Noisy metals Dislocations movement and hysteresis in Maraging blades

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Something very fishy happens here !

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Abstract

All seismic isolation systems developed for Gravitational Waves Interferometric Detectors, such as LIGO VIRGO and TAMA, make use of Maraging steel blades. The dissipation properties of these blades have been studied at low frequencies, by using a Geometric Anti Spring (GAS) filter, which allowed the exploration of resonant frequencies below 100 mHz. At this frequency an anomalous transfer function was observed in GAS filter. Static hysteresis was observed as well.

These were the first of several motivation for this work.

The many unexpected effects observed and measured are explainable by the collective movement of dislocations inside the material, described with the statistic of the Self Organized Criticality (SOC). At low frequencies, below 200 mHz, the dissipation mechanism can temporarily subtract elasticity from the system, even leading to sudden collapse. While the Young's modulus is weaker, excess dissipation is observed. At higher frequencies the applied stress is probably too fast to allow the full growth of dislocation avalanches, and less losses are observed, thus explaining the higher Q-factor in this frequency range. The domino effect that leads to the release of entangled dislocations allows the understanding of the random walk of the VIRGO and TAMA IPs, the anomalous GAS filter transfer function as well as the loss of predictability of the ringdown decay in the LIGO-SAS IPs. The processes observed imply a new noise mechanism at low frequency, much larger and in addition of thermal noise.

What happens at low frequency

- Dislocations start acting collectively
- Dissipation observed to switch
- from "viscous"
- to "fractal" (avalanche dominated)

- New, unexpected physics

- Much larger excess noise
- Reduced attenuation power

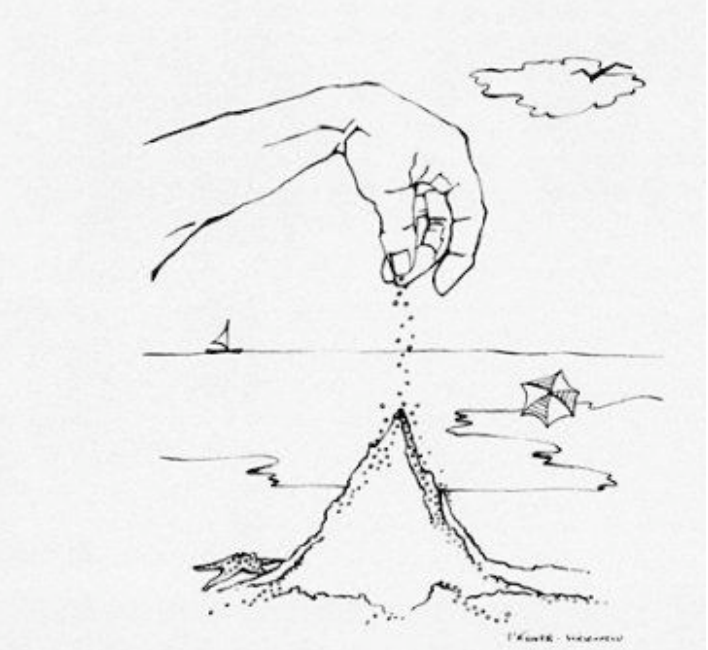


Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

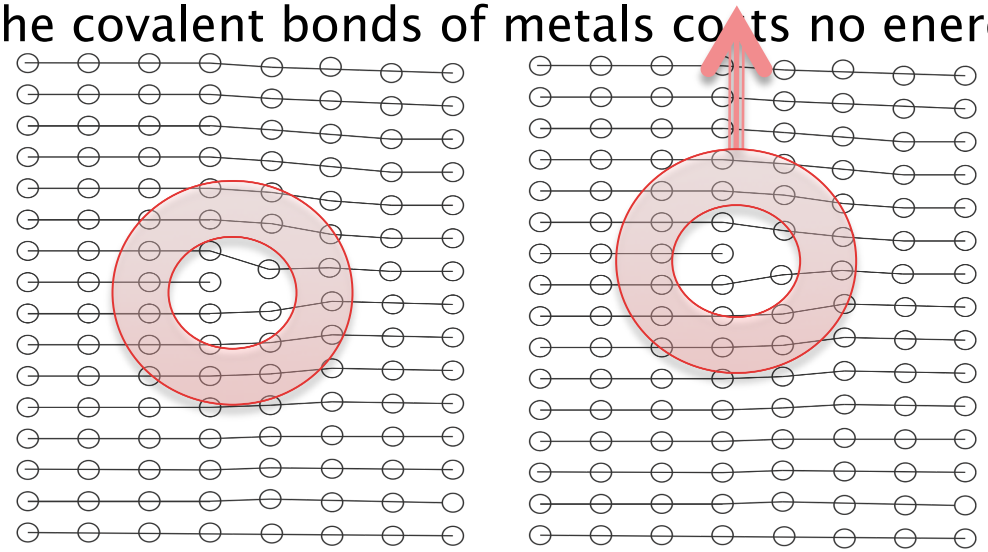
OUTLINE

- Theory
  - Dislocation movements
  - Collective dislocations movement
  - Self Organized Criticality (SOC)
- Experimental method
  - What is a GAS filter, why did we use it
- Data analysis and results
  - Hysteresis
  - Q factor measurements
  - Low frequency instability
  - Dissipation dependence from amplitude
  - Frequency dependence from amplitude
  - GAS transfer function
- Conclusions
- Future work

Dislocations

- Dislocations are crystal linear defects.
- Pushed by moving stress gradients, they can move "almost" freely in X and Y through a "zipper" effect

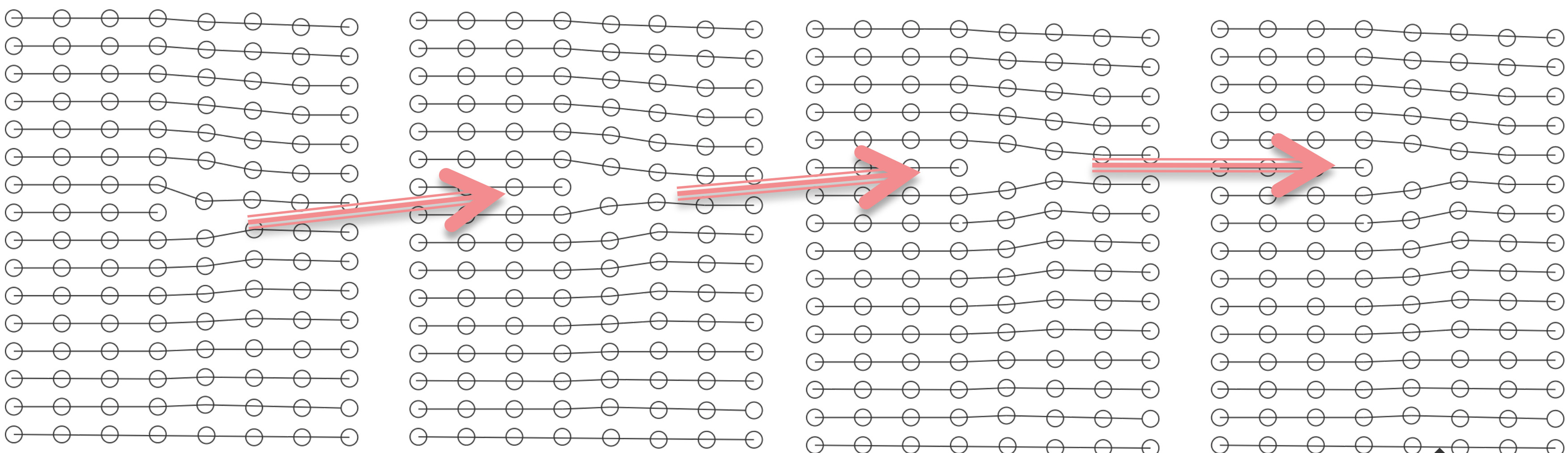
(switching the covalent bonds of metals costs no energy)



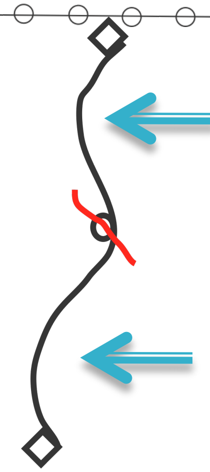
- They are voids in crystal that cost energy (=> they repel)
- They carry stress (their movement causes plasticity)
- They carry stiffness (work hardened metals are stiffer)

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)

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

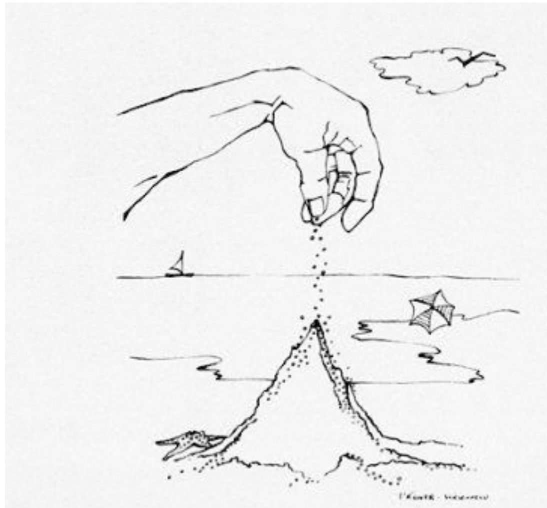


Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

- 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

- 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

Time scales

- Bond switching is almost instantaneous (<< ns)

- Zippering up and down a dislocation takes time
- Dislocation gliding takes longer
- Entanglement and disentanglement take even more time
- Larger avalanches take longer to build
- We experimentally observe effects in the time scale of <u>seconds</u>.

Space scales

- Entanglement and collective dislocation motions can extend beyond crystals, across the entire sample

- Avalanches of dislocations can theoretically propagate through the entire sample

- We observe "catastrophic" effects extending across the entire size of the blades, ~38 cm.

Theoretical models

- The scale-free nature of such process explains the 1/f noise and transfer function

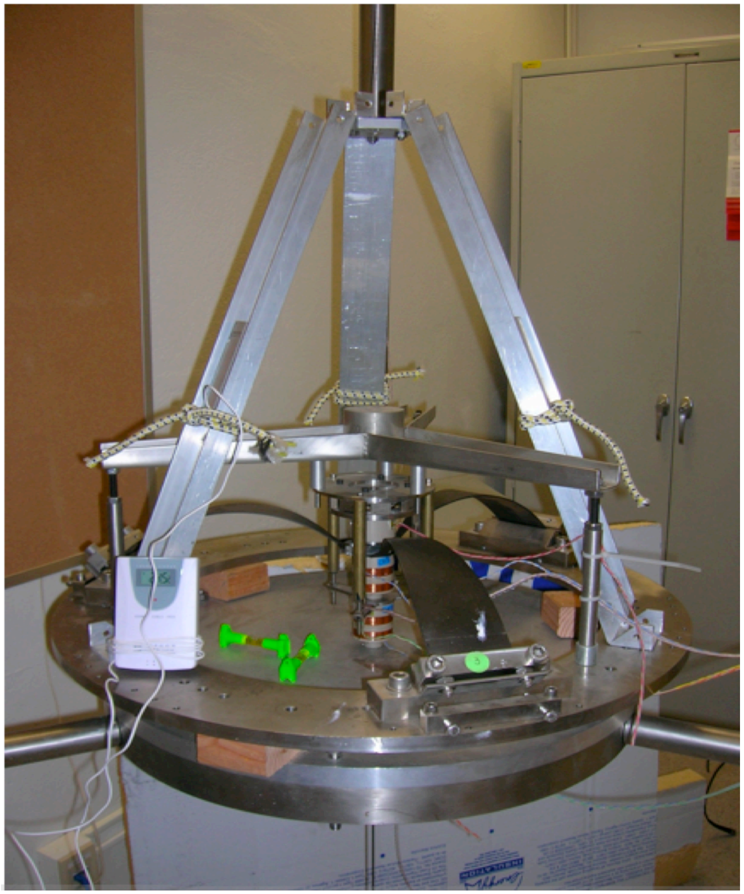
- Collective effects are not evident at high frequencies, because dislocation avalanches don't have time to develop and propagate
  - (lower and predictable losses are observed at HF)

- The underlying fractal noise mechanism never disappears
- The extension of its effects is at present unknown

Experimental setup

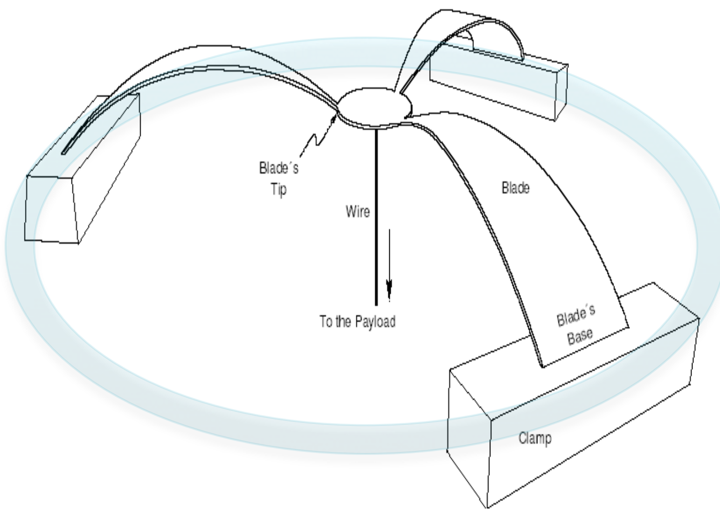
Experimental setup

- THE GAS-EMAS filter
- A "microscope" for mesoscale effects
- the arbitrarily low resonant frequency from the Anti-Spring effects (GAS and EMAS) allow the exploration of Hysteresis, Thermal effects, Self Organized Criticality , and other underlying effect.



The GAS mechanism

(Geometric Anti Spring)

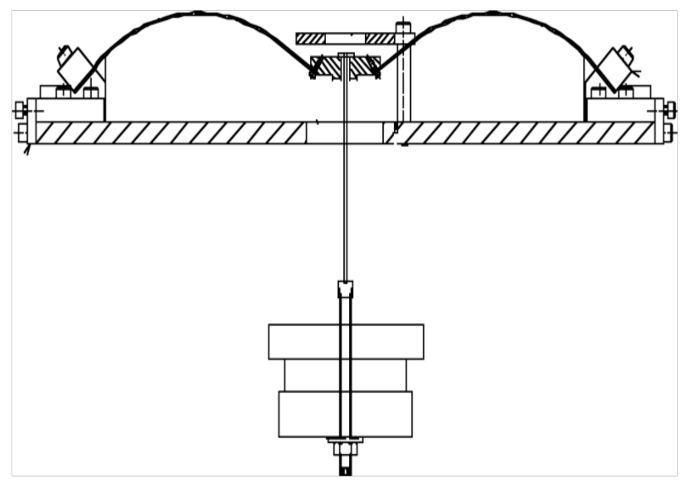


Radially-arranged Maraging blades clamped to a frame ring.

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 , thus generating low spring constant and low resonant frequency.



The EMAS mechanism

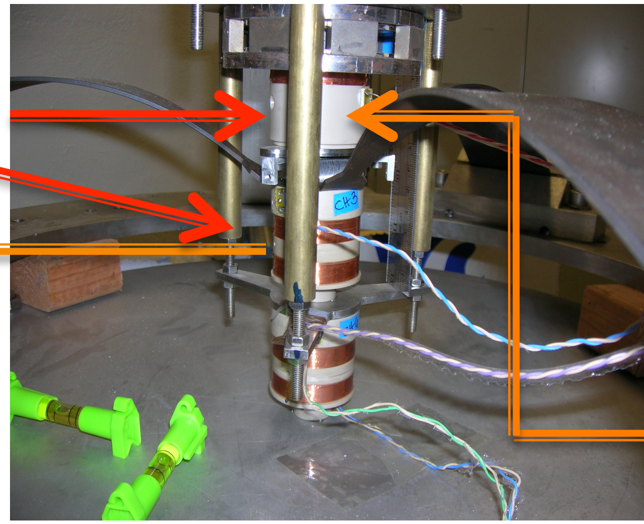
(Electro Magnetic Anti Spring)

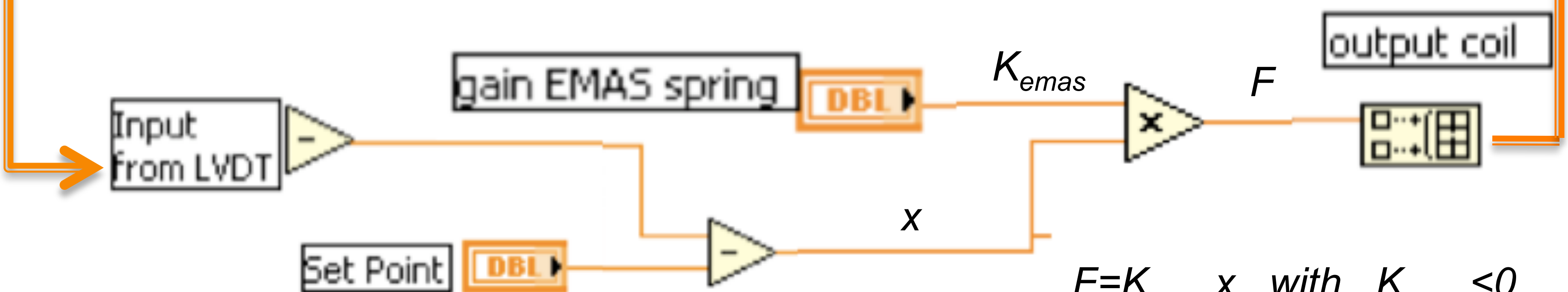
The EMAS mechanism is used to reach even lower restoring forces

It allows remote tuning and thermal compensation

Non contacting **actuator**

LVDT position sensors





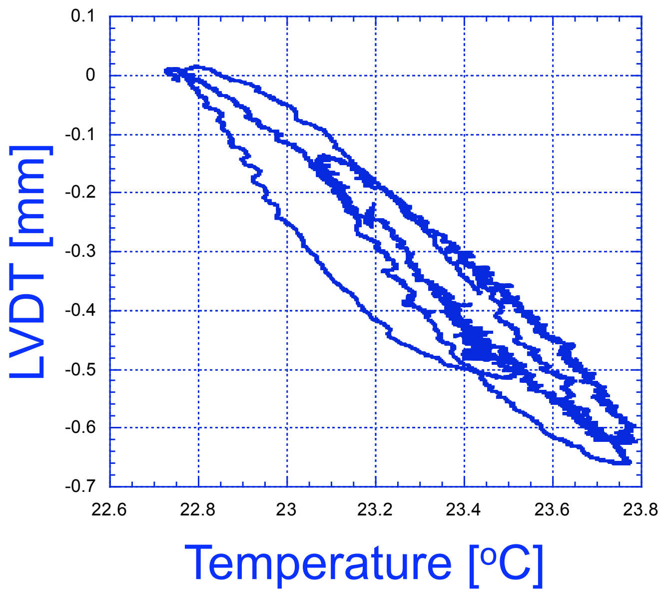
$F = K_{emas} x$ with $K_{emas} < 0$

M. Mantovani, R. DeSalvo, *One Hertz Seismic Attenuation for Low Frequency Gravitational Waves Interferometers*, accepted for publication on Nucl. Instr. and Meth. (2005).

Experimental results

Evidence of hysteresis without actual movement in the thermal feedback

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



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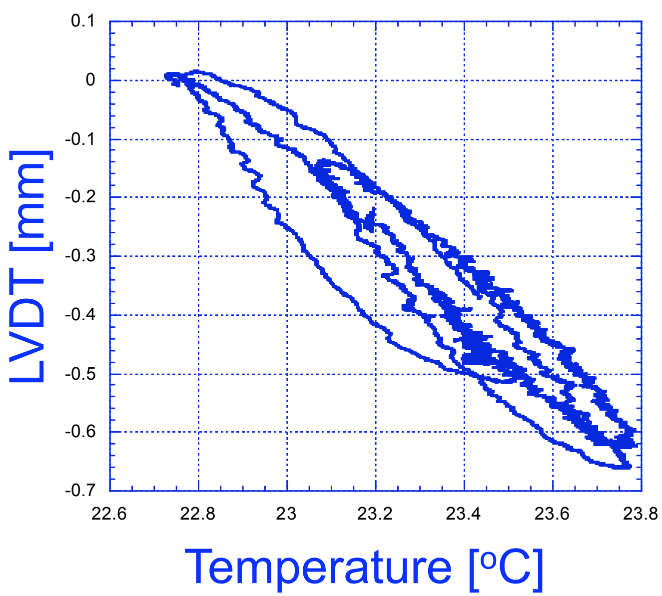
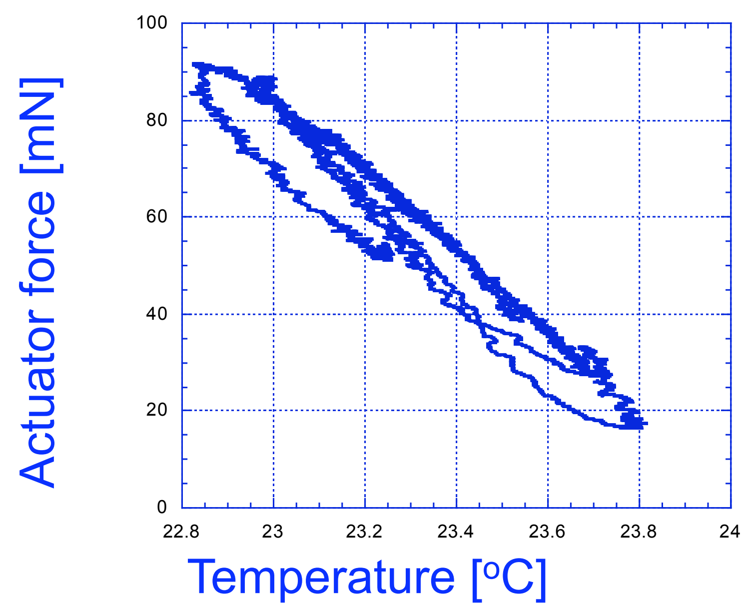


- Position feedback on
- No actual movement, expect no hysteresis
- Hysteresis shifts to the control current ! !



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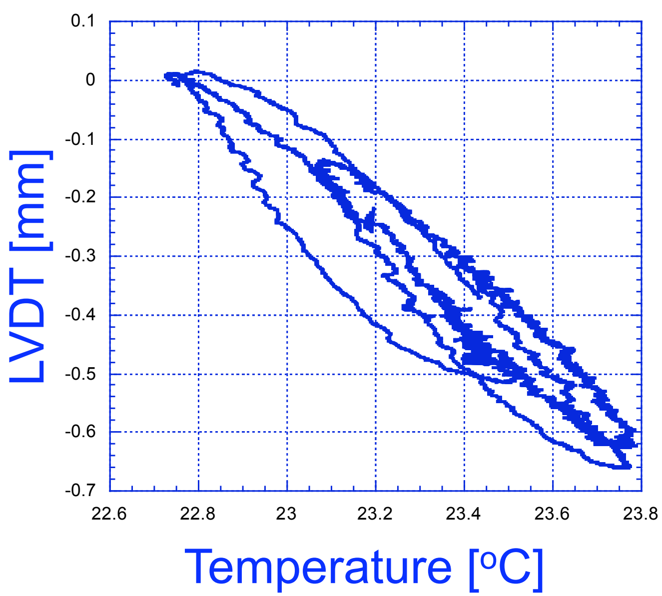

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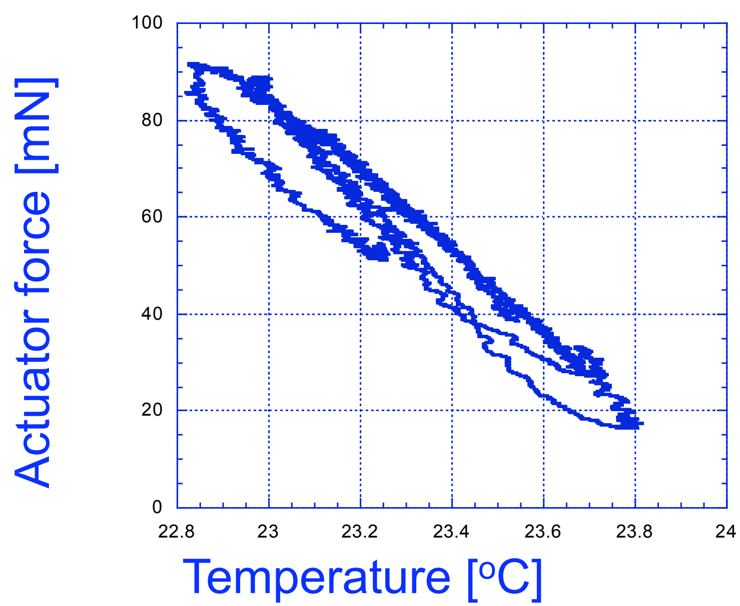
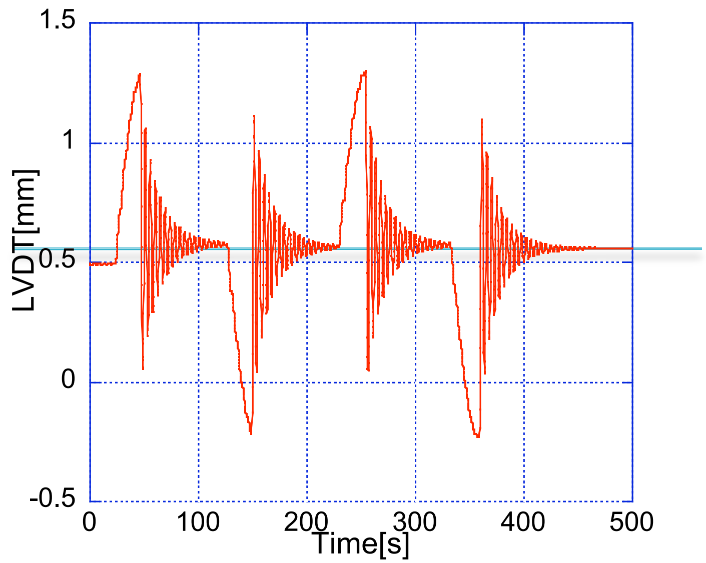


Hysteresis <u>does not</u> originate from the filter macroscopic movement **but from a microscopic dynamics** inside the blades material!

To explore the effects of hysteresis at various tunes, we applied excitations of different amplitude and shape.

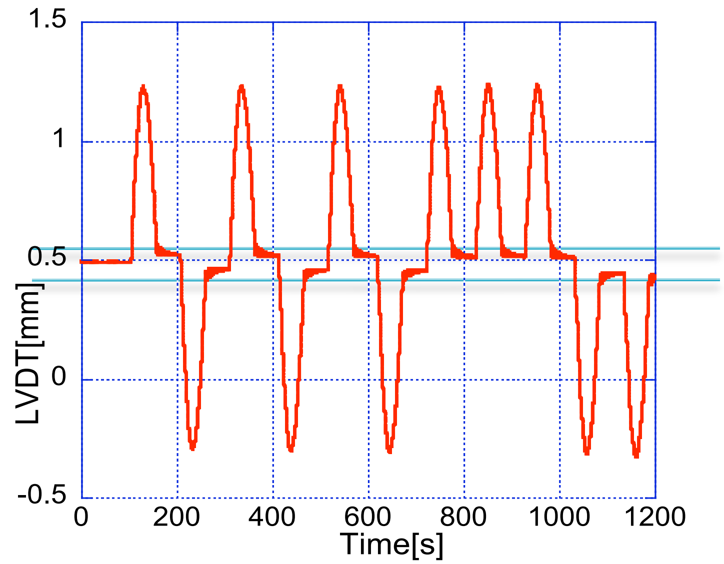
EMAS gain 0, frequency 0.21 Hz (>0.2Hz)



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



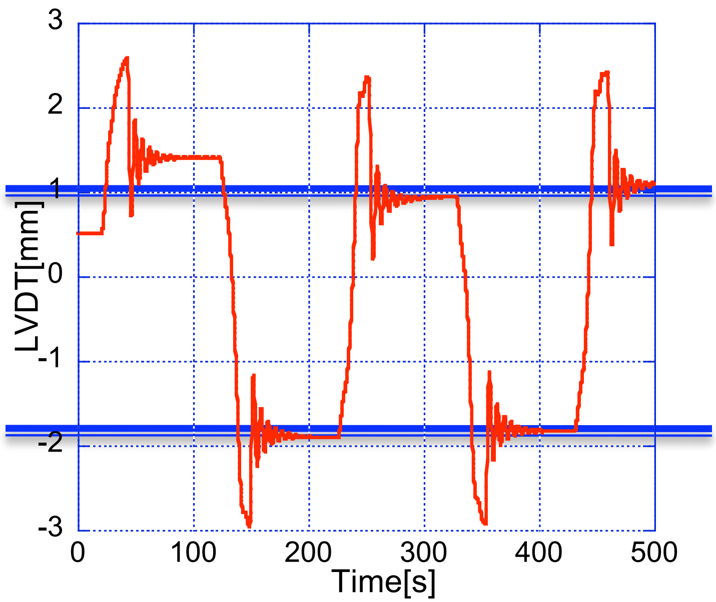
Subjecting the system to the same force, but slowly returning the lifting force to zero, thus allowing no oscillations:

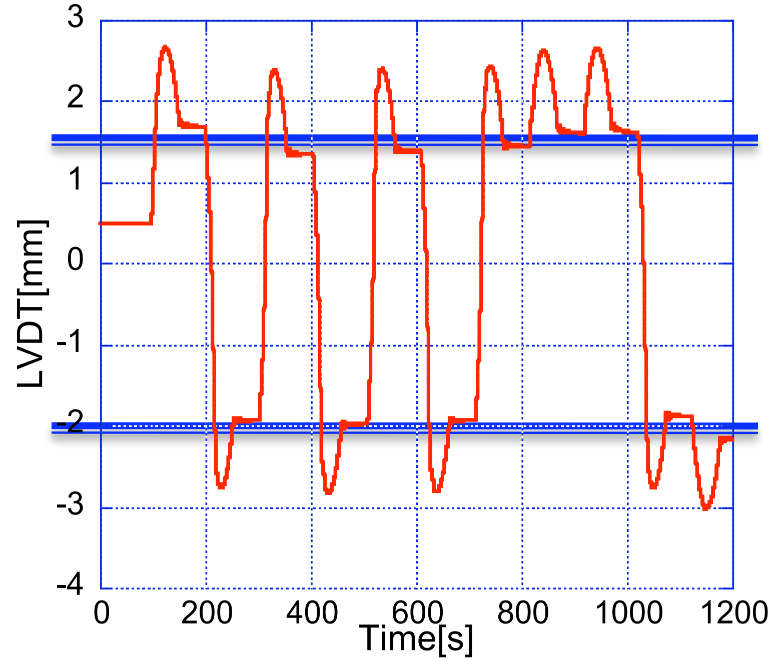
SOME HYSTERESIS OBSERVED FOR ALTERNATE SIGN EXCITATION

NO HYSTERESIS FOR SAME SIGN EXCITATION

Hysteresis amplitude grows with low frequency tune

EMAS gain -2, frequency 0.15 Hz





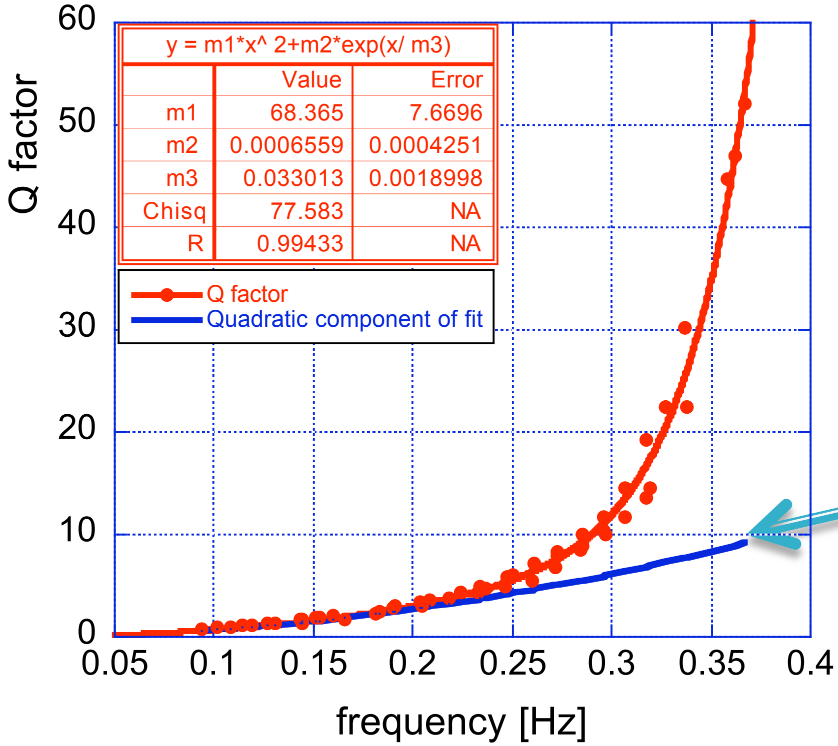
OSCILLATIONS APPEAR to be ineffective TO WASH-OUT HYSTERESIS at low frequency: not enough oscillations to delete hysteresis

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

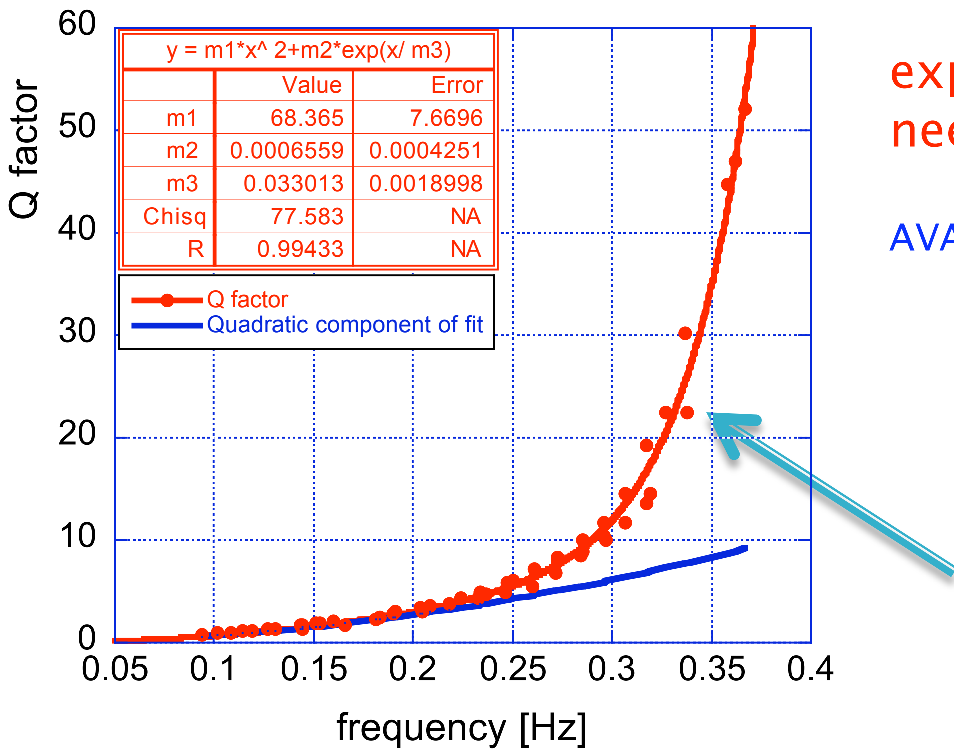


- METHOD
- Change the frequency with the EMAS mechanism
- Acquire ringdowns
- Measure $Q = \omega\tau$

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



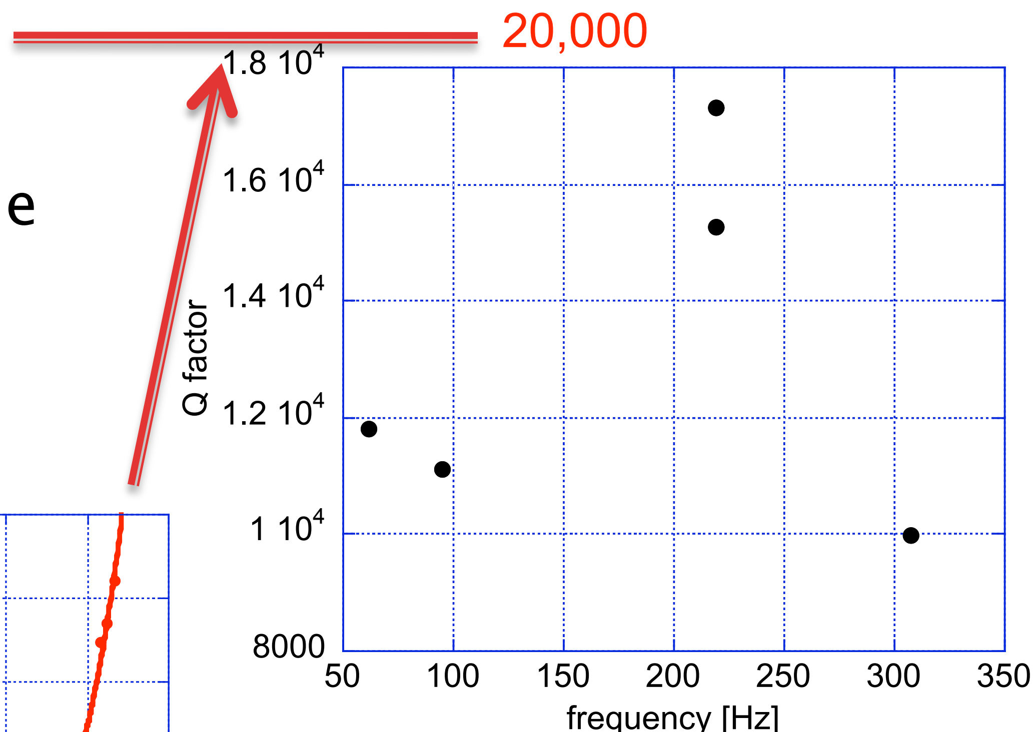
explainable if the dissipation process needs long time to develop:

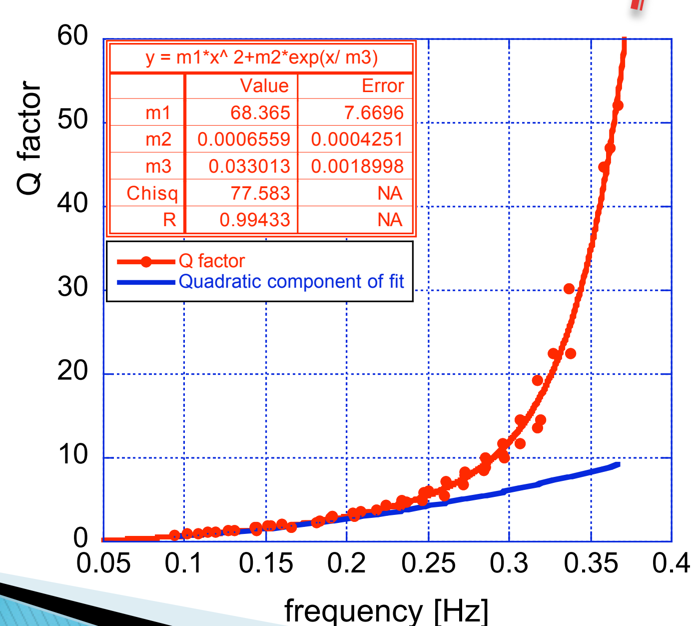
AVALANCHES NEED LONG TIME TO DEVELOP

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

Maraging free blades Q-factor

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





Low frequency instability

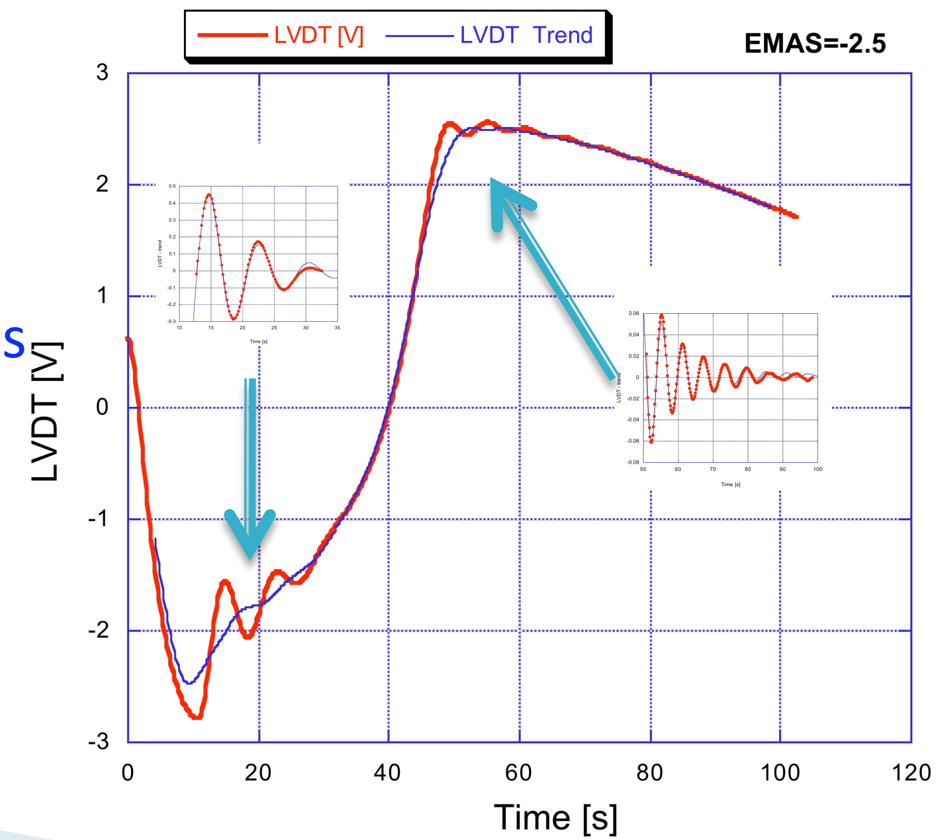
Low frequency instability

- As the system approaches lower and lower frequencies, sometimes it suddenly escapes from its equilibrium position in an un-predictable way

=> RUNS-OFF

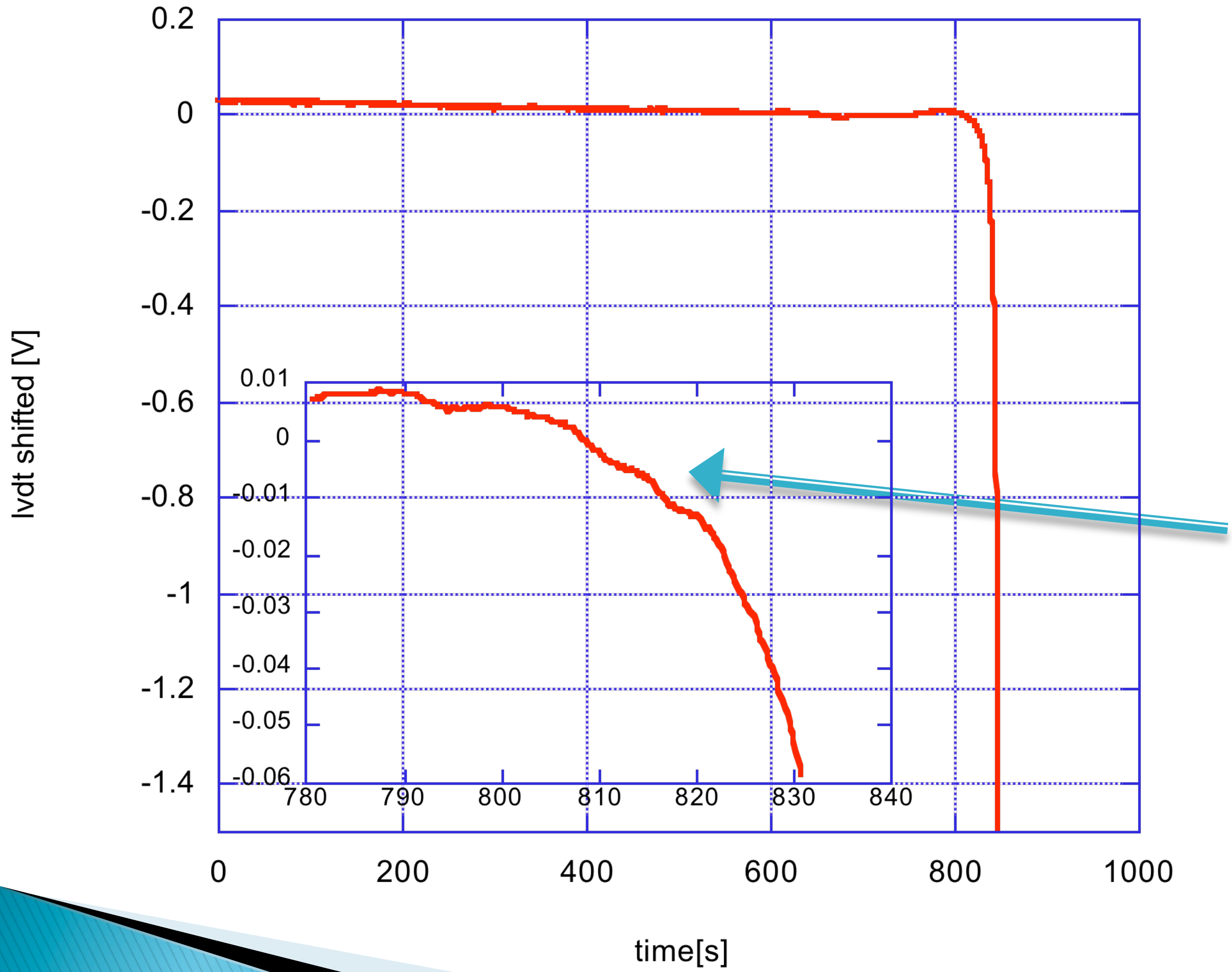
Example:

- excitation triggers a ringdown
- the spring spontaneously jumps to a new equilibrium point
- Oscillates around the new e.p.



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

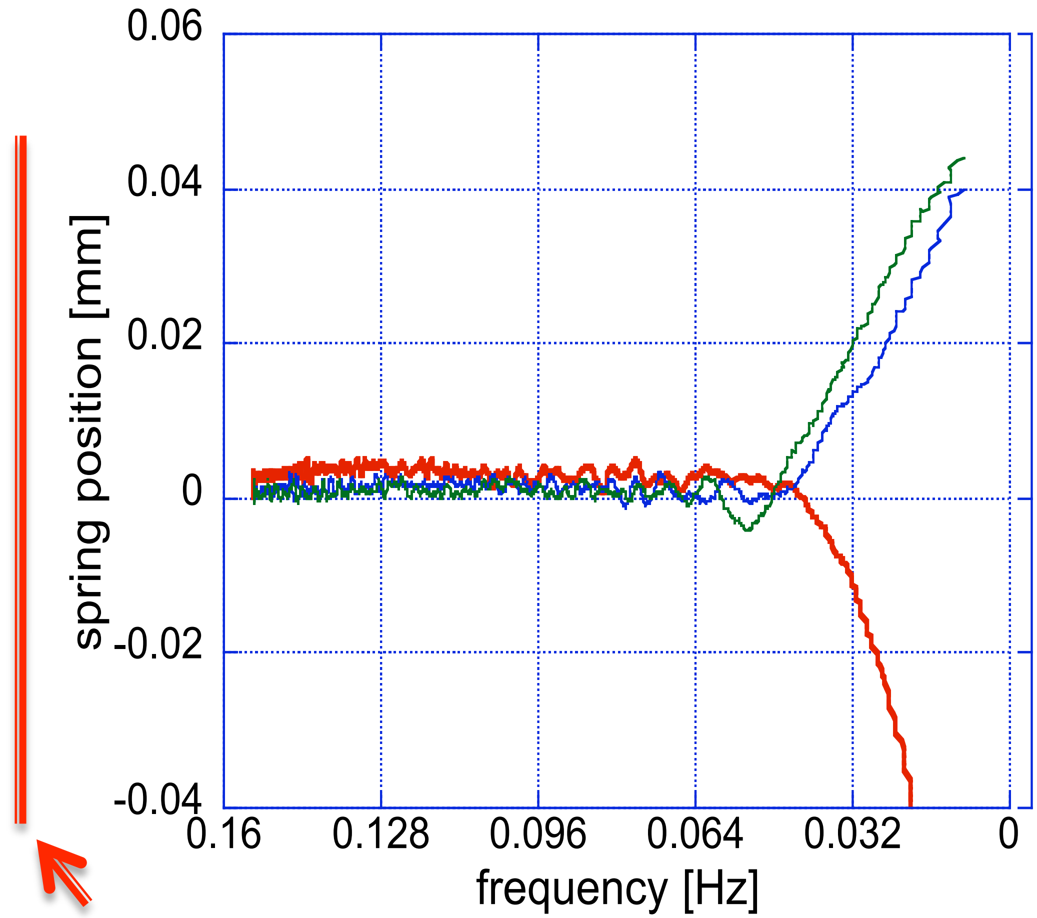
Avalanches propagate across the entire 38 cm blade length

Low frequency instability

65 kg payload
can fall
indifferently up
or down

NO CREEP ! ! !

NO GRAVITY
DRIVEN
EFFECT ! !

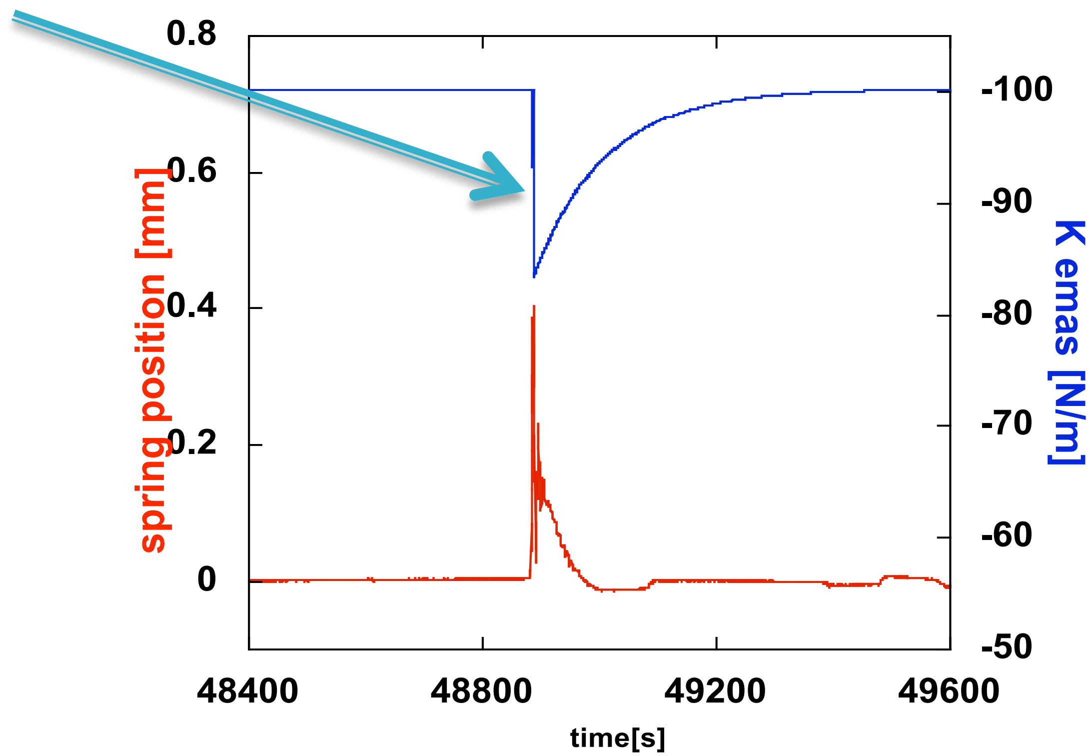


instability region μm
starting from ~ 0.2 Hz

The run-off can be controlled !

Control program detects the beginning of a run-off @ a threshold 30 mV=24μm

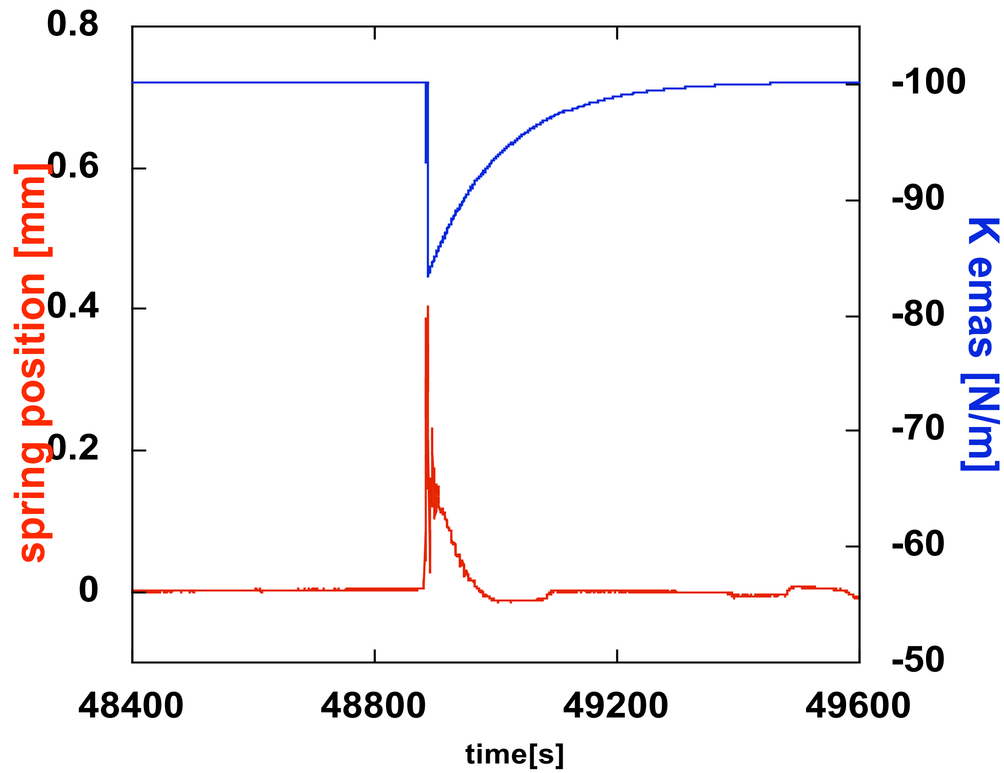
K_{emas} reduced toward less negative value, give more time for re-entanglement



The propagation of the avalanches across the blade is stopped

The system re-stabilizes at a different equilibrium position.

The feedback brings the spring back to the working point.

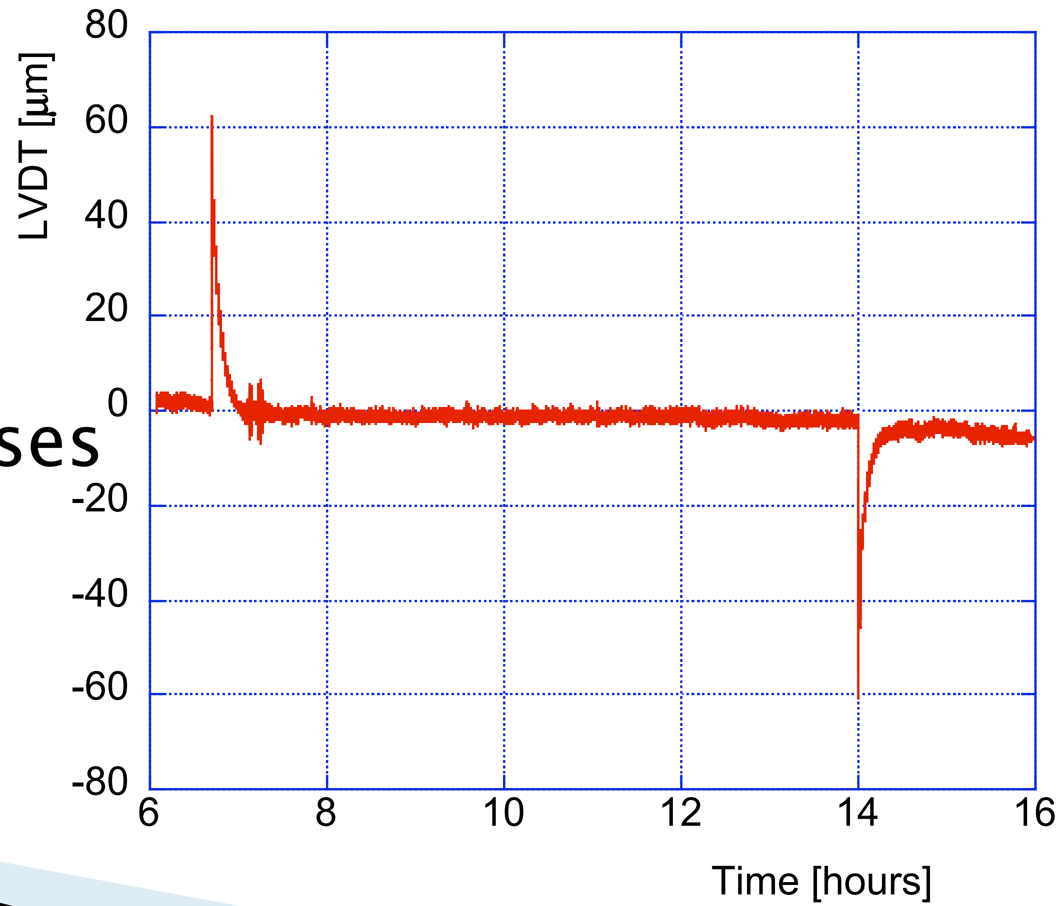


Explanation:

restoring force of the crystal lattice nulled by the GAS and EMAS mechanism,
System kept stable by the restoring force of entangled dislocations.
Perturbations cause some disentanglement, THE DOMINO EFFECT PROPAGATES AVALANCHES OVER THE WHOLE SPRING'S VOLUME,
trigger collapse
reduced EMAS gain gives back control to crystal elasticity
stops the spreading

Run-off causes

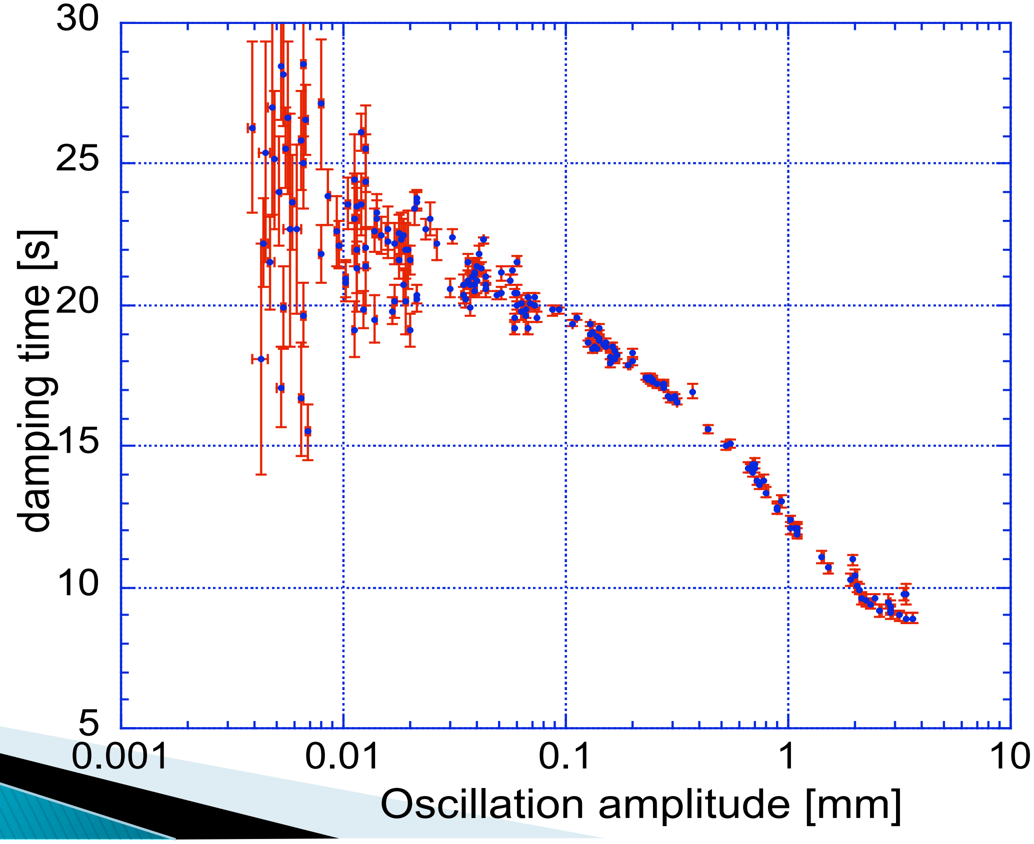
- Thermal drifts
- Drifting forces (tilts)
- External jerks



- No external causes
- No run-offs

Dissipation dependence from amplitude

- Analyzing ring-downs with a damped sinusoidal function.
- 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.



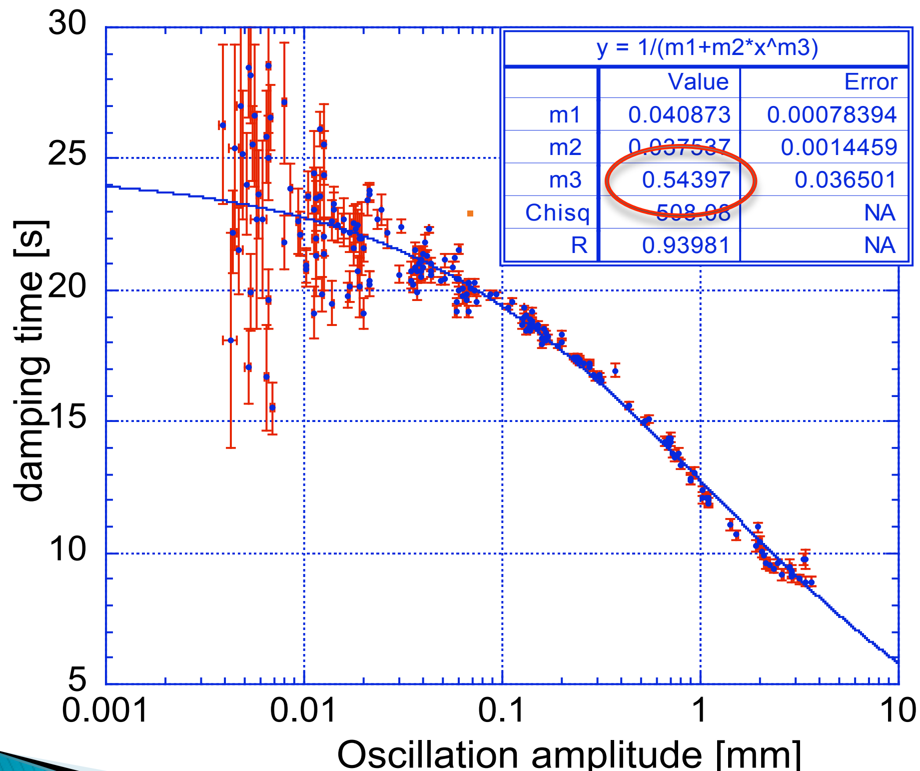
- Fitting the data with

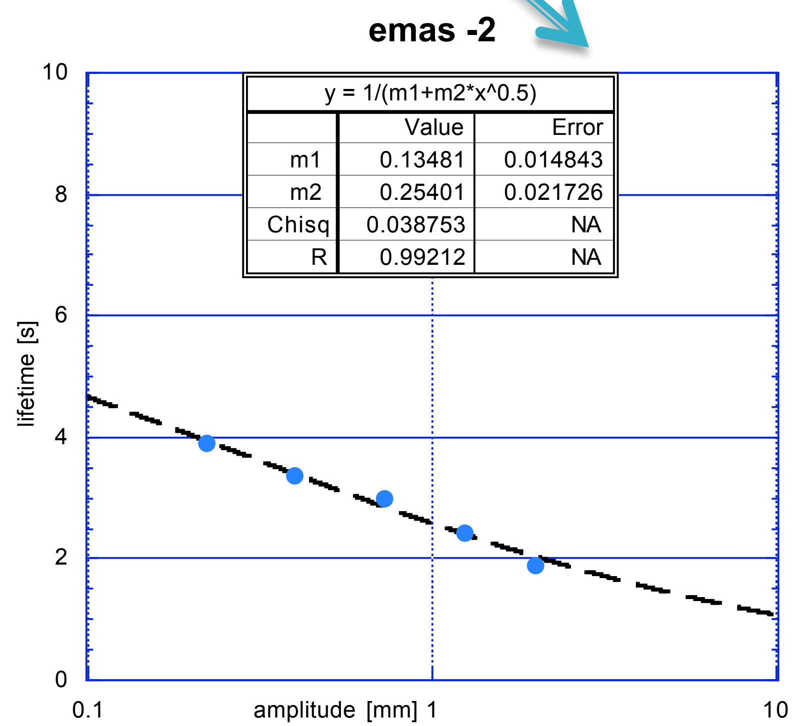
$$\tau = \frac{1}{d_0 + \delta A^{y}}$$

we found an amplitude exponent of ~ 0.5

power law => fractality / SOC

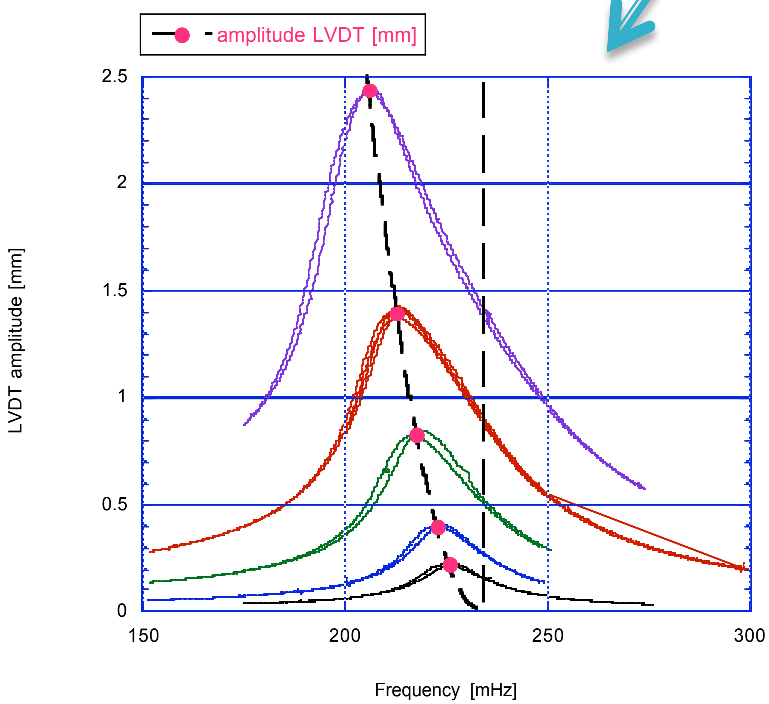
- Same behavior in the frequency domain

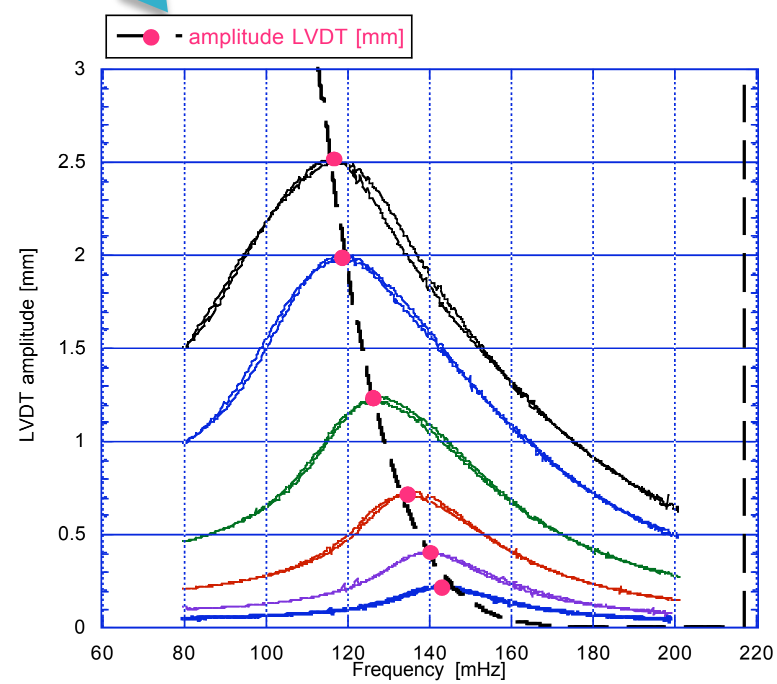




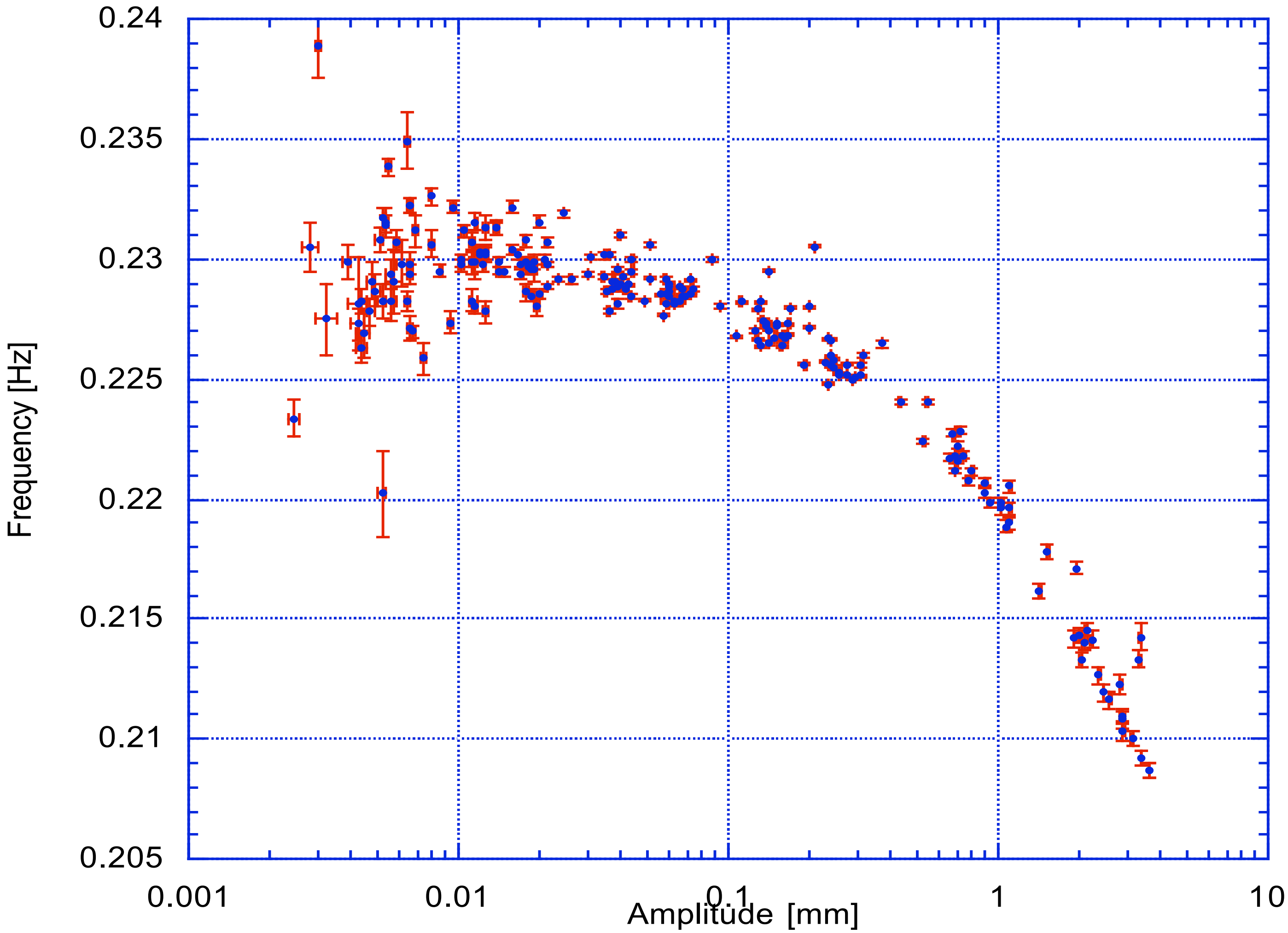
Frequency dependence from amplitude

Swept sine excitation of different amplitudes.
Observed reduction of frequency for increasing excitation amplitude.
Experiment repeated for EMAS gain 0 and -2.





Similar behavior in the time domain by studying ring-down measurements.

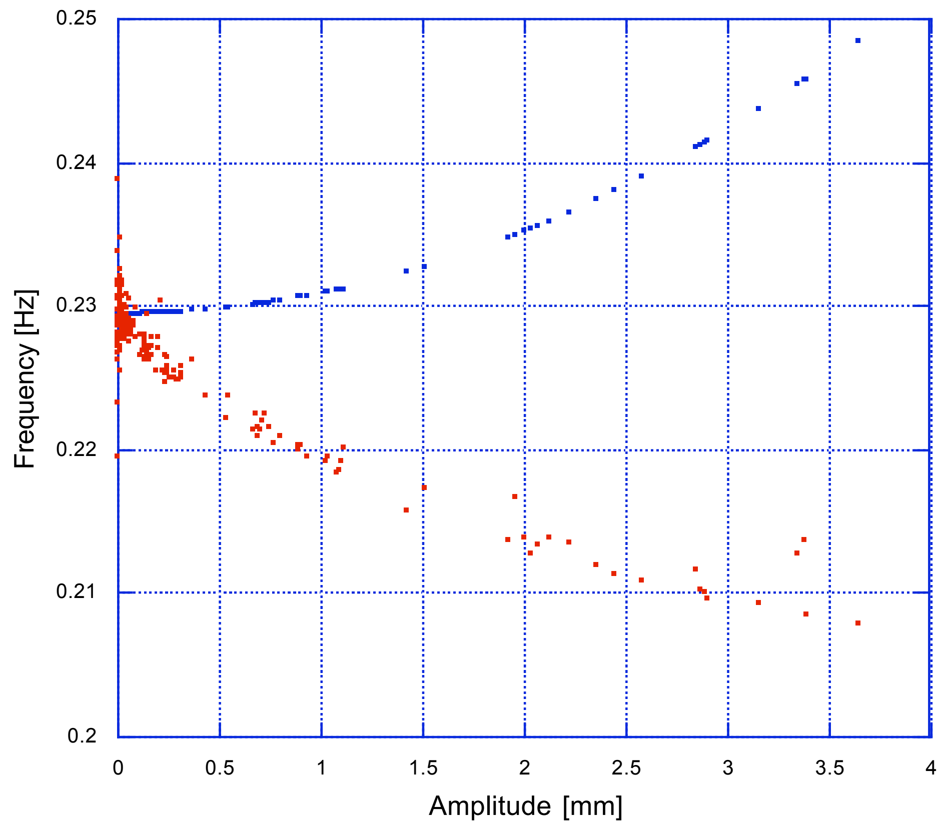


- We observe a frequency reduction at larger amplitudes…

- … while we expected the opposite!

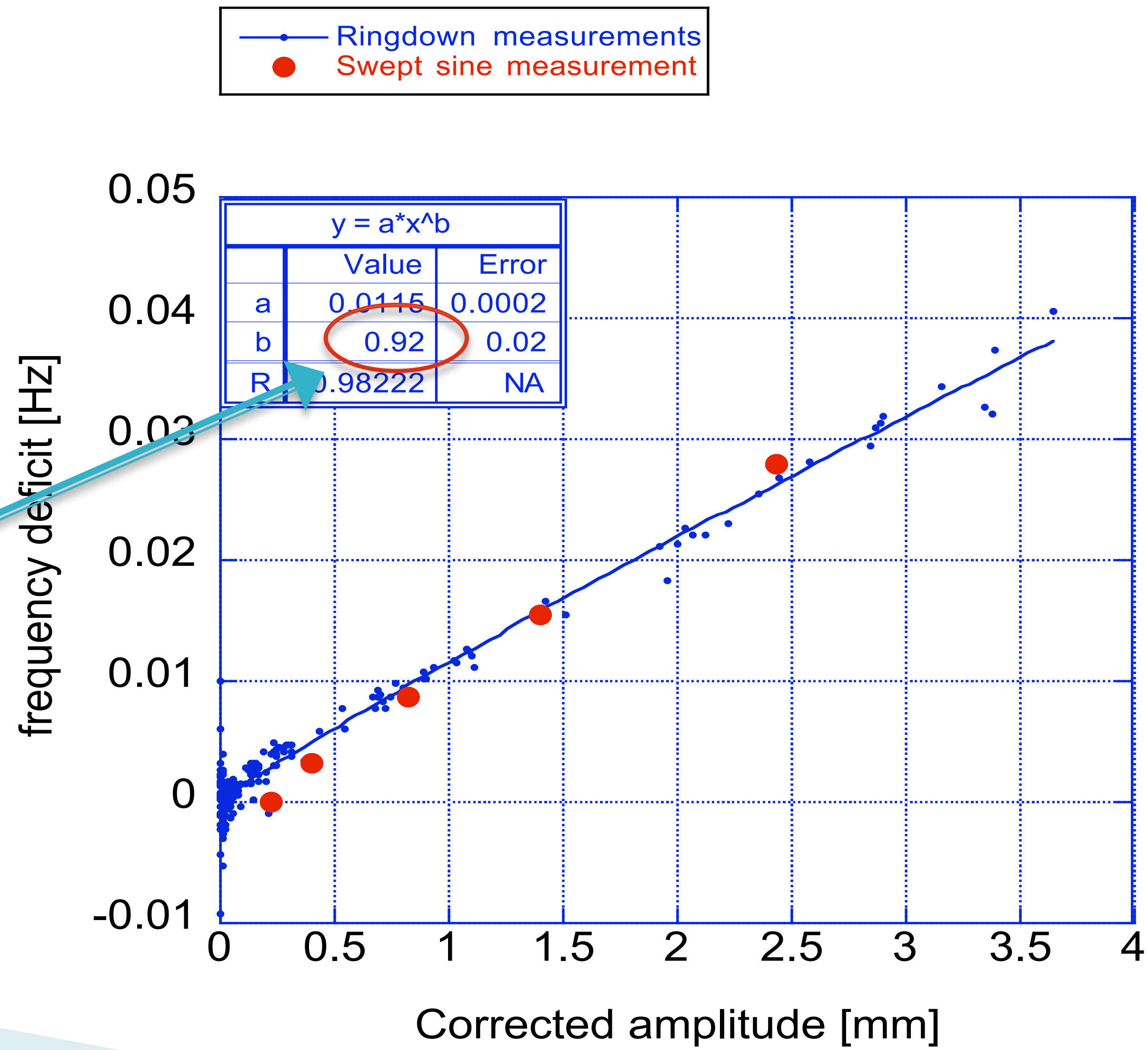
Blue=expected

Red=measured

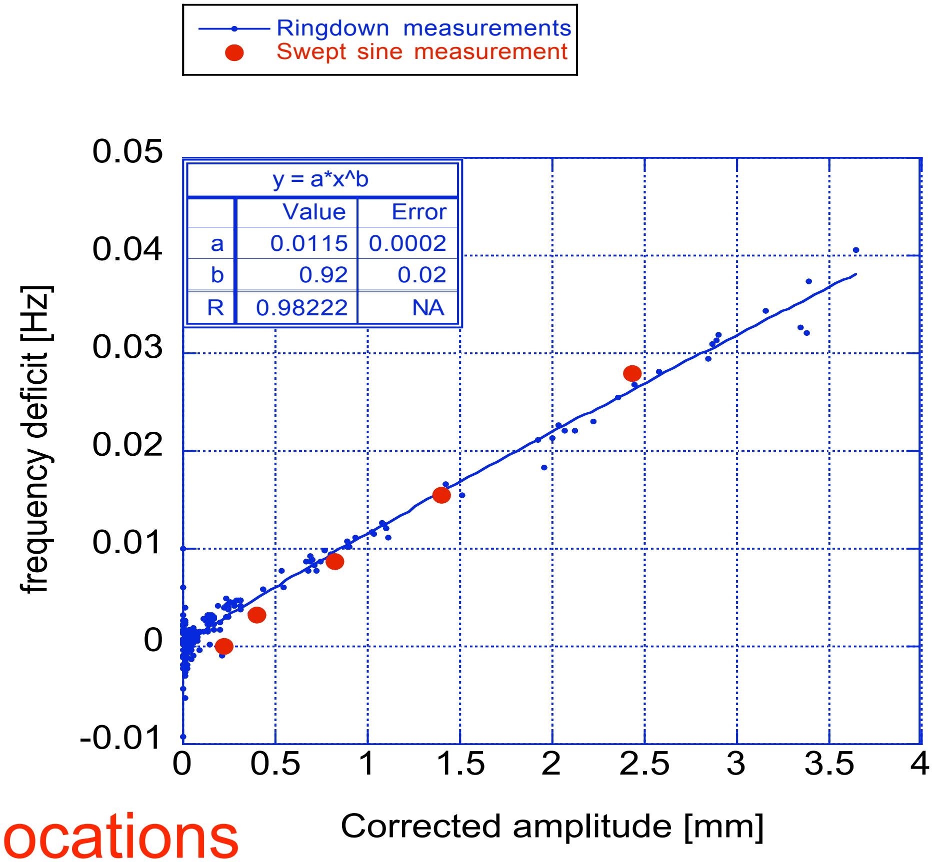


- Frequency deficit vs. amplitude is obtained subtracting the two data sets.

The dependence is a power law of the amplitude: An indication of the fractal dimension of the system ?



Interpretation



Explanation:

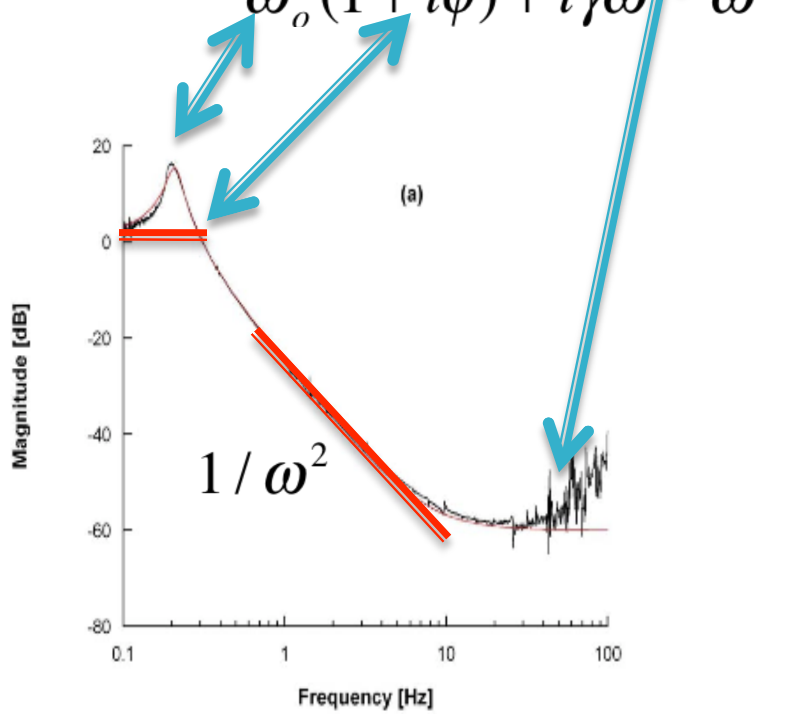
Motion disentangles some dislocations

Number proportional to amplitude

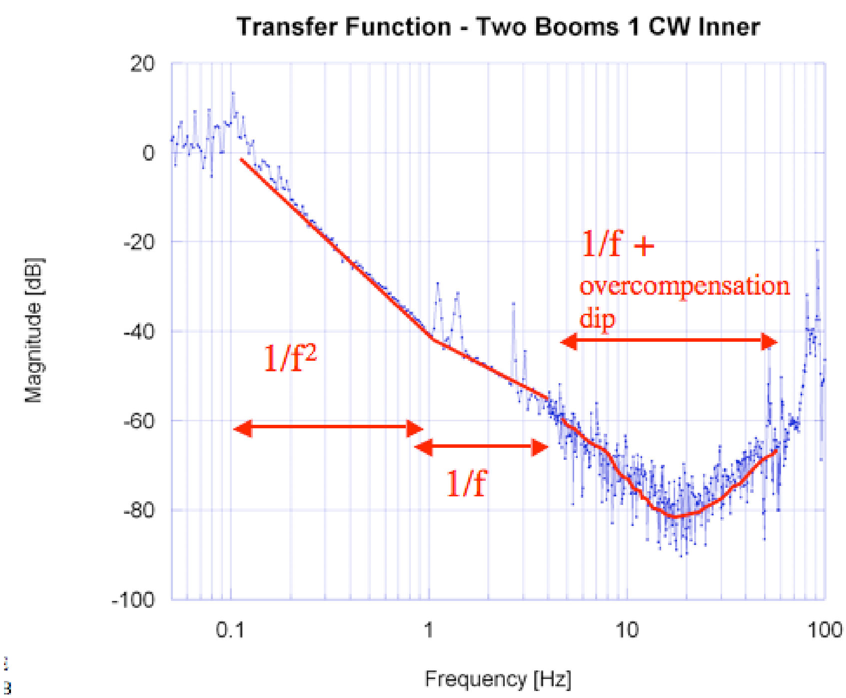
Restoring force contributed by entangled dislocations diminishes

Theoretical 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



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

explanation

- At much lower frequency
- When restoring forces are controlled by entangled dislocation rigidity, rather than crystal elasticity
- Individual avalanches can form
- Avalanches dominate the attenuation process

- Fractal behavior => 1/f power law

Conclusions

✓Static hysteresis was the first indicator of something shifting inside the material.

✓Hysteresis, run-offs, changing Young's modulus, the 1/f GAS filter TF, and several other unexpected effects were 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.

Future perspective

- New materials and processes need to be explored to design the seismic isolation of third generation, lower frequency GW interferometers
- and maybe 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 cryogenics would impede SOC dislocation noise

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

A nice thing !

- ✓ We set up to study the stars
- ✓ On the way there, we found some

interesting new physics

in the materials right in our labs

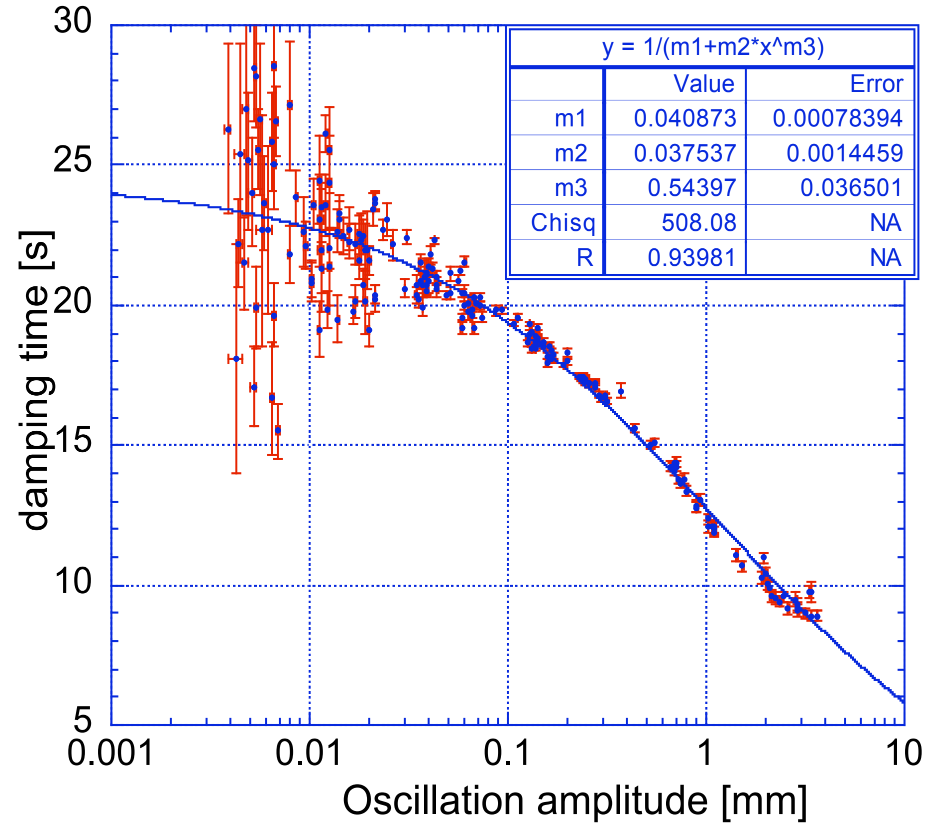
This is why I like this job

The damping “red shift”

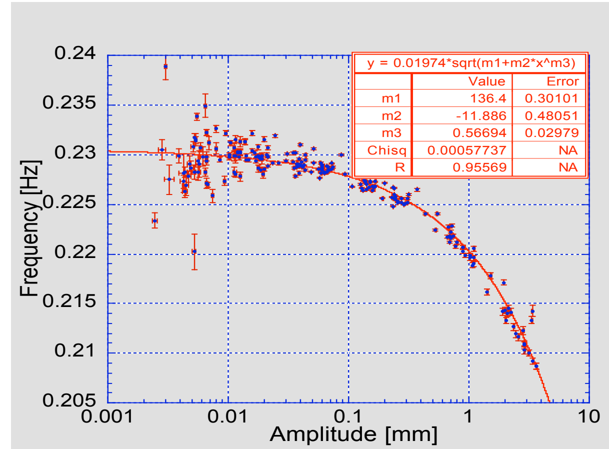
- We considered an additional amplitude-dependent contribution to the frequency coming from the damping constant γ which is proportional to the inverse of the lifetime

Since the damping time is amplitude dependent, we get $\gamma(A)$

In a damped oscillator the frequency is reduced by a factor γ^2 …



…we subtract this term γ^2 from each of the point of fig



We also add this viscous term in the equation of motion,

$$m\ddot{x} + \gamma\dot{x} + kx + cx^3 = 0$$

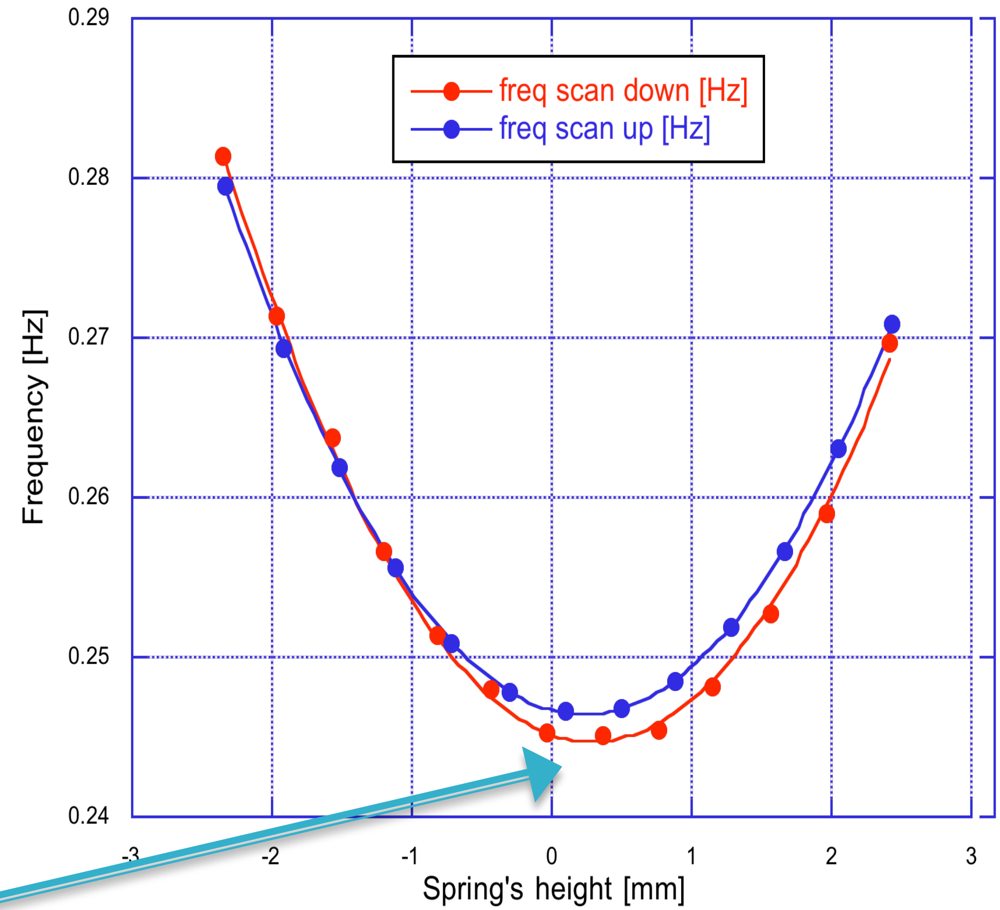
and calculated the frequency decreasing coming from this contribution.

In both cases we found a negligible reduction of the expected frequency in the amplitude range of interest. We can thus neglect $\gamma\dot{x}$

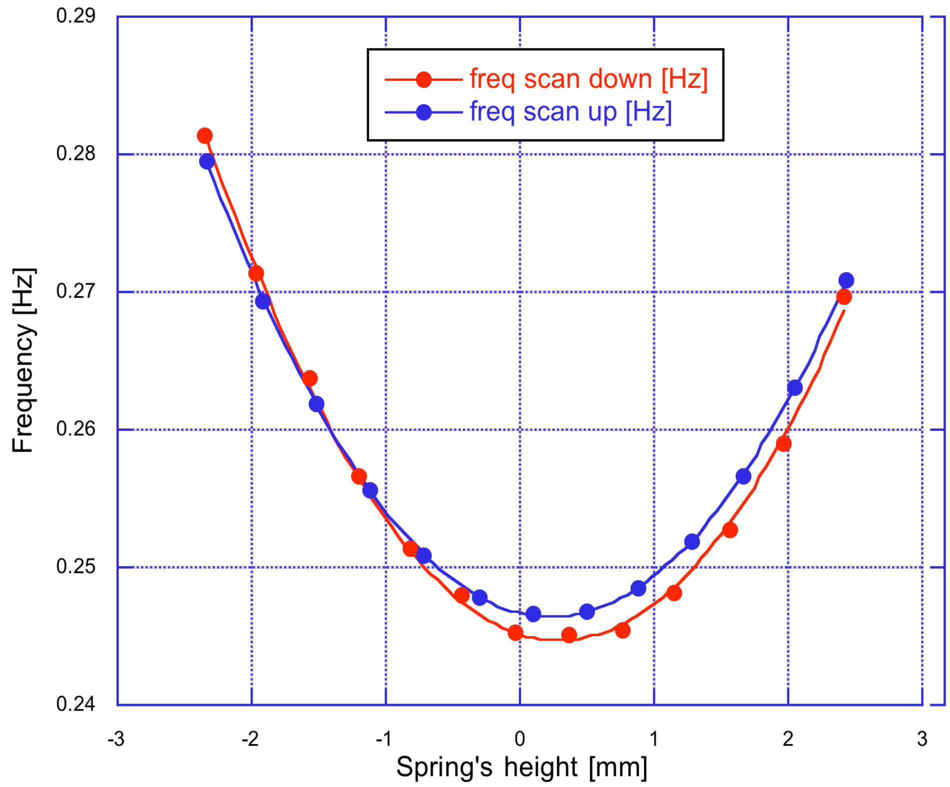
Calculating the expected frequency shift

Working point

- The GAS mechanism is optimized at the height where the radial compression of the blades is maximized.
- To determine the optimal working point we used the actuator to apply a progression of fixed vertical forces.
- At each height we applied a short pulse to excite the spring and found the oscillation frequency.
- We looked for the minimal resonant frequency (working point).

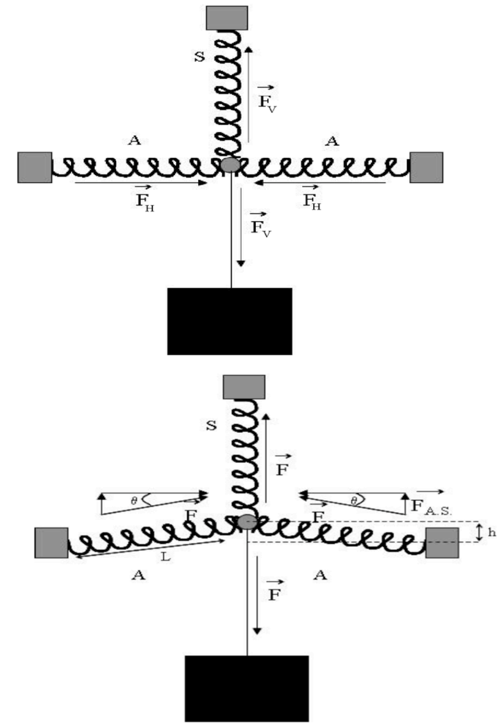


- Larger excitation amplitudes (around the working point), bring the system to explore regions of higher frequency.
- Higher resonant frequencies are expected.



- The GAS spring geometry requires a potential in the form $U = -\frac{1}{2}kx^2 - bx^4$ so that the equation of motion will be

$$m\ddot{x} + kx + cx^3 = 0$$



- We solve it numerically, with m=65Kg, k=125 N/m and the coefficient c =2200000 N/m^3 was tuned to match the measured frequency dependence from amplitude

- Then we simulated progressively larger oscillation amplitudes around the working point and monitored the frequency, thus obtaining..

Expected frequency vs. amplitude

Using the parameters of this quadratic fit, we calculated the expected frequency for each of the measured points