Dissipation processes in Metal springs

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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.

Introduction

- We study the dissipation properties of the Maraging springs used in the seismic isolation system of Ad-LIGO (but also Virgo, TAMA, …)

- With particular emphasis on the study of mechanical hysteresis, which seems to play a more important role than expected

Introduction

- 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)

- Anomalous instability is observed as well

- Hysteresis may be generating a new class of excess 1/f noise

Questioning the old models

- Viscosity was very successful to explain MANY material behaviors
- But viscosity is proportional to speed,
  its effects must disappear at lower frequencies

- We observe a static effect,
  viscosity is not adequate to explain it,
  we need a different model.

- The new model needs to
  include the effects previously attributed to viscosity

Which theory we like

- The theoretical bases that comes closer to our observation is Marchesoni's Self Organized Criticality of dislocations
- Dislocations can entangle forming a rigid lattice which can contribute to elasticity
- Dislocations can disentangle and produce viscous like effects
- They can re-entangle to produce static hysteresis

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

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

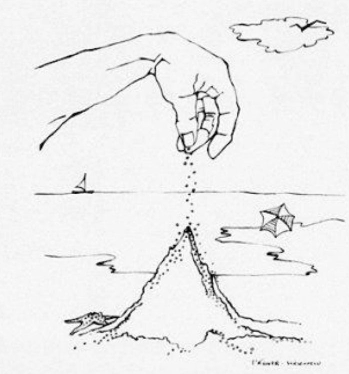
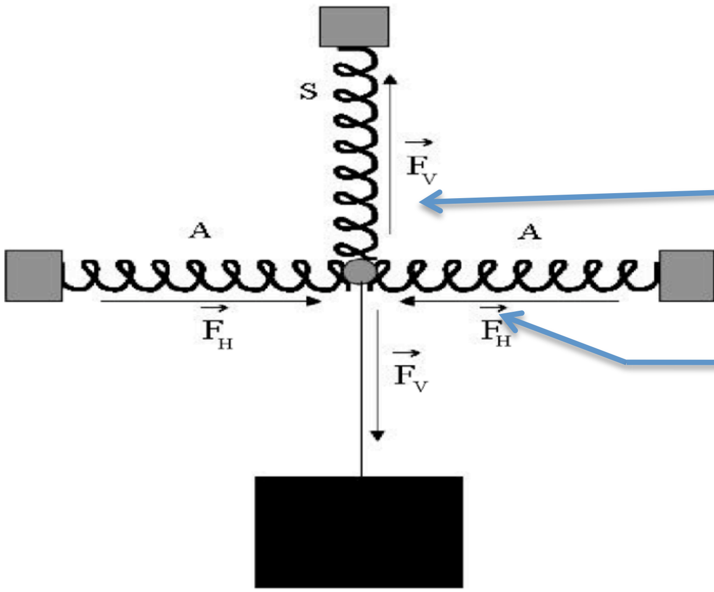


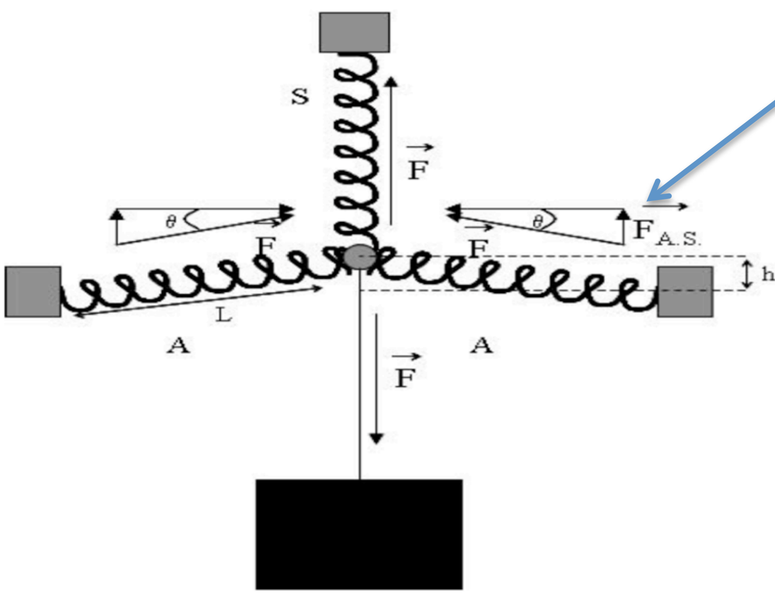
Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

Experimental technique

- Our experiment is based on a GAS spring
- The GAS mechanism is used to null the restoring forces of a spring
- It is a very useful tool to expose the dissipation properties of the materials, including hysteresis
- To study losses and hysteresis we need instruments, like LVDTs, actuators, controls, …
- But let’s start talking about GAS-filter first!

The GAS mechanism





At the working point the vertical spring (S) supports the weight of the payload.

The two horizontal springs (A) carry no load, they are radially compressed, but their forces cancel

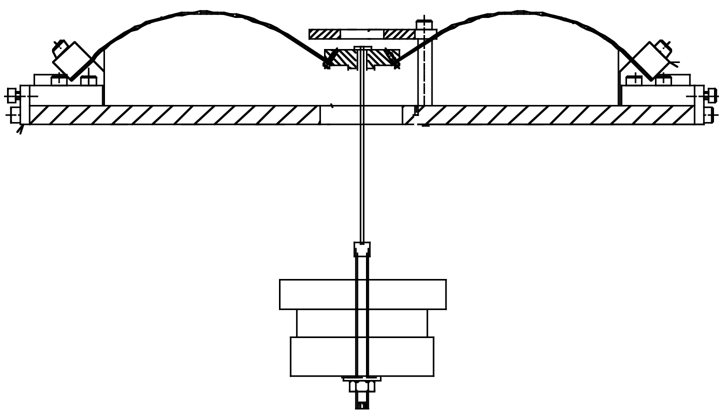
Moving away from the working point the compression of the A-springs results in a vertical component, proportional to the displacement, the Anti-Spring force.

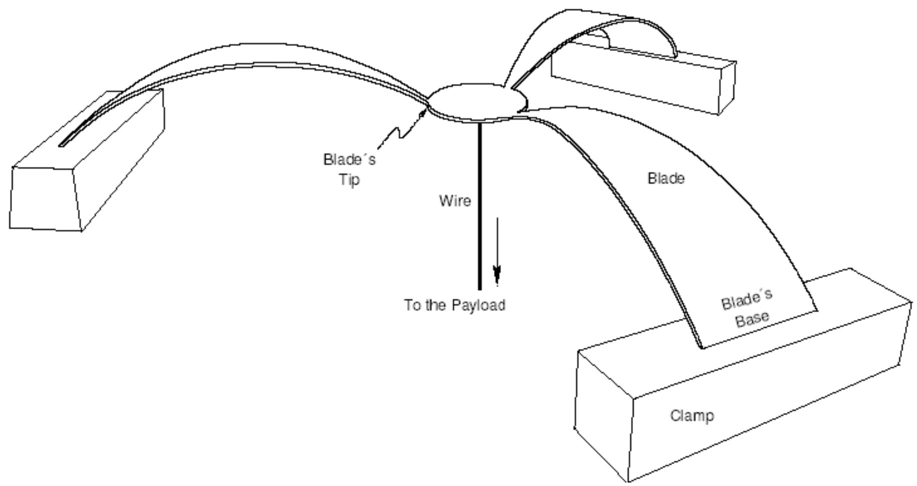
The Anti-spring effect is proportional to the radial compression.

The repulsive springs may be mechanical or magnetic.

the Geometric Anti Spring Vertical attenuation filter

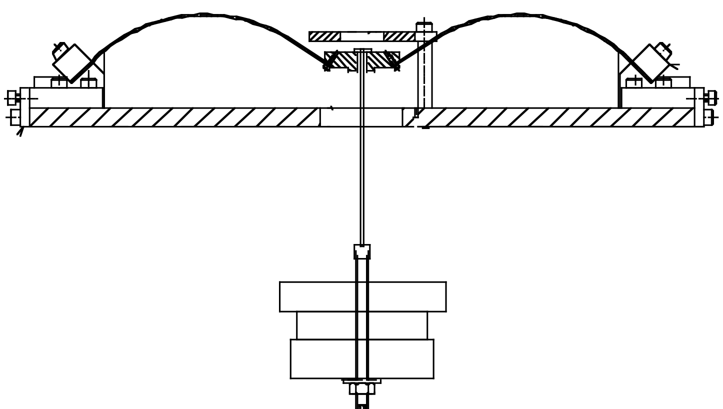
- In the Geometric Anti Spring filter, the functions of the supporting and repulsive springs are combined
- Specially designed leaf springs carry the load
- Arranging them in a symmetric radial configuration, and radially compressing one against the other, generates the Anti Spring effect

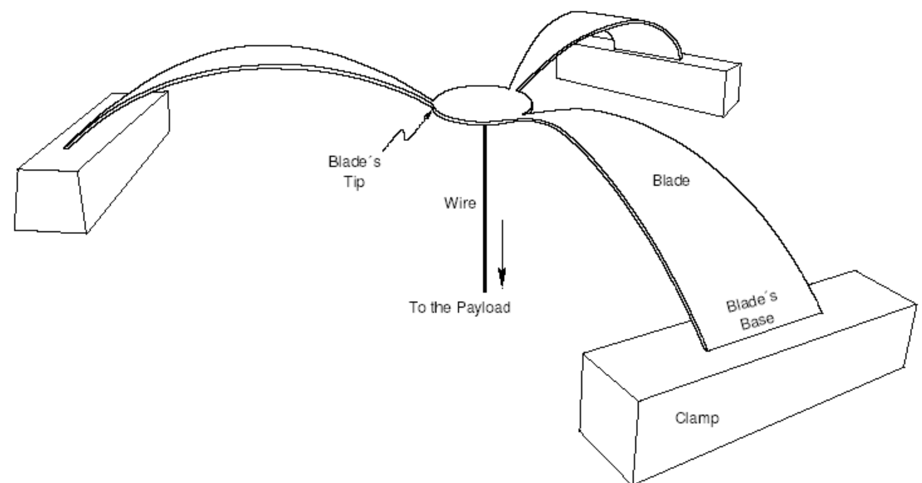




the Geometric Anti Spring Vertical attenuation filter

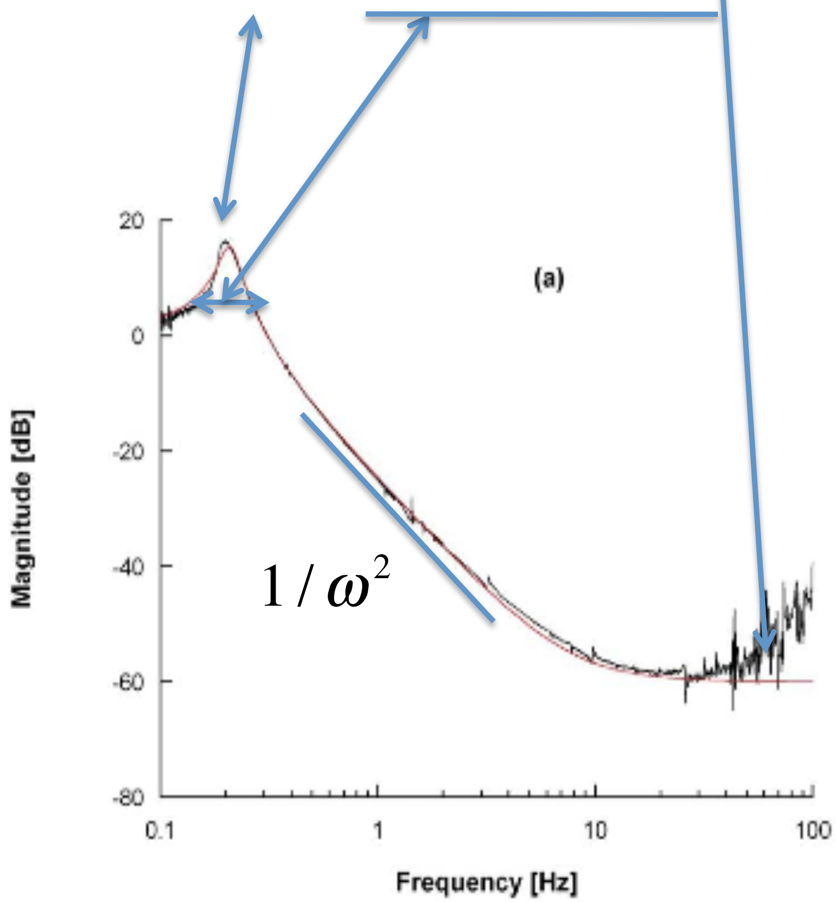
- Large amount of pre-stressing energy is stored in the blades because of the supporting function
- A tunable fraction of what would be the oscillation kinetic energy is stored in the radial compressive load

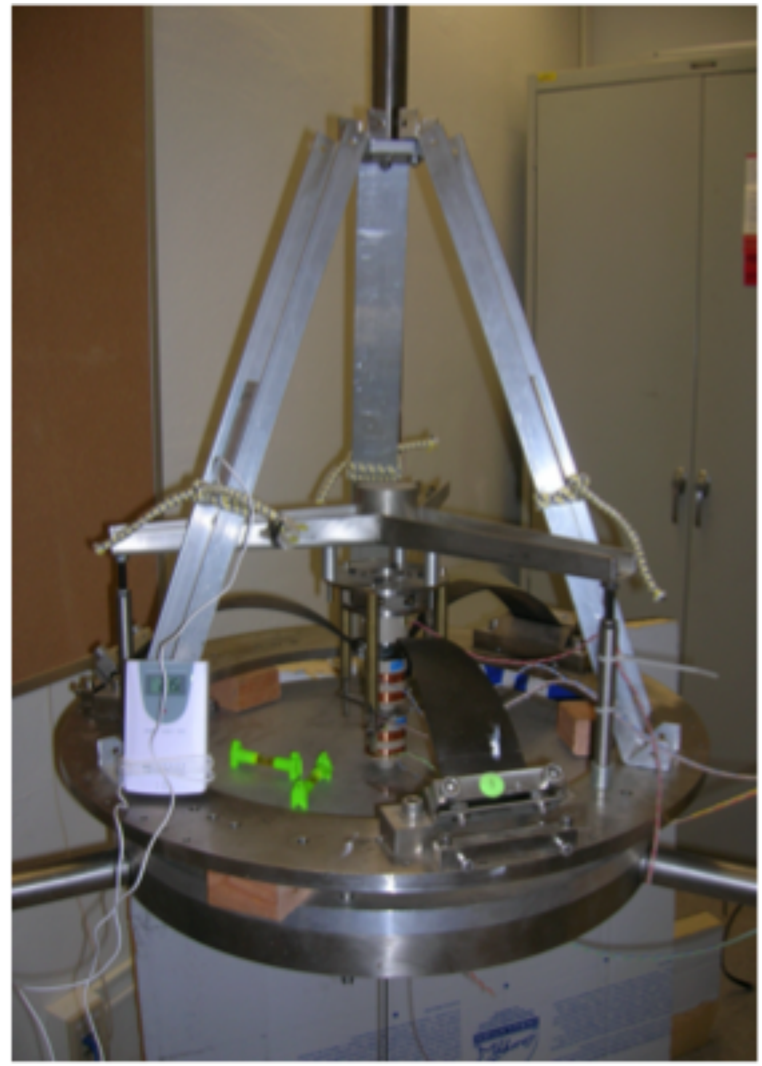




Theoretical transfer function of a GAS-filter

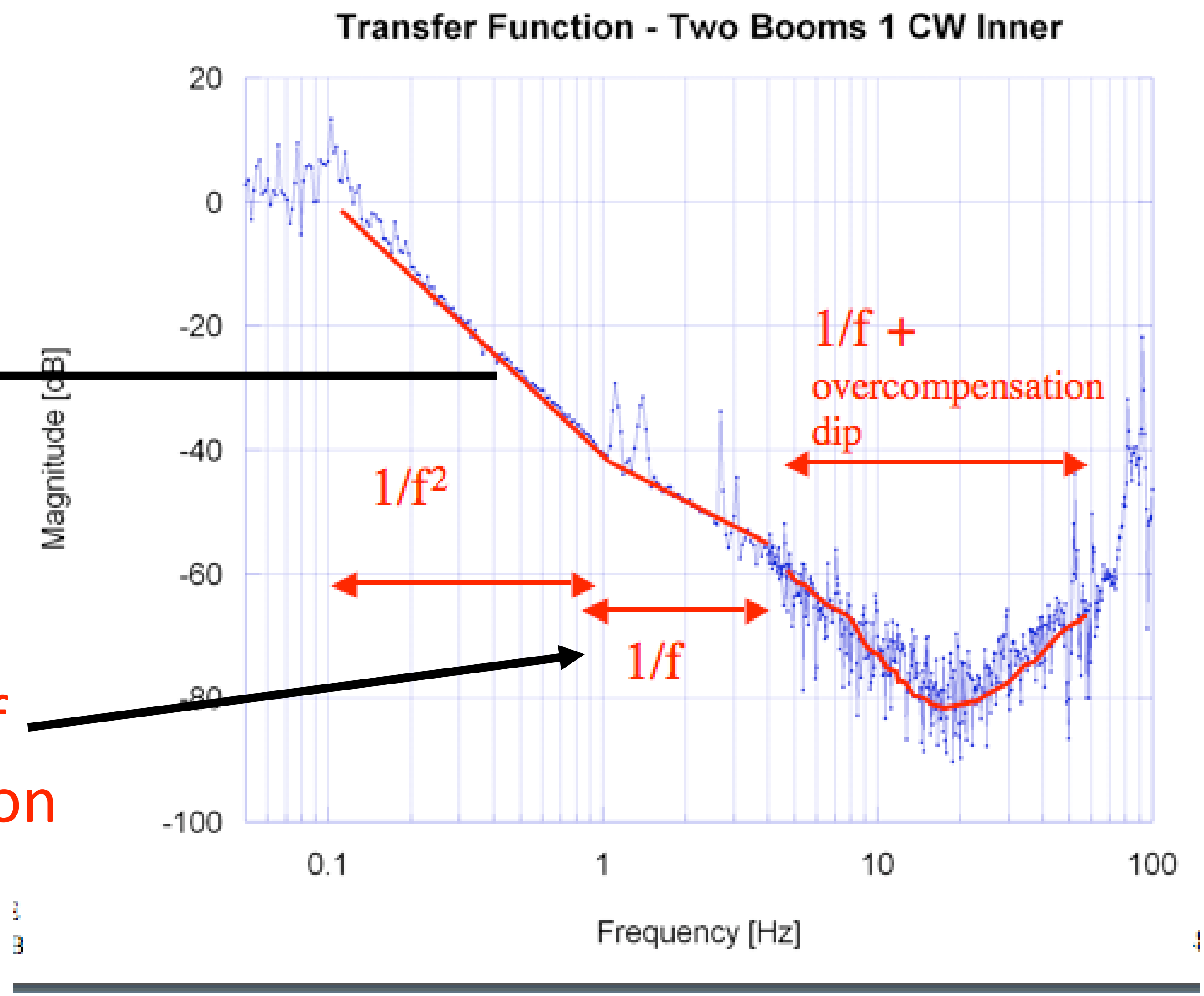
$$H_z(\omega) = \frac{\omega_o^2(1+i\phi)+\beta\omega^2}{\omega_o^2(1+i\phi)+i\gamma\omega-\omega^2}$$





Depressing transfer function with Electr-Magnetic Anti Springs and counterweights

Moves down
With ω tune



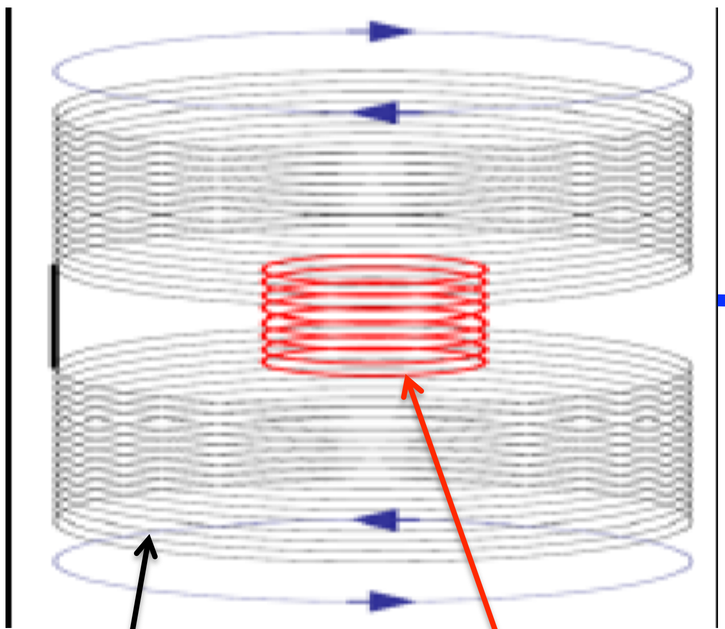
<u>Stationary and</u>
<u>Unexpected</u> 1/f
Transfer Function

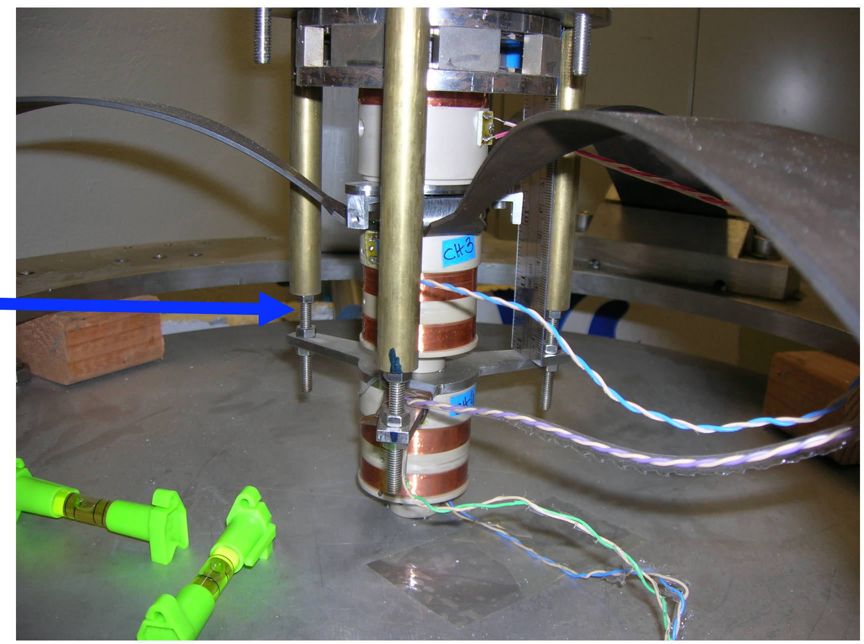
M. Mantovani, R. DeSalvo, *One Hertz Seismic Attenuation for Low Frequency Gravitational Waves Interferometers*, accepted for publication on Nucl. Instr. and Meth. (2005).

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.

The instrumentation used in this experiment

Linear variable differential transformer (LVDT)

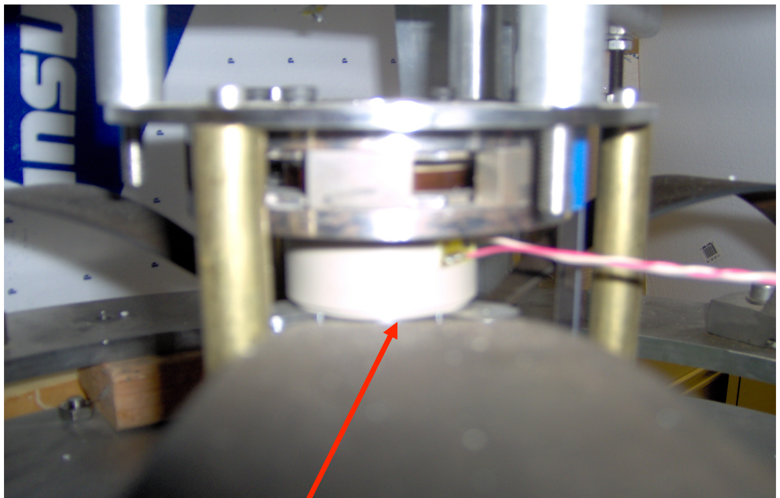




The RF emitter coil is mounted on ground

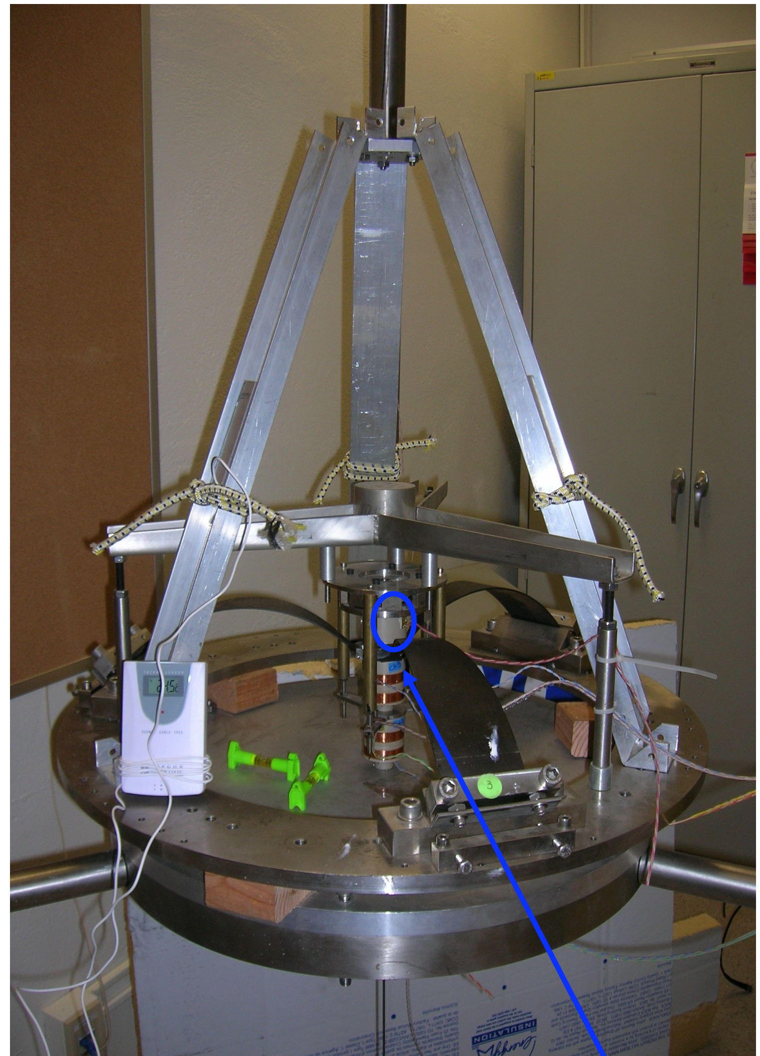
The two receiver coils on the moving blades

The actuator



Voice coil and magnet

driven by control program



ACTUATOR

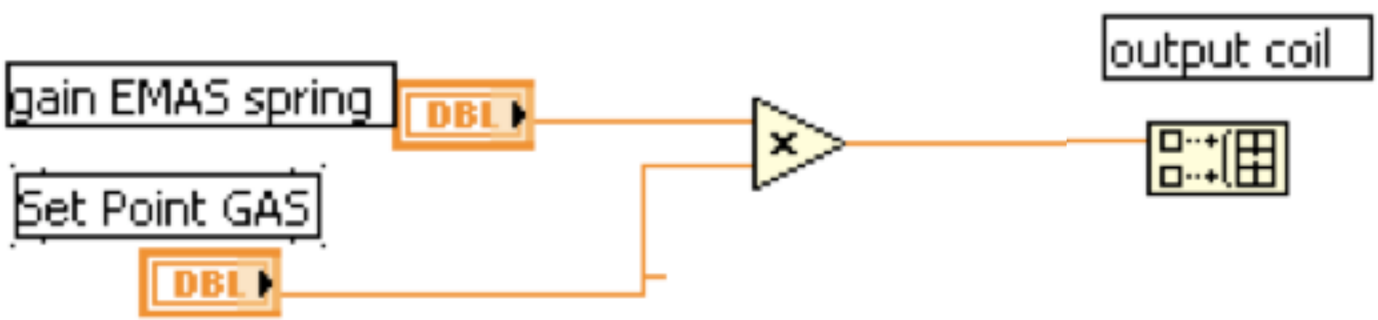
Electro Magnetic Anti Spring (EMAS)

•The GAS is tuned to obtain a low mechanical resonant frequency (typically 200 mHz)

•We need to work at lower frequencies

• To further reduce, and to remotely change the resonant frequency, we implemented the EMAS

• The EMAS is feeding the position sensor signal to the vertical actuator built in the spring, through an external gain.



- Effect of EMAS on the filter

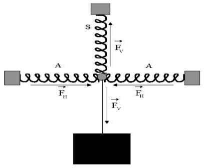
$$K_{effective} = K_{elastic} + K_{GAS} + K_{EMAS}$$

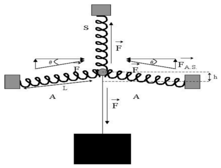
$$K_{effective} = K_o + K_{EMAS}$$

$$K_o = 124$$

(M= 65Kg
F=0.22Hz)

$$F = \frac{1}{2\pi}\sqrt{\frac{K_o + K_{EMAS}}{M}}$$





Initial tuning of the system
Finding the working point…

- The GAS effect is optimized when the radial compression of the blades is maximized
- The height of this optimal working point must be determined
- The GAS filter has minimal resonant frequency at this working point
- The working point is found by loading the filter with the appropriate load, and exploring the vertical movement by applying a progression of fixed vertical forces with the actuator

Initial tuning of the system
Finding the working point…

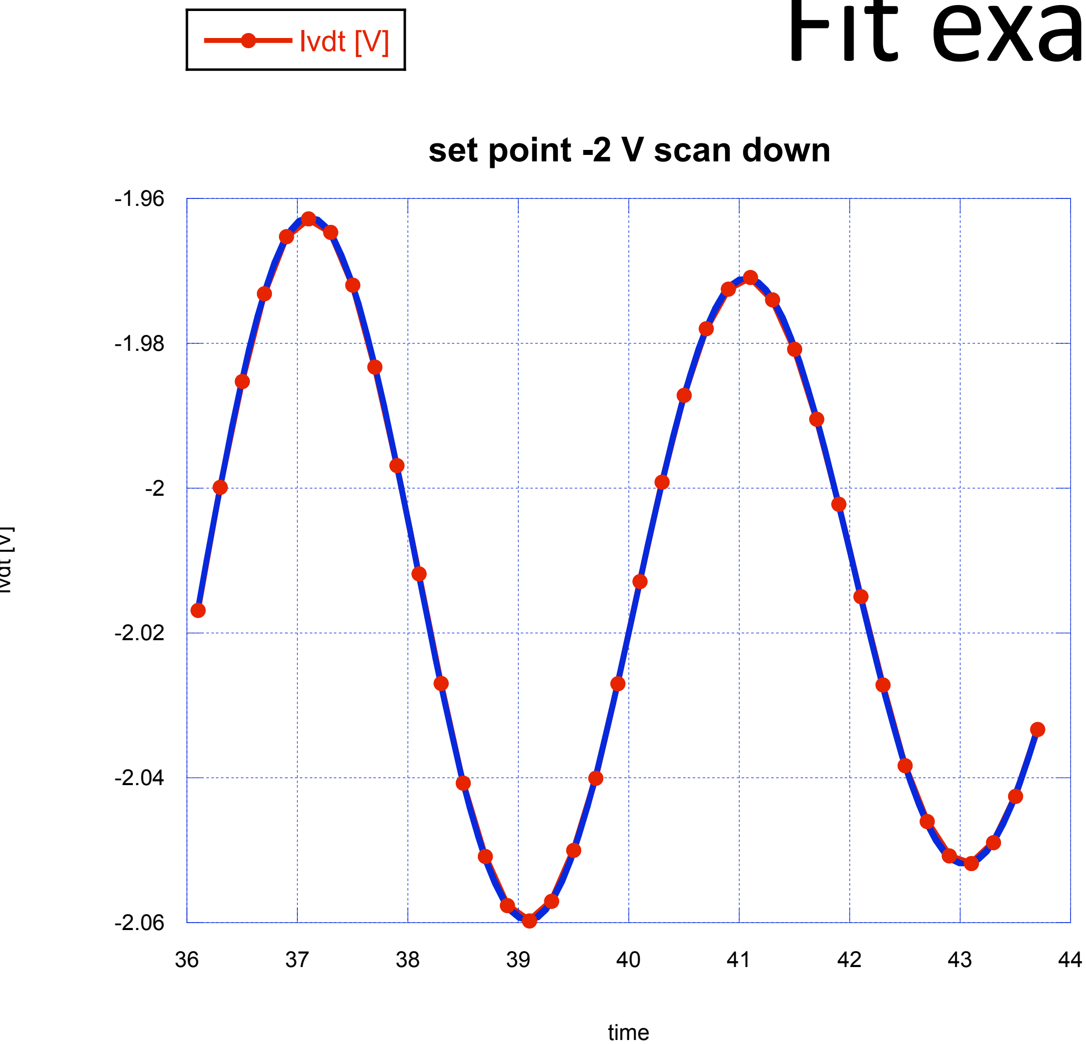
Procedure

- Scan the position by applying a progression of voltages (forces) on the actuator, in 0.5V steps starting from -3V to +3V and then back to -3V
- For every set point apply

  1V short pulse to generate a ring down
- Fit the observed oscillations with the function:

  $$h + A \sin[2\pi f\,(t-\phi)]\ \ \exp-[(t-\phi)/\tau]$$
- For each ringdown extract the actual height h and the oscillation frequency f of the system

Fit example



y = m1 + m2 * sin(2*pi*m3*(x...		
	Value	Error
m1	-2.0133	6.1936e-5
m2	0.053074	9.5289e-5
m3	0.25276	6.3668e-5
m4	36.139	0.0009679
m5	21.763	0.20493
m6	6.2979e-6	1.3574e-5
Chisq	9.9366e-7	NA
R	0.99999	NA

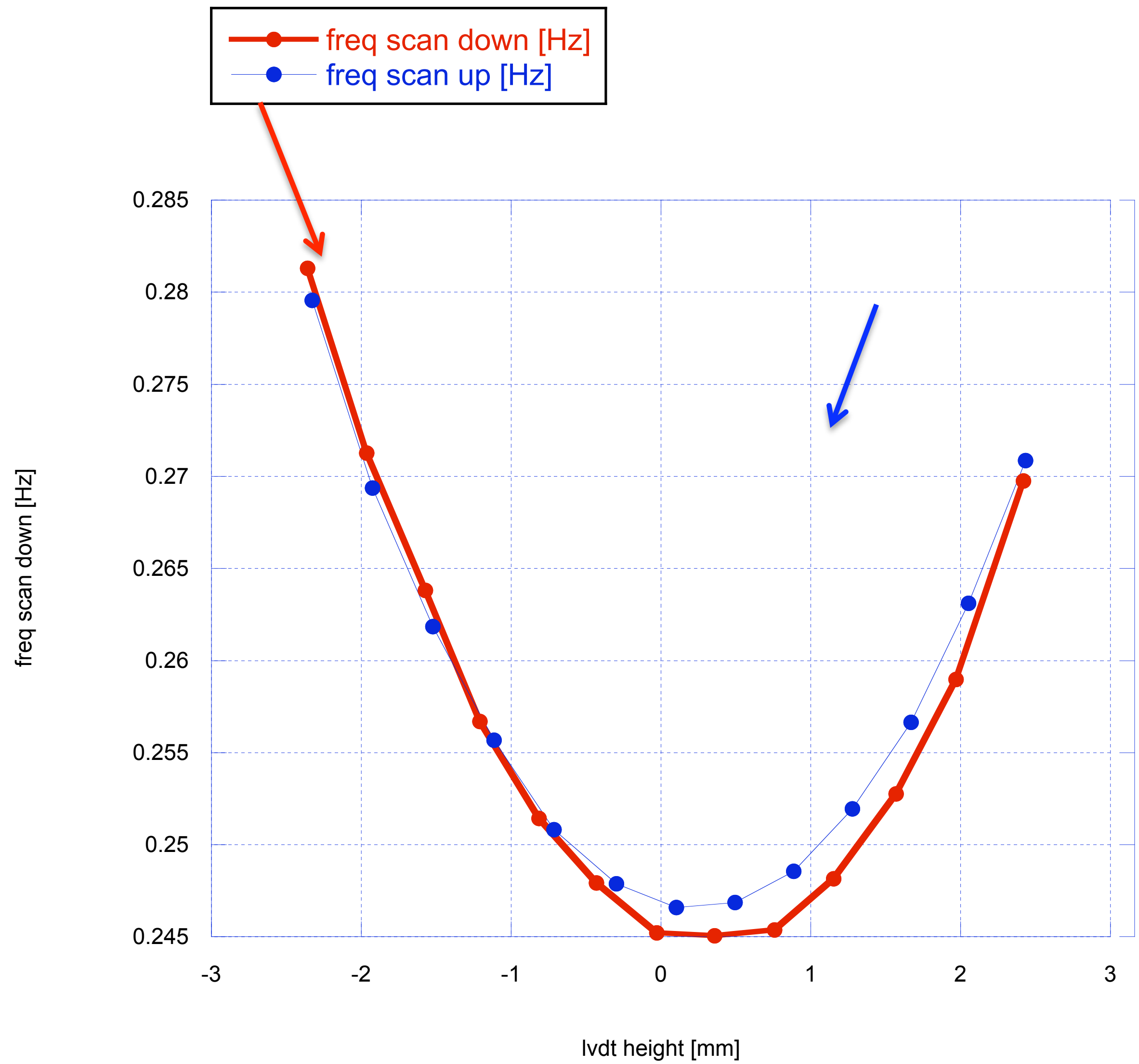
LVDT height [V]
Oscillation amplitude [V]
Frequency [Hz]
Time delay [s]
Lifetime [s]
Thermal slope [mm/s]

frequency fit performed when the oscillation amplitude is 0,053 V (0,04 mm)

Working point definition

Y = M0 + M1*x + ... M8*x^8 + M9*x^9	
M0	0.24669
M1	0.0018167
M2	0.0030609
R	0.99988

Y = M0 + M1*x + ... M8*x^8 + M9*x^9	
M0	0.24515
M1	0.0024165
M2	0.0032217
R	0.99886



Need of thermal correction

The principal source of perturbations for the spring is the variation of room temperature, causing the following fluctuations of lift force:

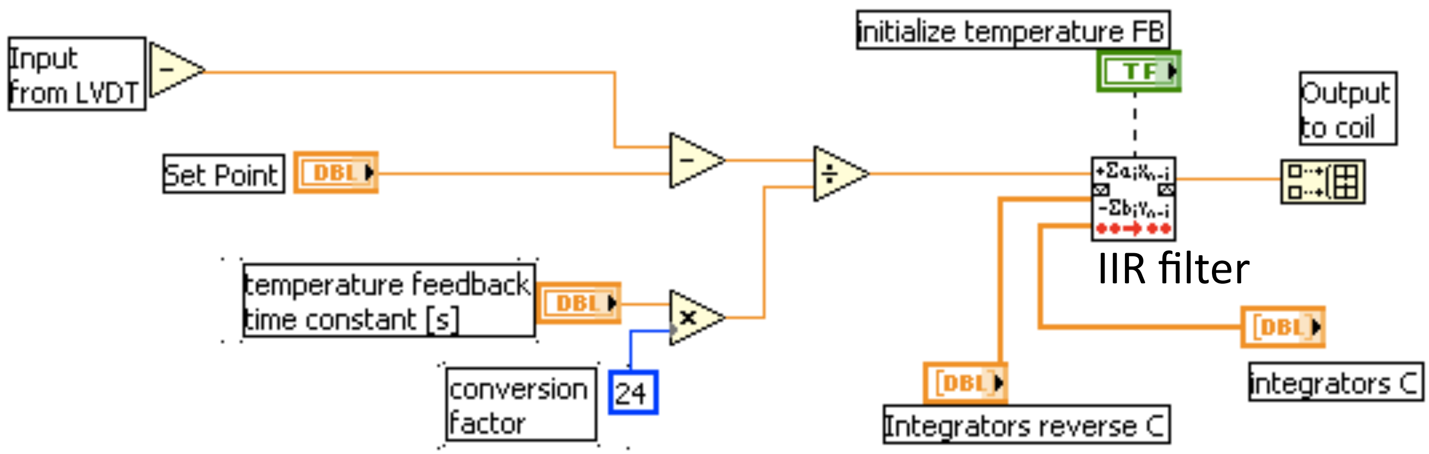
$$\Delta F_{lift} = g \bullet load \frac{\partial E_{Young}}{\partial T} \Delta T$$

This force is depends only on the load,

when the restoring force is tuned to be small

(low frequency) the displacements are large.

To reduce the wandering of the working point, we introduced a feedback integrator (IIR filter) that continuously sums the displacements from the working point and feeds the sum to the vertical actuator coil.



It also eliminate the need for very fine tuning of the load.

Thermal feedback

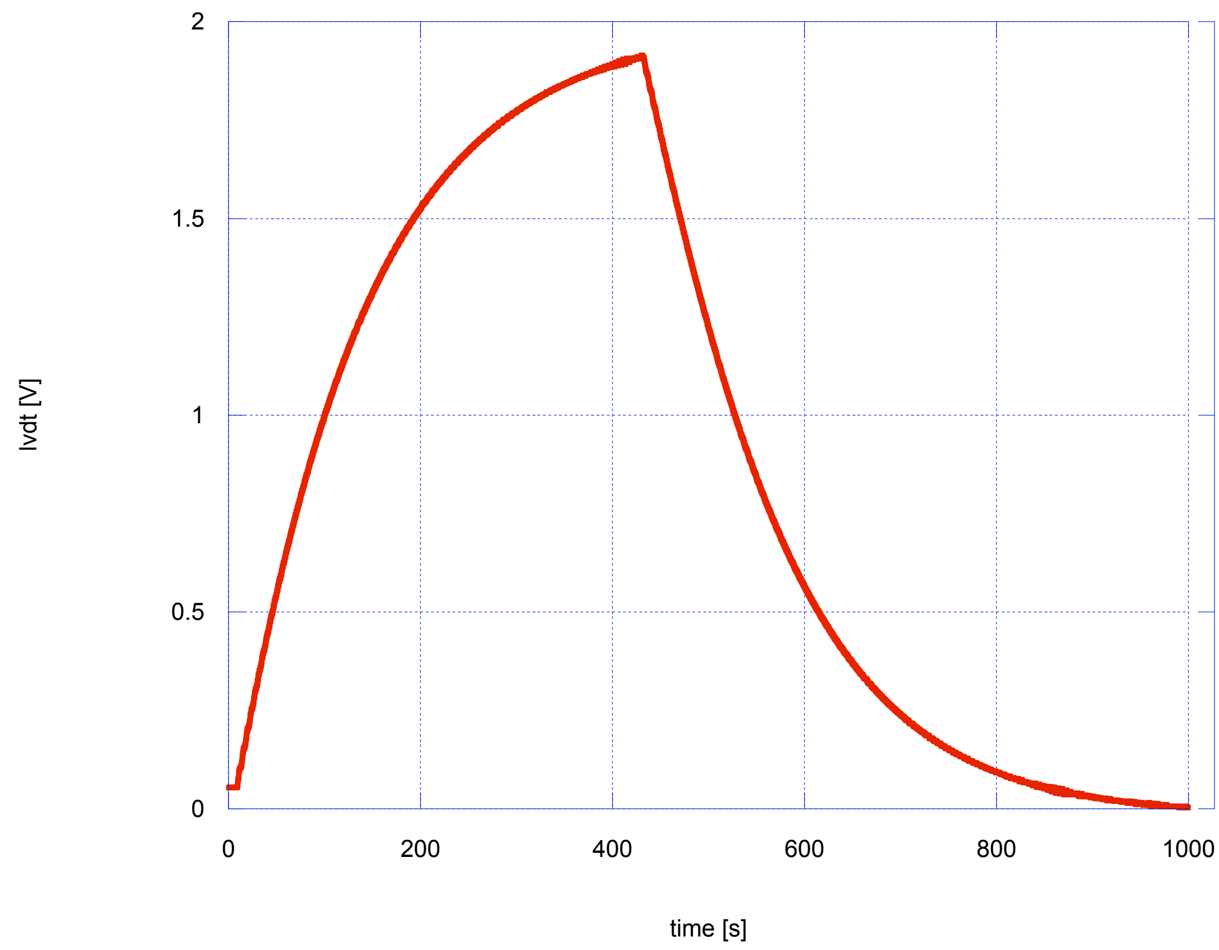
- Always maintains the spring at its working point
- The gain of this feedback determines
  - The time constant at which the system returns to the set point
  - The residual distance from the set point during temperature drifts
- High feedback gain keeps the spring from wandering,
- Too much gain interferes with the behavior of the spring.
- The thermal correction time constant must be kept much larger than the natural pulsation of the system

Thermal-feedback time-constant characterization

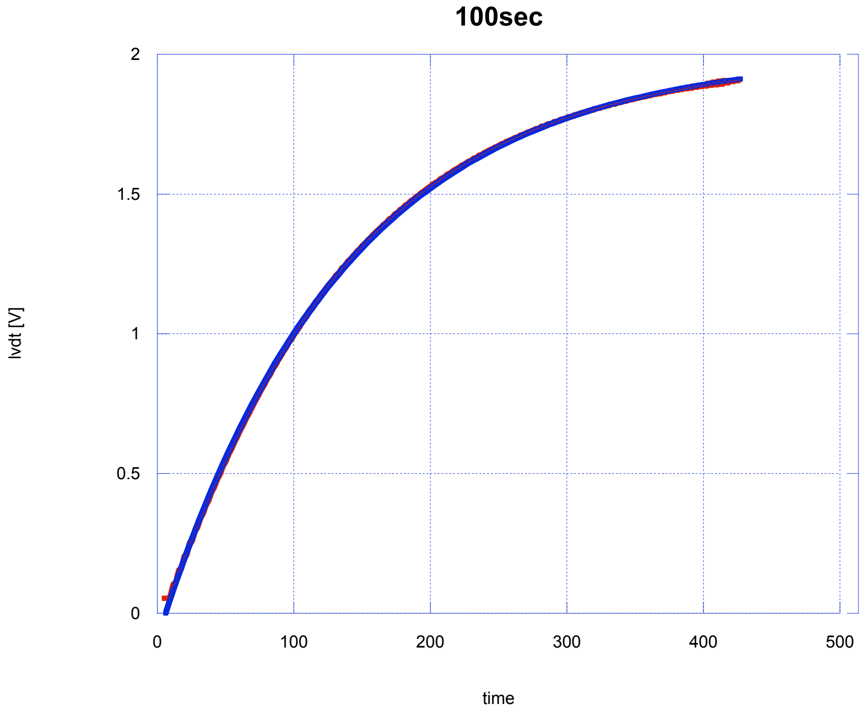
We set the integration constant to a nominal value (100 s)

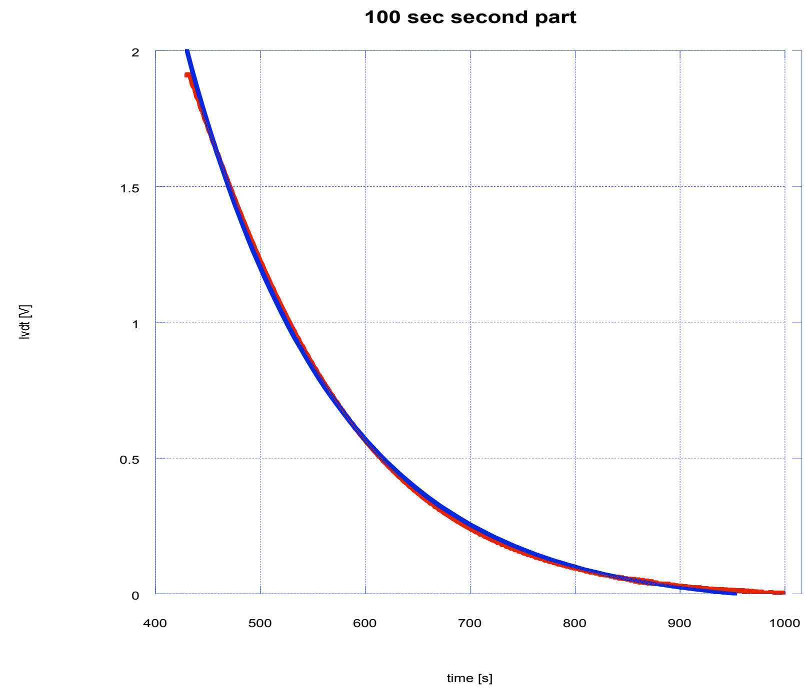
- we started from a set point (0.07V)
- We changed it to 2V
- Then we changed it back to 0V

We then fit the data with an exponential decay



100 seconds integration time

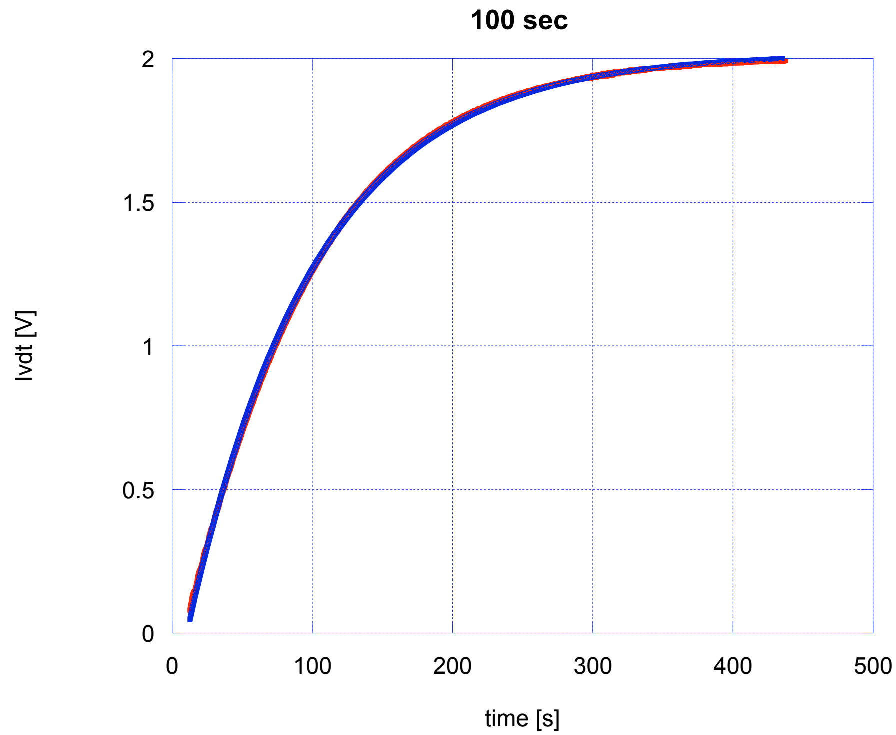


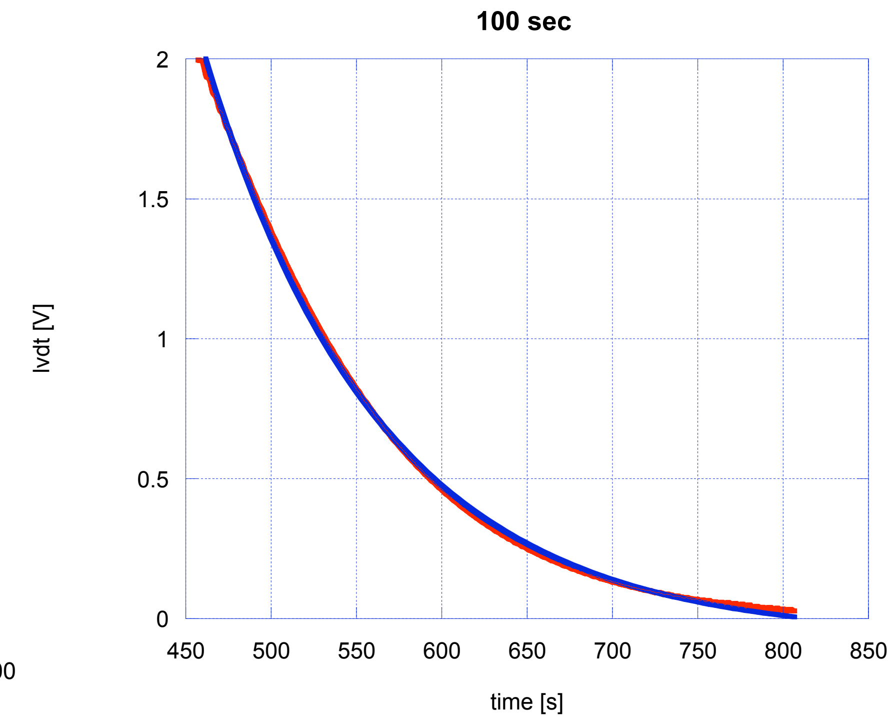


y = m1 + m2 *exp(-(x-cmin(c1...		
	Value	Error
m1	2.0027	0.00044849
m2	-2.0154	0.0004911
m3	136.06	0.10074
Chisq	0.070642	NA
R	0.99994	NA

The fit lifetime was different from the 100 s nominal integrator gain

y = m1 + m2 *exp(-(x-cmin(c1...		
	Value	Error
m1	-0.05233	0.0006974
m2	2.0595	0.0011303
m3	142.4	0.19836
Chisq	0.62706	NA
R	0.9996	NA





We added a multiplicative constant in the control program so that the value of the nominal integrator constant corresponds to the real thermal correction response time

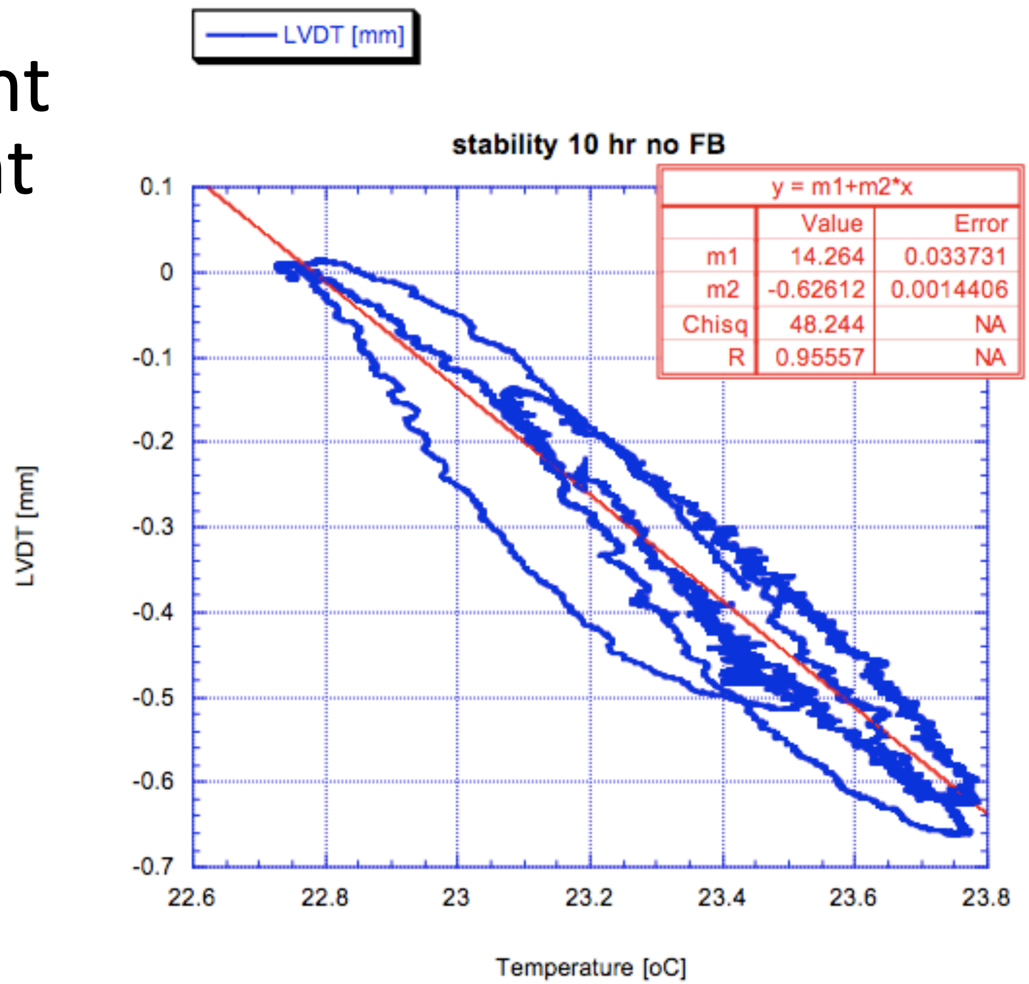
y = m1 + m2 *exp(-(x-cmin(c1...		
	Value	Error
m1	2.0188	0.00034287
m2	-1.9717	0.00071406
m3	90.462	0.073766
Chisq	0.12181	NA
R	0.99988	NA

y = m1 + m2 *exp(-(x-cmin(c1...		
	Value	Error
m1	-0.066957	0.0012122
m2	2.1588	0.0015052
m3	103.45	0.2077
Chisq	0.45709	NA
R	0.99958	NA

First relevant scientific understanding

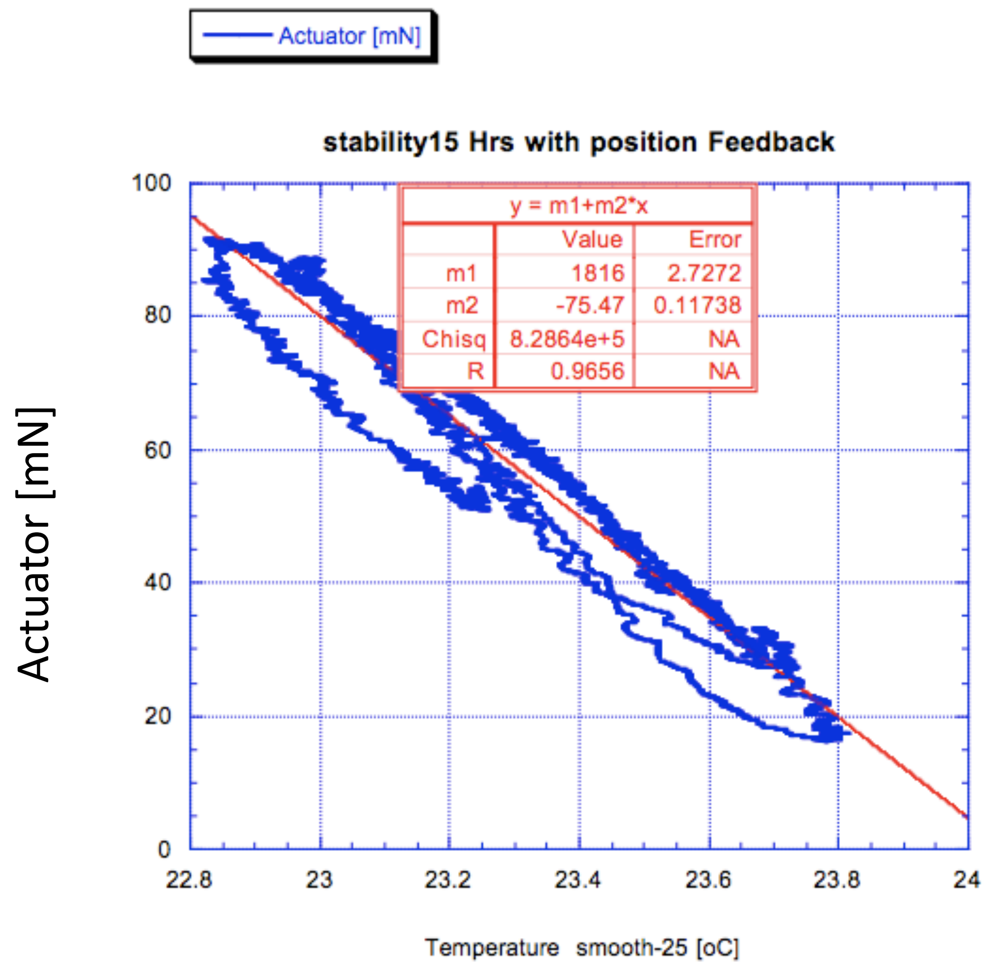
Thermal hysteresis

- Filter movement under overnight lab thermal variations
- No feedback
- The movement shows Thermal hysteresis



Thermal hysteresis

- Blade working point stabilized by integrator feedback
- No actual blade movement
- Hysteresis shifted to the control current ! !



Surprising (should not) evidence

- Hysteresis does not 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

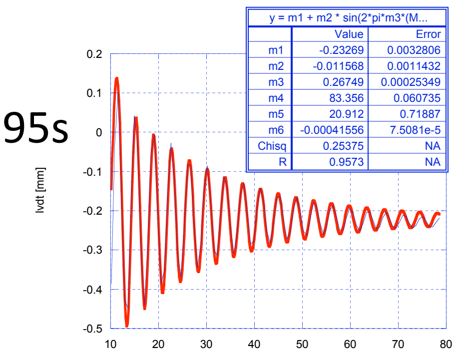
Electro Magnetic Anti Spring (EMAS)

•EMAS can be applied with positive or negative sign, and arbitrary gain, in parallel to the GAS effect.

•Used to stiffen or weaken the spring restoring force and change its frequency tune

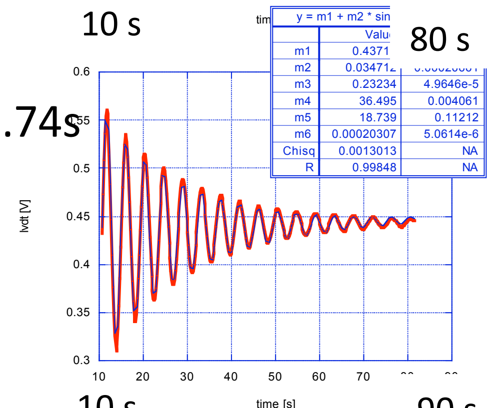
•Large negative gain brings instability

EMAS= 1
Lifetime= 20.95s



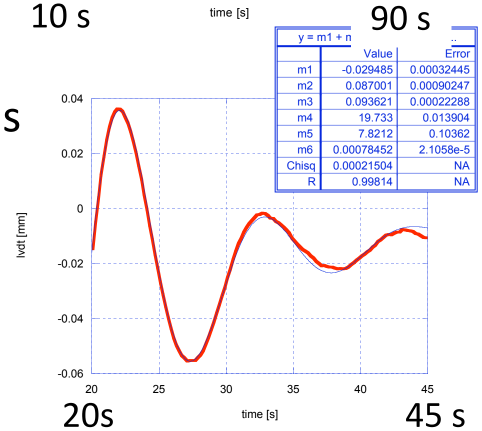
10 s 80 s

EMAS=-0.5
Lifetime= 18.74s



10 s 90 s

EMAS=-3.9
Lifetime = 7.82s



20s 45 s

EMAS measurements

The EMAS were used for different measurements:

•To measure the actual resonant frequency and oscillation quality factors as function of EMAS value

•To set the spring resonant frequency for swept frequency measurements

•To test the spring's stability at the lowest frequency tunings

Resonant Frequency and Quality factor measurements

• For each EMAS setting we excited the spring applying a short voltage pulse on the actuator, and monitored the ringdown.

• The pulse was typically ¼ period long.

• Larger excitation amplitudes (~1V) were used at highest frequency tunes (stiffer spring).

• Smaller excitation amplitudes (~0.1V) were used for the lowest frequency tunes.

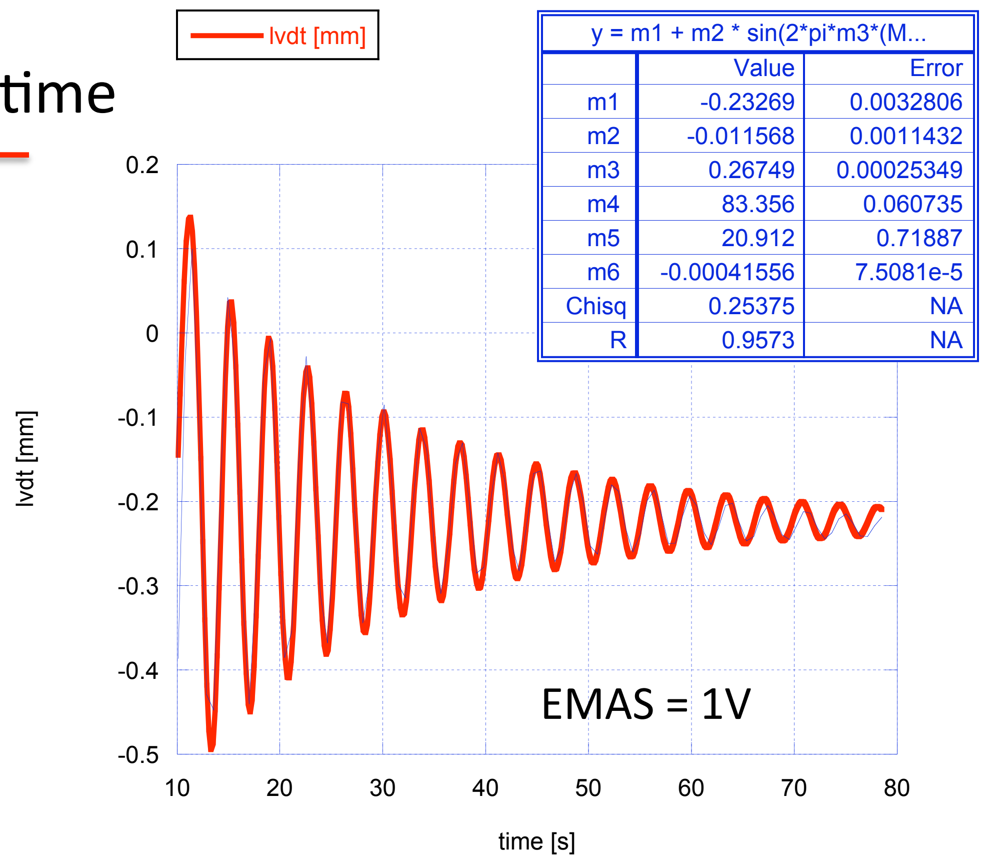
• All fitting procedures were applied for a fixed time window chosen to start the fit at the same signal amplitude.

Spring’s Height scan

- The data was analyzed with a damped sinusoid function
- *h+ A sin(2πf (t-ϕ))exp-((t-ϕ)/τ) +v(t−ϕ)*
- For each set point settings we extracted the spring’s

Height, the frequency and lifetime

y = m1 + m2 * sin(2*pi*m3*(M...	Value	Error
m1	0.28648	7.0417e-5
m2	0.019871	0.00016148
m3	0.27246	9.6981e-5
m4	82.722	0.0037224
m5	29.181	0.53387
m6	5.9868e-5	5.3453e-6
Chisq	1.5216e-5	NA
R	0.99919	NA



EMAS scan analysis: high frequency

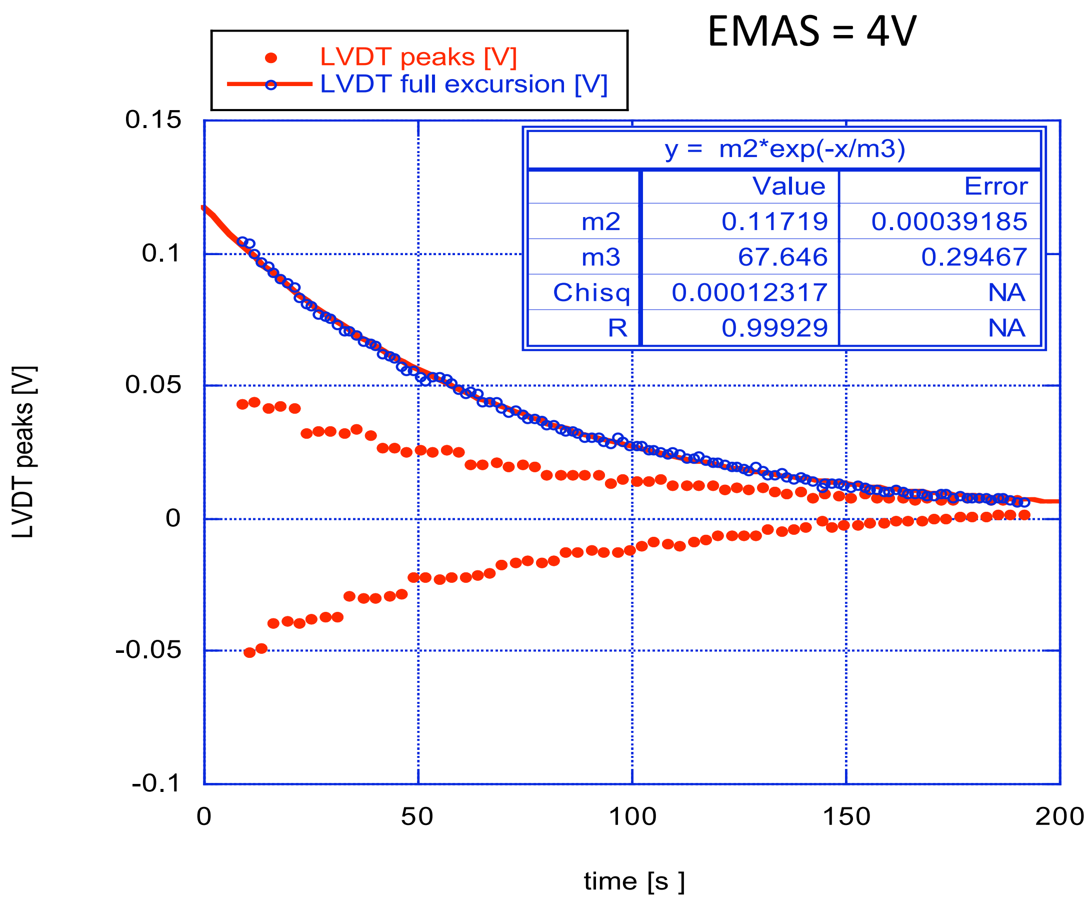
We observed that the frequency slowly changes with amplitude.

The damped sinus fails at high frequency, where the Q-factor is very high.

Different fitting procedure for higher freq.

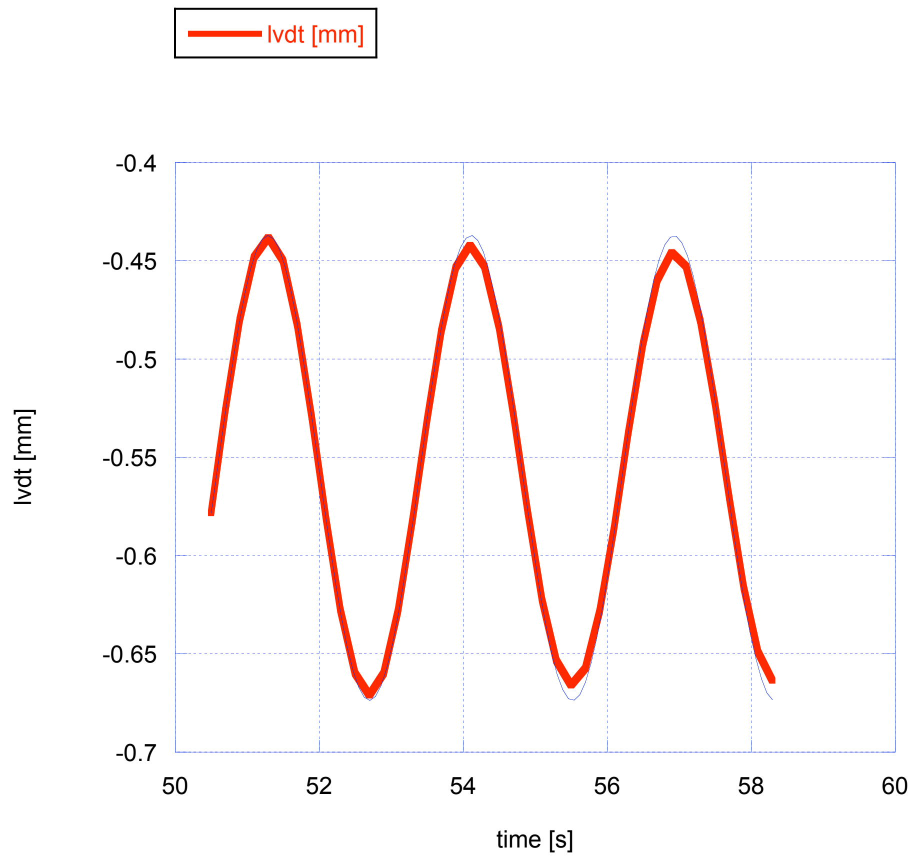
(More discussion about frequency versus amplitude later.)

EMAS scan analysis: high frequency



We used the ringdown envelope (difference between each maximum and next minimum of the LVDT signal) to calculate the ringdown lifetime.

EMAS scan analysis: high frequency

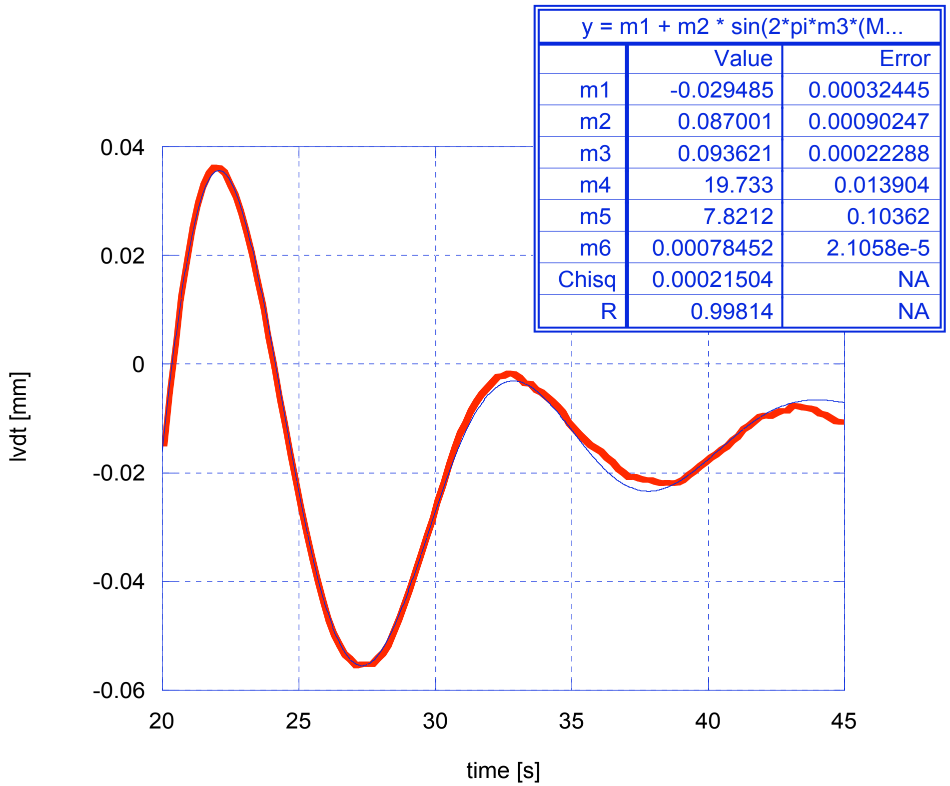


y = m1 + m2 * sin(2*pi*m3*(M...		
	Value	Error
m1	-0.55531	0.0014949
m2	0.11827	0.0021942
m3	0.35481	0.00062099
m4	50.588	0.0075029
m5	-2.6189e+6	2.7677e+10
m6	-2.0318e-5	0.00033651
Chisq	0.00074805	NA
R	0.99851	NA

The ringdown frequency was fit in a much shorter window

The error on the frequency was dominated by systematics, as the resonant frequency is amplitude dependent (see subsequent discussion)

Lowest achieved frequency



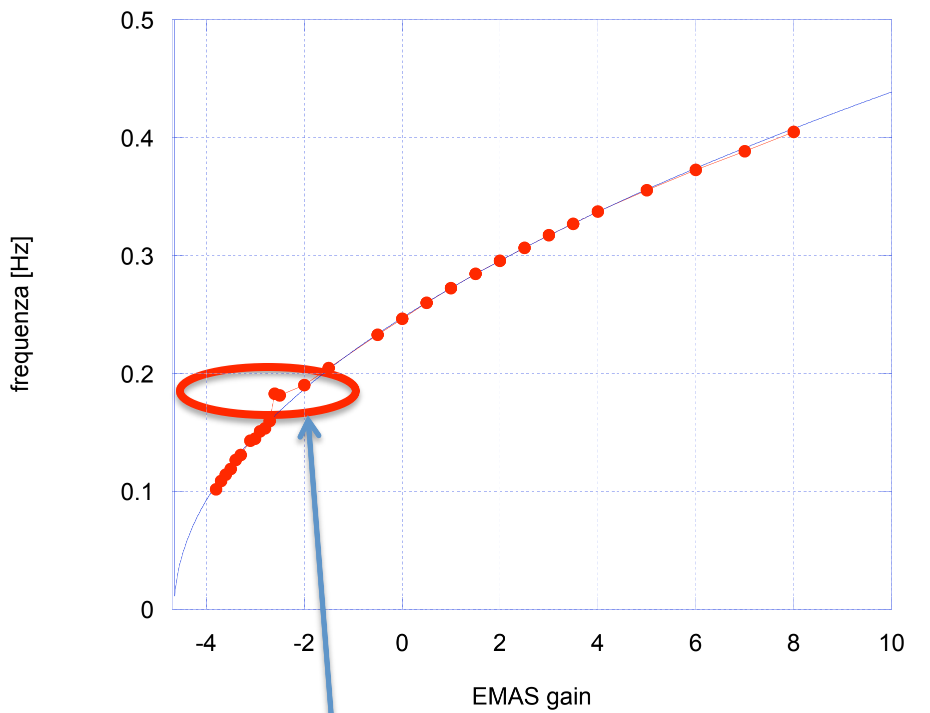
y = m1 + m2 * sin(2*pi*m3*(M...		
	Value	Error
m1	-0.029485	0.00032445
m2	0.087001	0.00090247
m3	0.093621	0.00022288
m4	19.733	0.013904
m5	7.8212	0.10362
m6	0.00078452	2.1058e-5
Chisq	0.00021504	NA
R	0.99814	NA

We were able to reach a lowest frequency, 93.6 mHz.

The scans showed though that the spring is not stable below 150-200 mHz.

External perturbations are capable to cause the system to run-off even if mathematically this should be impossible.

Fitting the frequency vs. EMAS data with a square root function



y = m1*sqrt(x-m2)		
	Value	Error
m1	0.11463	0.00060547
m2	-4.6508	0.035134
Chisq	0.00063909	NA
R	0.99873	NA

$$F = \frac{1}{2\pi}\sqrt{\frac{K_o + K_{EMAS}}{M}}$$

The data fits perfectly the expected function

(except for two points at 0.19 Hz that correspond to a load resonance).

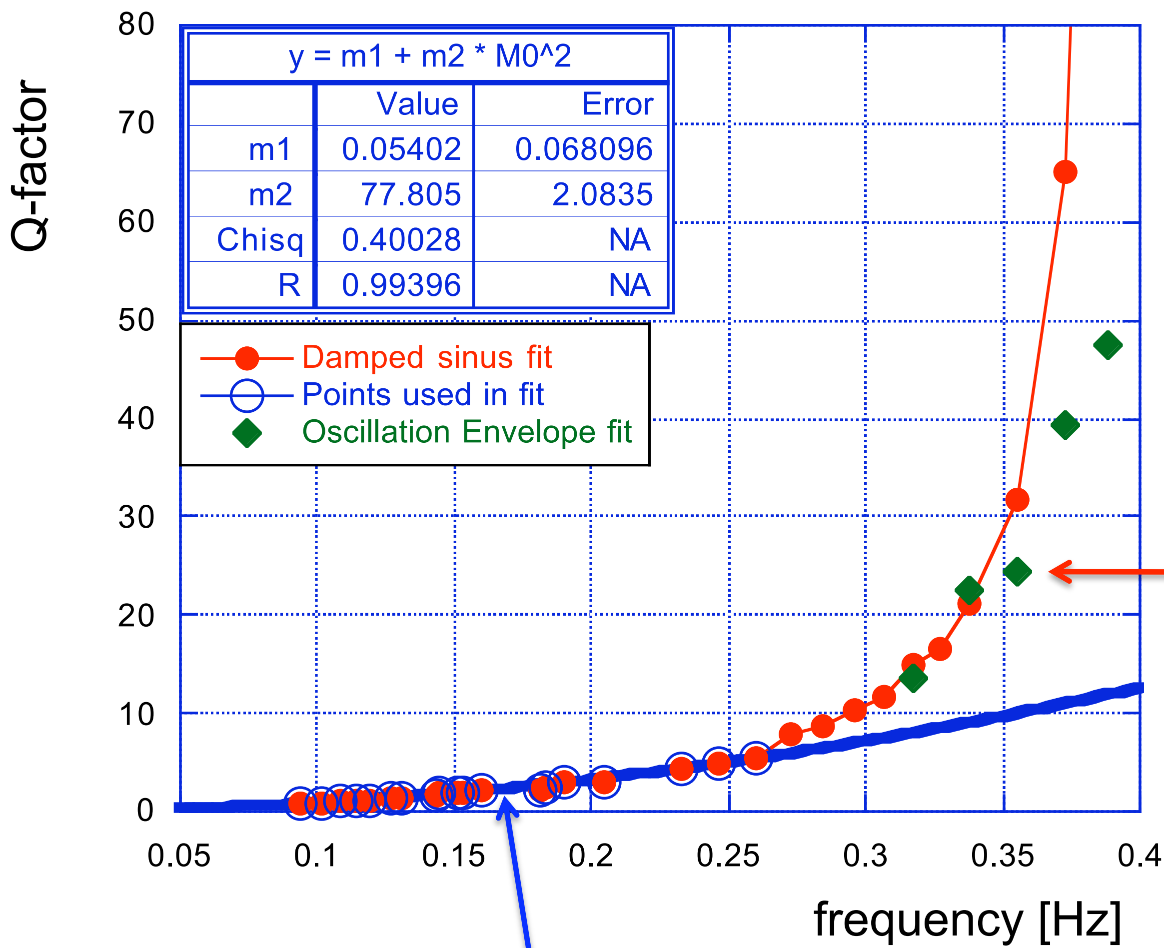
Quality factor vs. frequency

If the quality factors is a quadratic with frequency

=> the energy loss is independent from frequency

found a deviation from the quadratic rule for frequencies over 0.28Hz

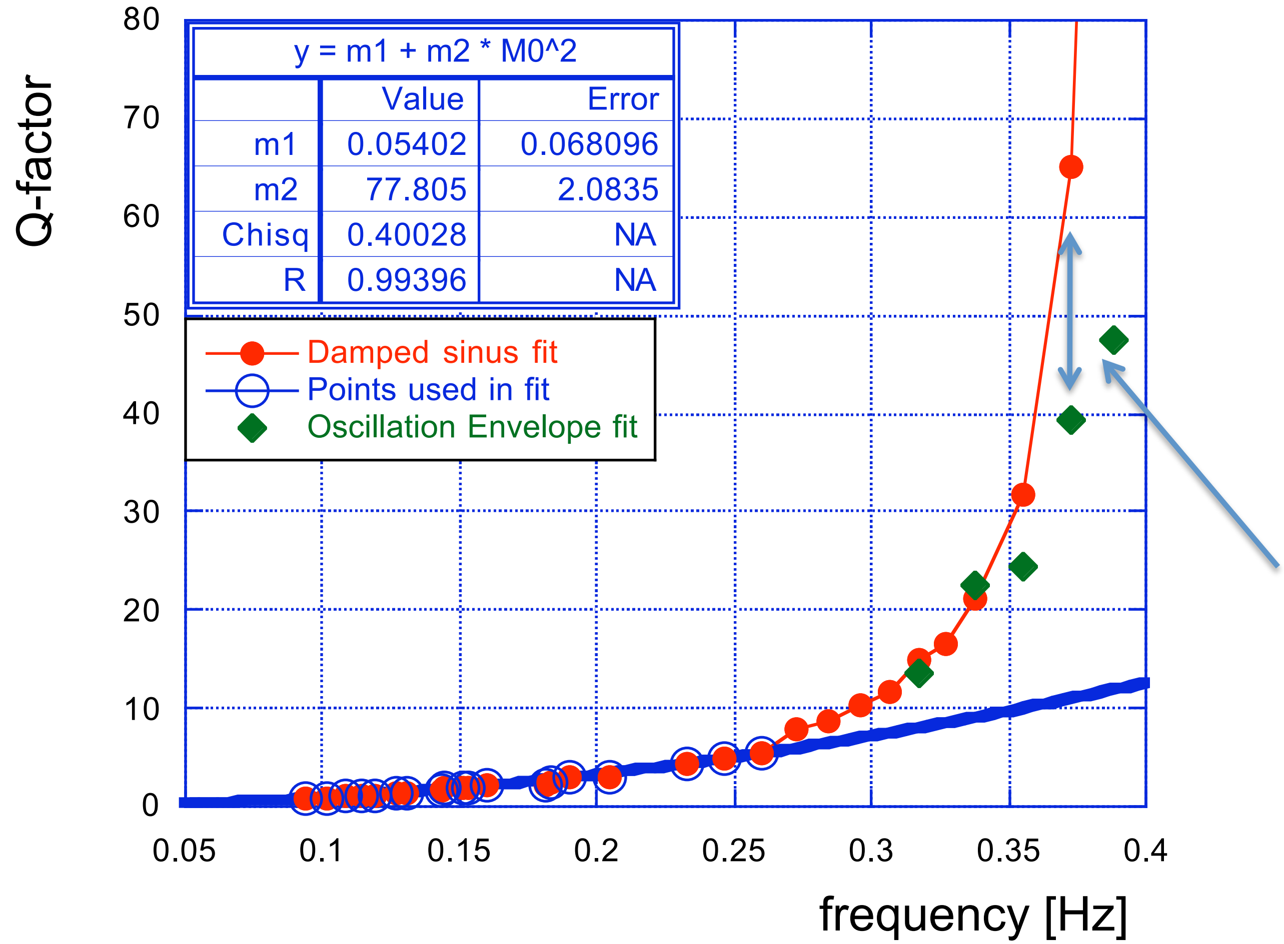
Resonant Frequency and oscillation Quality factor measurements



Deviation from quadratic
Above 0.27 Hz

the expected quadratic behavior

Resonant Frequency and oscillation Quality factor measurements



Looking for systematic errors that could fake the departure from the quadratic law,

repeated the fits using the oscillation envelope technique.
Found a problem with the fit for the three highest points, but not enough to eliminate the discrepancy

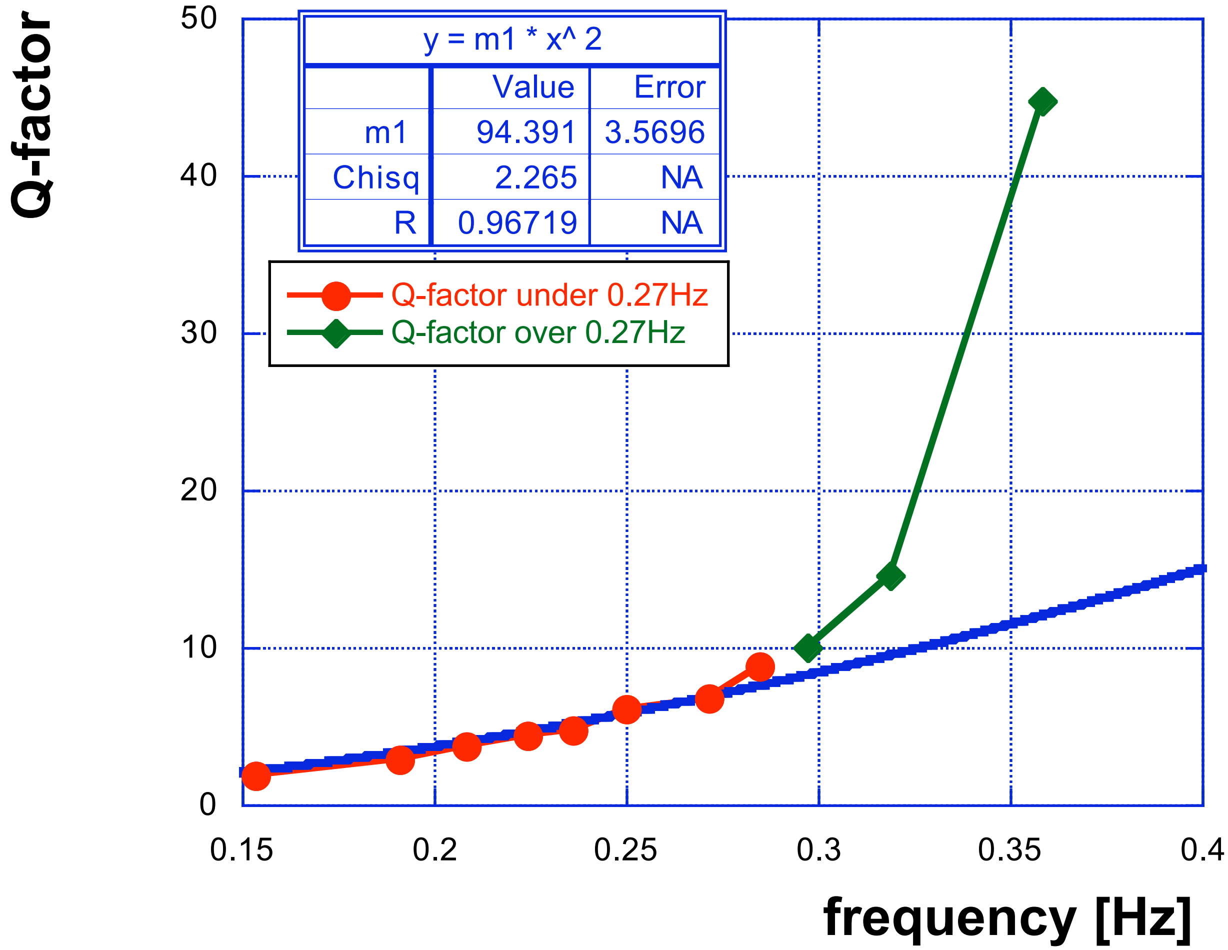
Note: As a cross check the procedure was also repeated with fit windows tuned to start for different amplitudes (0.1V and 0.01V) with no significant differences

Tuning the GAS system towards lower frequencies

- Suspecting that the departure from the quadratic law of the Q-factor could be somehow related to the EMAS and our control system, we changed the filter’s mechanical tune.
- Changing the radial compression of the blades by 1/6 mm we moved the resonant frequency from 245 to 219 mHz,

  a substantial amount, -25% in stiffness.

Lower GAS setting
Q-factor measurement



The Quality-factor follows the f^2 function but still jumps up above 0.27 Hz

confirmed the deviation from the f^2 law at ~270 mHz

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

  not tune dependent.

- <u>If confirmed it may indicate that dislocations need time to disentangle and mobilize.</u>

- Less losses and noise at higher frequency?

Oscillations and hysteresis

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

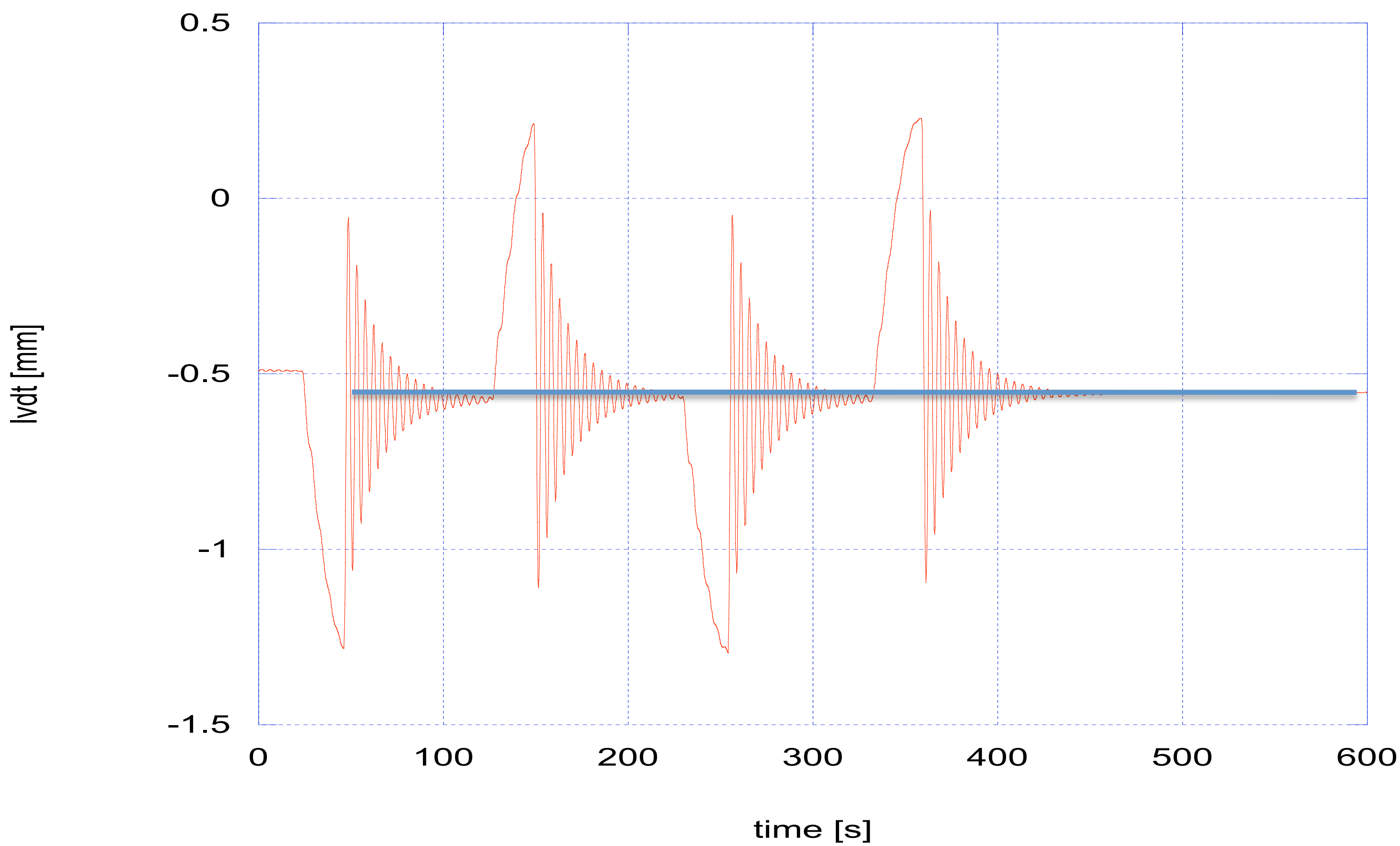
- Half sinusoid slow pulses to avoid ringdowns
- Quarter sinusoid to allow ringdowns

- Alternated sign pulses
- Same sign pulses

Hysteresis wash-out

If we lift the pendulum to a certain height,
abruptly cut the force,
and let it oscillate
we observe no hysteresis

EMAS=0



Hysteresis wash-out vs. Q-factor

Oscillations wash-out hysteresis

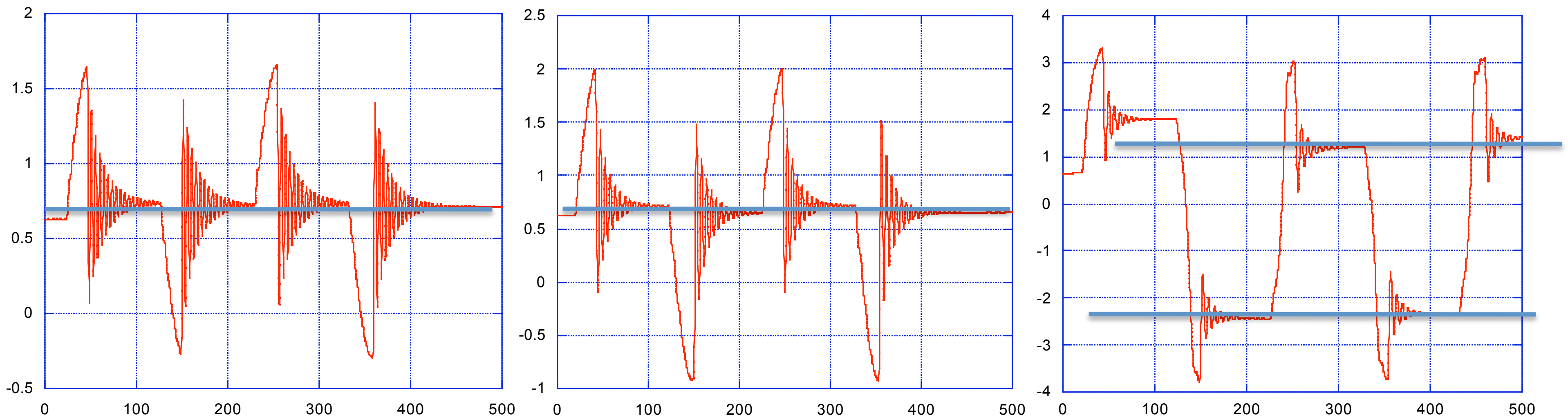
At low Q there are not enough oscillations to wash out hysteresis

Some “drag” hysteresis appears as the system gets close to instability

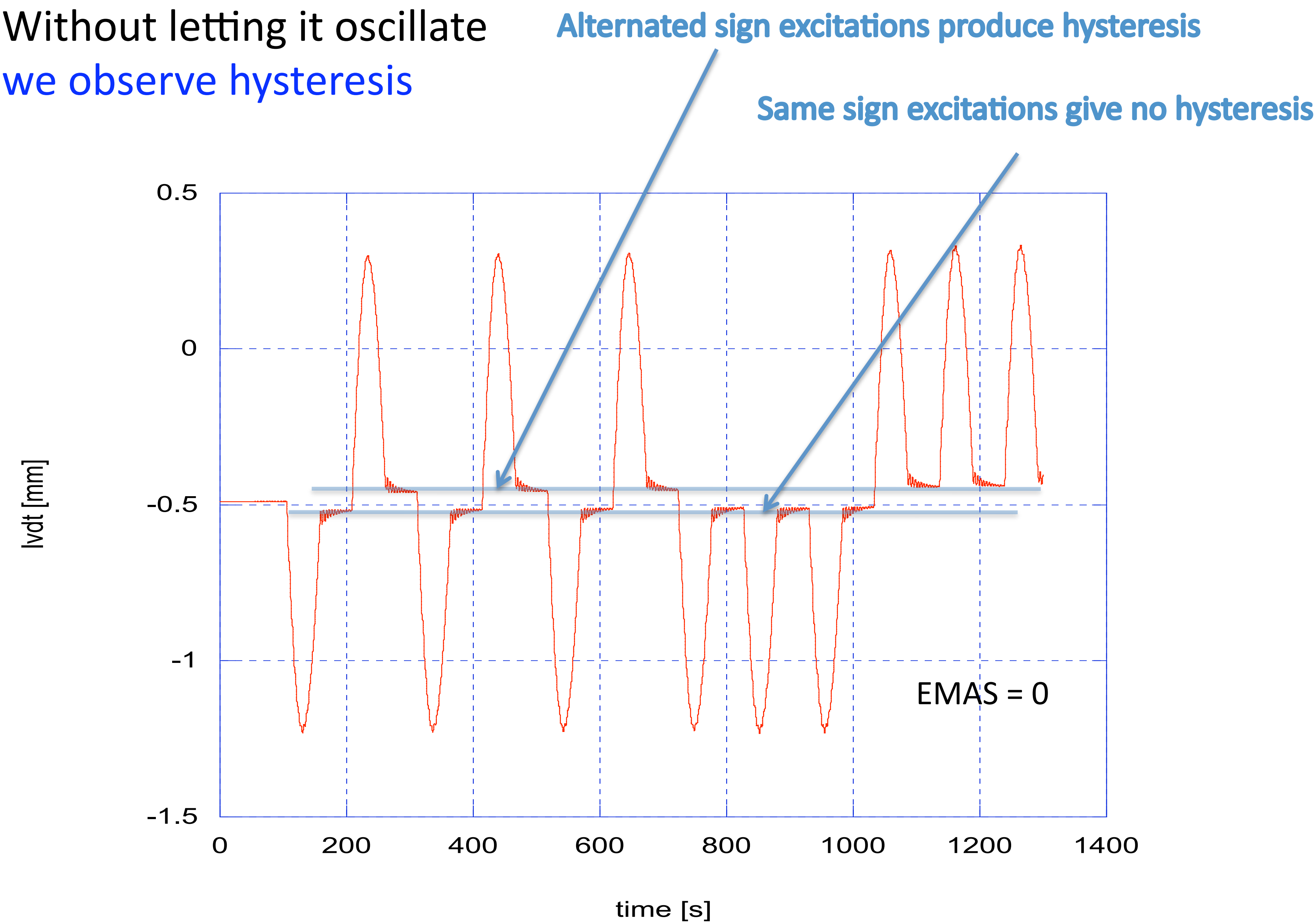
EMAS = 0
Res.freq. = 247 mHz
Q = 4.61
Hysteresis ~ 0.0

EMAS = -1
Res.freq. = 213 mHz
Q = 3.52
Hysteresis ~ 0.0

EMAS = -2
Res.freq. = 186 mHz
Q = 1.63
Hysteresis ~ 3.5V



If we lift the pendulum to a certain height,
Slowly reduce the force,
Without letting it oscillate
we observe hysteresis

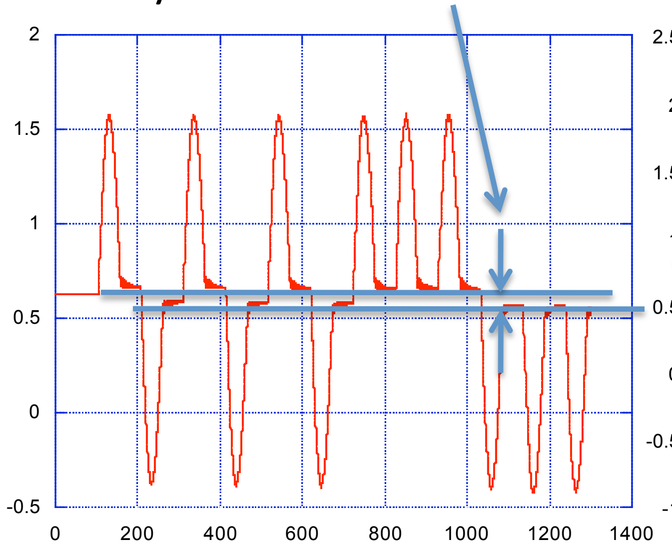


Hysteresis vs. frequency

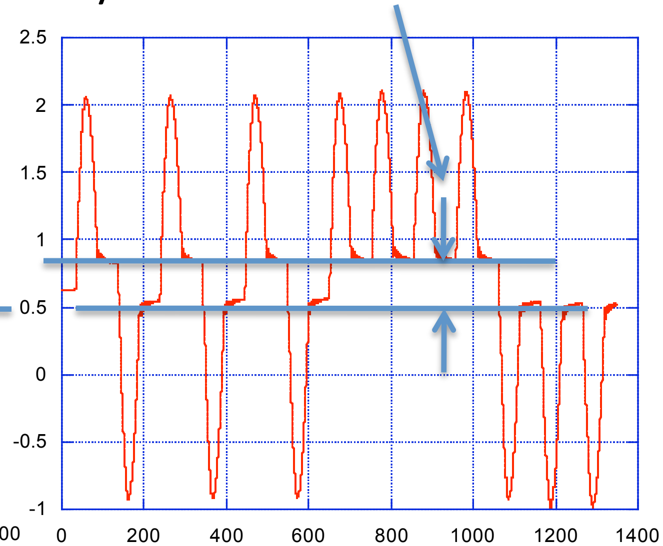
Hysteresis amplitude grows with low frequency tune

Much more than what could be expected from lowering of elastic constant K

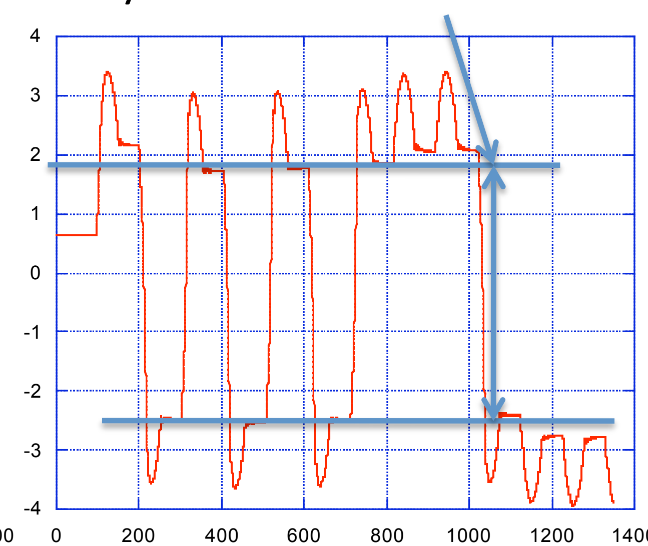
EMAS = 0
Res.freq. = 247 mHz
K =156 N/m
Hysteresis = 0.07V



EMAS = -1
Res.freq. = 213 mHz
K = 116 N/m
Hysteresis = 0.27V



EMAS = -2
Res.freq. = 186 mHz
K = 89 N/m
Hysteresis = 4.25V



Dissipation and stiffness dependence from amplitude

- We studied the movement of the resonant peaks of the LVDT signal versus frequency, using data taken with swept sine of different excitation amplitudes.
- The experiment was repeated for EMAS gain 0 and -2
- The total elastic constant of the system is :

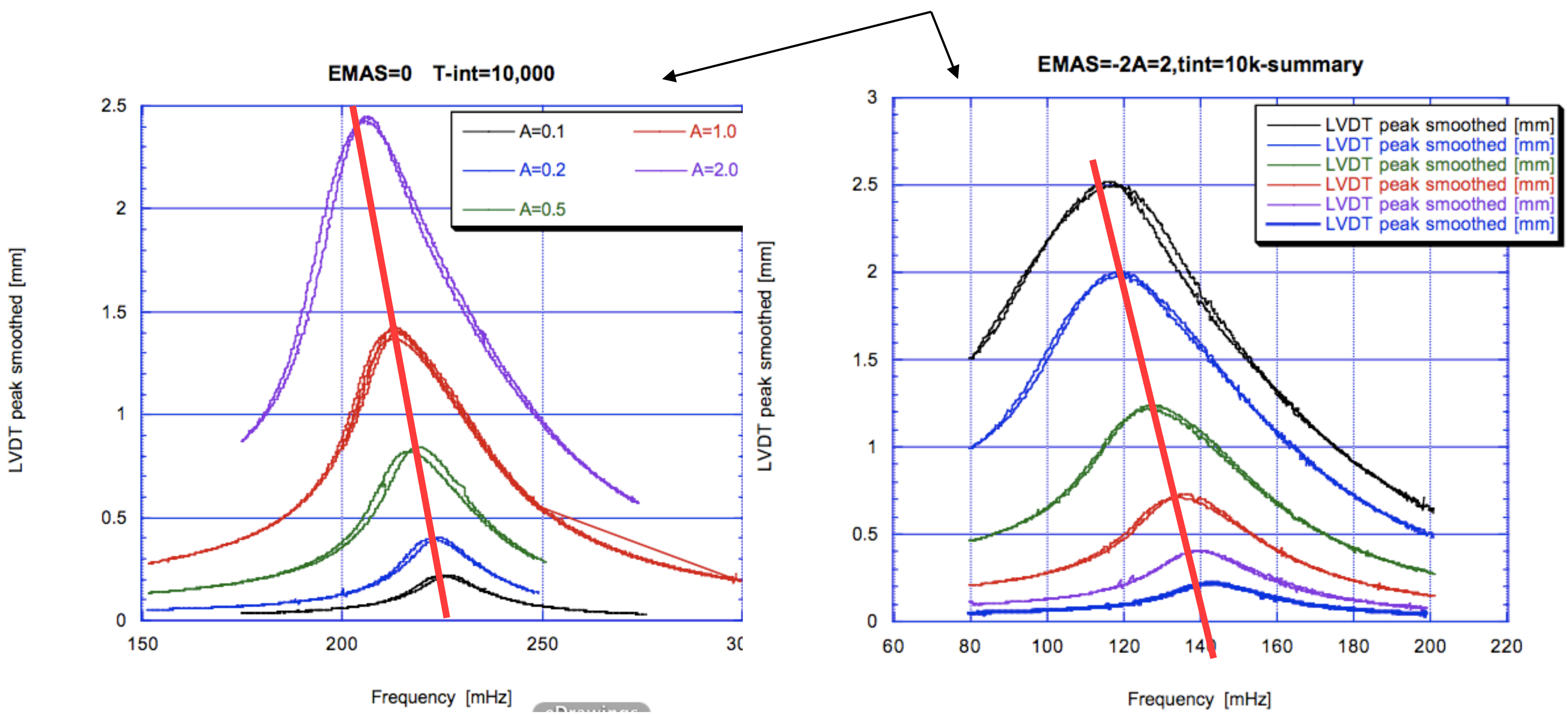
$$K_{effective} = \underbrace{K_{spring} + K_{gas}} + K_{emas}$$

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

- The experiment was repeated for EMAS gain 0 and -2

Amplitude/Frequency dragging

- Higher amplitudes induce lower frequencies
- Same effect for different filter tunes ! !



- We consider $K_{spring} + K_{gas} + K_{emas} = K_0 + K_a A$

K_0: usual spring constant

A: oscillation amplitude

K_a: interpreted as the variation of the elastic constant of the spring due to the progressive mobilization of the dislocations

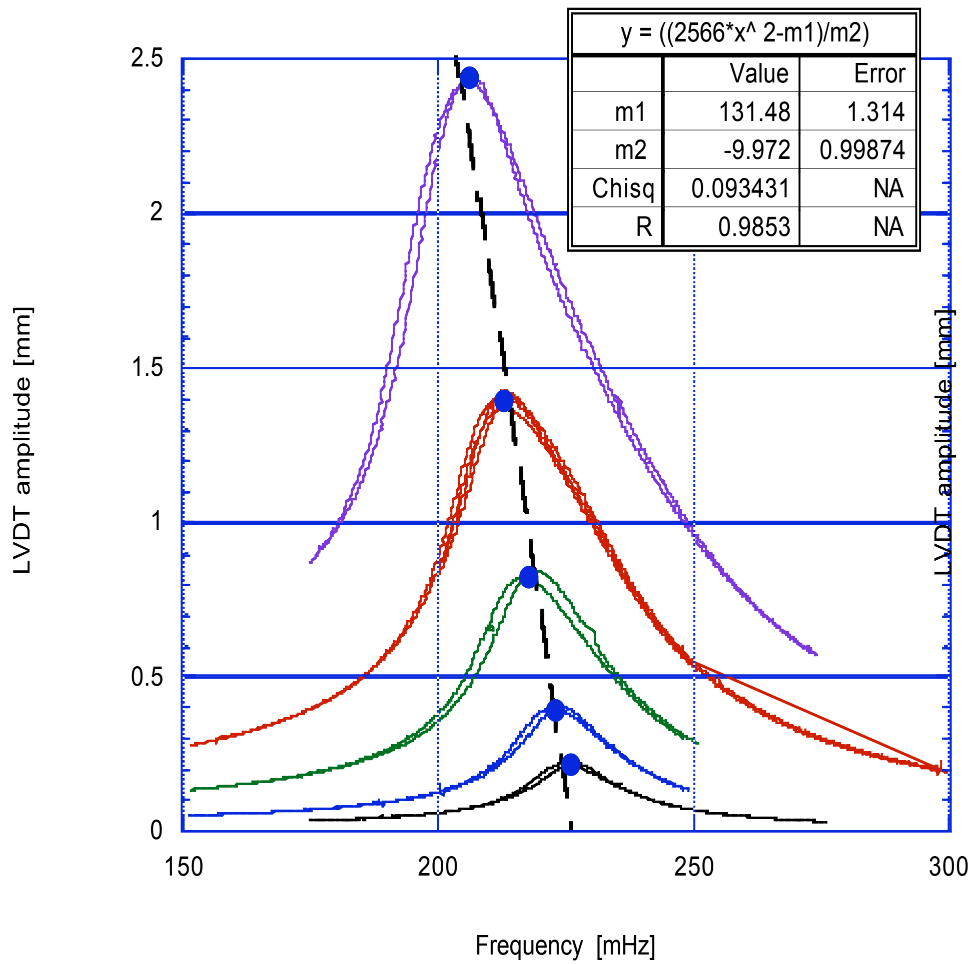
We are assuming here that the entangled dislocations contribute to the elasticity constant and that, changing the stress, some of them can be disentangled, thus reducing the effective Young modulus .

- The frequency becomes amplitude dependent if the number of disentangled dislocation is proportional to the excitation amplitude :

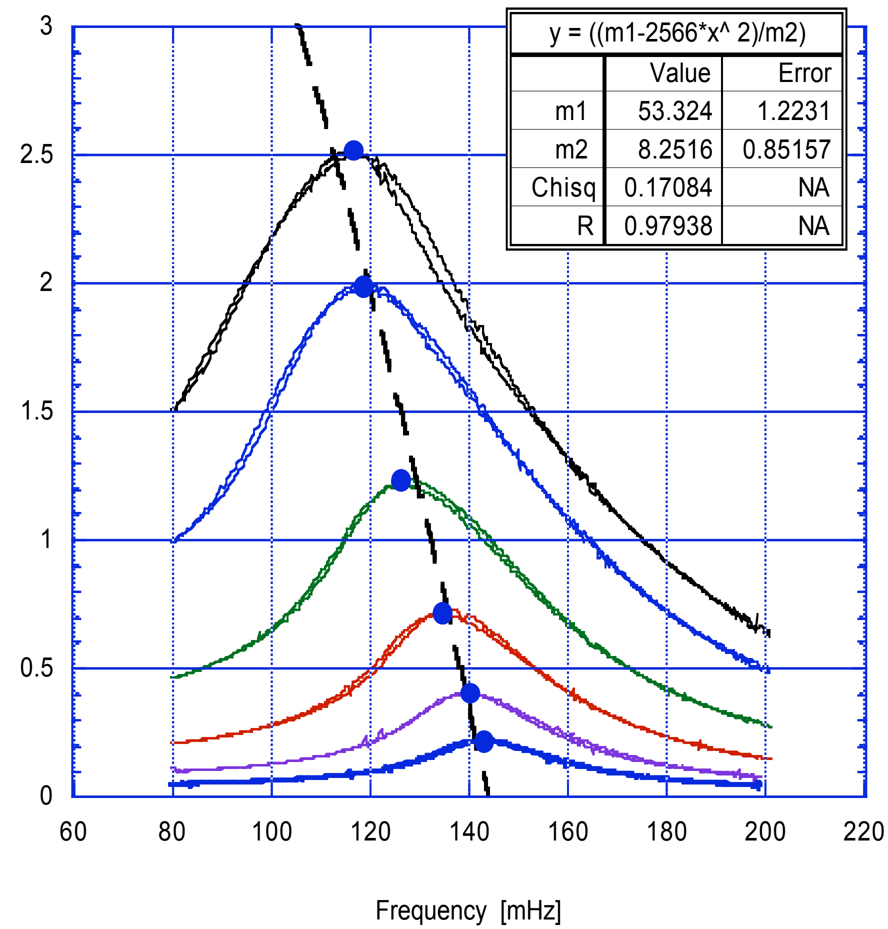
$$f = \frac{1}{2\pi}\sqrt{\frac{K_0 + K_a A}{M}}$$

- The idea is that for growing excitation amplitudes, the K will decrease, thus decreasing the resonant frequency
- Fitting the data with the previous equation…

EMAS 0


y = ((2566*x^ 2-m1)/m2)
Value
Error
m1
131.48
1.314
m2
-9.972
0.99874
Chisq
0.093431
NA
R
0.9853
NA
LVDT amplitude [mm]
Frequency [mHz]

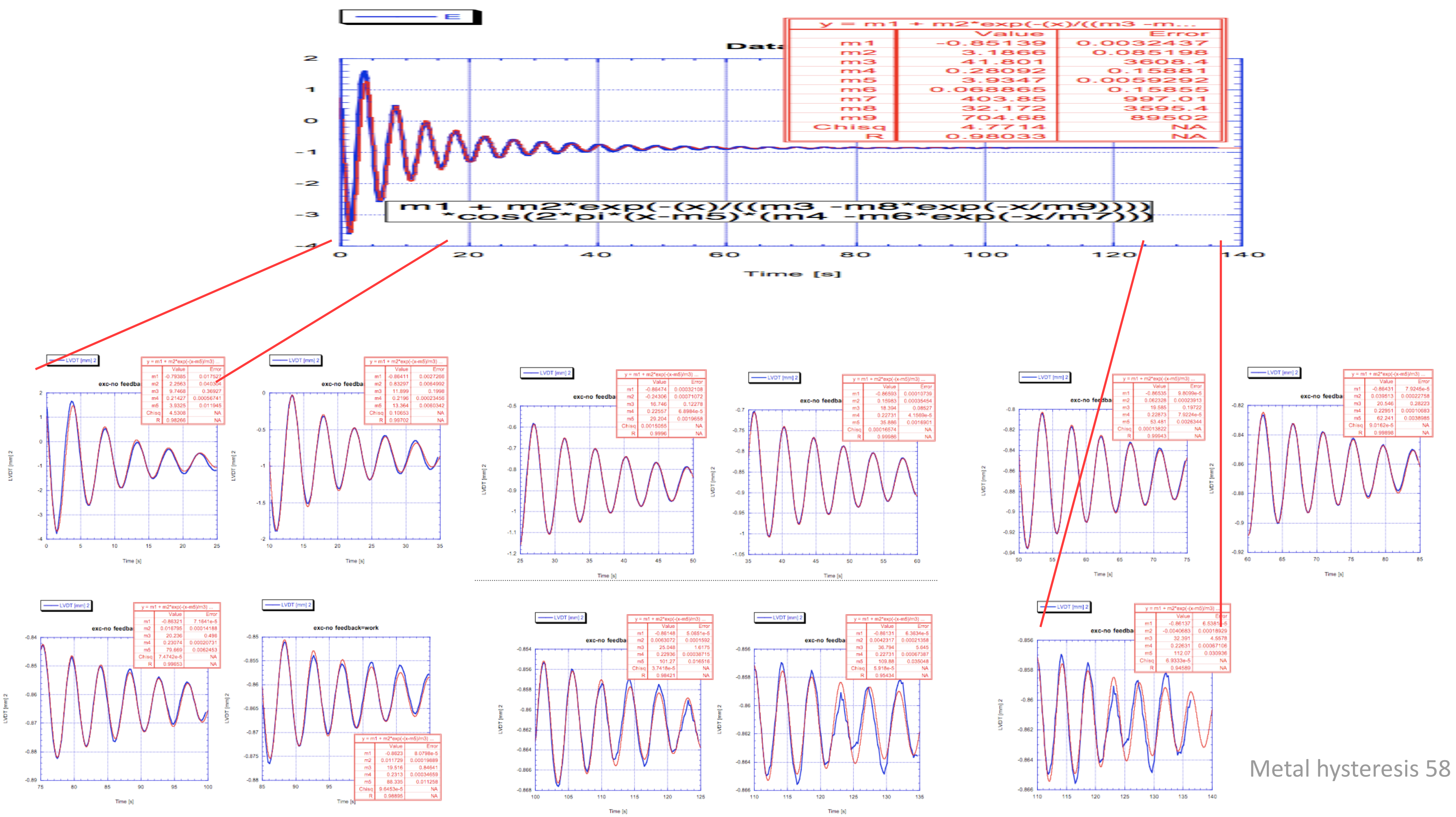
EMAS -2


y = ((m1-2566*x^ 2)/m2)
Value
Error
m1
53.324
1.2231
m2
8.2516
0.85157
Chisq
0.17084
NA
R
0.97938
NA
LVDT amplitude [mm]
Frequency [mHz]

- These fits match decently the data:
- It is a very surprising result
- We cross checked it in the time domain

looking for a similar effect in ringdowns

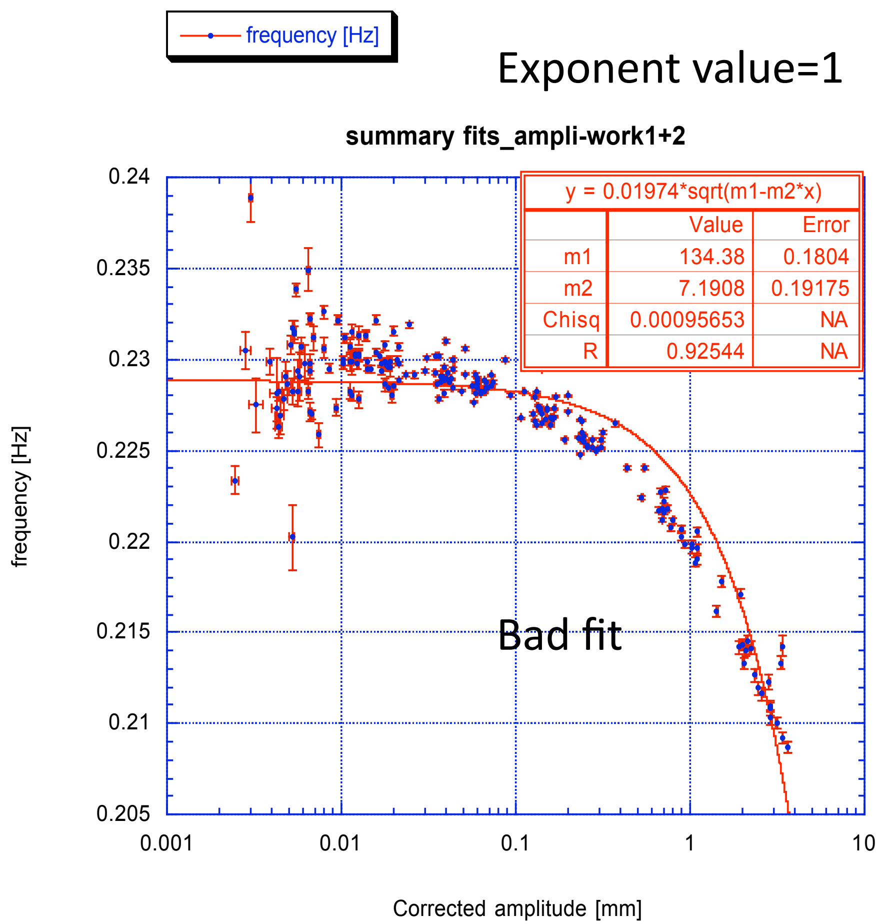
- Fitted Several ringdown plots with a sliding window

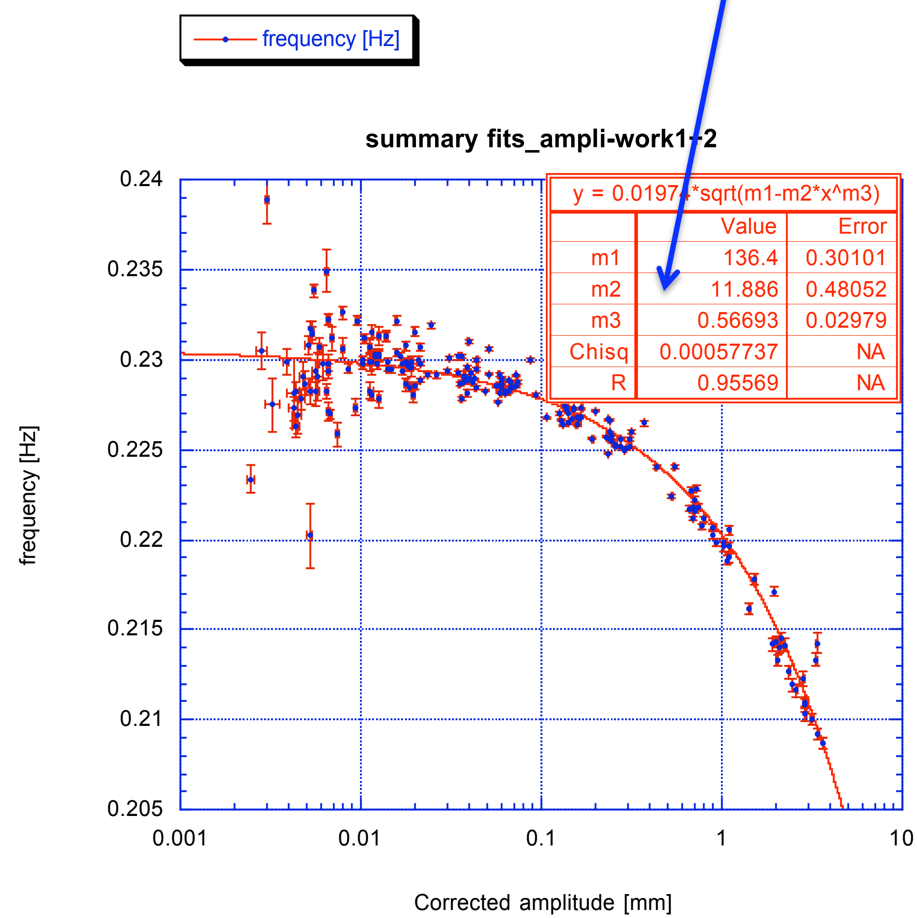


we found that the the same function does not fit this data

we repeated the analysis with the function $$f = \frac{1}{2\pi}\sqrt{(K_0 + K_a A^x)/M}$$

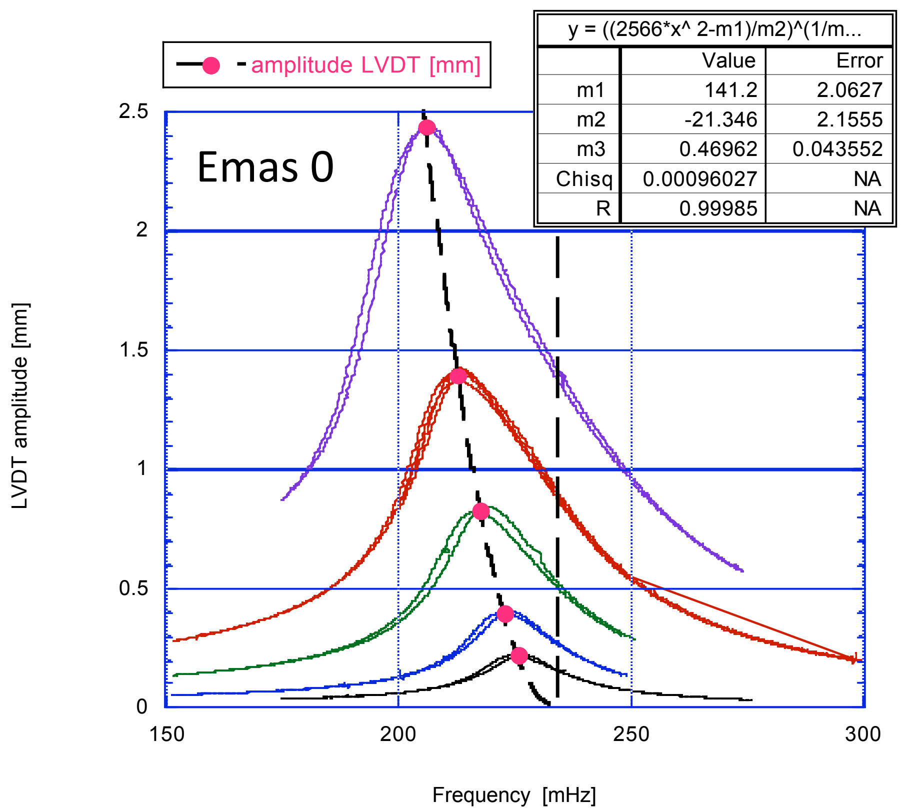
And found very good fit with an exponent compatible with 0.5.

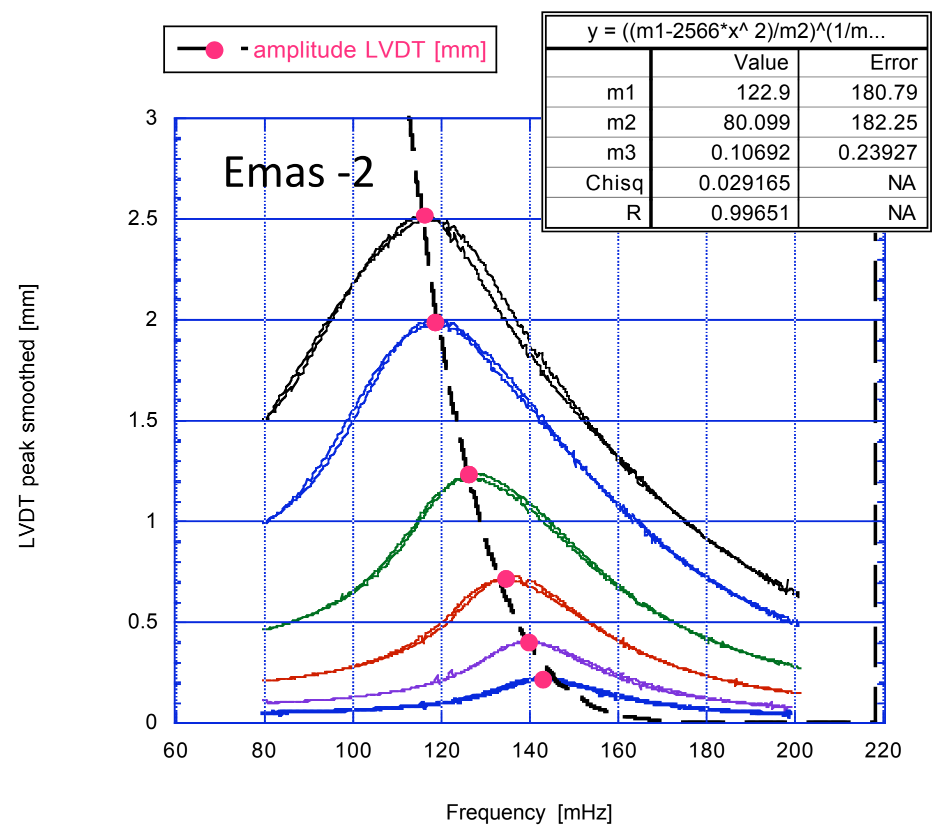


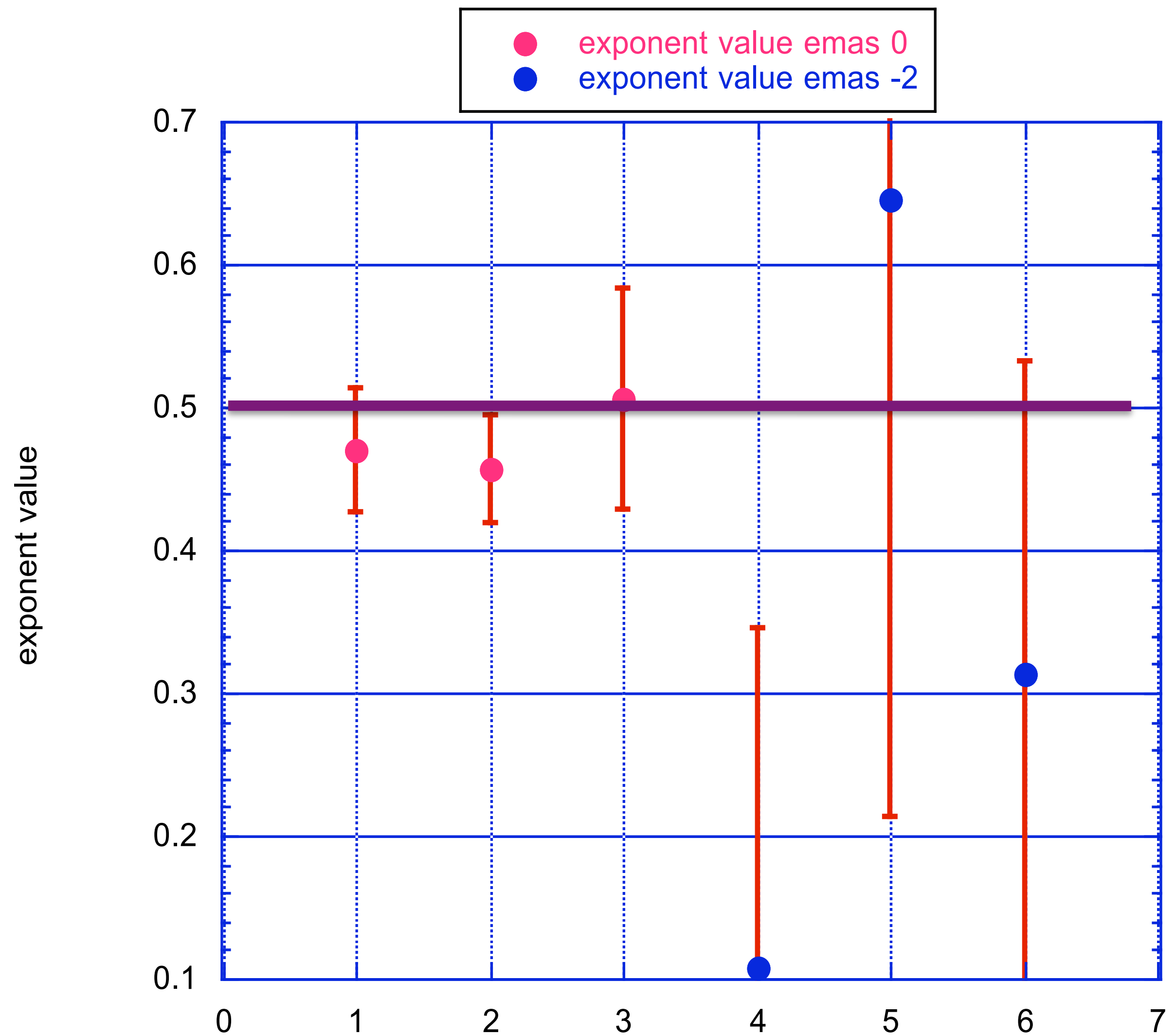


Returning to the original data and using the same function
we find an excellent fit , again compatible with a 0.5 exponent

$$f = \frac{1}{2\pi}\sqrt{\frac{K_0 + K_a\sqrt{A}}{M}}$$

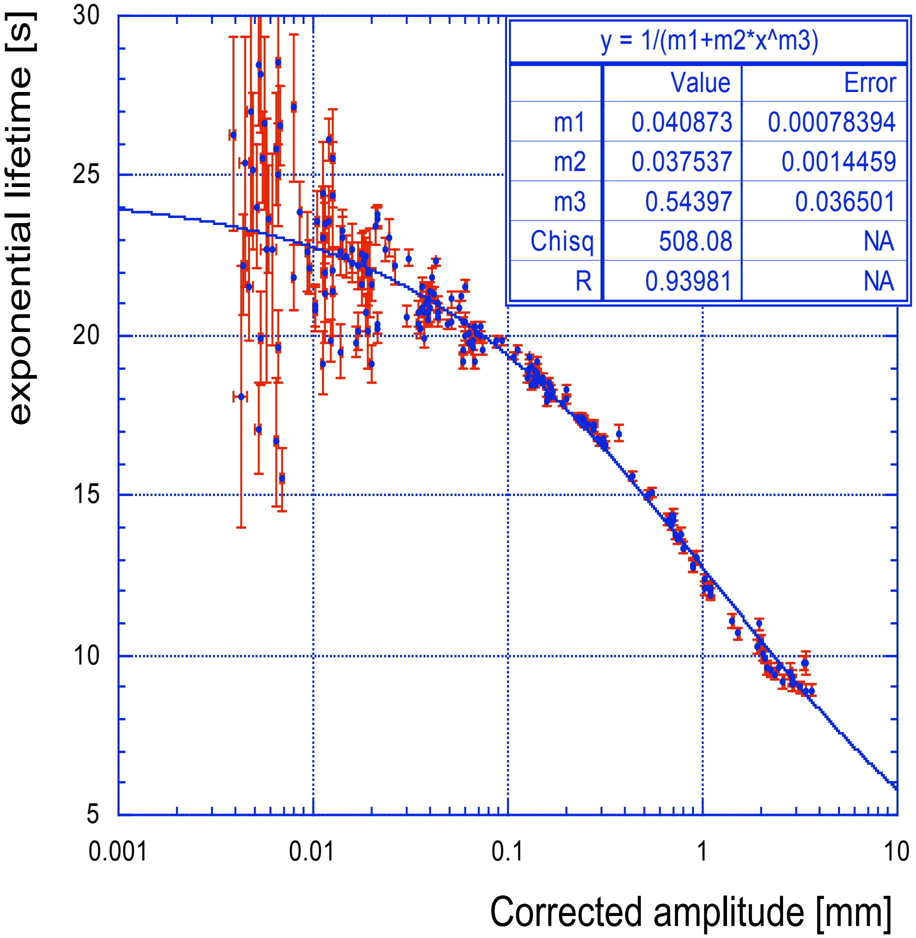


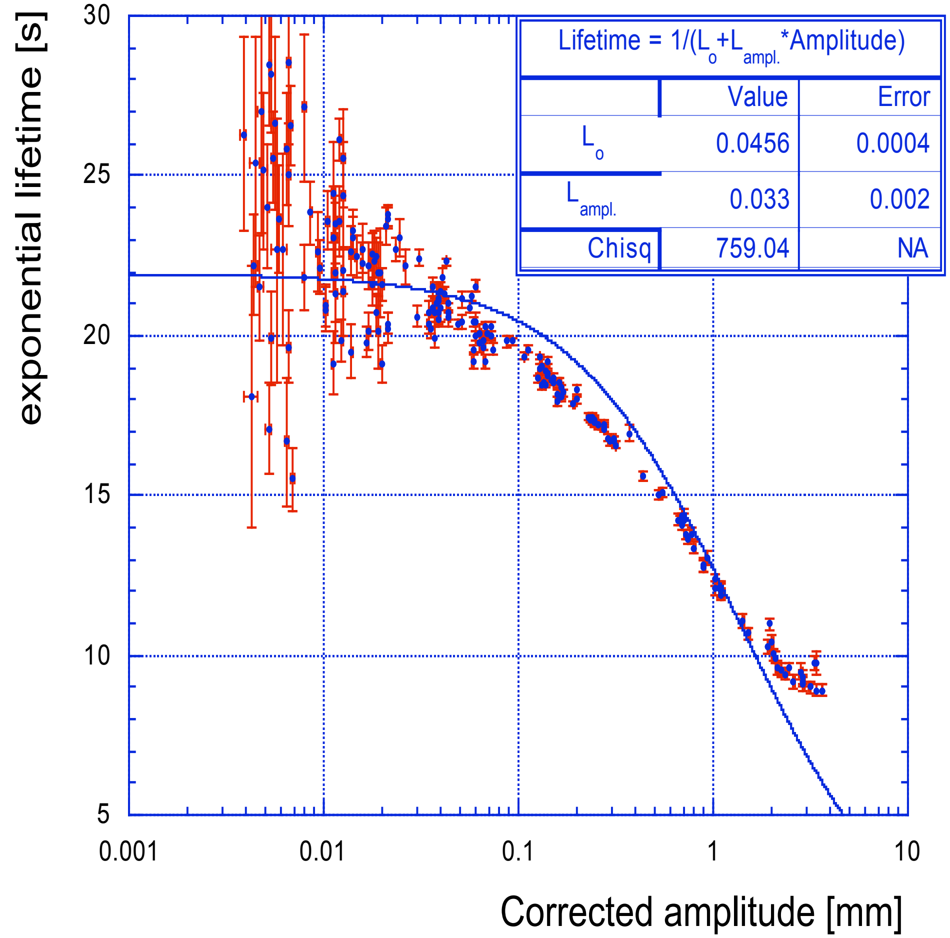




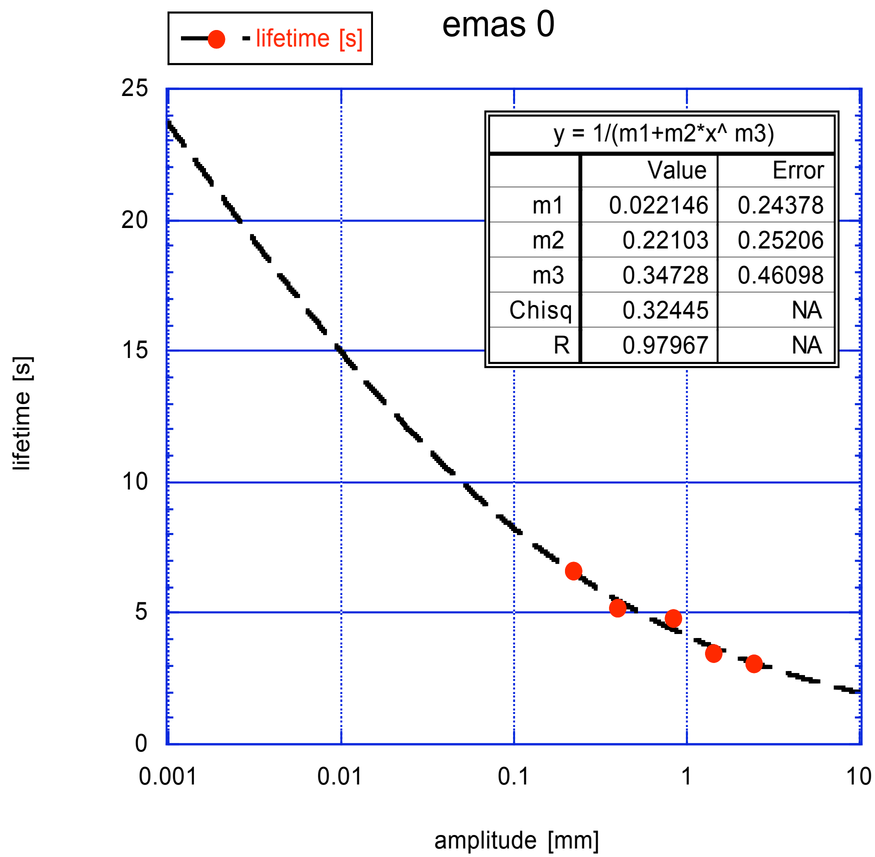
This plot is obtained by leaving the exponent as a free parameter in all our data and data analysis methods. Almost every value of the amplitude exponent is compatible with 0.5 within 1 standard deviation!

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

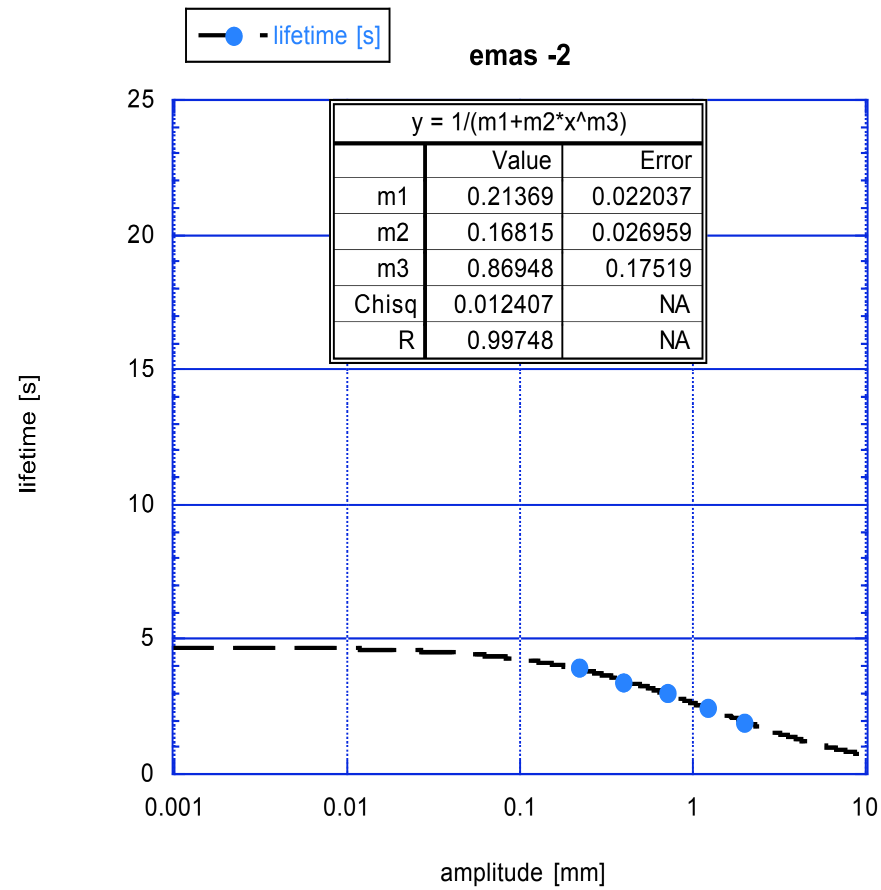




- Using the resonant width, we calculated the lifetime of the swept sine for different amplitudes and different EMAS gain.
- We fitted the lifetimes vs. amplitude to figure out the value of the exponent of the amplitude.

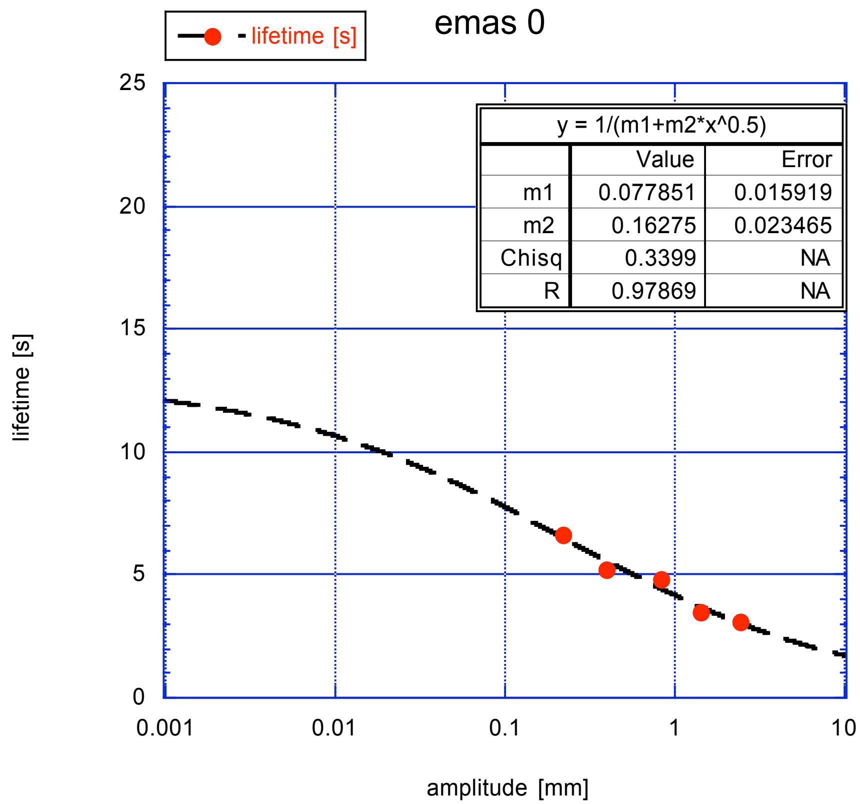


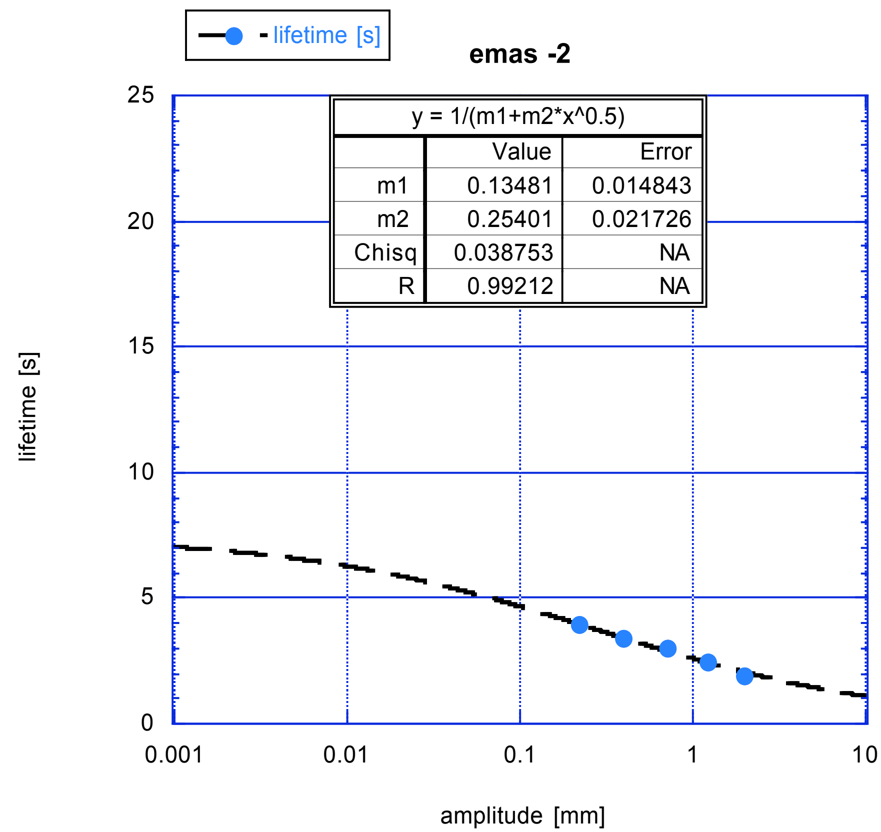
y = 1/(m1+m2*x^ m3)	Value	Error
m1	0.022146	0.24378
m2	0.22103	0.25206
m3	0.34728	0.46098
Chisq	0.32445	NA
R	0.97967	NA



y = 1/(m1+m2*x^m3)	Value	Error
m1	0.21369	0.022037
m2	0.16815	0.026959
m3	0.86948	0.17519
Chisq	0.012407	NA
R	0.99748	NA

- The result is roughly compatible with 0.5, but with large errors
- we fitted the data forcing the 0.5 exponent of the amplitude, and we still have a good results.





Conclusions…

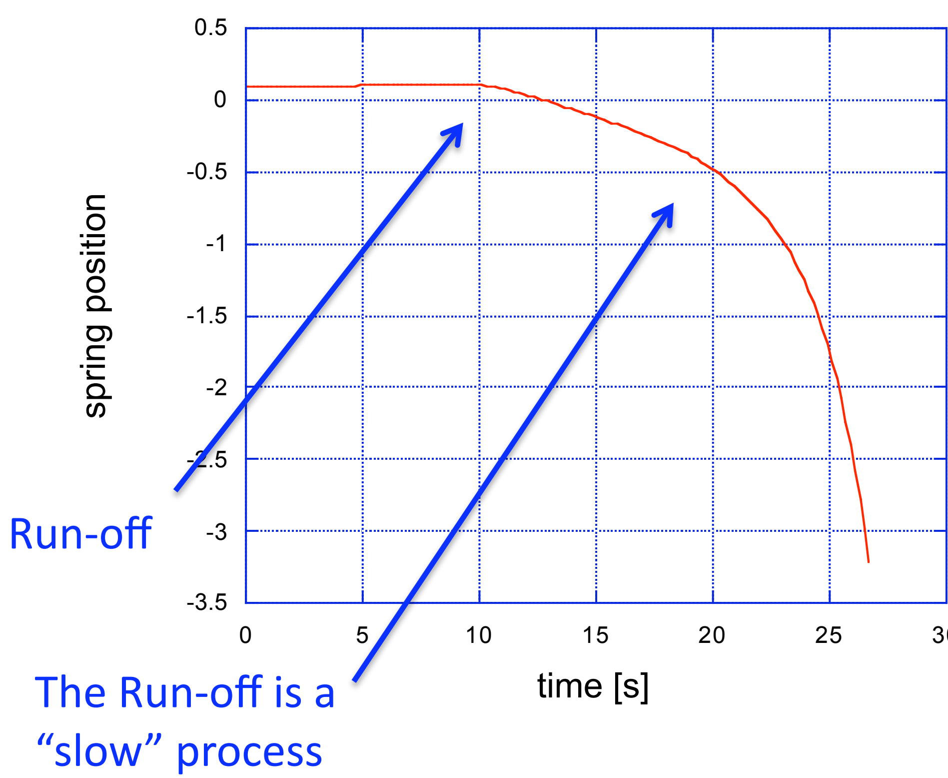
- The observed effects are compatible with a progressive disentanglement of dislocations
- The freed dislocations reduce the stiffness of the spring and increase the observed dissipation, possibly in a viscous manner
- The amplitude of both effects, and therefore of the disentangled dislocations, appear to be proportional to the square root of the strain

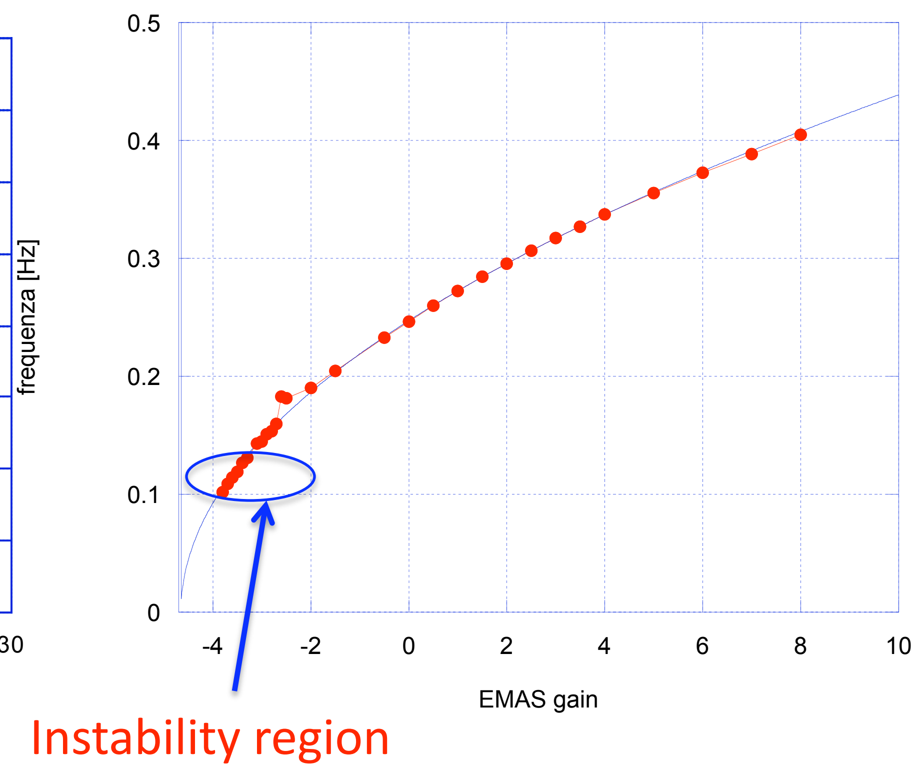
Fractal behavior of elasticity

- Entanglement and disentanglement of dislocations is an intrinsically fractal behavior (likeshifting sands).
- The observed 1/f Filter Transfer Function would be easily explainable
- Excess 1/f noise could be expected as well
- The excess noise found in tiltmeters could be explained
- Excess noise in suspended mirrors?

LF Instability and run off

- We observed that below 150 mHz the system is unstable.
- Perturbations internal or external drive the system to run off
- For lower frequency smaller perturbations are sufficient to destabilize the system



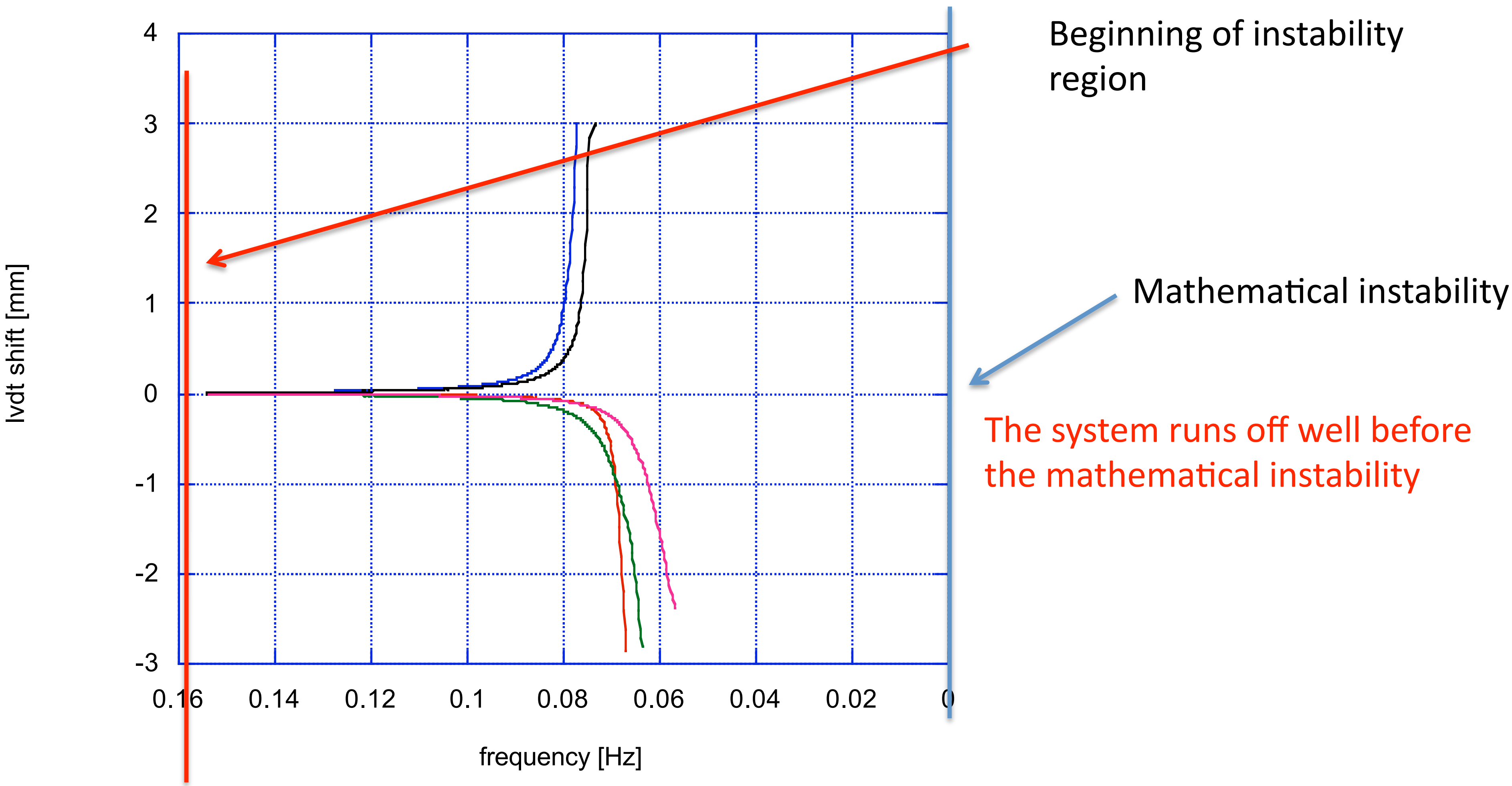


- To explore the LF instabilities we scanned the system with increasing negative EMAS gain
- At constant vertical position setting and no excitation

$$K_{effective} = K_{elastic} + K_{Gas} + K_{EMAS}$$

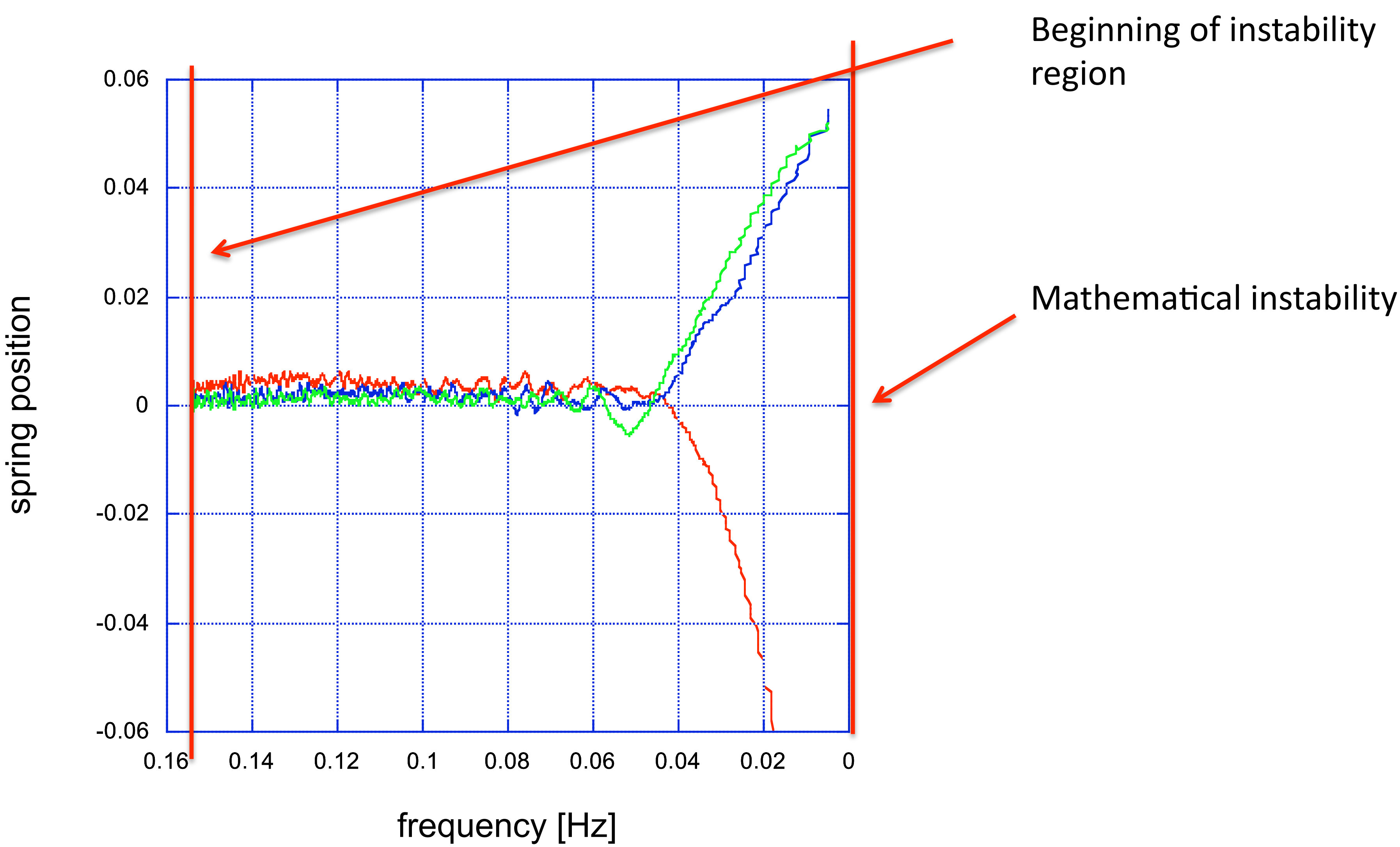
Fast EMAS gain ramp :

Spring deviation from the set point versus the resonant frequency



Small offsets are amplified by fast EMAS ramps and generate premature runoff

Slower EMAS ramp and Faster position integrator time constant result in run off at lower frequencies

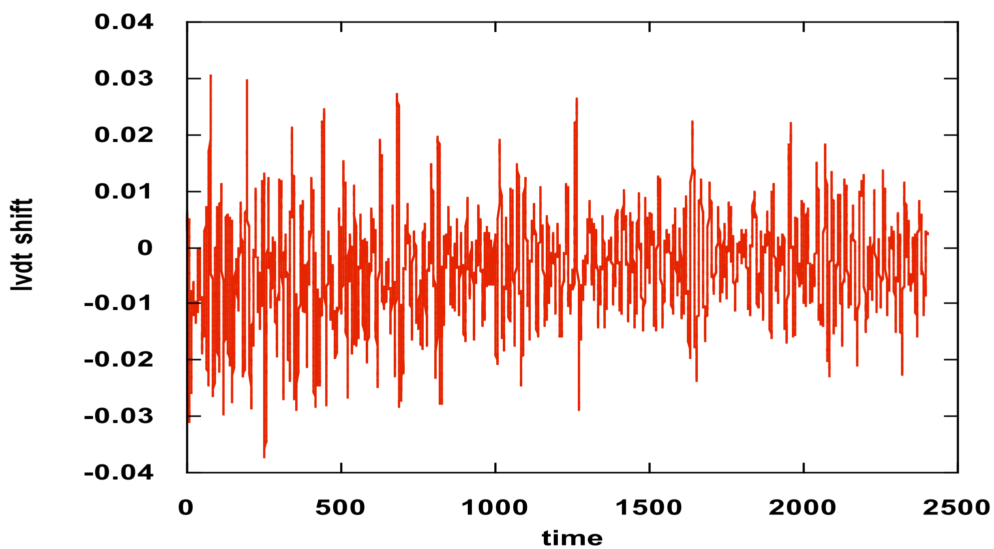


What causes the run-off?

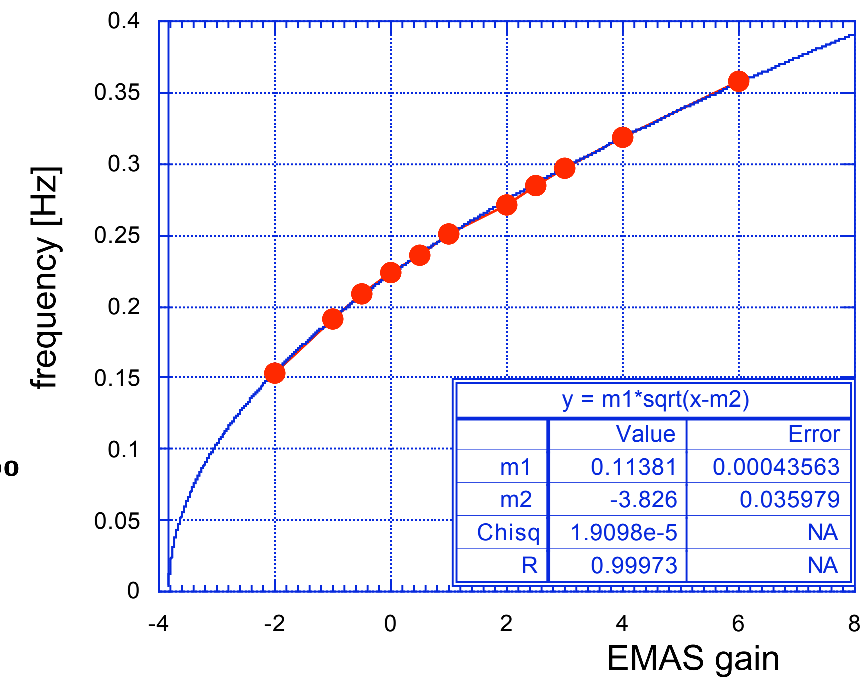
- We interpreted the run-off as a temporary loss of restoring forces due to mobilization of entangled dislocations by an external or internal excitation

What causes the run-off?

- In absence of perturbations the spring stays stable with resonant frequencies well below 100 mHz



- EMAS=-3.52
- F=63 mHz



How to stop a run-off?

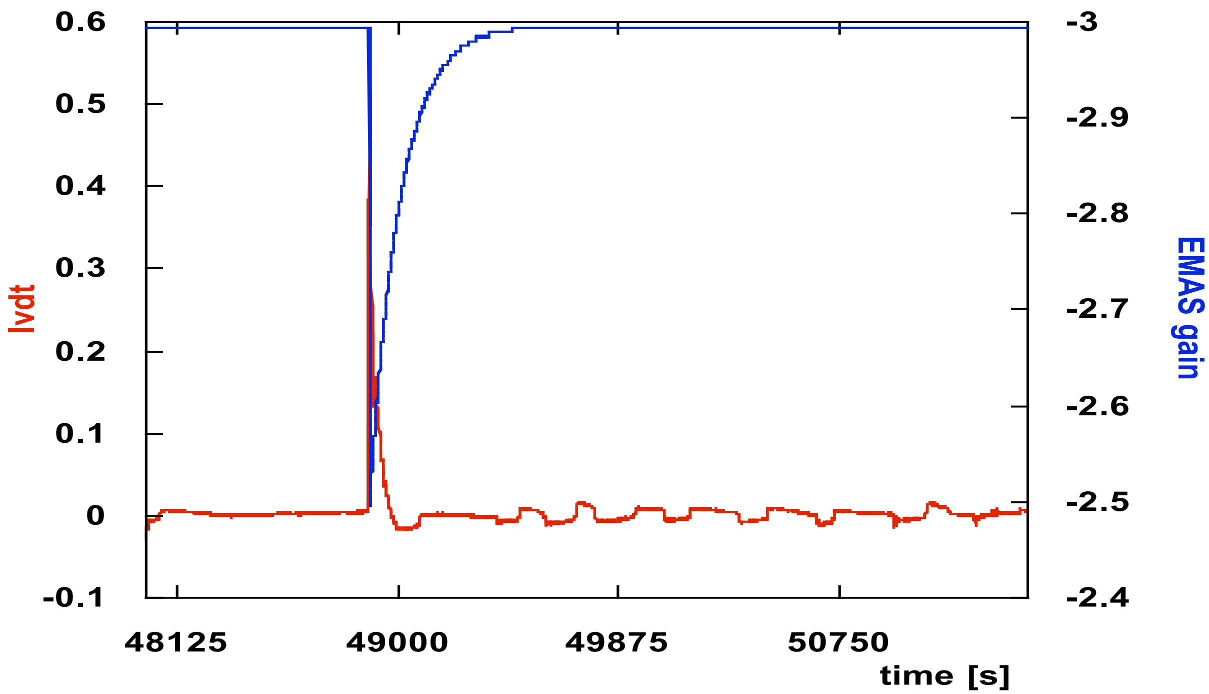
- If a perturbation and/or a runoff are detected in time:

- the spring can be re-stabilized by backing off the EMAS gain for the time necessary (seconds) to re-settle the dislocations

- then the EMAS gain can be ramped up again

Runoff recovery

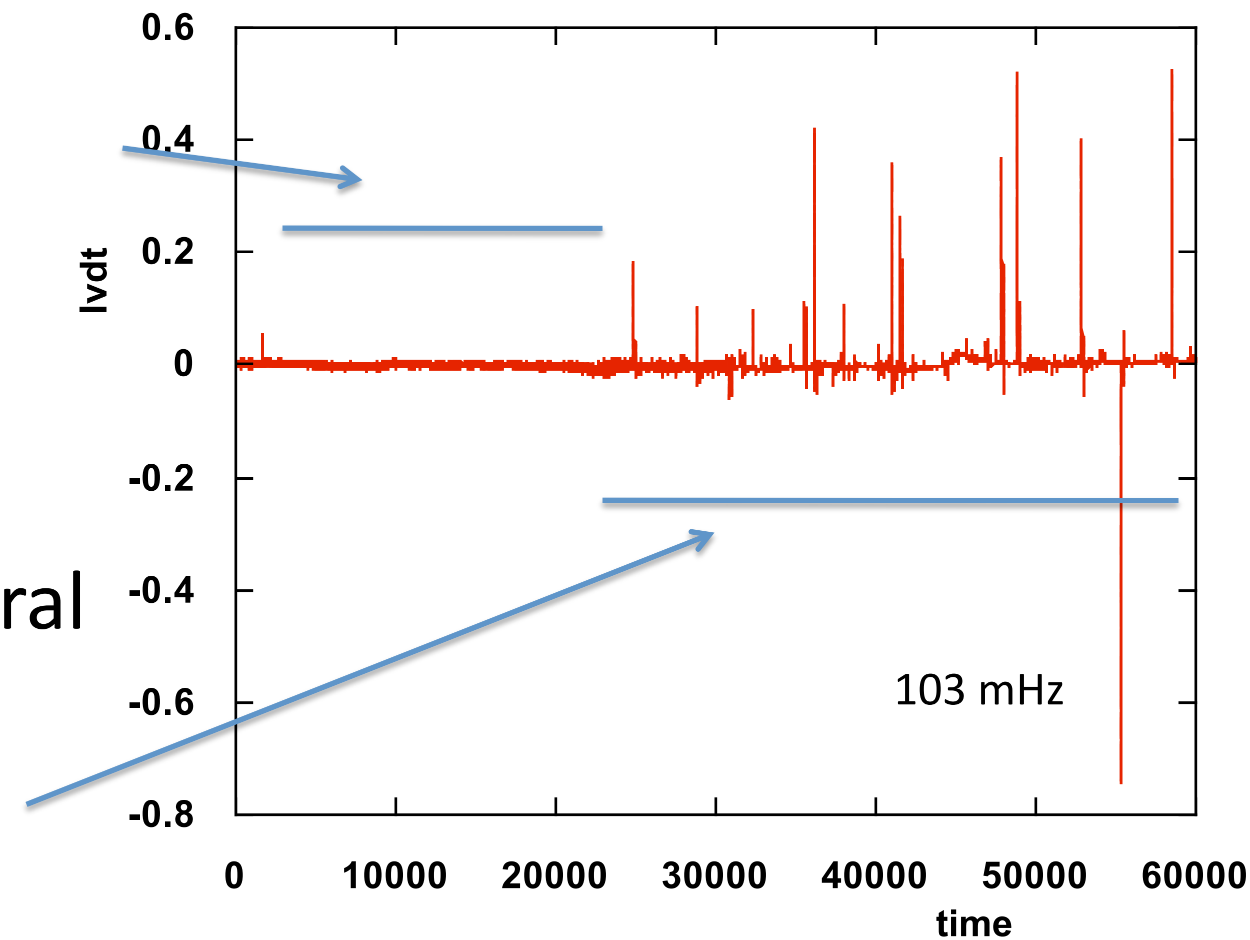
1. An external perturbation triggers run-off
2. As runoff is detected EMAS gain backs-off
3. EMAS ramps back to nominal



103 mHz

Run-off recovery

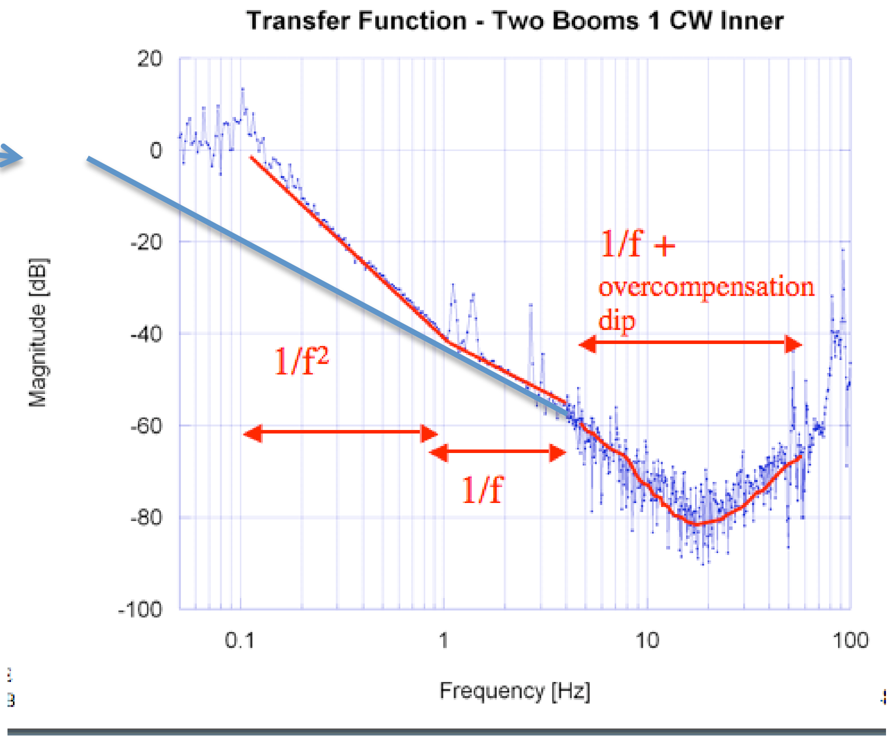
- Night-time no run-off is generated
- Day-time several run-offs are triggered and recovered



Advantages to operate inside the instability regime

- Maximal attenuation transfer function

- Critically damped response, all oscillations and excitations from payload automatically absorbed



Conclusions

- We have discovered anomalous dissipation mechanism connected with an equally anomalous stiffness reduction.
- These effects appear connected with the fractal behavior foreseen for entangled dislocations.
- This theory can explain the 1/f transfer function discovered by Stochino, but can predict also LF 1/f noise in the springs.