Studies of Hysteresis in metals

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LIGO-G080243-00-R

Hysteresis
First anomalies

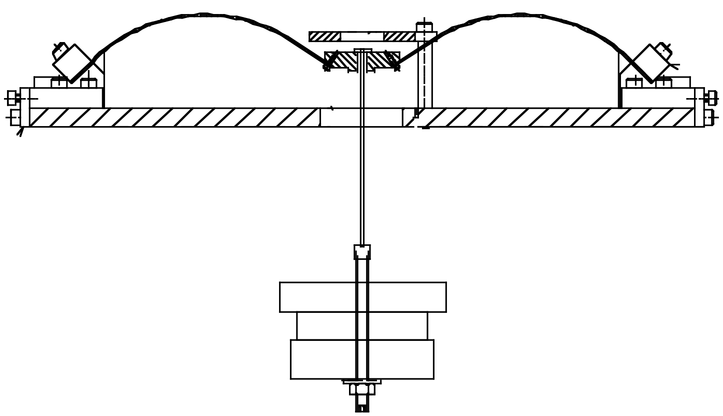
- Anomalous hysteretical behavior was observed in GAS filters and IP tables

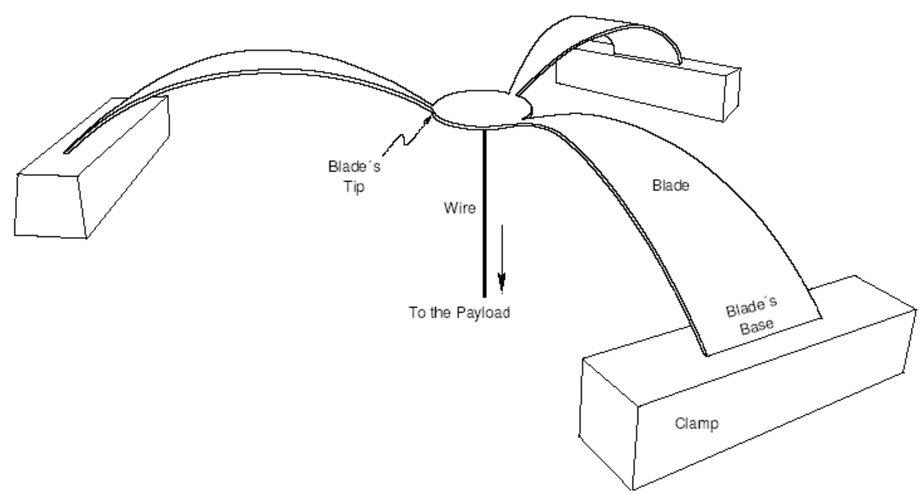
- Two very different systems

- One stress rich, the other stress poor
- Both <u>elastically controlled</u>

the Geometric Anti Spring Vertical attenuation filter

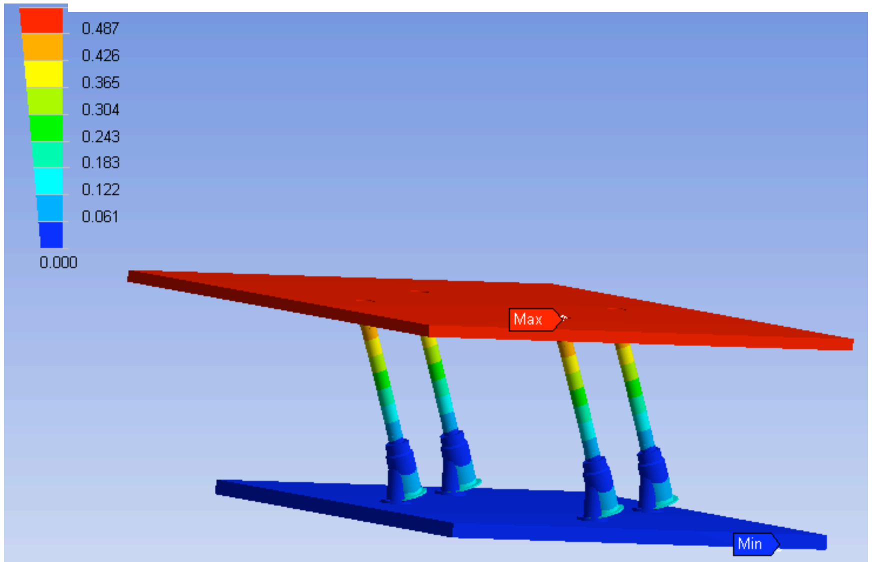
- Large amount of pre-stressing energy is stored in the blades
- The vertical oscillation energy is stored in the blades
- The GAS mechanism nulls the restoring forces and exposes the hysteresis





The Inverted Pendulum table

- No pre-stress energy
- The oscillation energy is stored in the flex joint
- The inverted pendulum mechanism exposes the effects



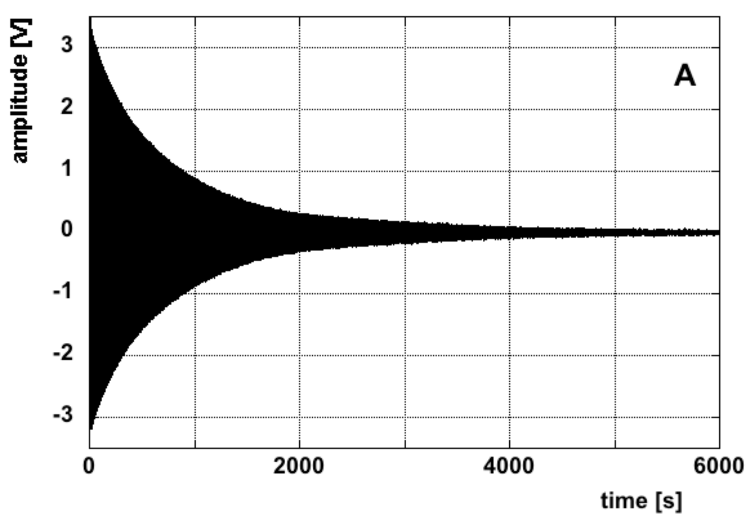
First Anomalies reported

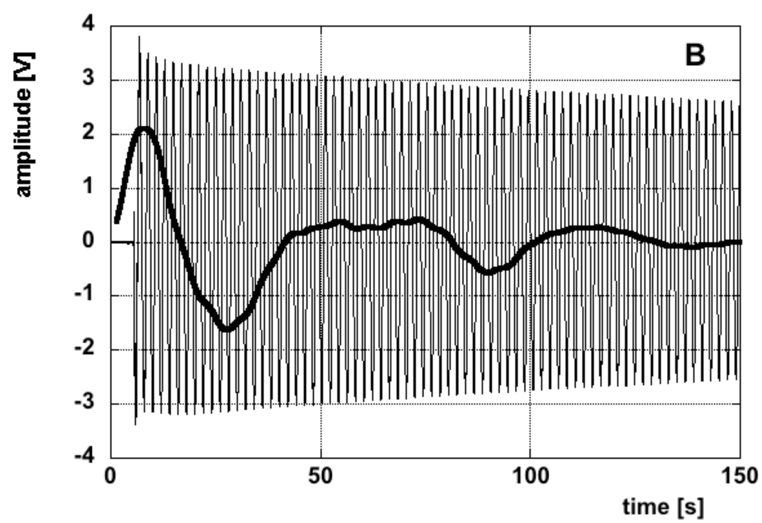
- "Study of quality factor and hysteresis associated with the state-of-the-art passive seismic isolation system for Gravitational Wave Interferometric Detectors"

- R. Desalvo, A. Bertolini, et al., Nuclear Instr. and Meth. A, Vol 538, 11 Feb. 2005, Pages 526-537

IP ringdown

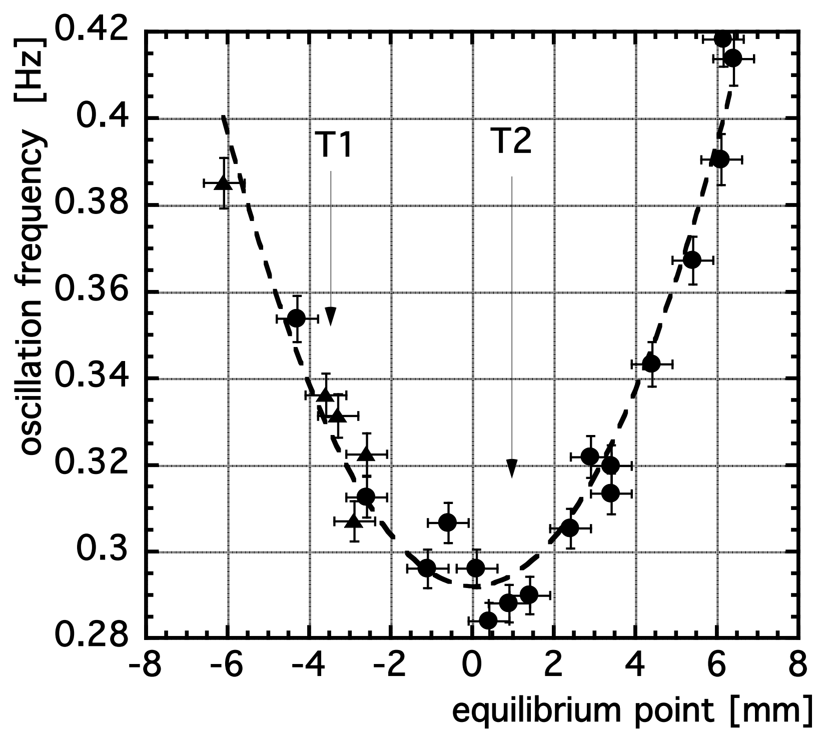
- At high frequency (1 Hz) it is an almost perfect oscillator
- At low frequency (30mHz) seismic re-injection and hysteresis yield a much less predictable sinusoid





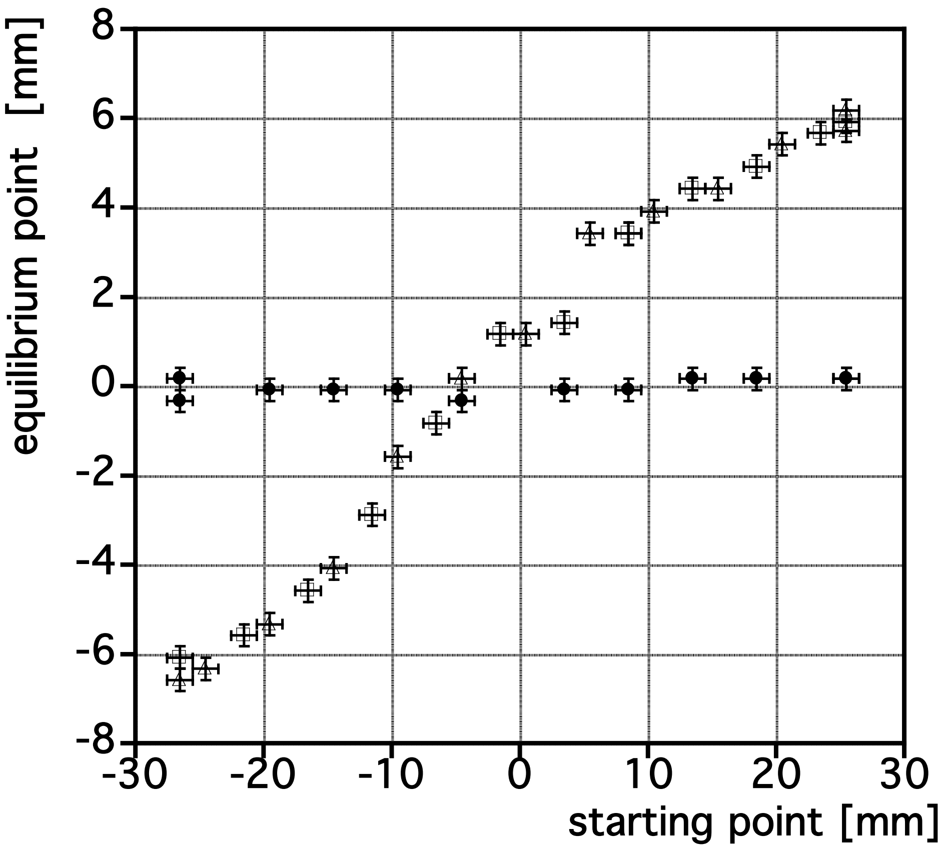
Hysteresis in GAS

- Large, non-oscillatory, forced movements induce mysterious changes of equilibrium position
- Small oscillation behavior normal at hysteresis-determined working points
- Hysteresis is equivalent to adding and removing small masses
- The Frequency Vs. Height curve is independent of how the working point is obtained (change of load, change of temperature or hysteresis)



- Small oscillations (<10%) (used to measure the frequency) DO NOT remove the bias introduced by hysteresis (even for weeks)

The metastable and stable equilibrium points



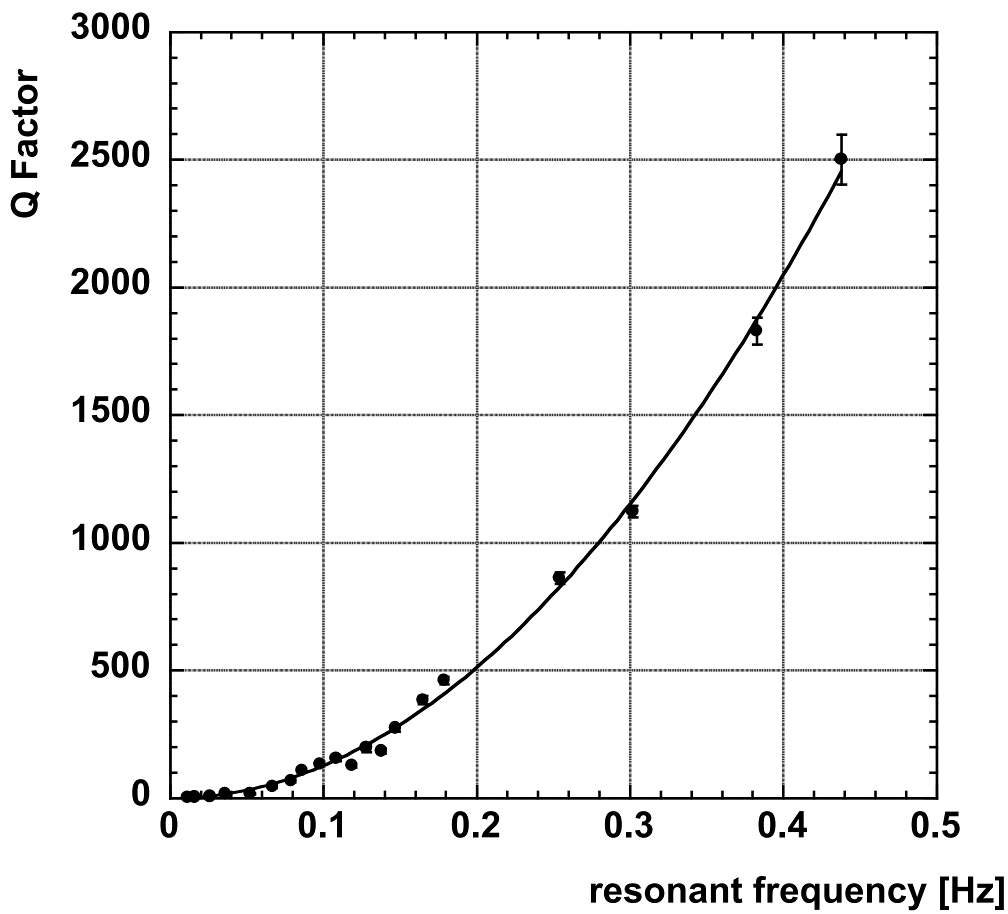
- Large forced excursions produce different equilibrium position depending on:
  - if the return motion is not allowed to oscillate, or
  - if the oscillator is allowed to freely oscillate and search for its equilibrium

- Note the Quality factor is still sufficiently large to allow oscillations

Hysteresis amplitude

- When tuning the system softer (to lower ω) Hysteresis fraction of excursion grows with $1/\omega^2$
- This is natural, considering that the restoring force constant $k \sim \omega^2$

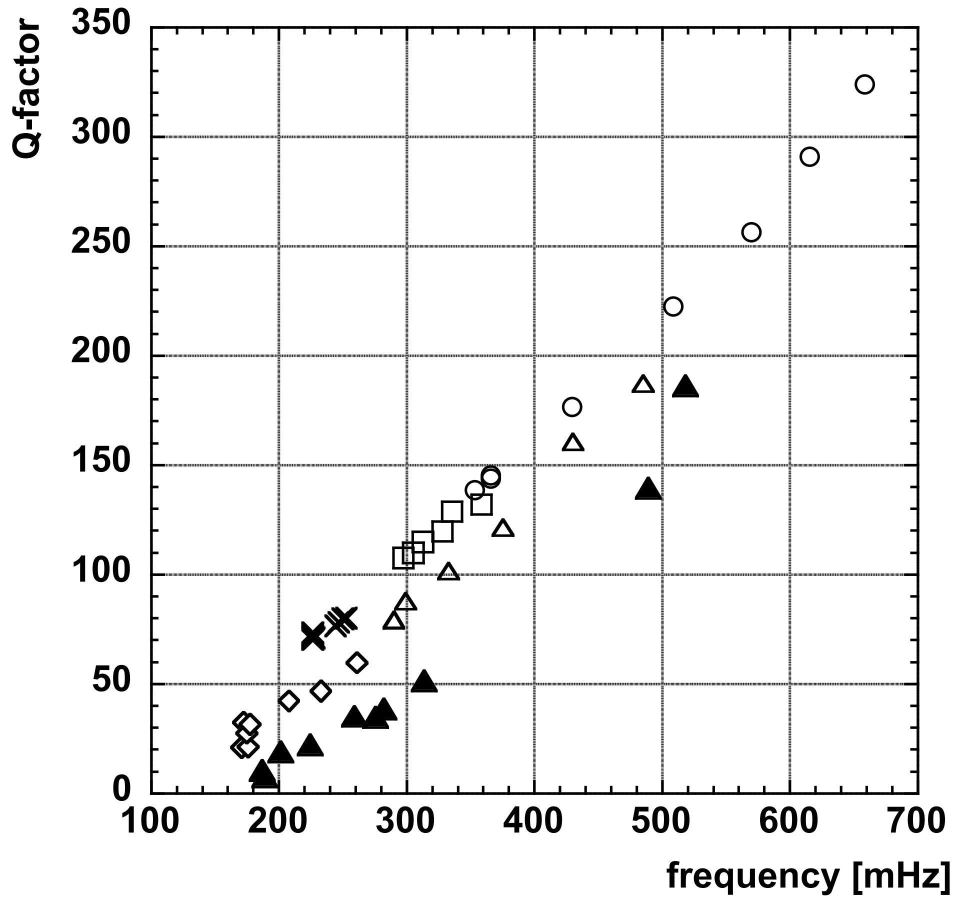
Quality factor versus frequency



- Quality factors in IP a quadratic curve with frequency
- Compatible with a constant (amplitude but not frequency dependent) hysteretic loss per cycle

- Once hysteresis is introduced, there is little need for “viscosity” and dashpots to explain most or all observed effects

Quality factor versus frequency



- Quality factors in GAS filters sometimes deviate from a quadratic dependency
- I now believe that these Deviations from the quadratic rule explainable with amplitude variation of hysteresis (to be further studied)
- Does this deviation depend on stress?

Observation

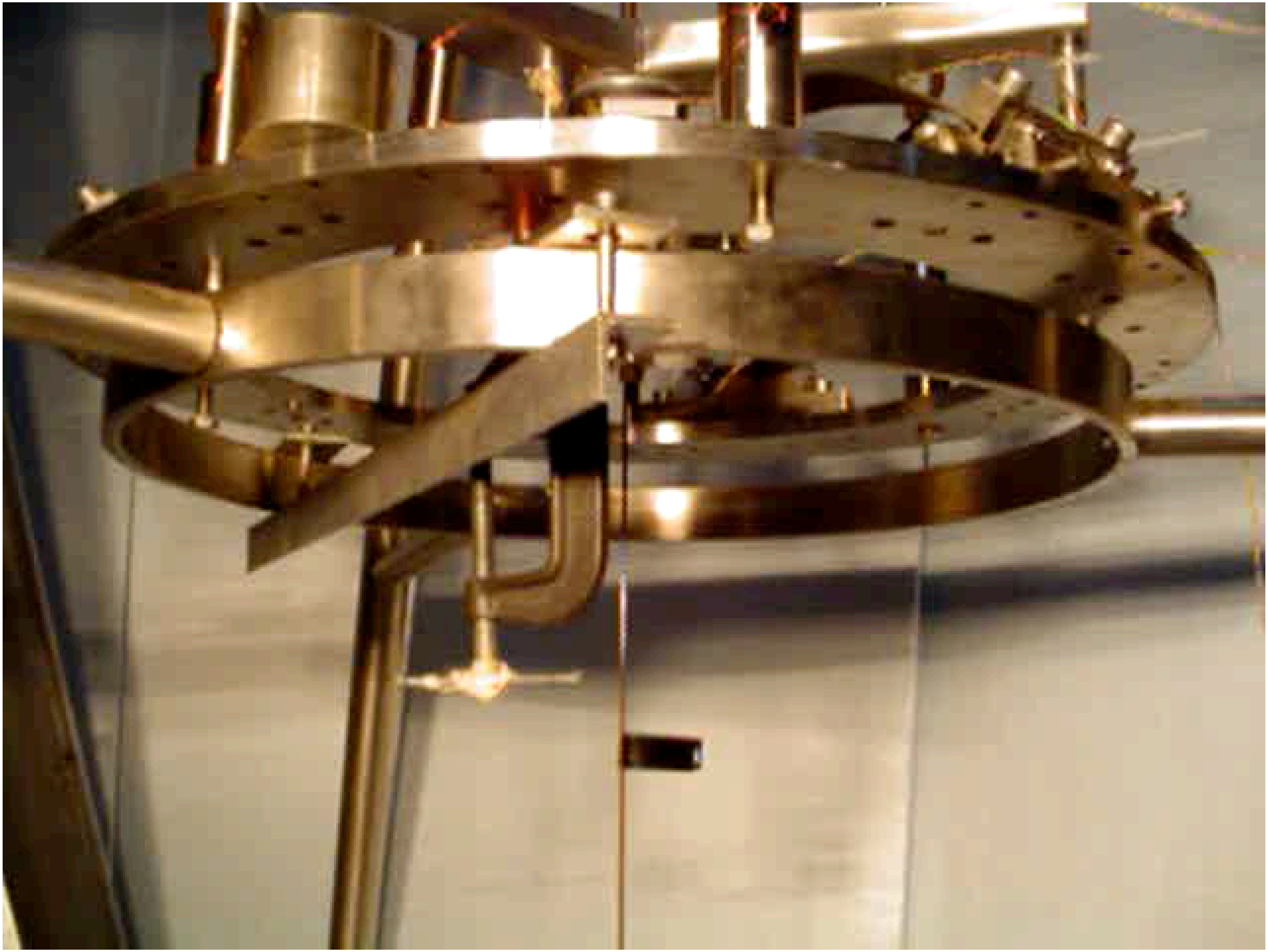
- It is very difficult to tune GAS filters below 200-300 mHz (or IPs below 20-30 mHz) because:
  - as the Quality factor approaches zero at low frequency,
  - the spring becomes sluggish
  - more or less indifferent equilibrium over some distance is observed
  - Runoff instability is eventually observed

Other comments

- Similar behavior was since observed in Maraging and Copper-Beryllium GAS springs

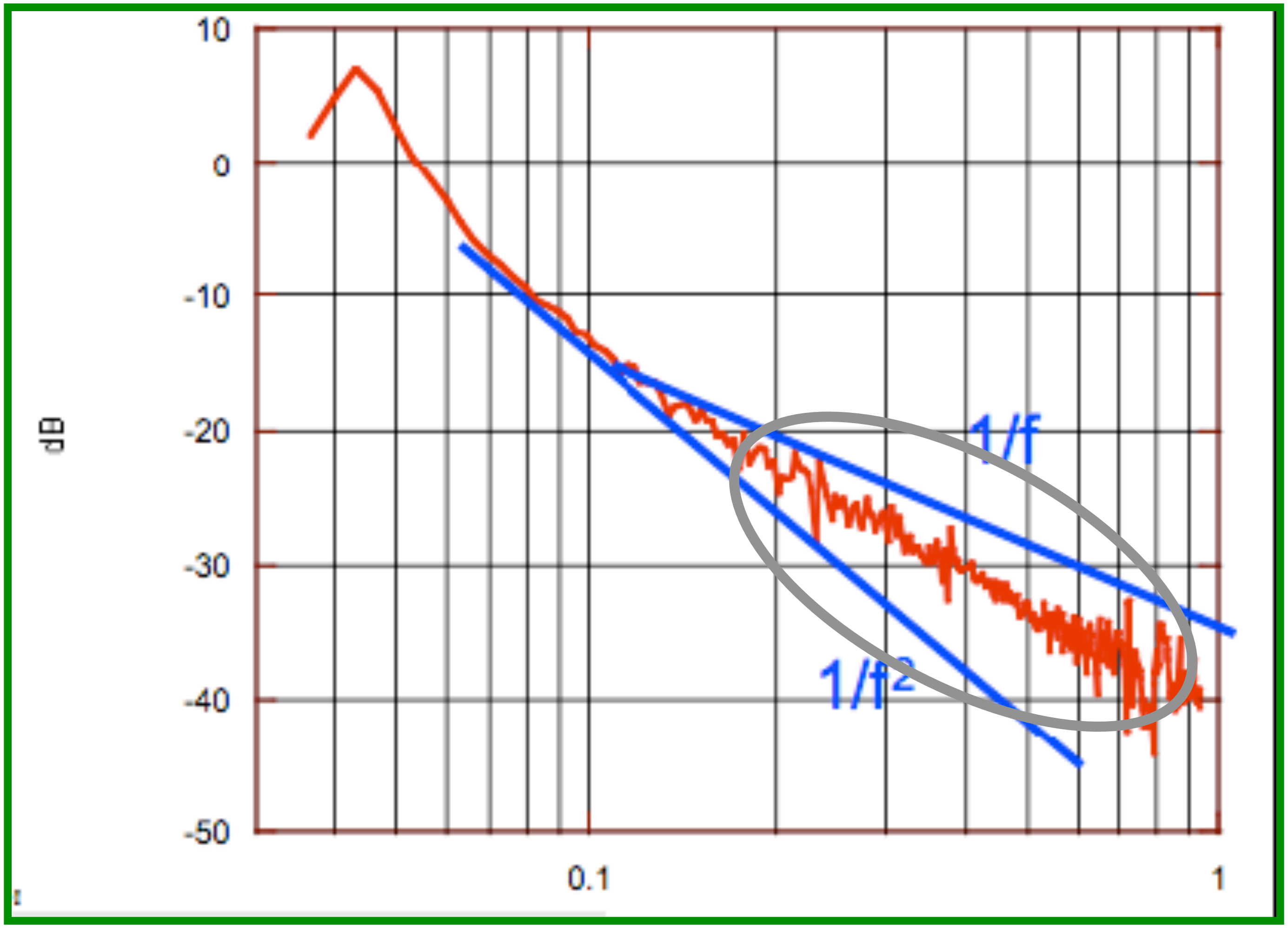
Additional strange observations in GAS filters

1/f attenuation emerging in the seismic attenuator transfer functions



Reducing ω with
ElectroMagnetic Anti Springs

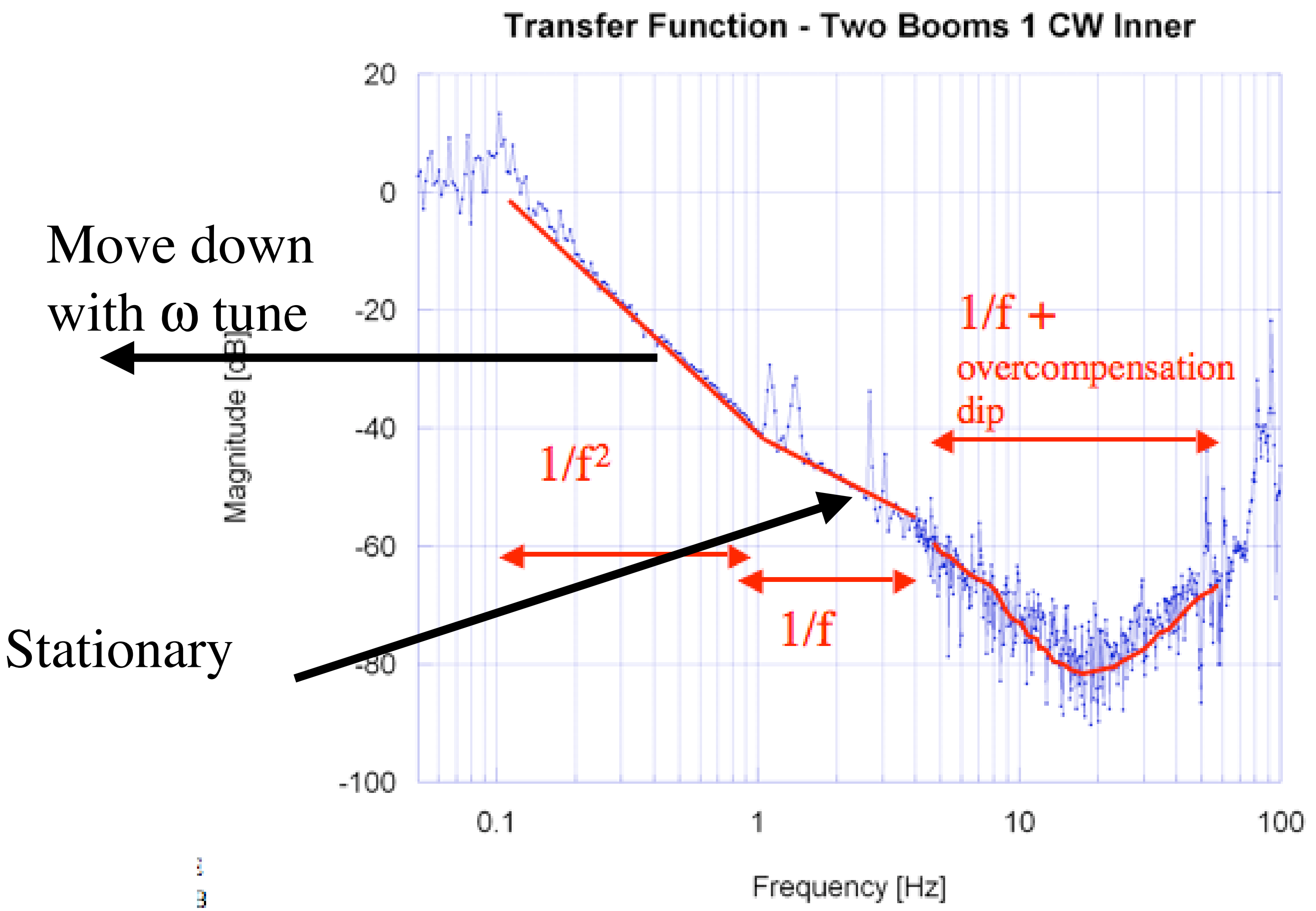
Maddalena Mantovani



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

Depressing transfer function with counterweights

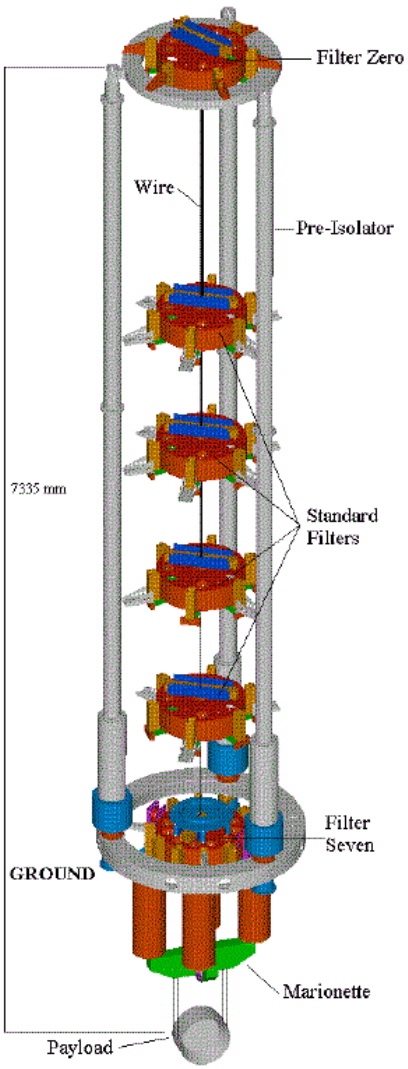
Alberto Stochino



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.

Other suspicious behaviors Virgo IPs



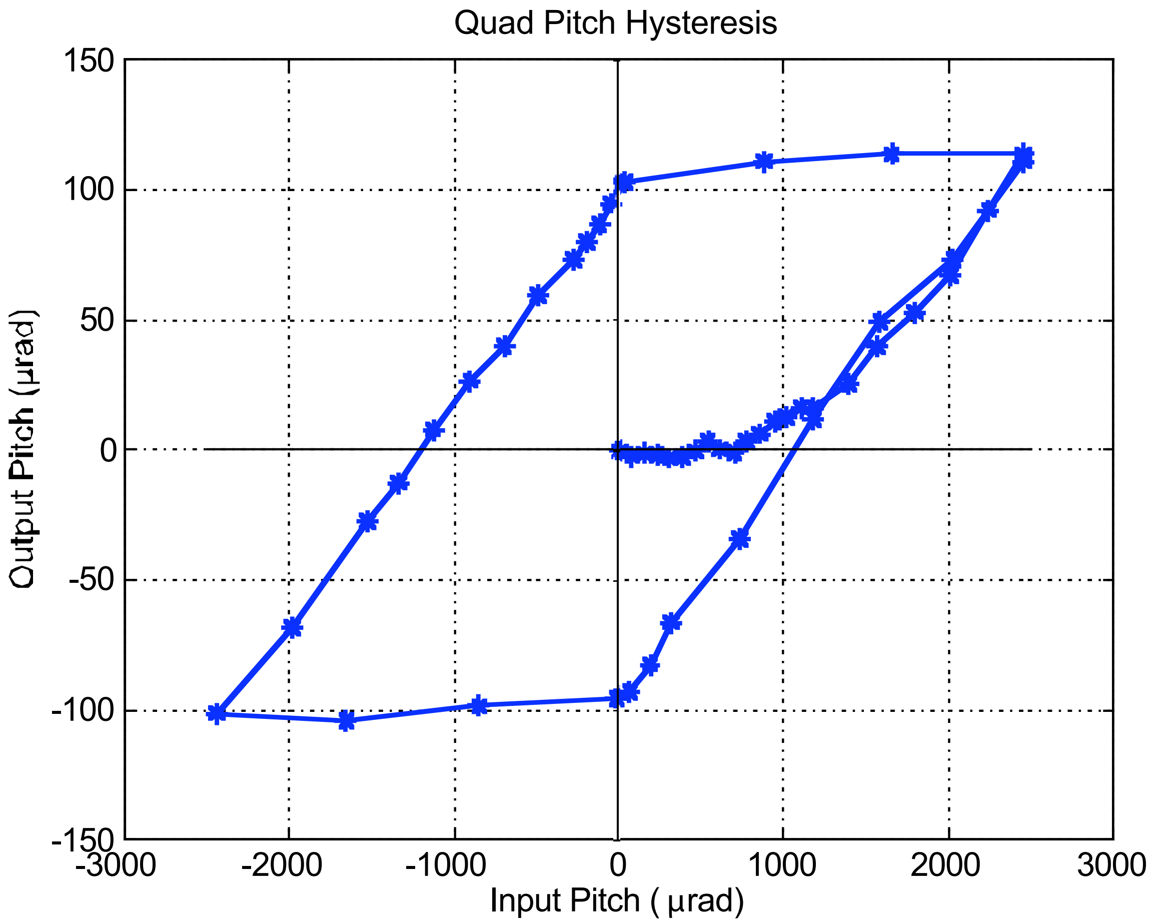
- Virgo has three identical Inverted Pendulum towers mounted on a single, small and very thick concrete slab.
- Despite this the low frequency coherence between the IPs is very weak
- The uncontrolled IPs equilibrium positions seem to follow random paths
- The control current of the IPs stabilized with LVDT feedback seem to random walk more or less independently
- P. Ruggi private communication

Other suspicious behaviors Seismometers

- Seismologists complain that:
- Poor LF coherence between huddled instruments (for example STS-2).
- During seismic events it is never possible to double integrate the acceleration signal to estimate the permanent displacement.
- Recorded Signal-to-Noise at LF during seismic events is incompatible with the noise curves measured in quiescent times.

Other suspicious behaviors

Tilt hysteresis in LIGO pendula



- Like in the GAS case, if the pendula are allowed to freely oscillate hysteresis washes away

Brett Shapiro, Justin Greenhalgh, …

Tilt hysteresis in LIGO pendula

- The material is high-carbon, work-hardened piano wires
- Anti-dilution from flex point close to the Center of weight
- Amount compatible with what observed with GAS filters and Maraging blades

Did we ever encounter hysteresis

- We probably already used hysteresis without recognizing it in LIGO
- Mirrors were "tilted" into alignment believing that we were somehow shifting its contact points
- Likely, instead, we were simply taking advantage of wire hysteresis
- Hysteretical tuning is Stable until earthquake or other large excitation "reset" the hysteretical setting by inducing large oscillations

Is hysteresis behind all these puzzles?

- Is there a basic characteristic of materials at the basis of this?
- Maraging, Copper-Beryllium, Piano Wire are all poly crystalline metal alloys

Doubts

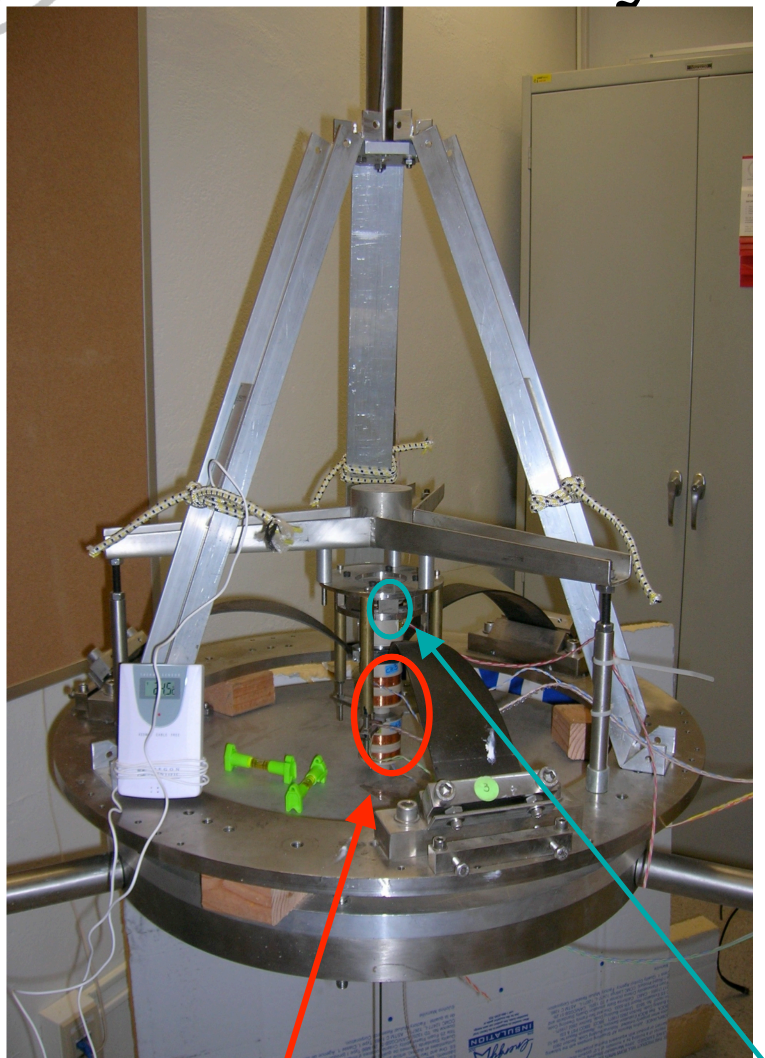
- 1/f Transfer Functions are typical of viscous systems
- Viscosity was very successful to explain MANY behaviors
- But viscosity is proportional to speed,

  its effects must disappear at lower frequencies

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

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

Hysteresis studies



Maria Sartor, Arianna DiCintio

Method:

- Geometric Anti Spring geometry reduces resonant frequency (0.2 Hz) and elastic restoring force thus exposing hysteresis

- Excite the attenuator using a coaxial Actuator
1. With a slow pulse
2. With a sinusoid

- Read the position with LVDT

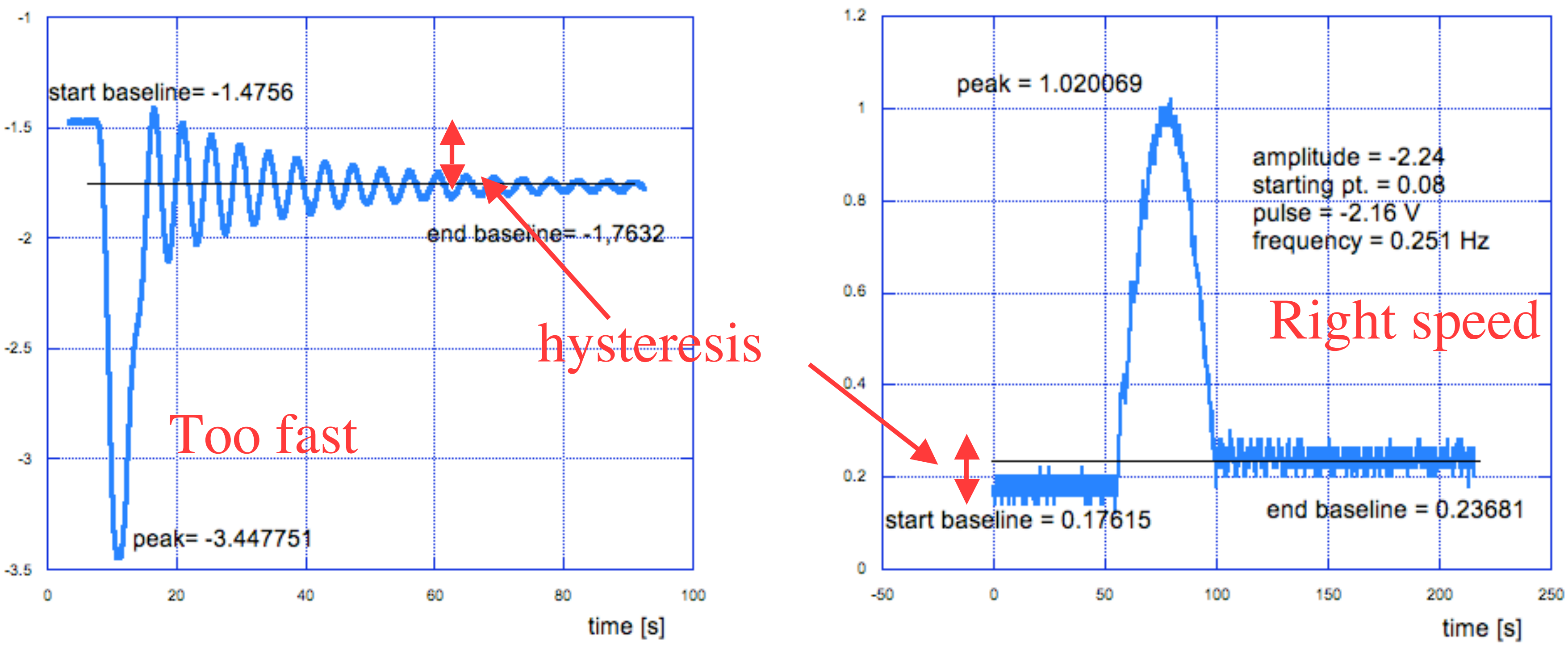
ACTUATOR

LVDT position sensor

Hysteresis studies pulse excitation

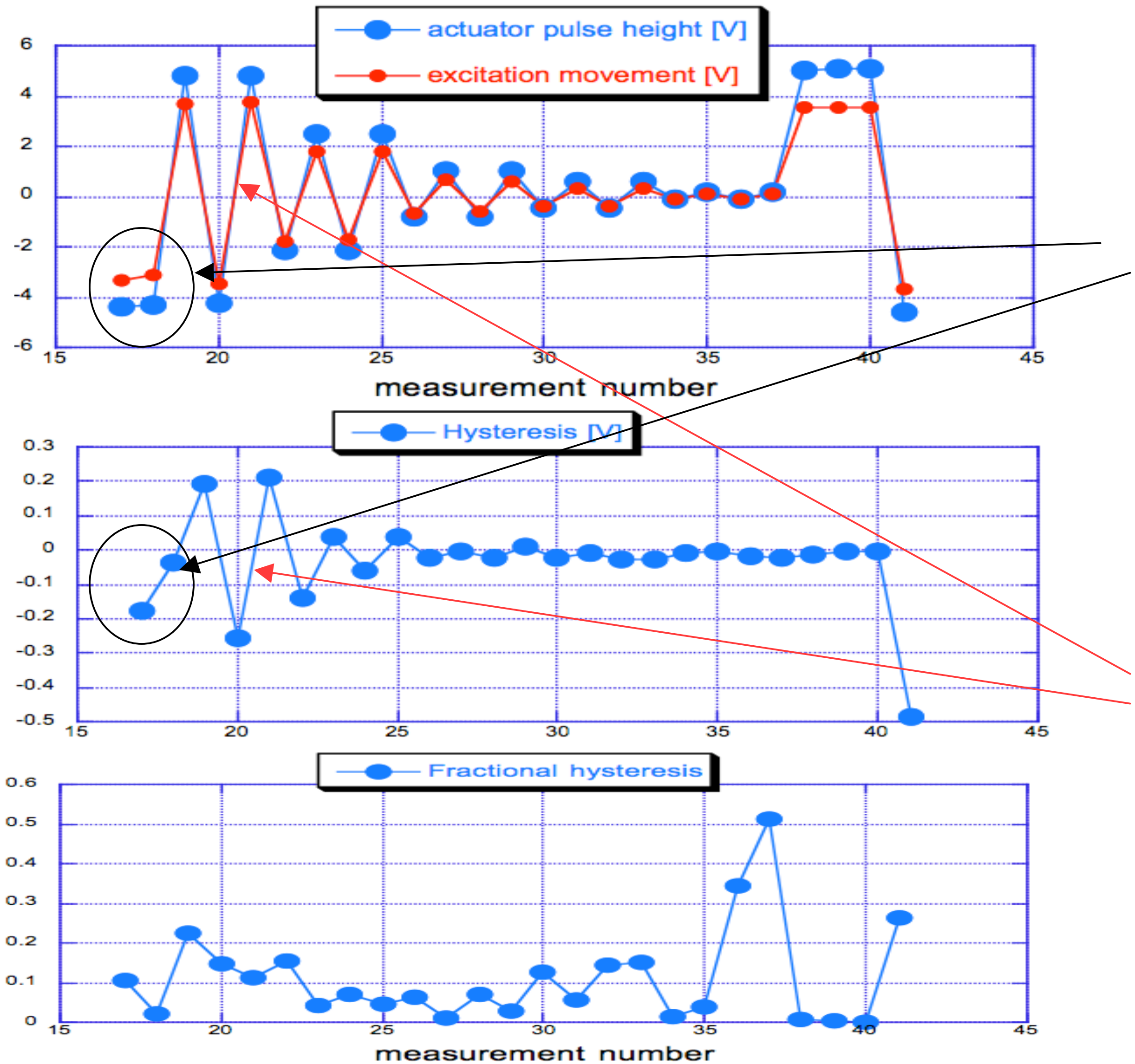
Maria Sartor (Mayfield senior High School)

Choosing the best pulse shape



Hysteresis studies pulse excitation

Maria Sartor

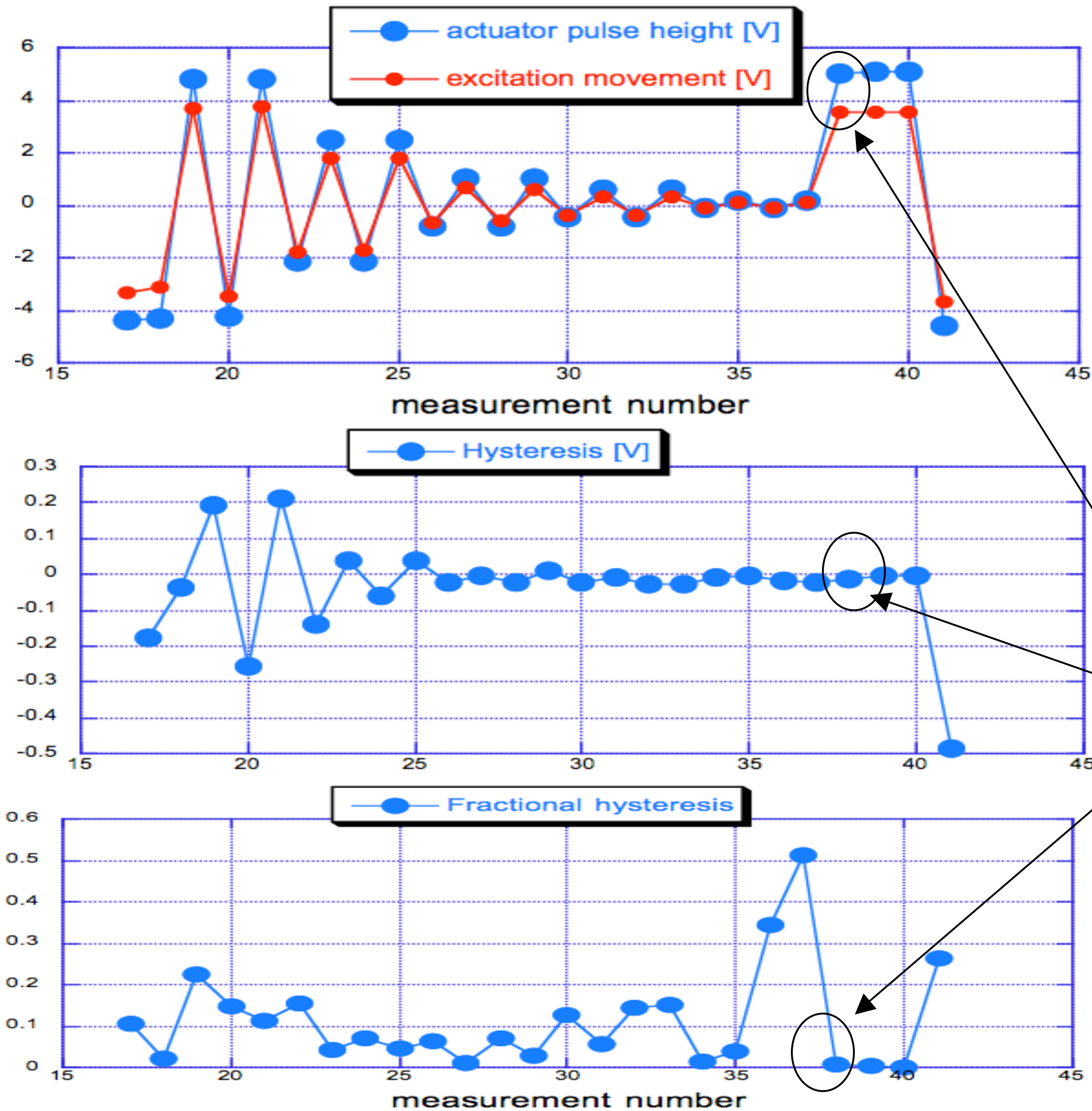


Repeated equal pulses result in vanishing hysteresis

Alternate sign pulses result in large and constant amplitude hysteresis

Hysteresis studies pulse excitation

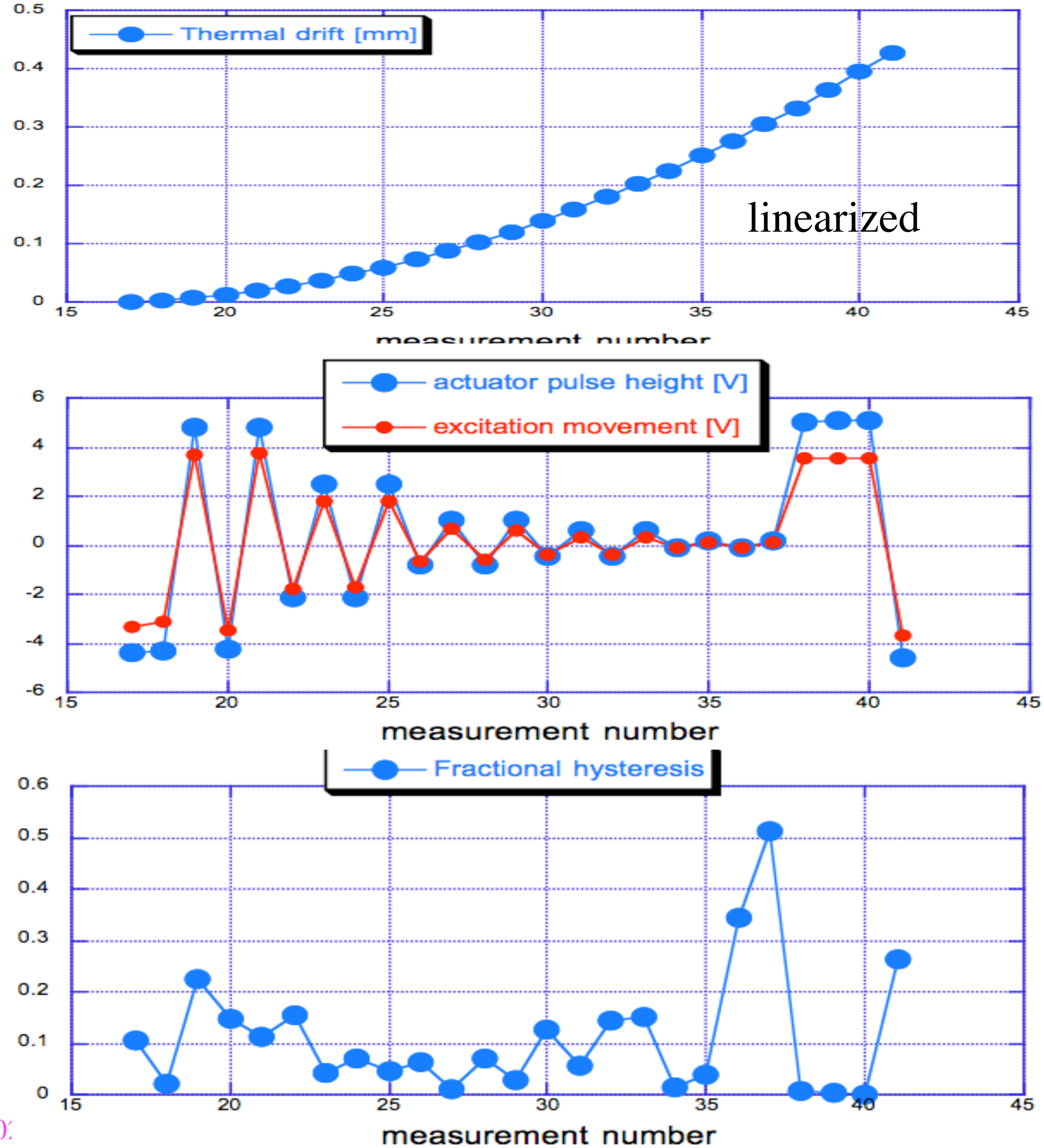
Maria Sartor



But

What happens to hysteresis here?

Hysteresis studies



(Calibration about 1.23 mm/V)

Thermal
Drift equivalent to
an excitation pulse.

Overwhelms
Hysteresis in one
Direction

Enhances it the
Opposite Direction

Work ongoing

Study to be continued and expanded
as function of stiffness

Some Implications of the pulse excitation results

- All varying stresses in the system contribute to hysteresis pile up and can generate LF noise.
- If hysteresis integrated from movements at higher frequencies is a source of the low frequency 1/f noise, during earthquakes the amplitude of the LF noise must be larger

- Corollary:The Low Frequency component may never stick out of the LF noise curve measured in quiet times

Hysteresis studies with pulse excitation: more questions

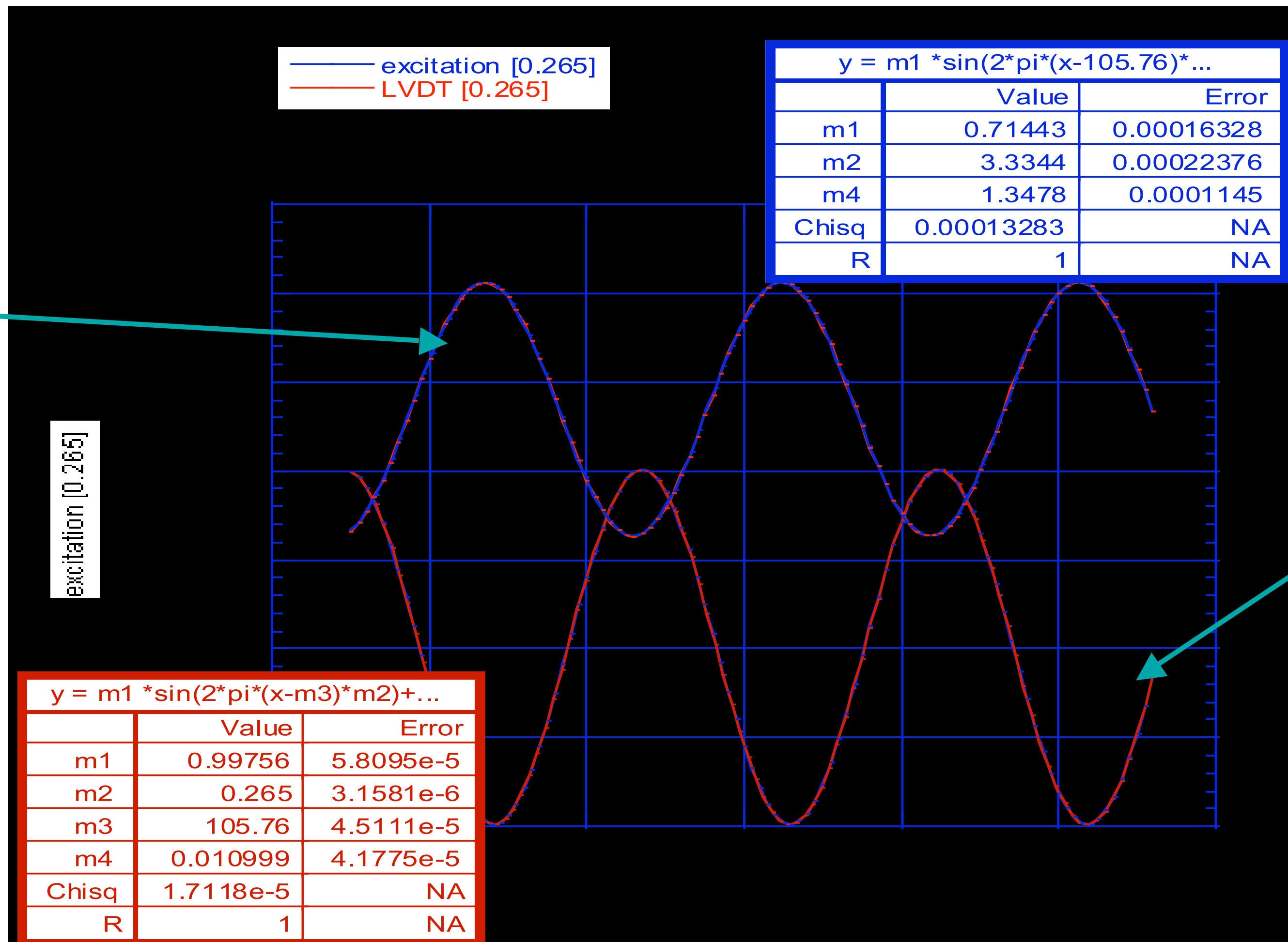
- Questions to be answered
- Is the measured amount of Hysteresis sufficient to explain all Low Frequency 1/f noise?
- Possible Experiment :
- Inject high frequency (>1Hz) noise in the system at various amplitudes and measure the LF frequency noise level

Hysteresis studies
sinusoid excitation

Arianna Di Cintio

Use the setup in an effort to quantize the problem

LVDT Position Signal[V]

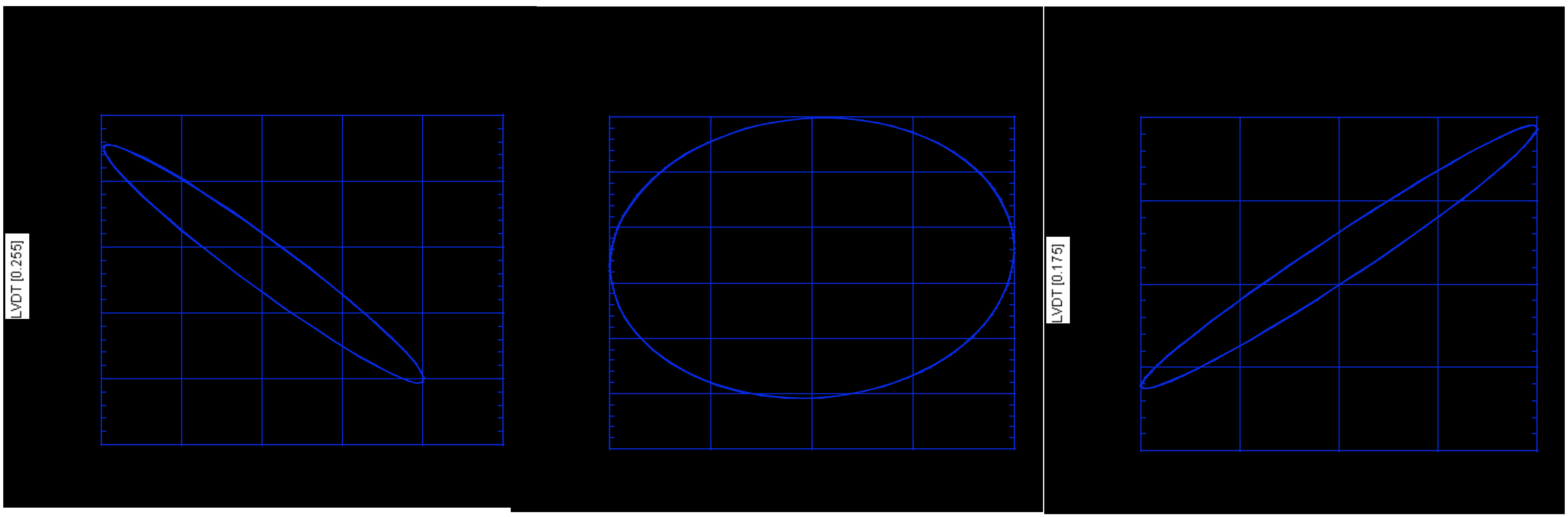


y = m1 *sin(2*pi*(x-105.76)*...	Value	Error
m1	0.71443	0.00016328
m2	3.3344	0.00022376
m4	1.3478	0.0001145
Chisq	0.00013283	NA
R	1	NA

y = m1 *sin(2*pi*(x-m3)*m2)+...	Value	Error
m1	0.99756	5.8095e-5
m2	0.265	3.1581e-6
m3	105.76	4.5111e-5
m4	0.010999	4.1775e-5
Chisq	1.7118e-5	NA
R	1	NA

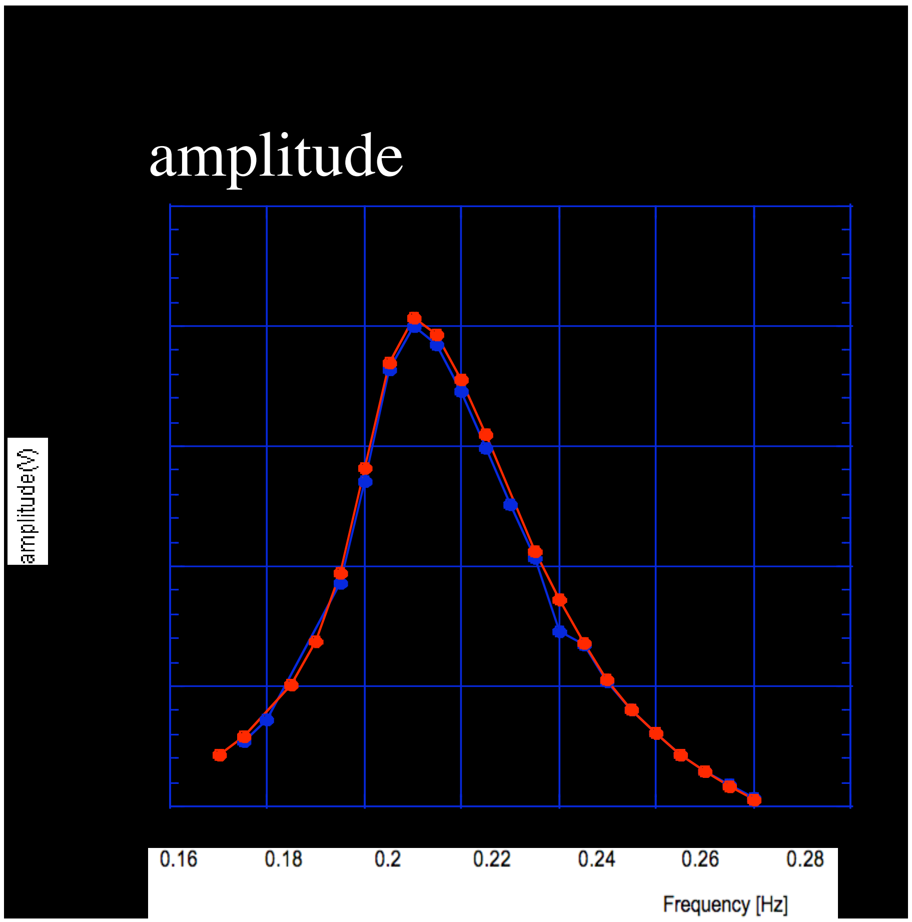
Excitation[V]

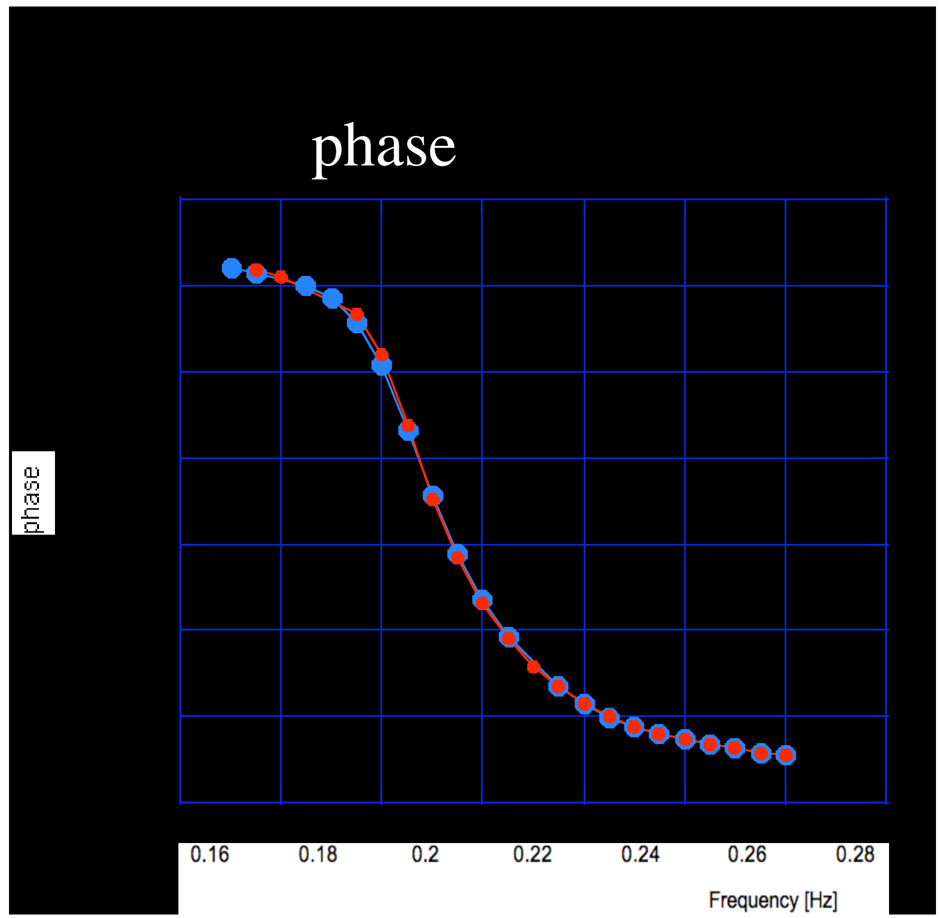
- phase changing sign around the resonance
- Hysteresis loop through resonance



COMPARISON STEP UP/DOWN

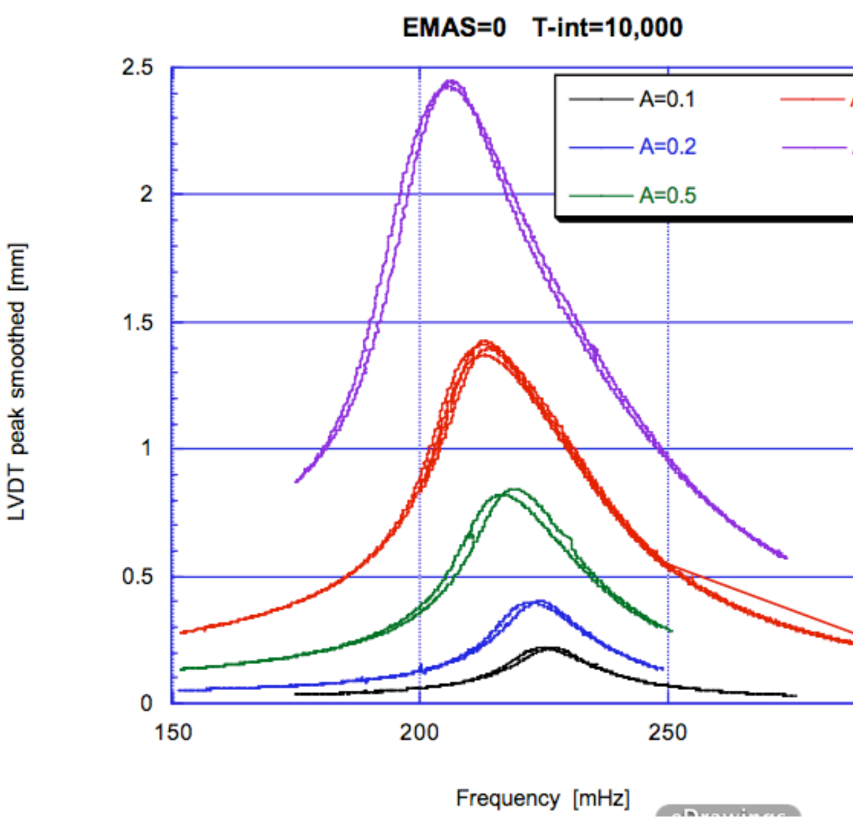
- We expect different behaviors for frequency scan-up and scan-down
- Asymmetry should appear increase for larger amplitude

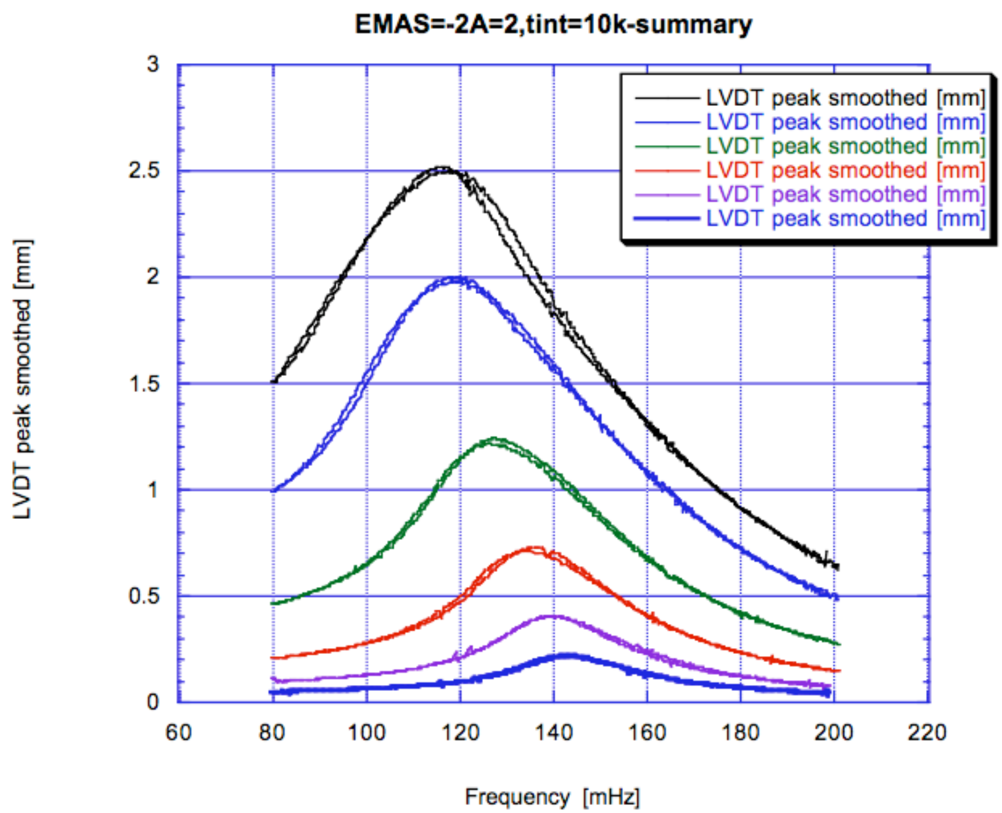




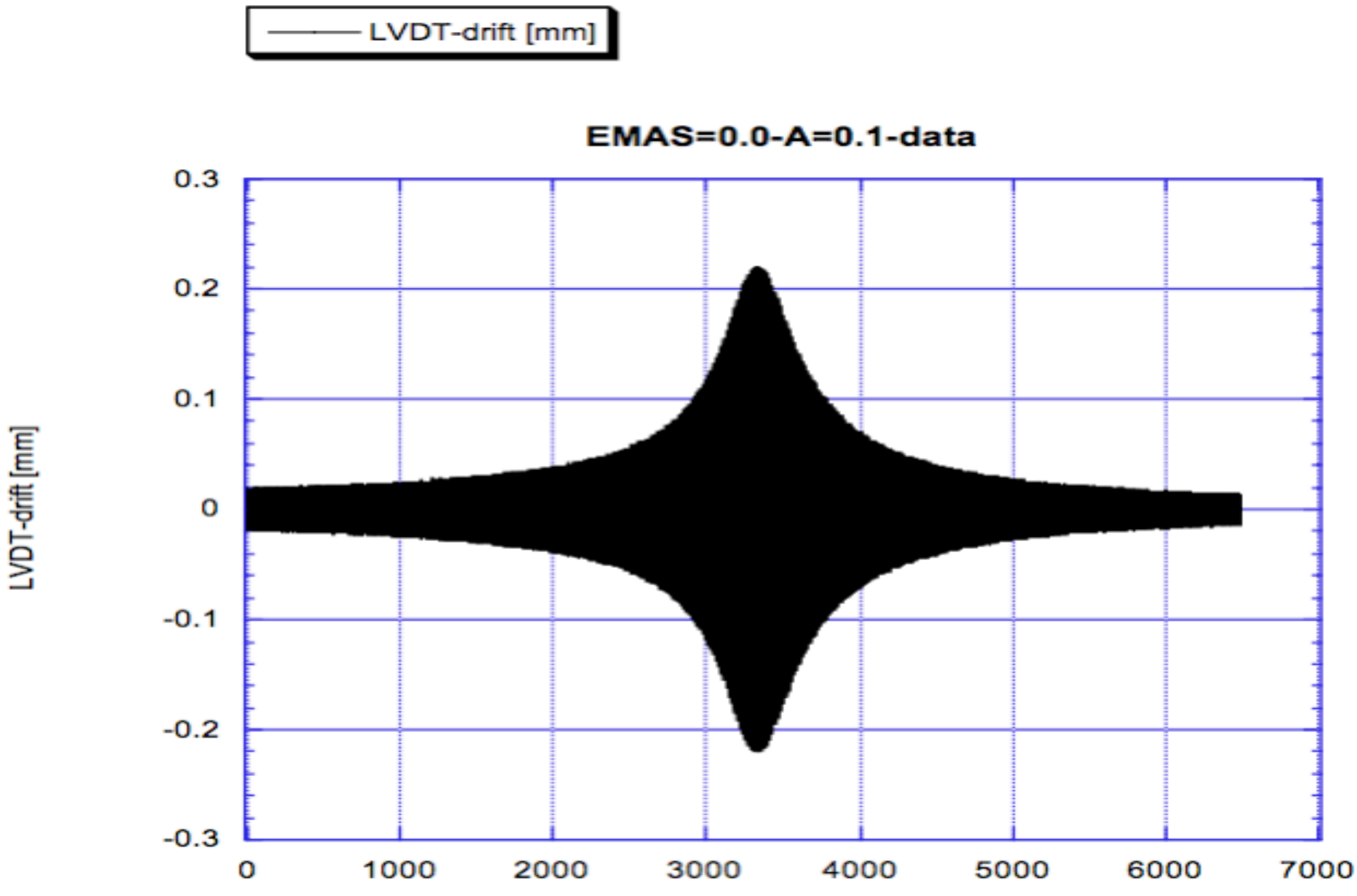
Search for difference between ring-up and ring-down scans for varying amplitudes

- No visible effect
- Will come back to these measurements





Frequency sweep analysis



Frequency sweeps fitting procedure

$$A(\omega) = \frac{C_0 / m}{\sqrt{(\omega_0^2 - \omega^2)^2 + (\omega_0^2\phi - \alpha\omega / m)^2}}$$

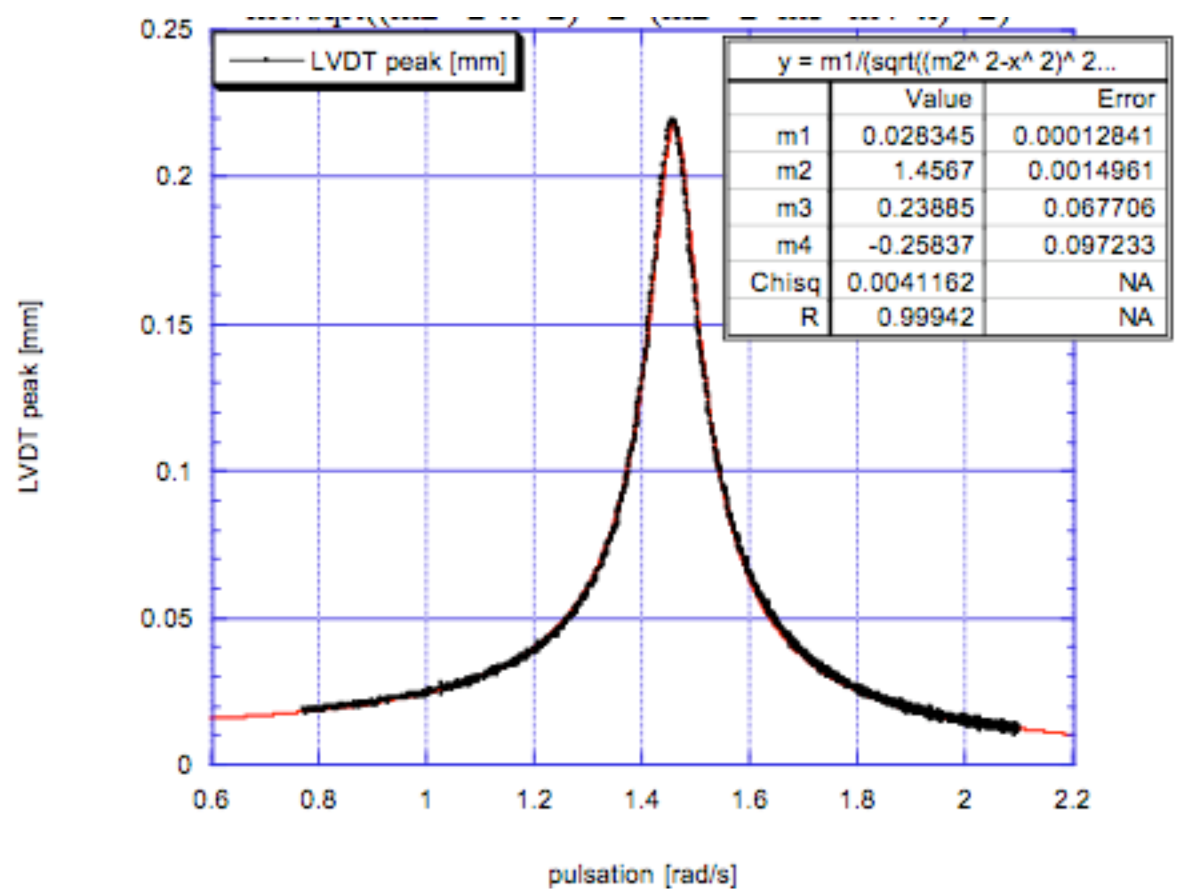
$$\omega_0^2 = \kappa / m$$

$$k = \kappa(1 + i\phi)$$

$$f(t) = C_0 e^{i\omega t}$$

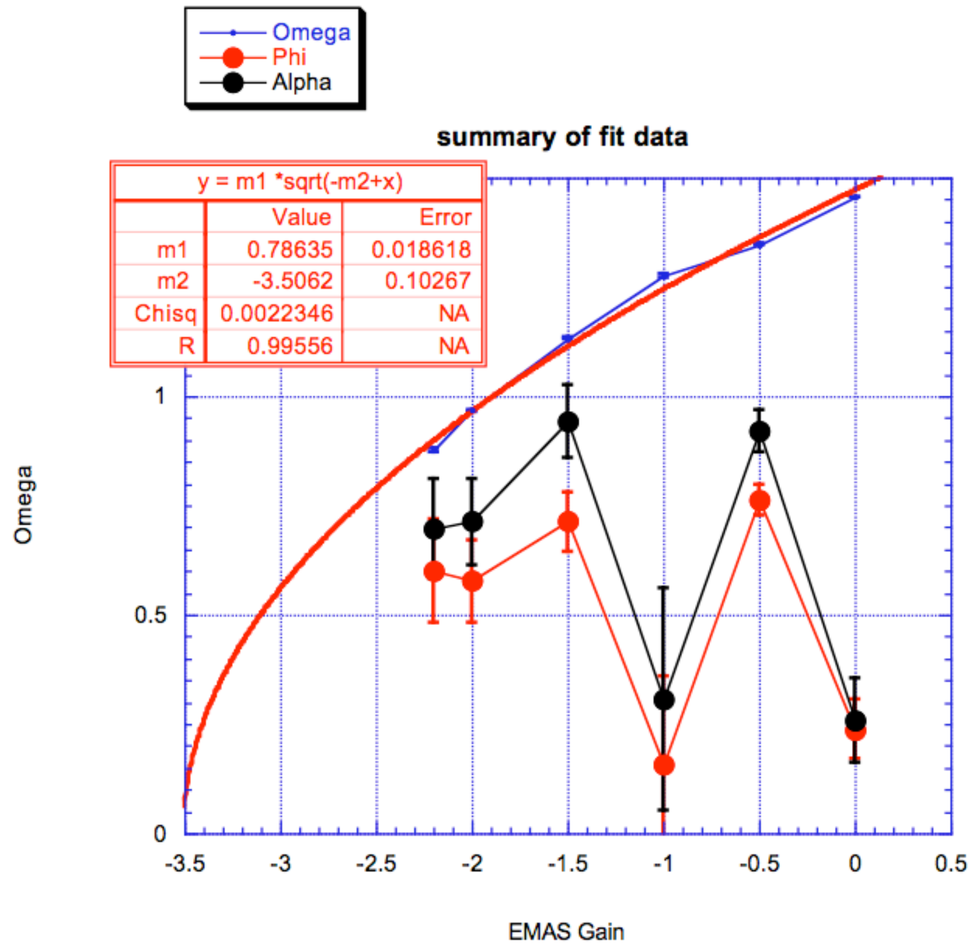
$$x_0(t) = A_0(\omega) e^{i\omega t}$$

- Both viscous (hysteresis?) (α) and "internal" (ϕ) dissipation included



Swept sine fit result

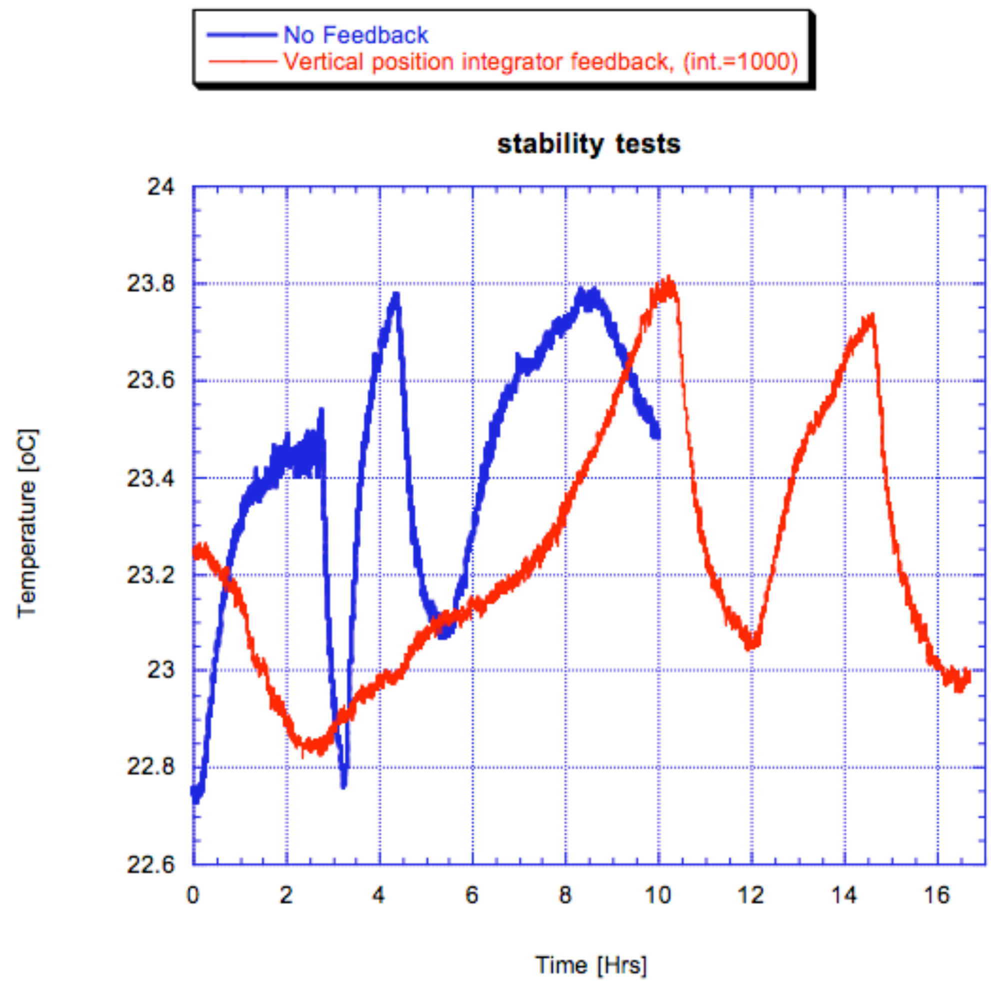
- ϕ and α correlated
- Not sufficient baseline to distinguish between ϕ and α
- Need better measurements



Thermal hysteresis

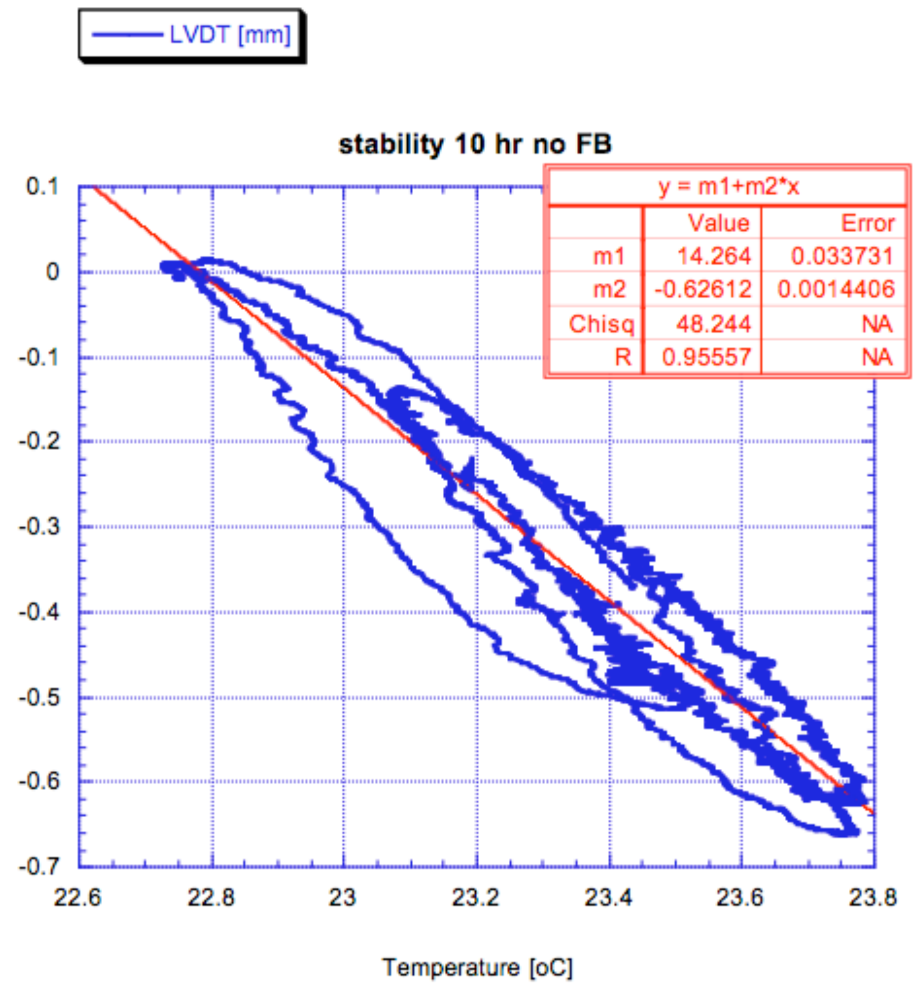
- A surprise

- GAS filter monitored as Room temperature drifts



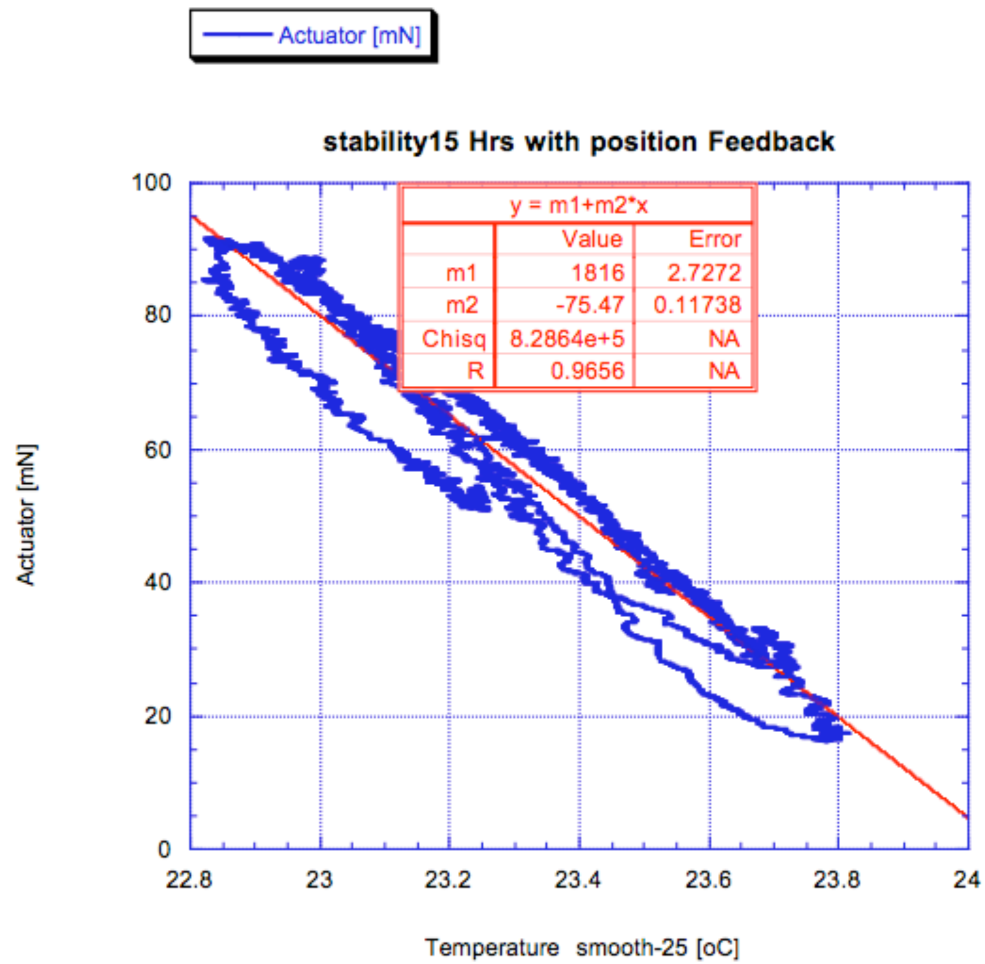
Thermal hysteresis

- Free blade
- Thermal Movement shows hysteresis
- 17% residual



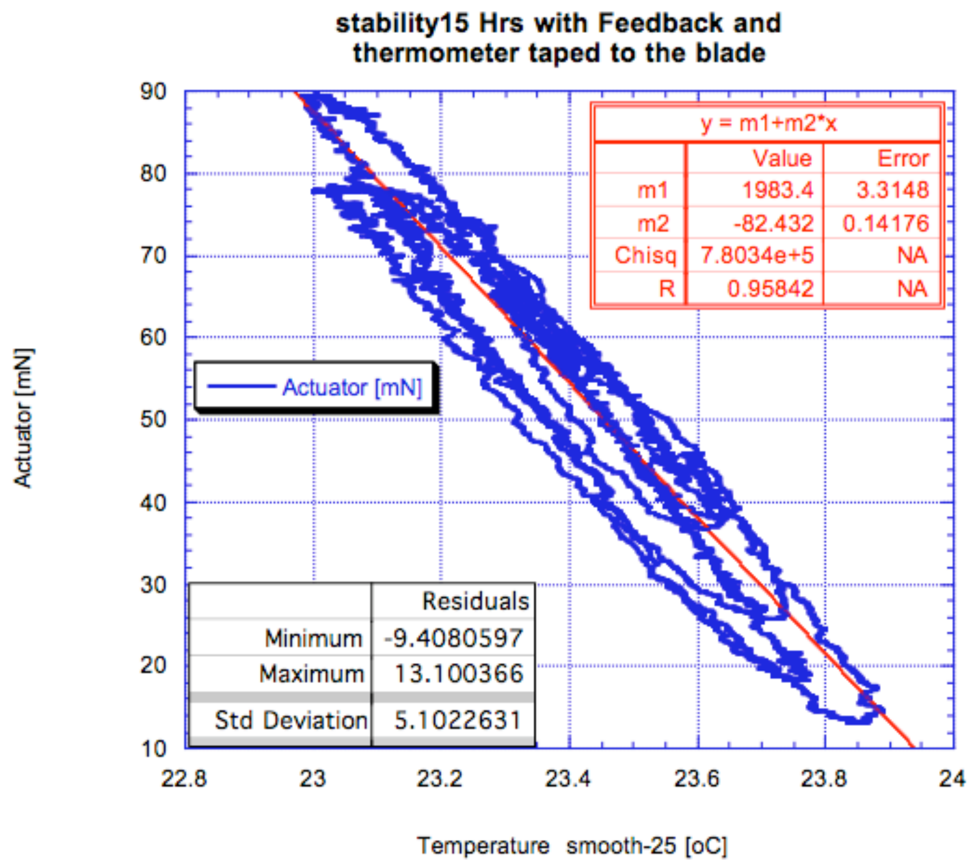
Thermal hysteresis

- Blade working point stabilized by position integrator feedback
- Hysteresis on control current
- 17% residual



Thermal hysteresis

- Repeat with thermometer glued on blade
- Same hysteresis
- 17% residual



Surprising (maybe not) evidence

- To all apparent evidence hysteresis does not originate from the actual movement, but from the changing internal stresses inside the materials.

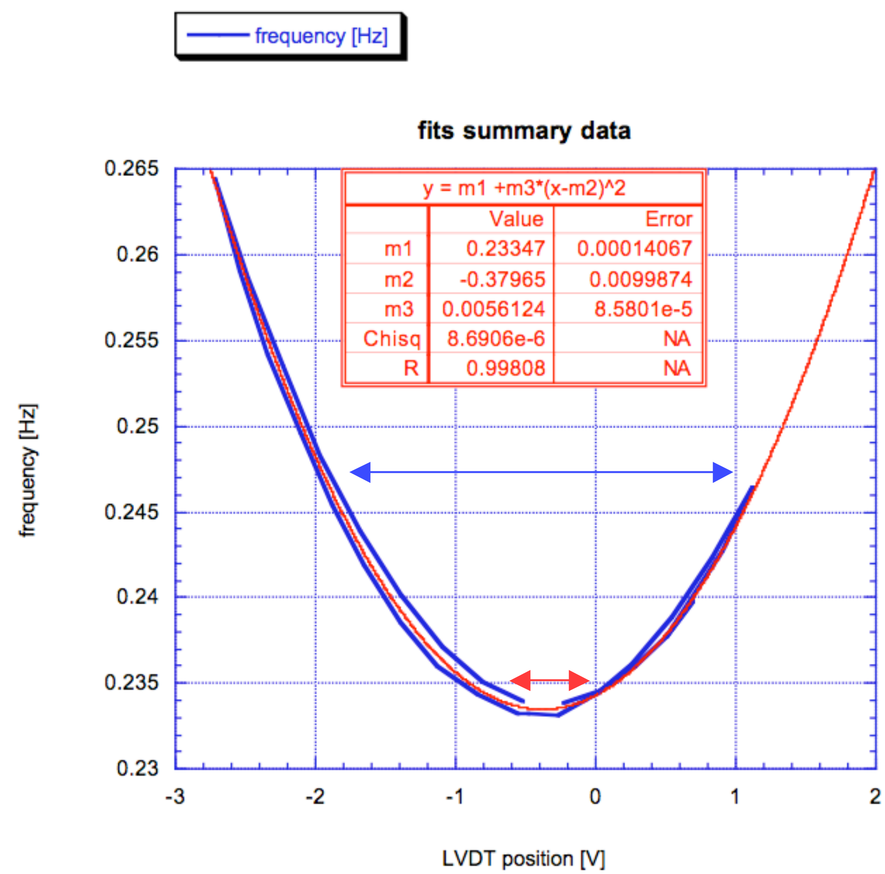
- **Hysteresis derives from evolving stresses rather than from evolving geometry**

Consequences of hysteresis from evolving stresses

- All stresses transiting through a flex joint contribute to the hysteresis total
- A flex joint supporting an IP, or an accelerometer test mass, absorbs all vibrations and fast motion
- These contribute to random walk and LF noise even if the system is kept "at position" by a feedback mechanism

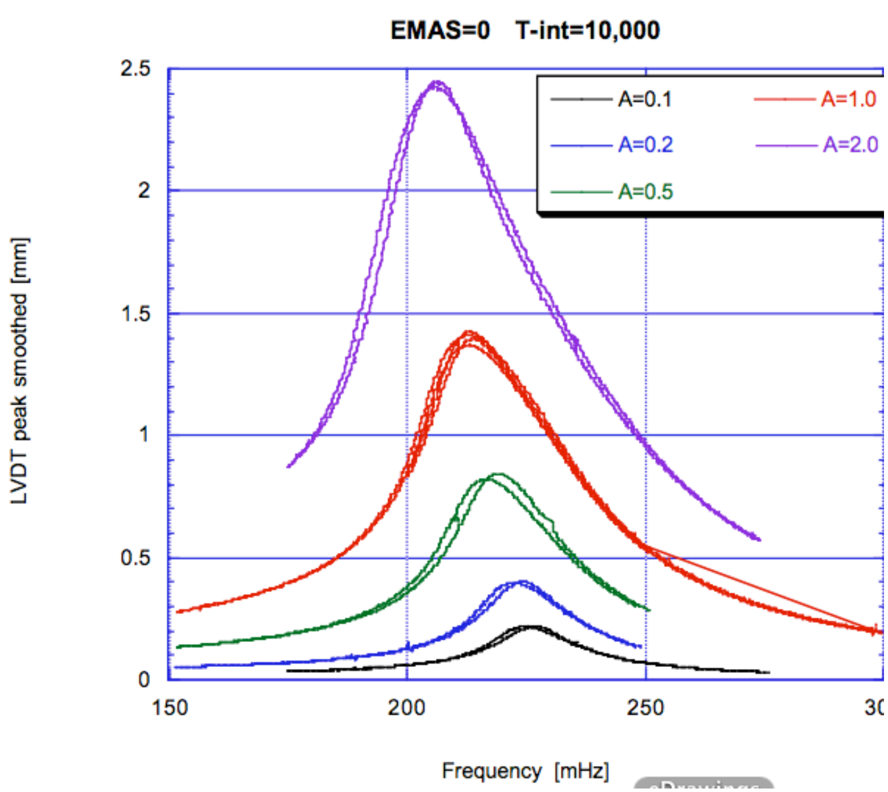
Swept frequency tests

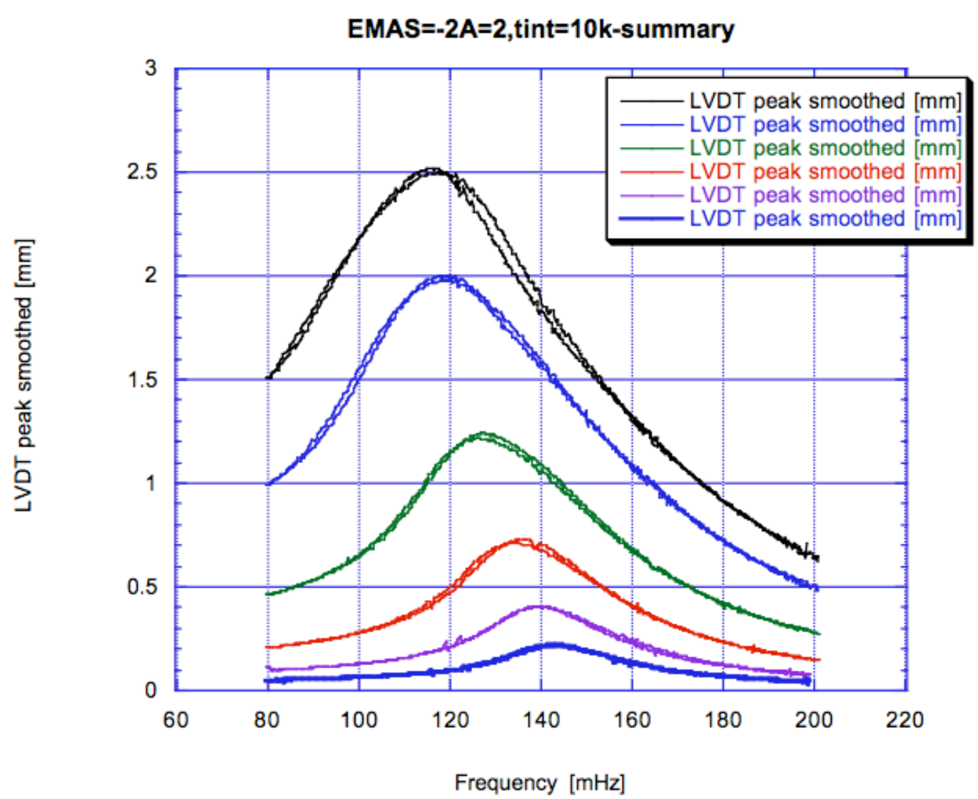
- Operated at minimum of frequency curve.
- For large oscillations the filter "explores" areas of higher frequency
- Non-sinusoidal behavior expected and observed
- Shift to higher frequencies expected for higher amplitudes



Amplitude/Frequency dragging

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





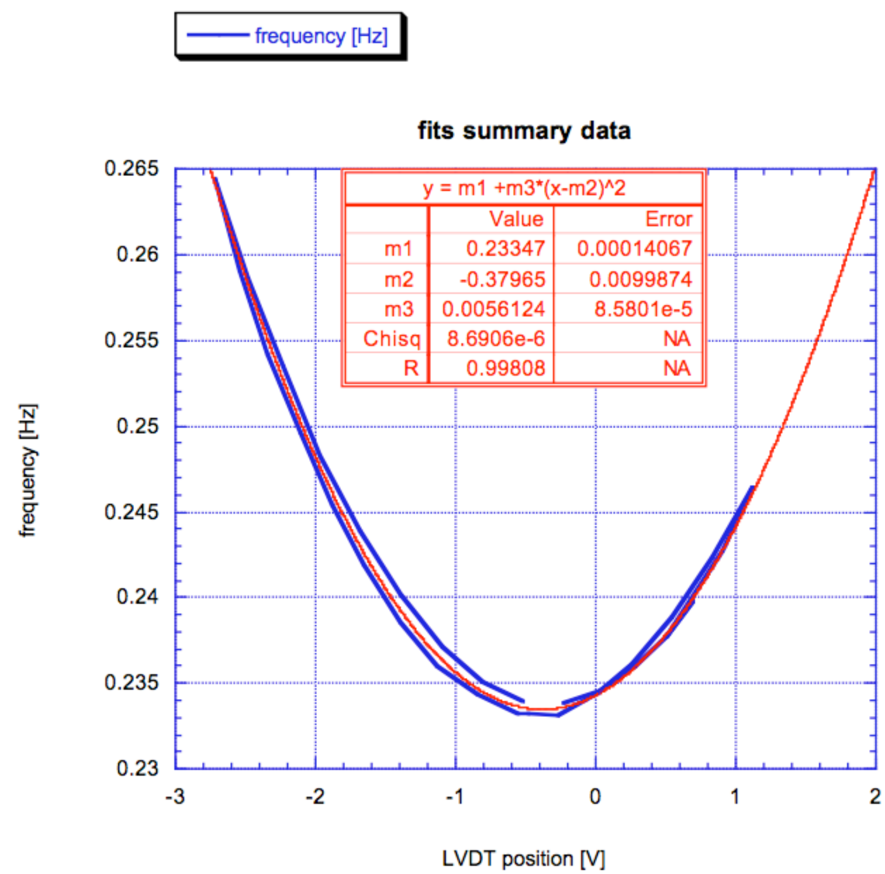
- Something is dragging the oscillator and slow it down
- There is more drag for higher amplitudes.

- Against most models and assumptions

- Is it a real effect?
- Different measurement to cross check

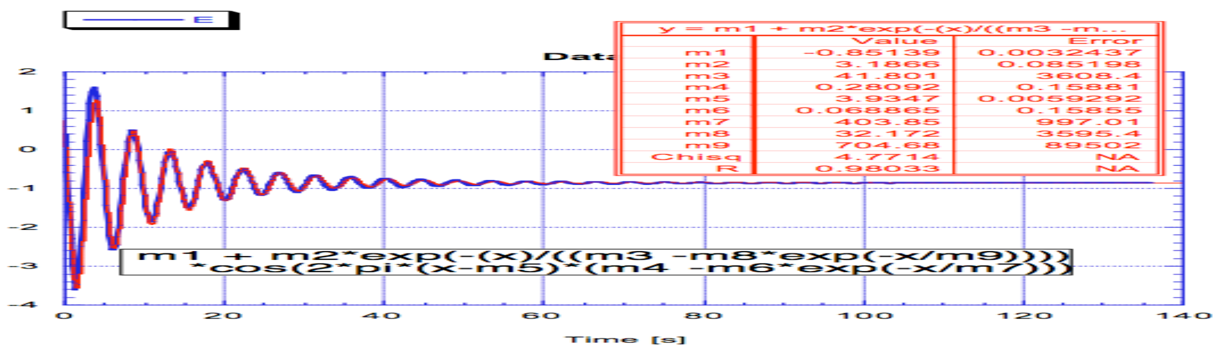
Damping/frequency versus amplitude

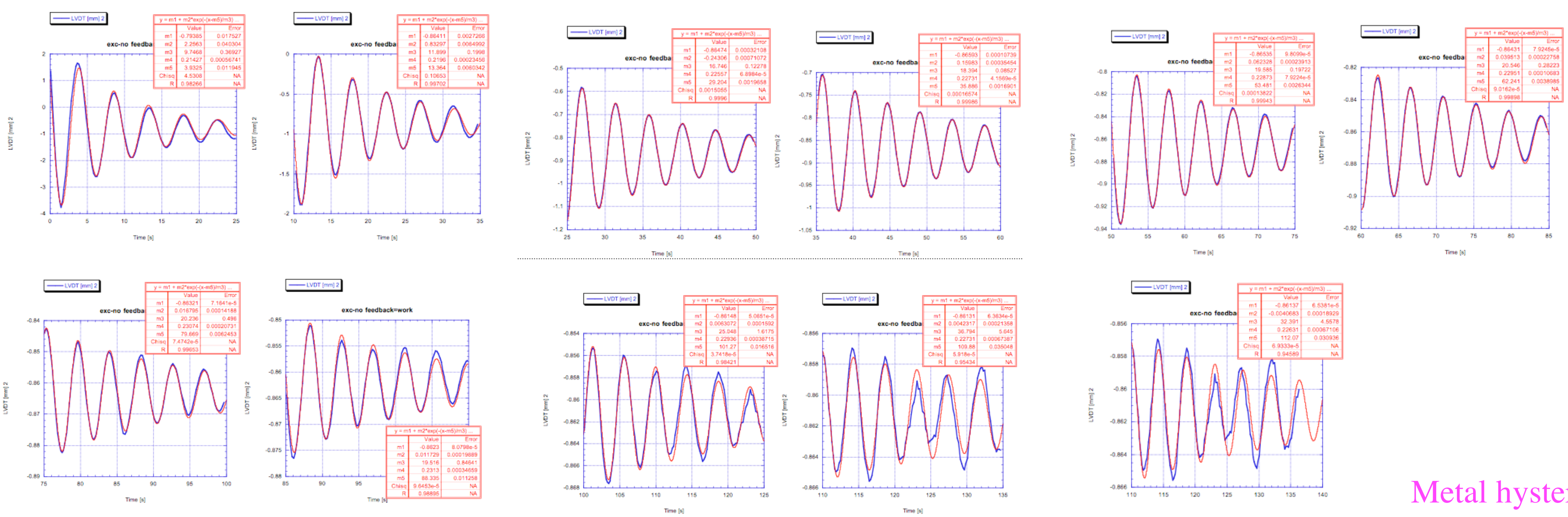
- Acquire many ringdown curves



Damping versus amplitude

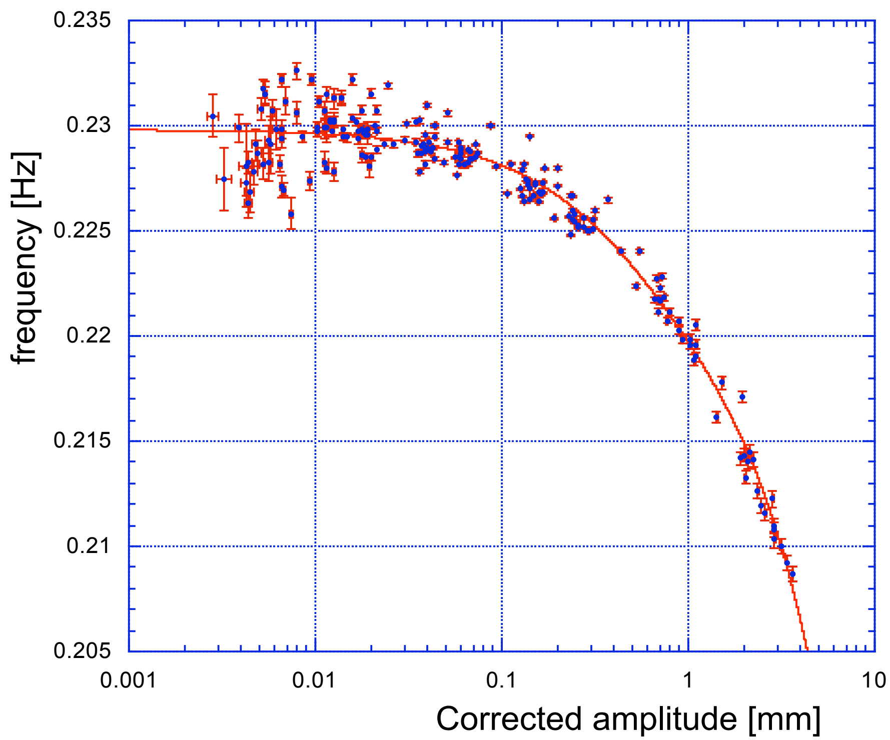
- Each ringdown fitted with a sliding window

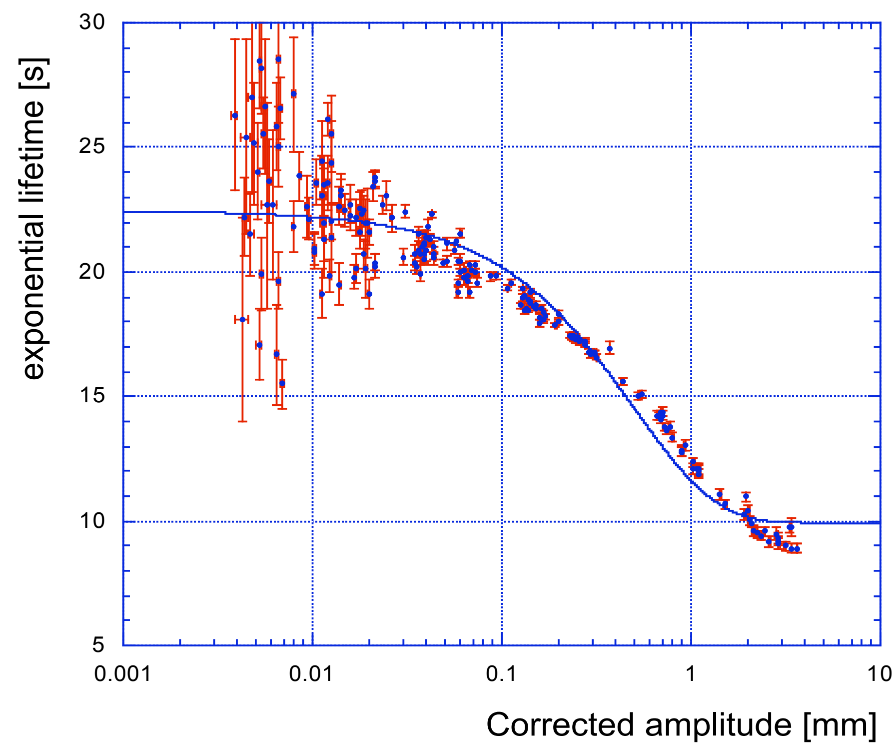




Damping versus amplitude

- Damping diminish at low amplitude
- Drag slowing frequency also diminish
- Fits to guide the eye only

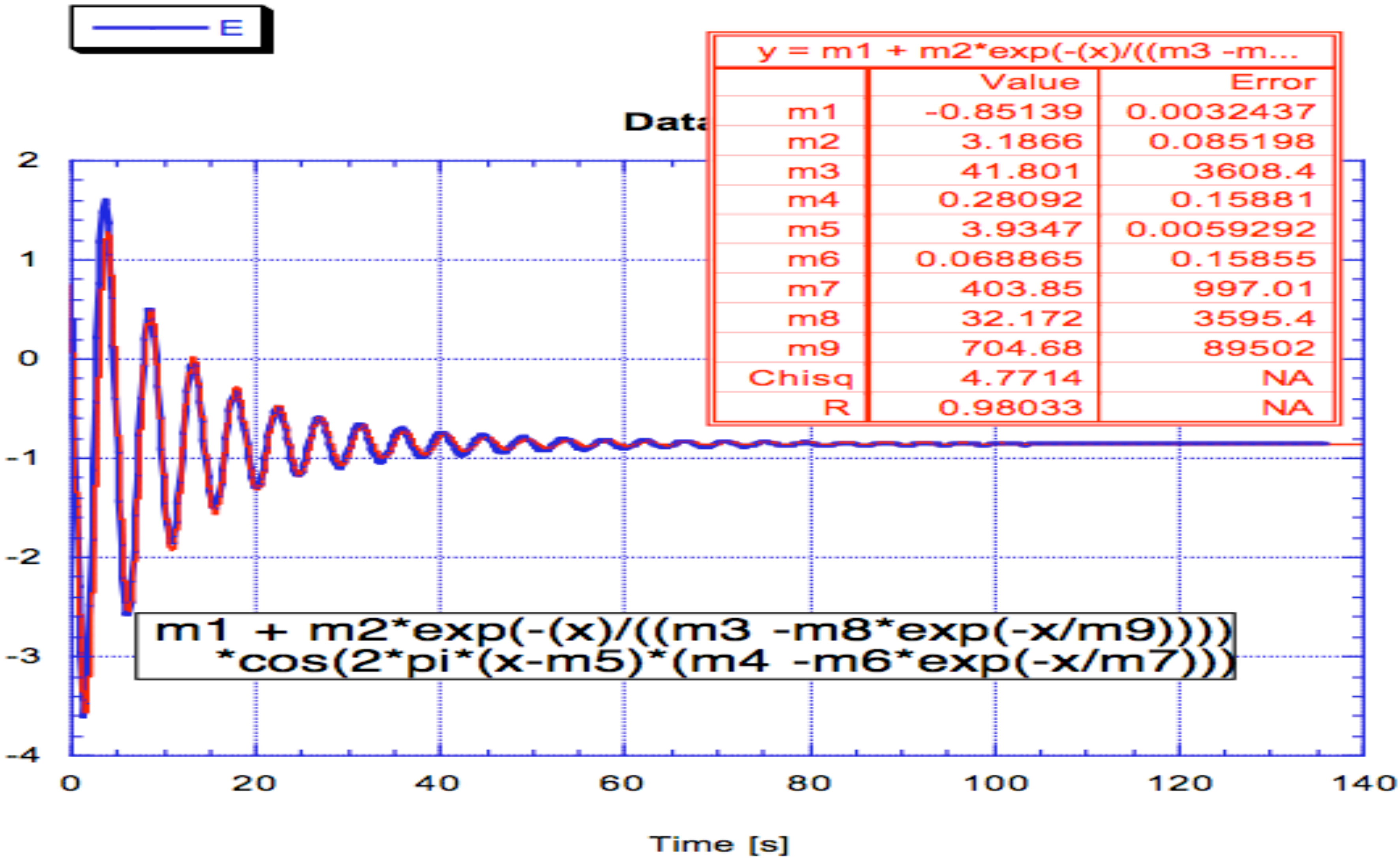




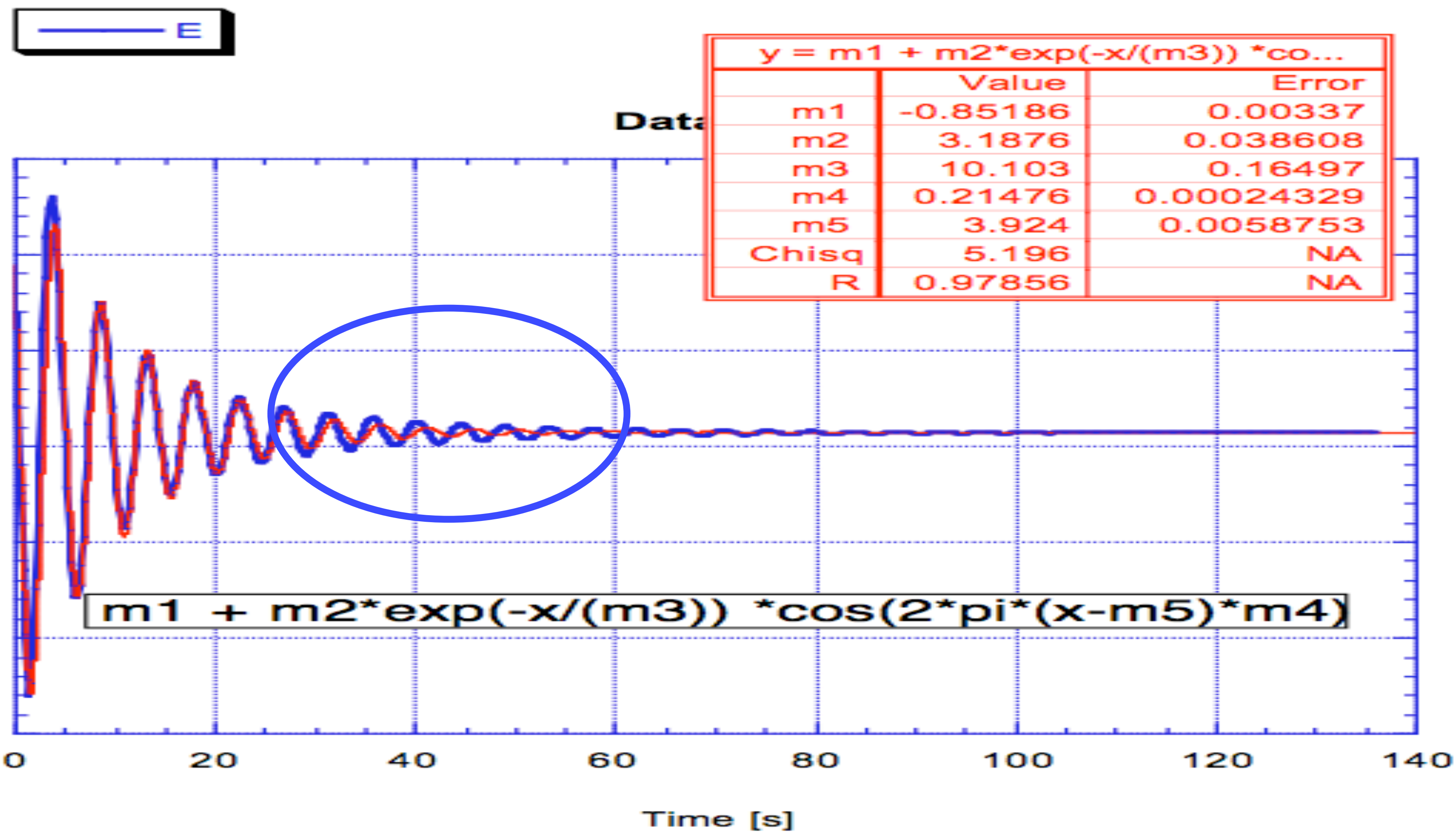
- Additional Cross check

- Fit with sliding frequency and attenuation instead of window
- Use starting values from sliding window test

Ringdown fit with "Sliding" frequency and damping constant



Comparison:
Ringdown fit with fixed frequency and damping constant fails



Sand model

- The sand model comes out naturally once one consider the movements of dislocations in the materials
- Each dislocation is a grain of sand
- Dislocations and grains of sand can interlock (entanglement)
- Some may be completely free to move
- Some may be sticking
- Some may be entangled by the presence of other dislocations

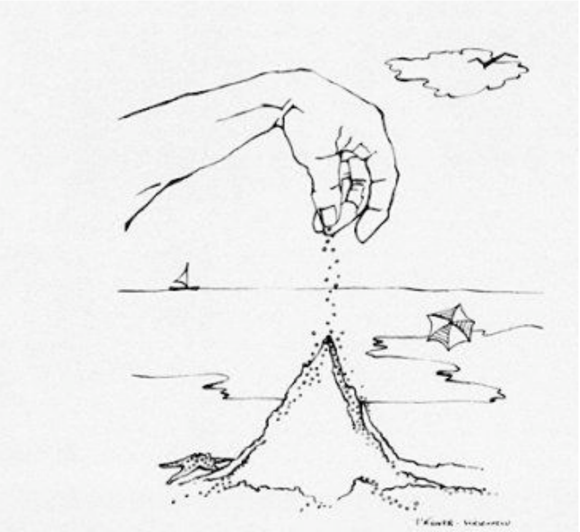


Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

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

Shifting Sand model

- Consider potential Energy surfaces and dislocations
- Applied stress tilts potential Energy surfaces
- Dislocations shift to stay near the bottom
- Shifted dislocations contribute to the potential Energy tilt and give hysteresis

- Sprinkle sand in a bowl
- Sand shifts down from the increasing slope as tilt is applied
- The bowl does not return completely
- The end effect looks like hysteresis

Shifting Sand model

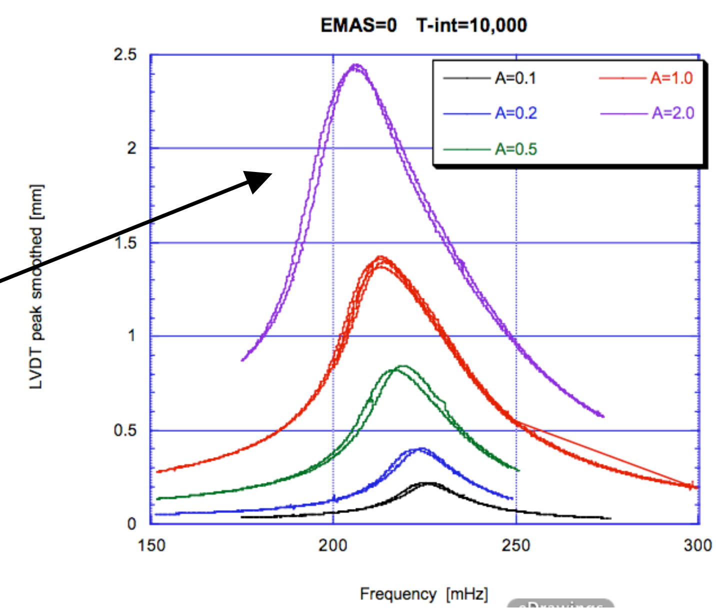
- Progressive tilt causes the sand to shift down from increasing slopes
- Shifting happens only above a critical slope
- Avalanching limits the slope

Shifting Sand model

- Sand flow from a critical slope is a fractal
- As tilt is smoothly increased, critical slope flow (avalanching) happen at unpredictable times, and at all scales,
  thus generating 1/f noise

Shifting Sand model

- Only a small fraction of available sand is shifted for low amplitude oscillations ! !
- As larger tilts are applied, larger quantities of sands are moved by larger distances
  => more dragging at larger amplitudes
- This can explain the observed
  frequency down-shifting
  for larger amplitudes



The Sand model

- Looks suspiciously like Marchesoni's Self Organized Criticality of dislocations

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

- Sand mimics viscosity and dashpot models
- But allows for the observed static hysteresis

- Settled sand does not move much.
- Allows for almost free oscillations

The Sand model

- Hysteresis masks itself

  if the system is allowed to self oscillate and settle the sand

- Most previous measurements may have overlooked hysteresis or misinterpreted it as viscosity or internal dissipation

Quinn T J, et al. 1992 Phil. Mag. A 65 261–76
Speake C C et al. 1999 *Meas. Sci. Technol.* **10** 430
Gonzalez G I and Saulson P R 1995 *Phys. Lett.* A **201** 12
. . . . .

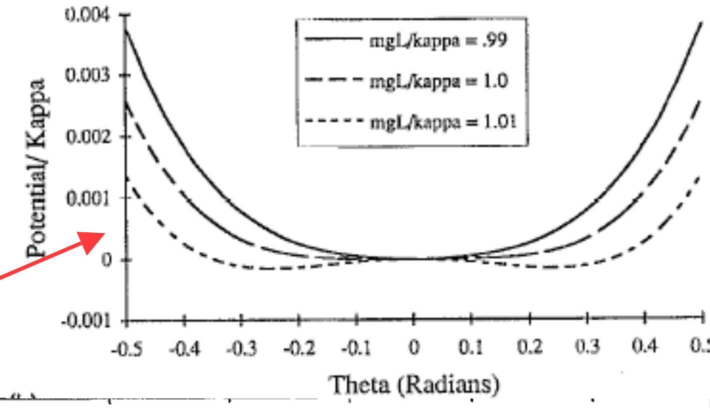
The sand model, anelasticity

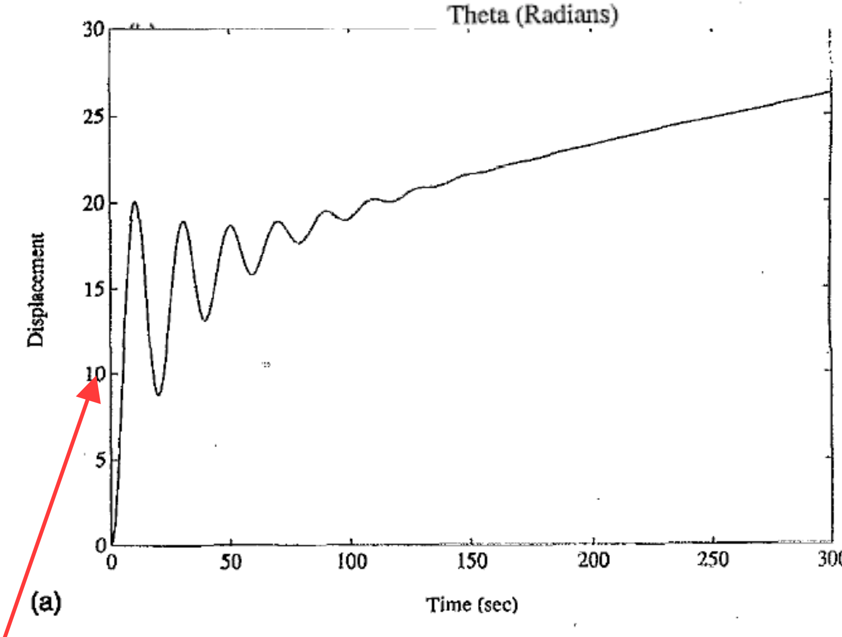
- Some shifting sand after effects may be thermally triggered, thus causing the anelastic-like delayed effects described by Saulson

- Anelasticity can be explained with the same process that produces static hysteresis, without the need of infinite series of dashpots
  - (Which made no sense to start with)

The sand model, Saulson's IP instability

- Saulson's observed Inverted Pendulum instability at low frequency tune can be simply explained (similarly for GAS filters)
- In absence of friction the IP should be either <u>stable or bistable</u>
- In presence of sand friction we observed that the resonant frequency becomes lower for larger amplitudes , i.e. weaker restoring forces
- This adds a term that, for very low frequency tune, reverses the slope of the potential and renders it <u>unstable</u>
- Friction allows for a range of indifferent equilibrium
- Small excitations can push the system out of indifferent equilibrium and trigger collapse

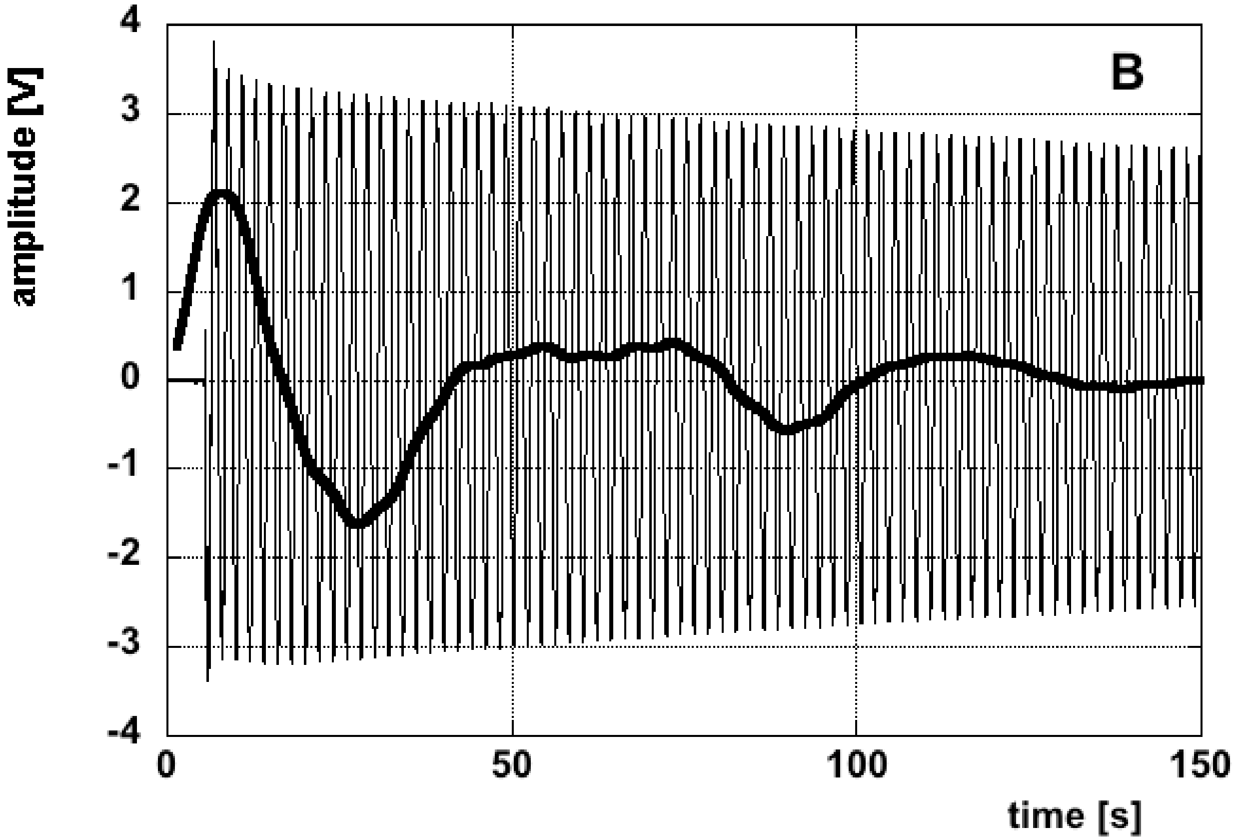




PR Saulson, et al., Rev. Sci. Instrum. 85 (l), January 1994

The sand model can also explain the transition from highly predictive to almost random oscillator

- Individual avalance statistics dominates at LF



Warnings from the sand model

- Even arbitrarily slow and smooth stress variations will produce:
- up-conversion at all frequencies because each single sand avalanche is FAST compared to external time scales
- down-conversion all the way to zero frequency because each individual sand avalanche can have any size or time scale, only limited by the outer scale of the local system but then is stable until the slope is changed

What does the sand model predicts about 1/f noise

- 1/f noise is produced during stress variations of any kind (not even requiring motion)
- Large excursion motion should enhance 1/f noise production

What does the sand model predicts about 1/f noise

- More 1/f noise will be produced if system is moving long distance or over unexplored regions
  - Build up of sand piles with critical slope necessary to make noise
  - They maintain critical slope by avalanching on the forward slope
- Less 1/f noise if moving back a short distance to freshly explored areas
  - Diminish the critical slope

- This may explains the better behavior of seismometers after some settling time

Best practices to reduce noise

- Oscillate the system around the equilibrium position
  - To smooth out all critical slopes
  - Minimize avalanching
- Minimize motion, temperature variations and any other stress changing source

Hysteresis conclusions

- "Static" Hysteresis has a much more important role than often acknowledged
- Dominated low frequency systems
  - IP, GAS, Seismometers, quadrupole pendula, et c.
- It may generate the effects presently interpreted as viscosity
- Qualitatively similar results observed on different (poly-crystalline) materials
- Need to quantify
- Would other materials without dislocations (glasses, mono-crystals) be any better ? ?

Obvious questions

- Are the dislocations involved in hysteresis the same involved in creep?
  - Most likely not. Creep happens in timescales of days, not instantaneous (or minutes for anelasticity effects)
- Are the dislocations involved in hysteresis the same involved in acoustic emission?
  - Possibly yes, the time scale is minutes
  - Beware acoustic mission signals grain calving and plastic deformations, different from hysteresis and creep

- Stop here

- More slides and discussion on
  what to do next   after questions

- If anybody still have the stamina and desires the discussion

A comment

- Related issues about micro-plasticity/acoustic emission, creep, anelasticity and hysteresis.
- All of them depend on dislocation motion and activation
- In all cases we deal with exhaustion of available dislocations and logarithmic relaxation after end of stimuli
- Are these completely separated phenomena?
  – Probably not

More things to do

- Most authors assumed that losses in mechanical oscillators are independent from amplitude
- Measurements suggest that losses may not be independent from amplitude
- But, larger amplitude -> larger stress
- How do losses depend from stress?
- Need to measure and quantize

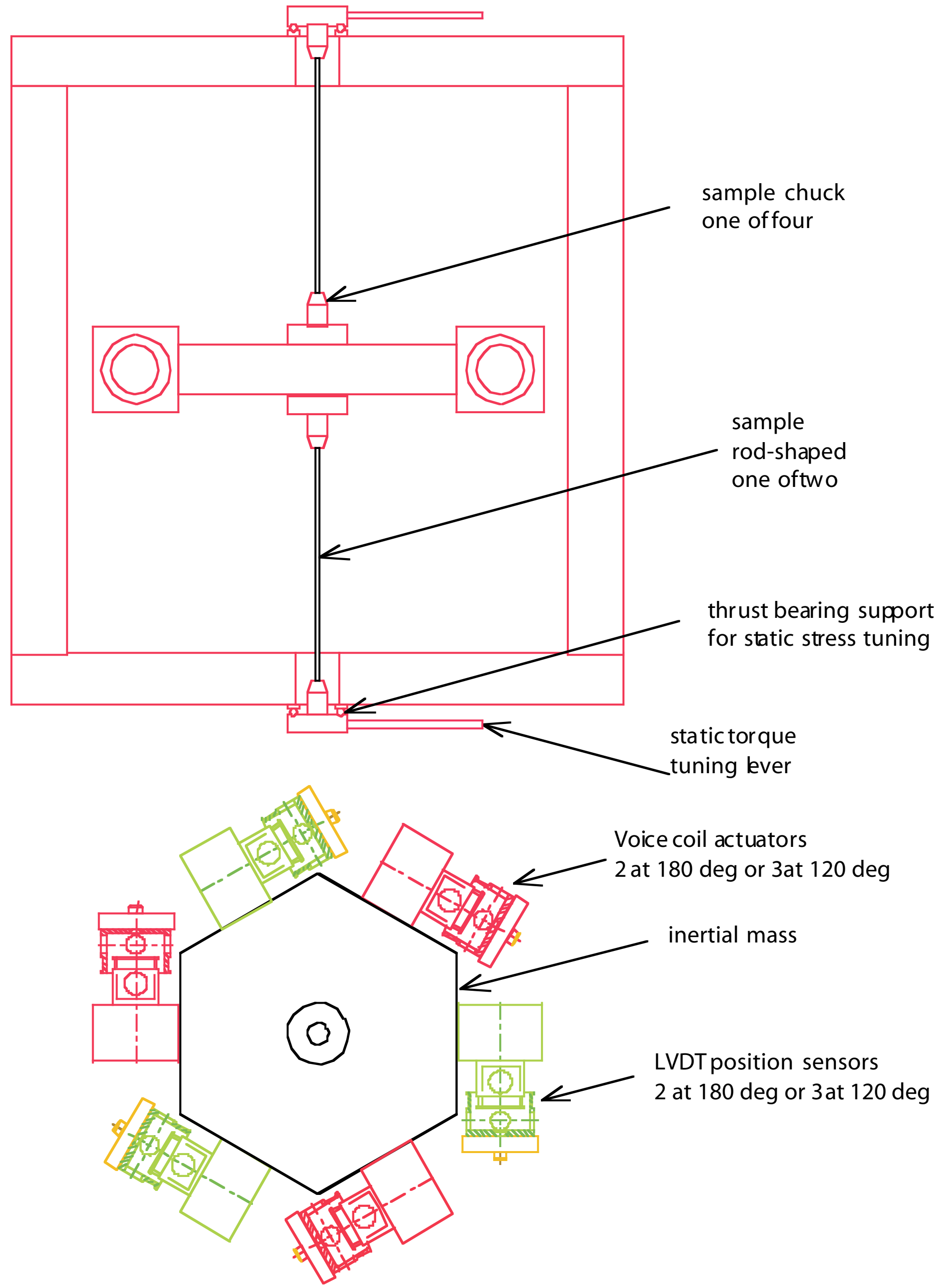
- Beware: different materials may have different behaviors

Material comparison: two methods considered

- Double Torsion pendulum for measurement of losses and hysteresis under controlled varying stresses
- Balances for precision direct comparison
- Note: Tilt-meters (balances) are also needed and developed for Ad-LIGO

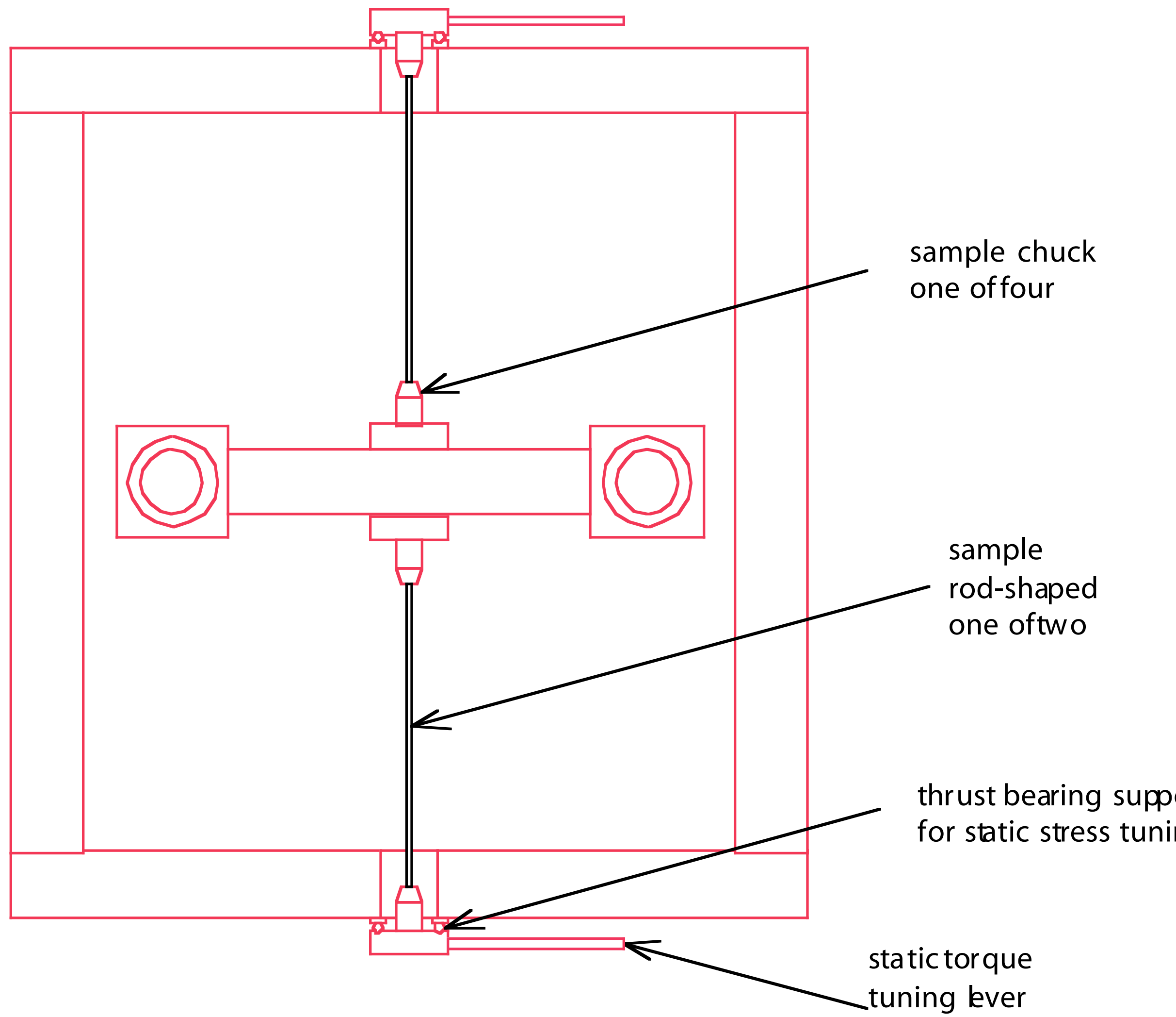
Torsion pendulum measurement

- To measure losses in different materials for different stress levels
- Dale Conner

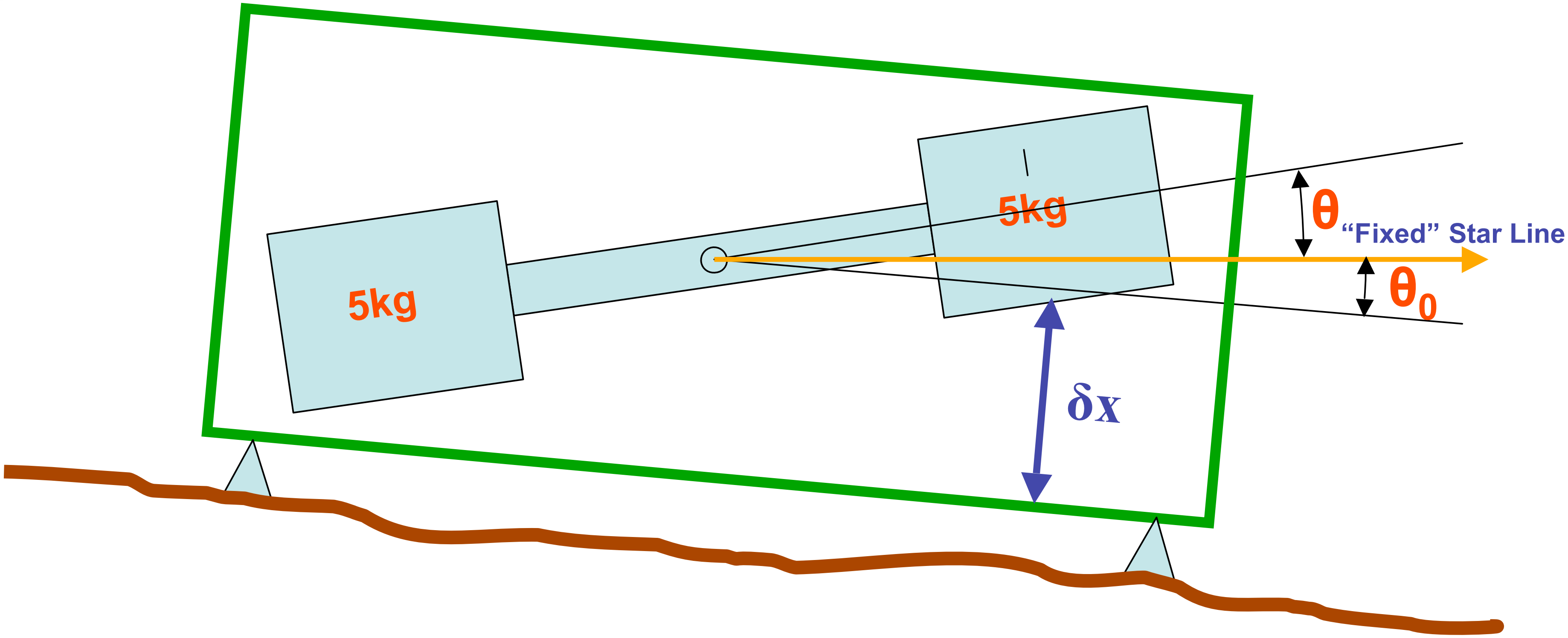


Torsion pendulum measurement

- Caltech LIGO
- Caltech Material Science Department
- California State University at Northridge



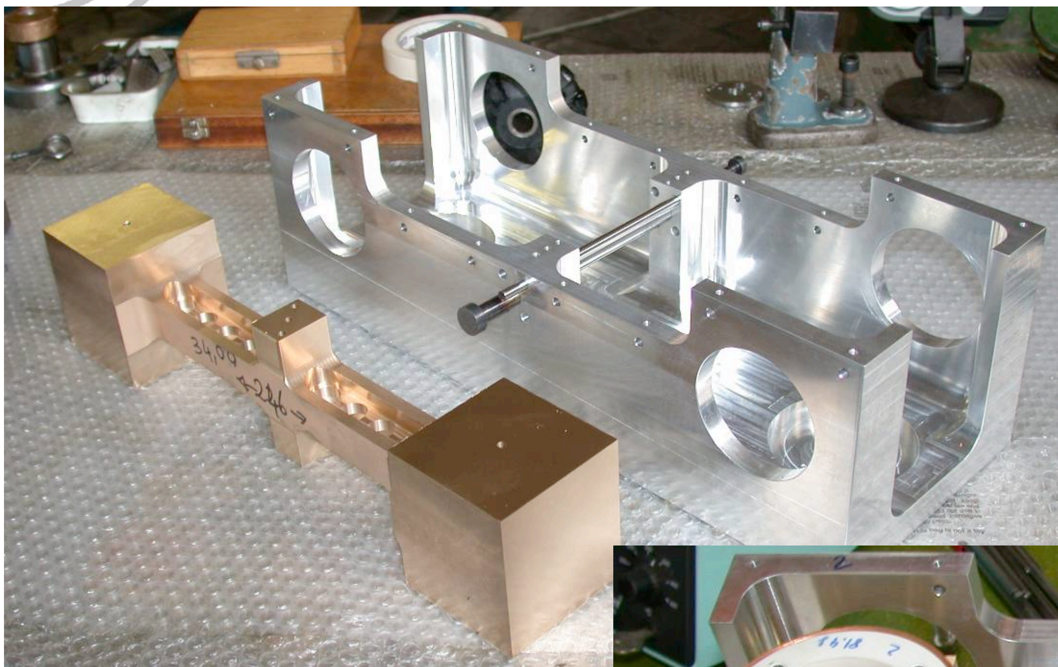
Tilt meter conceptual design:

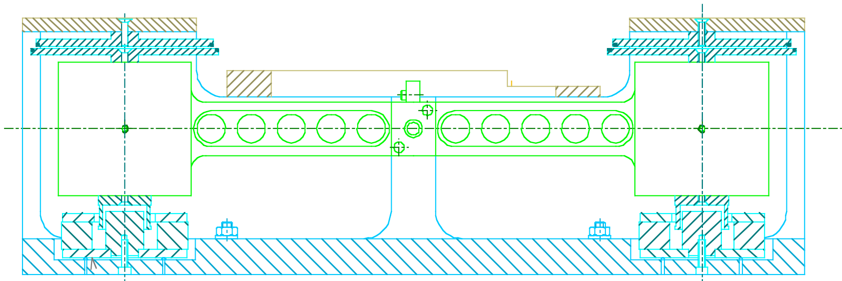


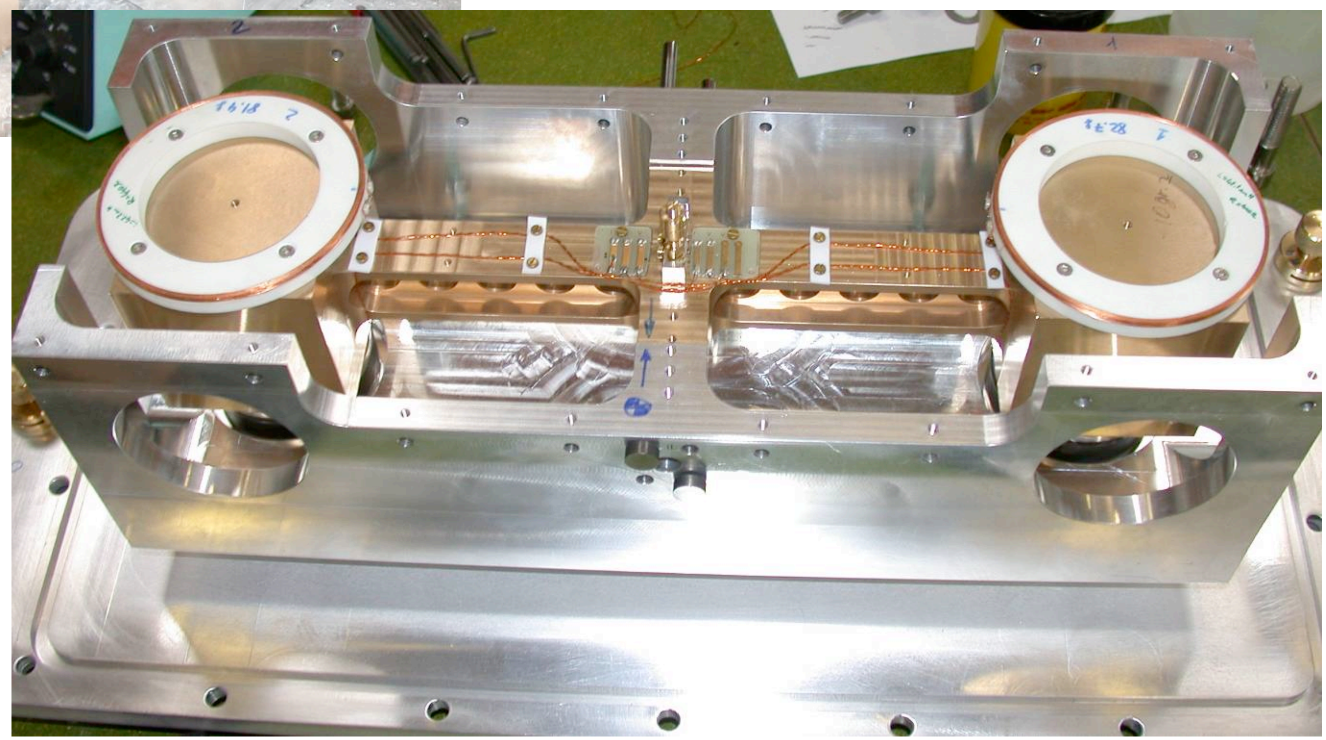
A large moment of inertia bar suspended on a soft angular flex joint

Development with V. Fafone and other Virgo collaborators

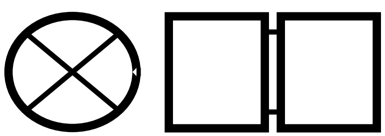
Virgo Tiltmeter prototype







Bendix flex joint



Bendix problems

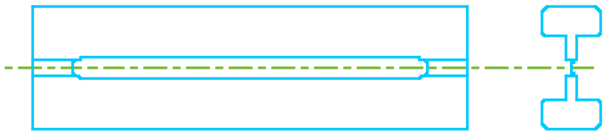
Used in Speake tiltmeter 1990, Saulson's IP 1993, Luiten et al. tiltmeter 1996
V. Fafone et al. tiltmeter (ongoing)

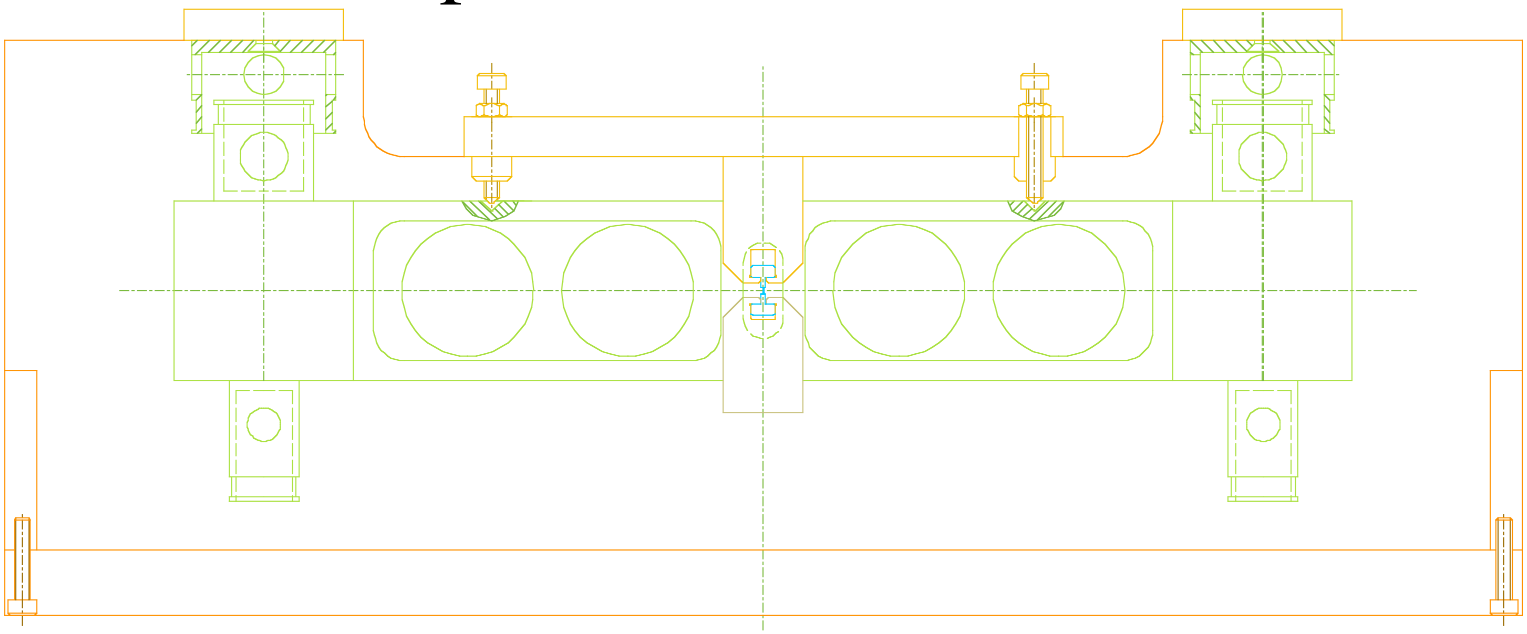
- Ill defined flex point
- Brazing can influence the losses

CC Speake, et al., Rev. Sci. Instrum. 61 (5), May 1990, A. N. Luiten, et al., Rev. Sci. Instrum. 68 (4), April 1997

The flex joint LIGO design

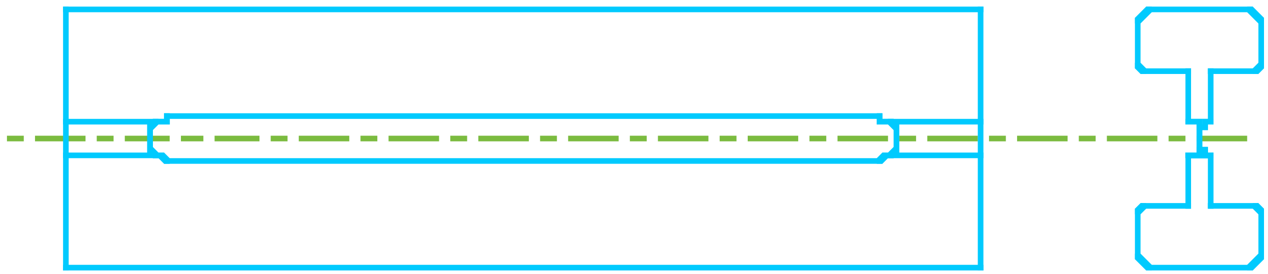
- Single flex joint replacing Bendix crossed beam flexures
- Better control of parameters





The flex joint design

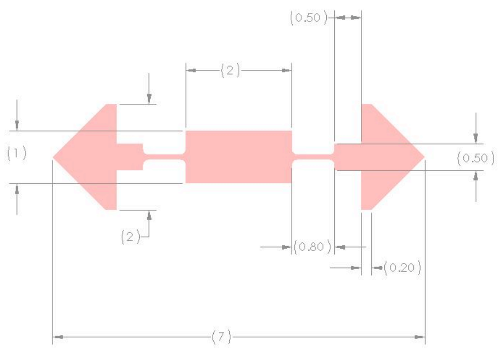
- Dual flex joint EDM-ed out of single bar for self alignment

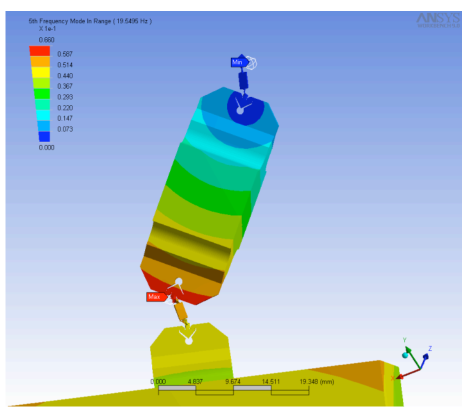


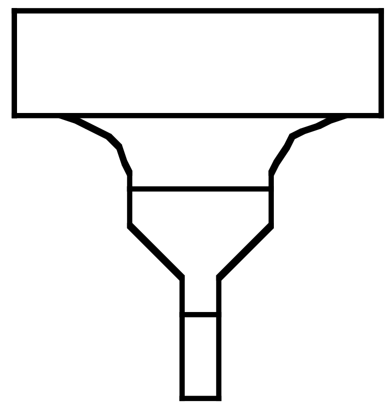
- Can test several different materials for dissipation and hysteresis on same structure
- Can easily test many different flex joint surface treatments

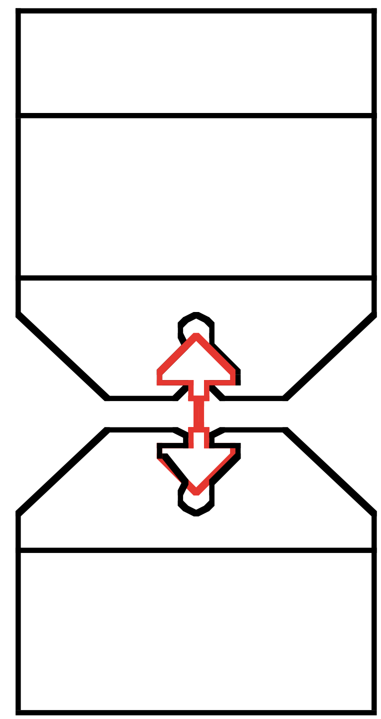
Previous prototype flexures tests

Carl Justin Kamp, Sean Mattingly



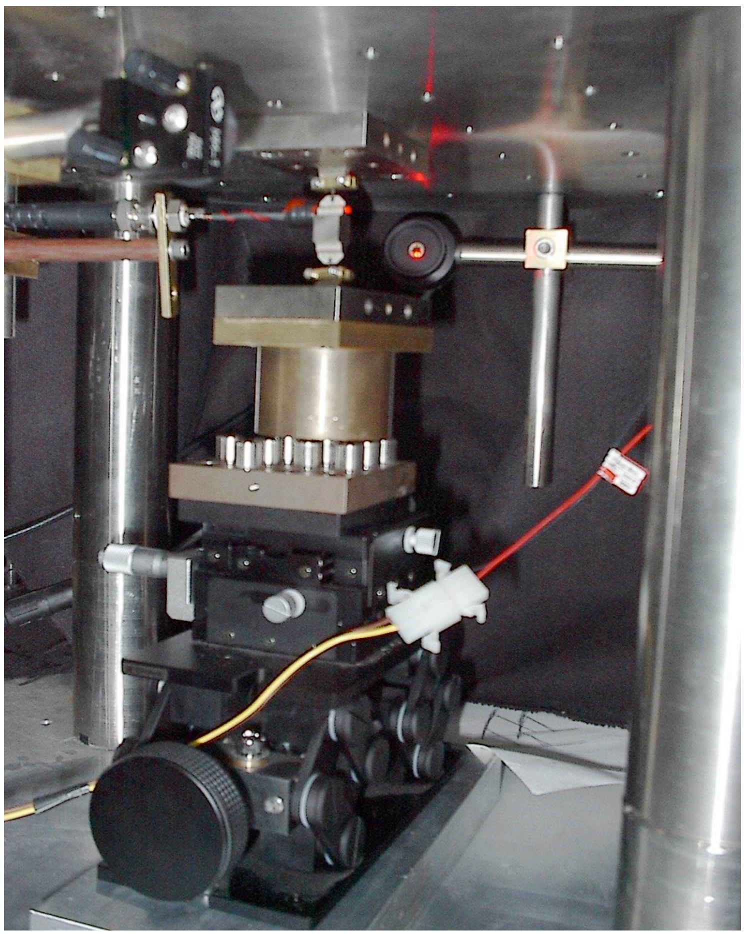


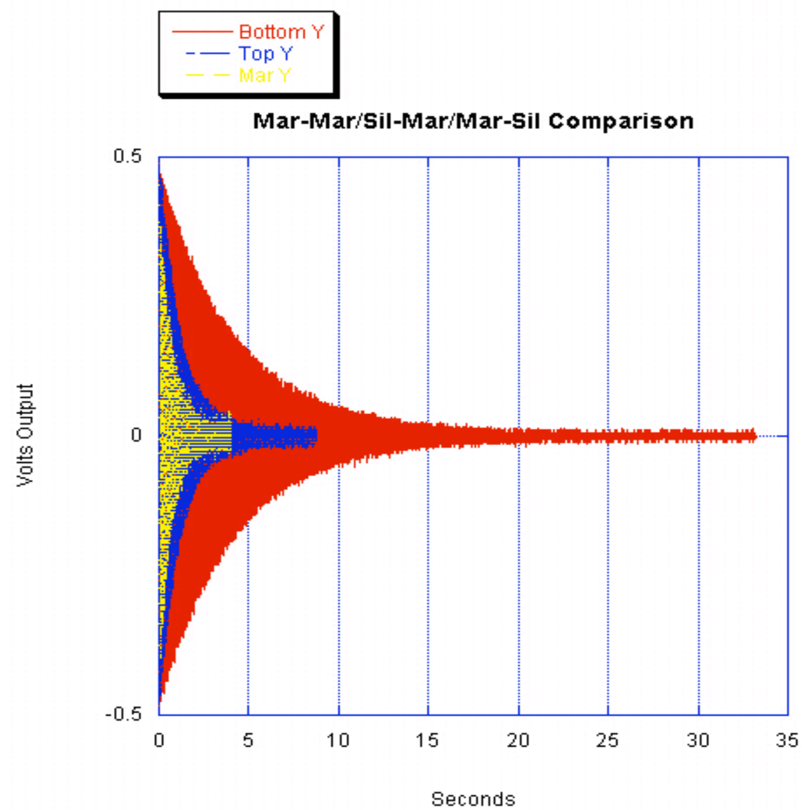




Steel and silicon flexures tested

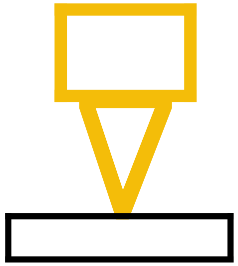
Q-Factor Analysis of Mono-Crystalline Silicon Flex Joints for Advanced LIGO





The old guy's scale design

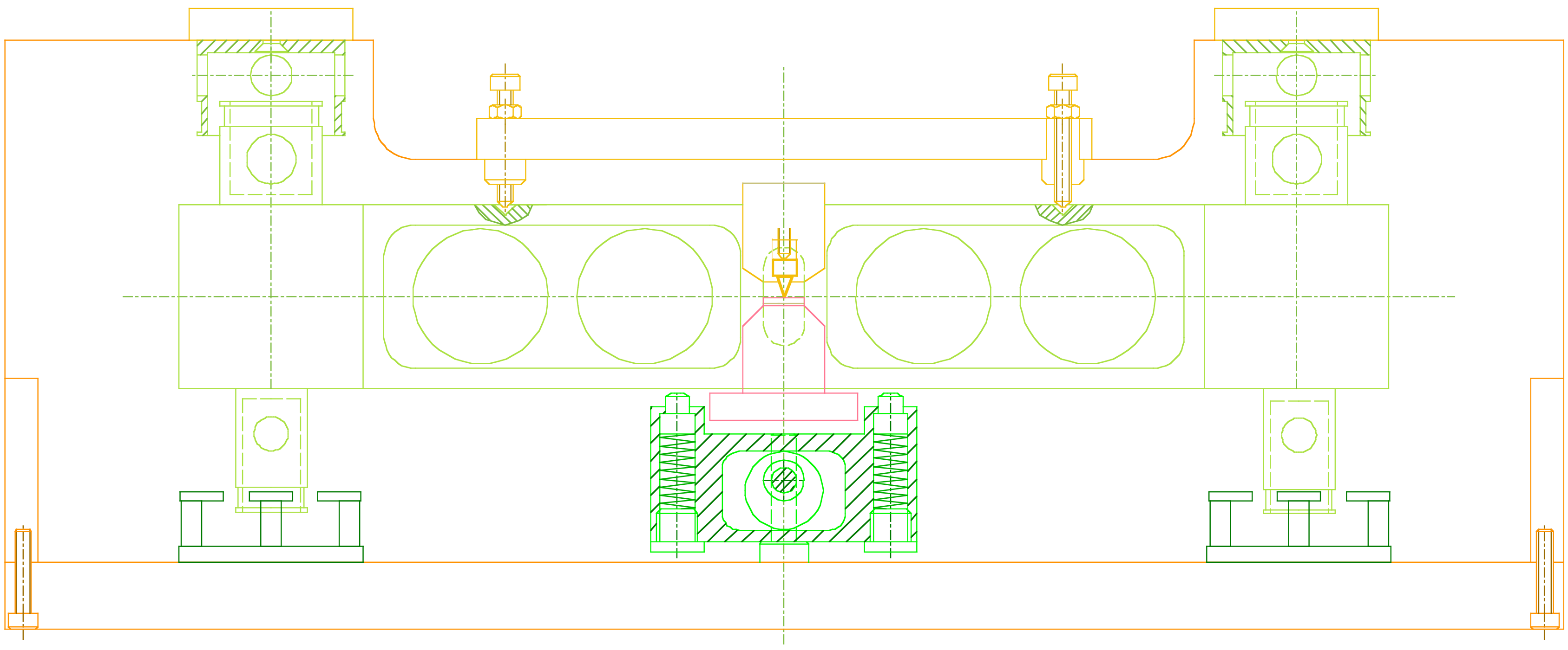
- The old guys knew about flex joints (fused silica torsion pendula)
- Still they built scales out of knife edges on Agate surfaces
- Maybe they knew better ! !



- Now we dispose of new materials, Tungsten Carbide, Titanium Nitride, harder and easier to manufacture

The old guy's scale design applied to a tiltmeter

- It is easy to apply the same tiltmeter geometry and compare



Final conclusion

- Lots of work still to do and
  lots of good physics to produce

- Lots of spillover from and on other fields