Collective dislocations movement and anomalous dissipation in Maraging blades

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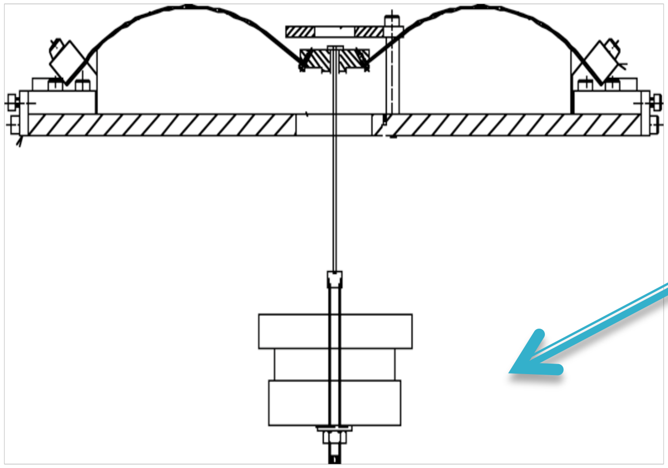
Abstract

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.

The GAS mechanism



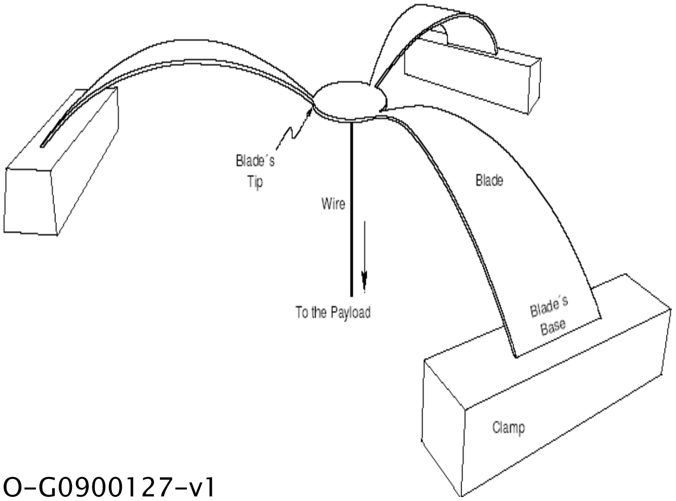
The GAS filter consists of a set of radially-arranged Maraging blades, clamped at the base to a common frame ring.

Blades loaded with a 65 Kg weight

Moving away from the working point the compression of the springs results in a vertical component, proportional to the displacement, the Anti-Spring force.

The GAS mechanism is used to null up to 95% of the spring restoring force , thus generating low spring constant and resonant frequency.

Exploring hysteresis, thermal effects and any other underlying effect.



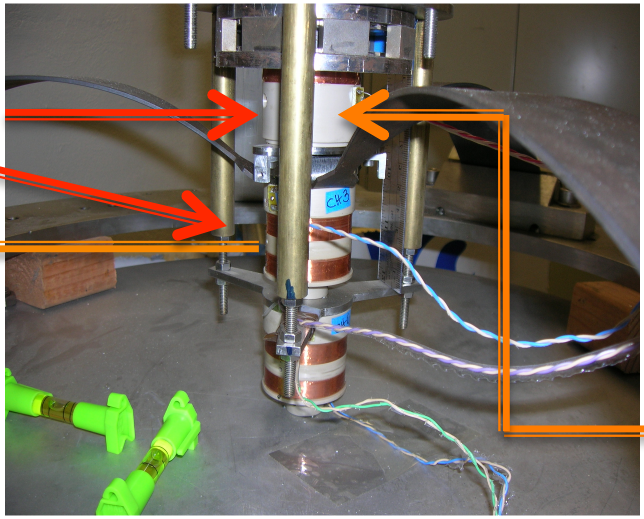
The experiment: EMAS mechanism

The GAS is tuned to obtain a low mechanical resonant frequency (typically 200 mHz) at the working point. The EMAS mechanism is used to reach even lower restoring forces.

Remote control

Non contacting **actuator**

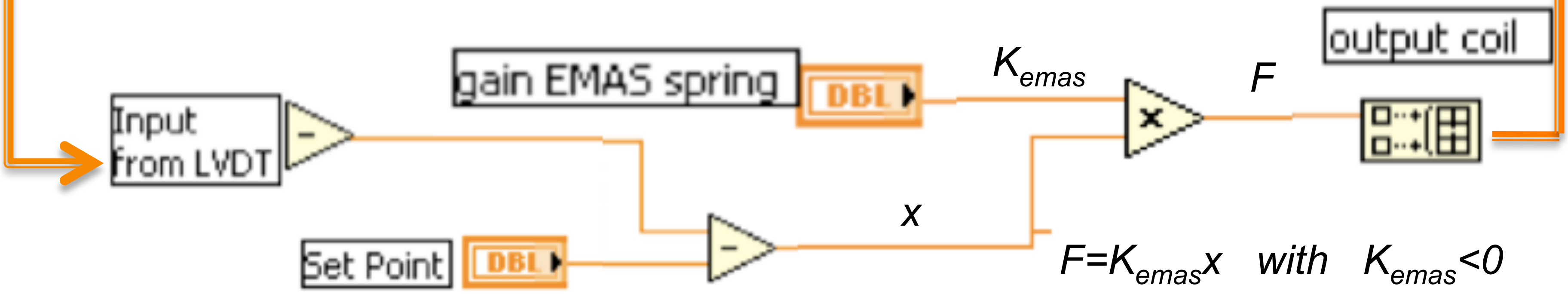
LVDT position sensors



Box around the filter to prevent air turbulence

IIR integrator for thermal compensation: keeps the system at the working point

EMAS with variable gain: further reduces the resonant frequency

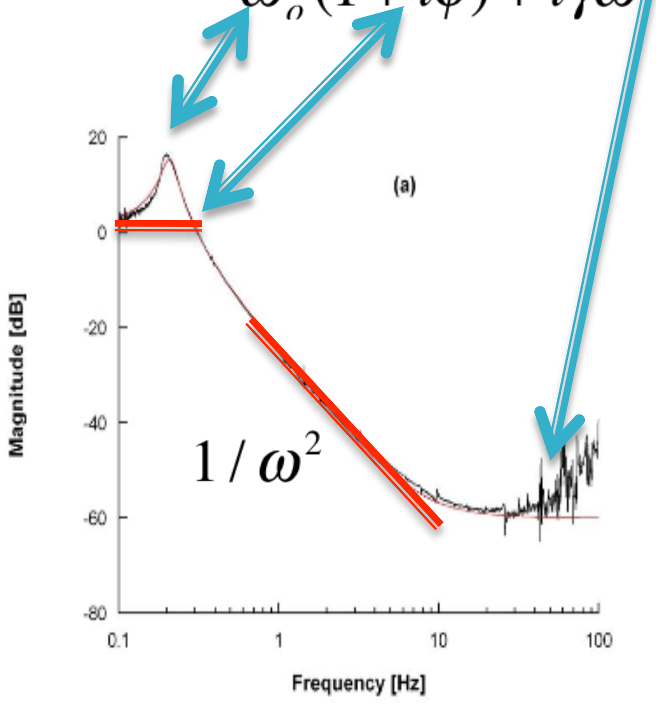


$F=K_{emas}x$ with $K_{emas}<0$

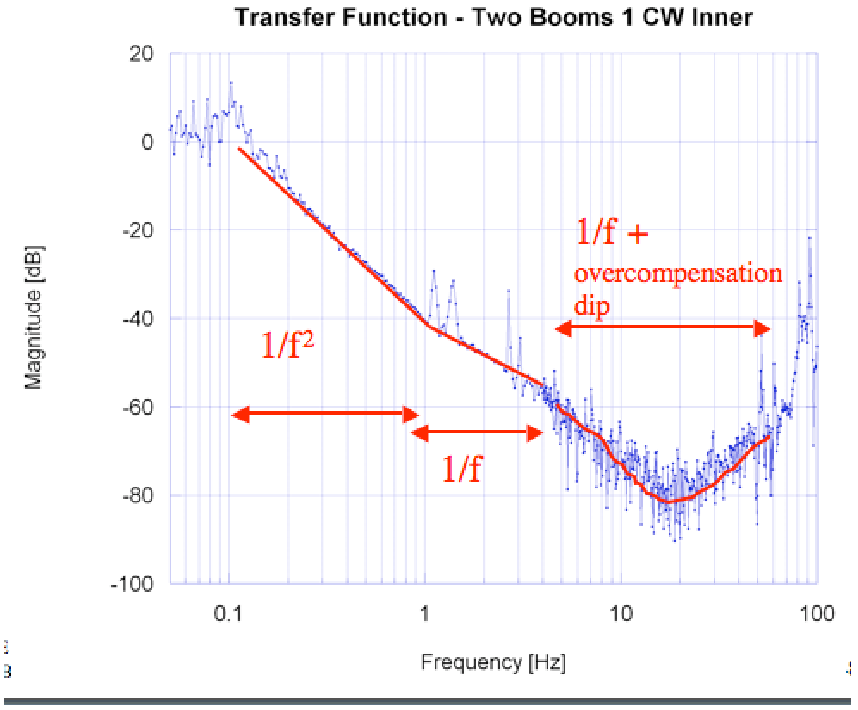
M. Mantovani, R. DeSalvo, *One Hertz Seismic Attenuation for Low Frequency Gravitational Waves Interferometers*, accepted for publication on Nucl. Instr. and Meth. (2005).

Theoretical transfer function of a GAS-filter

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



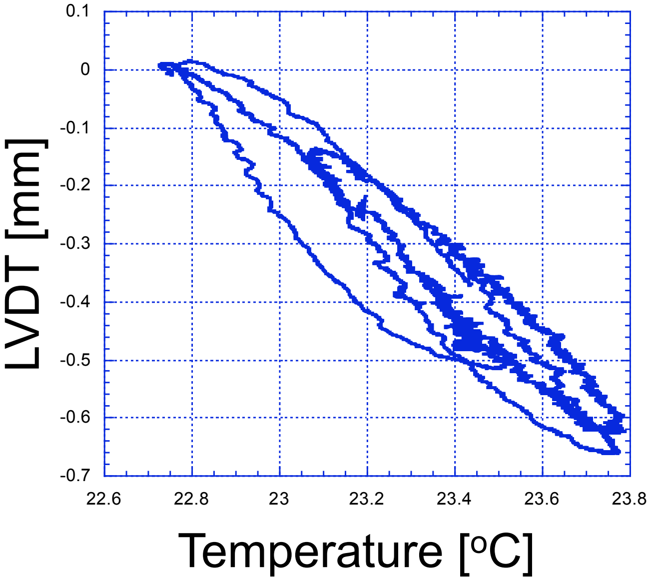
Stationary and Unexpected 1/f Transfer Function has been found when the GAS filter was tuned at or below 100 mHz



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

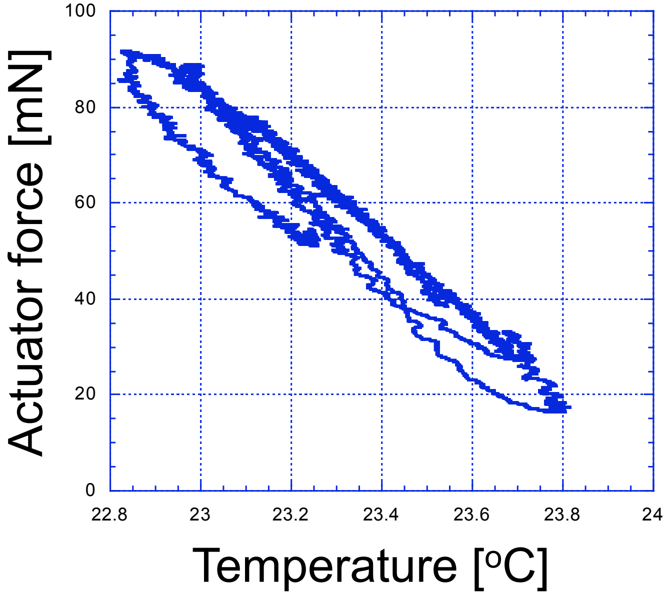
Evidence of hysteresis without actual movement in the thermal feedback

- Filter movement under overnight lab thermal variations
- Without feedback
- The movement shows Thermal hysteresis of the equilibrium point



With position feedback, no actual movement, we expected no hysteresis

But hysteresis shifted to the control current ! !



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

Theoretical models and experimental observations

- Viscosity fails to explain static hysteresis
- Collective dislocation losses provide the most convincing interpretation of our experimental findings
- In a precipitation hardened alloy, that is our case (*), dislocations are not numerous enough to fully interlock, and can disentangle under changing stress conditions in a domino effect

- These collective motions of dislocations can be seen as dislocation avalanches described by Self Organized Criticality (SOC)
- Avalanches of dislocations can theoretically, and we observed them to, propagate through the entire size of the blades ~38 cm in the time scale of seconds

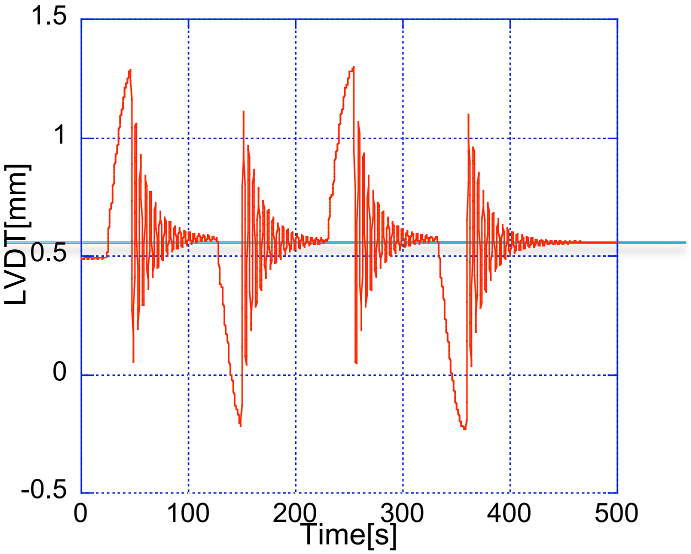
(*) but some of the same effects also observed in Stainless steel, spring steel and the piano wires used in suspensions

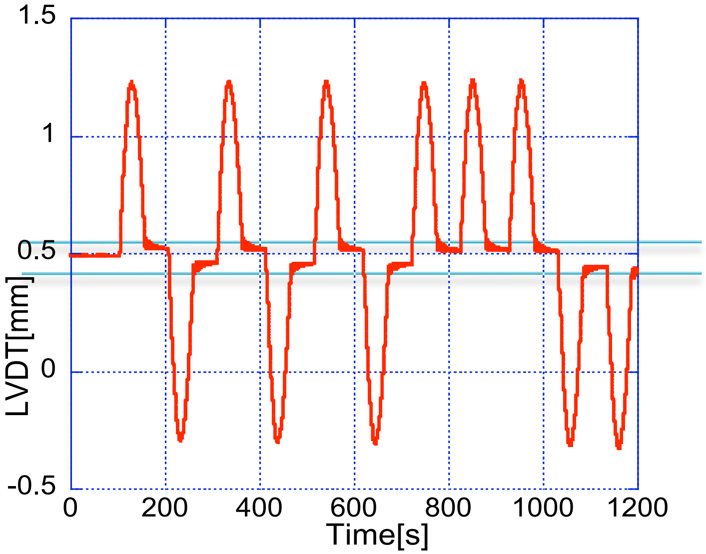
Theoretical models

- SOC: the dislocation network can rearrange by following a self-organized pattern, scale-free in space and time
- While disentangled, dislocations subtract elasticity from the system , and additional viscous like effect are observed
- Eventual re-entanglement of different patterns of dislocations explain the observed static hysteresis
- The scale-free nature of such process explain the 1/f slope of the GAS filter TF
- All these effects are not evident at high frequencies, since dislocation avalanches don’t have time to grow and propagate, and lower losses are observed
- This underlying noise mechanism never disappears and the extension of its effects is at present unknown

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

EMAS gain 0, frequency 0.21 Hz





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

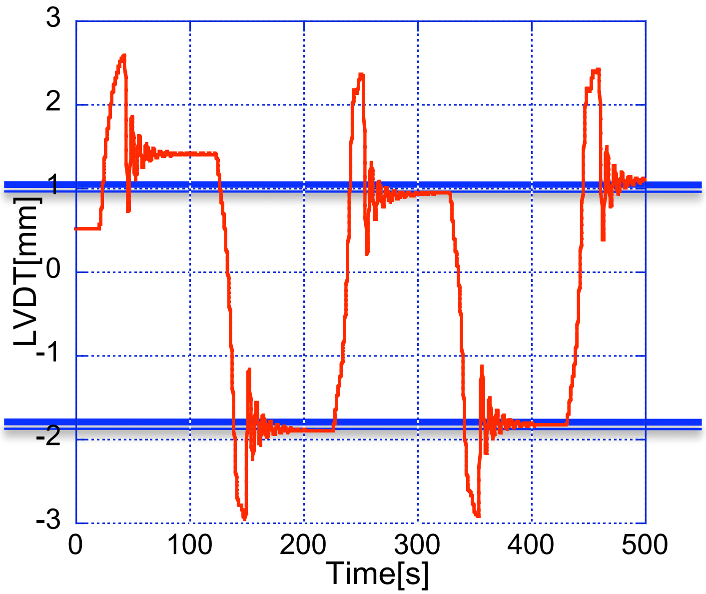
Subjecting the system to the same force, but slowly returning the lifting force to zero, thus generating no oscillations:

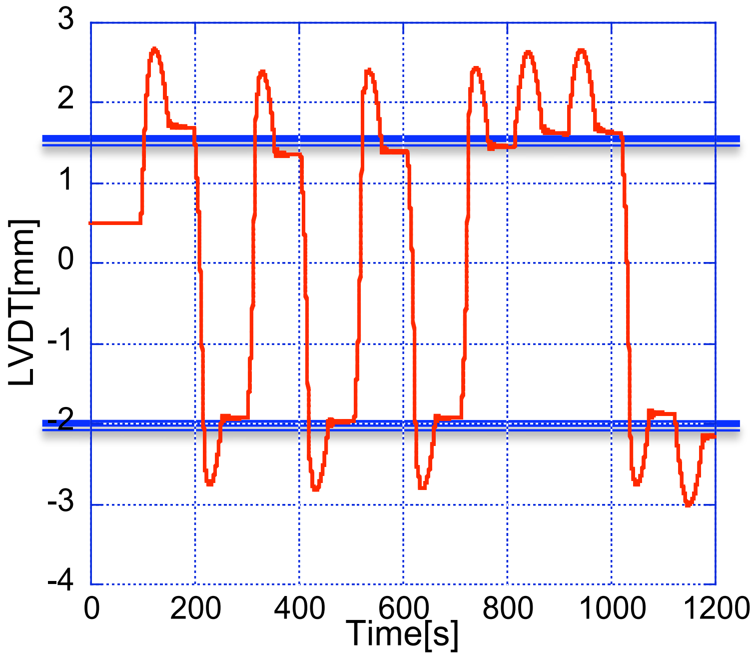
HYSTERESIS OBSERVED FOR ALTERNATE SIGN EXCITATION

NO HYSTERESIS FOR SAME SIGN EXCITATION

Hysteresis amplitude grows with low frequency tune

EMAS gain -2, frequency 0.15 Hz





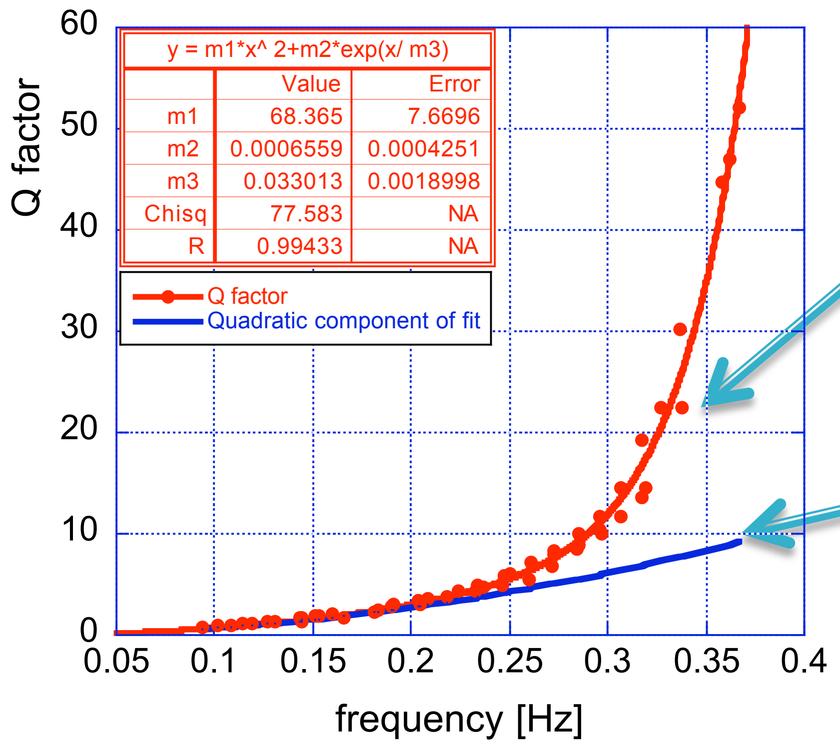
OSCILLATIONS APPEAR to be ineffective TO WASH-OUT HYSTERESIS at low frequency: not enough oscillations to delete hysteresis

Proposed explanation:

percentage of elasticity provided by entangle dislocations that, under pulses stresses, can mobilize and eventually re-entangle in different equilibrium position, thus explaining the observed hysteresis.

Quality factor measurement

two different mechanical tuning, resonant freq. 0.24 and 0.21 Hz



	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

Deviation from quadratic above 0.20 Hz, confirmed even after changing the radial compression of the blades , as if a loss mechanism were depressed at high frequencies

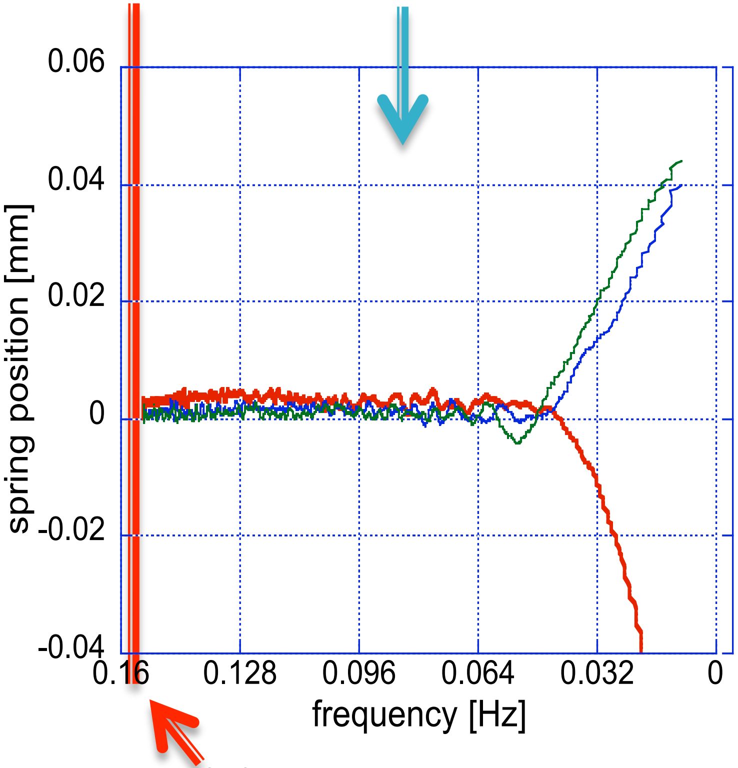
the expected quadratic behavior

The deviation of Q from the f^2 function seems to be material dependent

The increase of the Q-factor implies reduced losses at higher frequencies: explainable if the dissipation process needs a longer time to develop. If the system is slow enough, a limit loss level is reached, corresponding to an hysteretic regime in which dislocation avalanches can completely mobilize ➡TIME INDEPENDENT DISSIPATION

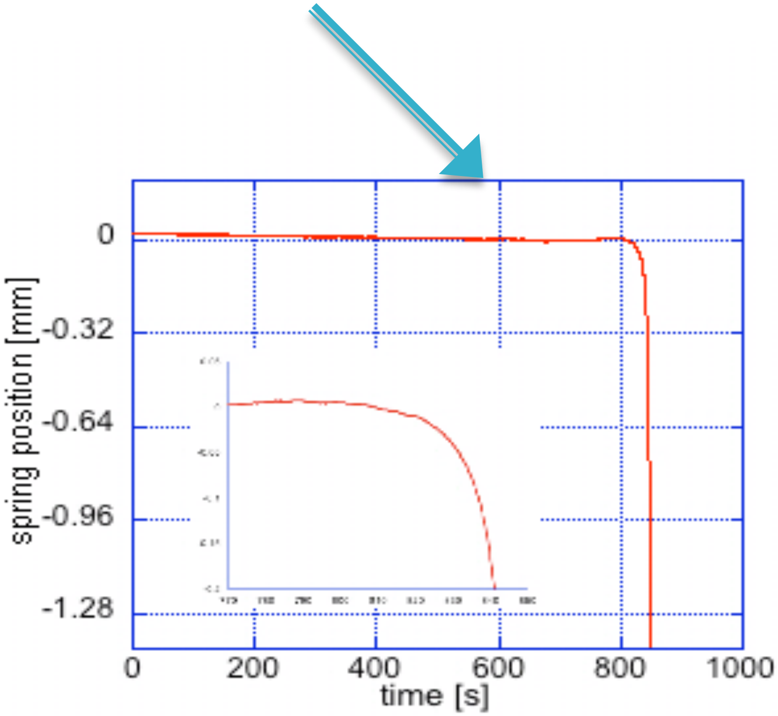
Low frequency instability

System scanned with decreasing frequencies and no excitation



instability region starting from ~ 0.2-0.15 Hz

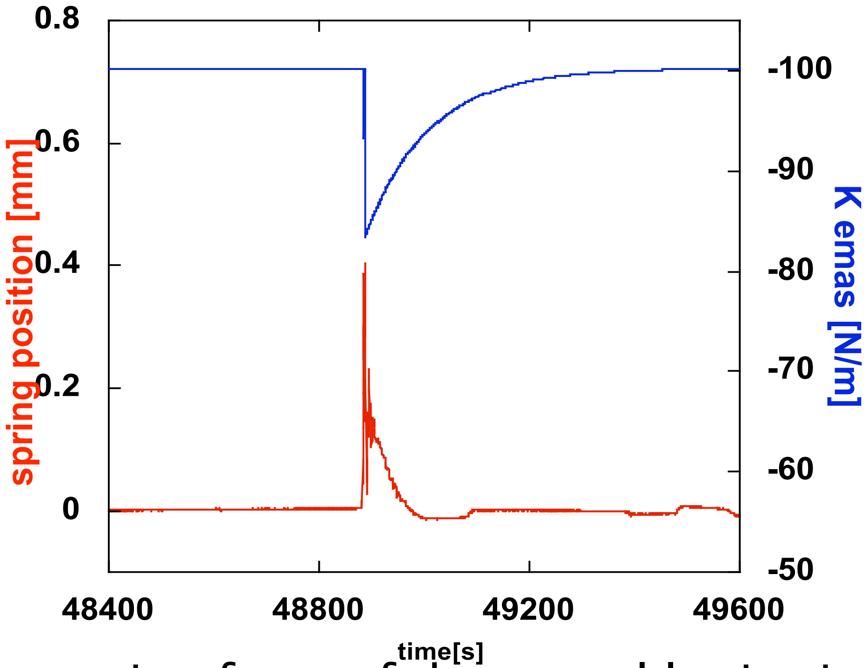
Zoom-in of a collapse event: the filter abandons the equilibrium position very slowly, then accelerates
Single run-off at fixed frequency



Some suddenly-activated mechanism occurred inside the blades!

Control program detects the beginning of a run-off → threshold 30 mV=24μm
K_{emas} reduced toward less negative value, increasing the resonant frequency
→ more re-entanglement time to the system

WE ARE ABLE TO STOP THE RUN-OFF MECHANISM



Explanation: The restoring force of the crystal lattice is nulled by the GAS and EMAS mechanism, the system is kept stable only through the restoring force provided by entangled dislocations.

Perturbations causing disentanglement can trigger collapse →

THE DOMINO EFFECT, INVOLVING AVALANCHES OF DISLOCATIONS, PROPAGATES OVER THE WHOLE SPRING'S VOLUME

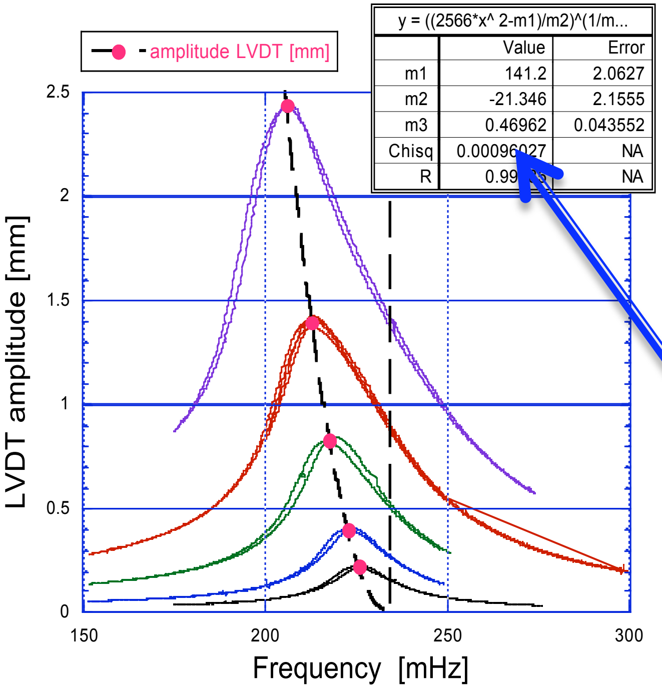
Dissipation and stiffness dependence from amplitude

Looking at the behavior of the resonances, for swept sine excitation of different amplitudes. Experiment repeated for EMAS gain 0 and -2. Considering a scenario involving SOC of dislocations contributing to stiffness, the total elastic constant of the system can be thought as

$$\boxed{K_{effective} = K_B + K_A A^x}$$

The resonant frequency for the 65Kg payload mass becomes amplitude dependent

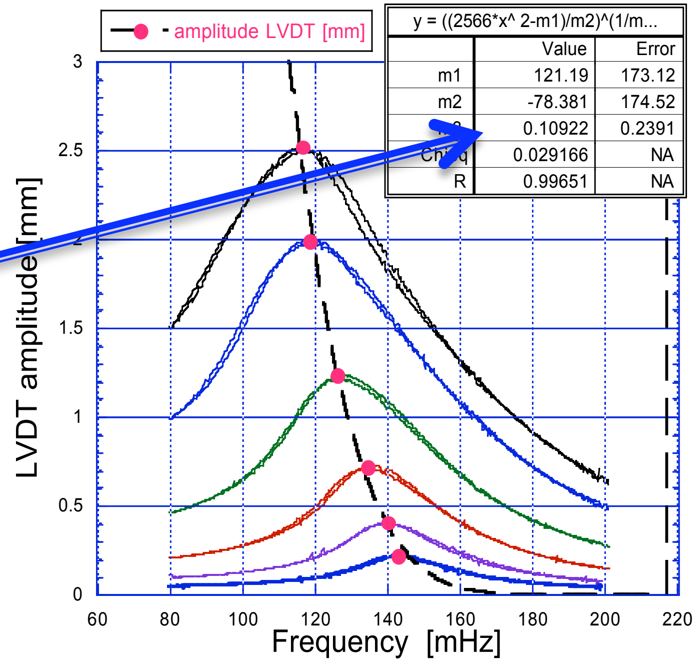
$$\boxed{f = \frac{1}{2\pi}\sqrt{\frac{K_B + K_A A^x}{M}}}$$



y = ((2566*x^ 2-m1)/m2)^(1/m...

	Value	Error
m1	141.2	2.0627
m2	-21.346	2.1555
m3	0.46962	0.043552
Chisq	0.00096027	NA
R	0.99[illegible]	NA

X=0.5
within
~1σ

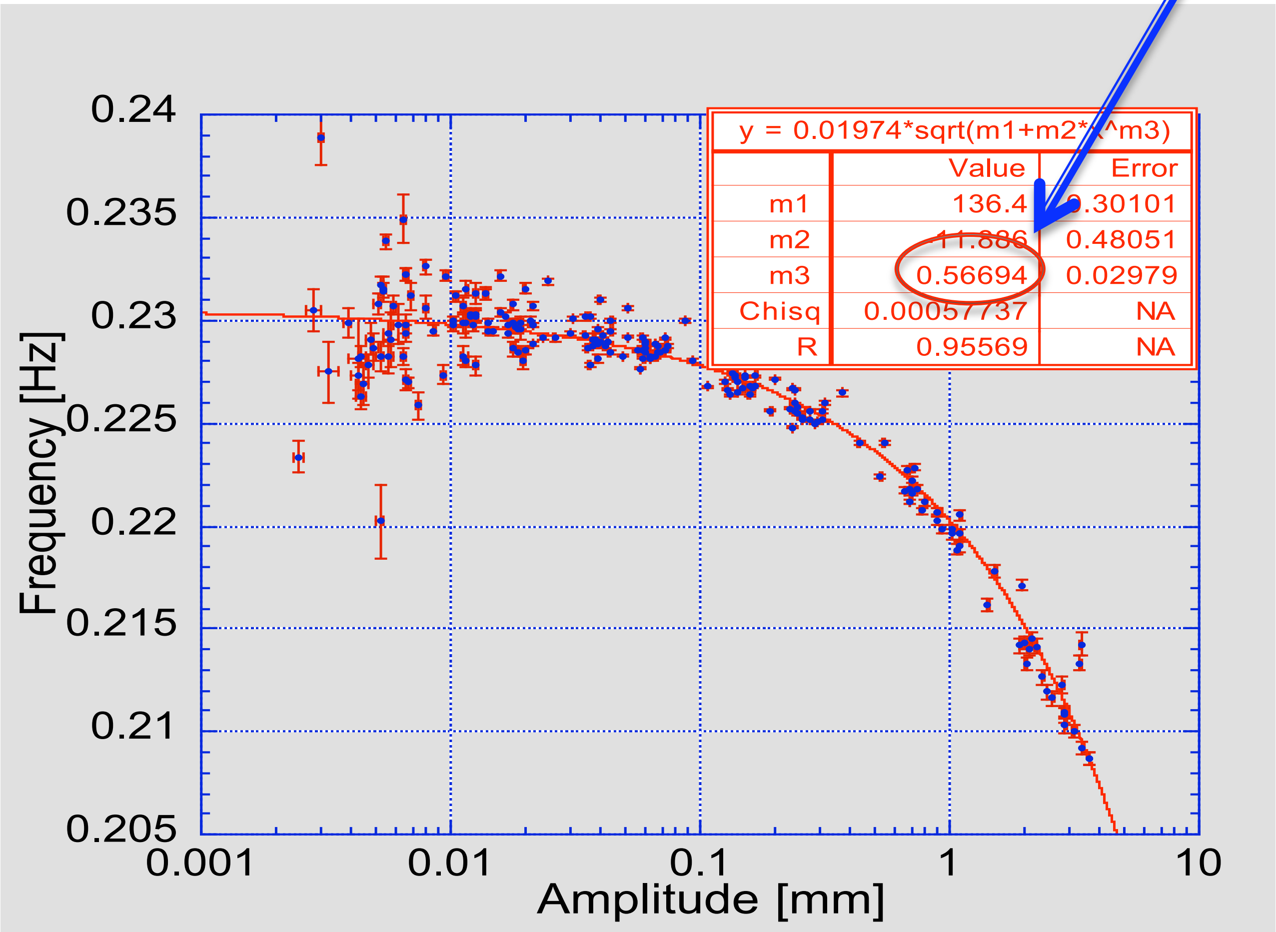


y = ((2566*x^ 2-m1)/m2)^(1/m...

	Value	Error
m1	121.19	173.12
m2	-78.381	174.52
m3	0.10922	0.2391
Chisq	0.029166	NA
R	0.99651	NA

Cross checking it in the time domain by studying ring-down measurements, again the best fit is obtained for an exponent of 0.5:

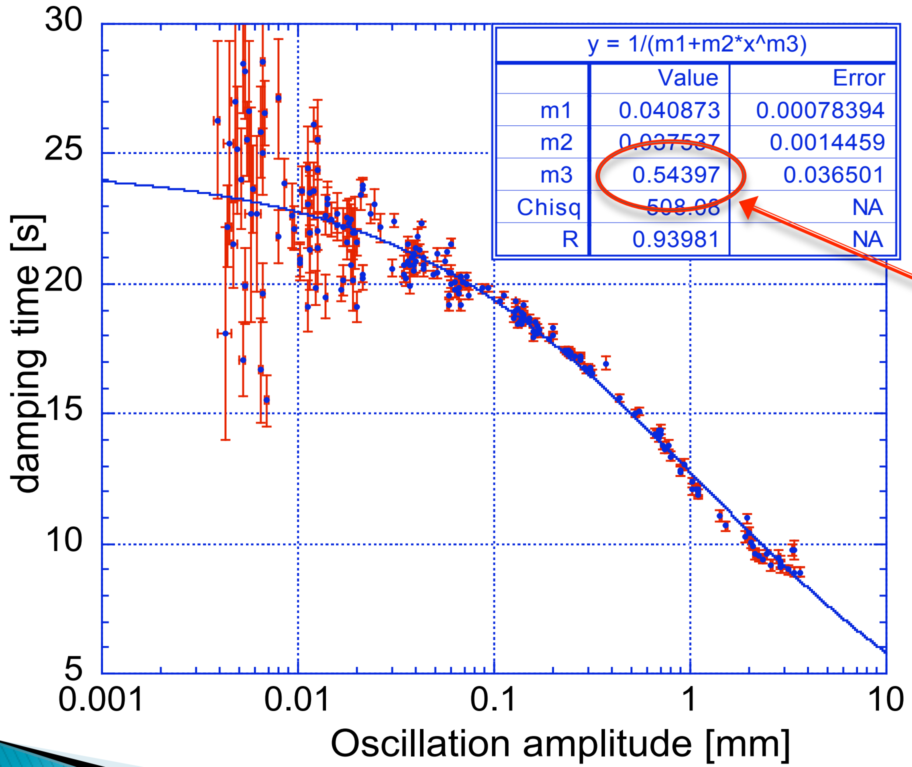
$$f = \frac{1}{2\pi}\sqrt{\frac{K_B + K_A A^x}{M}}$$



y = 0.01974*sqrt(m1+m2*x^m3)

	Value	Error
m1	136.4	0.30101
m2	11.886	0.48051
m3	0.56694	0.02979
Chisq	0.00057737	NA
R	0.95569	NA

- Disentangled dislocations weaken the material Young's modulus => freed dislocations might cause increased dissipation.
- Analyzing ring-downs with a damped sinusoidal function to find the damping time τ and the oscillation amplitude A and fitting the data with



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

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

we found again an amplitude exponent of 0.5 within 1.2 σ

The observed loss of Young's modulus and the increase of dissipation follow the same power law: this is a confirmation that the two effect share the same source, most likely disentangled dislocations.

Conclusion and future perspective

✓Static hysteresis was the first indicator of something shifting inside the material. This, the previously observed 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.

✓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 may be the ultimate materials for seismic attenuation filters and inertial sensors, but they need to be studied deeply since different losses mechanism may still spoil their performance

✓Dislocation movement impede fragility => we want to avoid this movement => fragility will be an unavoidable effect