

# On Going Thermal Noise Research

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## **VIRGO** Project

### Overview

- **VIRGO** deliverables
  - clamps and wires
  - reference solution
- thermal noise predictions
- wire and clamp research
- creep research (preliminary)
- full scale prototype  $Q$  measurements
- long term R&D

# VIRGO deliverables

- Suspension
  - (7 m inverted pendulum with milliHertz horizontal resonance)
  - 7 stage pendulum (superattenuator)
- last stage
  - one wire to a "marionetta"
  - two wire loops hung from marionetta
    - ◊ allows pitch of mirror to be controlled by marionetta
  - wire clamped on marionetta
  - wires simply looped around mirrors
- Perugia Group must deliver clamps and wires for all last stage components by Sept. 96 (March 97?)

## VIRGO Reference solution

- VIRGO arm length- 3 km
- Pendulum length 700mm or pend. freq=0.6Hz
- wire loop separation 50 mm
- mirror made of Herasil with unpolished sides (ground finish)

- near mirror
  - thickness=100 mm
  - diameter=350 mm
  - mass=21.2 kg
  - C85 harmonic steel wire with diameter = $200\mu m$  (safety factor of .65 with breaking load= $300kg/mm^2$  (3 GigaPascals))
  - yaw mode frequency=1.2 Hz
  - pitch mode frequency=1.8 Hz
  - vertical mode frequency=6.7 Hz
- far mirror
  - thickness=200 mm
  - diameter=350 mm
  - mass=42.4 kg
  - C85 harmonic steel wire with diameter = $300\mu m$
  - yaw mode frequency=1.0 Hz
  - pitch mode frequency=1.7 Hz
  - vertical mode frequency=6.9 Hz
- clamps
  - aluminum with tool steel inserts
  - (put grooves  $130\mu$  deep on only one inner tool steel face)
  - use 2 M6 screws tightened to 14 Nm torque to clamp two pieces on wire

## wire and clamp research

- small pendulum in vacuum
  - loaded with only a few hundred grams
  - test pendulum  $Q$
  - find pendulum  $Q$  agrees with material  $\phi$  if wire is clamped with sufficient pressure
  - will now start to look at violin modes also (preliminary results seem to agree with wire loss and thermoelastic effect)
- traditional internal friction tests (inverted pendulum, torsional pendulum, temperature dependence, annealing effects) also done at
  - University of Camerino (Italy)
  - Technical University of Gdansk (Poland)
- looked at some monolithic designs
  - electroerosion of strip—promising, but geometry not good
  - centreless grinding of wire—damages both yield strength and  $\phi$
- tests of yield strength and ageing effects in wire

## creep research

- baking at  $150^{\circ}$  for 1 week
- long term sinking of mirror
- creep noise coupling into gravity wave signal
- some preliminary tests
- development of sensitive shadow meter
- eventual search for creep events

# Full Scale Prototype Q Measurements

low recoil loss structure

- Q limited by recoil losses

$$\frac{E_1}{Q_1} = \frac{E_2}{Q_2}$$
$$k_1 \phi_1 = k_2 \phi_2$$
$$Q = \frac{Mg}{kl\phi}$$

- predicted k (using finite element analysis) =  $2 \times 10^8 \text{ N/m}$
- predicted  $\phi = < 1^\circ$ ???
- Q limited to (M=20 kg)  $> 4 \times 10^7$ ???
- structure
  - Steel plates welded in an "A" frame type structure
  - Structure bolted directly to vacuum tank
  - Vacuum tank clamped to concrete block
  - 1.5m X 1.5m X 0.5m
  - 6 bolts embedded in block
- Dynamic characterization test using a 65 kg mass hung as a pendulum
  - Measure both phase and magnitude of transfer function
  - measure at pendulum frequency ( $\approx 0.6 \text{ Hz}$ )
  - use DC coupled accelerometer to measure acceleration (force) of mass
  - shadow meter measures displacement at the top of the structure
  - important that shadow meter reference is stationary
  - must calibrate both magnitude and phase of accelerometer

- must calibrate shadow meter  
(phase is negligibly small since shadow meter is large bandwidth device)
- do a DC test to measure elastic constant of structure
  - use a string, pulley and some weight to exert a force on the top of the structure
  - measure displacement using shadow meter
  - serves as independent test of elastic constant
- structure itself
  - measured relative to base of vacuum system
  - spring constant  $k = 1.13 \pm 0.03 \times 10^8 N/m$
- recoil of total system
  - measured relative to wall of building
  - spring constant  $k = 3.5 \pm 0.1 \times 10^7 N/m$
  - phase  $0.94 \pm 0.08^\circ$
  - cement block moves
  - depends upon orientation of pendulum motion
  - depends upon tightness of clamping tank to block
- Recoil losses of structure set an upper limit to the  $Q$  measurement (for a 20 kg mass) of  $Q = 7.6 \pm 0.7 \times 10^6$  (best predicted  $Q = \frac{1}{2} \times 5 \times 10^6$ )
- system will be moved in the near future (by Sept. 96)
  - new lab space available
  - installation of overhead crane to meet EC regulations
  - bigger concrete block and more bolts
  - test the structure with a mechanical shaker for a better characterization (better phase measurement over a broader frequency)

## Pendulum (and violin mode) Q measurements

- Q depends upon
  - internal losses in wire
  - clamping (both top and bottom)
  - recoil losses in structure
  - vacuum
- a Q of  $10^6$  and a pendulum frequency of 0.60 Hz gives
  - relaxation time of  $5.3 \times 10^5$  seconds (147 hours or 6 days)
  - seismic noise of  $10^{-6} m / \sqrt{Hz}$  gives an  $x_{r.m.s.} = 0.8 \text{ mm}$
  - linewidth of resonance is  $0.6 \mu Hz$
- hang mass using springs to pre-tension wires
- excite pendulum mode (and violin modes) electrostatically using positive feedback
- measure wire motion with traditional shadow meter technique (bi-cell photodiode and LED)
- place shadow meter near top of wire
  - large motions of mass can still be measured using wire as shadow
  - allows violin modes to be measured with same device
- record time series with PC
  - take amplitude and fit with exponential decay
  - also use two decaying exponentials that are close in frequency

$$A(t) = A_1 e^{-\gamma_1 t} + A_2 \sin[2\pi(f_2 - f_1)t] + \phi |e^{-\gamma_2 t}$$

- measure resonance linewidth with FFT spectrum analyser
  - fit curve with Lorentzian



## Al dummy mirror

- aluminum mass with same dimensions ( $350 \times 100mm$ ), but larger mass ( $\rho_{Al} = 2.7g/cm^3$  vs.  $\rho_{SiO_2} = 2.2g/cm^3$  or  $m_{Al} = 26.0kg$  vs.  $m_{SiO_2} = 21.2kg$ )
  - $Q_{pend} = \frac{1}{2} \times 5.6 \times 10^6$
  - violin mode  $f_n = n \times 362 Hz$
  - violin mode  $Q$  (at  $362 Hz$ ) =  $7.5 \times 10^5$
- reference solution set up (no clamps)
  - $Q$  of pendulum extremely amplitude dependent
  - best  $Q$  (limited by seismic excitation) of  $1 \times 10^5$
  - violin mode  $Q$  also amplitude dependent
  - best violin mode  $Q \sim 2 \times 10^4$
- wire attached with epoxy to test mass
  - $Q$  of pendulum less amplitude dependent
  - best  $Q$  (limited by seismic excitation) of  $1 \times 10^5$
  - violin mode  $Q \sim 8 \times 10^4$
- wire attached with clamps to test mass
  - $Q$  of pendulum shows little amplitude dependence
  - best  $Q$  of  $Q \sim 6 \times 10^5$
  - violin mode  $Q \sim 2.2 \times 10^5$
  - $Q$  of pendulum could be limited by eddy current damping of Al mass moving through the earth's magnetic field (Thank you Sheila for the calculation!)

## Herasil test mass

- reference solution suspension
  - pendulum mode  $Q \sim 10^4$
  - violin mode  $Q \sim 8 \times 10^3$
  - both very highly amplitude dependent
  - **not** acceptable  $Q$  for VIRGO
- measured Herasil mirror with cylindrical AL spacers between wire and mirror surface
  - pendulum mode  $Q \sim 4 \times 10^5$
  - violin mode  $Q \sim 1.5 - 2 \times 10^5$
  - tried both 5mm and 10mm diameter and did not see much difference
- measured Herasil mirror with cylindrical SS spacers between wire and mirror surface
  - pendulum mode  $Q \sim 3 \times 10^5$
  - violin mode  $Q \sim 9 \times 10^4$
- measured Herasil mirror with grooved, cylindrical AL spacers between wire and mirror surface
  - grooves were narrower than wire radius
  - pendulum mode  $Q \sim 4 \times 10^5$
  - violin mode  $Q \sim 2.1 - 2.5 \times 10^5$
- measured Herasil mirror with clamps attached to cylindrical AL spacers between wire and mirror surface
  - pendulum mode  $Q \sim \ell \times 10^5$
  - violin mode  $Q \sim 2 - 4 \times 10^5$

- measured dummy glass mirror with Al clamps epoxied onto mirror surface

- pendulum mode  $Q \geq 5 \times 10^5$

- violin mode  $Q \sim 2 \times 10^5$

other modes (using Herasil mass)

- yaw mode

- excite electrostatically by rotating and displacing plate

- Ref. Solution  $f = 1.16 \text{ Hz}$ ,  $Q = 2.1 \times 10^4$  (amplitude dependent)

- spacers with grooves  $f = 1.17 \text{ Hz}$ ,  $Q = 5.6 \times 10^5$

- pitch mode

- excite electrostatically by displacing plate

- Ref. Solution  $f = 1.91 \text{ Hz}$ ,  $Q = 1.3 \times 10^3$

- spacers with grooves  $f = 1.78 \text{ Hz}$ ,  $Q = 3.1 \times 10^3$

- vertical mode

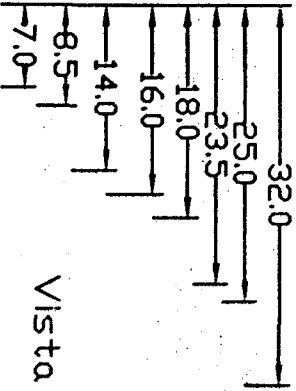
- excite by shaking ground mechanically

- Ref. Solution  $f = 6.65 \text{ Hz}$ ,  $Q = 1.9 \times 10^3$

- spacers with grooves  $f = 6.44 \text{ Hz}$ ,  $Q = 1.8 \times 10^3$

## long term R&D

- new wire materials
  - search for specialty materials
  - fused quartz (small prototype had  $a\phi = 5 \times 10^{-6}$ )
- better clamps
  - collet type clamp
  - monolithic designs
- sapphire test masses
  - collaboration with LIGO and Univ. of Western Australia
  - sapphire to be obtained by LIGO an VIRGO
  - optics to be tested in Paris
  - suspension and  $Q$  to be tested in Australia
- cryogenics
- direct thermal noise measurement

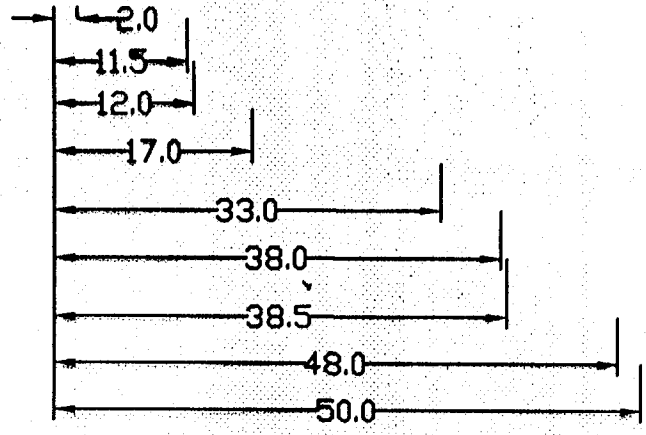
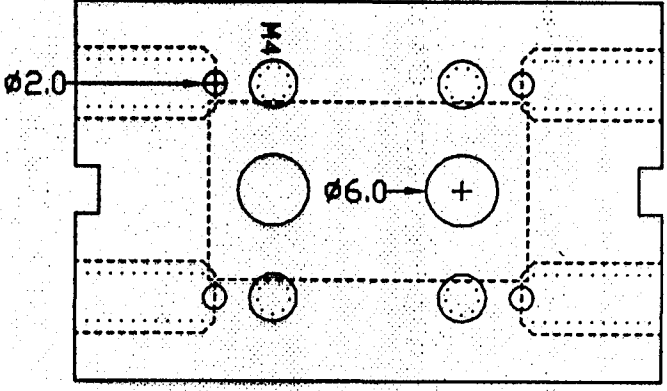


Vista dall'alto

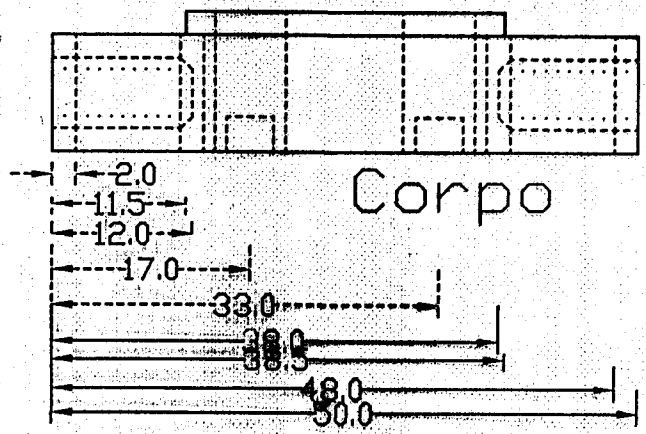
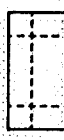
L1



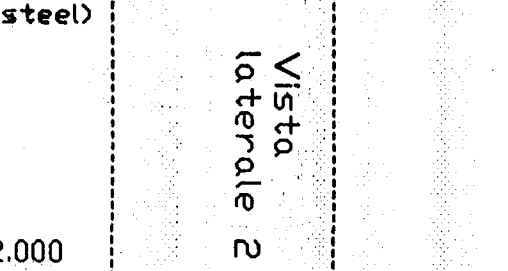
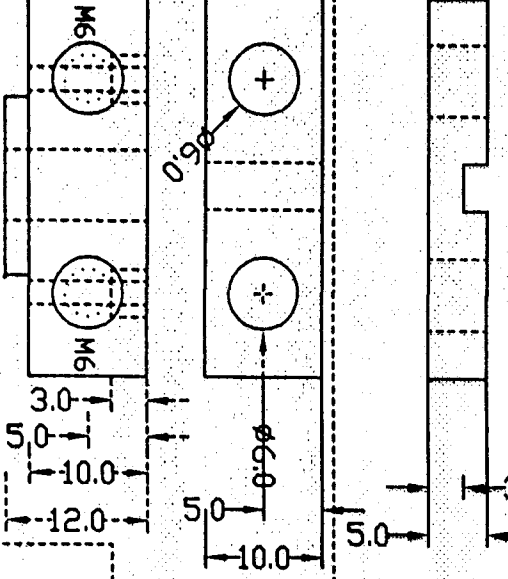
Materiale alluminio



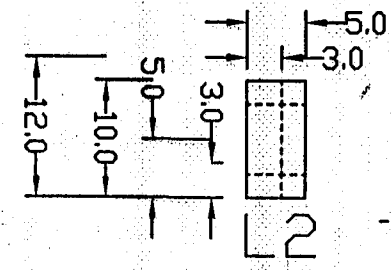
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Corpo

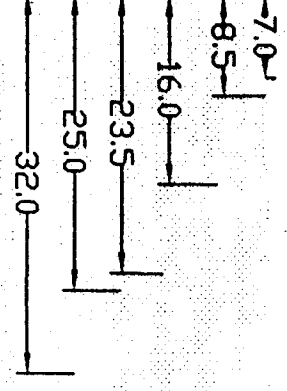


Vista laterale 2



Corpo po

L1-2



Inserti in acciaio da attrezzi (tool steel)

