Present and future of Superattenuator control system

V. Boschi
(Università di Pisa and INFN)

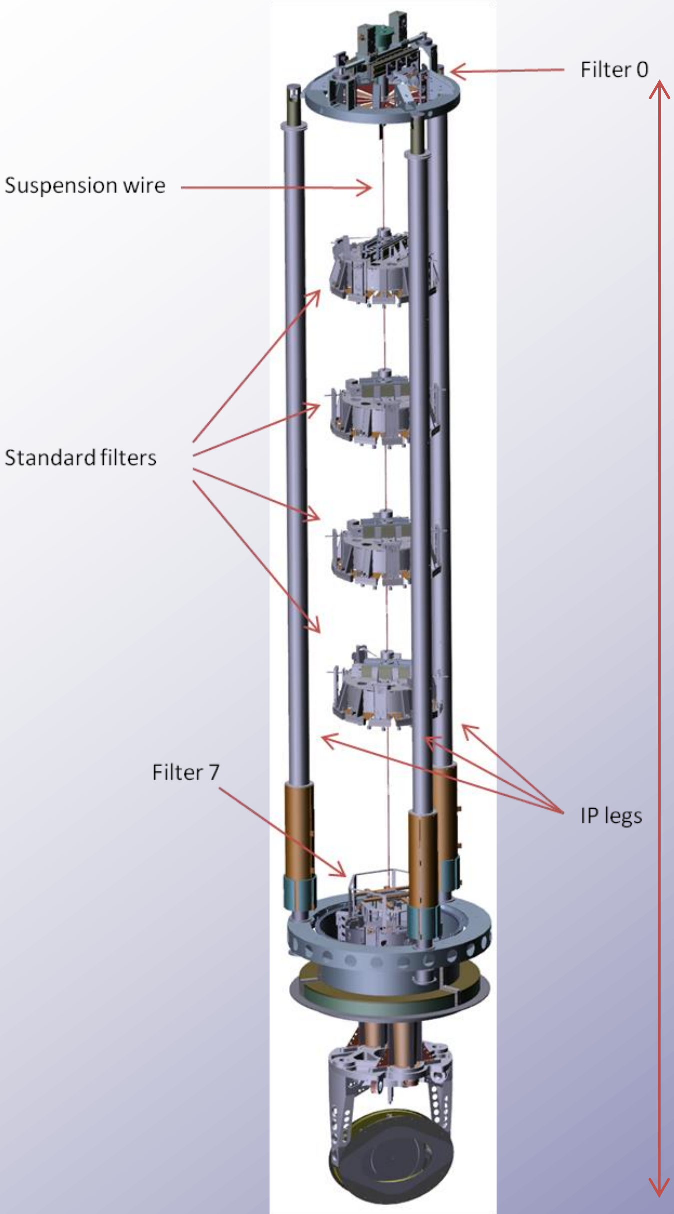
Outline

- Present Superattenuator control system
- Near term future (< 1 yr)
  - System identification
  - Optimal control
  - Adaptive control
- Long term future (> 1 yr)
  - Tilt Control
  - New Sensors
- Conclusions

People involved

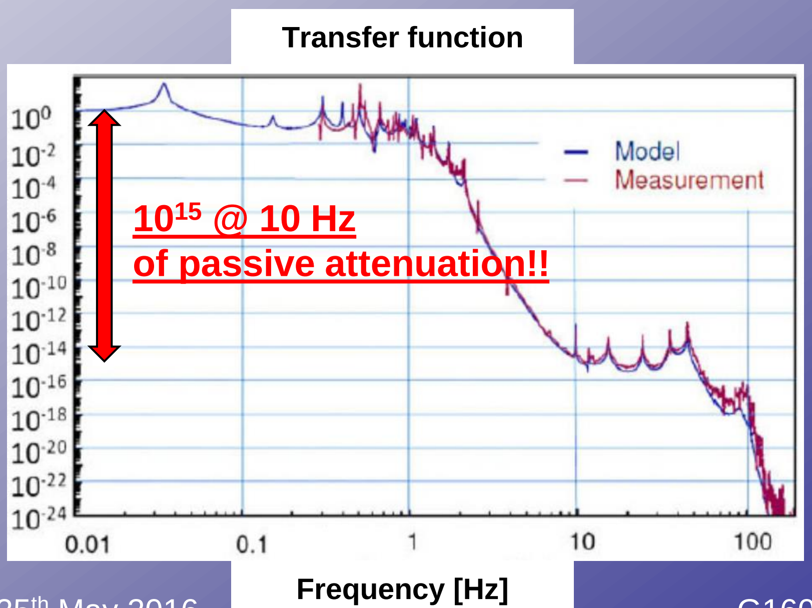
- G. Ballardin (EGO)
- M. Bitossi (EGO)
- V. Boschi (Università di Pisa and INFN)
- C. Carissimi (EGO)
- V. Dattilo (EGO)
- G. Cerretani (Università di Pisa and INFN)
- A. Gennai (INFN)
- E. Majorana (INFN)
- C. Magazzu (INFN)
- D. Passuello (INFN)
- F. Frasconi (INFN)
- R. Passaquieti (Università di Pisa)
- P. Ruggi (EGO)
- L. Trozzo (Università di Siena and INFN)
- EGO Electronics and Software Groups

The superattenuator



The AdVirgo superattenuator (SA) is a complex mechanical device capable of providing more than 10 orders of magnitude of passive seismic isolation in all six degrees of freedom above a few Hz

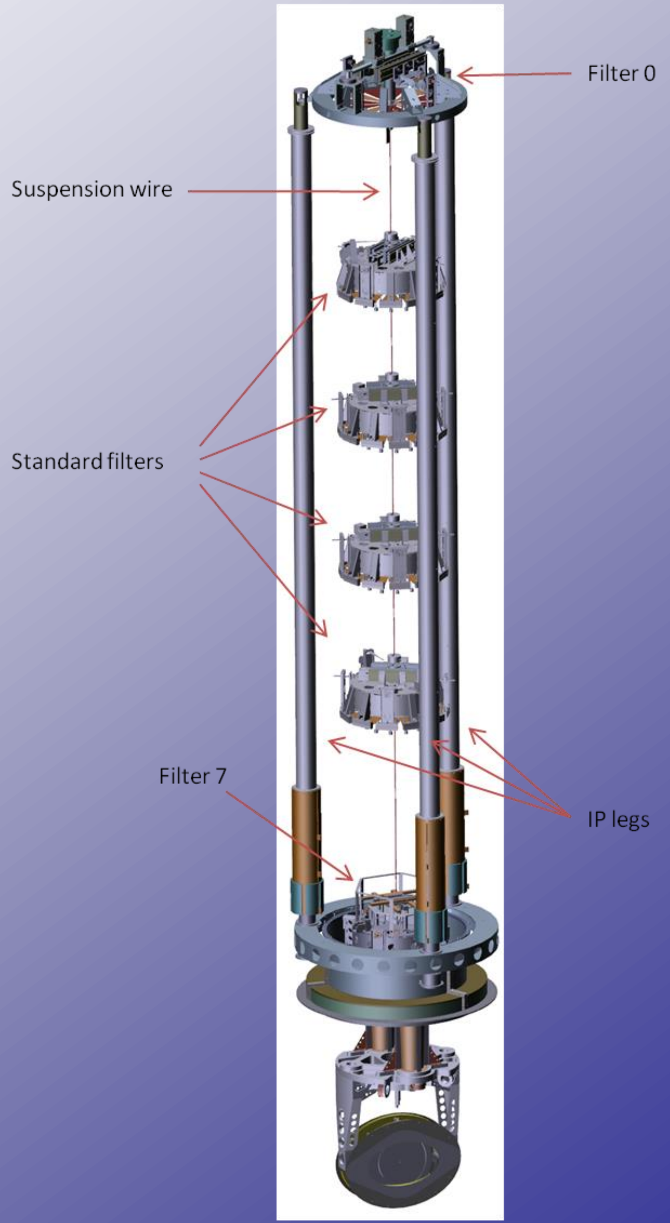
- The SA is a passive mechanical system constituted by a 5 stage pendulum supported by a 3-leg elastic pre-isolator called inverted pendulum (IP).
- All the normal mode resonance frequencies of the SA are kept below 2 Hz.
- The SA mechanical structure, consists of three fundamental parts: the inverted pendulum, the chain of standard filters, the payload.
- Mechanical design for AdVirgo is essentially the same of Virgo except for the payload.



SA Control System
Overview

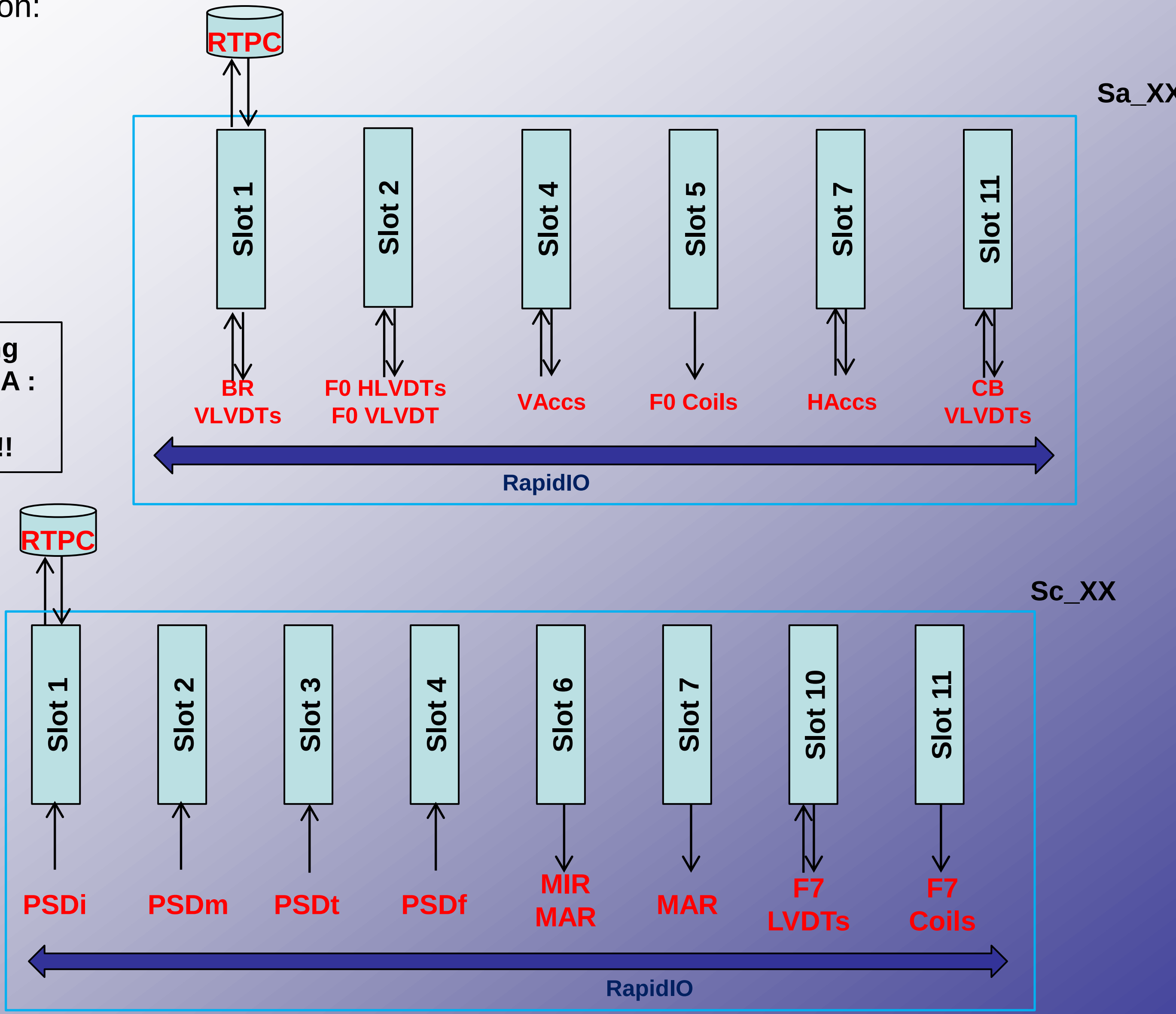
On a long tower suspensions are installed:

- **18 LVDTs** of 3 different types
  - 9 Vertical LVDTs (F0 – F7 Crossbar, Bottom Ring)
  - 3 F0 Horizontal LVDT
  - 6 F7 LVDTs
- **5 Accelerometers** of 2 different types :
  - 3 Horizontal Accs
  - 2 Vertical Accs
- **23 Coils** of 4 different types
  - 5 F0 Coils
  - 6 F7 Coils
  - 8 Marionette coils
  - 4 Mirror coils
- **3 Piezos** on bottom ring (**New in ADV**)
- **21 Motors**
  - 1 Top screw F0 vertical motor
  - 3 F0 trolley motors
  - 6 Fishing rod motors
  - 2 Marionette motors
  - 4 F7 motors
  - 5 Accelerometer motors



SA Control System
Overview

• A total of 14 boards, each one equipped with an 8-core TMS320C6678 DSP, are connected to a long suspension:



Total computing power of each SA :

> 2.2 TFLOPs !!

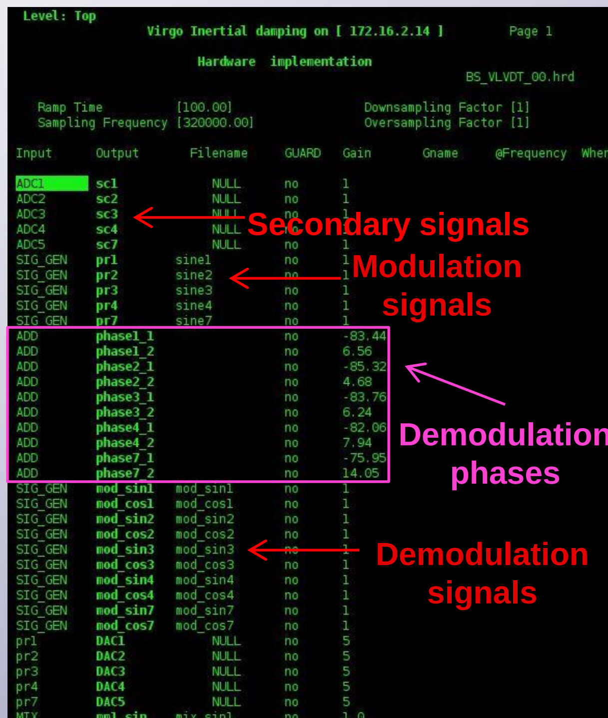
SA Control System

LVDTs

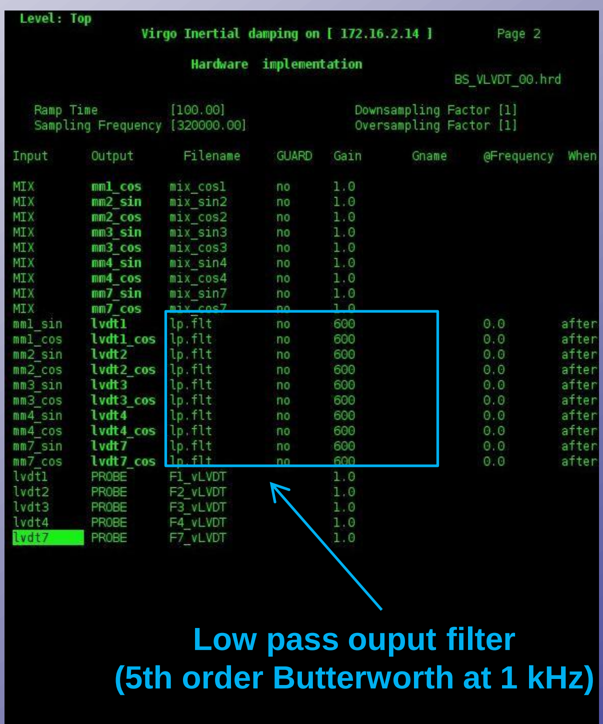
- There are 18 LVDTs installed on long tower suspensions of 3 different types
    - 9 Vertical LVDTs (F0 – F7 Crossbar, Bottom Ring)
    - 3 F0 Horizontal LVDT
    - 6 F7 LVDTs

    - Typical sensitivity is 1 nm/sqrt(Hz)

- All the LVDTs are operated using a digital demodulation scheme at 320 kHz sampling frequency:



Input	Output	Filename	GUARD	Gain	Gname	@Frequency	When
ADC1	sc1	NULL	no	1			
ADC2	sc2	NULL	no	1			
ADC3	sc3	NULL	no	1			
ADC4	sc4	NULL	no	1			
ADC5	sc7	NULL	no	1			
SIG_GEN	pr1	sine1	no	1			
SIG_GEN	pr2	sine2	no	1			
SIG_GEN	pr3	sine3	no	1			
SIG_GEN	pr4	sine4	no	1			
SIG_GEN	pr7	sine7	no	1			
ADD	phase1_1		no	-83.44			
ADD	phase1_2		no	6.56			
ADD	phase2_1		no	-85.32			
ADD	phase2_2		no	4.68			
ADD	phase3_1		no	-83.76			
ADD	phase3_2		no	6.24			
ADD	phase4_1		no	-82.06			
ADD	phase4_2		no	7.94			
ADD	phase7_1		no	-75.95			
ADD	phase7_2		no	14.05			
SIG_GEN	mod_sin1	mod_sin1	no	1			
SIG_GEN	mod_cos1	mod_cos1	no	1			
SIG_GEN	mod_sin2	mod_sin2	no	1			
SIG_GEN	mod_cos2	mod_cos2	no	1			
SIG_GEN	mod_sin3	mod_sin3	no	1			
SIG_GEN	mod_cos3	mod_cos3	no	1			
SIG_GEN	mod_sin4	mod_sin4	no	1			
SIG_GEN	mod_cos4	mod_cos4	no	1			
SIG_GEN	mod_sin7	mod_sin7	no	1			
SIG_GEN	mod_cos7	mod_cos7	no	1			
pr1	DAC1	NULL	no	5			
pr2	DAC2	NULL	no	5			
pr3	DAC3	NULL	no	5			
pr4	DAC4	NULL	no	5			
pr7	DAC5	NULL	no	5			
MIX	mm1_sin	mix_sin1	no	1.0			



Input	Output	Filename	GUARD	Gain	Gname	@Frequency	When
MIX	mm1_cos	mix_cos1	no	1.0			
MIX	mm2_sin	mix_sin2	no	1.0			
MIX	mm2_cos	mix_cos2	no	1.0			
MIX	mm3_sin	mix_sin3	no	1.0			
MIX	mm3_cos	mix_cos3	no	1.0			
MIX	mm4_sin	mix_sin4	no	1.0			
MIX	mm4_cos	mix_cos4	no	1.0			
MIX	mm7_sin	mix_sin7	no	1.0			
MIX	mm7_cos	mix_cos7	no	1.0			
mm1_sin	lvdt1	lp.flt	no	600		0.0	after
mm1_cos	lvdt1_cos	lp.flt	no	600		0.0	after
mm2_sin	lvdt2	lp.flt	no	600		0.0	after
mm2_cos	lvdt2_cos	lp.flt	no	600		0.0	after
mm3_sin	lvdt3	lp.flt	no	600		0.0	after
mm3_cos	lvdt3_cos	lp.flt	no	600		0.0	after
mm4_sin	lvdt4	lp.flt	no	600		0.0	after
mm4_cos	lvdt4_cos	lp.flt	no	600		0.0	after
mm7_sin	lvdt7	lp.flt	no	600		0.0	after
mm7_cos	lvdt7_cos	lp.flt	no	600		0.0	after
lvdt1	PROBE	F1_vLVDT		1.0			
lvdt2	PROBE	F2_vLVDT		1.0			
lvdt3	PROBE	F3_vLVDT		1.0			
lvdt4	PROBE	F4_vLVDT		1.0			
lvdt7	PROBE	F7_vLVDT		1.0			

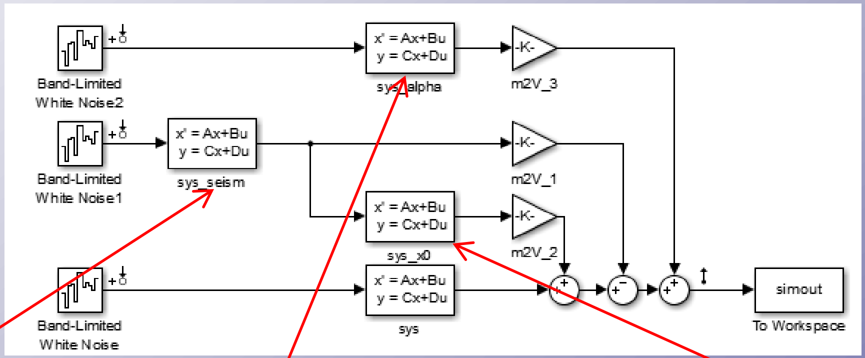
SA Control System
Accelerometers

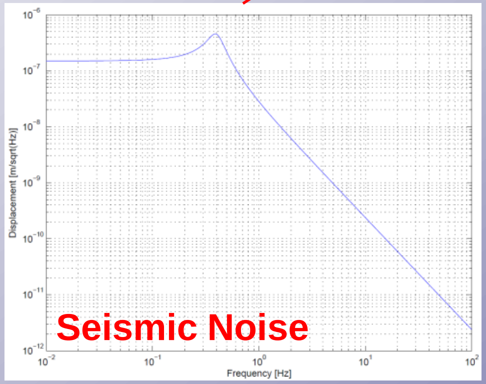
- There is a total of 5 Accelerometer (Accs) installed on the suspension F0 of 2 different types
  - 3 Horizontal Accs
  - 2 Vertical Accs

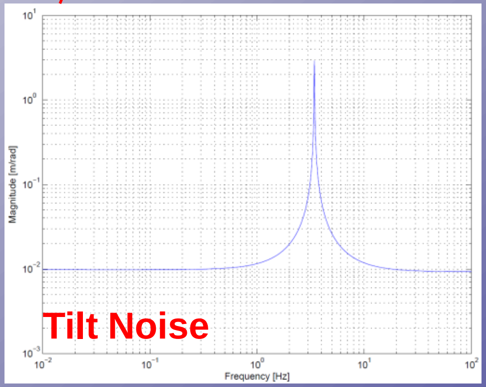
- Each sensor has been characterized and calibrated

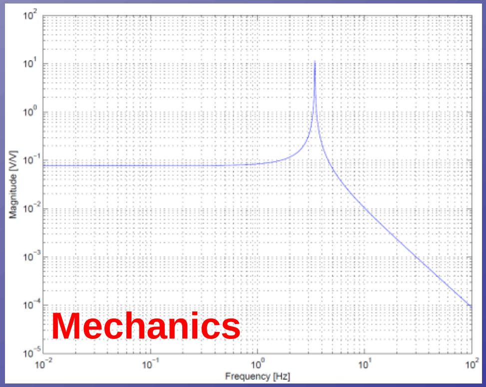
- A model of the sensor mechanics and its disturbances has been developed in order to design the Kalman estimator and the controller.

AccModel









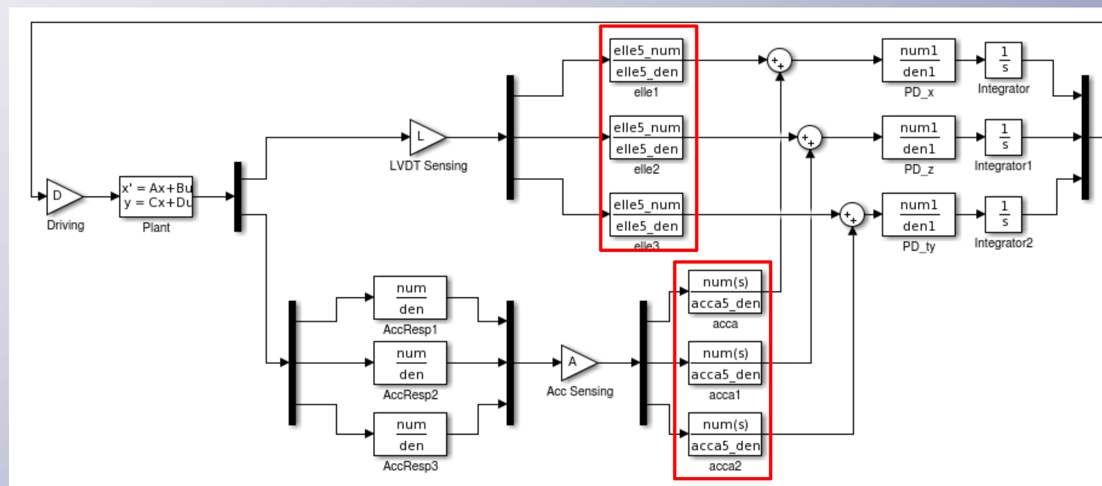
SA Control System
Control Overview

- **Two loops are currently used to control IP motion**:

Horizontal Inertial Damping

6 x 3 plant matrix:
(3 LVDTs + 3 Accelerometers) x 3 Coils
on filter 0

3 x 3 Diagonalized Control matrix

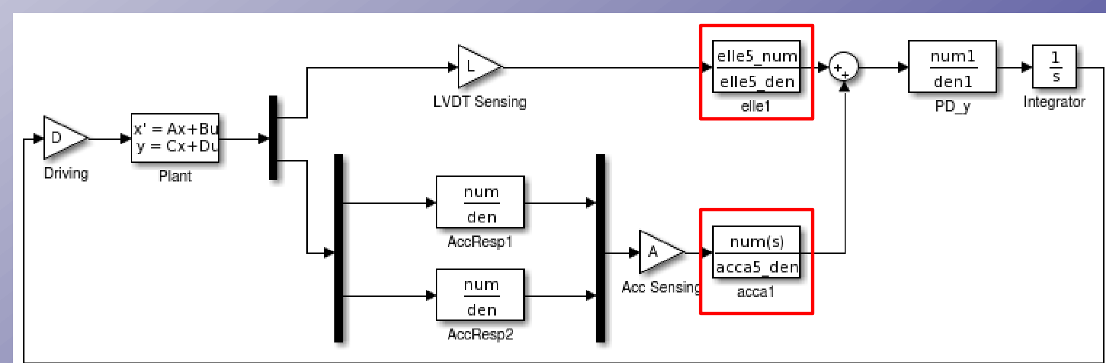


Blending filters

Vertical Inertial Damping

3 x 2 control matrix:
(1 LVDTs + 2 Accelerometers) x 2 Coils
on filter 0

1 x 2 Diagonalized Control matrix



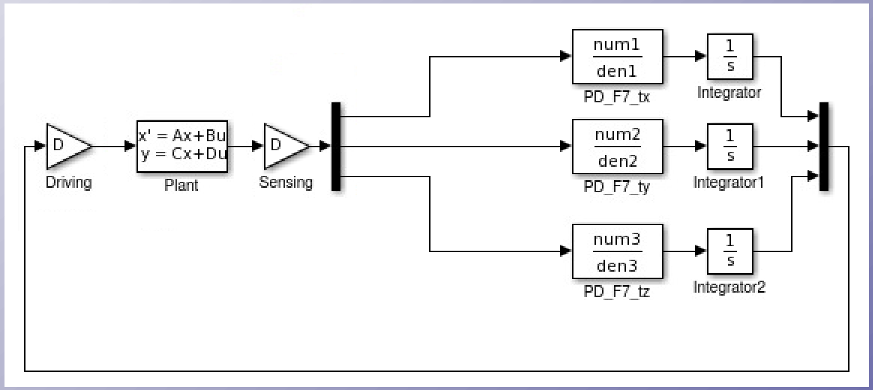
SA Control System
Control Overview

- **Two loops are currently used the bottom stage of the SA**:

F7

6 x 6 plant matrix:
6 LVDTs x 6 Coils on the F7

3 x 3 Diagonalized Control Matrix

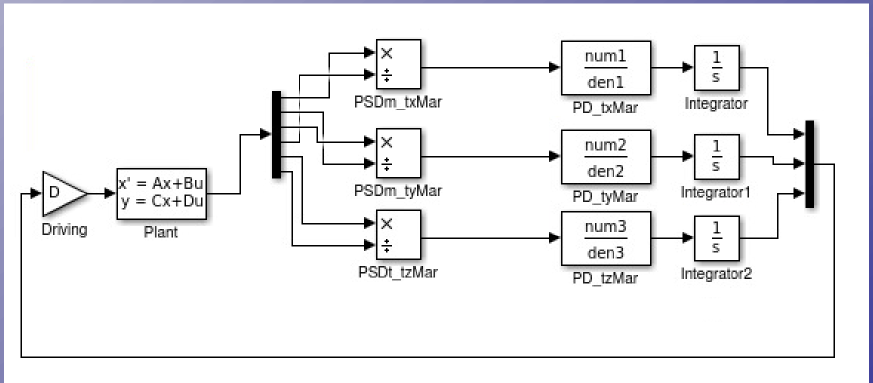


Local Control

3 x 8 plant matrix:
3 PSD signals x 8 Coils on Marionette

3 x 3 Diagonalized Control Matrix

Bang-bang control (Coarse)
PID (Fine)



SA Control System
Problems

- Classical design methods have several limitations:
  - Static sensing and driving matrices are valid in a limited frequency range
  - Controller Design is user dependent and therefore not repeatable
  - Loop optimization (for example ID best blending frequency) is tricky
- Low Robustness:
  - Many intrinsic and environmental parameters affect system status and performance
  - Most of our control loops operate in small neighborhood of n-dimensional working point, where we can assume systems to be linear.
  - In most cases, changing working point produce very large variation of system parameters and therefore variation of control loops performances that can produce a degradation of stability margins.

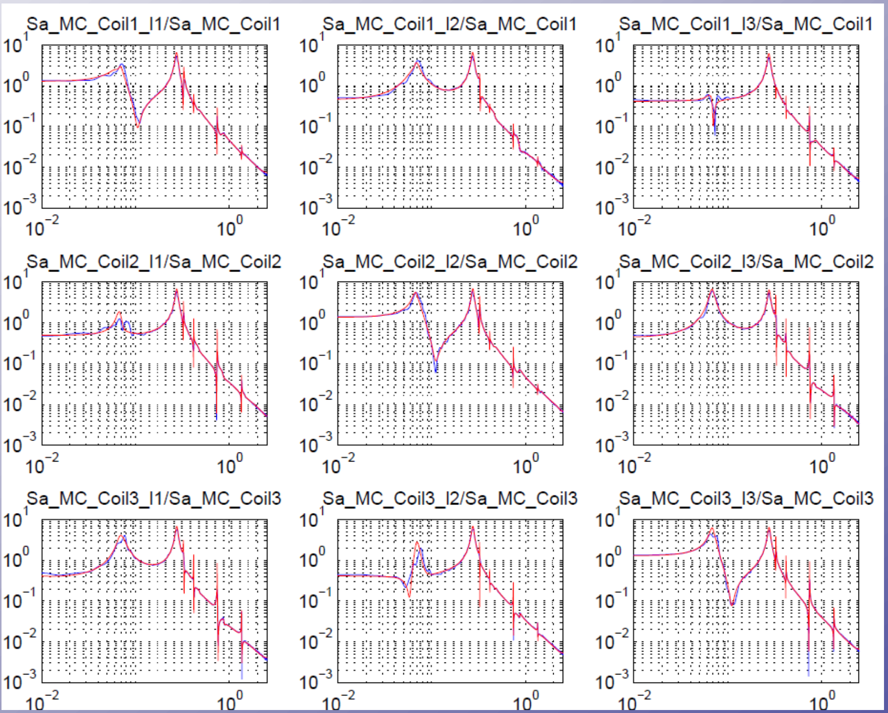
Near term future
Modeling

• Complete system identification of all controllable DOFs of each SA: MIMO state space models can be obtained from time domain data with subspace identification methods

• Problems:

- Find the right measurement (single coils vs diagonalized coils) could be difficult
- The accuracy of the results strongly depends by the model order and by the sampling frequency chosen

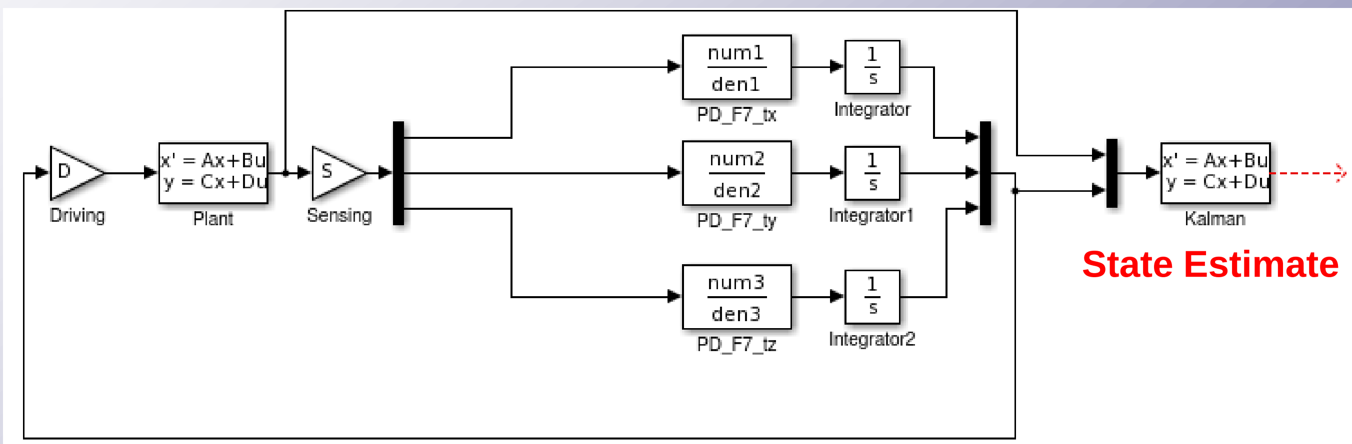
• Here we show the system identification results (red curves) for the MC superattenuator IP obtained with an order-30 model, using the subspace method.

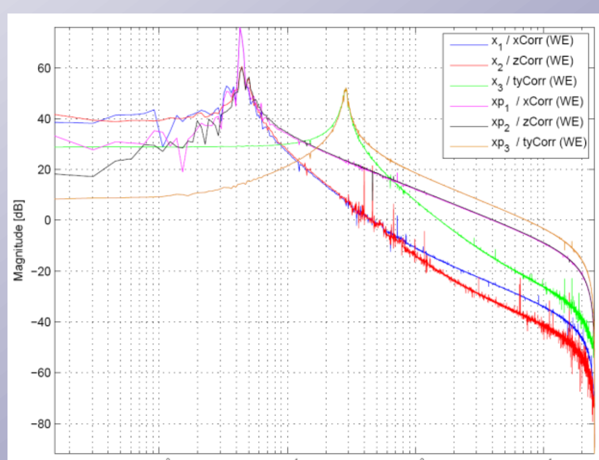


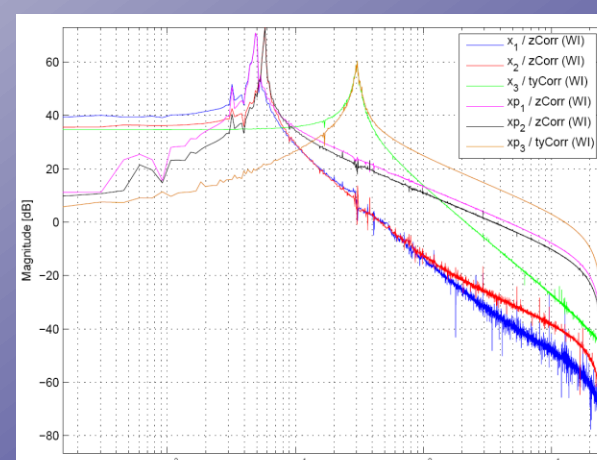
Near term future
Estimation

• Model the process and measurement noises: sensors and actuators noise budget.

• Calculate a Kalman filter and put it in parallel to the current controllers to continuously monitor in real-time the control system performance along its normal modes.







Near term future
Optimal control

The general idea of optimal control is to place the poles and zeros automatically and optimally acting on the state of the system.

Given a discrete time state-space:

$$\begin{cases} \boldsymbol{x}(k+1) = \boldsymbol{Ax}(k) + \boldsymbol{Bu}(k) \\ \mathbf{y}(k) = \boldsymbol{Cx}(k) + \boldsymbol{Du}(k) \end{cases}$$

In a linear quadratic regulator (LQR) the feedback law is simply

$$\boldsymbol{u}(k) = -\boldsymbol{Kx}\left(k\right)$$

The gain matrix K minimizes the quadratic cost function *J*

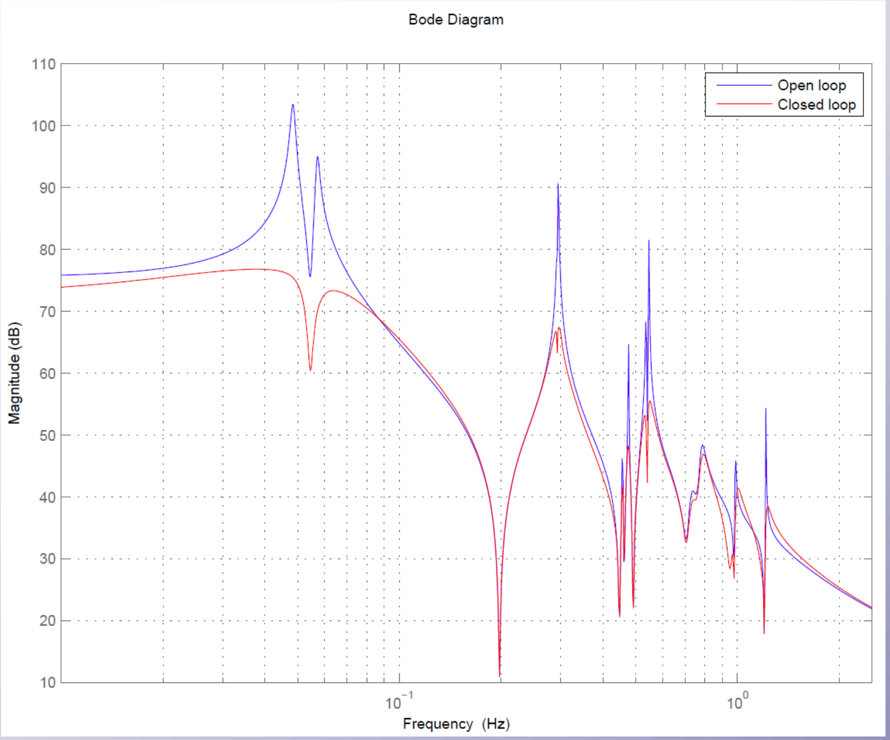
$$J = \sum_{k=0}^{\infty} \mathbf{x}^T(k)\mathbf{Q}\mathbf{x}(k) + \mathbf{u}^T(k)\mathbf{R}\mathbf{u}(k) + \mathbf{2x}^T(k)\mathbf{N}\mathbf{u}(k)$$

Regulation Performance

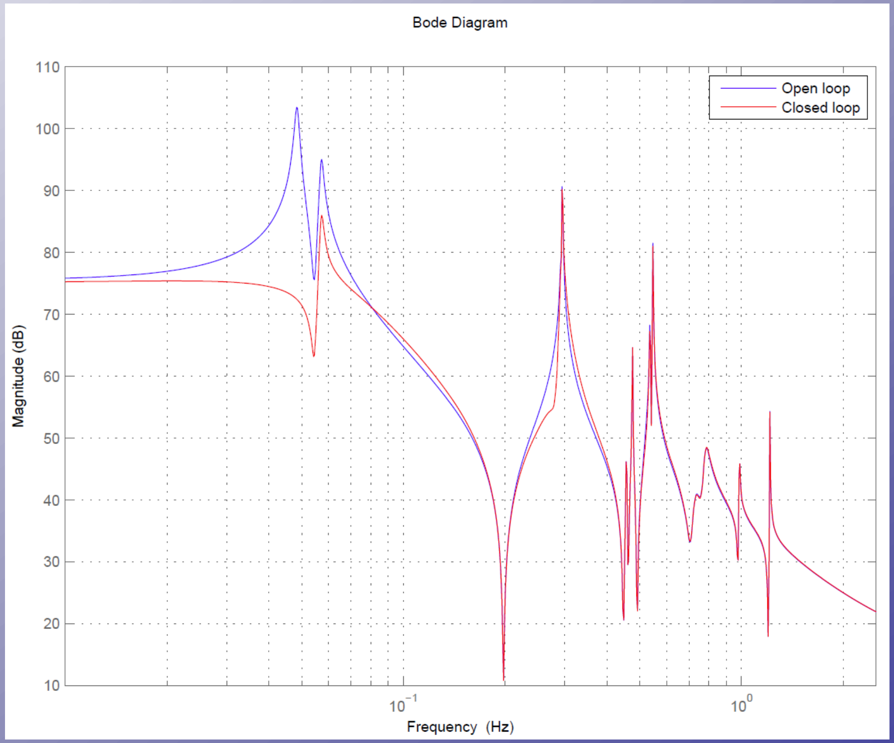
Control Effort

Near term future
Optimal control

If the state-space system is in modal canonical form, choosing the state weights in the ***Q*** matrix of the cost function we automatically design a controller that damps only the selected state vector components.



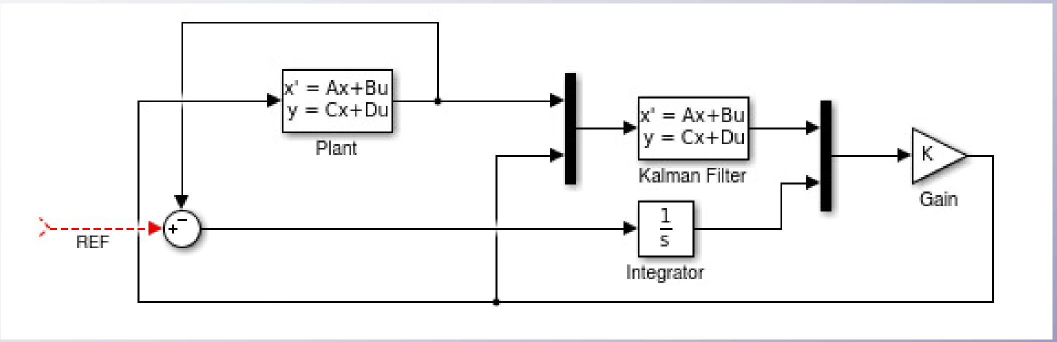
The weights of all state vector components are equal:
All modes are damped

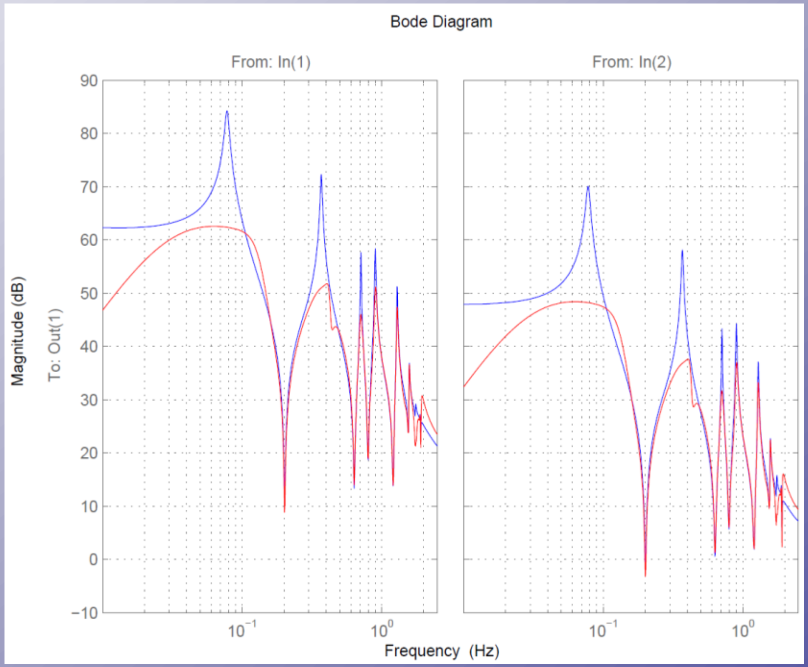


The weights of the state vector components are not equal:
Only the selected modes are damped

Near term future
Optimal control

- Example: an optimal tracking regulator for the IP vertical position control

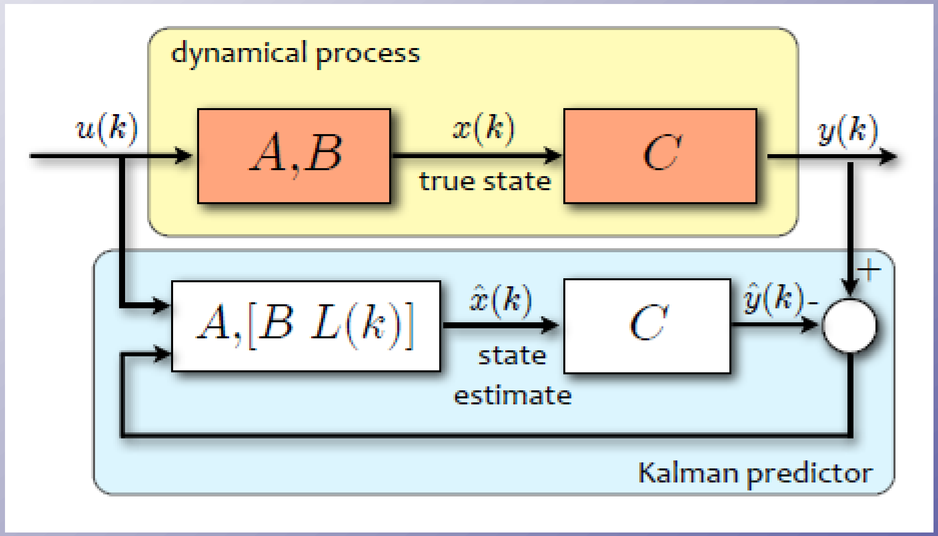




Near term future
Adaptive control

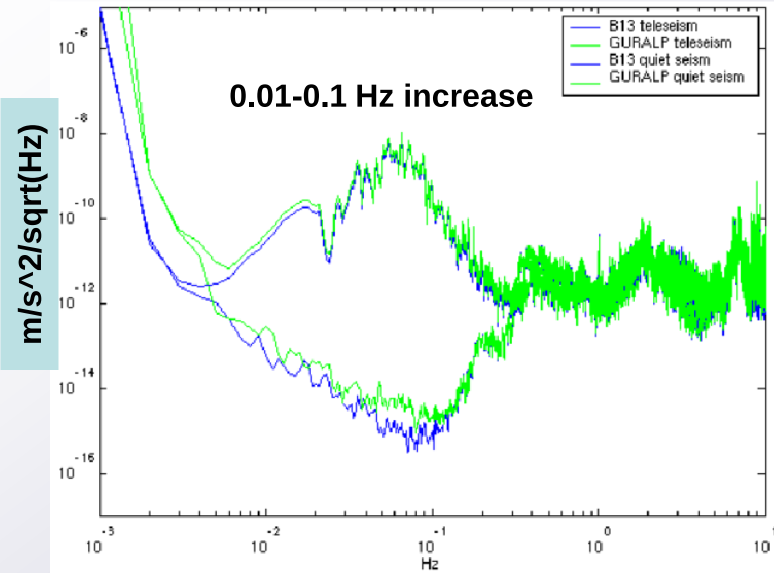
- The next step is to develop adaptive versions of the Kalman filters

- From the mathematical point of view, this will require to change the Kalman gain L dynamically using the predicted measurement and process noises (see MATLAB adaptive Model Predictive Control for example)

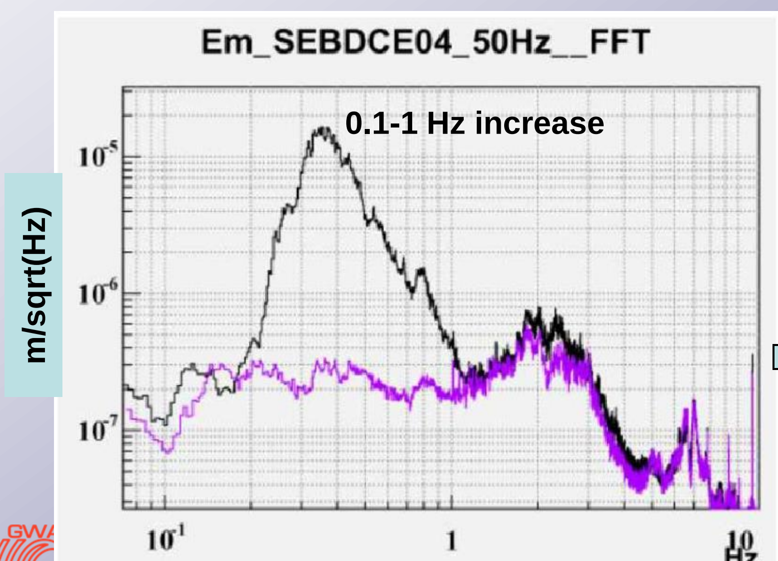


Long term future
IP Tilt Control: Motivation

Earthquake effect on seismic noise



Wind effect on seismic noise



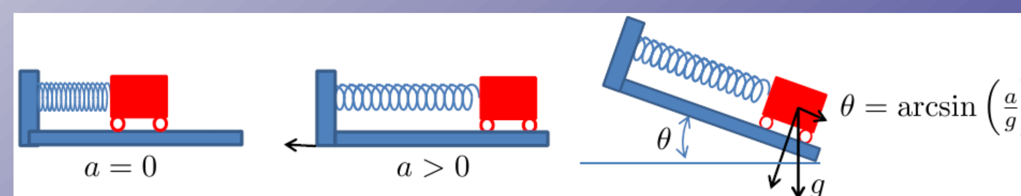
Experimentally, due to earthquakes or bad weather conditions, seismic noise grows up to 2 or 3 orders of magnitude in 100 mHz -1 Hz band with its maximum between 400 and 500 mHz (micro-seismic peak).

How to compensate the noise increase?

- **Piezo actuators are installed on bottom ring**

We need to know how much of the noise increase is tilt since

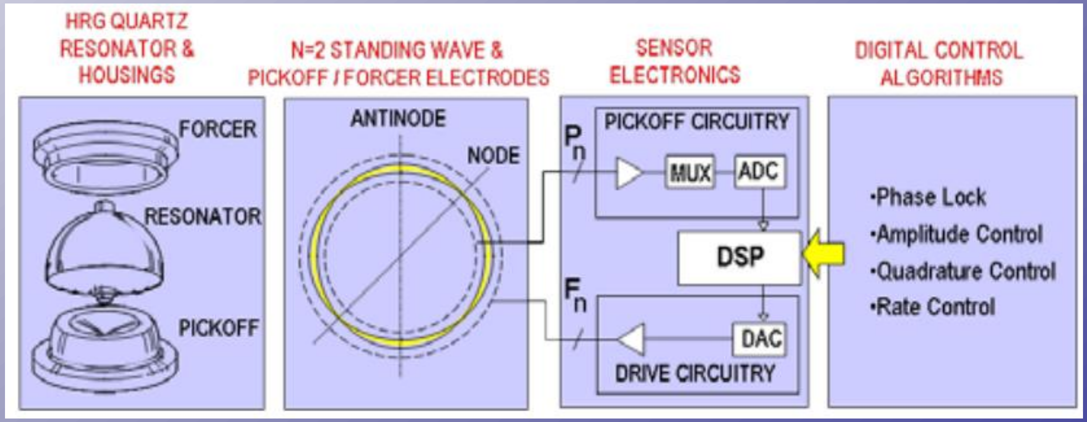
- Ground tilt is transmitted to Superattenuator (SA) top stage without any attenuation.
- Accelerometers on SA top stage are sensitive both to tilt and acceleration



A pure-tilt inertial sensor is mandatory to increase the duty-cycle of the interferometer

Long term future
IP Tilt Control: The sensor

- A custom made Coriolis Vibratory Gyroscope made by the Irish firm Innalabs is being tested.
- The device exploits the so-called Bryan's effect: the bending modes of a vibrating shell generate a standing wave that, once the system is tilted, precess in the direction of the inertial rotation, due to the Coriolis forces induced on the structure.
- Each sensing element consists of a metallic cylindrical resonator which has two flexural second order resonant modes which occur at the same frequency.

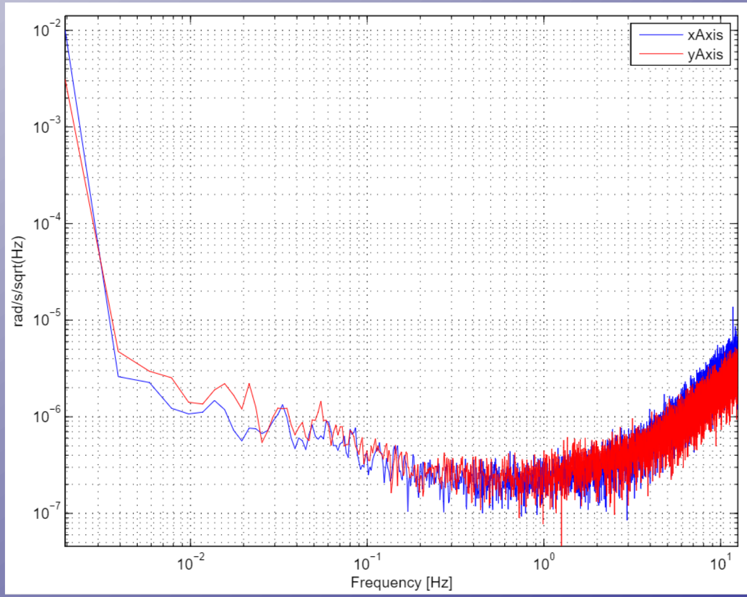


Long term future
IP Tilt Control: The sensor

- We made a series of preliminary tests (see bottom plot) when we received the sensor a year ago.
- New tests (Calibration, g-sensitivity, …) are ongoing thanks to fresh forces (2 new MS students)
- The sensor is connected to a DSP board and its outputs are available in VIRGO DAQ (SAT_Fb Framebuilder)

Parameter	Unit	Value	
		GI-CVG-U2110A	GI-CVG-U2210A
Number of Axis		One U2110A: X axis U2111A: Y axis	Two (X and Y)
Output Format		Analog	
Output Interface	V DC	Differential +/- 10 VDC for full scale (Note #1)	
Measurement Range	deg/sec	± 25 * see section 3.5	
Bandwidth	Hz	≥ 25 (-3dB) * see section 3.6.4	
In run Bias Stability (room temp. 1σ)	deg/hr	0.03 typical * see section 3.7.2	
Bias stability, full temperature range, 1σ	deg/hr	≤ 10 * see section 3.7.6	
Bias repeatability, turn-on to turn-on, 1σ	deg/hr	1 typical * see section 3.7.5	
Angular Random Walk (steady conditions)	deg/√hr	0.003 typical * see section 3.7.4	
Quiescent Noise (1 – 100 Hz), RMS	deg/sec	≤ 0.002 * see section 3.7.3	
Scale factor error, full temperature range, 1σ	ppm	≤ 3,500 * see section 3.6.3	
Scale factor Linearity	ppm	≤ 1500 * see section 3.6.2	
Misalignment	mrad	≤ 8 * see section 3.8	
Input signal (MIL STD 461 and 1275)	VDC	+12 VDC to +36 VDC	
Power Consumption	Watt	≤ 1.7 @15V	≤ 2.3 @15V
Vibration, Survival	g RMS,Hz	3.63 g rms (DEF STAN 00-35) and 12 g rms, 1-2kHz * see section 5.5.2	
Shock, Survival	g, ms	800 g, 0.6ms	
Electromagnetic Environmental Effects		MIL-STD-461F	
Built-in-self-test		Yes	

Manufacturer specification

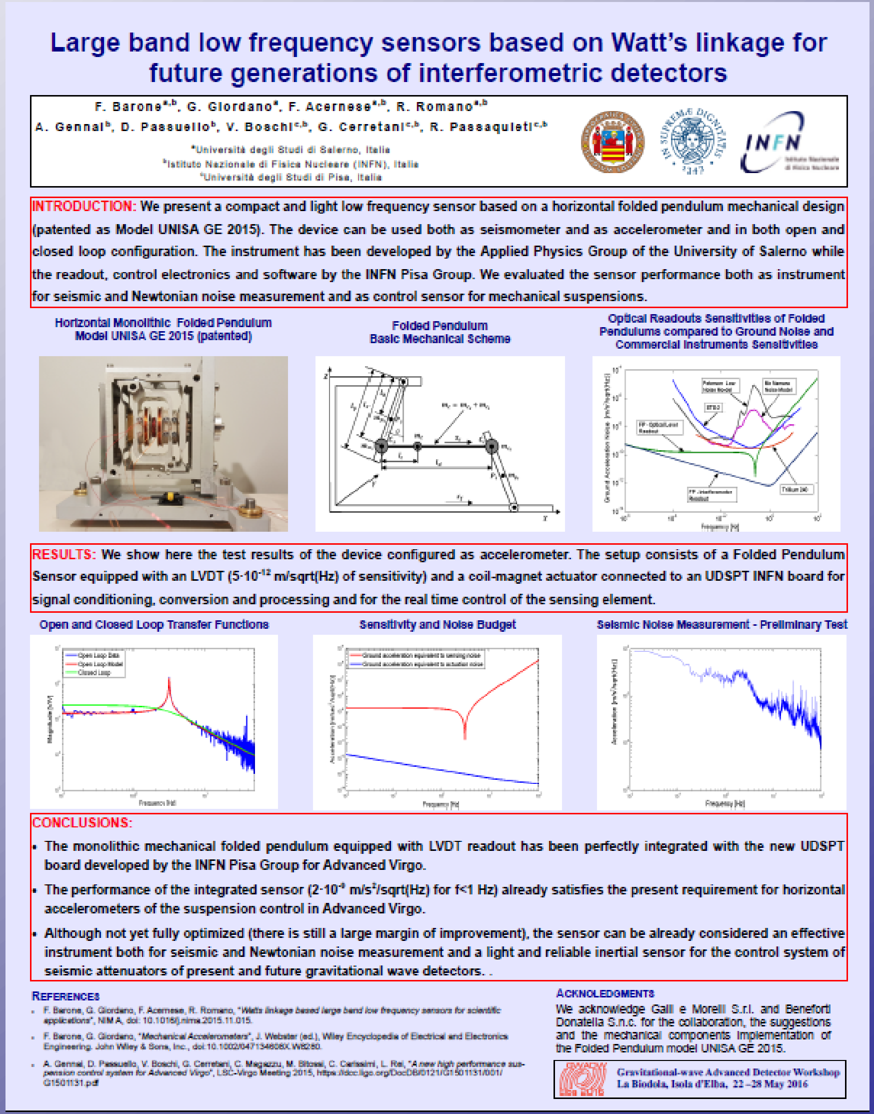


Calibrated outputs preliminary measurement

Long term future
New Sensors

- Optimal and adaptive control can increase robustness and reduce the level of the noise injected but only sensors with higher sensitivity can drastically increase the performance

- Several groups are developing new inertial sensors: for example a compact and light accelerometer developed by the University of Salerno has been tested using the same electronics and the same optimal controller of present accelerometers installed on IP (see the poster we presented yesterday, shown on the right).



Large band low frequency sensors based on Watt's linkage for future generations of interferometric detectors

F. Barone[a,b], G. Giordano[a], F. Acernese[a,b], R. Romano[a,b]
A. Gennai[b], D. Passuello[b], V. Boschi[c,b], G. Cerretani[c,b], R. Passaquieti[c,b]

[a]Università degli Studi di Salerno, Italia
[b]Istituto Nazionale di Fisica Nucleare (INFN), Italia
[c]Università degli Studi di Pisa, Italia

INTRODUCTION: We present a compact and light low frequency sensor based on a horizontal folded pendulum mechanical design (patented as Model UNISA GE 2015). The device can be used both as seismometer and as accelerometer and in both open and closed loop configuration. The instrument has been developed by the Applied Physics Group of the University of Salerno while the readout, control electronics and software by the INFN Pisa Group. We evaluated the sensor performance both as instrument for seismic and Newtonian noise measurement and as control sensor for mechanical suspensions.

Horizontal Monolithic Folded Pendulum Model UNISA GE 2015 (patented)

Folded Pendulum Basic Mechanical Scheme

Optical Readouts Sensitivities of Folded Pendulums compared to Ground Noise and Commercial Instruments Sensitivities

RESULTS: We show here the test results of the device configured as accelerometer. The setup consists of a Folded Pendulum Sensor equipped with an LVDT ($5 \cdot 10^{-12}$ m/sqrt(Hz) of sensitivity) and a coil-magnet actuator connected to an UDSPT INFN board for signal conditioning, conversion and processing and for the real time control of the sensing element.

Open and Closed Loop Transfer Functions

Sensitivity and Noise Budget

Seismic Noise Measurement - Preliminary Test

CONCLUSIONS:

- The monolithic mechanical folded pendulum equipped with LVDT readout has been perfectly integrated with the new UDSPT board developed by the INFN Pisa Group for Advanced Virgo.
- The performance of the integrated sensor ($2 \cdot 10^{-9}$ m/s^2/sqrt(Hz) for f<1 Hz) already satisfies the present requirement for horizontal accelerometers of the suspension control in Advanced Virgo.
- Although not yet fully optimized (there is still a large margin of improvement), the sensor can be already considered an effective instrument both for seismic and Newtonian noise measurement and a light and reliable inertial sensor for the control system of seismic attenuators of present and future gravitational wave detectors. .

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- F. Barone, G. Giordano, F. Acernese, R. Romano, "*Watts linkage based large band low frequency sensors for scientific applications*", NIM A, doi: 10.1016/j.nima.2015.11.015.
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- A. Gennai, D. Passuello, V. Boschi, G. Cerretani, C. Magazzu, M. Bitossi, C. Carlesimi, L. Rei, "*A new high performance suspension control system for Advanced Virgo*", LSC-Virgo Meeting 2015, https://dcc.ligo.org/DocDB/0121/G1501131/001/G1501131.pdf

ACKNOLEDGMENTS

We acknowledge Galli e Morelli S.r.l. and Benefortí Donatella S.n.c. for the collaboration, the suggestions and the mechanical components implementation of the Folded Pendulum model UNISA GE 2015.

Gravitational-wave Advanced Detector Workshop
La Biodola, Isola d'Elba, 22 –28 May 2016

Conclusions

• Current SA control is based on filters designed using classical Nyquist-like techniques, diagonalizing the sensor-actuator space with static matrices in order to obtain a set of single-input single-output (SISO) systems. This approach has several limitations.

• The near term plan (<1 yr) is:

- Keep current controller but monitor them continuously system performance using Kalman filters
- Design and Implement MIMO optimal controllers and evaluate their performance
- Design and Implement adaptive versions of the controllers

• The long term plan (>1 yr) is :

- Test and eventually install new inertial sensors: accelerometers and gyroscopes
- Implement IP tilt-control