Dissipation processes in Metal springs

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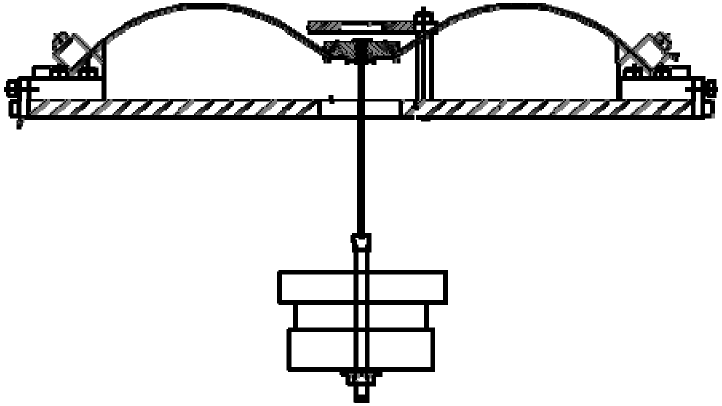
Pisa November 24, 2008

LIGO-G0810032-v1

Abstract

- We studied the dissipation properties of the Maraging springs used in the seismic isolation system of Advanced LIGO, Virgo, TAMA, et c., with emphasis on mechanical hysteresis, which seems to play a more important role than expected. The Monolithic Geometric Anti Spring vertical attenuation filter at very low frequency presented an anomalous transfer function of 1/f instead of the expected $1/f^2$, static hysteresis and eventually instability.
- While characterizing these effects we discovered a new dissipation mechanism and an unexpected facet of elasticity. Not all elasticity comes from the rigid crystalline structure. A non-negligible fraction of elasticity is contributed by a changing medium, probably entangled dislocations. Oscillation amplitude (or other external disturbances) can disentangle some of these dislocations thus reducing the available restoring force of a spring. The disentangled dislocations temporarily provide boosted viscous like dissipation, then they lock back providing elasticity with a different equilibrium point. A stable oscillator can be made unstable by small external perturbation and fall over, or can be re-stabilized by externally providing temporary restoring forces while the dislocations re-entangle. The process likely explains the anomalous transfer function.
- We may be getting closer to solve the old dilemma if dissipation in metals is better described by viscous losses or by a loss angle.

The GAS mechanism



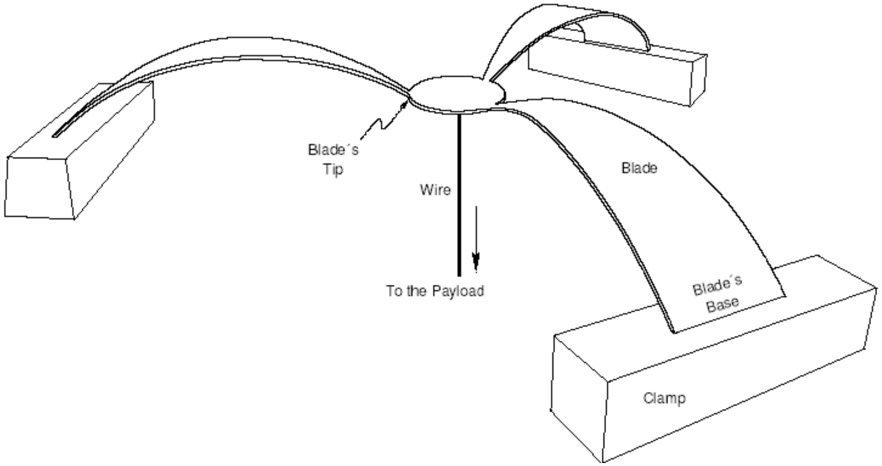
The GAS filter consists of a set of radially-arranged cantilever springs, clamped at the base to a common frame ring.

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 Anti-spring effect is proportional to the radial compression.

The GAS mechanism is used to null the restoring forces of a spring.

This exposes hysteresis, thermal effects and any other underlying effect.

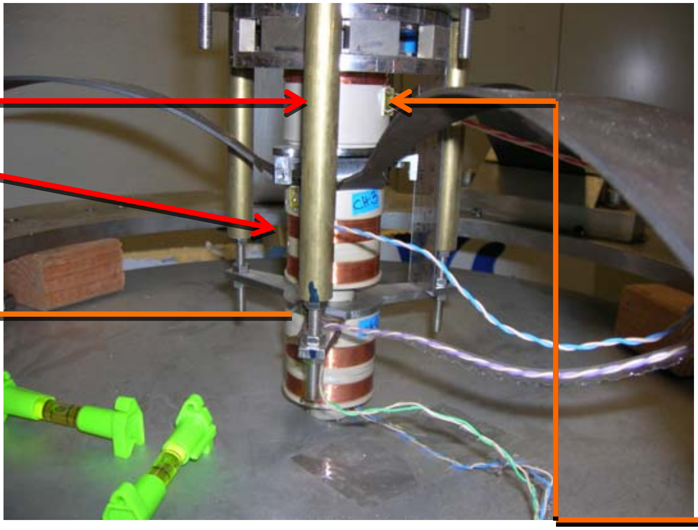


The experiment: EMAS mechanism

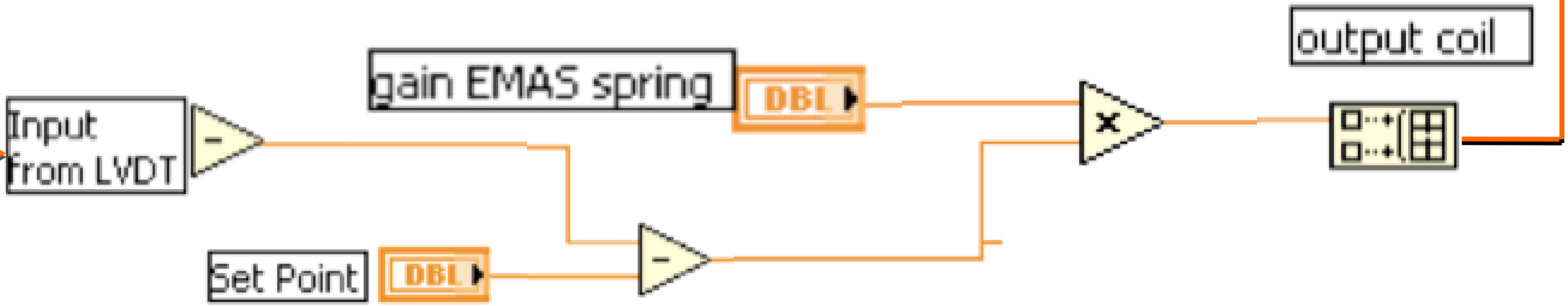
The SAS seismic attenuation system for the Advanced LIGO Gravitational Wave Interferometric Detectors. A.Stochino et al., 2008

The GAS is tuned to obtain a low mechanical resonant frequency (typically 200 mHz) at the working point

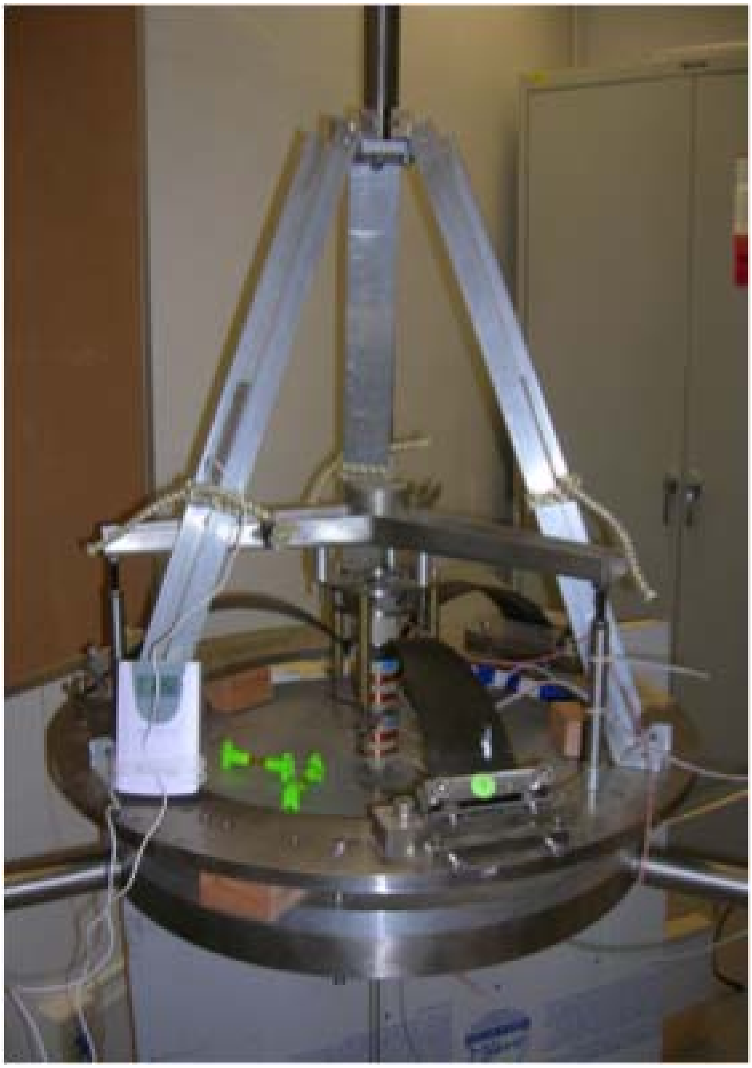
Remote control
Non contacting **actuator**
LVDT position sensors



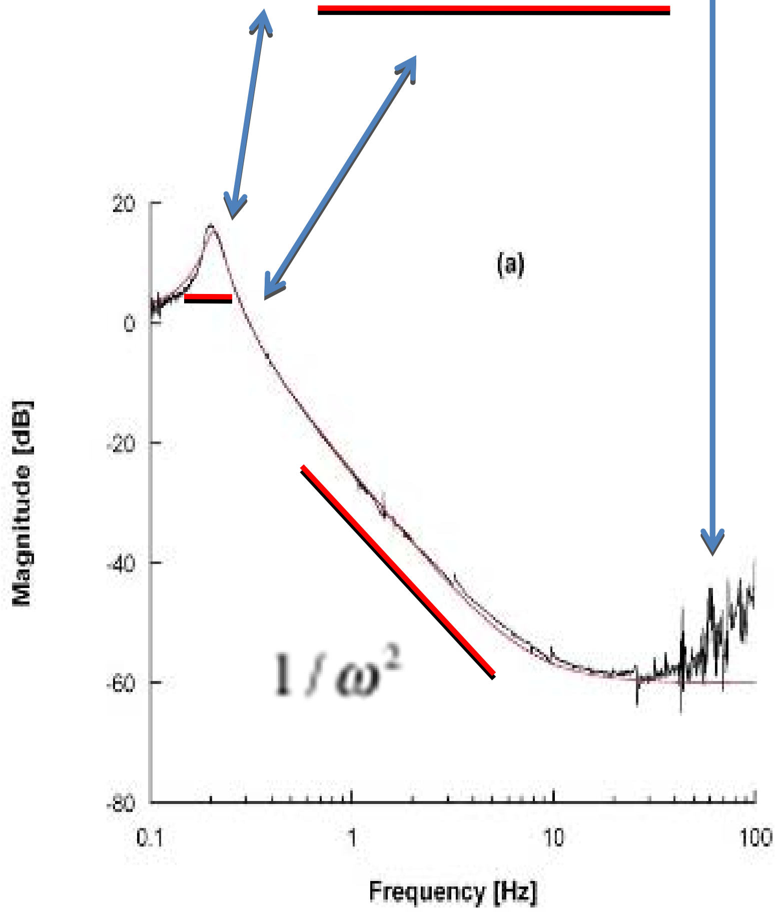
Box around the filter to prevent air turbulence
IIR integrator for thermal compensation: keeps the system at the working point
EMAS with variable gain: further reduces the resonant frequency



Theoretical transfer function of a GAS-filter



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



Instead we found….

Depressing transfer function with Electro-Magnetic Anti Springs and counterweights

Moves down
With ω tune

Stationary and Unexpected 1/f Transfer Function

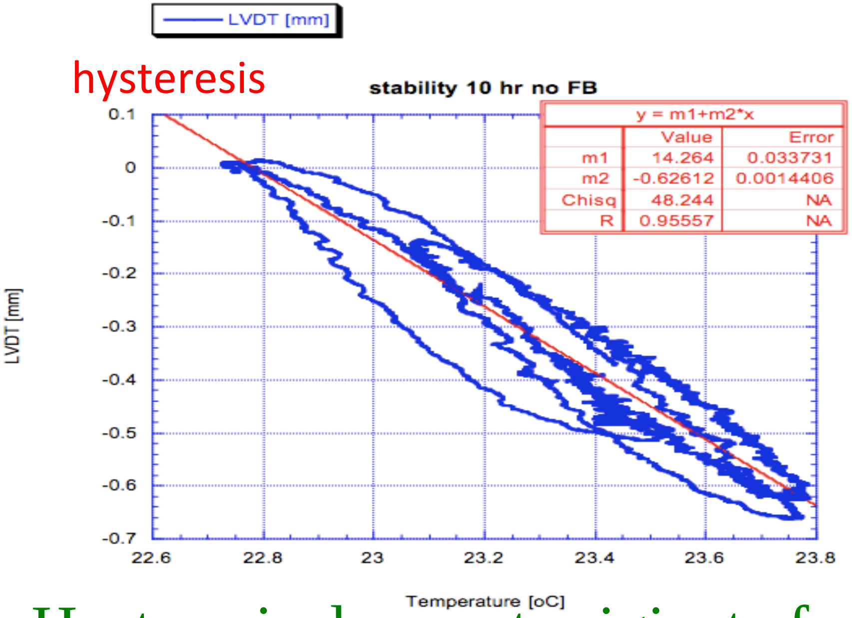
Hysteresis is likely responsible for the unexpected 1/f attenuation behavior observed in the GAS-filter transfer function, when the system is tuned at very low frequency,
at or below 100 mHz

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

A. Stochino, *Performance Improvement of the Geometric Anti Spring (GAS) Seismic Filter for Gravitational Waves Detectors*, SURF-LIGO 2005 Final Report, LIGO-P050074-00-R.

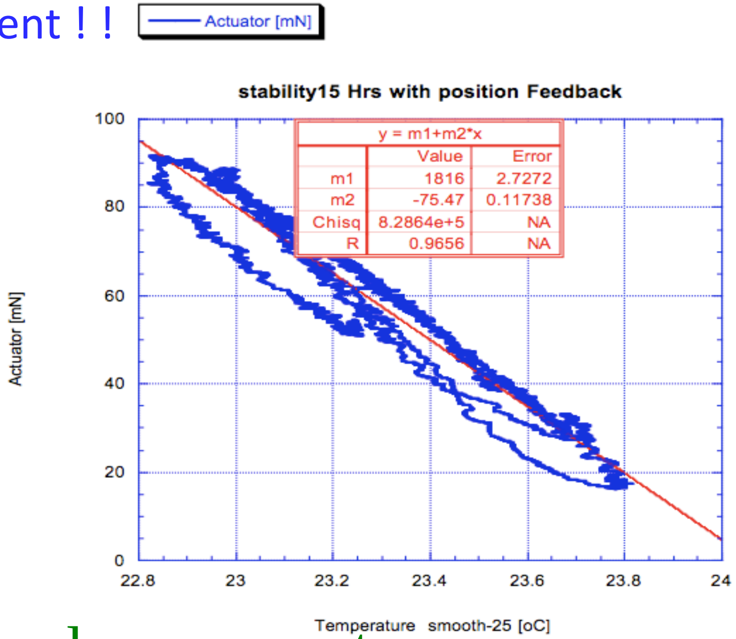
Evidence of hysteresis in the thermal feedback

- Filter movement under overnight lab thermal variations
- Without feedback
- The movement shows Thermal hysteresis



Switching on the feedback, that means no system movement, we expected no hysteresis

But hysteresis shifted to the control current ! !



Hysteresis <u>does not</u> originate from the actual movement…

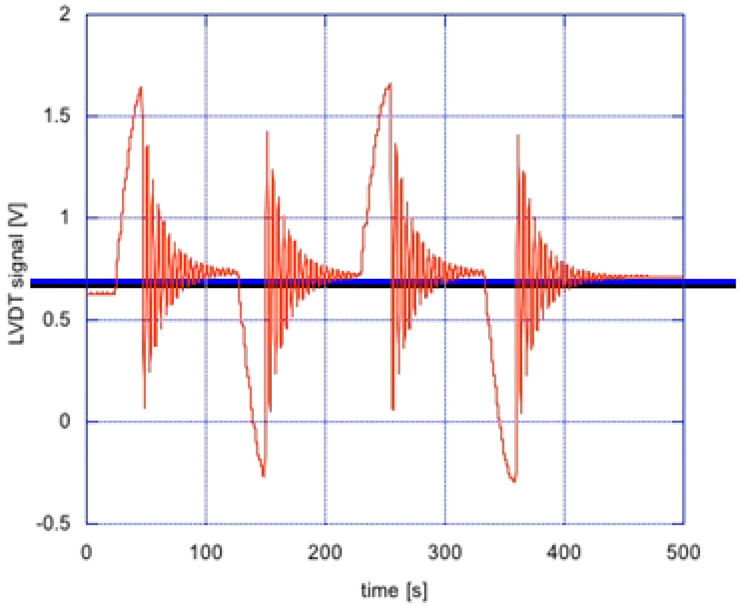
Hysteresis derives from evolving stresses inside the materials!

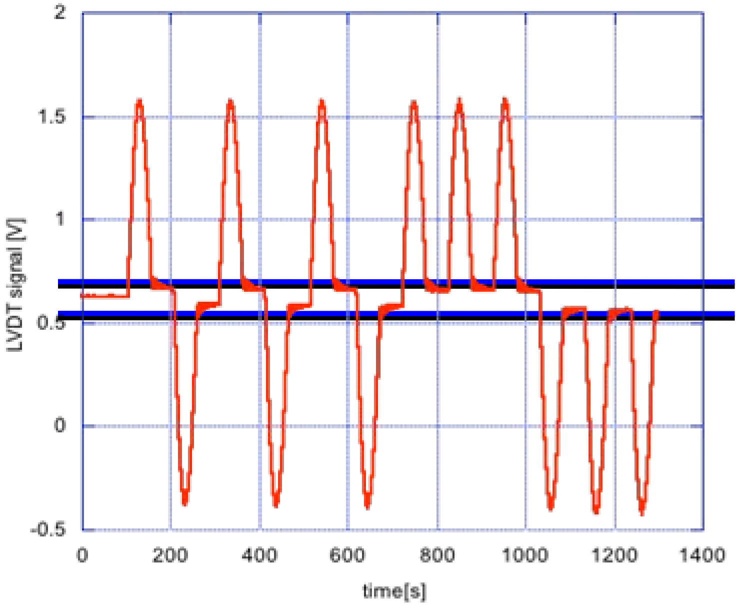
Obvious if you think that metal grains can only “see” internal stresses

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

Thermal feedback time constant much longer than experiment duration

EMAS gain 0, frequency 0.21 Hz



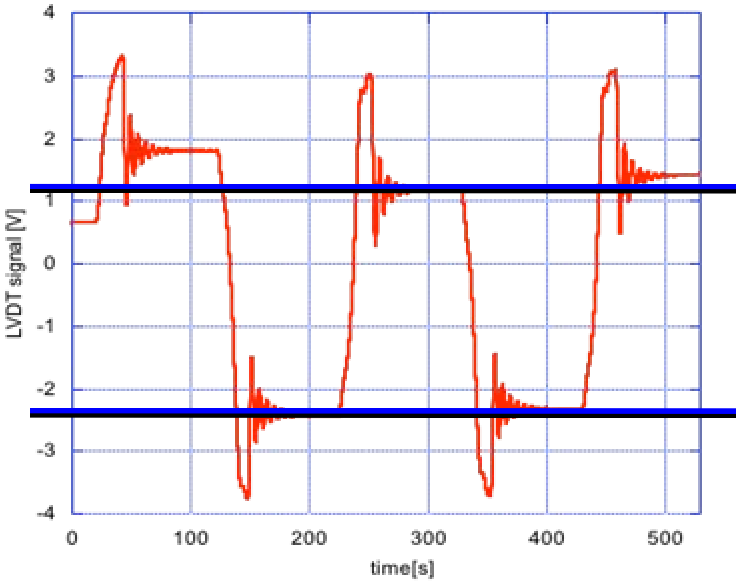


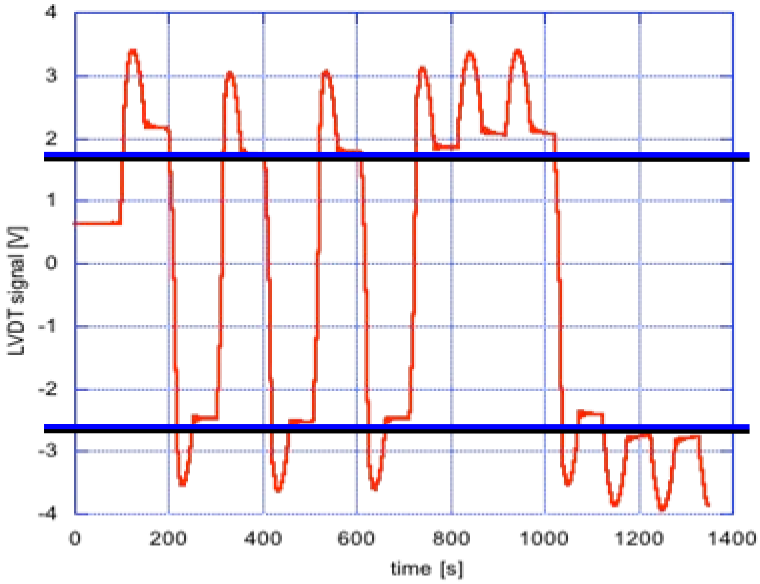
We apply a force lifting the spring to a certain height,
then cut the force and let the system oscillate freely:
NO HYSTERESIS OBSERVED

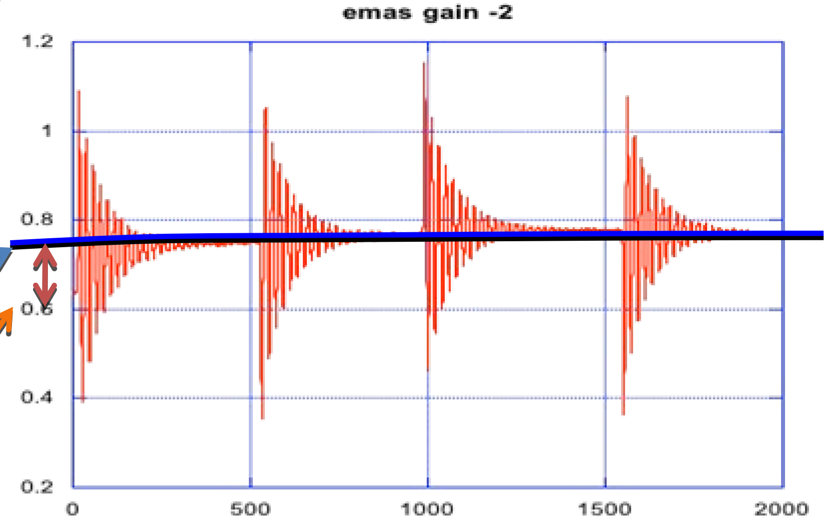
Subjecting the system to the same force, but slowly returning the lifting force to zero, thus generating no oscillations:
HYSTERESIS OBSERVED FOR ALTERNATE SIGN EXCITATION
NO HYSTERESIS FOR SAME SIGN EXCITATION

Hysteresis amplitude grows with low frequency tune

EMAS gain -2, frequency 0.15 Hz







Applying a slow oscillatory force, whose amplitude reduces with an exponential profile, we observe a thermal drift but no hysteresis

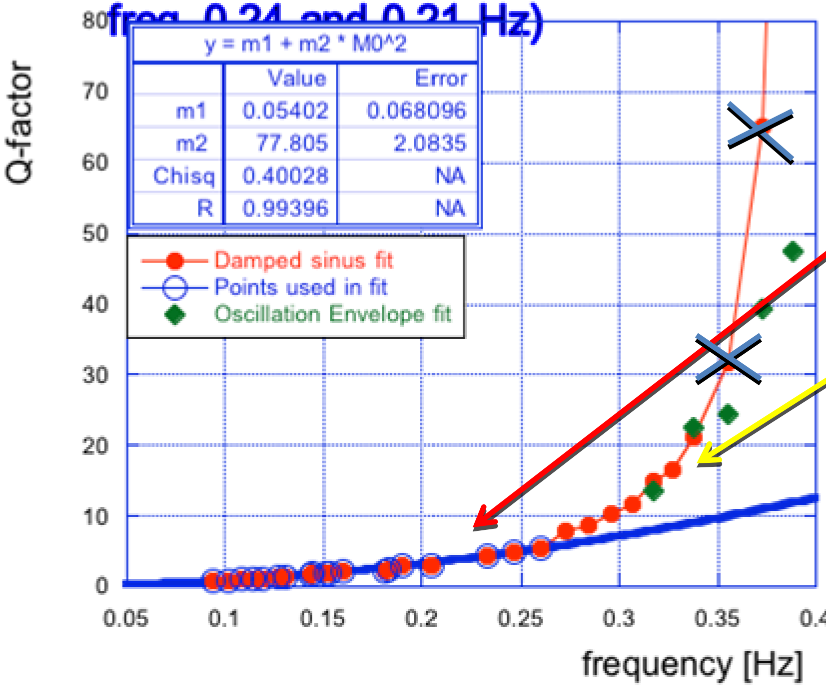
OSCILLATIONS APPEAR TO WASH-OUT HYSTERESIS:

not at very low frequencies, where there are not enough oscillations to delete hysteresis

Large initial hysteresis due to previously integrated stresses

Quality factor measurement

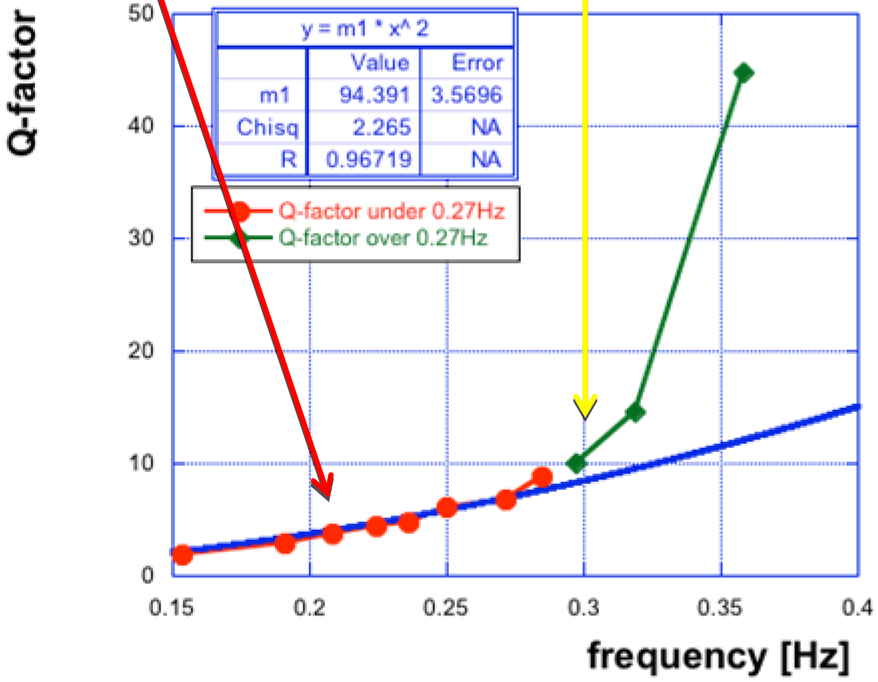
For each EMAS setting we excited the spring applying a short voltage pulse on the actuator, monitored the ringdown and extracted the spring's height, frequency and lifetime using a damped sinus fit. We repeated the analysis with different tuning (resonant freq. 0.24 and 0.21 Hz)



y = m1 + m2 * M0^2	Value	Error
m1	0.05402	0.068096
m2	77.805	2.0835
Chisq	0.40028	NA
R	0.99396	NA

the expected quadratic behavior

Deviation from quadratic above 0.27 Hz, confirmed after changing the radial compression of the blades



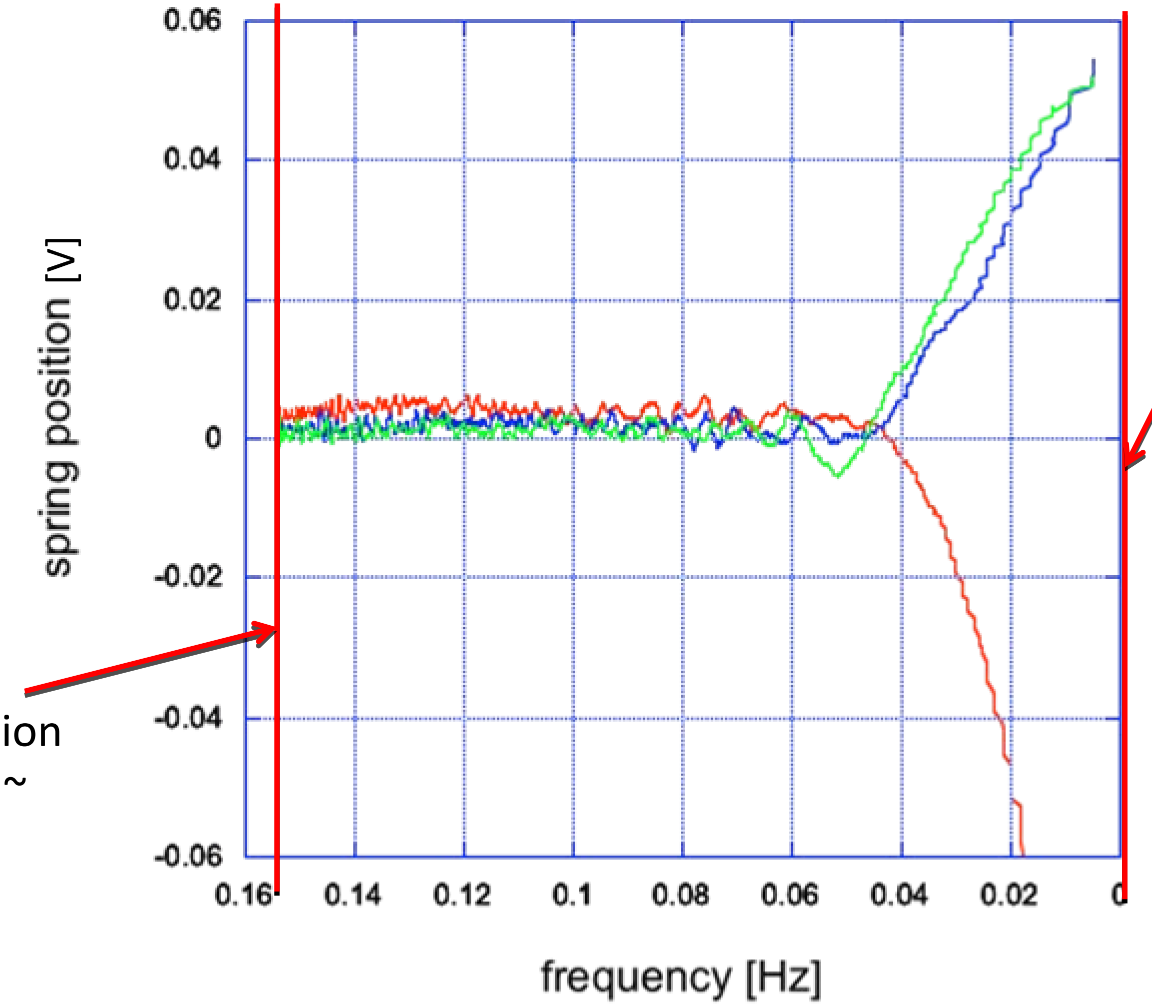
y = m1 * x^ 2	Value	Error
m1	94.391	3.5696
Chisq	2.265	NA
R	0.96719	NA

The deviation of Q from the f^2 function seems to be material dependent, not tune dependent.

Low frequency instability

System scanned with increasing negative EMAS gain and no excitation

Mechanical noise triggers the runoffs

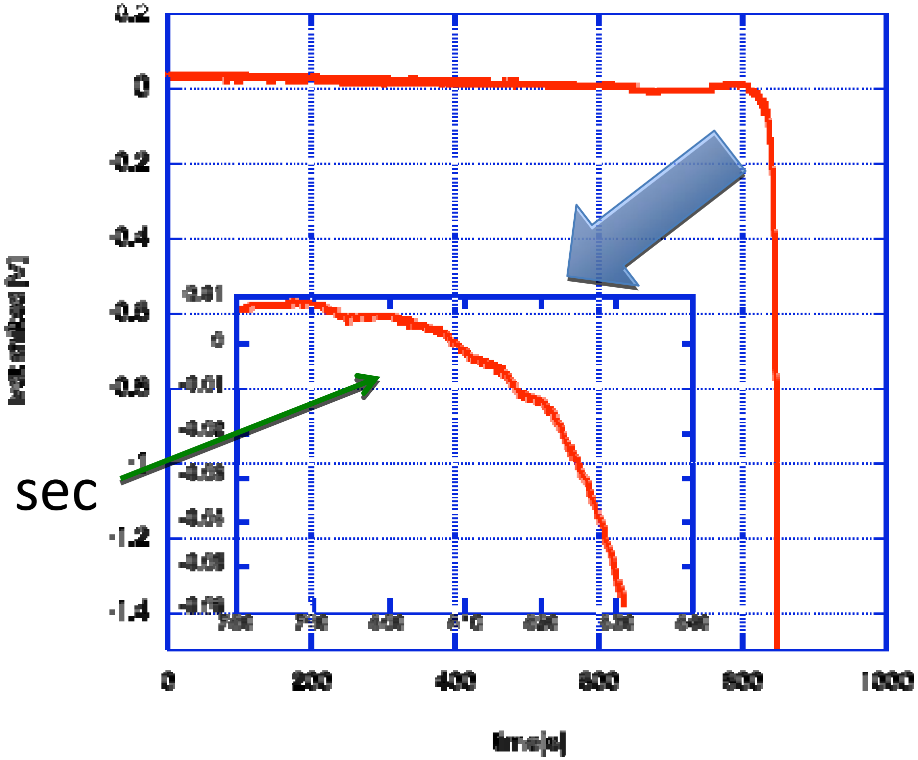


Mathematical instability

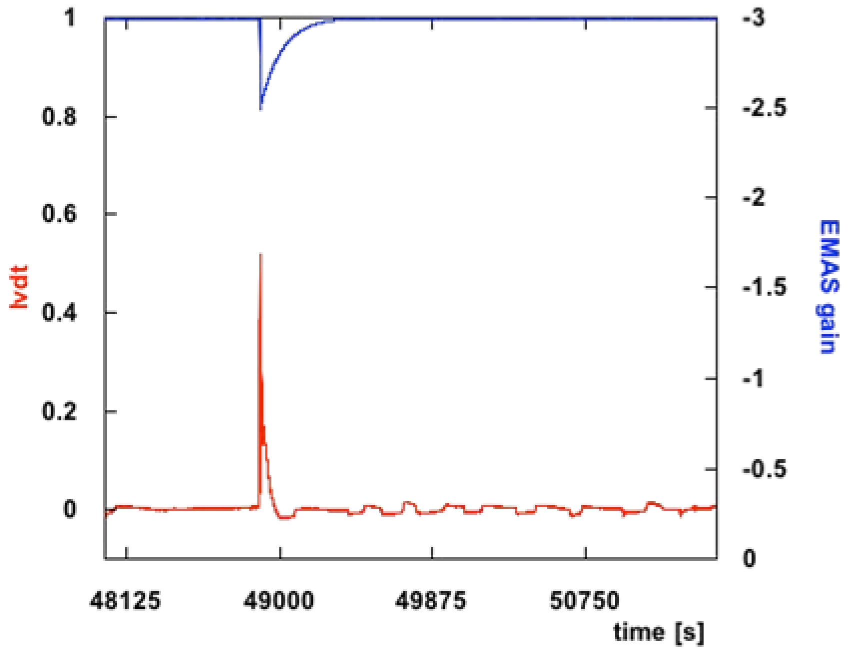
instability region starting from ~ 0.2-0.15 Hz

The initial runoff is slow, much slower than the spring time constant (~4 sec, for runoff starting at 40 mHz), and then accelerate progressively faster

The same runoff is observed in IP (Saulson et al., *The IP as a probe of anelasticity, 1993*)



~20-30 sec



An external perturbation triggers run-off, as runoff is detected EMAS gain backs-off and ramps back to nominal value.

The process can be stopped by providing temporary stiffness to the system.

Dissipation and stiffness dependence from amplitude

We studied the behavior of the resonant peaks, for swept sine excitation of different amplitudes.
The experiment was repeated for EMAS gain 0 and -2
We divide the total elastic constant of the system into :

movement of dislocations inside the material, when the material is subjected to stress + crystal lattice elasticity

We consider =

oscillation amplitude

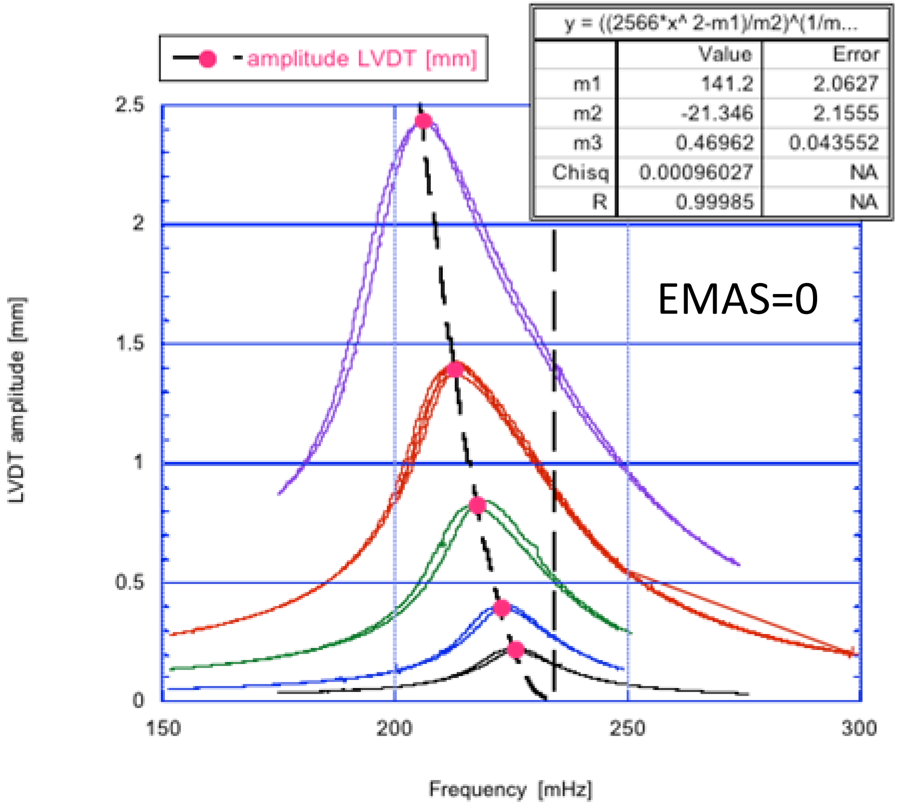
usual spring constant

amplitude dependence variation of the spring elastic constant due to progressive mobilization of the dislocations

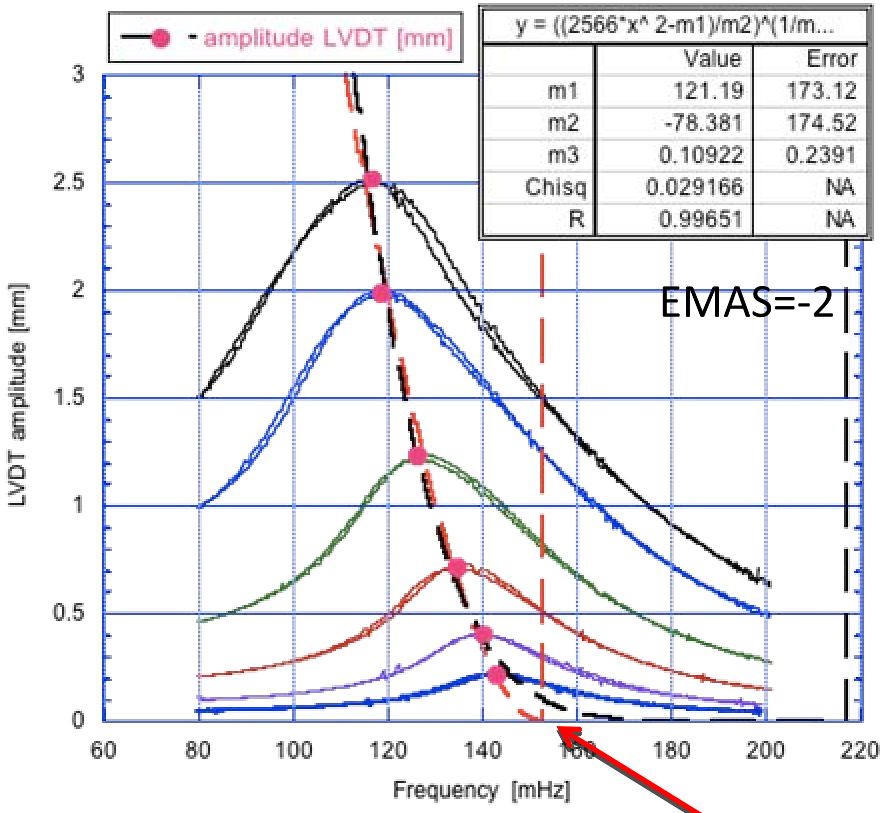
We are assuming here that the entangled dislocations inside the material contribute to the elasticity constant and that, changing the stress, some of them can be disentangled, thus reducing the effective Young modulus

The frequency becomes amplitude dependent if the number of disentangled dislocation is function of the excitation amplitude according to:

Fitting in the frequency domain..



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	0.99985	NA

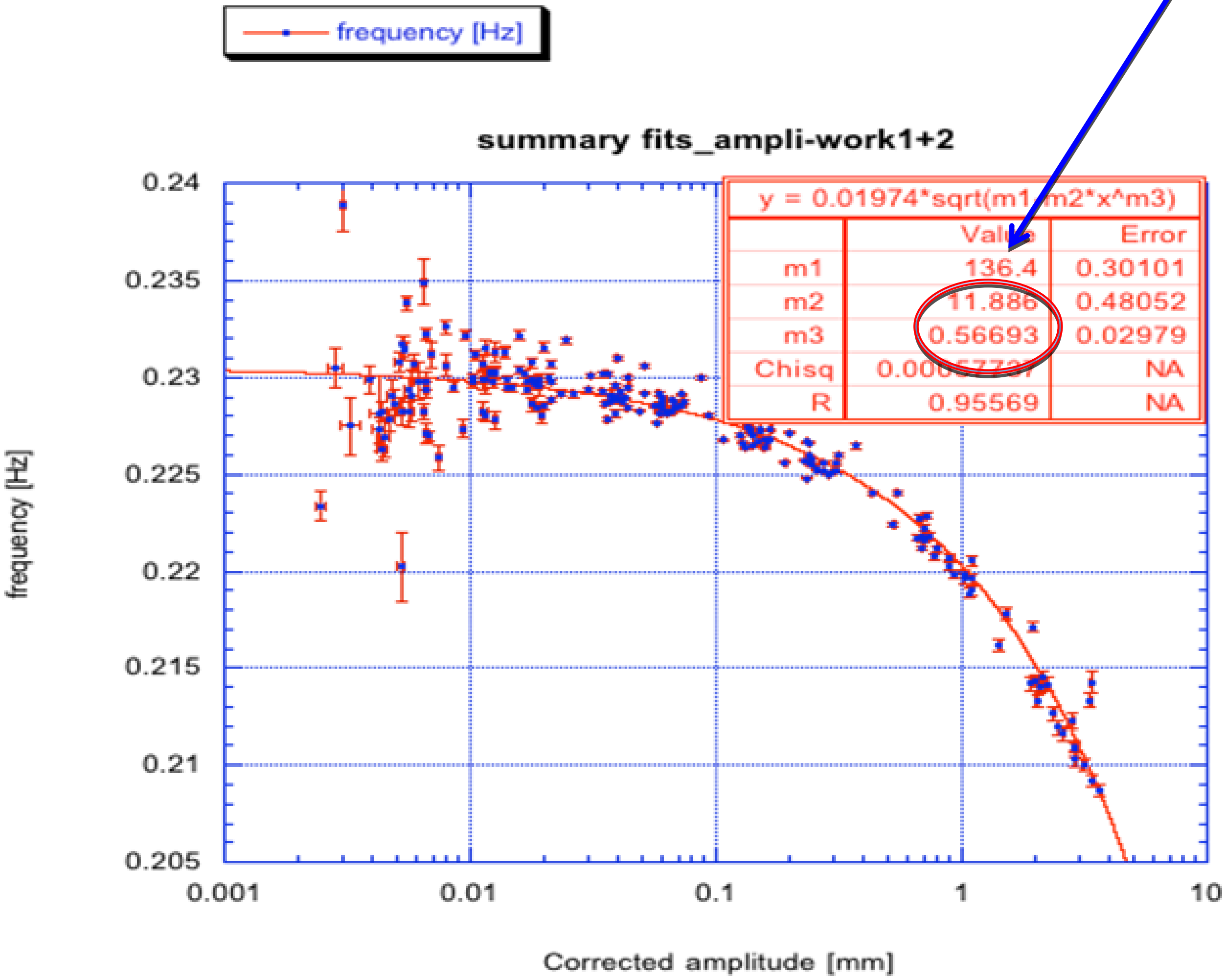


y = ((2566*x^ 2-m1)/m2)^(1/m...	Value	Error
m1	121.19	173.12
m2	-78.381	174.52
m3	0.10922	0.2391
Chisq	0.029166	NA
R	0.99651	NA

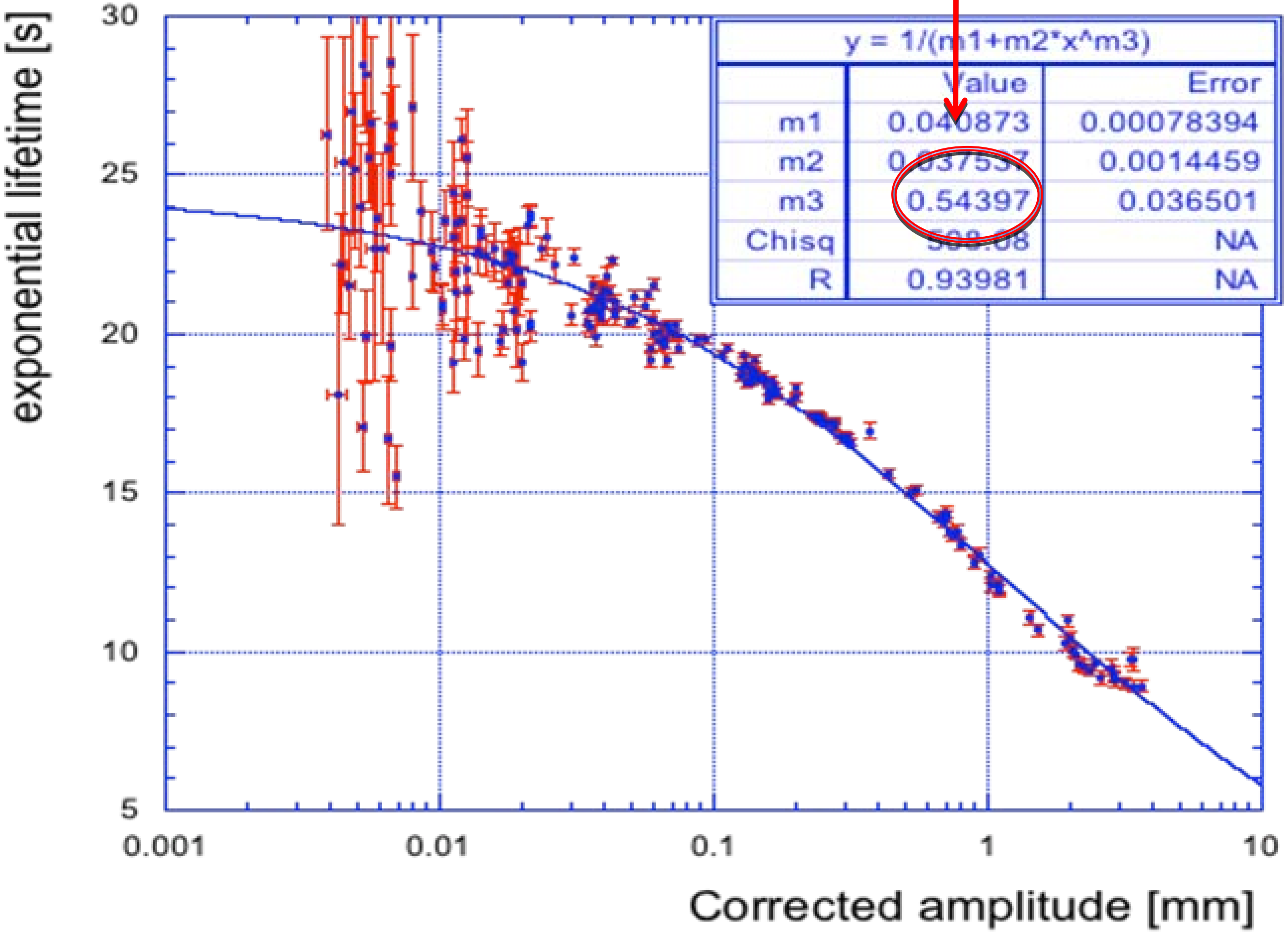
Fit forced to 0.5

The fit is compatible with an amplitude exponent of 0.5

Cross checking it in the time domain, again the best fit is obtained for exponent 0.5:



Remarkably, the same thing happens with the lifetime of the ring down oscillation… the fit requires a o.5 exponent for the changing losses



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

Which theory we like

- We observe a static effect, viscosity is not adequate to explain it, we need a different model.
- The theoretical bases that comes closer to our observation is Marchesoni's On dislocation damping at low frequencies, based on Self Organized Criticality (Bak, Tang and Wiesenfeld)
- Dislocations entangle forming a rigid lattice which contribute to elasticity
- Dislocations can disentangle, move and produce viscous like effects, when subjected to varying stress
- They eventually re-entangle, thus producing static hysteresis

Cagnoli G, et al.
1993 Phil. Mag. A 68 865

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

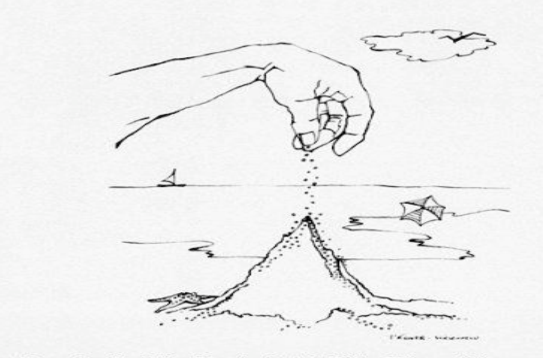


Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

Self organized criticality could explain transition from highly predictive to an almost random oscillator in LIGO-Ips

- Transition from “gaussian” to full-blown-avalanche dominated statistics at LF

500mHz

30mHz

CONCLUSIONS summary

Disentanglement and re-entanglement of dislocations inside the material can explain

➢Appearance of hysteresis in the GAS filter, : dislocation can disentangle and mobilize, thus re-entangle, generating hysteresis. The effect is more evident at low frequencies

➢The quadratic law of the Q-factor, followed if the system is slow enough. A fixed amount of loss per period is reached, corresponding to disentangled dislocations regime

➢The departure from the quadratic law: at higher frequencies dislocations don't have time to fully mobilize and less losses are observed

➢Run-off interpreted as a temporary loss of restoring forces due to mobilization of dislocations (triggered by an external or internal excitation). That's proved by the switch-off mechanism, attributed to re-entanglement

➢Reduction of the spring's elastic constant due to the progressive mobilization of the dislocations: larger stress variations, more dislocations disentangled, thus reducing the effective K_{spring}

➢Corresponding increase of pseudo-viscosity from mobilized dislocations, thus reducing the damping time constant

…and more

- Entanglement and disentanglement of dislocations is an intrinsically fractal behavior
- The observed 1/f Filter Transfer Function would be explainable
- Excess 1/f noise could be expected as well, as aspect of Self-Organized Criticality
- The excess noise found in tiltmeters could be explained
- The loss of predictability of the ringdown decay in the LIGO-SAS Inverted pendula
- The very low coherence and apparent random walk of the Virgo [Ruggi, private comm.] and TAMA [Koji Arai private comm.] Inverted Pendula equilibrium point
- Excess noise in suspended mirrors?

Thermoelastic peak

The heat diffusion produces a contribution to the elastic energy dissipation given by equation

where   is the relaxation time.

For Maraging blades with *h*= 3.44 mm of thickness and an heat-diffusion coefficient

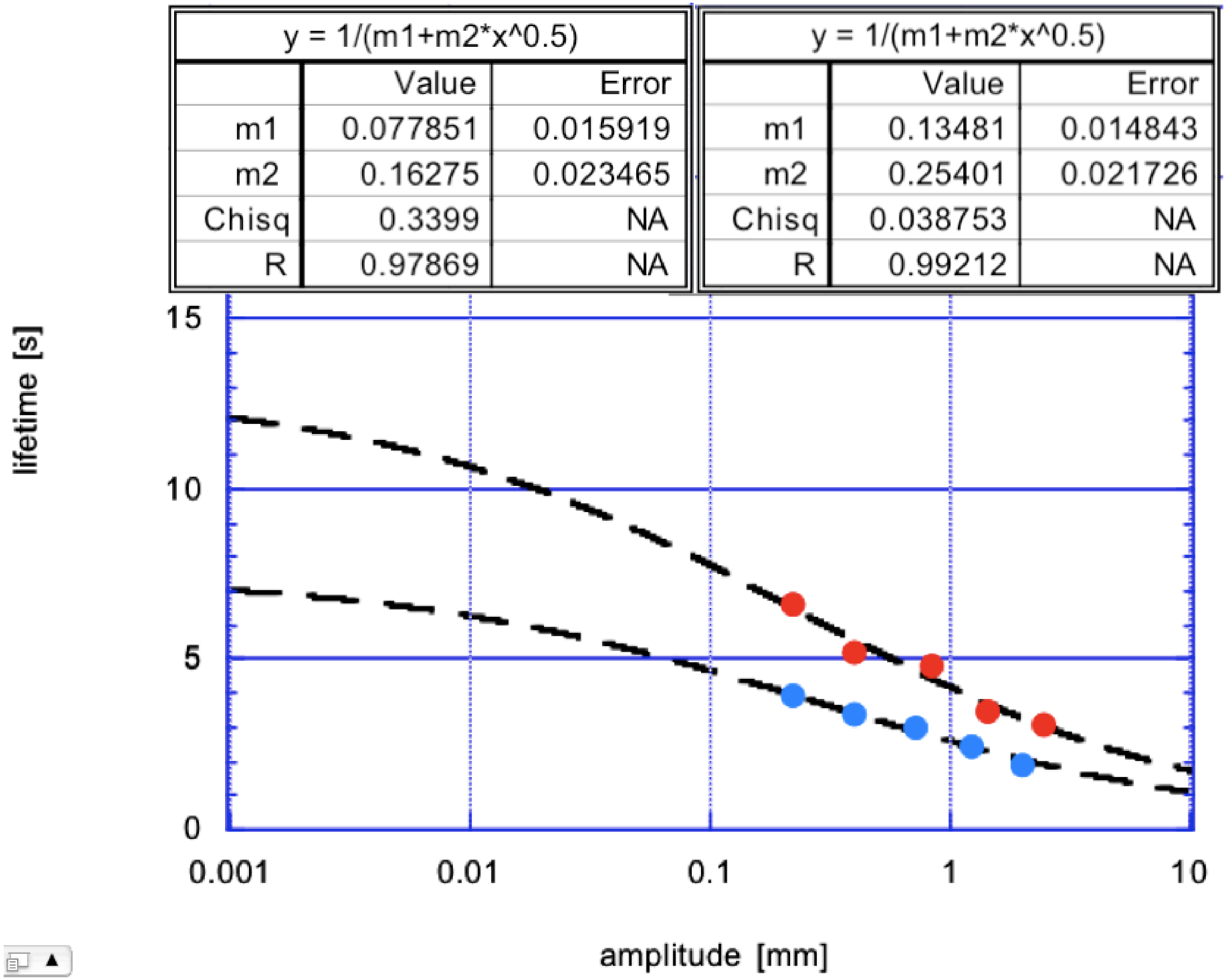
we obtain a peak frequency of 0.73 Hz.

The peak height is not into the 1/f range of the GAS filter transfer function.

CLAMPING PROBLEM...

DECAY OF THE LIGO IP PROTOTYPE

From the frequency domain data we extracted the damping constant from the swept sine FWHM response. We fitted the data with the same function, but fixing the exponent to 0.5.



y = 1/(m1+m2*x^0.5)	Value	Error
m1	0.077851	0.015919
m2	0.16275	0.023465
Chisq	0.3399	NA
R	0.97869	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