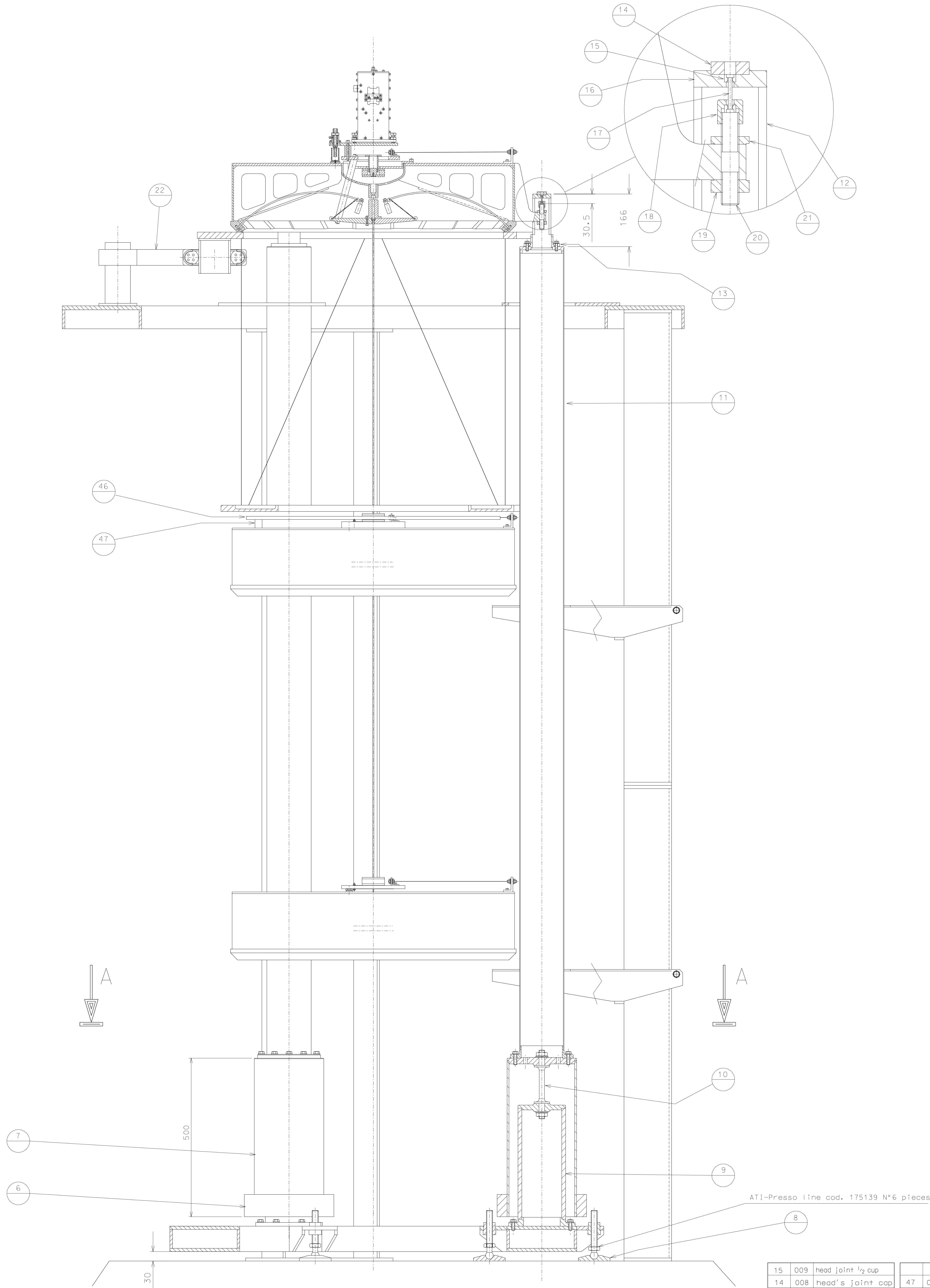
Presentation Overview

- Riccardo SAS Concept Overview
- Szabolcs Prototypes & Results
- Alessandro Sensors and Actuators
- Akiteru Simulations & Controls
- Riccardo Final Important Remarks

LIGO-G000066-00-D



ref.	draw.	added legend
15	009	head joint $^1/_2$ cup
14	008	head's joint cap
13	008	leg's head retention disk
12	008	leg's head
11	008	main leg
10	009	elastic joint
9	007	base column
8	008	footing
7	007	bell
6	008	counterweight

ref.	draw.	added legend
47	026	copper plate
46	026	spacer
22	013	peripheral magnets
21	009	height tuning c'nut
20	009	height tuning rod
19	009	height tuning nut
18	009	height tuning cap
17	009	head's flex joint
16	008	leg's head top disk

Size A1

ref.	note	date	signature
	pendulum rotated	30-7-99	

modifications

LIGO PROJECT

designed for R. De Salvo

ass. numb. Test-tower.003

draw. PROMEC 2-7-99

scale 1:6

replaces dr. Numb.

title TEST-TOWER

LATERAL VIEW

SAS Concept

1. Ultra Low Frequency pre-attenuation stage
   - Filters out micro seismic peak
   - Platform for inertial damping and controls
   - Gain height for passive seismic chains
2. Active Inertial Damping / Position Control
   - Drains energy from chain resonances
   - Positions the mirror
3. Passive attenuation chain
   - Provides all in-band seismic attenuation.
4. Mirror Suspensions and Controls

SAS Key Points

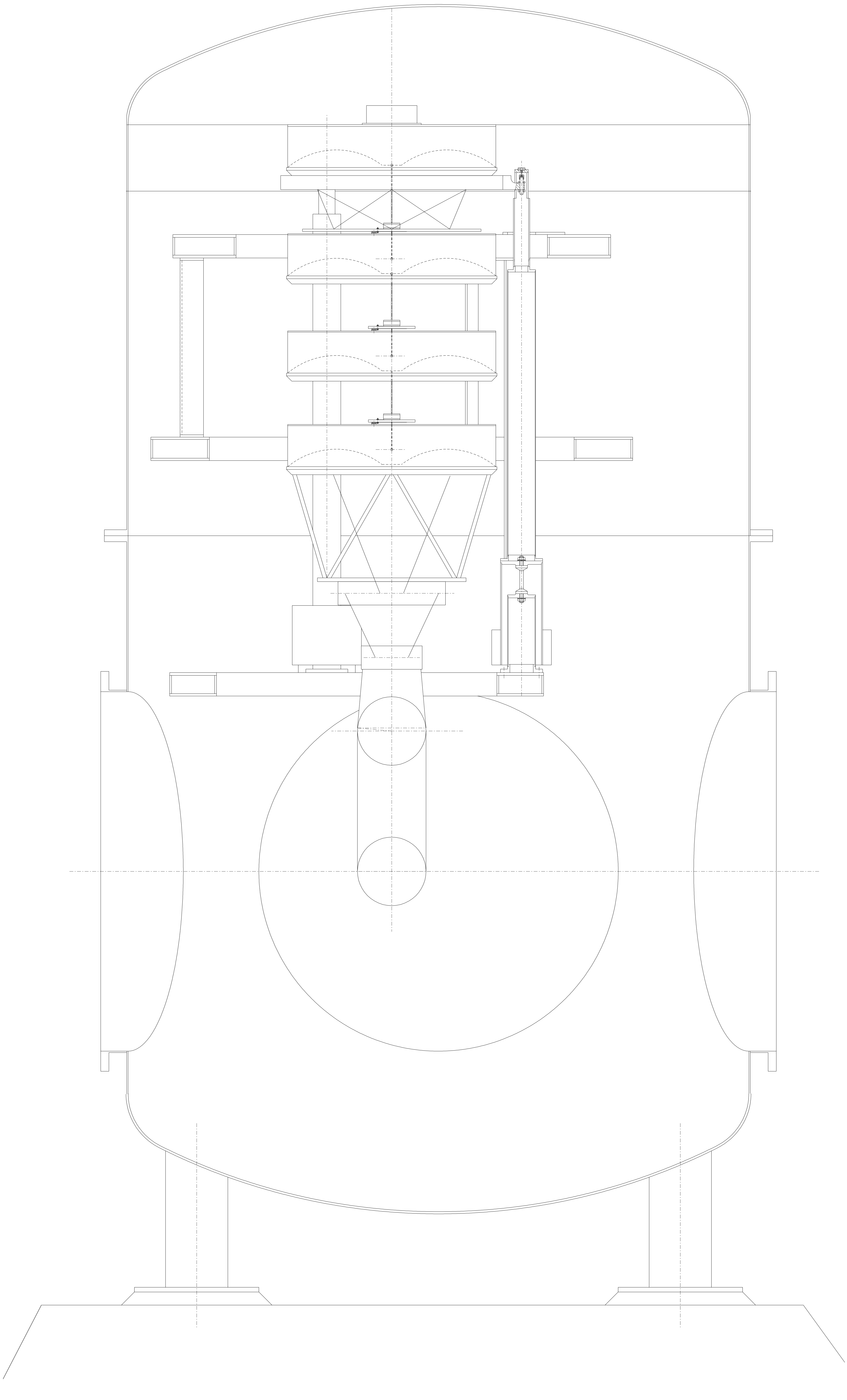
- Entirely passive attenuation
  - For reliability and excess noise reduction
- Relocation of maximum fraction of controls above the passive attenuation stages
  - Minimize noise/excess noise re-injection risk
  - Ease of controls
- Do not burden main attenuation chain with ancillary optics
  - Ancillary optics separately dealt with
  - Optical table possible (even easy) see Ham design

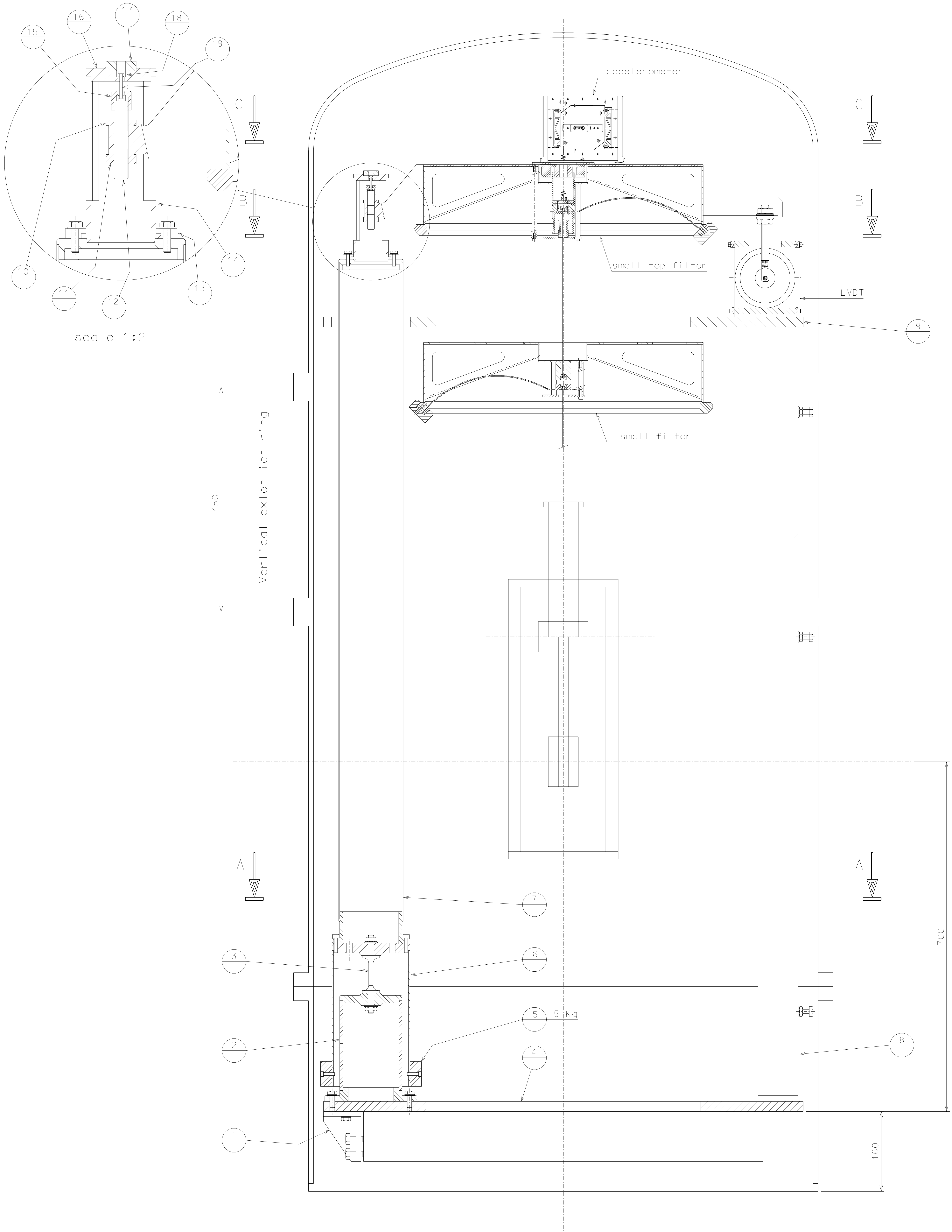
SAS Key Advantages

- Reliability:
    - passive components always work
- Resilience
    - Loss of power and/or controls => system stays put
    - Loss of active component => system survives
- Low frequency, low residual motion
    - Low residual speed for lock acquisition
- Softness
    - Low actuation power (mW), no damage potential

SAS Design Flexibility

- Modular assembly
- Scalability
- Application examples
  - LIGO
  - TAMA
  - 40 m
  - 2-in-1
- HAM and BSC topologically similar





NOTE:preassembly sub assemblies with SS screws:
deliver assembled do not tighten screws

ref.	draw.
TAMA double pendulum	
accelerometer	
small top filter	008
small filter	007

ref.	draw.	added legend
10	013	reteiner nut
9	016	top reference ring
8	014	safety strut
7	011	leg
6	010	c.weight bell
5	010	counterweight
4	015	inteface disk
3	010	main flex joint
2	009	flex joint base
1	009	stiffener

ref.	draw.	added legend
19	012	small flex joint
18	012	1/2 cups
17	011	1/2 cup retainer
16	012	top disk
15	013	load nut
14	011	leg head
13	012	rotation flange
12	012	tuning stud
11	013	support tuning nut

Size A1

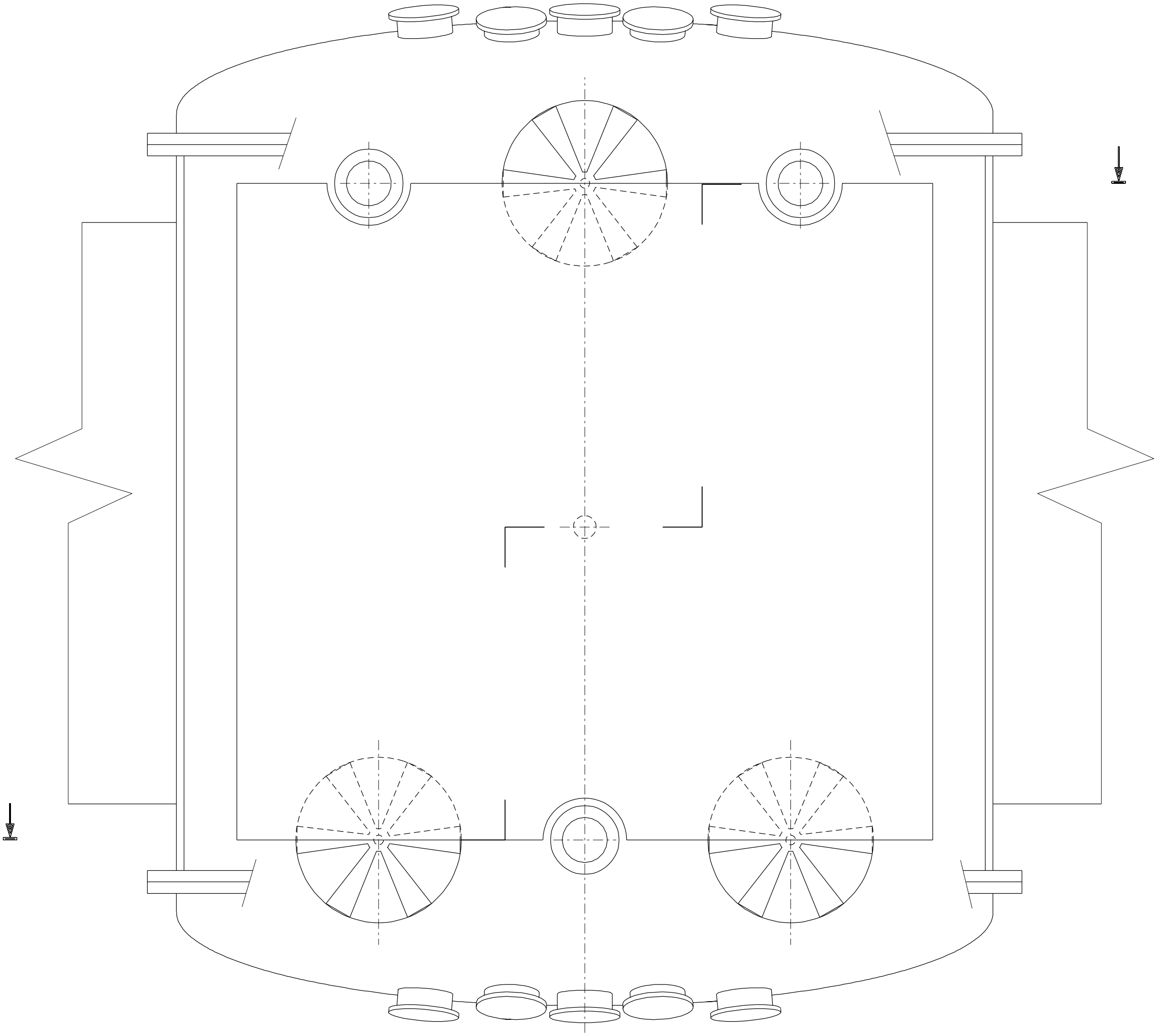
ref.	note	date	signature

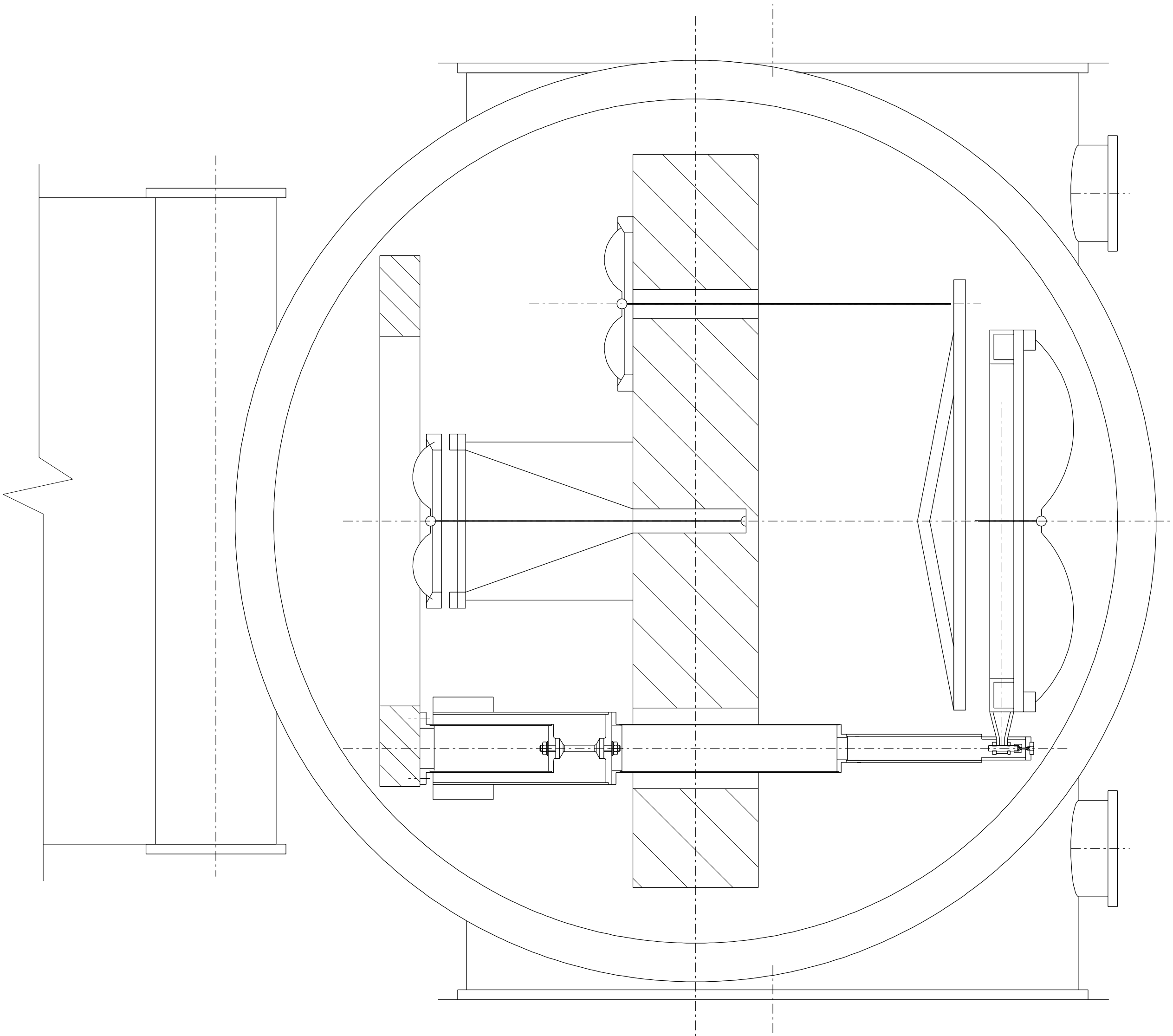
modifications

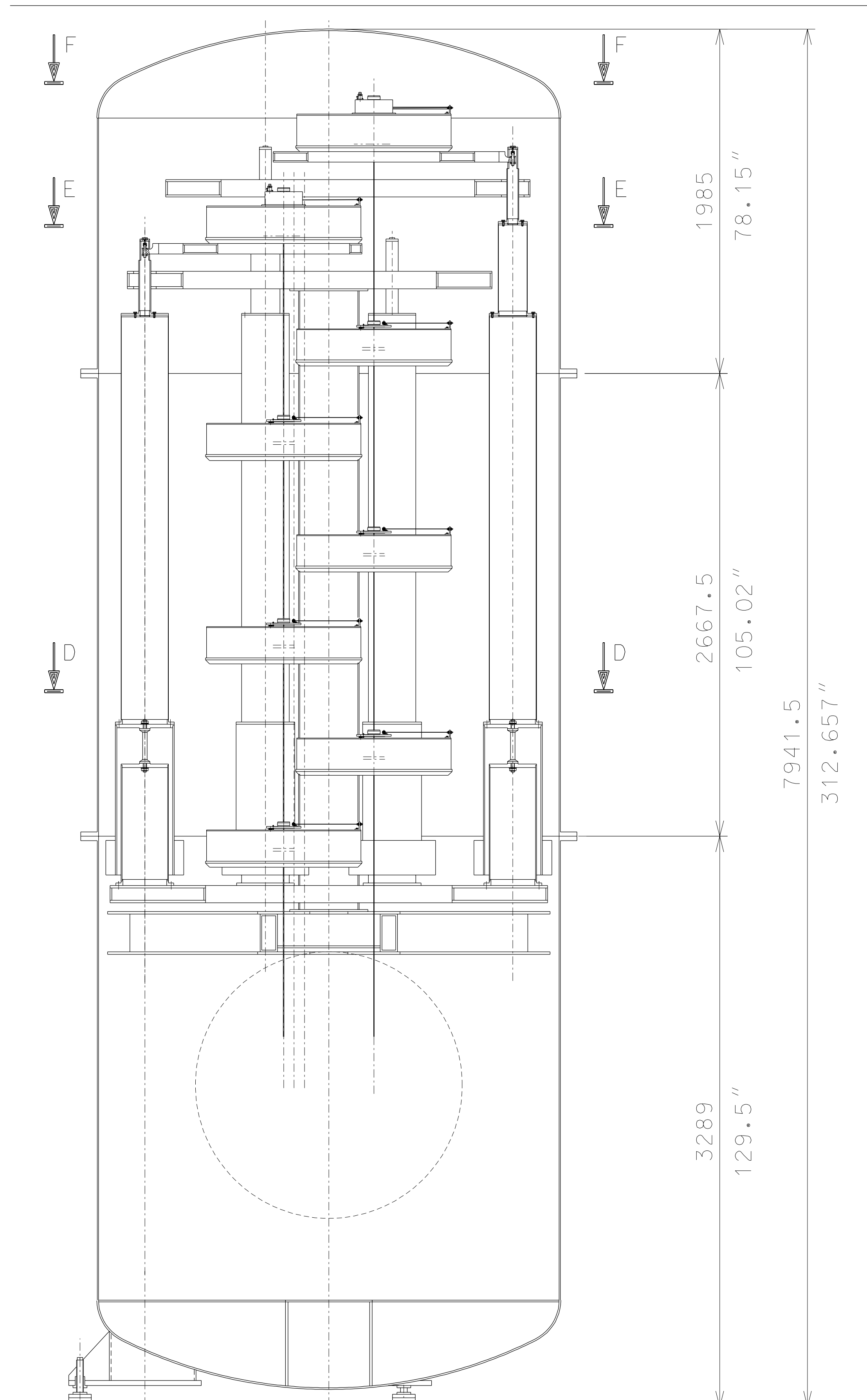
LIGO PROJECT

title
TAMA-SAS-TOWER
SECTION D-D

designed for R. De Salvo
ass. numb. Tama.000
draw. PROMEC 6-2-00
scale 1:4
replaces dr. Numb.







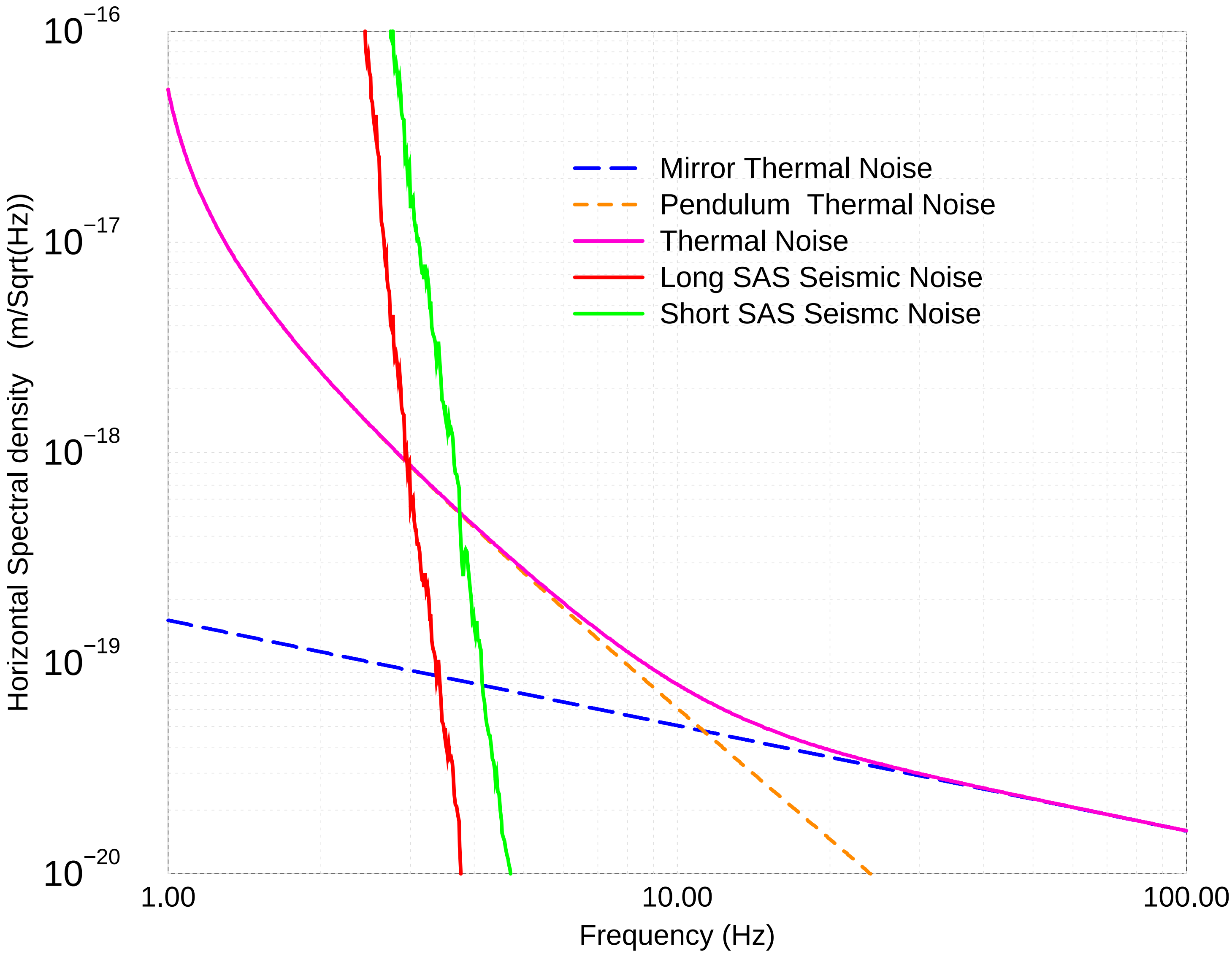
Sez. A-A

Development Advancement

- Built, tested and debugged 1:1 prototype of all components (GASFs, IP, LVDTs,2D voice coils, Accelerometers)
  - Perfectly viable systems Designed with tested components
- Advanced components prototyped (MGASFs) and being tested
  - Will lead to better performances

    and further simplifications

Sensitivity Curve
(Preliminary Results)



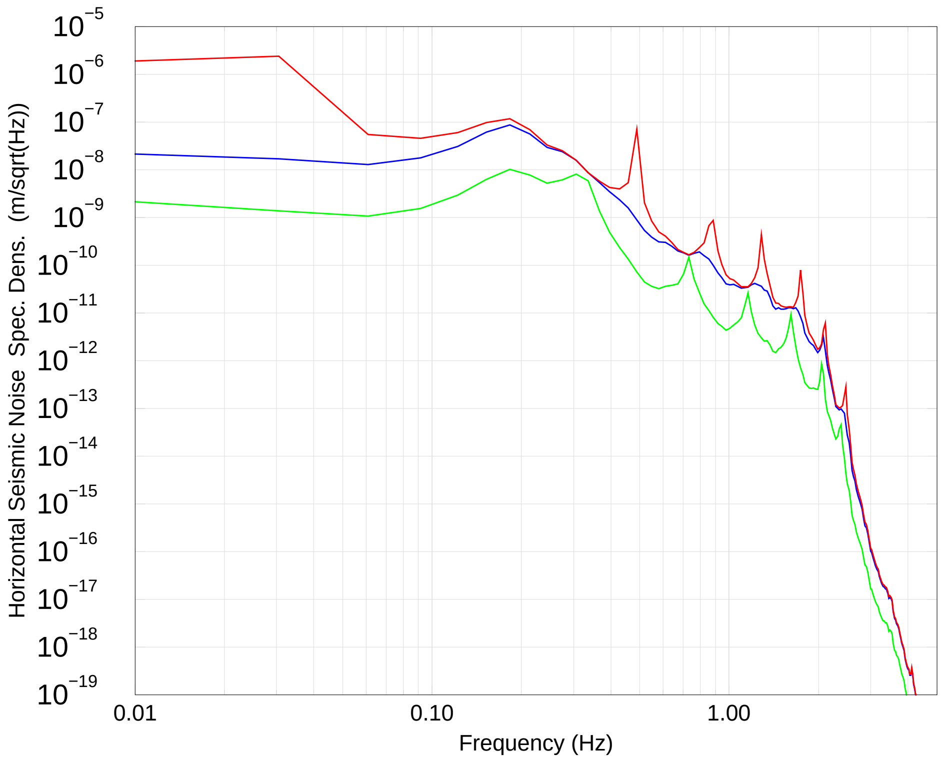
SAS Development Advancements

- Full Interferometer Test in Vacuum
  in Japan, Fall 2000

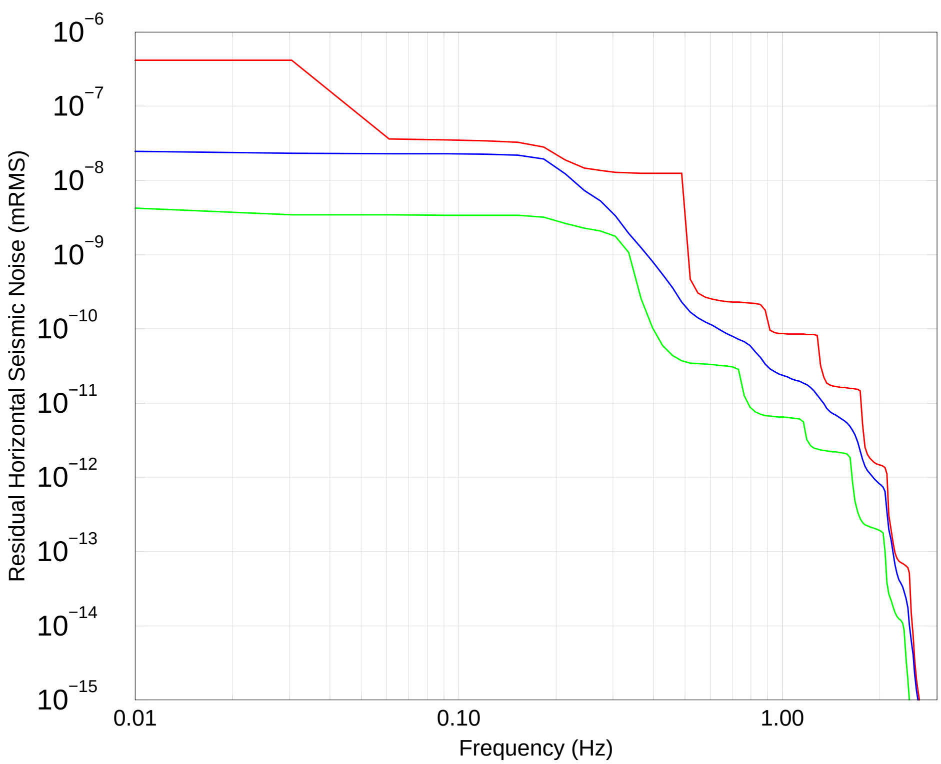
- Attenuation and control performance under test at Virgo

-> Achieved 50 nm r.m.s. (integrated >100 mHz)

SAS-SUS Inertial Damping



Horizontal Seismic Noise Spectral Densities



Horizontal Seismic RMS Residual Displacement

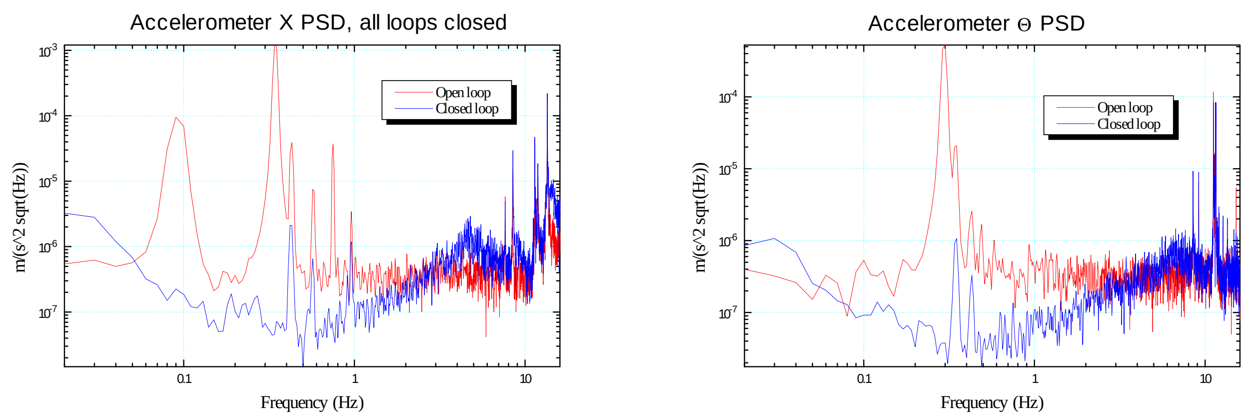


Figure 9: Spectra of the virtual accelerometers X and Θ with the damping ON and OFF.

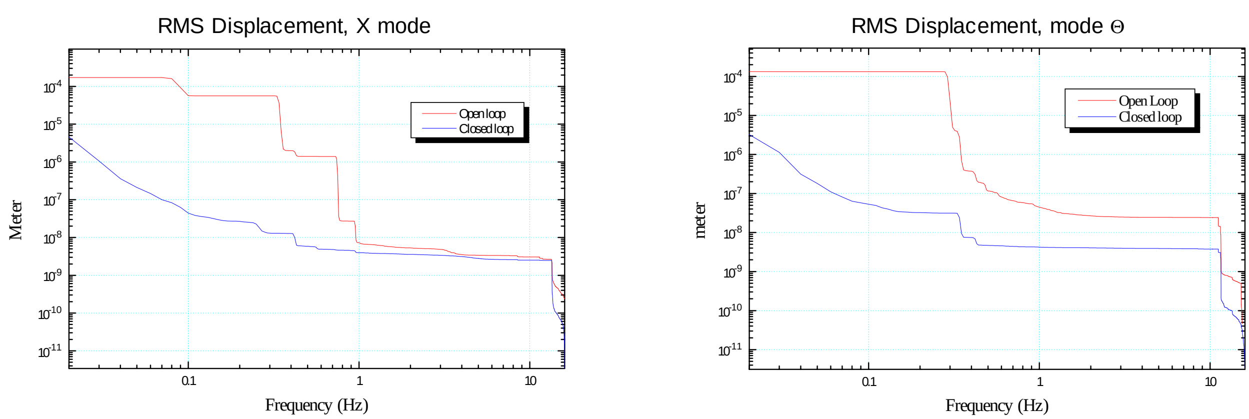


Figure 10: RMS motion of the IP top table, calculated from the spectra of fig. 9. The translational RMS motion at 100 mHz is reduced from ~ 70 μm (damping OFF) to ~ 50 nm (damping ON).

GAS Filter : Measurements

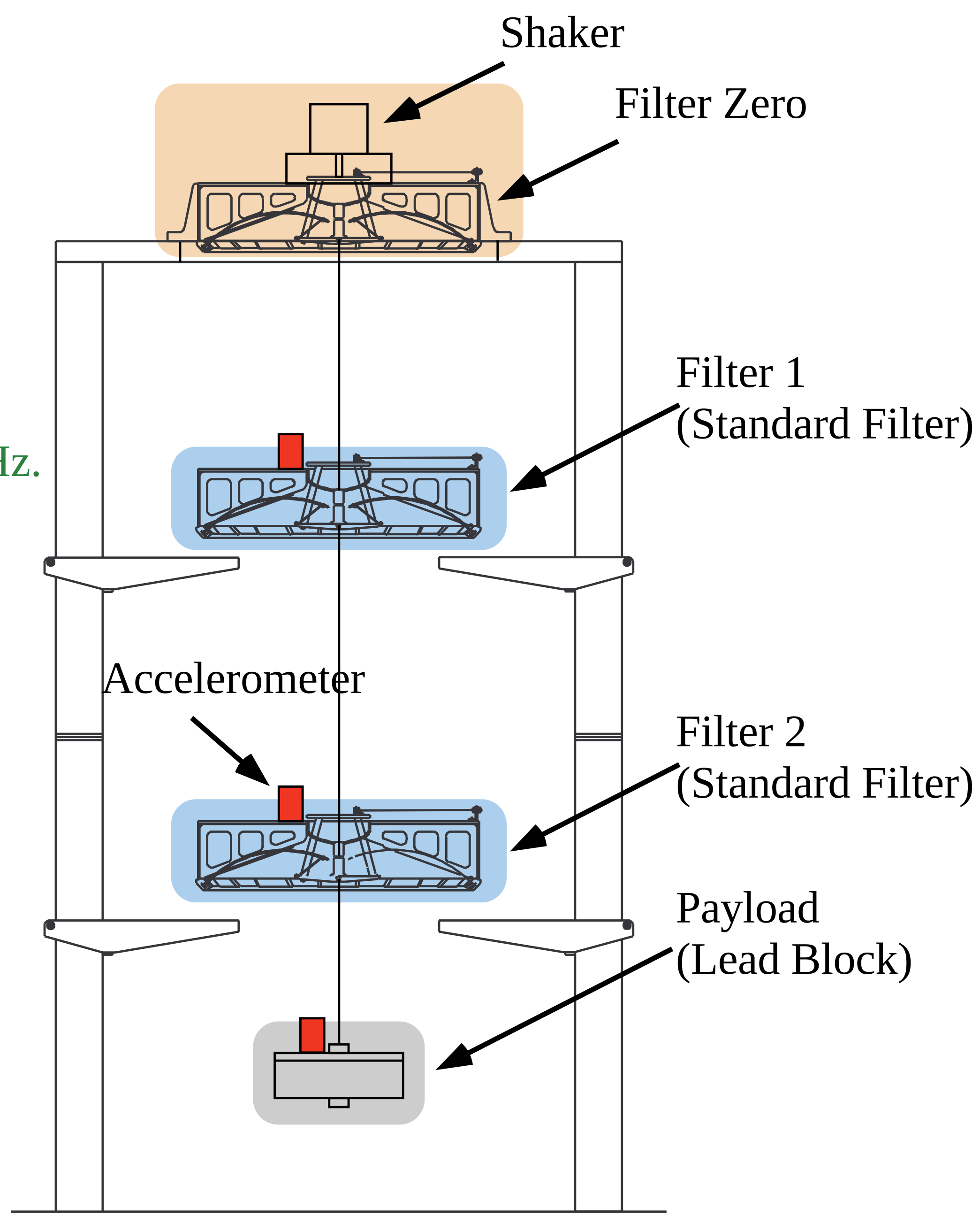
Vertical Isolation Performance

- Double GASF Chain

  - GASF Chain + Payload

  - Filter Zero is connected to a shaker.

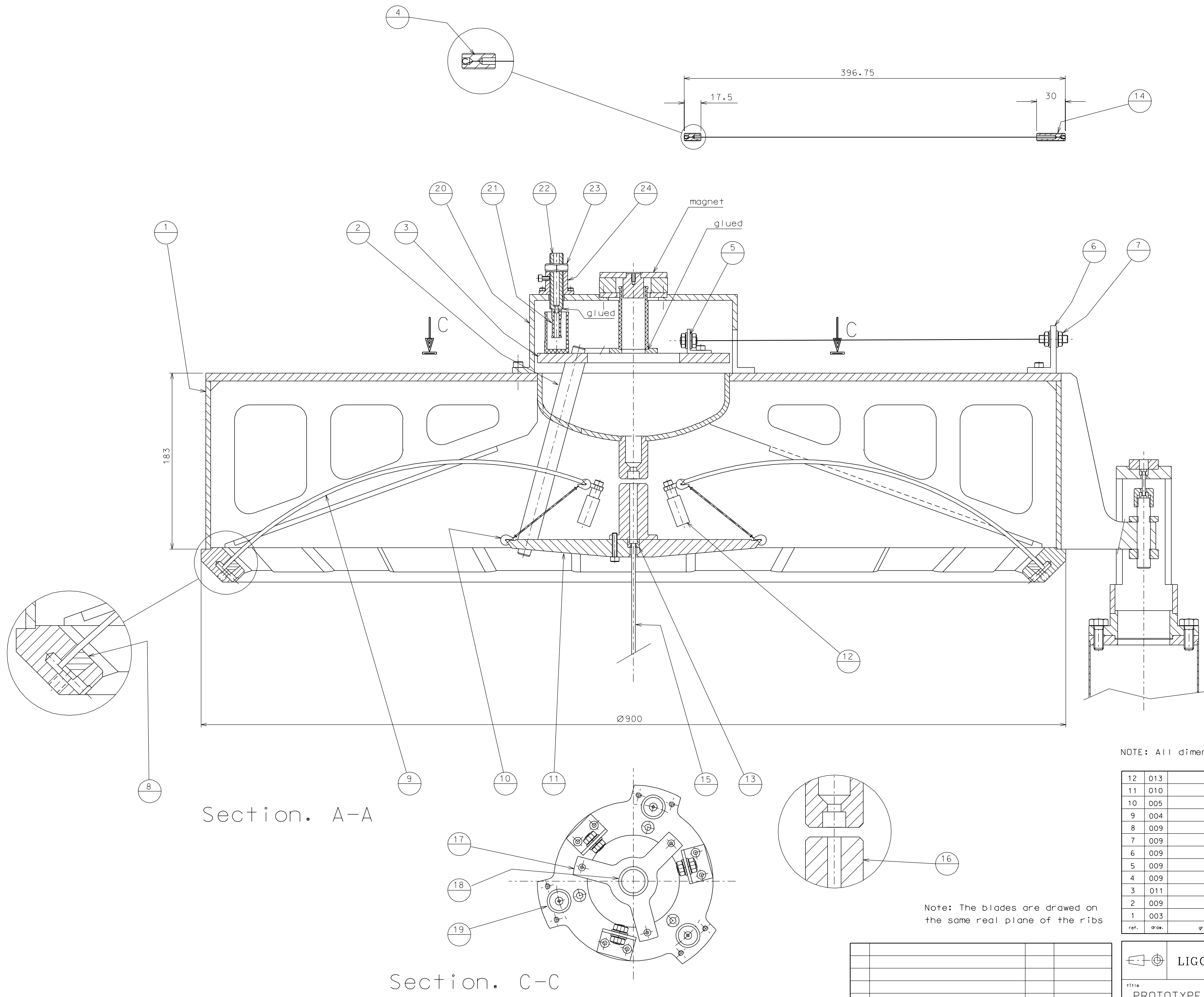
  - Standard Filters are tuned to about 450mHz.




CAUTION DO NOT ENTER CAUTION DO NOT ENTER CAUTION DO NOT ENTER CAUTION DO NOT ENTER

Test Tower

Filter Prototype



NOTE: All dimension in mm

ref.	drow.	group
12	013	
11	010	
10	005	
9	004	
8	009	
7	009	
6	009	
5	009	
4	009	
3	011	
2	009	
1	003	

ref.	drow.	group
24	016	
23	016	
22	016	
21	016	
20	016	
19	016	
18	016	
17	016	
16	011	
15	013	
14	009	
13	009	

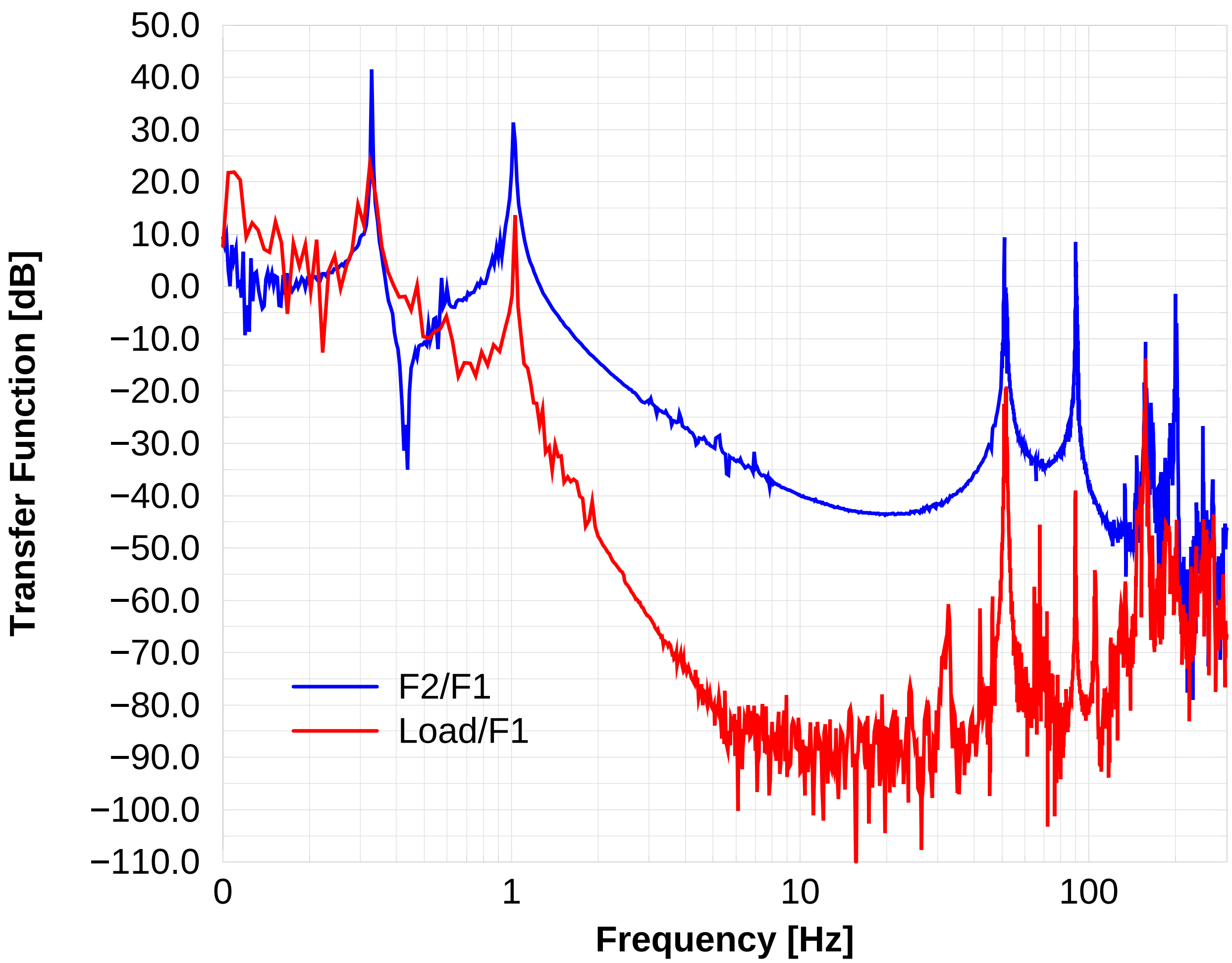
Note: The blades are drawed on the same real plane of the ribs

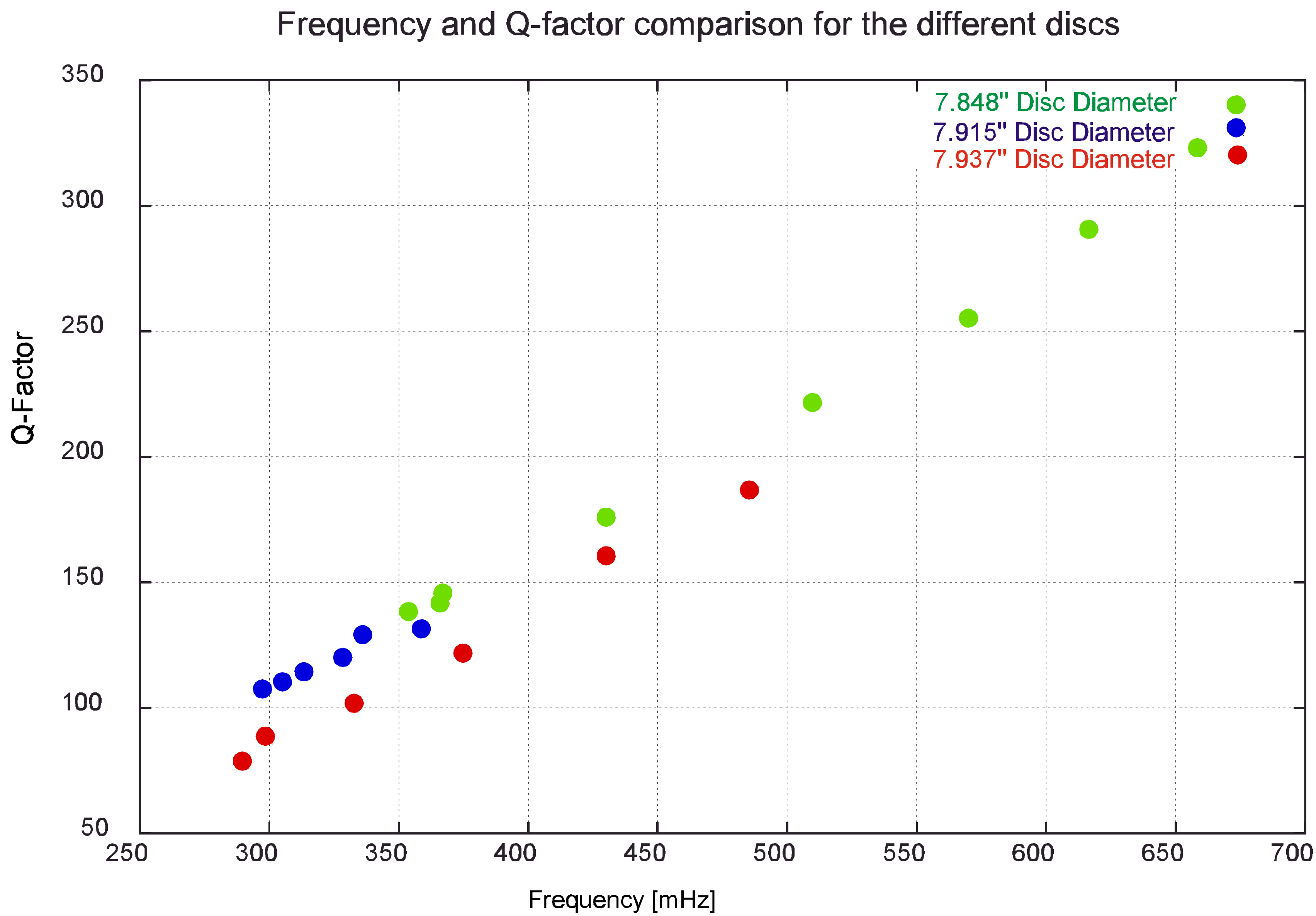
ref.	note	date	signature

modifications

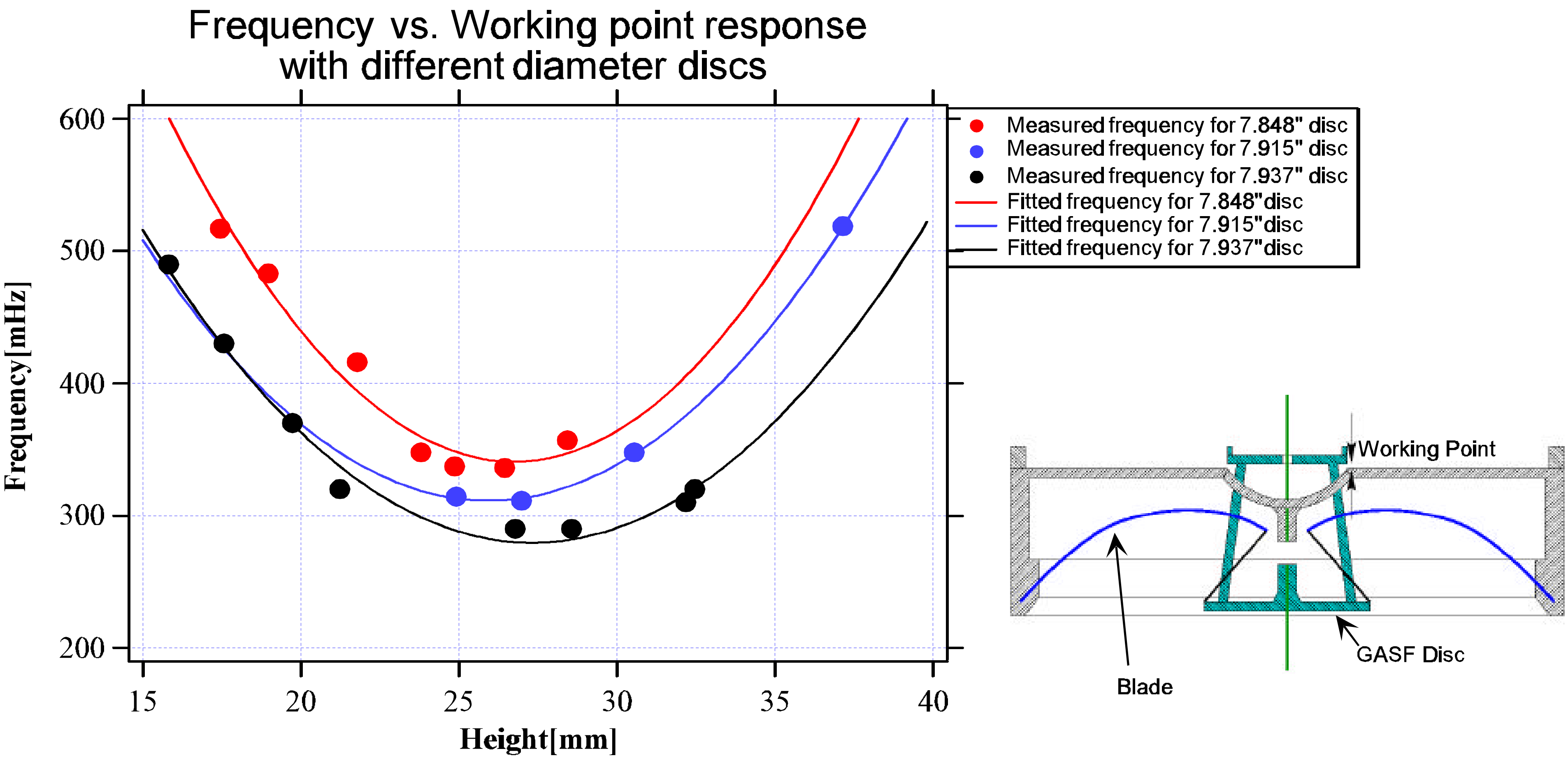
LIGO PROJECT	designed for R. De Salvo
	ass. numb. Filter_0.000
title PROTOTYPE FILTER_0	drow. PROMEC 30-1-99
LATERAL SECTION	scale 1:2
	replaces dr. Numb.

2 Standard Filter Chain, Vertical Transfer Function (Good filters balance)

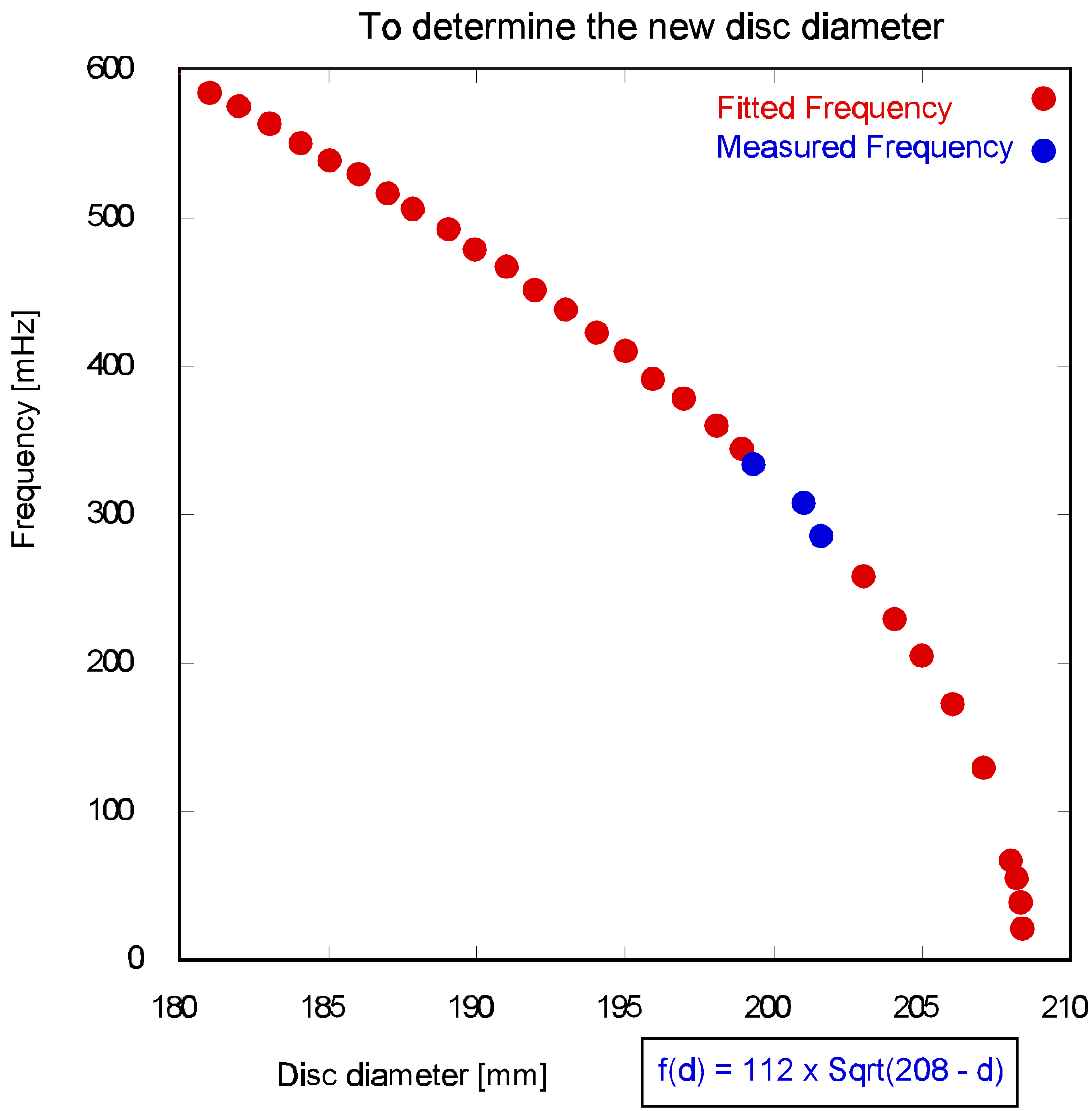




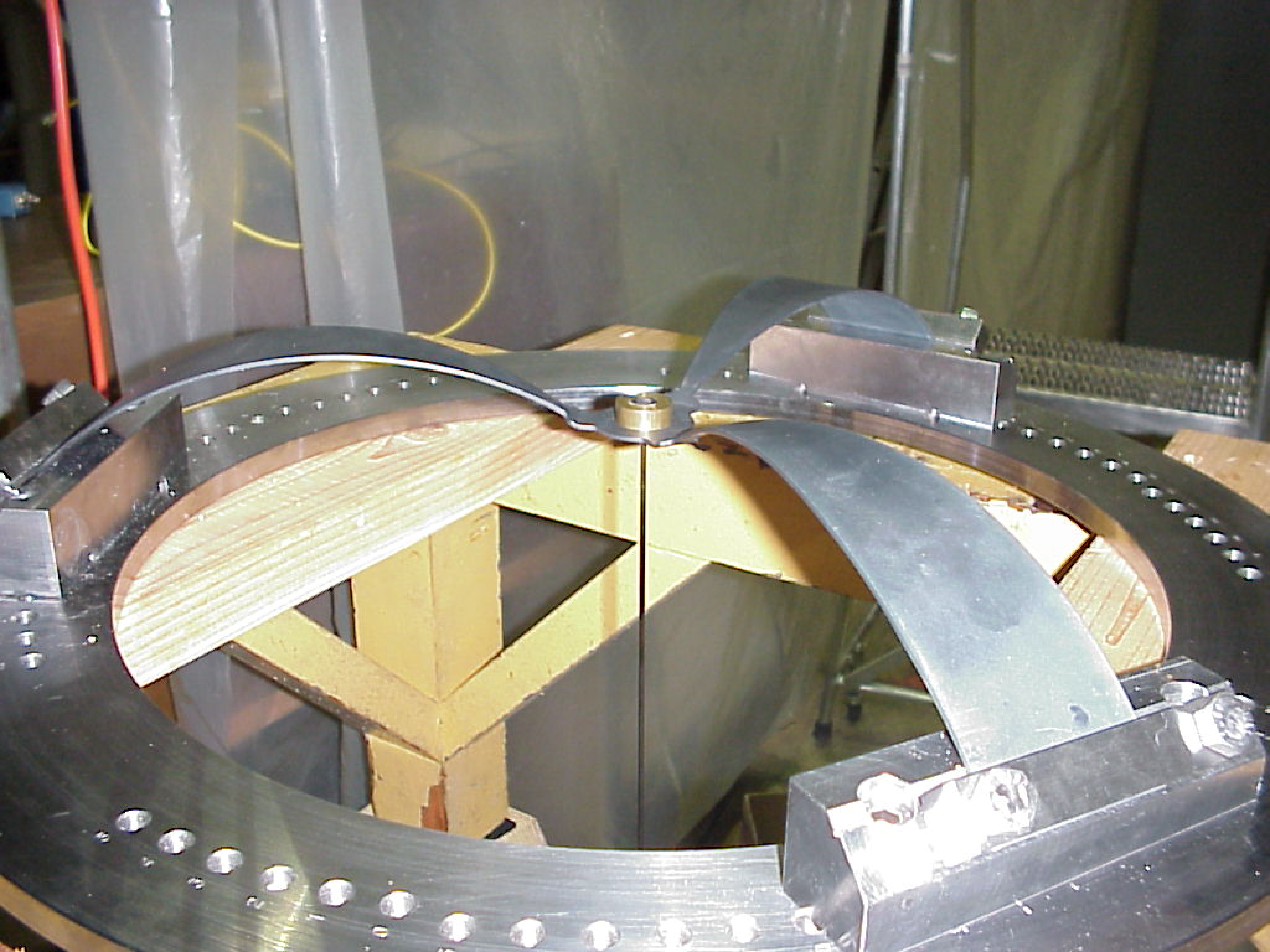
Hareem Tariq
Chenyang Wang



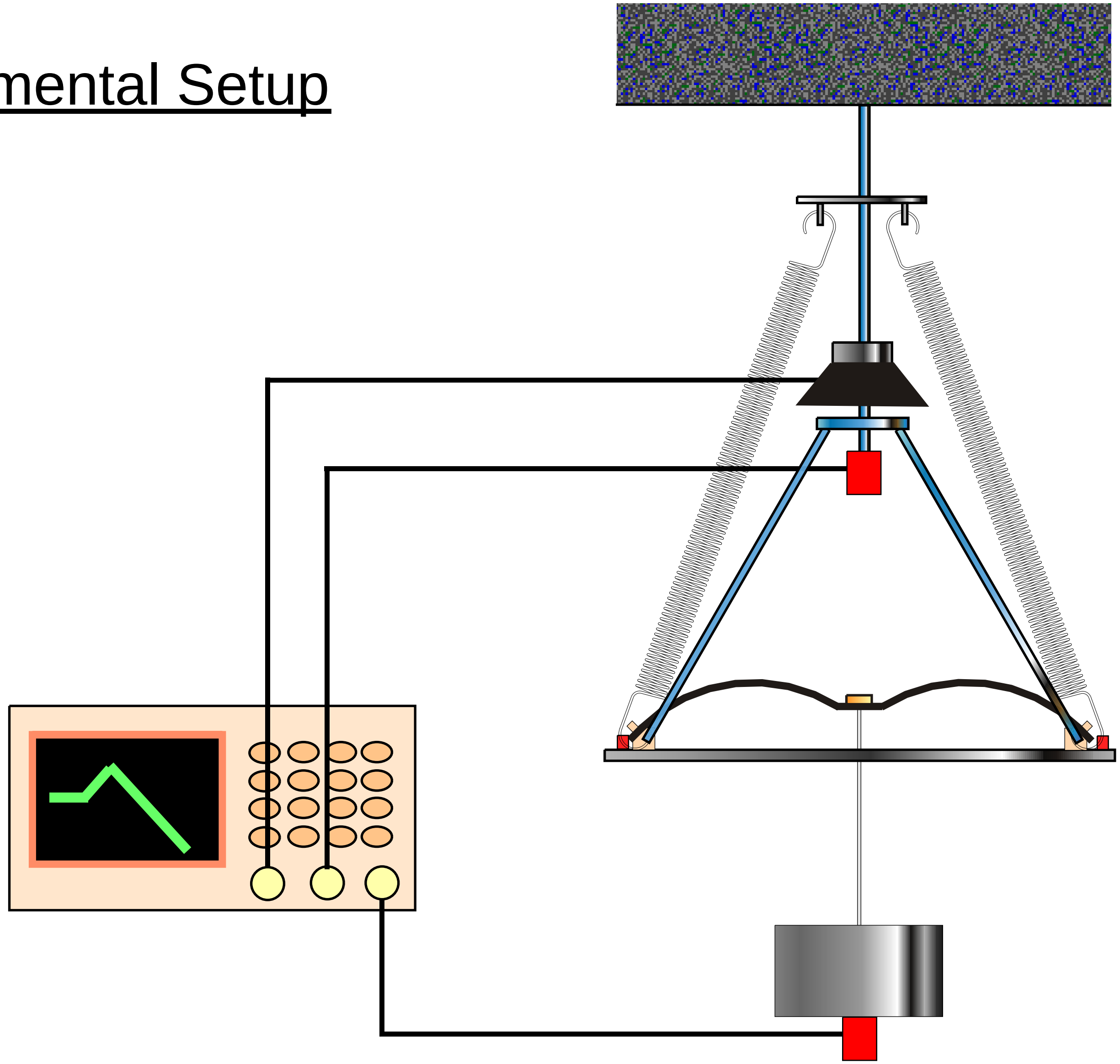
Hareem Tariq
Chenyang Wang

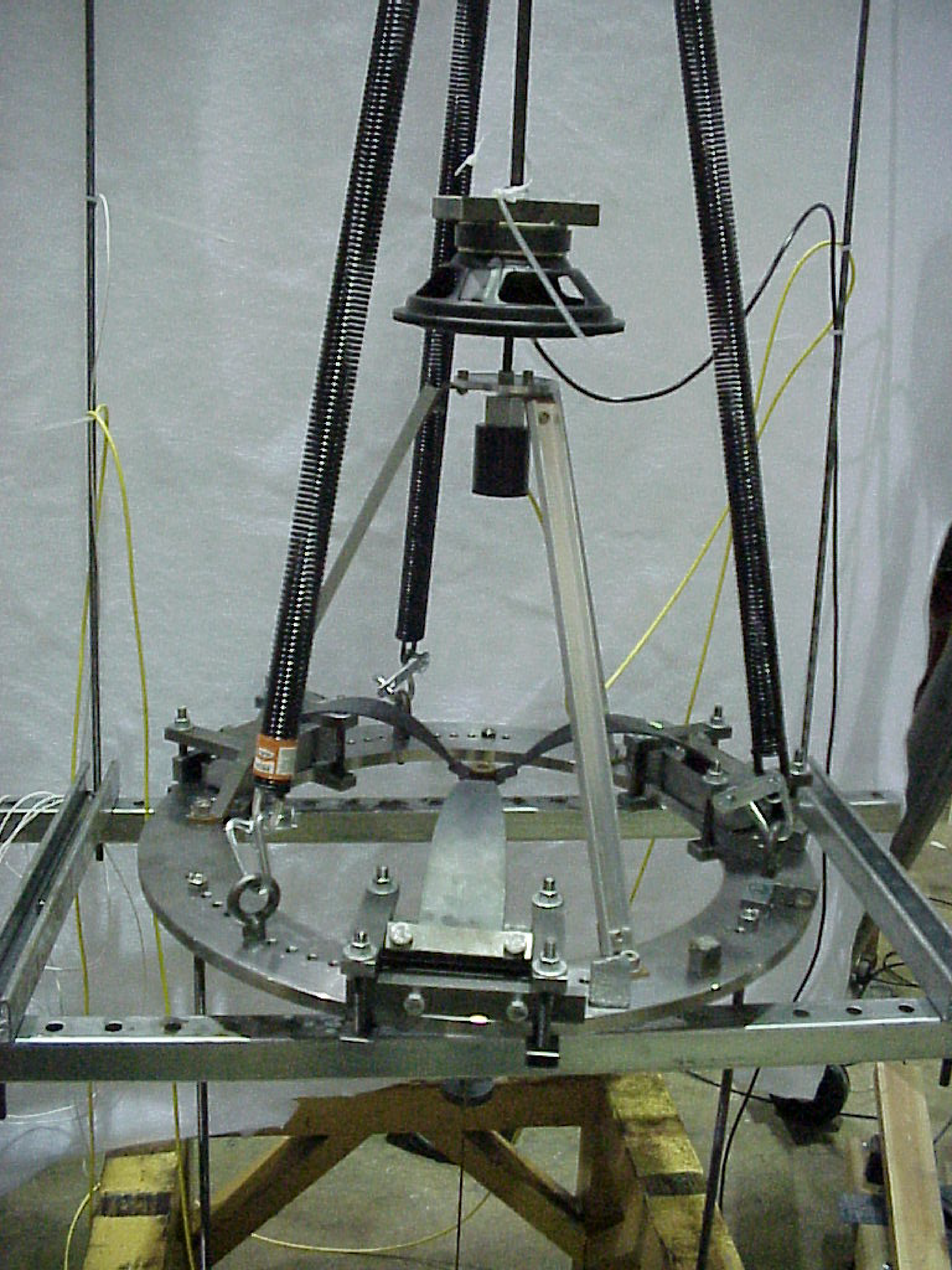


Hareem Tariq
Chenyang Wang

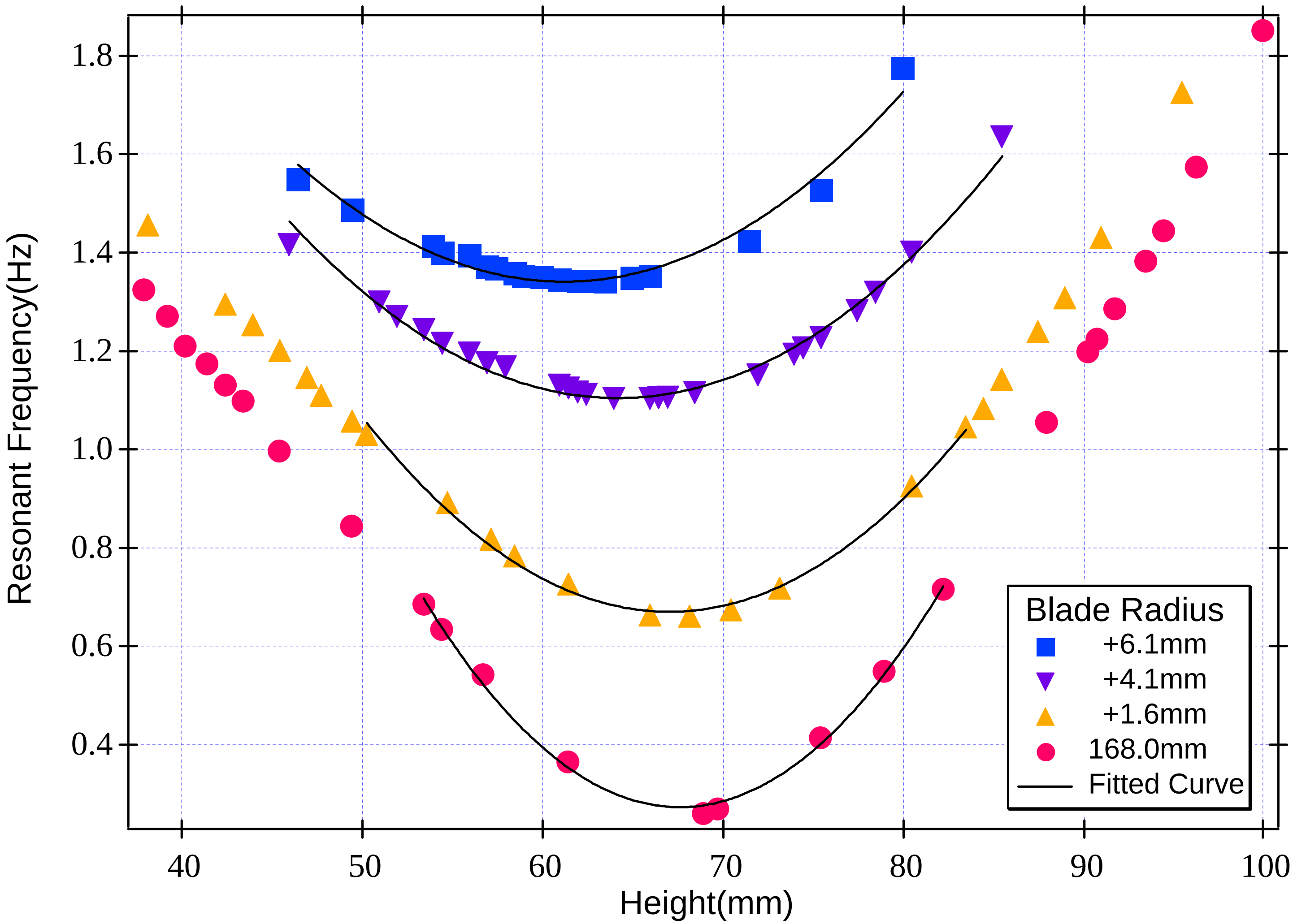


Experimental Setup





Resonant Frequency vs Working Point



LIGO SAS

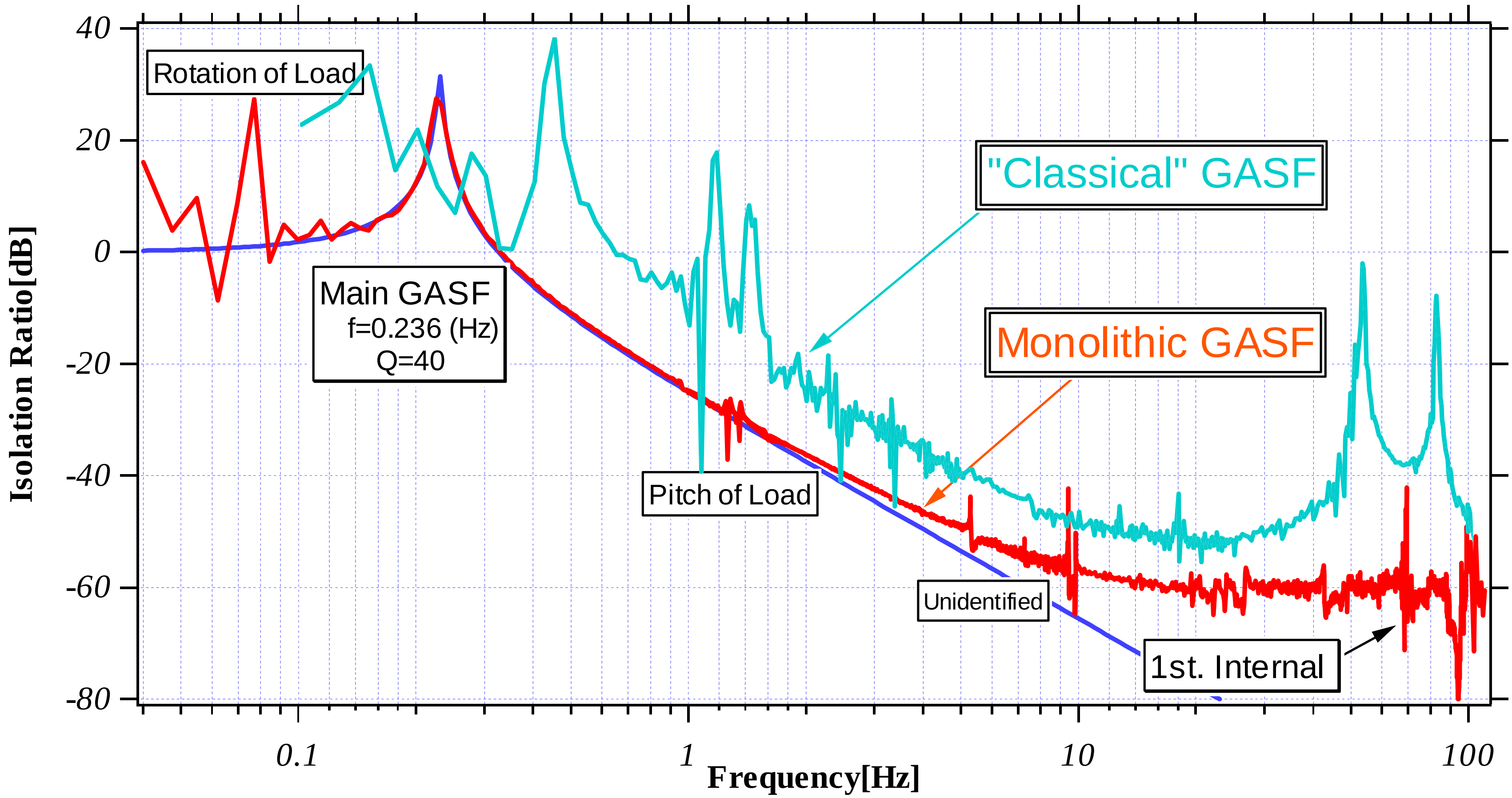
Transfer Function

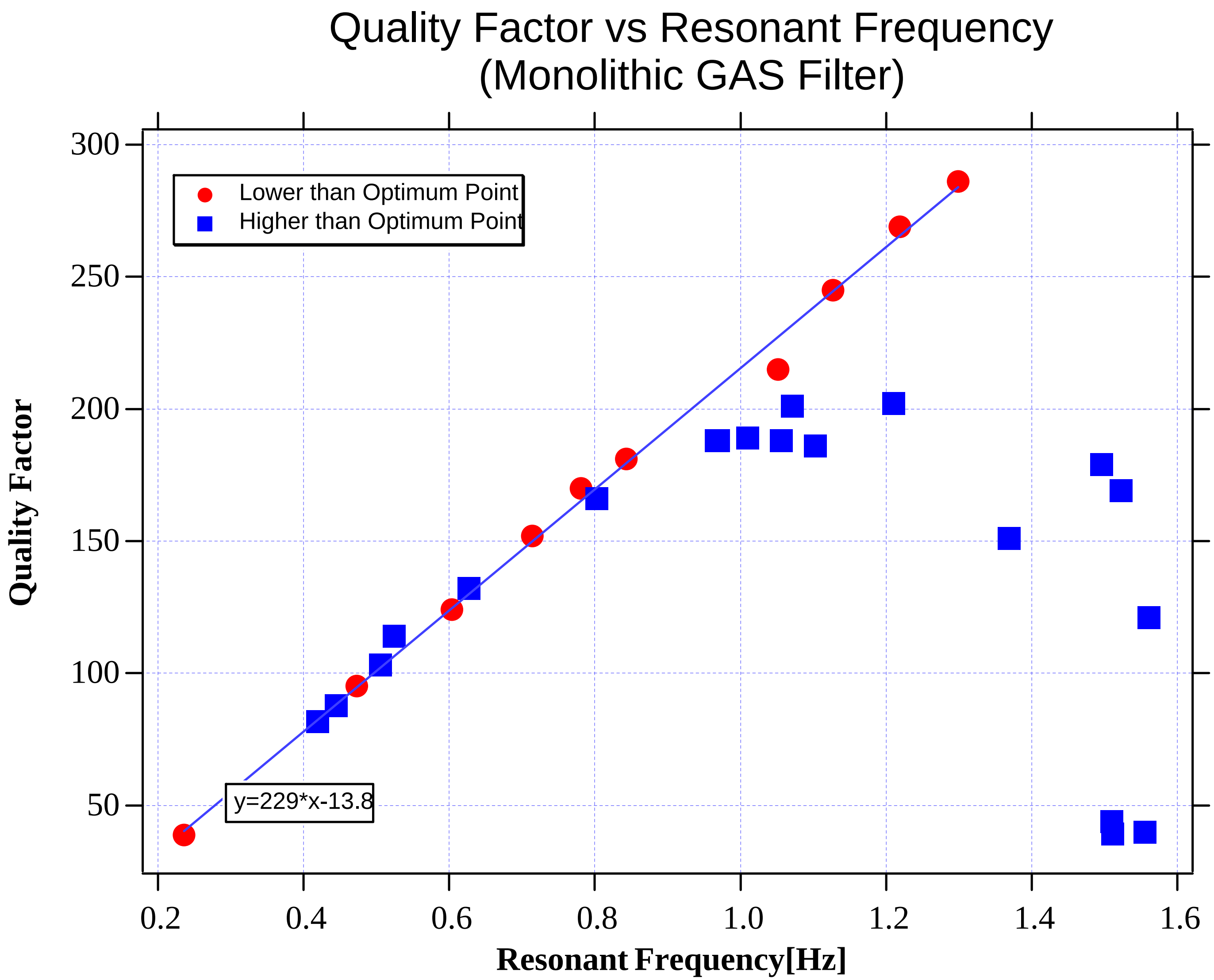
■High Isolation Ratio

- ●~ -60dB @10Hz

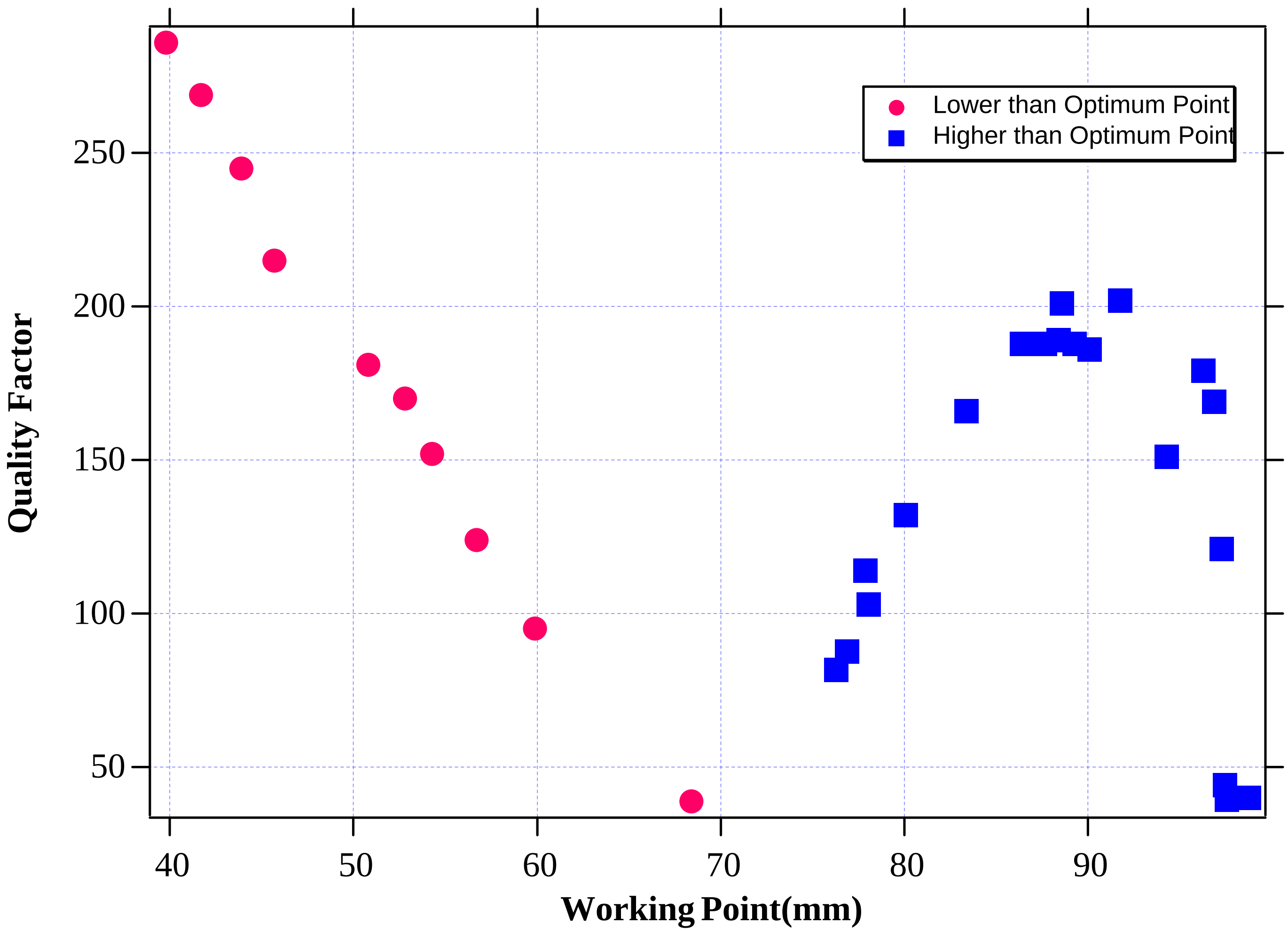
■Internal Mode

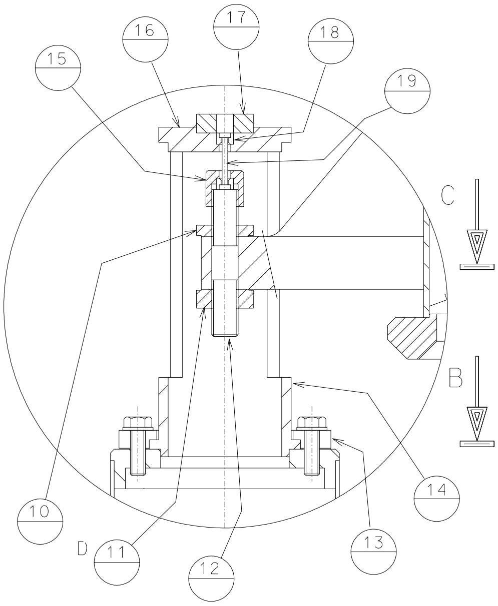
- ●Small Contribution?



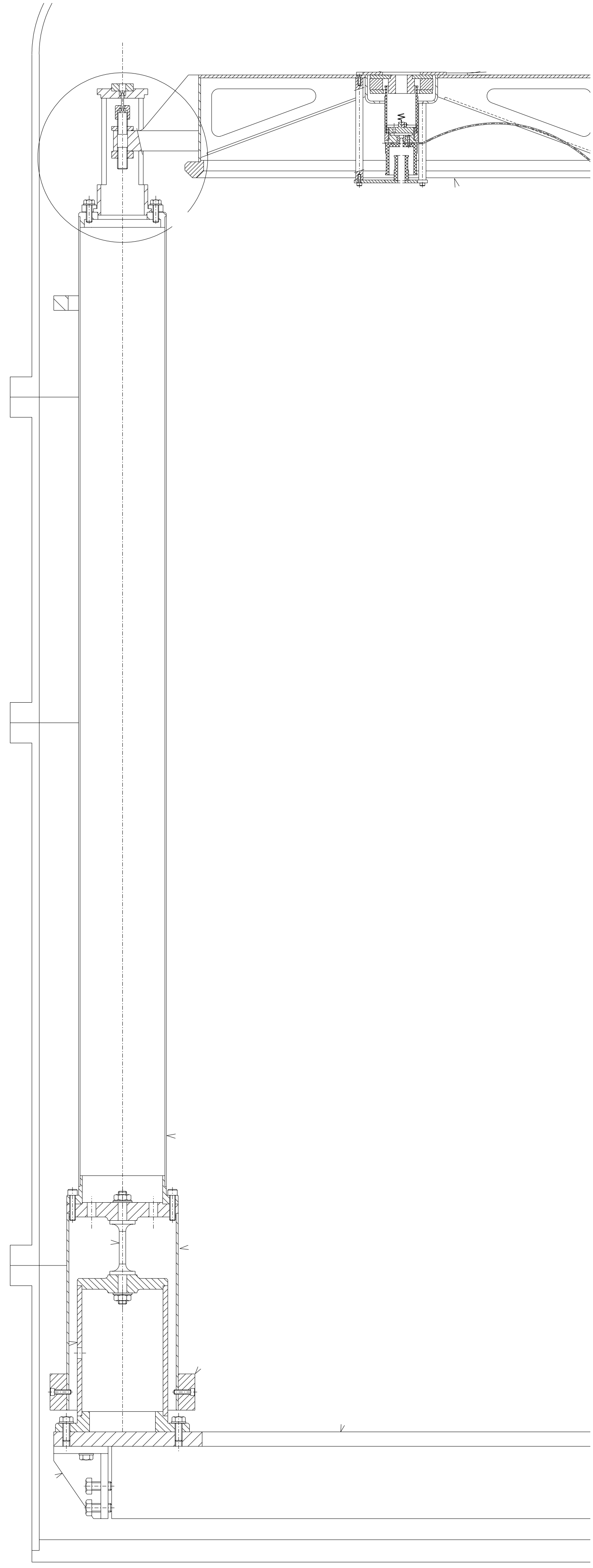

Quality Factor vs Resonant Frequency
(Monolithic GAS Filter)
Lower than Optimum Point
Higher than Optimum Point
y=229*x-13.8
Quality Factor
300
250
200
150
100
50
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Resonant Frequency[Hz]

Quality Factor vs Working Point (Monolithic GAS Filter)

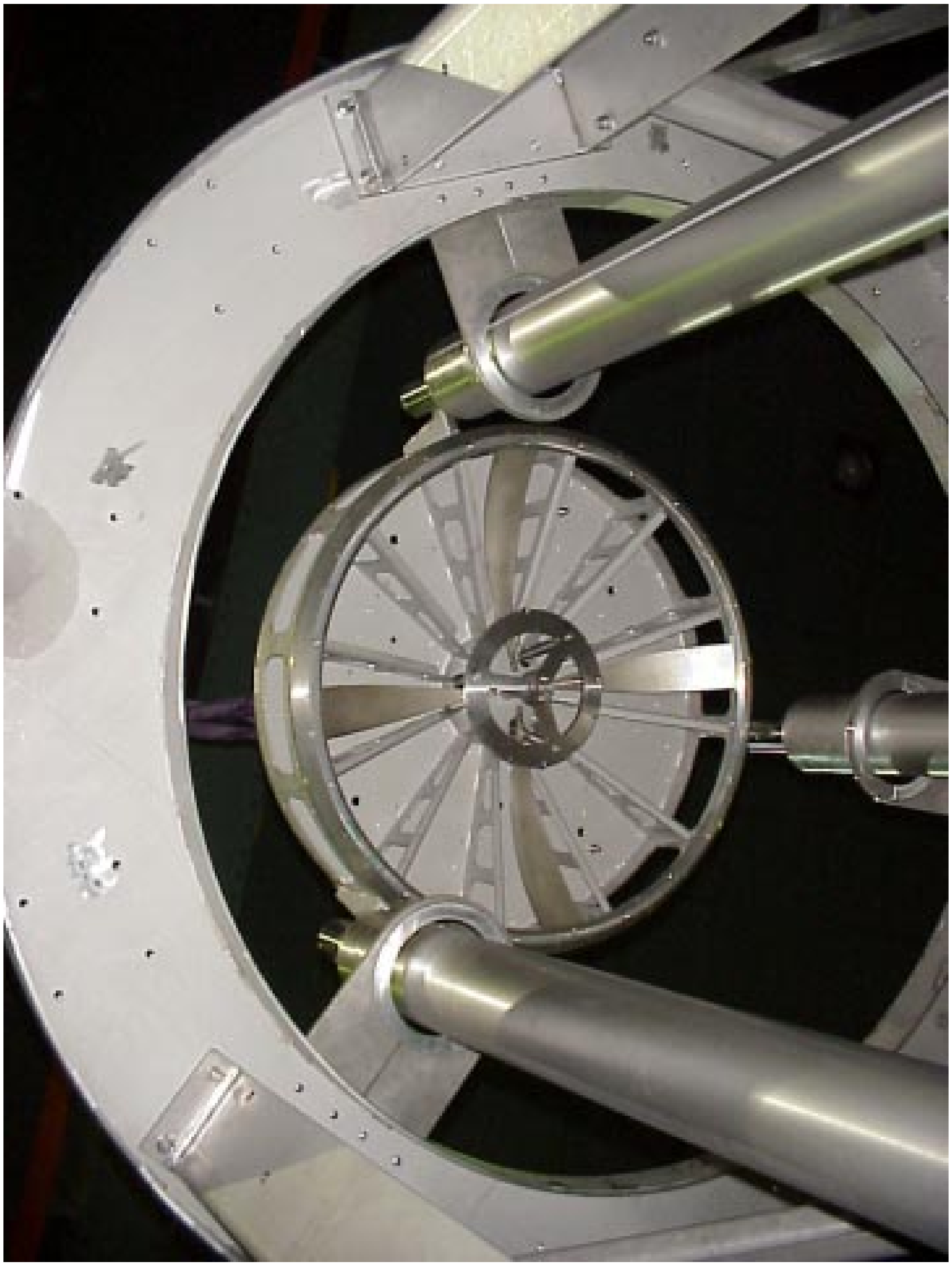


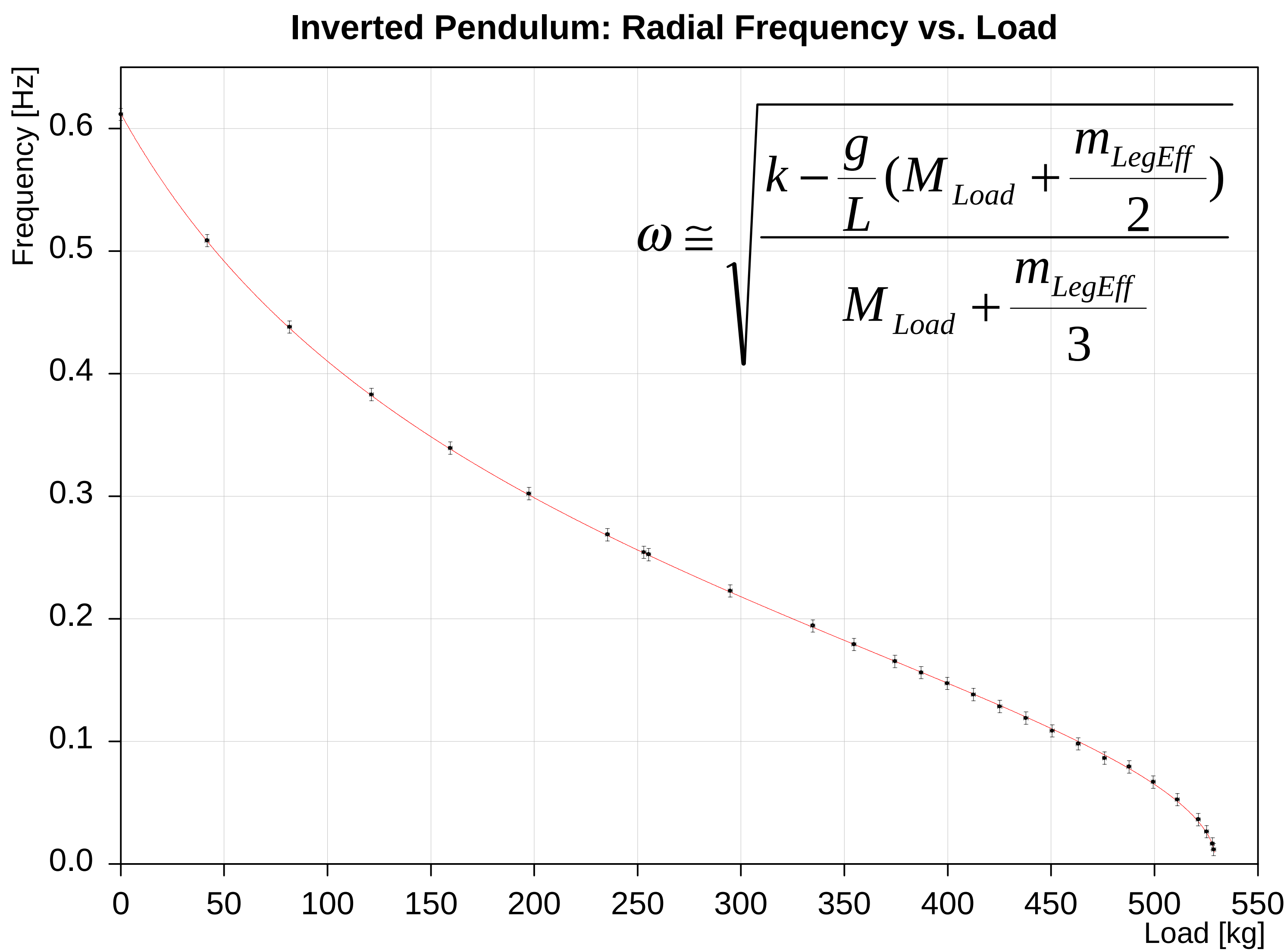


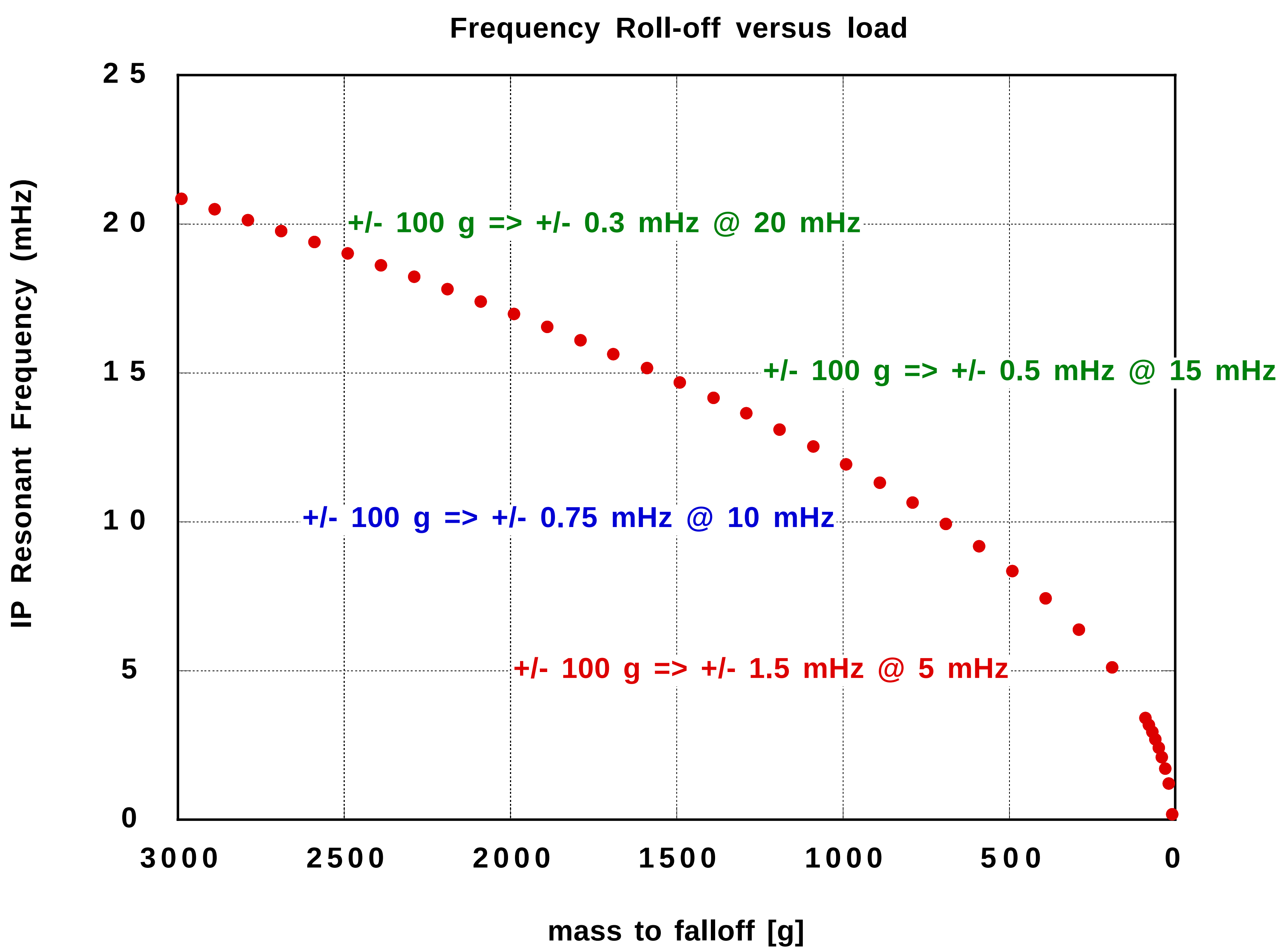
scale 1:2



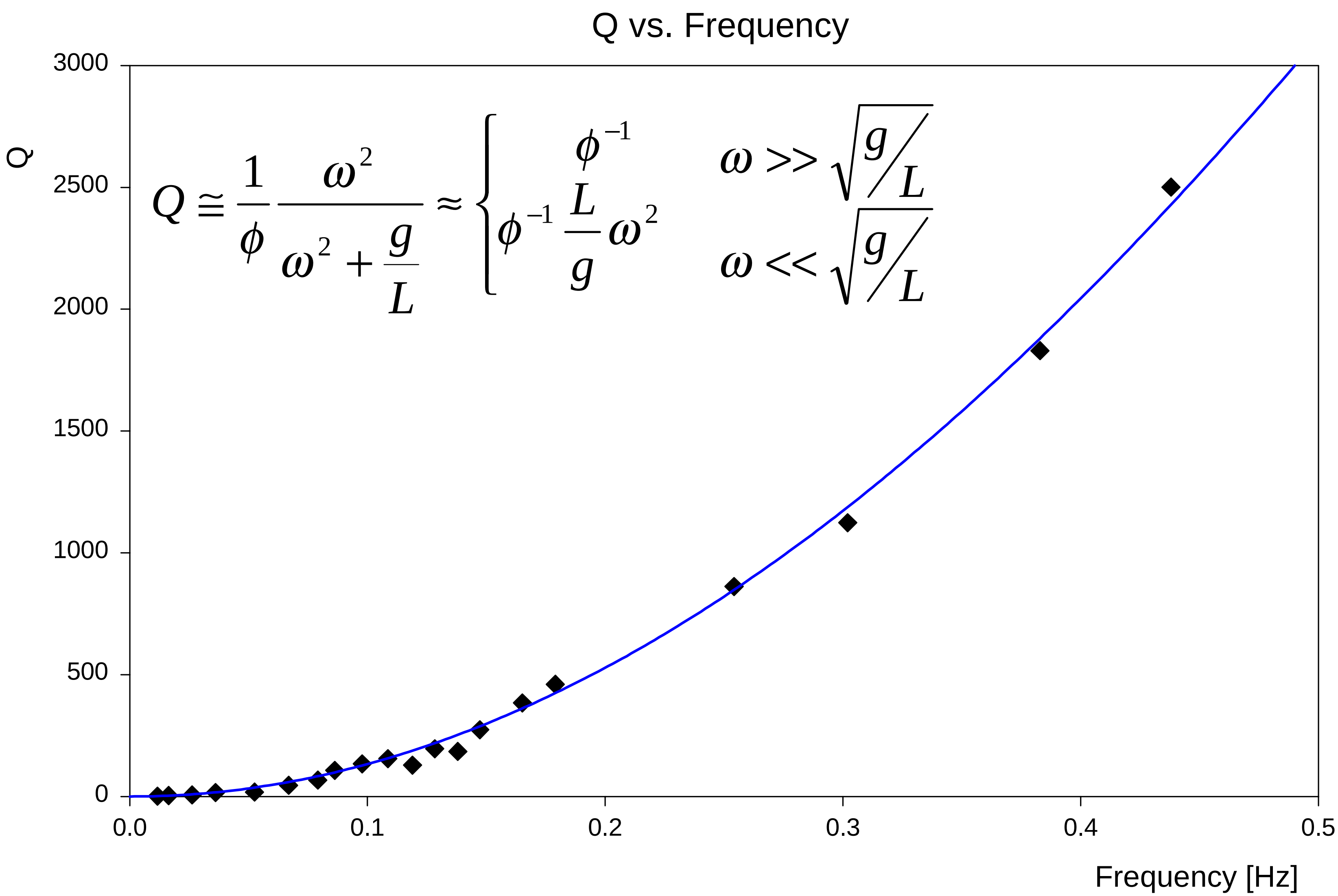
IP Assembly



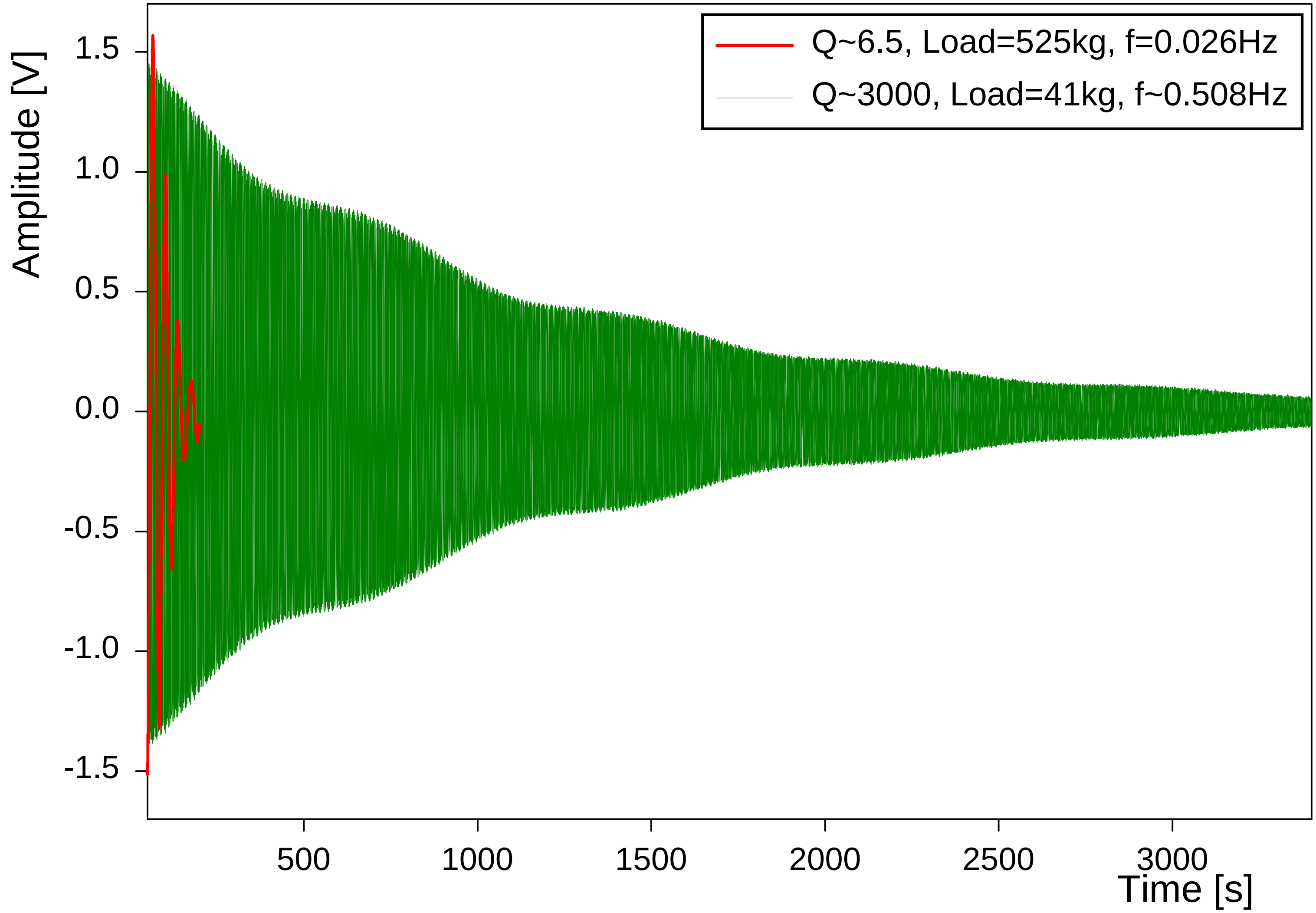

Inverted Pendulum: Radial Frequency vs. Load
Frequency [Hz]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
50
100
150
200
250
300
350
400
450
500
550
Load [kg]
$$\omega \cong \sqrt{\frac{k - \frac{g}{L}\left(M_{Load} + \frac{m_{LegEff}}{2}\right)}{M_{Load} + \frac{m_{LegEff}}{3}}}$$

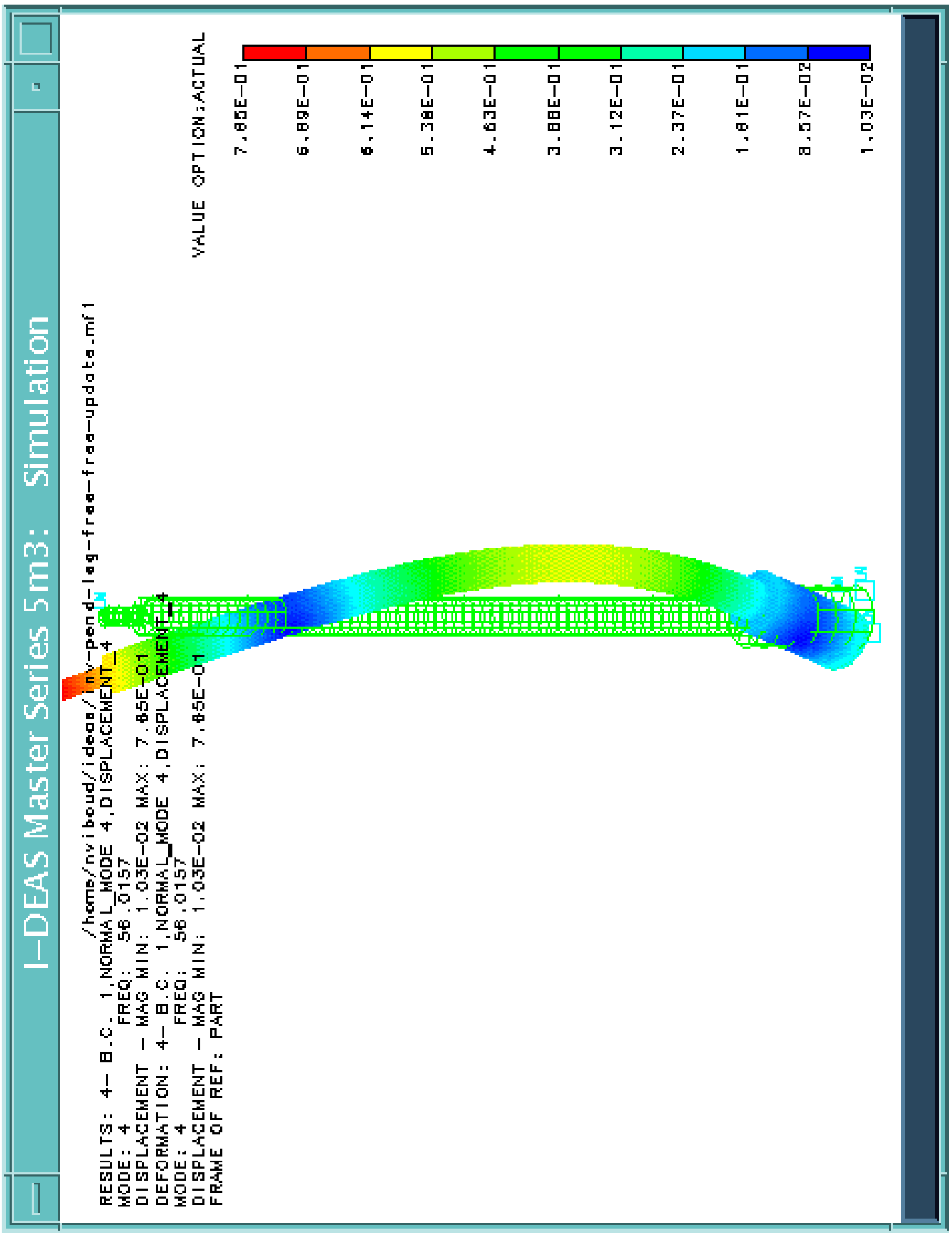


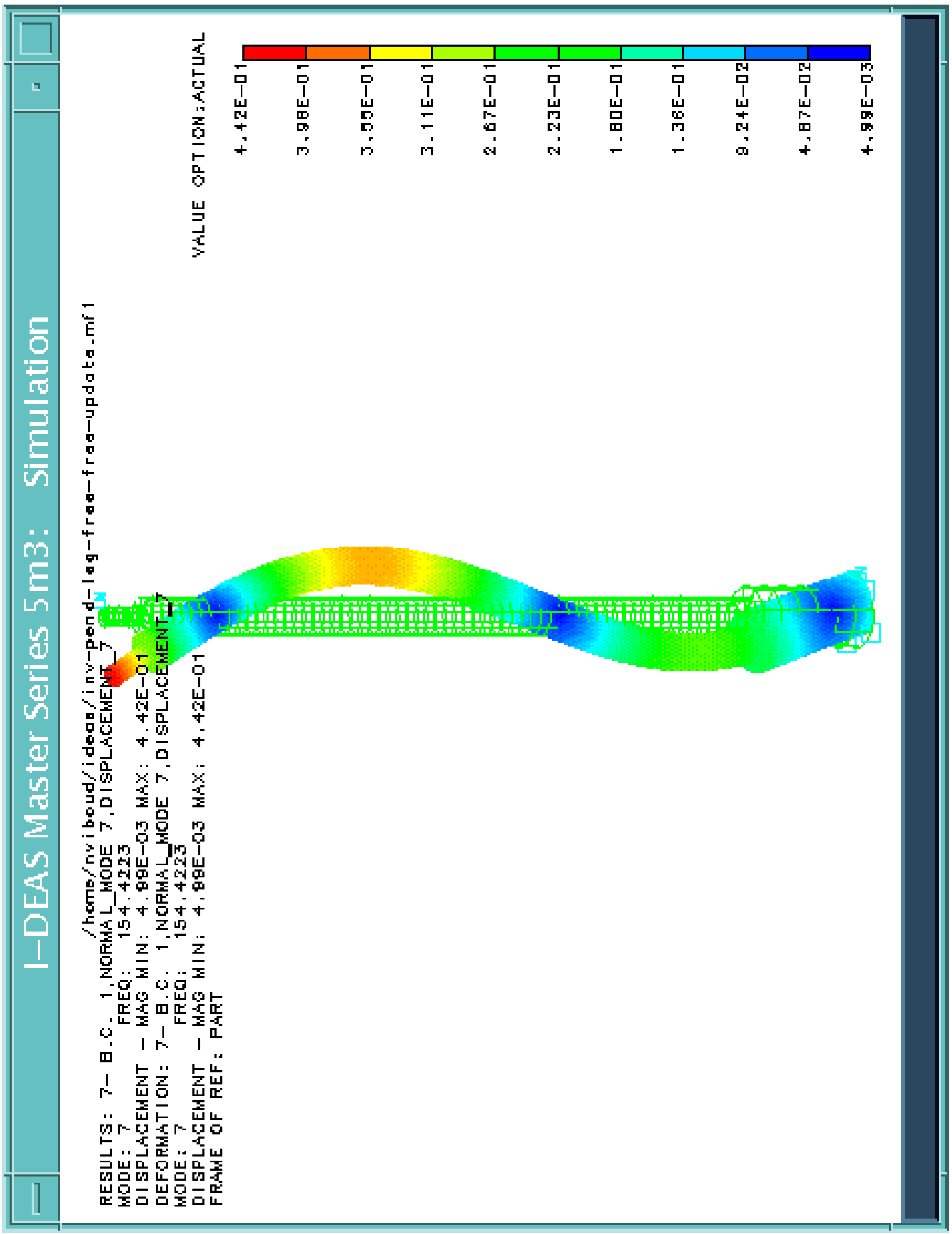
Frequency Roll-off versus load
IP Resonant Frequency (mHz)
25
20
15
10
5
0
+/- 100 g => +/- 0.3 mHz @ 20 mHz
+/- 100 g => +/- 0.5 mHz @ 15 mHz
+/- 100 g => +/- 0.75 mHz @ 10 mHz
+/- 100 g => +/- 1.5 mHz @ 5 mHz
3000
2500
2000
1500
1000
500
0
mass to falloff [g]


Q vs. Frequency
Q
Frequency [Hz]
3000
2500
2000
1500
1000
500
0
0.0
0.1
0.2
0.3
0.4
0.5
$$Q \cong \frac{1}{\phi}\frac{\omega^2}{\omega^2+\frac{g}{L}} \approx \begin{cases} \phi^{-1} & \omega \gg \sqrt{g/L} \\ \phi^{-1}\frac{L}{g}\omega^2 & \omega \ll \sqrt{g/L} \end{cases}$$

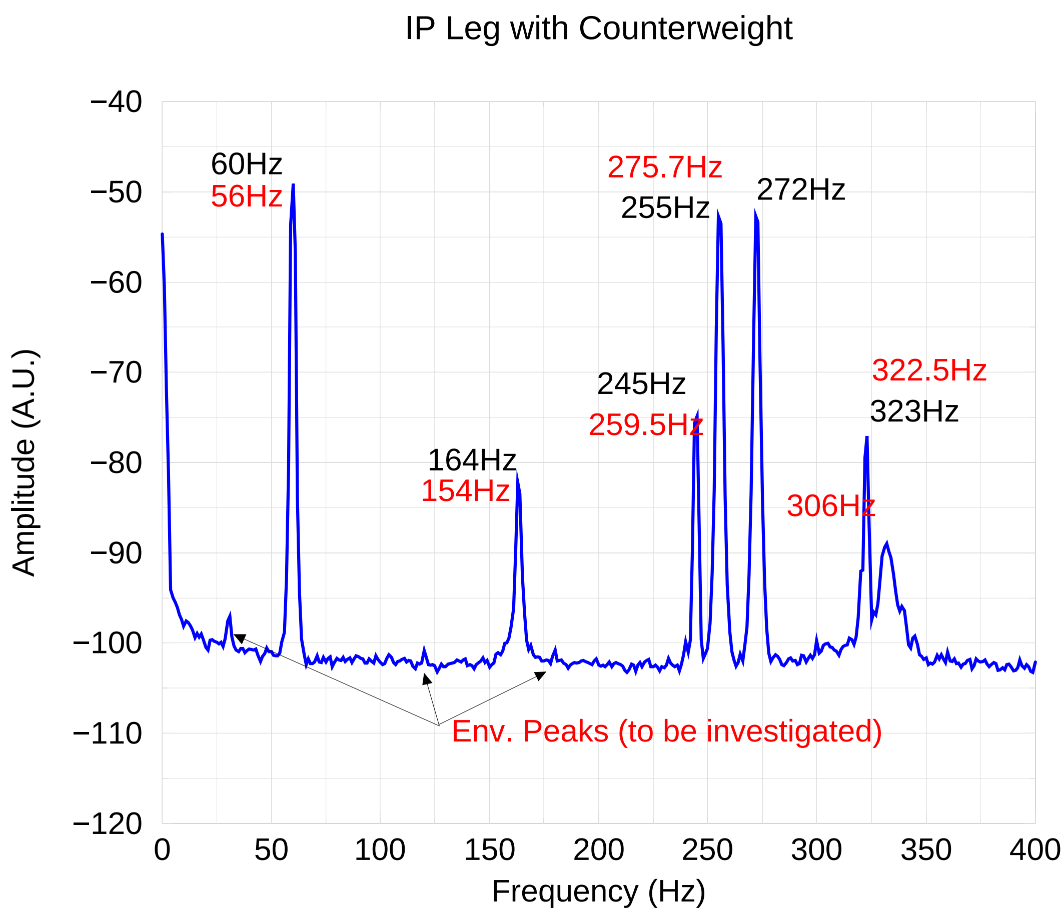
Comparison of High and Low Q Waveforms (Time Domain)



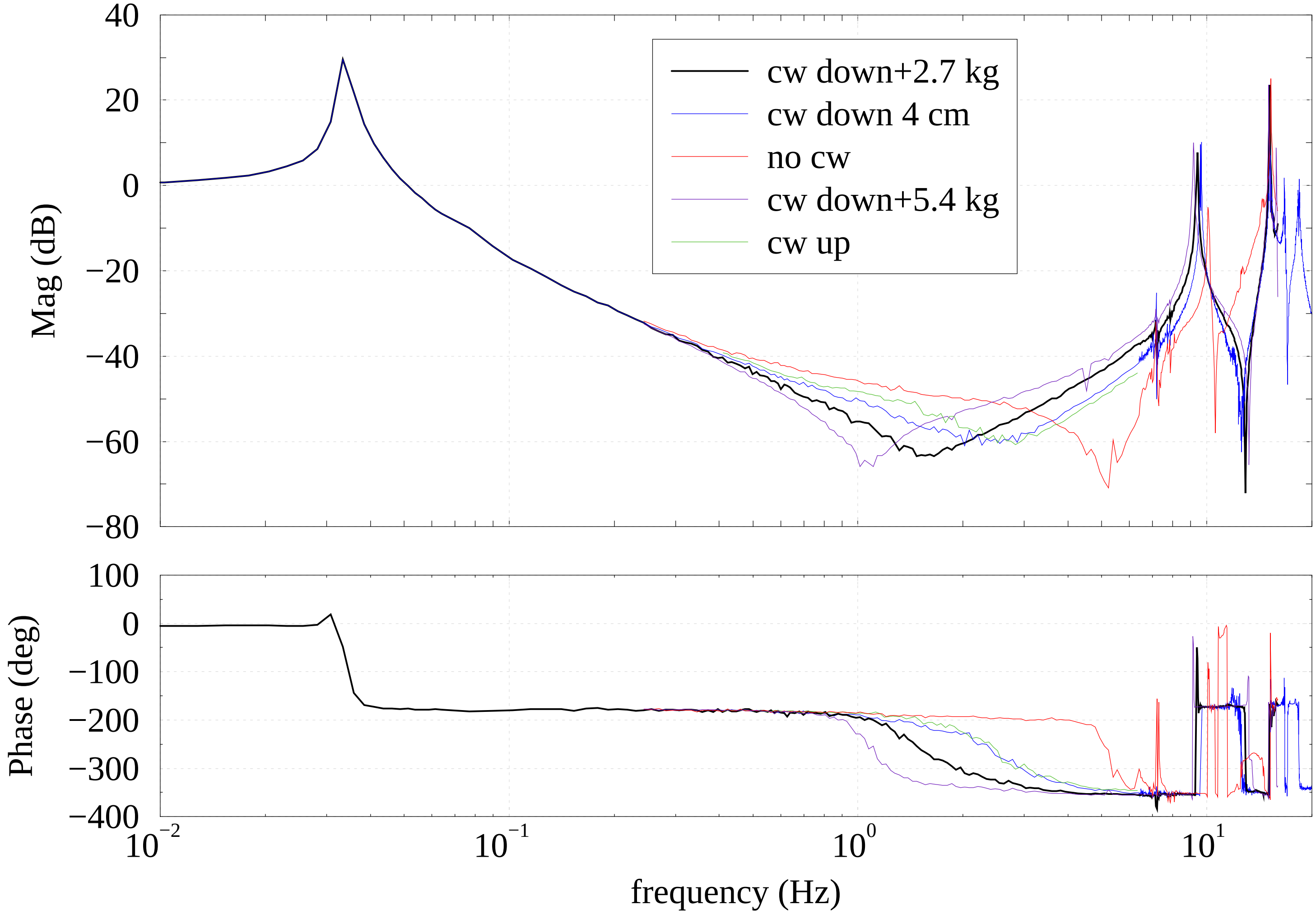

I–DEAS Master Series 5 m3: Simulation
/home/nviboud/ideas/inv-pend-leg-free-free-update.mf1
RESULTS: 4- B.C. 1,NORMAL_MODE 4,DISPLACEMENT_4
MODE: 4 FREQ: 56.0157
DISPLACEMENT - MAG MIN: 1.03E-02 MAX: 7.85E-01
DEFORMATION: 4- B.C. 1,NORMAL_MODE 4,DISPLACEMENT_4
MODE: 4 FREQ: 56.0157
DISPLACEMENT - MAG MIN: 1.03E-02 MAX: 7.85E-01
FRAME OF REF: PART
VALUE OPTION:ACTUAL
7.85E-01
6.89E-01
6.14E-01
5.38E-01
4.63E-01
3.88E-01
3.12E-01
2.37E-01
1.61E-01
8.57E-02
1.03E-02


I–DEAS Master Series 5m3: Simulation
/home/nviboud/ideas/inv-pend-leg-free-free-update.mf1
RESULTS: 7- B.C. 1,NORMAL_MODE 7,DISPLACEMENT_7
MODE: 7 FREQ: 154.4223
DISPLACEMENT - MAG MIN: 4.99E-03 MAX: 4.42E-01
DEFORMATION: 7- B.C. 1,NORMAL_MODE 7,DISPLACEMENT_7
MODE: 7 FREQ: 154.4223
DISPLACEMENT - MAG MIN: 4.99E-03 MAX: 4.42E-01
FRAME OF REF: PART
VALUE OPTION:ACTUAL
4.42E-01
3.98E-01
3.55E-01
3.11E-01
2.67E-01
2.23E-01
1.80E-01
1.36E-01
9.24E-02
4.87E-02
4.99E-03

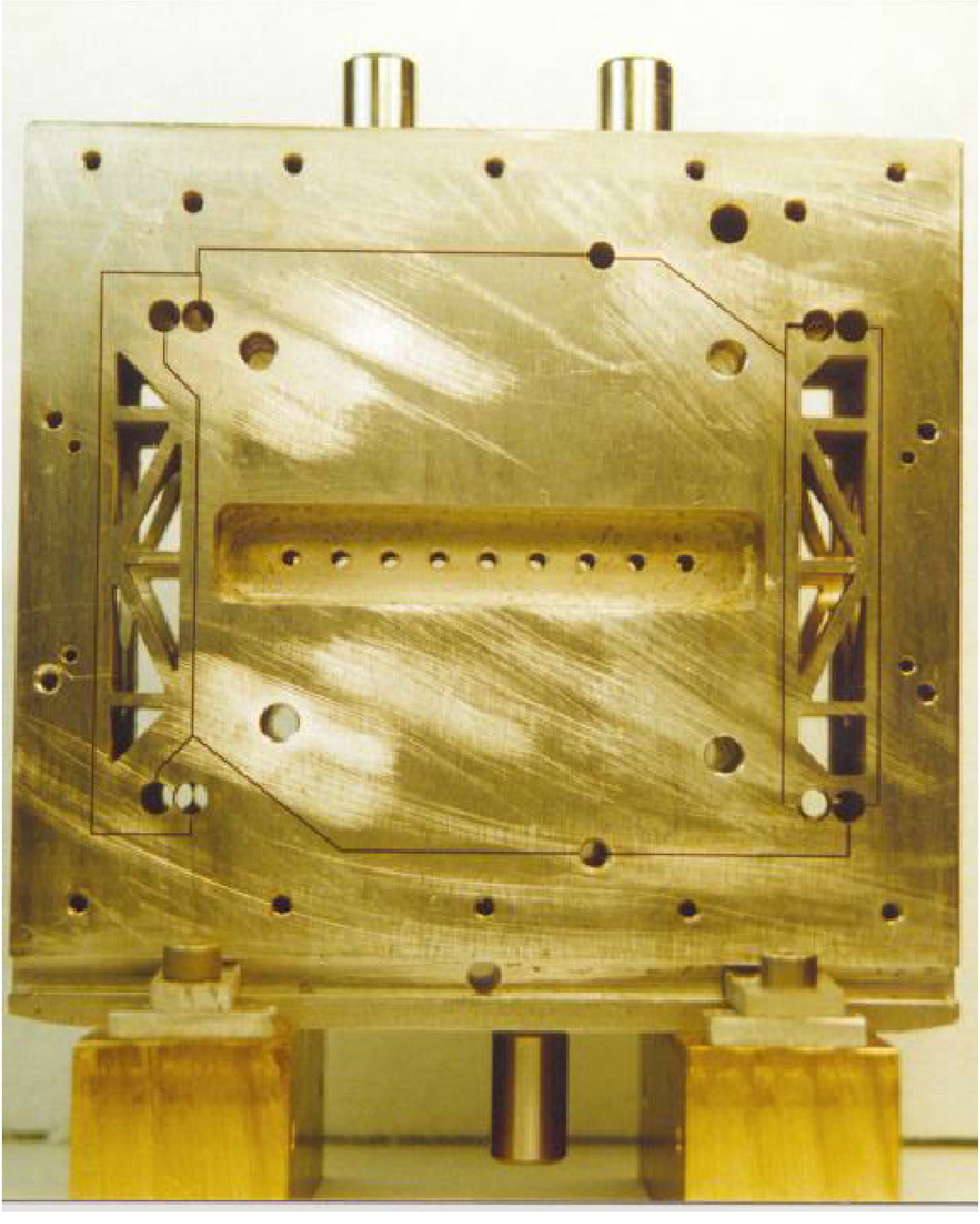
IP Leg + C.W Resonances



272Hz

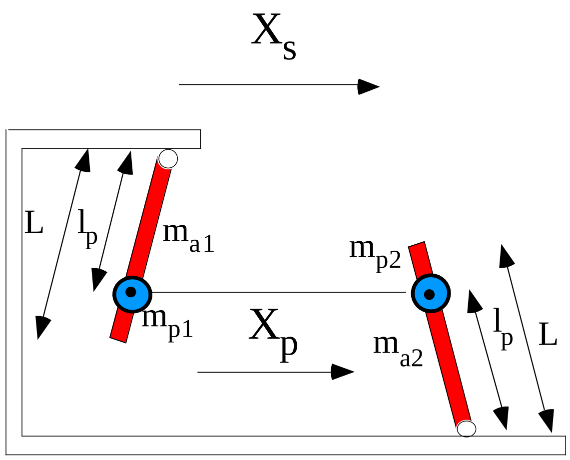


40
20
0
−20
−40
−60
−80
Mag (dB)
cw down+2.7 kg
cw down 4 cm
no cw
cw down+5.4 kg
cw up
100
0
−100
−200
−300
−400
Phase (deg)
10^{-2}
10^{-1}
10^{0}
10^{1}
frequency (Hz)



The folded pendulum

The folded pendulum dynamics:

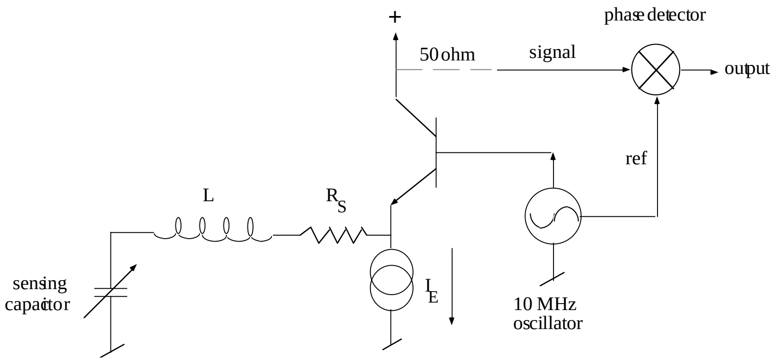


$$\omega_0^2 = \frac{\frac{L}{2l_p}\left(m_{a_1} - m_{a_2}\right) + \left(m_{p_1} - m_{p_2}\right)}{\frac{L^2}{3l_p^2}\left(m_{a_1} + m_{a_2}\right) + \left(m_{p_1} + m_{p_2}\right)} \cdot \frac{g}{l_p} + \gamma$$

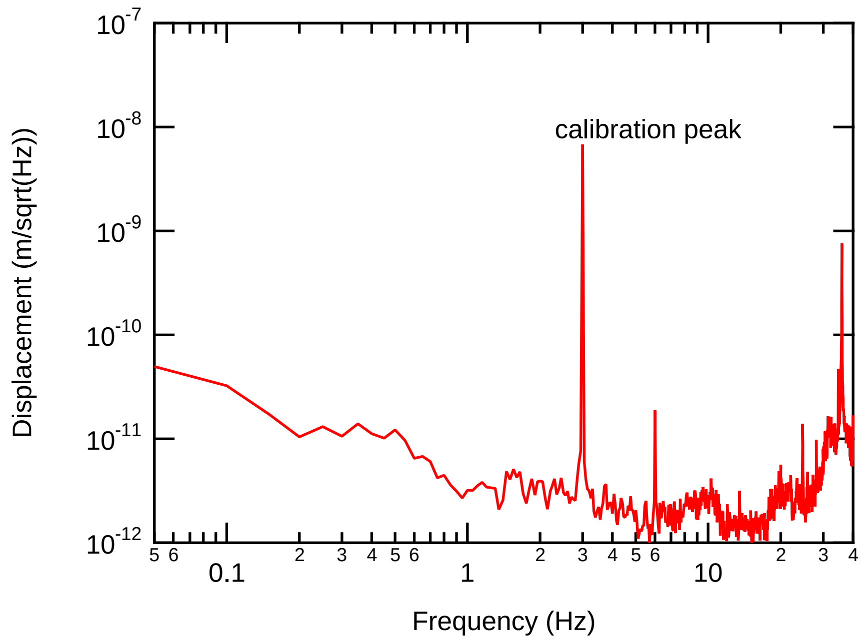
Features:

- low resonant frequency: 0.01–1 Hz
- compactness: arm length less than 10 cm
- low dissipation: gravitational anti-spring effect

Resonant phase shift capacitance sensor



- low losses toroidal inductor: Q ~ 110
- high efficiency passive phase detector
- dynamic range ~ 4 µm
- output gain: 300 mV/ µm



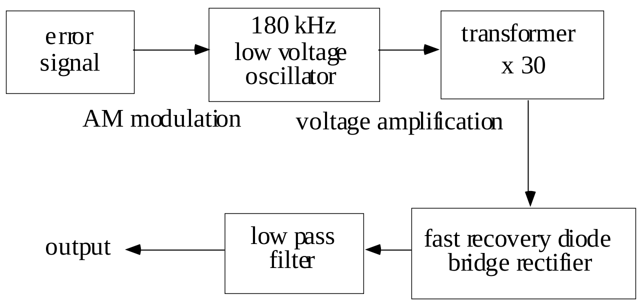
Sensor calibration

The capacitance actuator

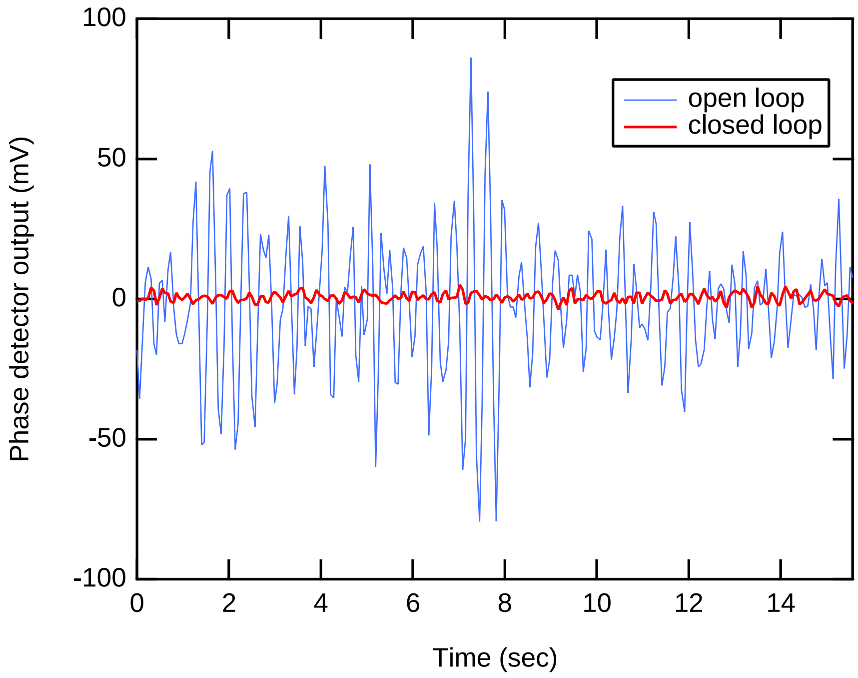
$$F(V_s) = \frac{\varepsilon S}{2d^2} V_0^2 + \frac{\varepsilon S V_0^2}{d^3} \Delta x + \frac{\varepsilon S}{d^2} V_0 V_s$$

- capacitance gap: 250 μm
- gain: 10 μN/Volt
- non–linearity ~ 1% with $V_0 = 100$ V

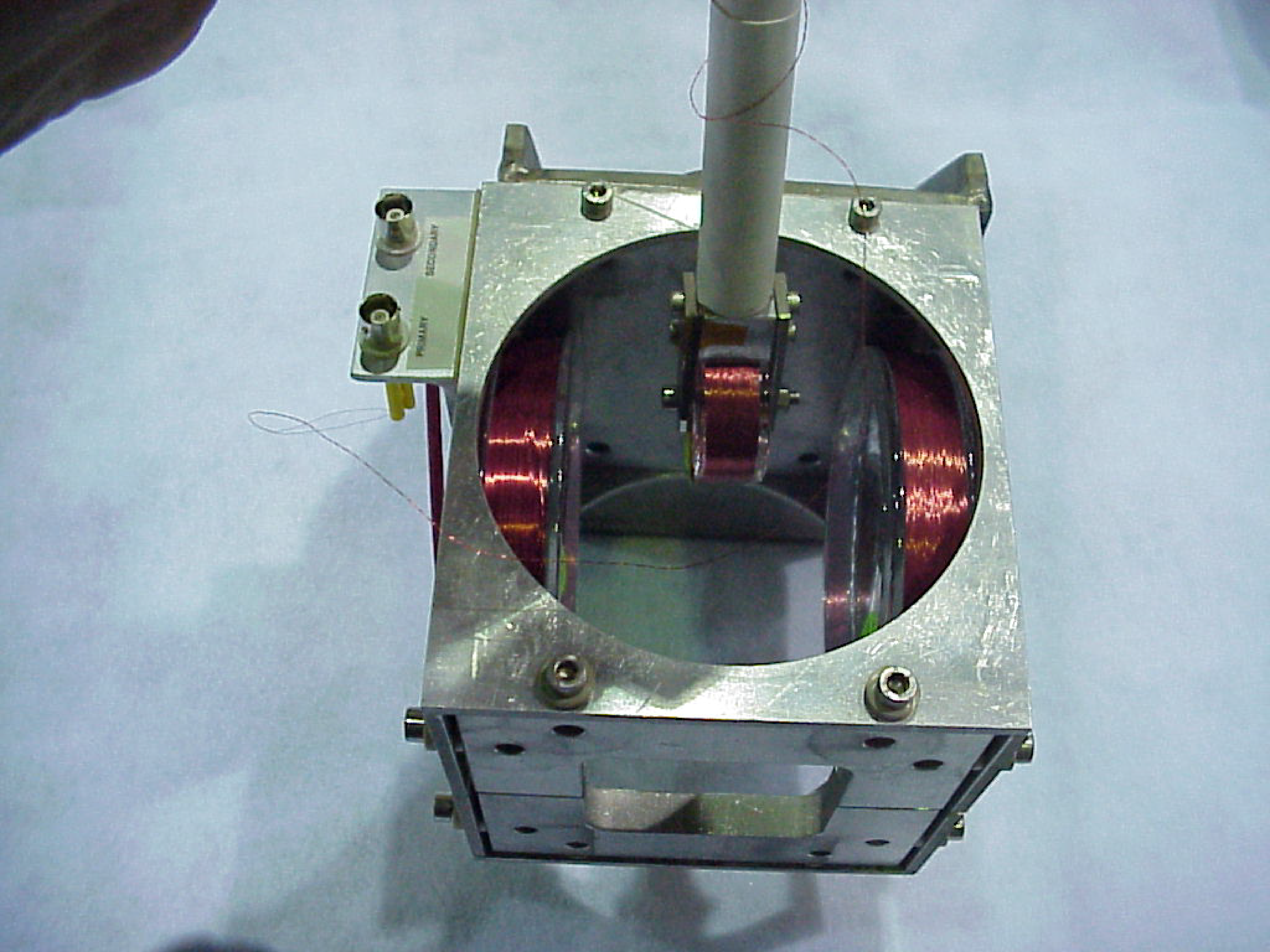
the actuator driver:

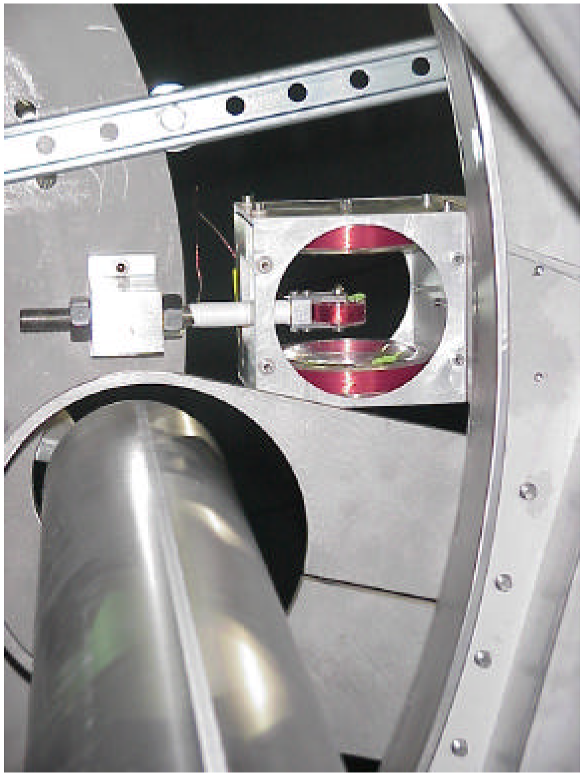


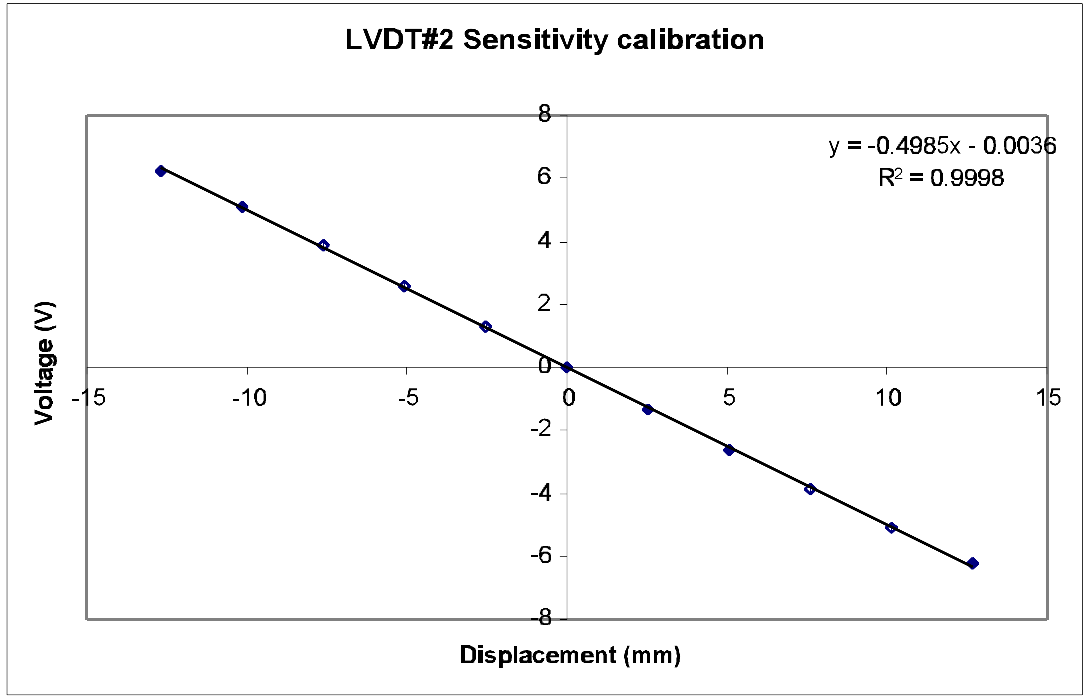
- noise: 5 μV_{p-p} between 0.1 and 1 Hz.

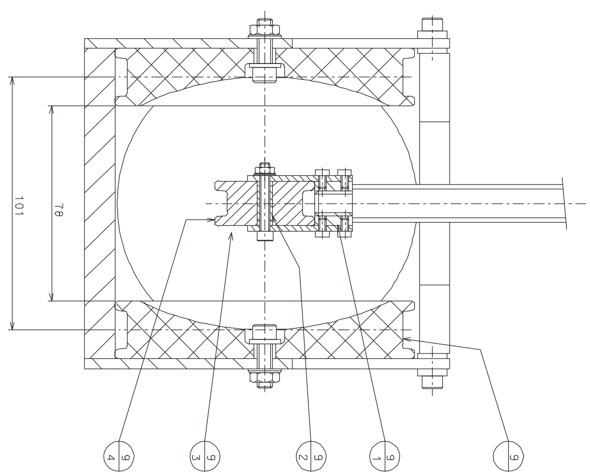


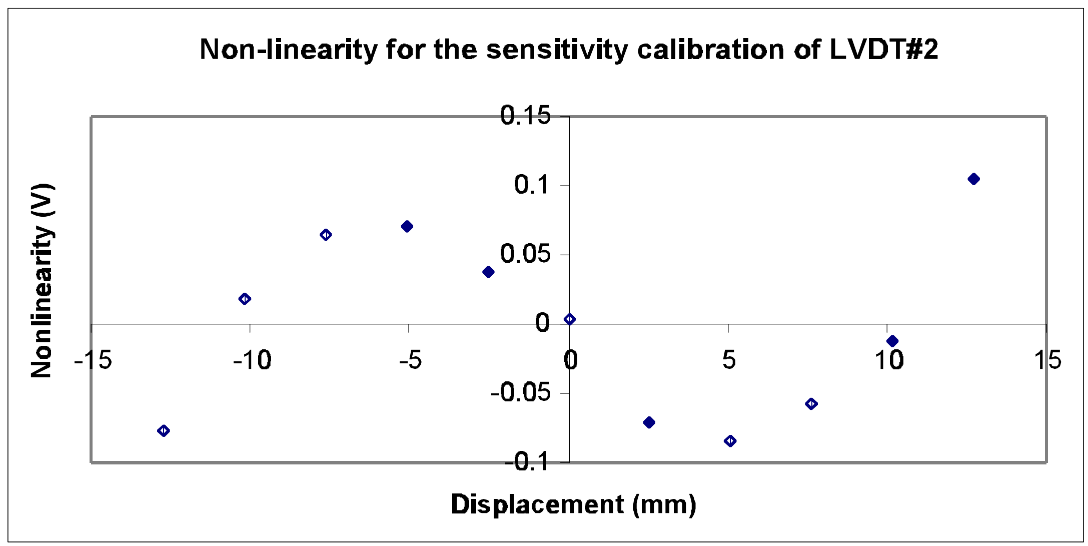
Active control of a 3 Hz resonant inverted pendulum


SECONDARY
PRIMARY









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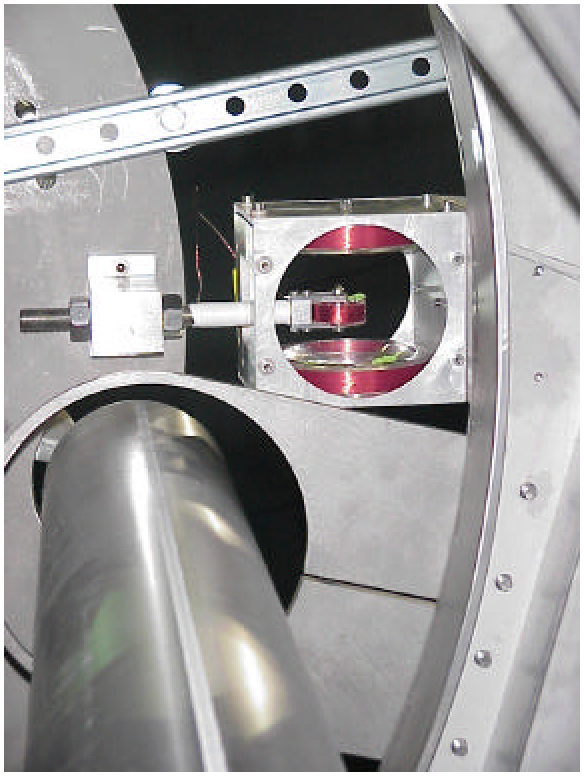
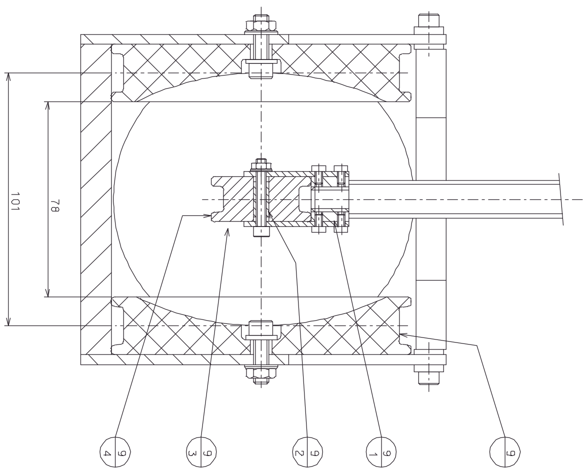
Chenyang Wang

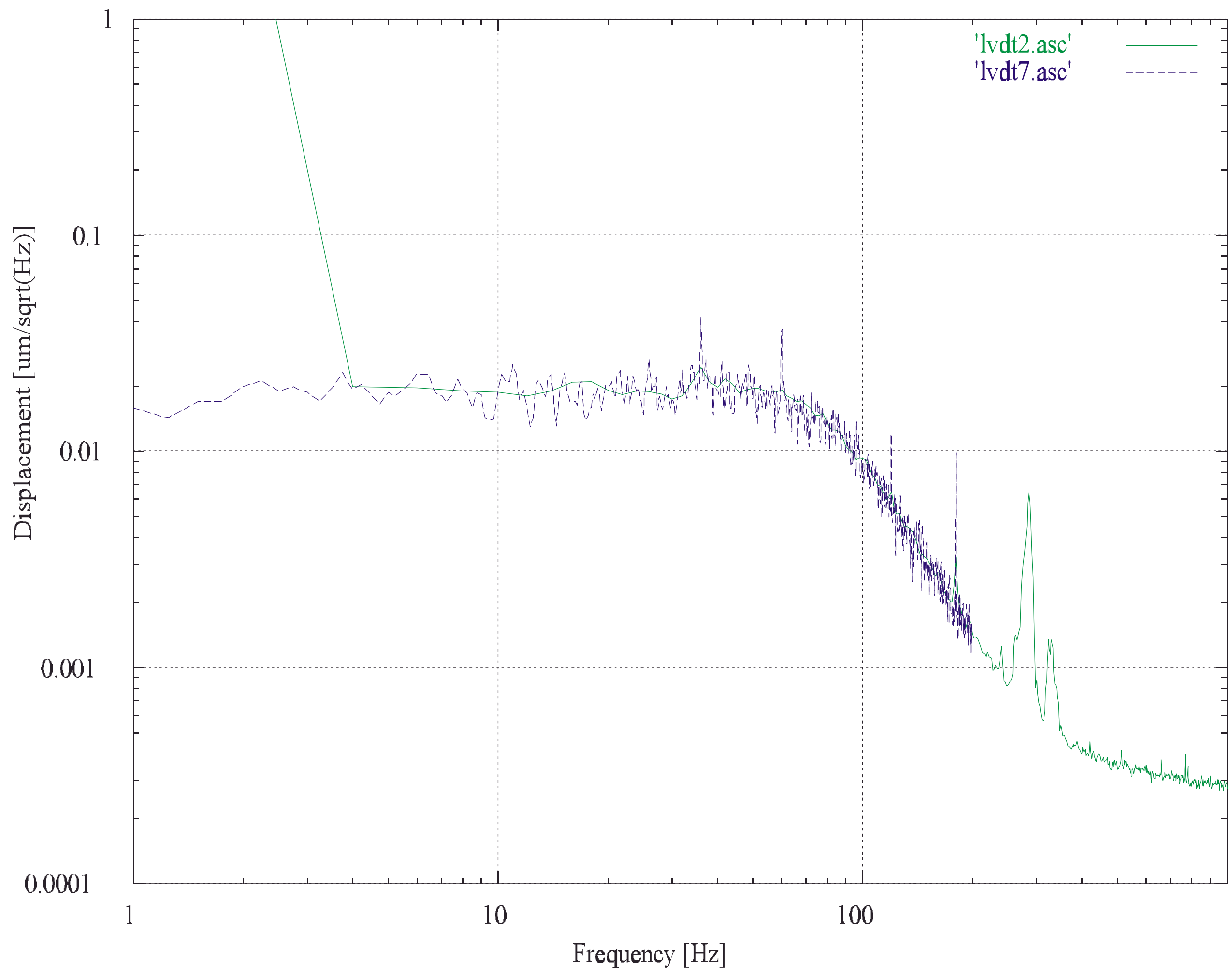
LSC Metting at LLO

03/16/00





Noise Spectra for LVDT #2



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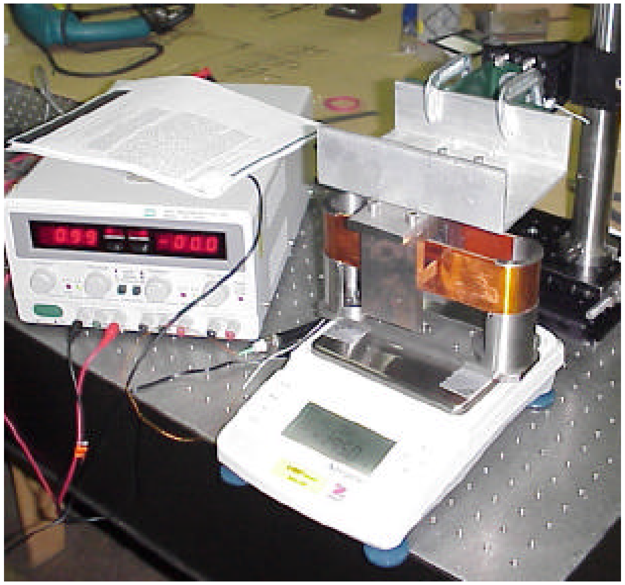
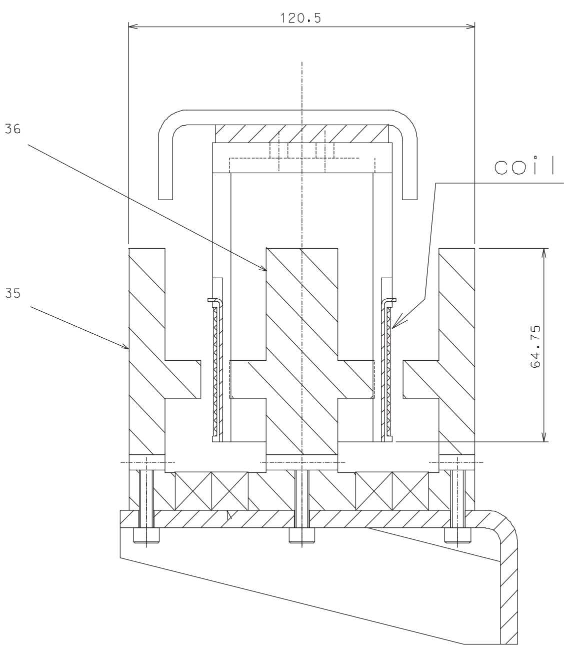
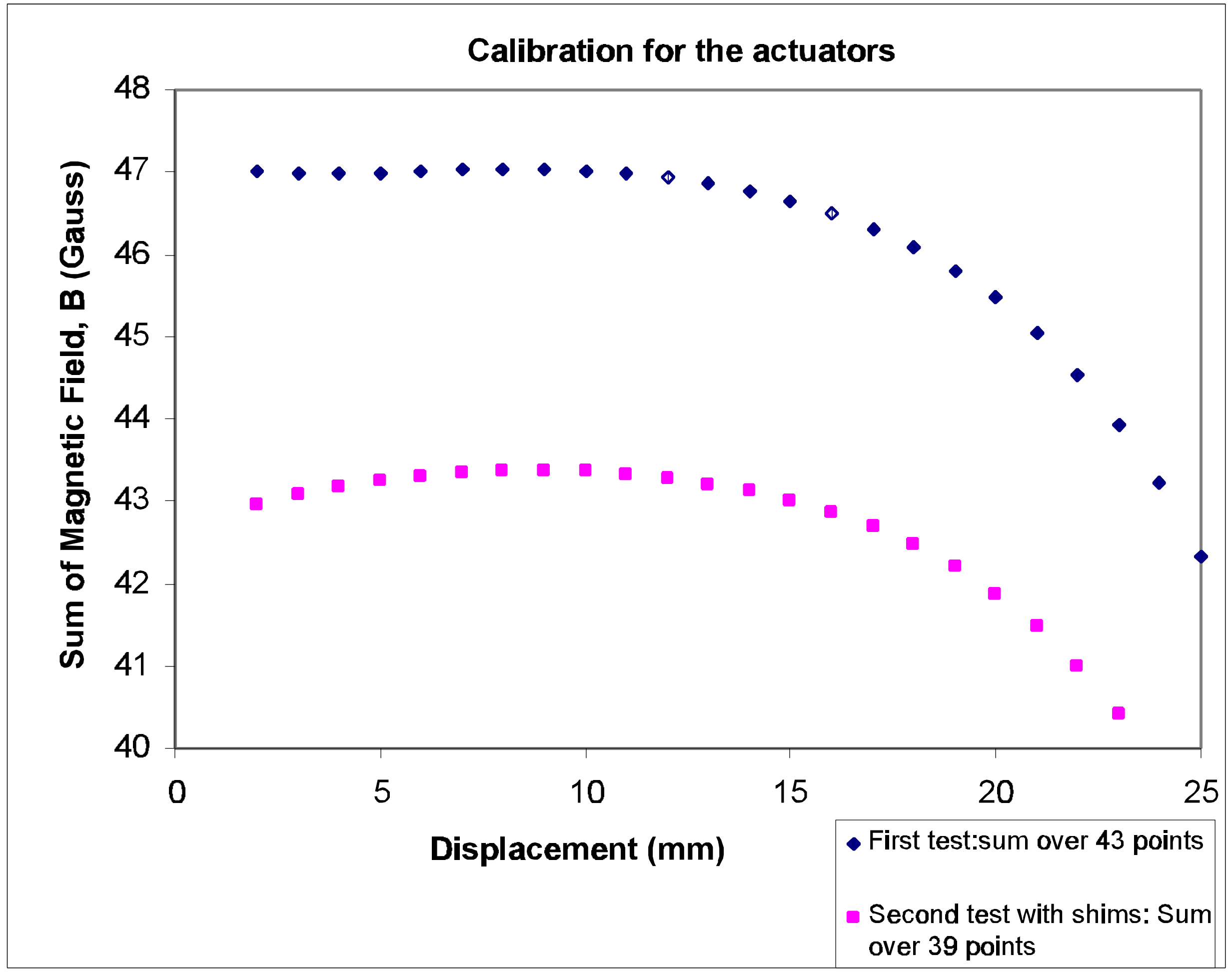
LIGO SAS

LSC Metting at LLO

03/16/00







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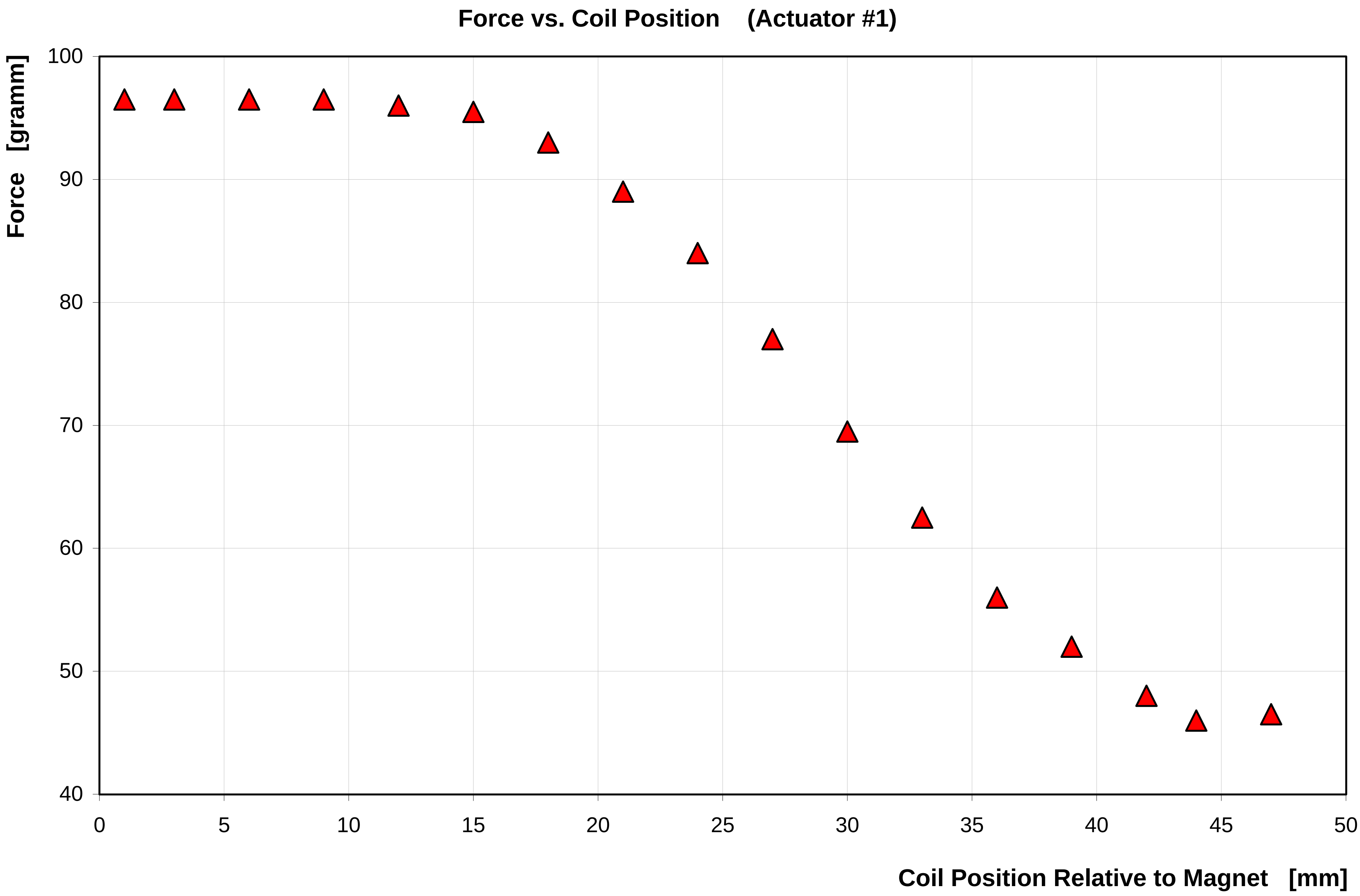

Force vs. Coil Position (Actuator #1)
Force [gramm]
100
90
80
70
60
50
40
0
5
10
15
20
25
30
35
40
45
50
Coil Position Relative to Magnet [mm]

SAS Simulation for LIGO II

1. Overview

- Working Process
- Simulation Tools
- Example

2. Mechanical Simulation Engine (MSE) and SAS Simulation

- Features
- Status
- Demonstration

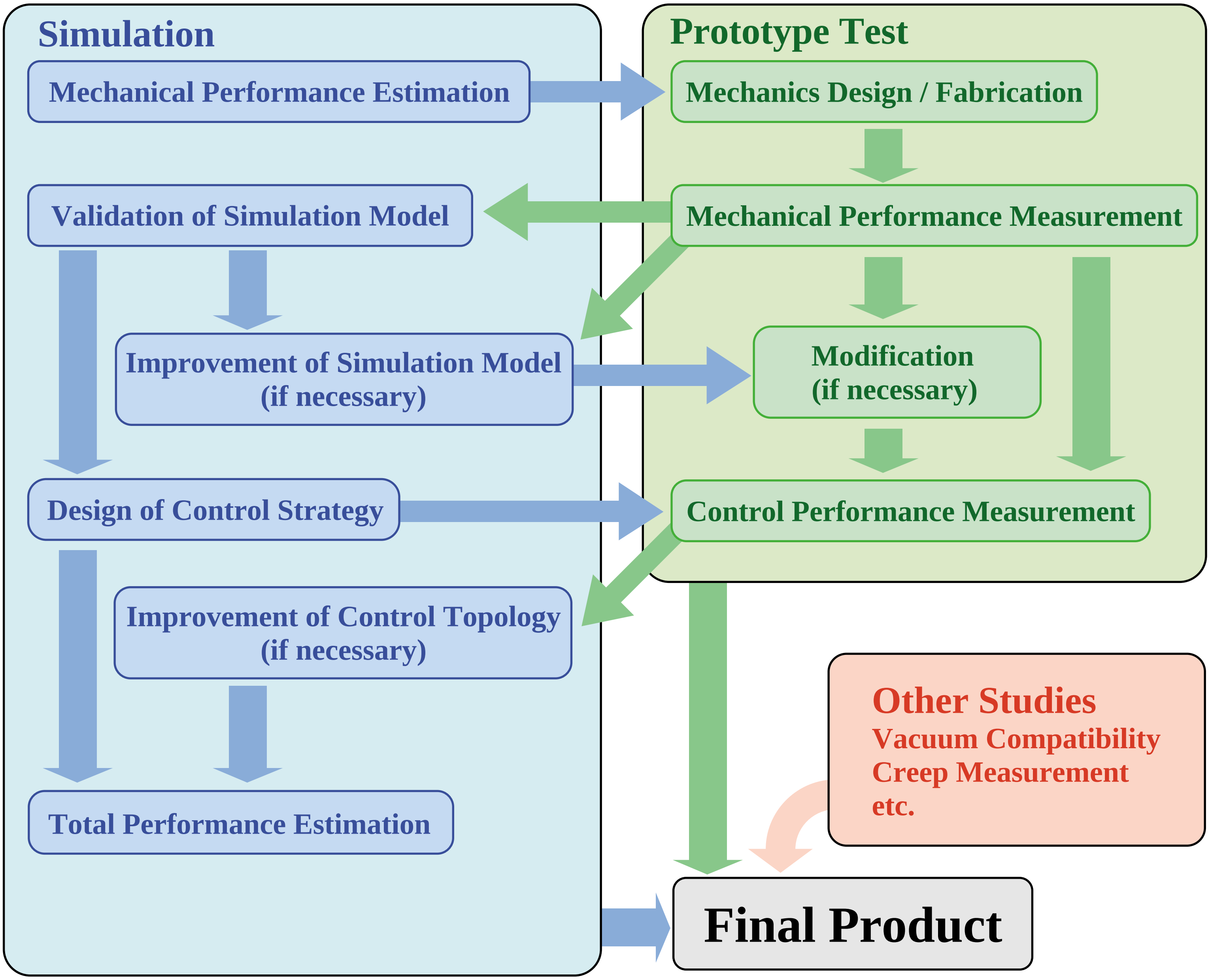
3. Control

- Features
- Example

1. Overview

LIGO SAS

1.1. Working Process



- Close Interaction between Simulations and Measurements

- Performance extrapolation for LIGO II will be done in both simulations and measurements.

1.2. Simulation Tools

MSE - *Mechanical Simulation Engine*

- Mechanics Design

- Performance Study

Mechanical Transfer Function/ Admittance

Control Study: Interface to Other Program (MatLab)

Matlab

- Control Study

Design and Validation of Control

IDEAS, ANSYS *Finite Element Analysis*

- Design of Components

Stress Distribution

Internal Mode

Other Software

- Component Design

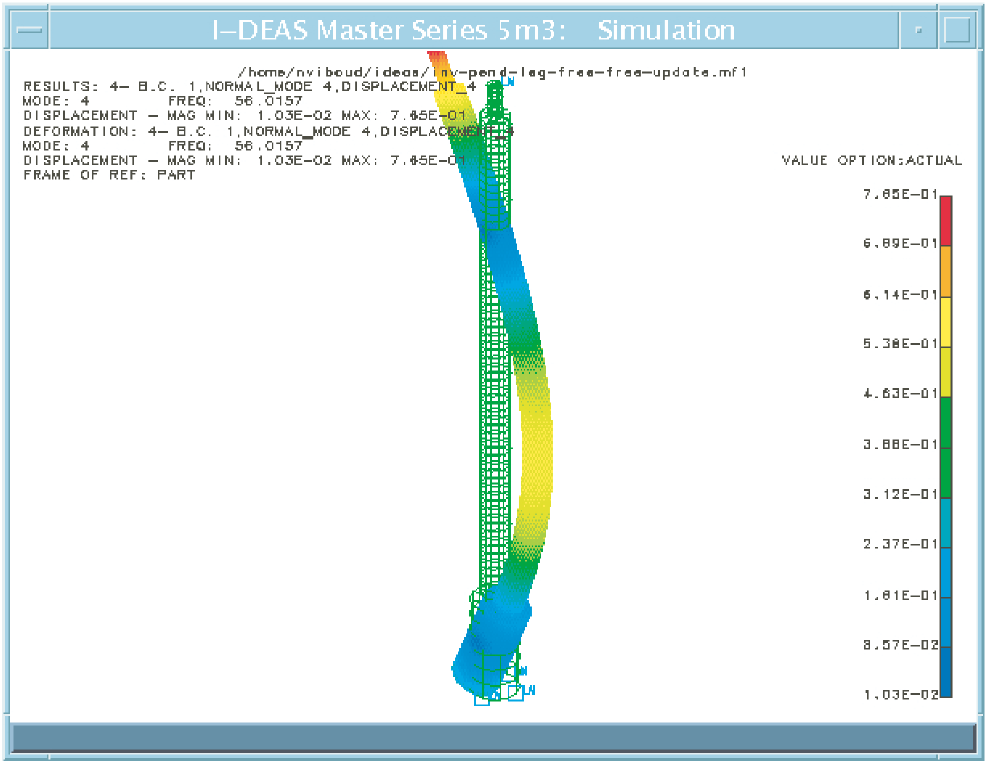
GAS Blade

- Auxiliary Use

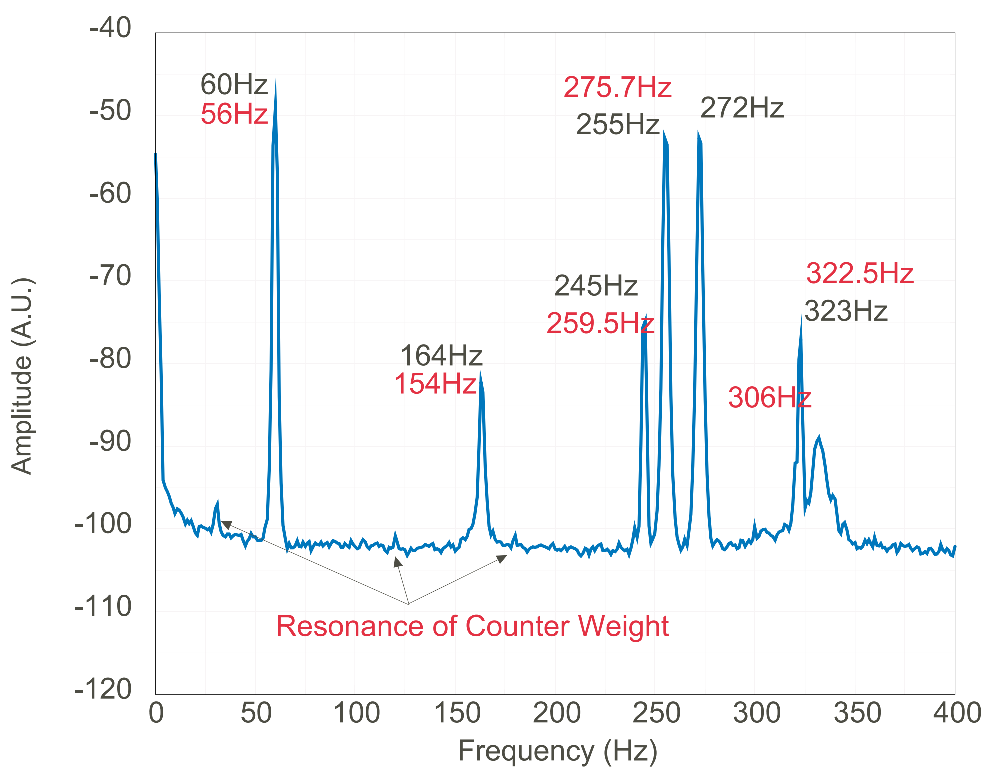
Cross Check of Results from Other Programs

1.2. Example

- Finite Element Analysis

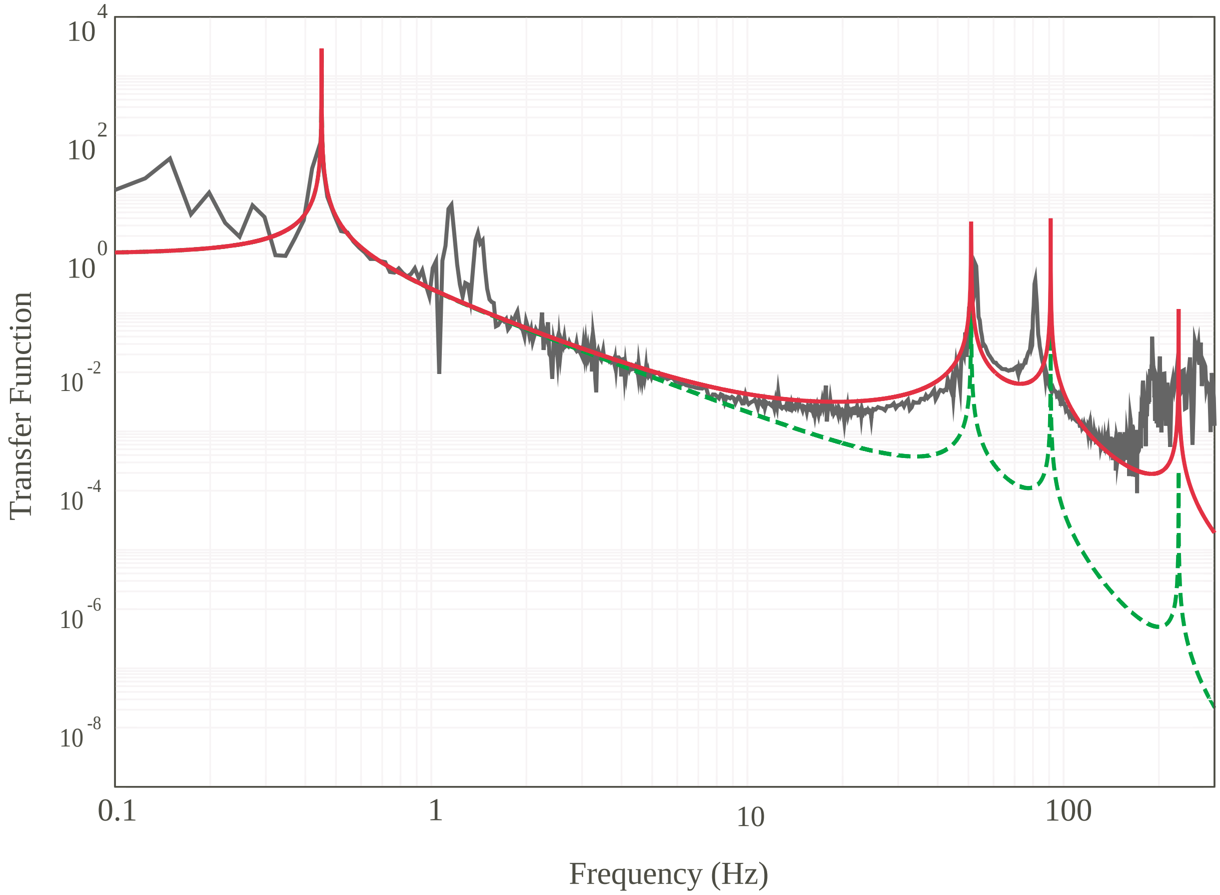


IP Leg with Counterweight



1.2. Example

- Design of GAS Blade



Vertical Transfer Function of a single GASF

2. MSE and SAS Simulation

2.1. Features

Functionality

- **Handle Fully 3D Model**

  Asymmetry in Mechanics

- **Numerical Approach**
- **Frequency / Time Domain Simulation**
- **Computation of Transfer Function / Mechanical Admittance**
- **Control Study**

  Interface to Matlab

- **Internal Resonance**

  Distributed Mass and Elasticity

Object Oriented Architecture

- **Provided as C++ Libraries**
- **Physical Object = C++ Object**

  Rigid Body, Spring, Wire, etc.

- **High Flexibility**

  Modification of Object Classes

  Simple Subsystem >> Complex System Study

Subsystem of LIGO e2e Model

- **Study of Interaction with Interferometers**

2. MSE and SAS Simulation

LIGO SAS

2.2. Working Procedure

Construction of Mechanical System

- Declaration of System
- Declaration of Mechanical Objects
- Connection of Objects

↓

Preparation

- Working Position (Equilibrium) Acquisition
- Linearization of Equation of Motion
  (Computation of Mass, Stiffness, Damping Matrices)

↓

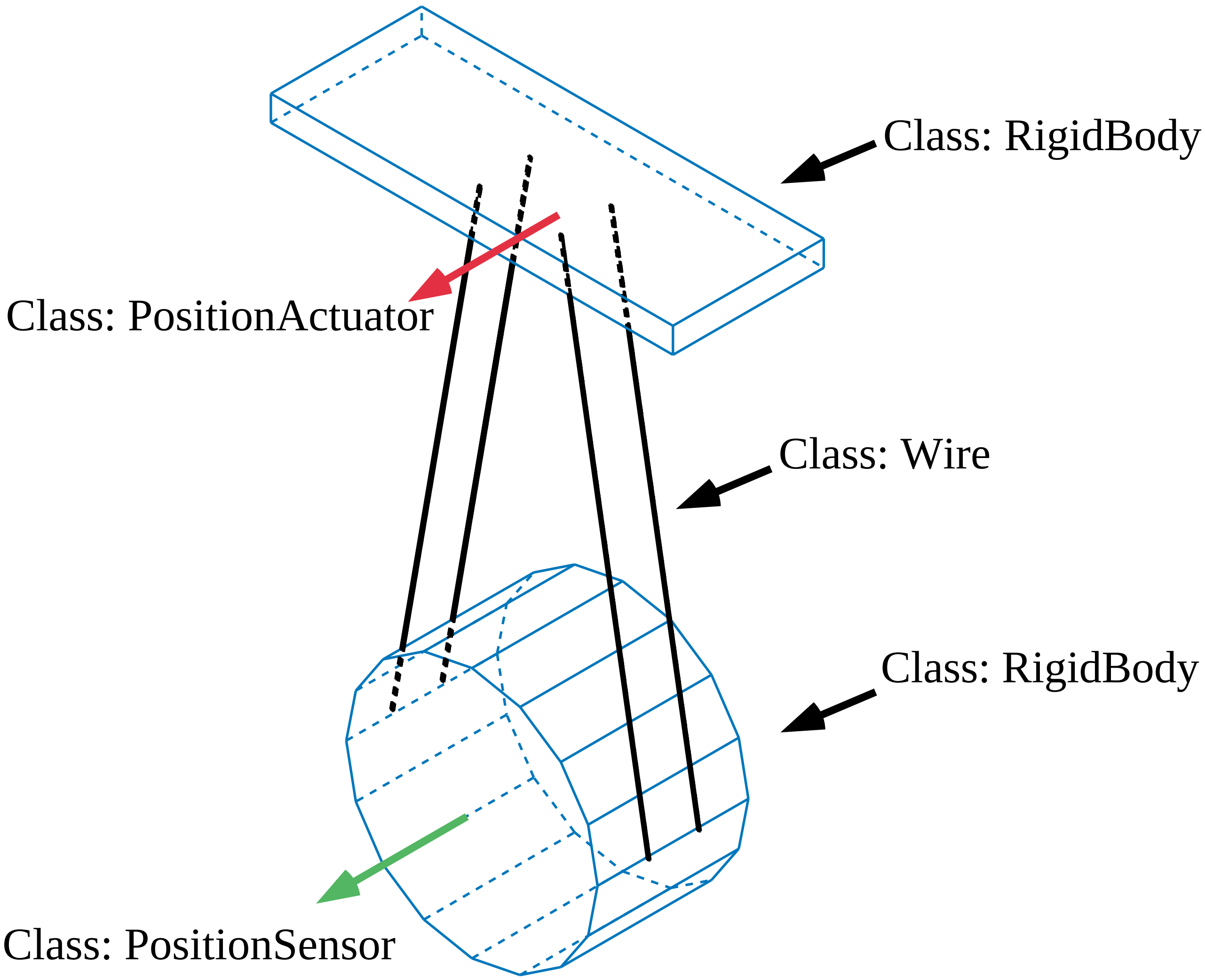
Specification of Analysis

↓

Computation of System Response

2.3. Example

Simple Suspension



2. MSE and SAS Simulation

2.3. Status

Current Work

- Validation

By Other Simulations / Measurements

- Debug of Some Objects

GAS Blade, Beam, etc. are in debugging phase.

But these objects can be emulated by validated objects.

- Study of Some Systems with Validated Objects

Quadrupole Suspension for BSCs

Triple Suspension for HAMs

Inverted Pendulum

Entire SAS, etc.

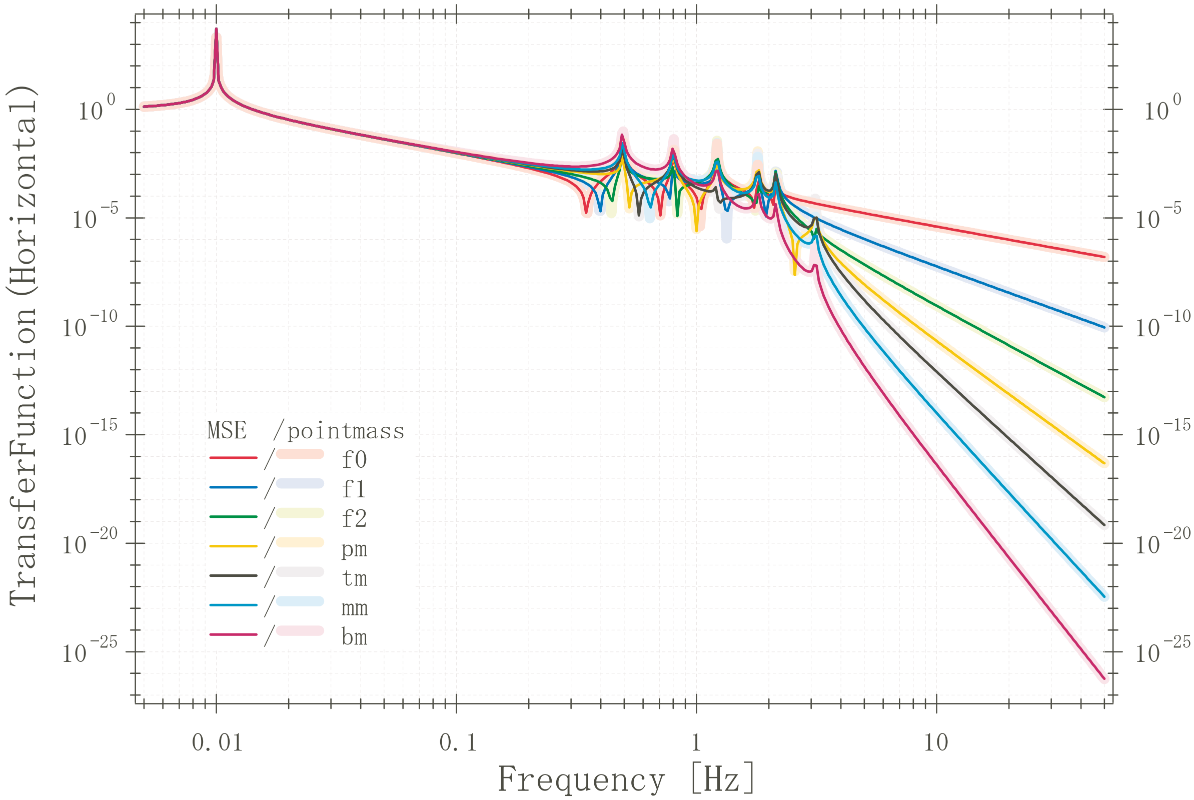
2.4. Results

- Example of Validation

Comparison with Point-Mass Model

Each mass in MSE model is suspended at the level

of its center of mass. >> No coupling with pitching.



Horizontal Transfer Function of the SAS for BSCs

2. MSE and SAS Simulation

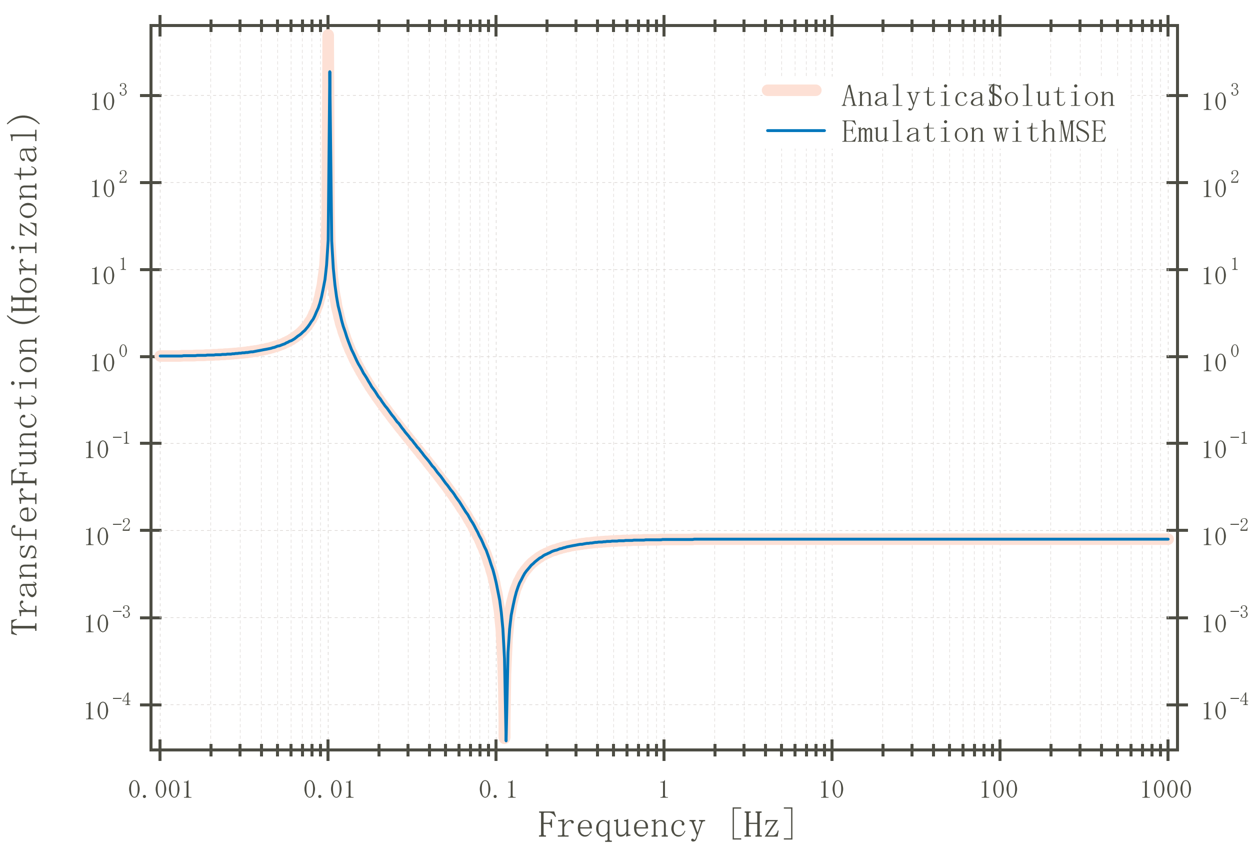
LIGO SAS

2.4. Results

- Example of Emulation

IP <=> Simple Pendulum with Distributed Mass

IP without Counter Weight to Compensate Center of Percussion Effect



3. Control

LIGO SAS

3.1. SAS Control

Positioning (Local / Global) ~ 10 mHz

- **Sensing**

  LVDTs in Locking Acquisition Phase

  IFO signal in Operation Phase

- **Actuation**

  Stepping Motors

  Coil-Magnet Actuators

Inertial Damping ~ a few Hz

- **Sensing**

  Accelerometers

- **Actuation**

  Coil-Magnet Actuators

Mirror Control

- **Sensing**

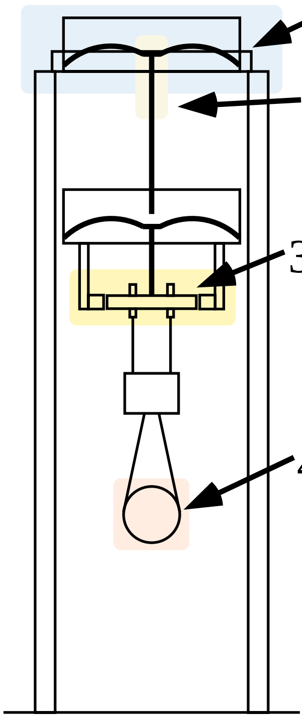
  IFO signal

- **Actuation**

  Electro-Static Actuators (Small Range)

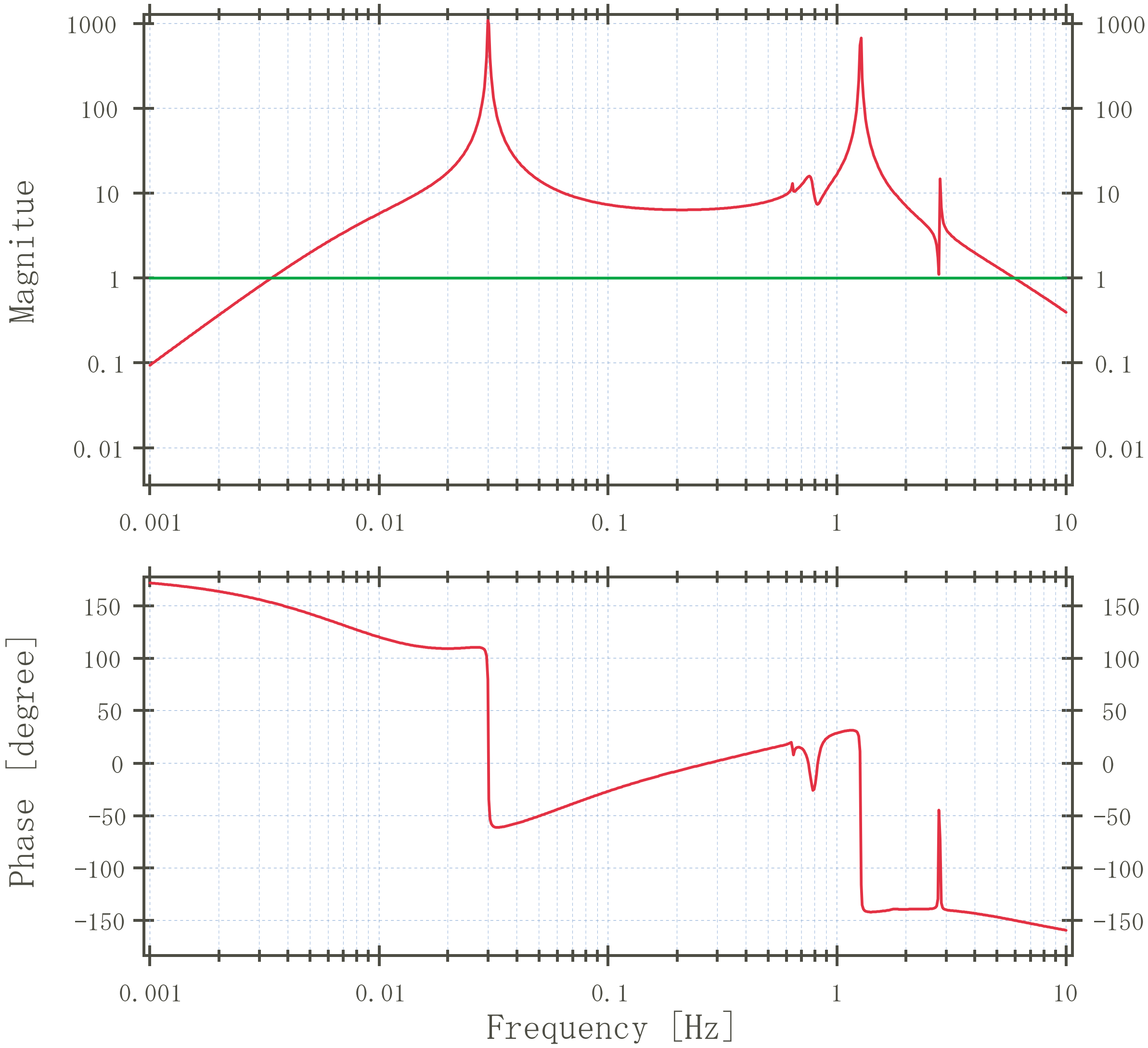
3.2. Example

Study of Local Control for TAMA SAS



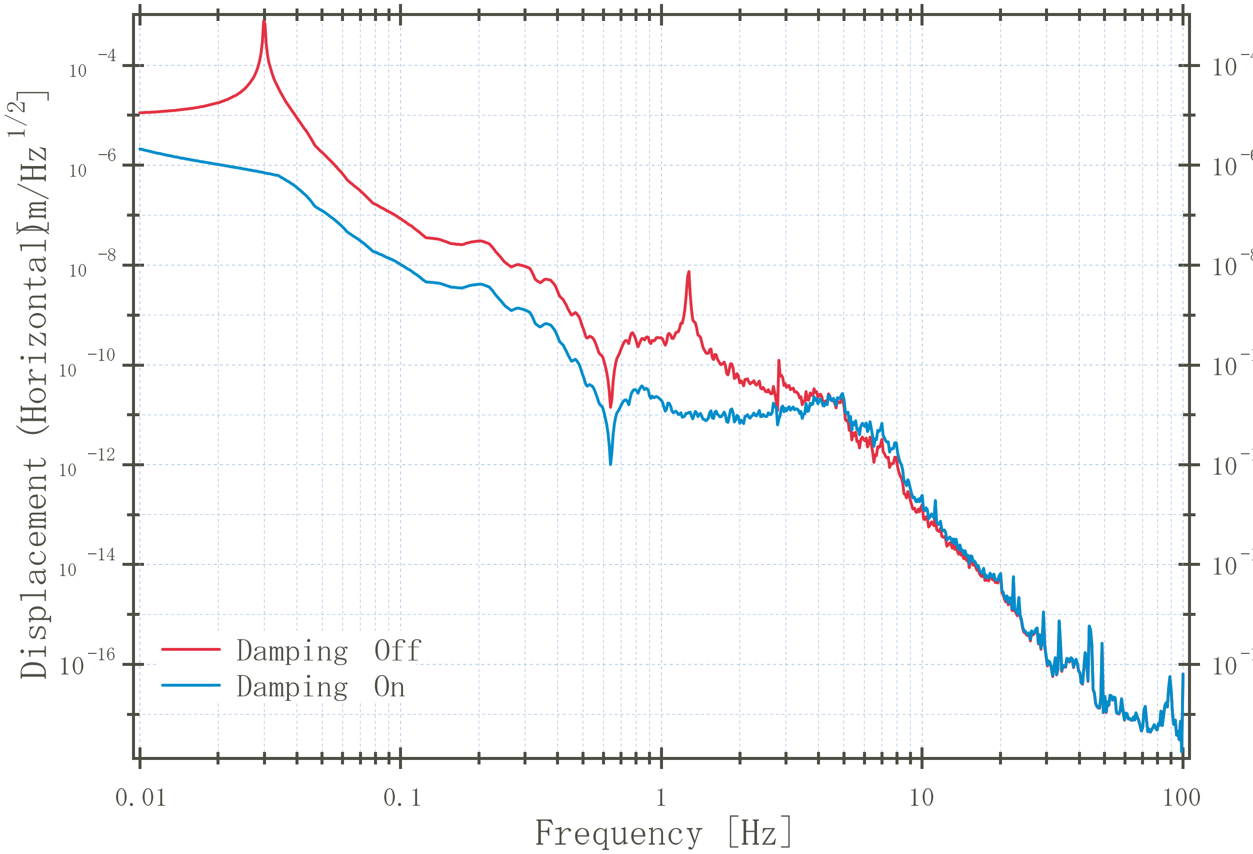
1. IP top table: *X, Y, Yaw*	LVDT Accelerometer	Stepping Motor Coil-Magnet Actuator
2. Filter zero: *Z*	LVDT Accelerometer	Stepping Motor Coil-Magnet Actuator
3. Suspension point: *Yaw, Pitch*	Optical Lever	Coil-Magnet Actuator
4. Mirror: *X, Yaw, Pitch*		

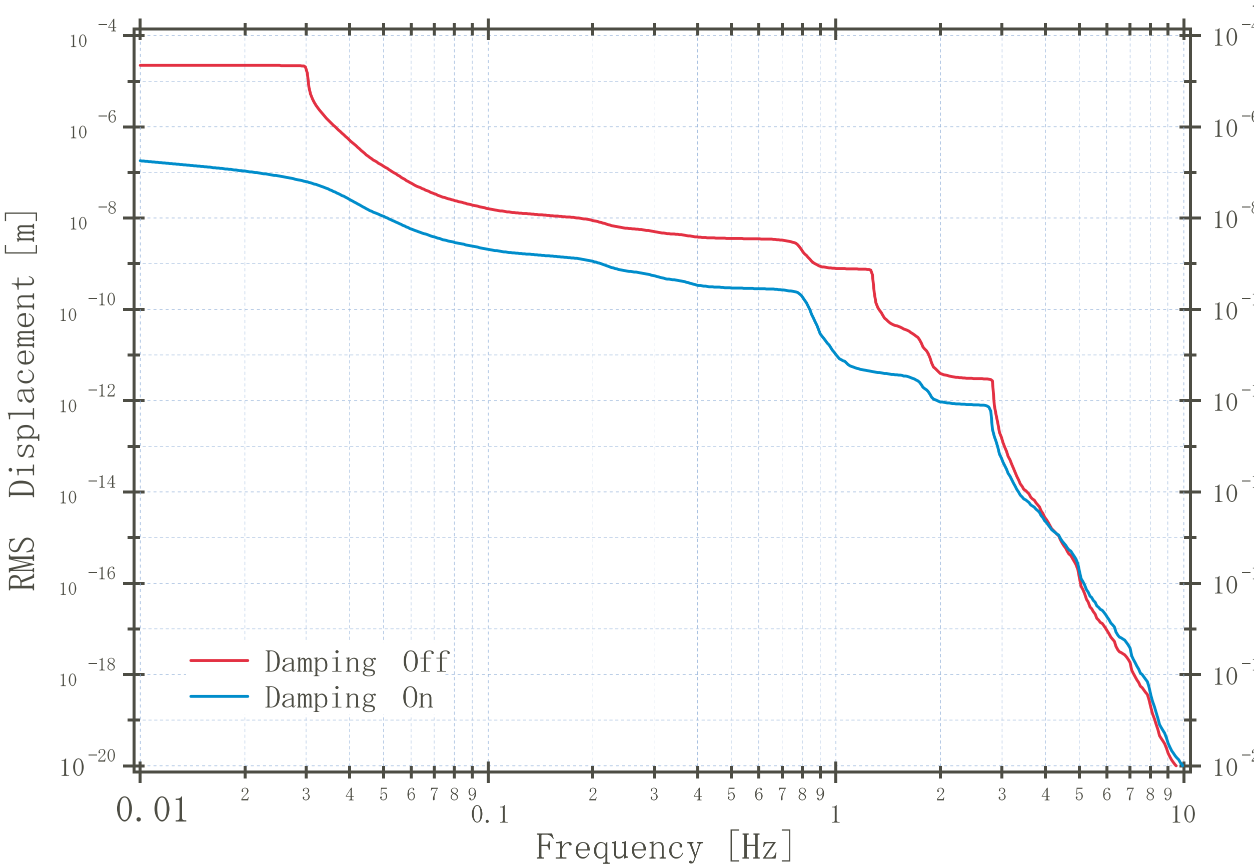
Inertial Damping for TAMA SAS



Open Loop Transfer Function
for Horizontal Inertial Damping

Inertial Damping for TAMA SAS





SAS Active Components

- Simple and modular
- Passive in vacuum (External electronics, except accelerometer)
- Safe, Redundant design (duplication)
- Custom made Well understood, tested and characterized; controlled materials, traceable.
- UHV compatible (by construction)
  - Fully Bakeable
  - No gas bladders
  - No volatile compounds
- Low power   milli-Watts

SAS passive components

- Simple and modular
- Passive
- UHV compatible (all metal)

- Note: low frequency from clever shapes not higher stress.

Reliability

Stiff

- Active components in vacuum
- Watts/sensor in vacuum
- Gas bladders
- Strong actuators
- Dynamic equilibrium (hydraulic) positioning

SAS

- All passive comp.s in vacuum
- mWatts sensors in vacuum
- No enclosed gases
- Soft actuators
- Static equilibrium(soft springs) positioning

Reliability (2)

Stiff: active attenuation

- 3 nested layers
- 6 d.o.f. each

Sensors/actuators

Active, in vacuum

Critical for attenuation!

SAS: inertial damping

- Single layer
- 3 + 1 d.o.f.

Sensors/actuators

Passive in vacuum

Non critical!

Effect of failures

Stiff: Loss of one active component

⇒ Loss of attenuation stage,

⇒ IFO stopped

⇒ Require replacement

⇒ Easy replacement but vacuum break required

→Significantly replacements are foreseen! ←

⇒Possible collateral damage

Effect of Failures

SAS: Loss of one active component:

- Attenuation is intact ! !
- Actuator: Use redundant coil.
- LVDT: redundant during lock, lower level of position control in lock acquisition
- Accelerometer: Use LVDTs in lock acquisition, lower level of damping during lock, chase with other towers.

Effect of Failures

- Stiff: internal Gas leak

=> IFO stopped or mirror damaged

- SAS: no Gas enclosures