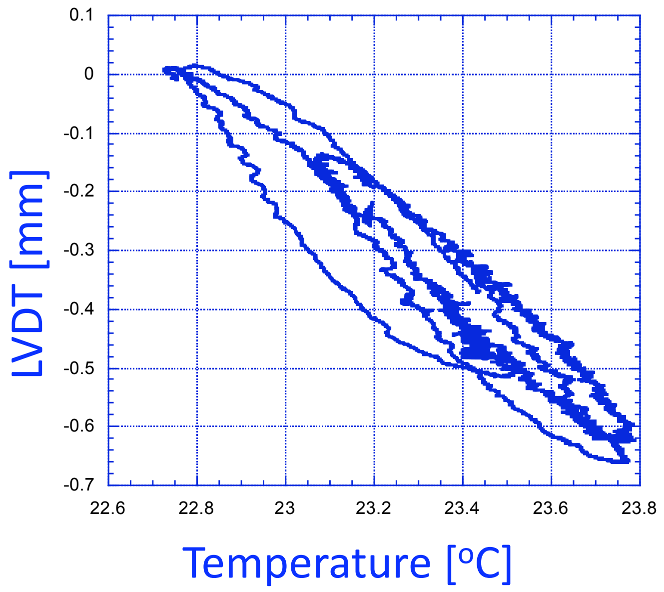

- Position feedback on
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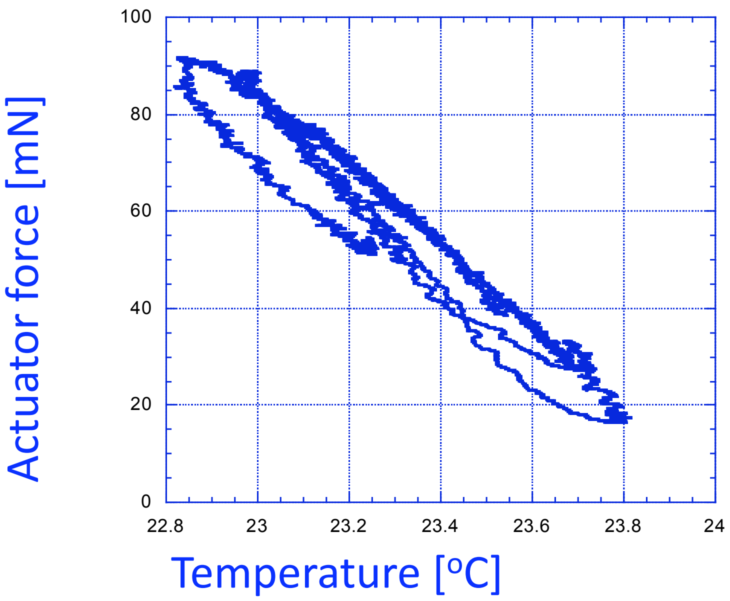
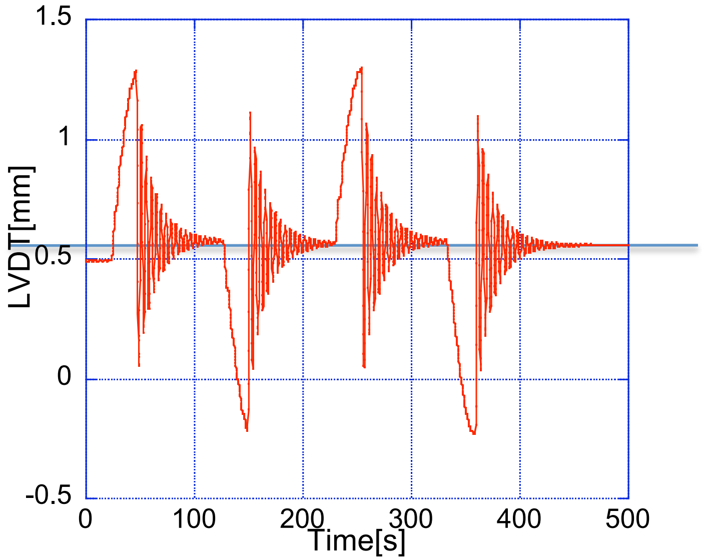


Hysteresis does not originate from the macroscopic movement **but from a microscopic stress dynamics** inside the material!

To explore the effects of hysteresis at various frequencies

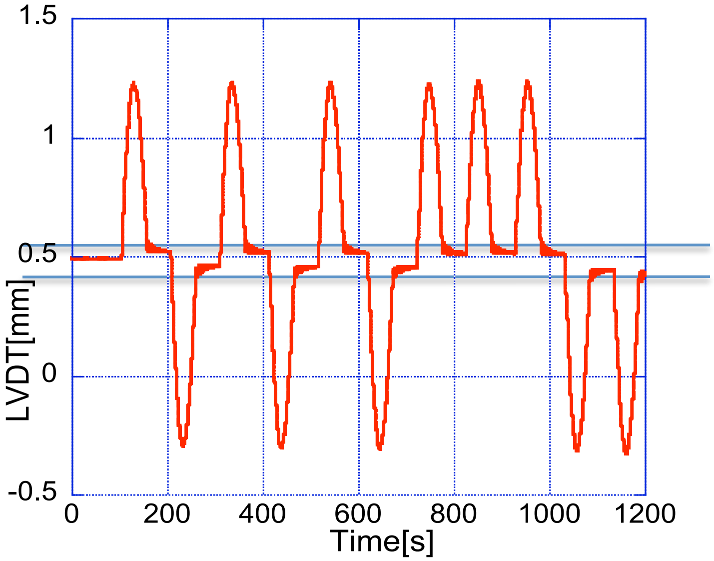
frequency 0.21 Hz (>0.2Hz)



We apply a force lifting the spring to a certain height, then cut the force and let the system oscillate freely:

NO HYSTERESIS OBSERVED

OSCILLATIONS APPEAR TO WASH-OUT HYSTERESIS



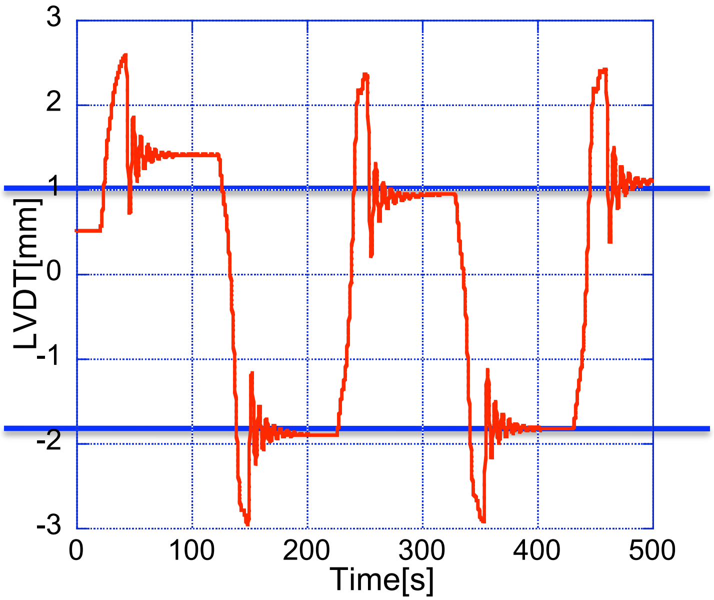
Subjecting the system to the same force, but slowly returning the lifting force to zero, thus generating no oscillations:

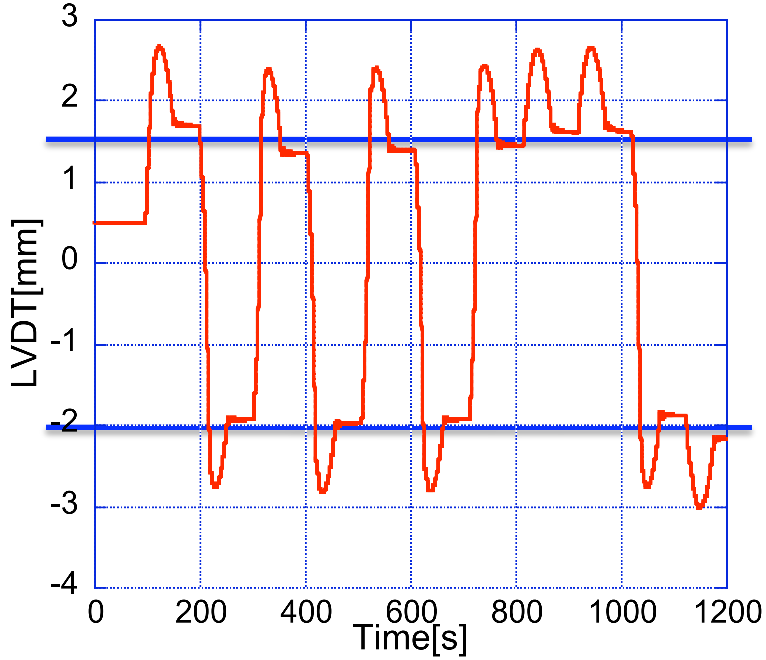
HYSTERESIS OBSERVED FOR ALTERNATE SIGN EXCITATION

NO HYSTERESIS FOR SAME SIGN EXCITATION

Hysteresis grows much larger at lower frequency

frequency 0.15 Hz (<0.2Hz)





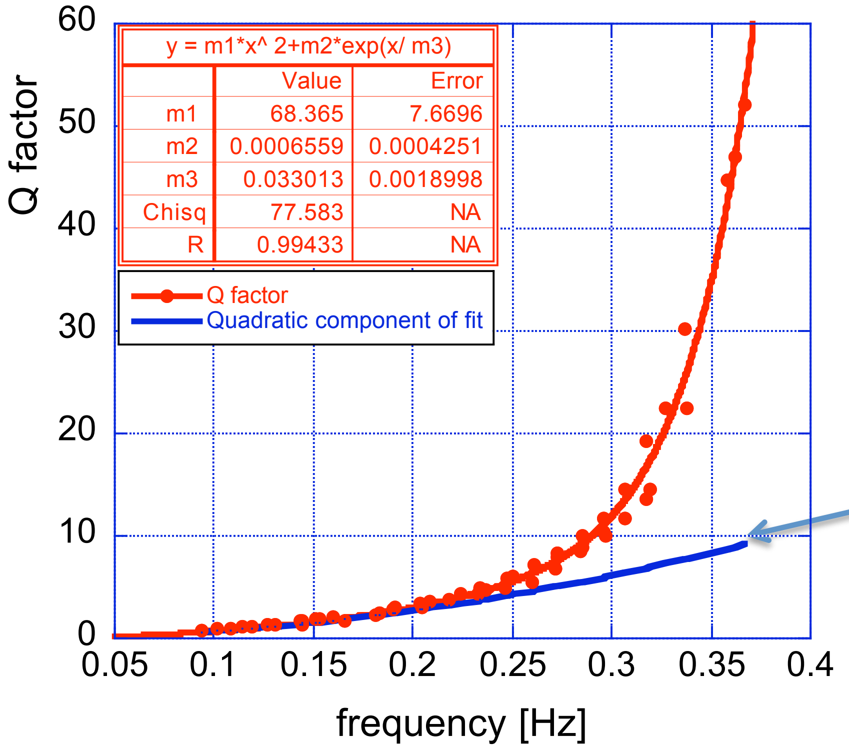
OSCILLATIONS APPEAR to be ineffective TO WASH-OUT HYSTERESIS at low frequency: not enough oscillations to delete hysteresis

Proposed explanation:

below 0.2 Hz the restoring force is dominated by entangled dislocations. Under pulsed stresses dislocations mobilize and eventually re-entangle elsewhere generating a different equilibrium position.

Explaining the observed hysteresis.

Quality factor measurement



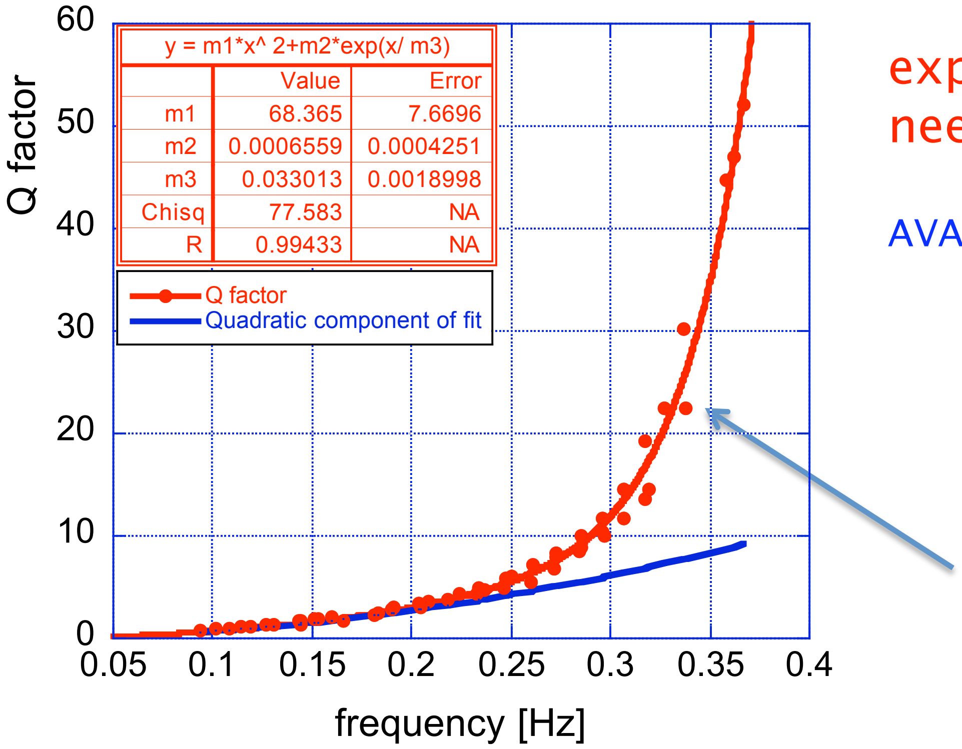
	Value	Error
m1	68.365	7.6696
m2	0.0006559	0.0004251
m3	0.033013	0.0018998
Chisq	77.583	NA
R	0.99433	NA

- METHOD
- Change the frequency with the EMAS mechanism
- Acquire ringdowns
- Measure Q = $\omega\tau$

the expected behavior is quadratic
if the losses are frequency independent

Quality factor measurement

The fast increase of Q-factor implies reduced losses at higher frequencies



y = m1*x^ 2+m2*exp(x/ m3)

	Value	Error
m1	68.365	7.6696
m2	0.0006559	0.0004251
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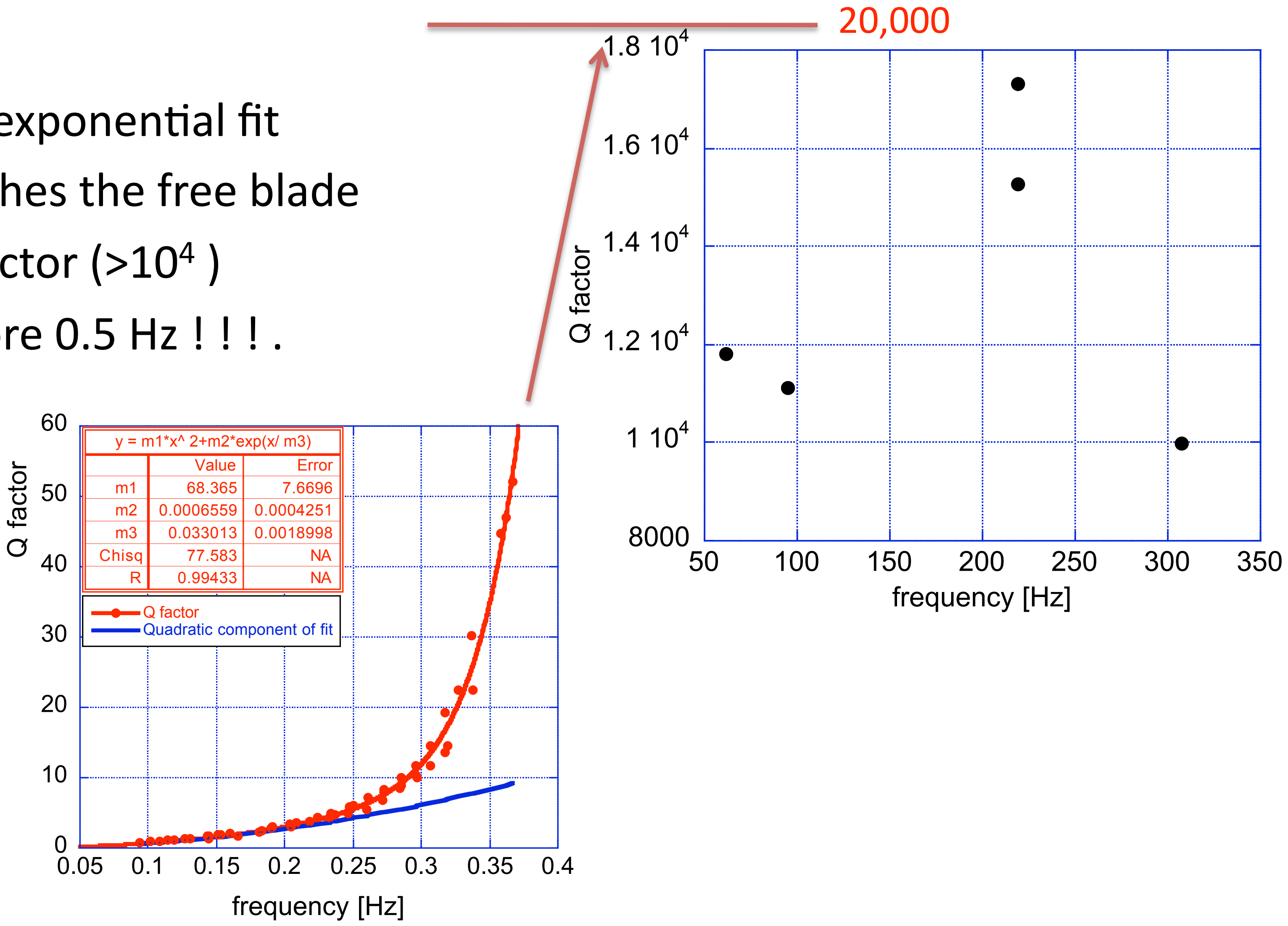
explainable if the dissipation process needs long time to develop:

AVALANCHES NEED LONG TIME TO DEVELOP

The deviation from quadratic was fit with an exponential function accounting for the exponential growth of avalanches with time

Transition between fractal and viscous

- the exponential fit reaches the free blade Q-factor (>10^4) before 0.5 Hz ! ! ! .



20,000

y = m1*x^ 2+m2*exp(x/ m3)

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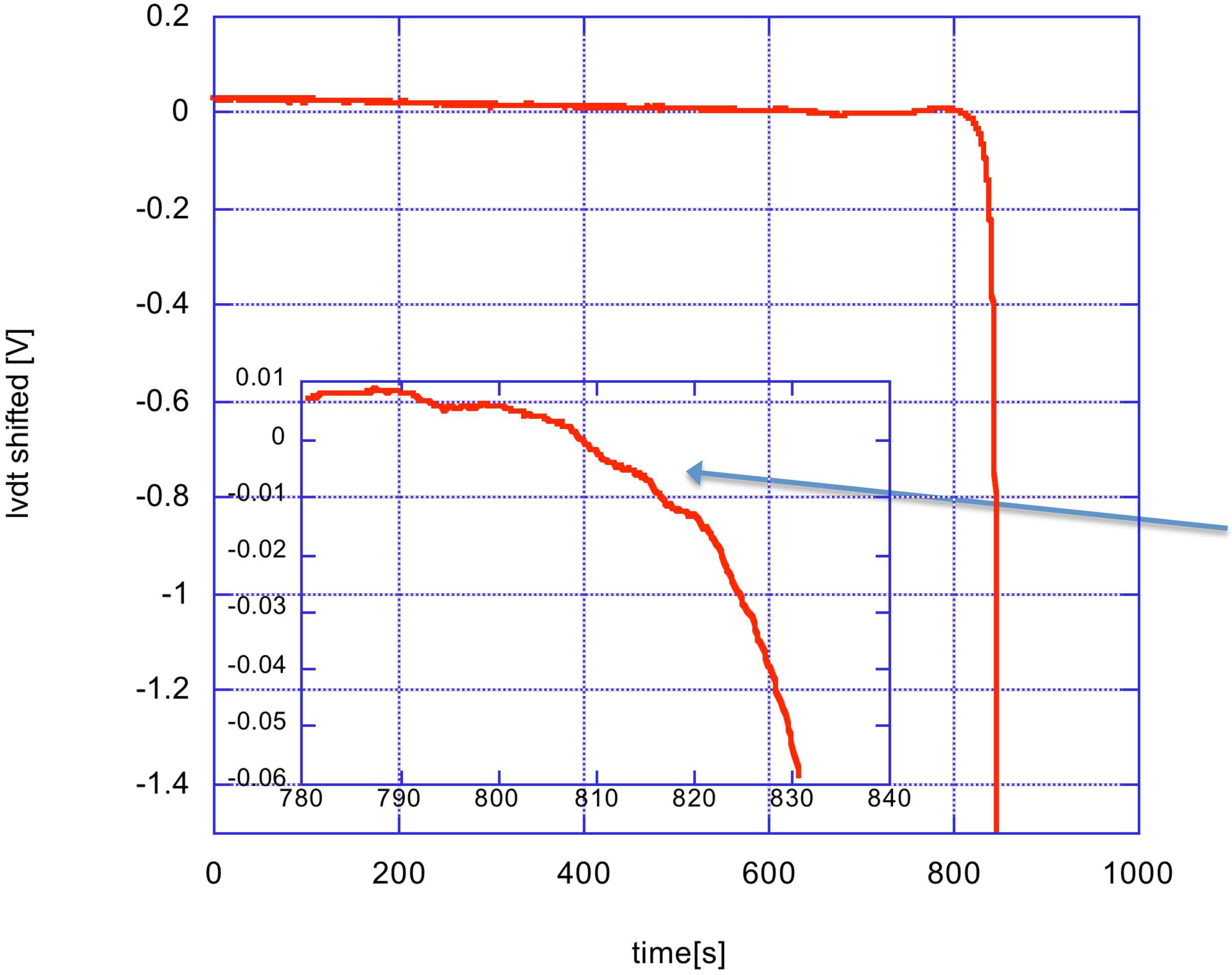
Low frequency instability

Some suddenly-activated mechanism occurs inside the blade



The filter abandons the equilibrium position slowly, then accelerates away

The time scale is of many seconds

The acceleration is "bumpy" due to individual avalanches

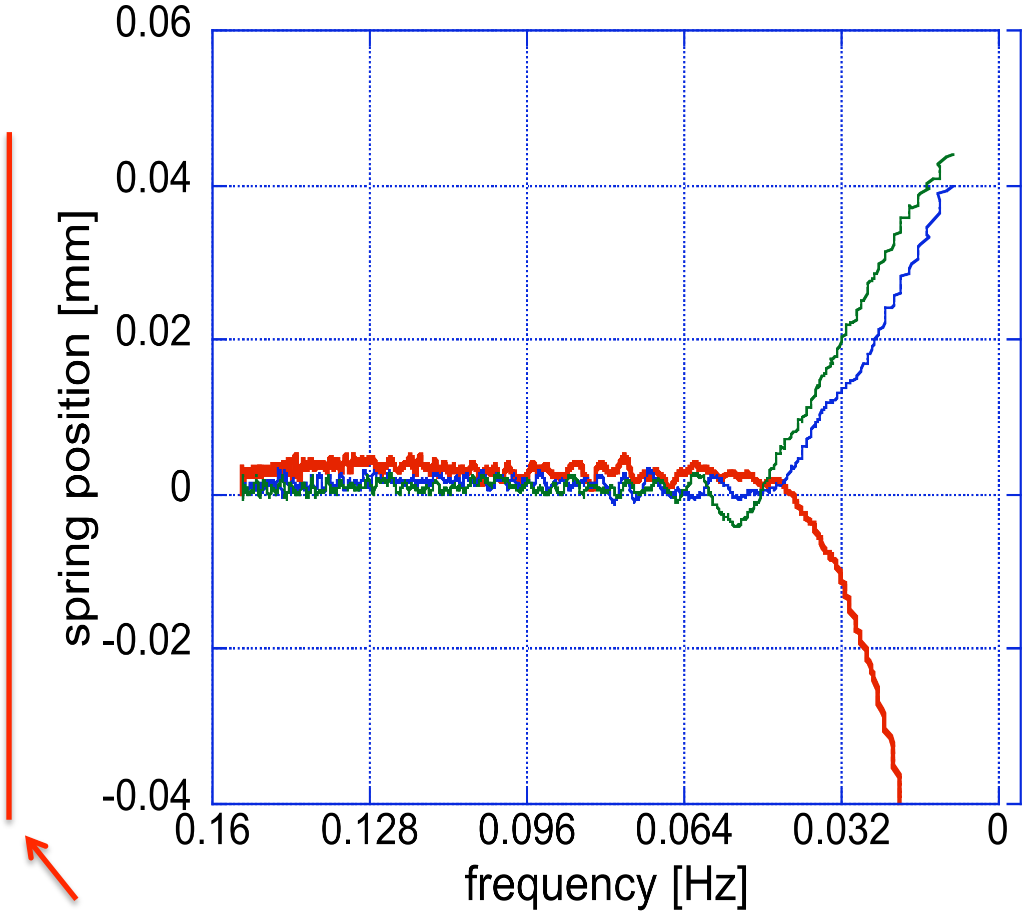
Avalanches propagate across the entire 38 cm blades

Low frequency instability

65 kg payload
can fall
indifferently up
or down

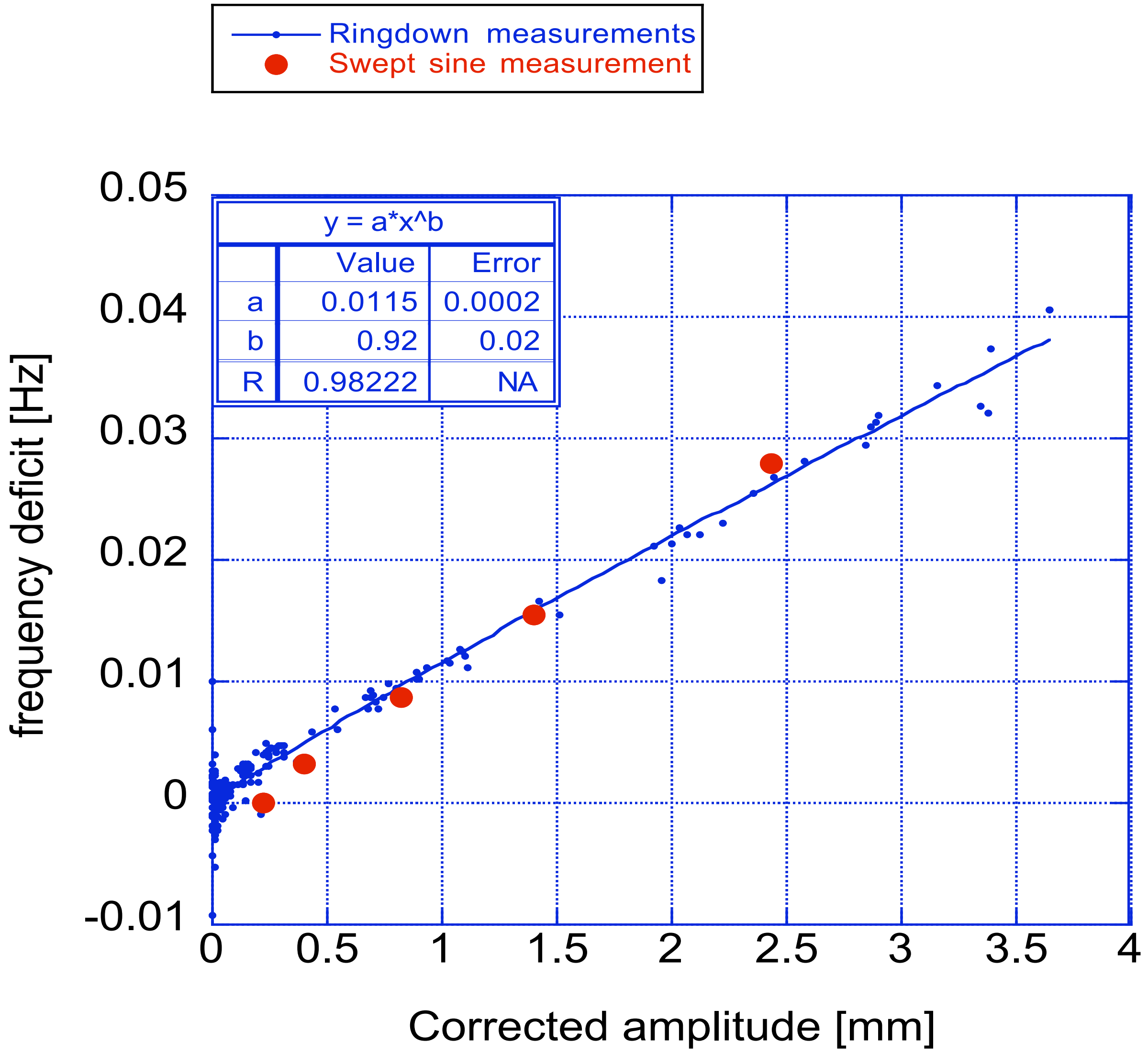
NO CREEP,

NO GRAVITY
DRIVEN EFFECT



instability region µm
starting from ~ 0.2 Hz

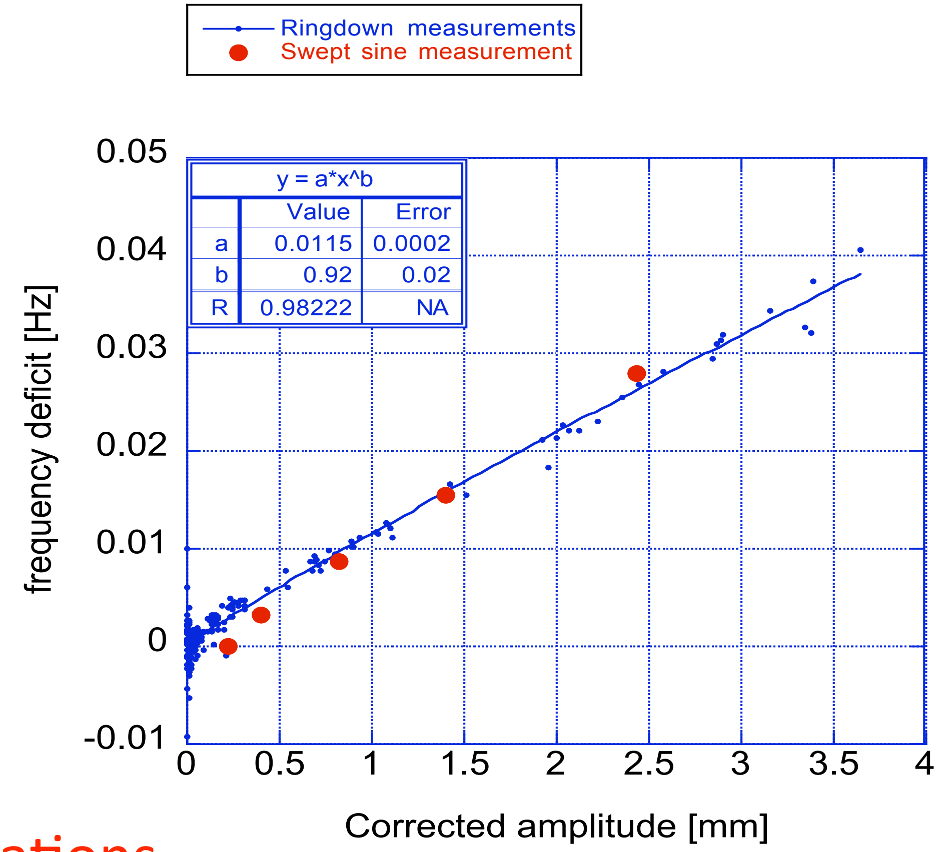
• *Frequency deficit vs. oscillation amplitude*



y = a*x^b

	Value	Error
a	0.0115	0.0002
b	0.92	0.02
R	0.98222	NA

Interpretation



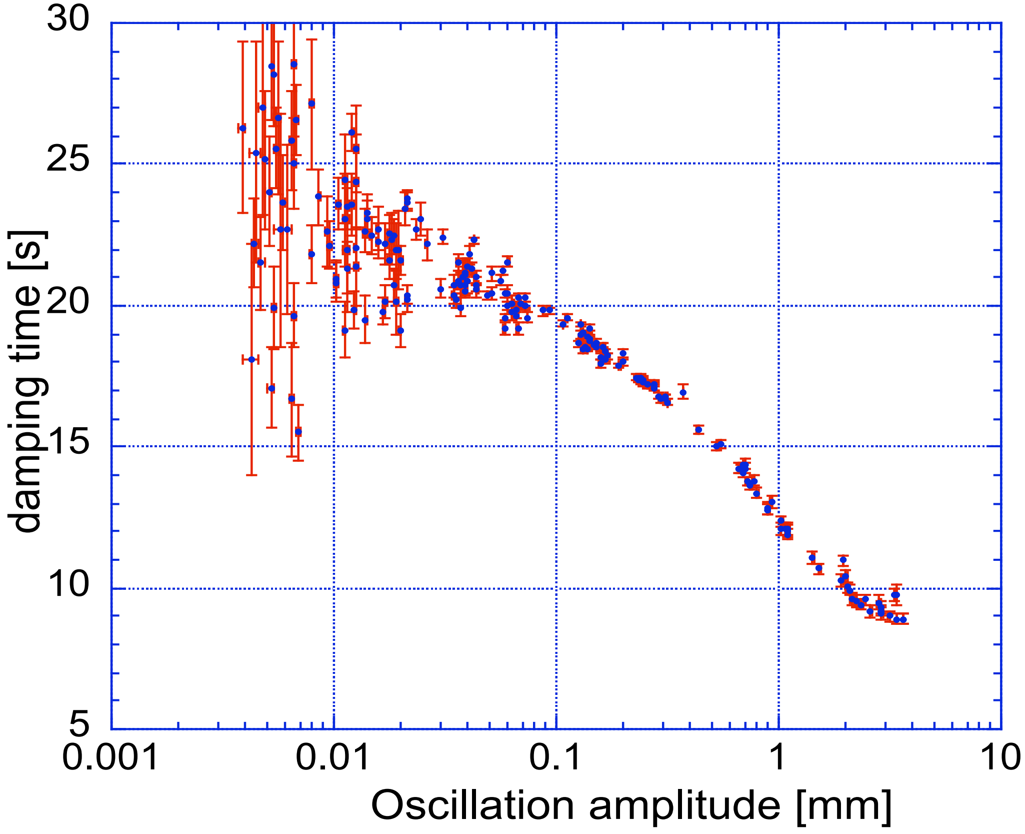
Motion disentangles some dislocations

Number proportional to amplitude

Restoring force contributed by entangled dislocations diminishes

Excess Dissipation at larger oscillation amplitude

- Analyzing ring-downs.
- damping time τ growing for smaller oscillation amplitude
- Proposed explanation: larger oscillations can disentangle more dislocations, which then move freely and cause increased dissipation and shorter damping times.



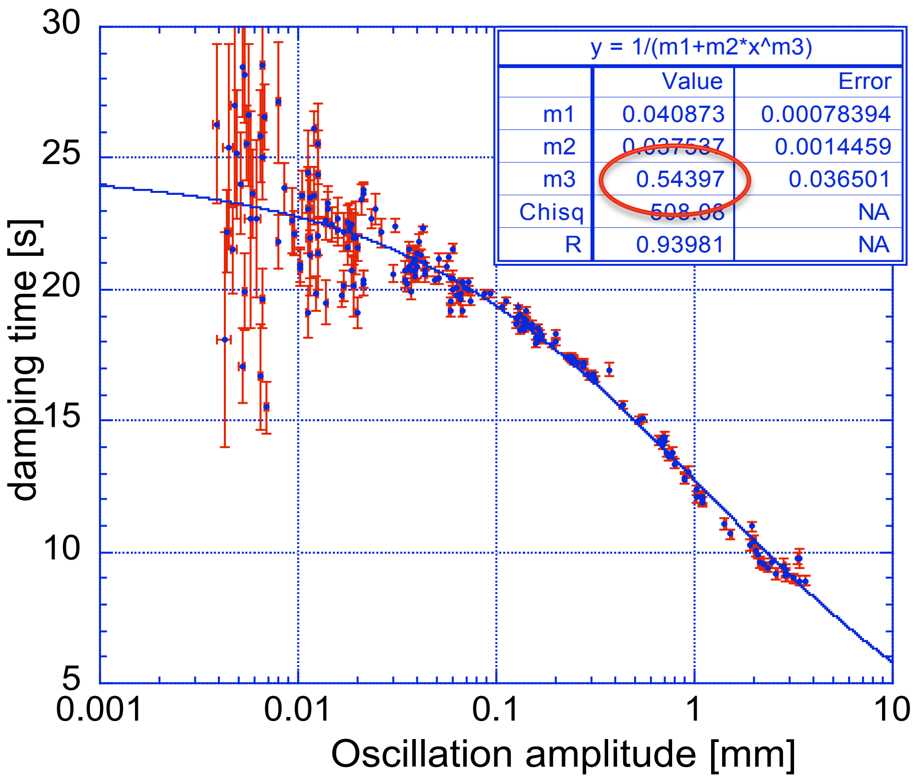
- Fitting the data with

$$\boxed{\tau = \frac{1}{d_0 + \delta A^y}}$$

we found an amplitude exponent of ~ 0.5

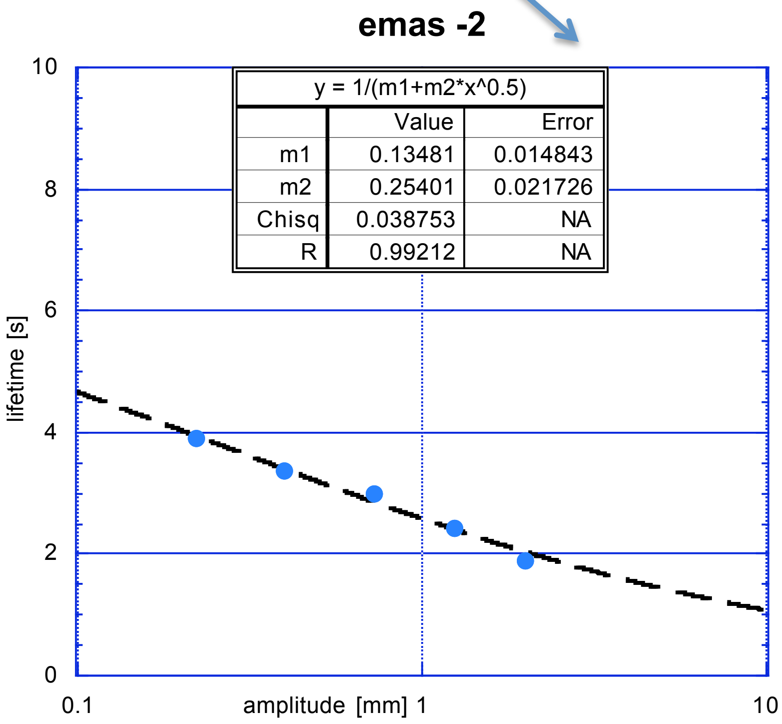
Power law, => fractality

- Same behavior in the frequency domain



y = 1/(m1+m2*x^m3)

	Value	Error
m1	0.040873	0.00078394
m2	0.037537	0.0014459
m3	0.54397	0.036501
Chisq	508.08	NA
R	0.93981	NA



y = 1/(m1+m2*x^0.5)

	Value	Error
m1	0.13481	0.014843
m2	0.25401	0.021726
Chisq	0.038753	NA
R	0.99212	NA

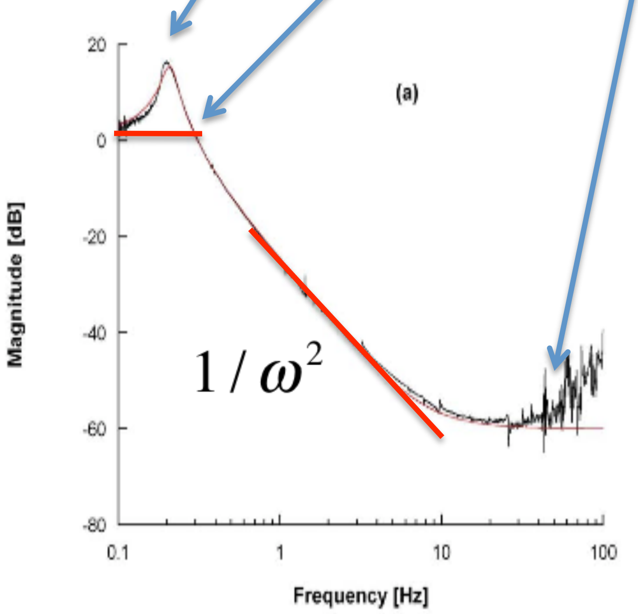
explanation

- Dislocations disentangled by motion

  lead to increased dissipation

Transfer function of a GAS-filter

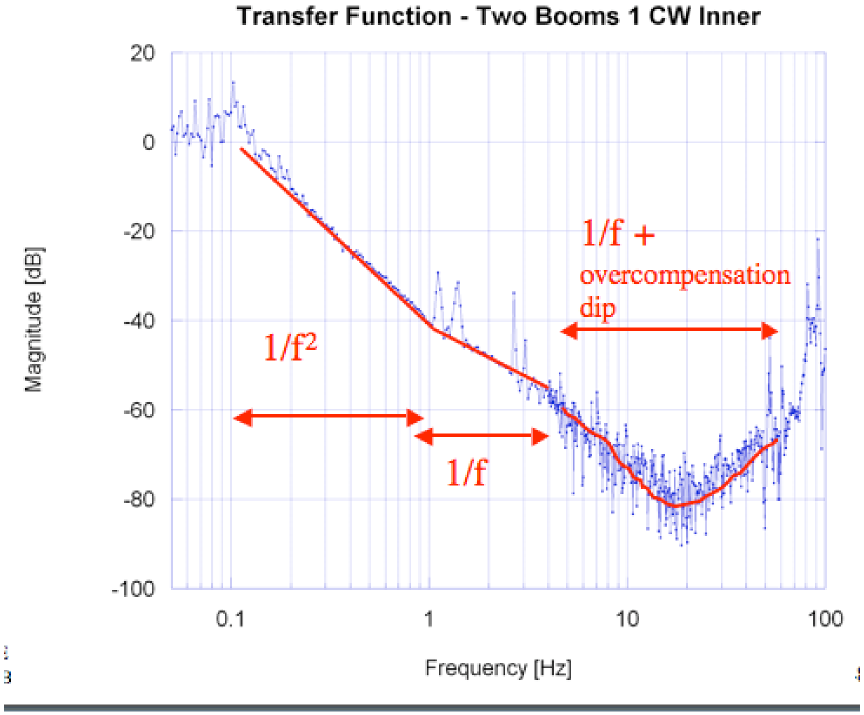
$$H_z(\omega) = \frac{\omega_o^2(1+i\phi)+\beta\omega^2}{\omega_o^2(1+i\phi)+i\gamma\omega-\omega^2}$$



Experimentally found

Stationary and Unexpected 1/f

Transfer Function has been found when the GAS filter was tuned at or below 100 mHz



Fractal dynamics predicts 1/f noise

The SAS seismic attenuation system for the Advanced LIGO Gravitational Wave Interferometric Detectors. A.Stochino et al., 2008

Conclusions

✓Static hysteresis was the first indicator of something funny inside the materials.

✓Hysteresis, run-offs, changing Young's modulus, changing damping constants, the 1/f GAS filter TF, and several other surprising effects can be explained in terms of SOC dynamics of entangled/disentangled dislocations.

✓ An avalanche dominated 1/f noise is expected at low frequencies.

✓The behavior observed in Maraging blades may actually be typical of most polycrystalline metals at sufficiently low frequencies.

Work to do

- ✓ New materials and processes need to be explored to design the seismic isolation of third generation, lower frequency GW interferometers

- ✓ And to better control the mechanical noise of those presently under construction.

- ✓ Glassy materials that do not contain dislocations or polar compounds that do not allow dislocation movement are candidate materials for seismic attenuation filters and inertial sensors
- ✓ Maybe refrigeration or cryogenics would impede SOC dislocation noise

- ✓ Dislocation movement impede fragility => we want to avoid their movement => fragility may be an unavoidable effect