LIGO-Quiet Hydraulics 101

LIGO Livingston Observatory

March 5 2004

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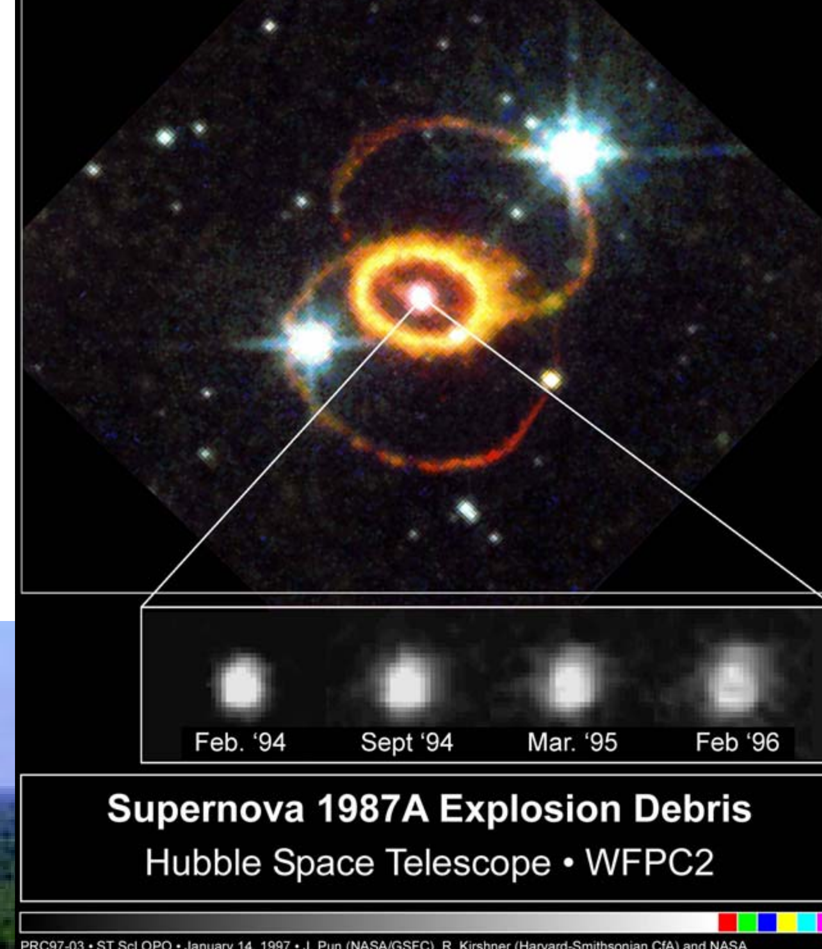
Originally prepared for the
Quiet Hydraulics Consultancy Board
Rich Duder, Stephen Osder

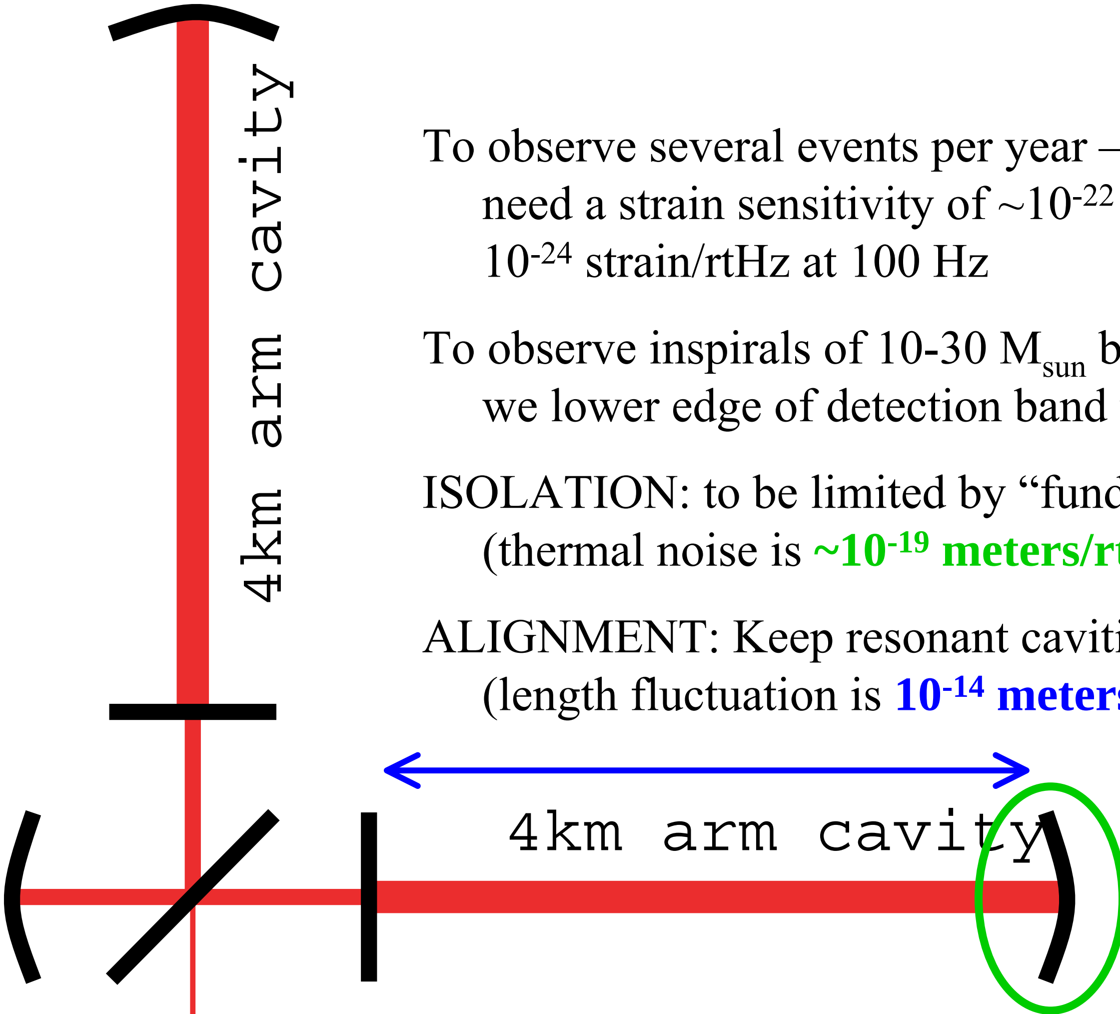
LIGO

a new window on the universe



LIGO Livingston Observatory – courtesy of the LIGO webpage

Gravitational waves are difficult to detect.



Advanced LIGO specs

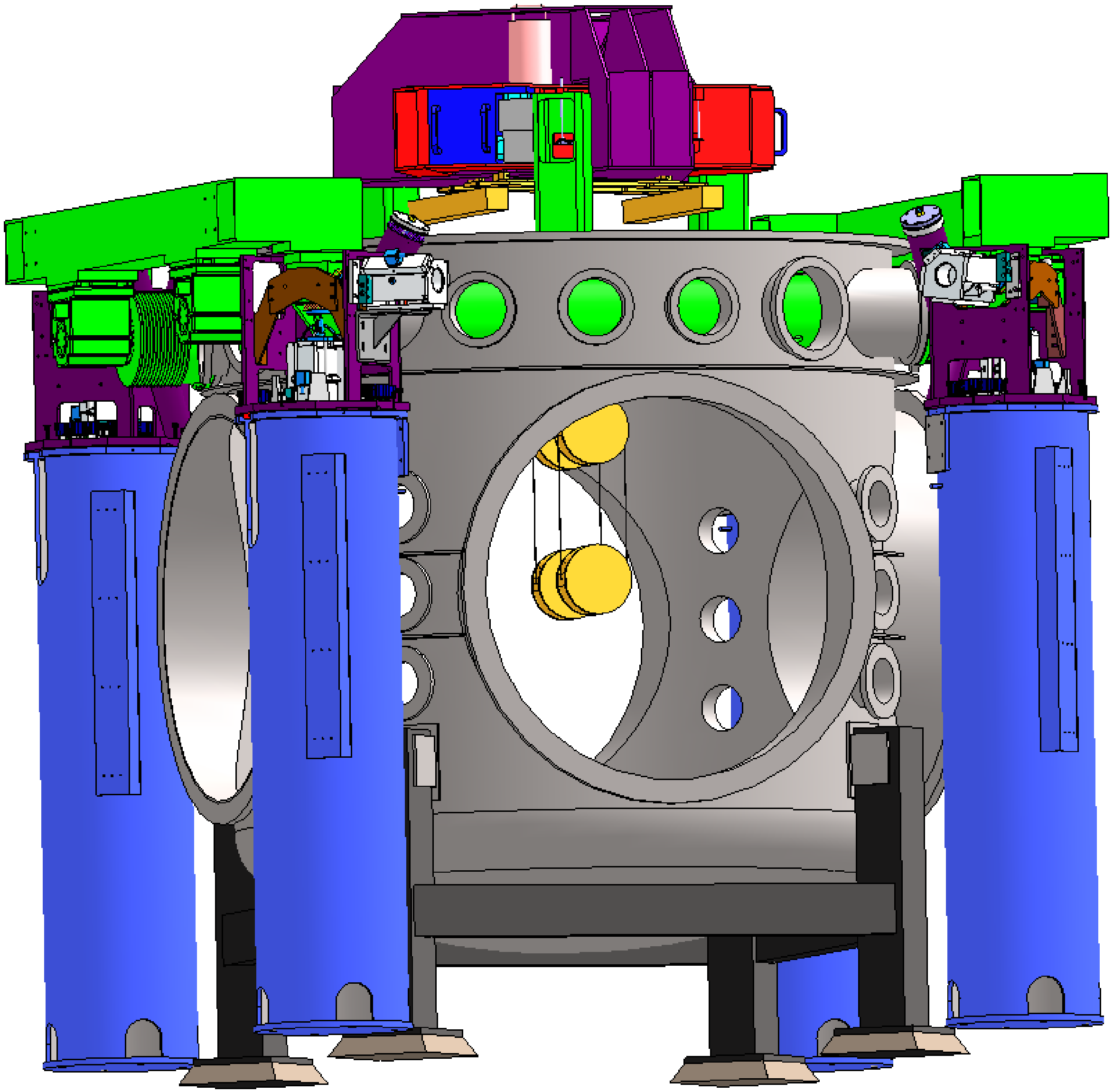
To observe several events per year –
need a strain sensitivity of ~10^{-22} rms around 100 Hz
10^{-24} strain/rtHz at 100 Hz

To observe inspirals of 10-30 M_{sun} black holes
we lower edge of detection band to 10 Hz

ISOLATION: to be limited by "fundamental" processes
(thermal noise is **~10^{-19} meters/rtHz at 10 Hz**)

ALIGNMENT: Keep resonant cavities at operating point
(length fluctuation is **10^{-14} meters rms**)

Advanced LIGO Seismic Isolation and Alignment System



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Motivation for an External Stage

- Isolation
  - From the micro-seismic peak to 10 Hz
- Alignment
  - Seasonal Temperature Changes, Tides
- Control Reallocation
  - Reduce control effort / noise from inner stages
- High Impedance Support
  - Inner stages react against stiff, damped foundation

Today - My Purpose

A more detailed understanding of how the hydraulic system works

A bit of the history

Some perspective on how Stanford thinks about the system.

Three cool facts

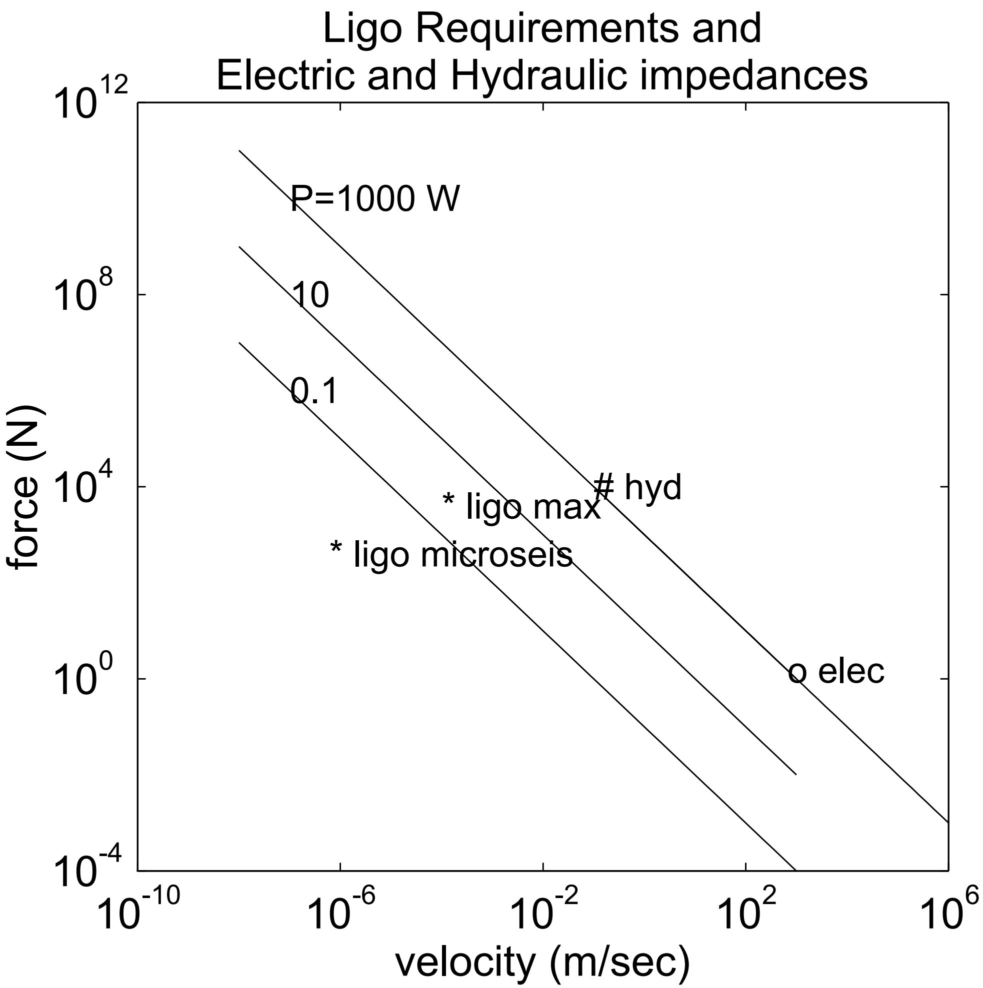
Performance Requirements

- Range of Motion
  - Mechanical Adjustment: 5 mm
  - Active Control: +/- 1 mm

- Response
  - Initial Response: 1 mm in 12 sec (80 μ/sec)
  - Bandwidth: 0.1 - 10 Hz

- Resolution and Noise
  - Reduce the ground motion by 15 from 0.1 to 3 Hz

Actuators



Outer Stage

Laminar Flow Hydraulic

- Well matched to requirement
- easily maintains large offsets
- stiff and well damped

Inner Stages

Electromagnetic

- quiet
- force actuation is independent of position of support
- high bandwidth

Hydraulics is a clear choice for

- Impedance Match
- Inelastic Foundation

Can it provide

- Quiet Actuation (No Stiction)
- Quiet Control (No Turbulence)

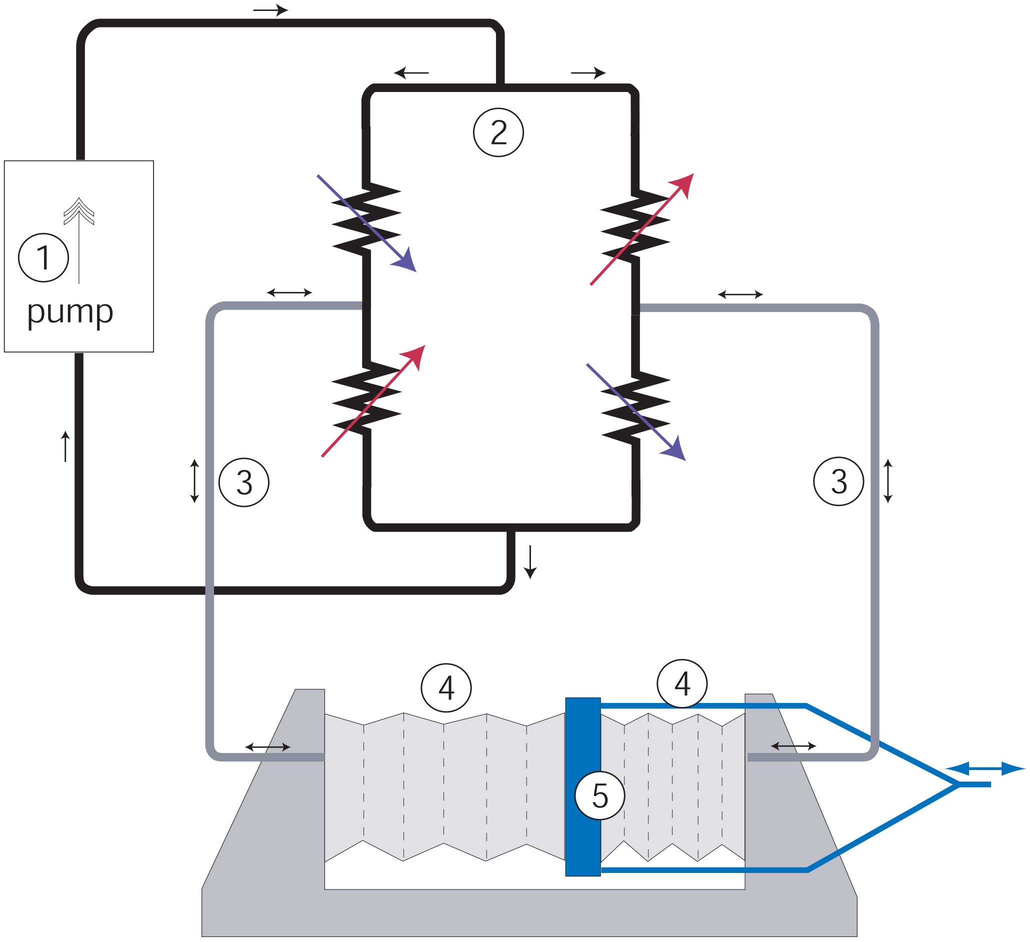
Smooth actuation:

- Elastic Actuator-Bellows, or
- Dynamic Seals (Open system unacceptable)

Quiet operation

- Laminar Flow, and
- Power supply isolation

Quiet-Hydraulic Actuation



History of Valve Development

1. Oostman design for QH machine tools
2. HSC design
3. HSC with modified nozzles
4. Dynamic Valve to the rescue
5. Current design, Valve insert and its role
6. Performance
    1. Freedom from turbulent disturbances
    2. Linearity
    3. Calibration Techniques
    4. Procurement and roles and responsibilities

History of Bellows Actuator

- 1 dof device. Kinematics of elastic decoupling
- Conflict in design: range of motion vs ‘hydraulic’ resonance
- Design principle: don’t depend on control for damping:KIS

  Hydraulic resonance damper

- Material and fabrication history
- Leakage and contamination are a design drivers

  No threaded joints, all o-ring seals

  Weldments where possible

Power Supply Design

- Commercial components except LFR
- LFR (Laminar Flow Resistors)…free of turbulence
- Heat exchanger is the distribution plumbing

  End Stations are air-conditioned (a/c)
- Pumps are isolated on pad with a/c machinery
- Fluid choice
  1. High viscosity, μ=0.086 Pa-sec
  2. No mineral oil (optical sensitivity)
  3. Compatible with COTS pumps & components

Schedule

- Introduction
- Motivation and Specs
- The Valve
- The Actuator and Control
- Power Supply

Outline

- Description of our requirements for isolation and alignment
  - Advanced LIGO and Livingston retrofit
- Valves
  - Basic function
  - laminar flow math
  - linearization of the control
- Distribution System
  - Parts
  - Controlling Pump Noise
  - Controlling Cross-regulation Noise

Advanced LIGO specs

Isolation

ground motion at 10 Hz: ~$3*10^{-10}$ m/rtHz

requirement at 10 Hz: 10^{-19} m/rtHz

difference is 9½ orders of magnitude

Alignment

microseism at .16 Hz: a few 10^{-6} m

tides: +/- 150 µm

we'd like (seasons, etc): +/- 1 mm

requirement: 10^{-14} m rms

difference is 8 - 11 orders of magnitude

Advanced LIGO specs

Seven Layers of Isolation and Alignment

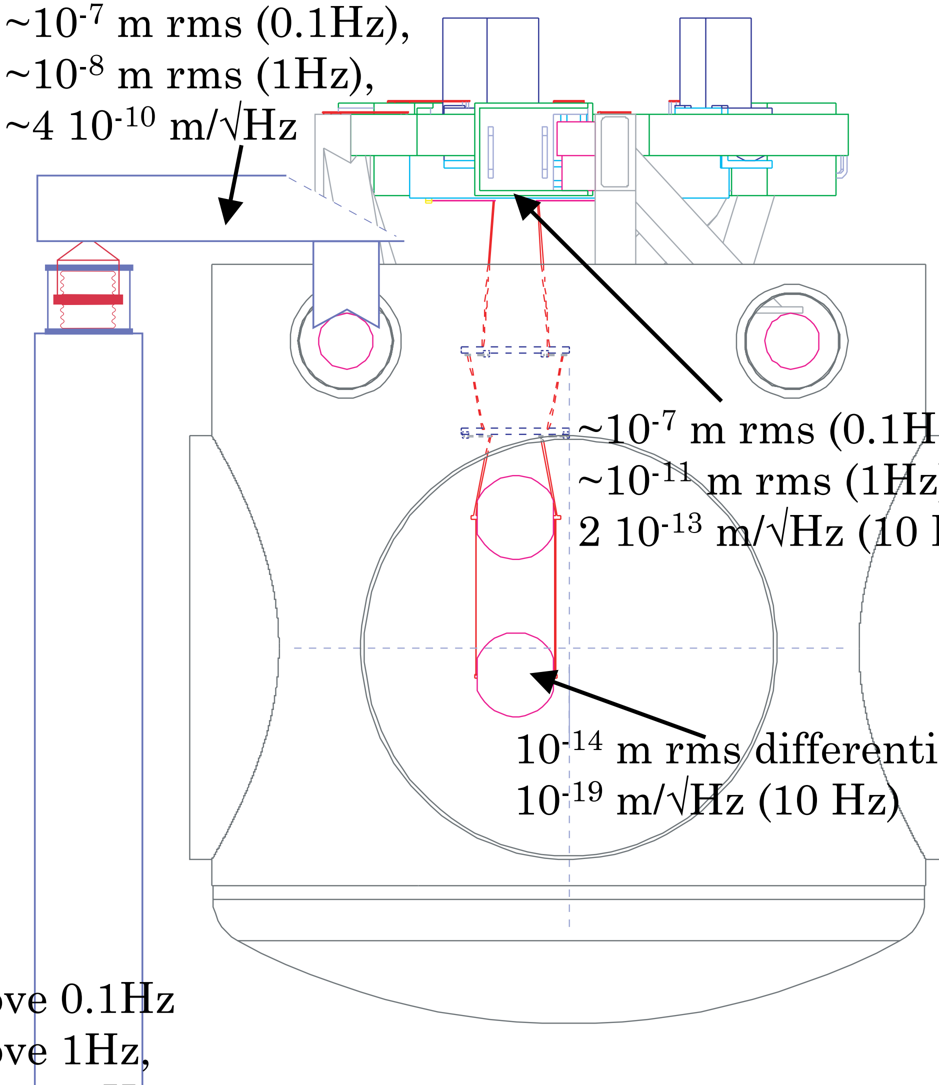
LIGO-I Subsystem	LIGO-II Subsystem
Single-pendulum test mass suspension →	Quad-pendulum test mass suspension
Mass-spring four-layer isolation stack →	Two-layer active noise reduction platform
1-DOF, 5 Hz BW Fine actuation system →	6-DOF, 2 Hz BW Hydraulic fine actuation system
6-DOF, 0 Hz BW coarse actuation system →	6-DOF, 0 Hz BW coarse actuation adjustment in hydraulic system

Minimize thermal noise, passively isolate test mass

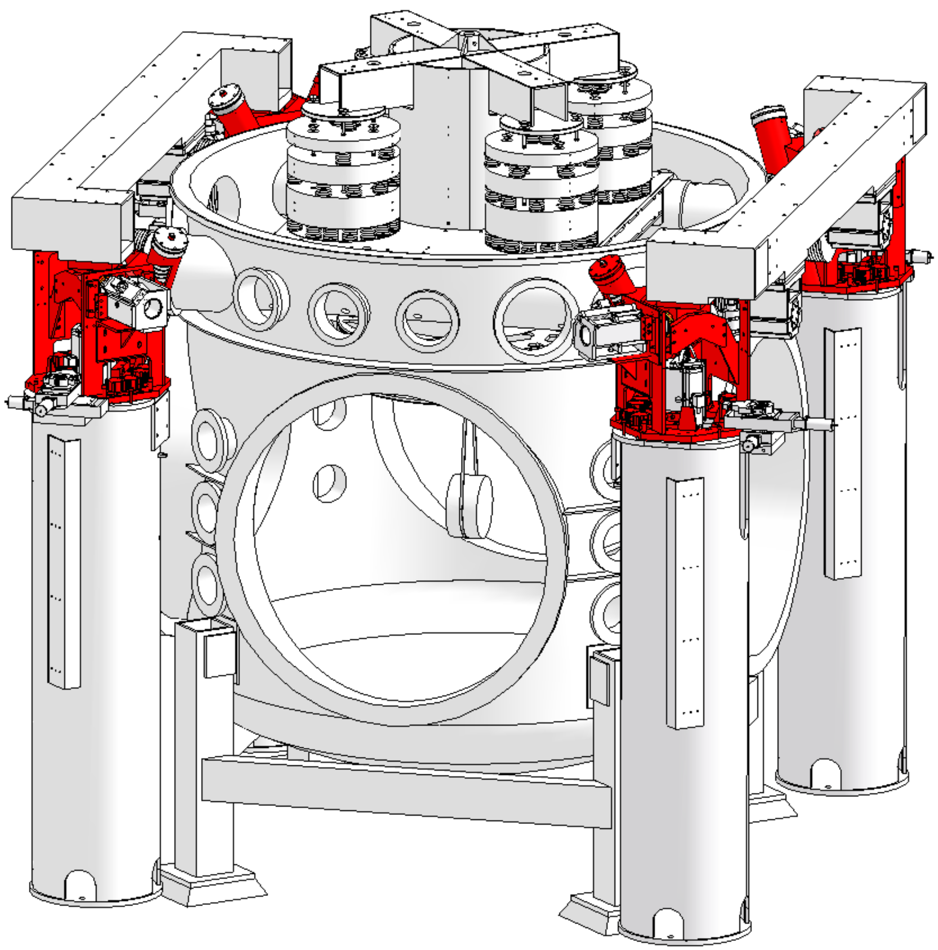
GW band isolation, (LIGO-II: RMS motion reduction)

Feedback/ feedforward compensation of earthtides and microseismic motion

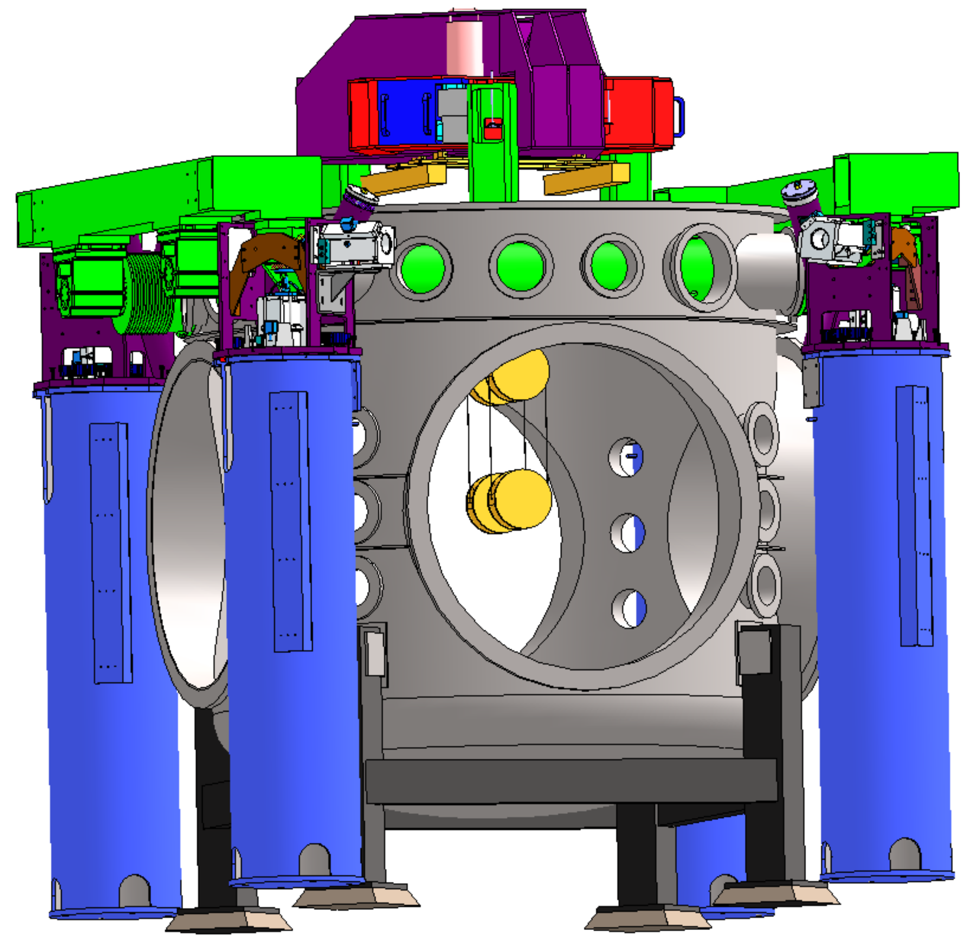
Coarse alignment during installation and occasional drift correction



Isolation and Alignment Systems

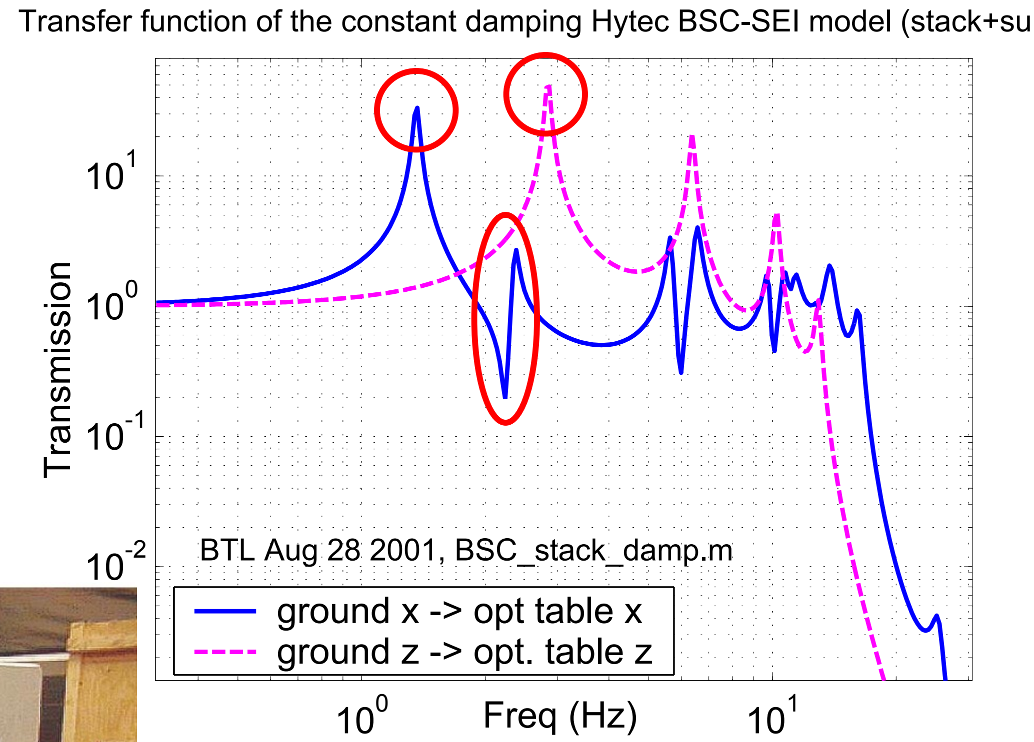


Initial LIGO



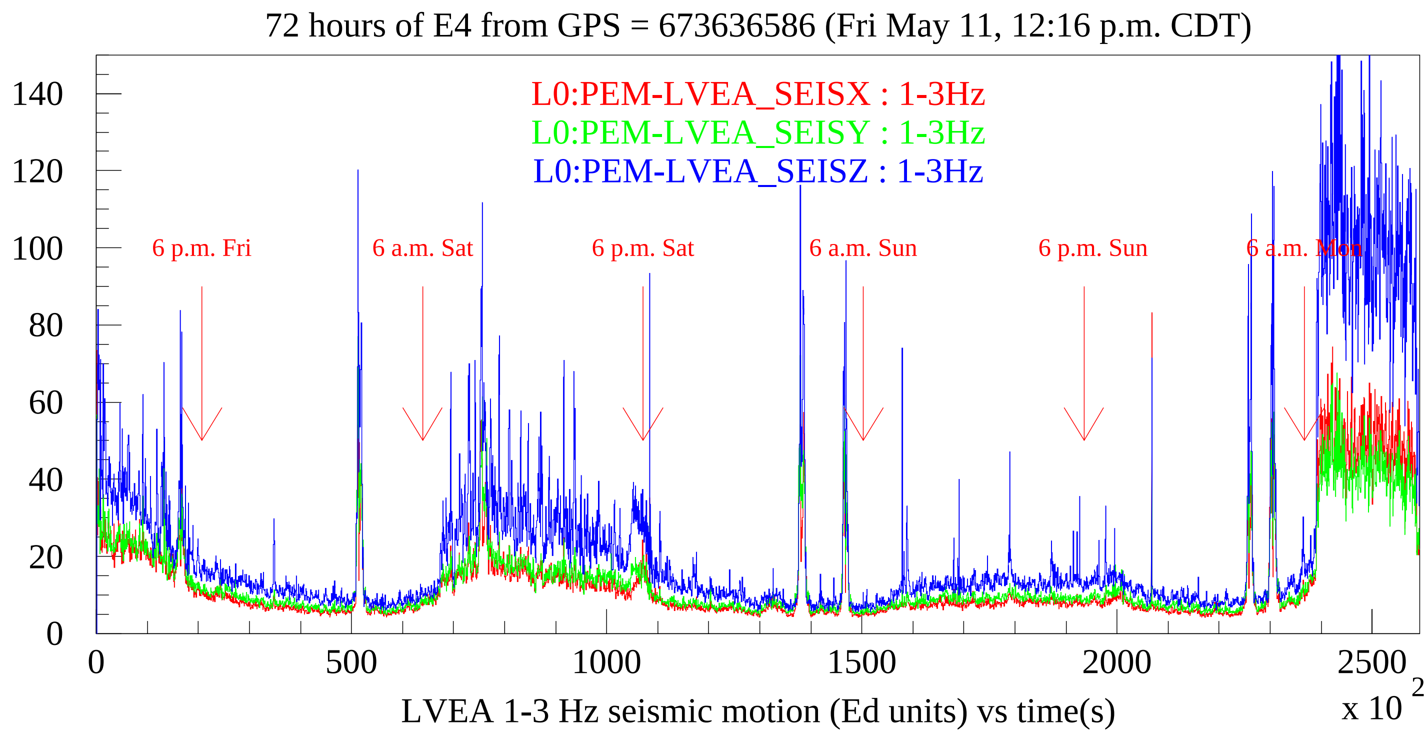
Advanced LIGO

Problem with Existing System

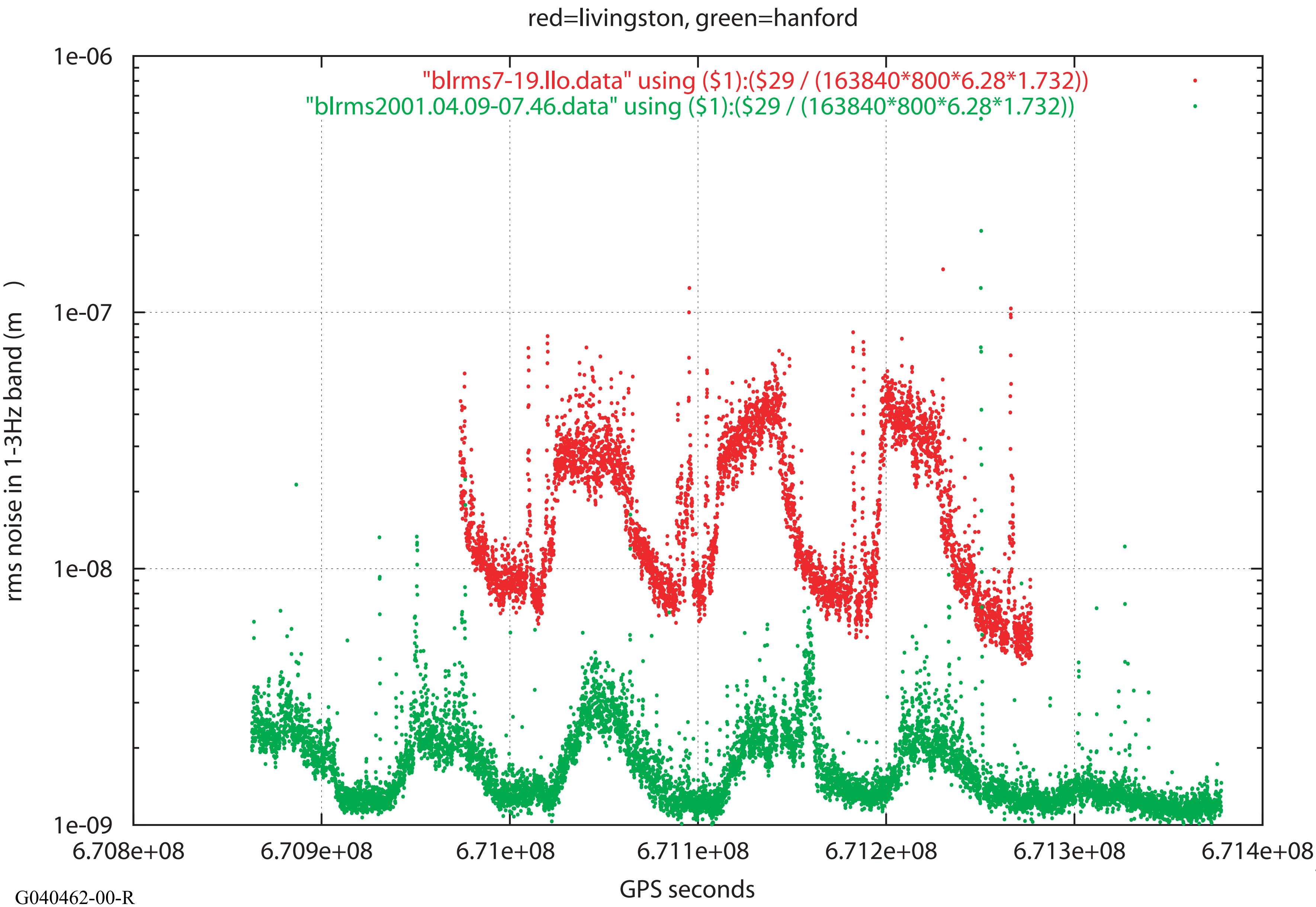


Picture courtesy of Eric Ponslet, Hytec Inc.

Monday Morning

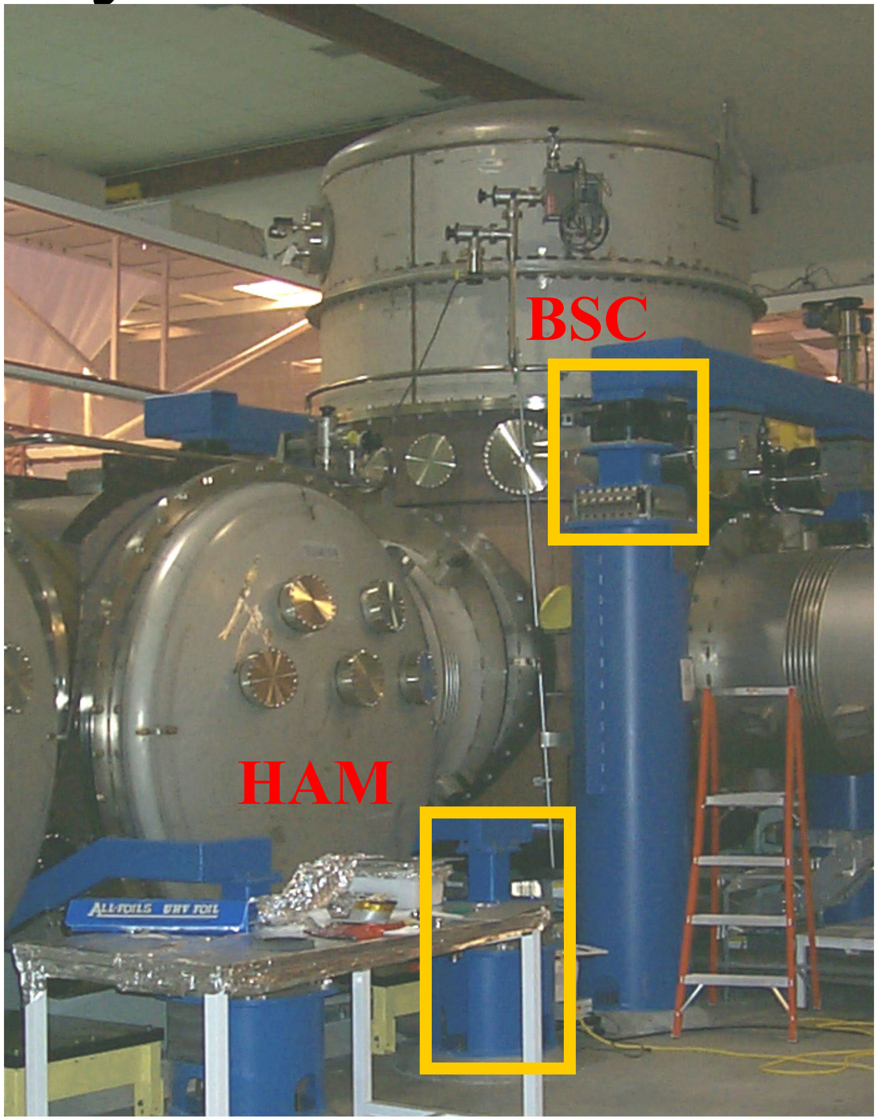


and the Rest of the Time…

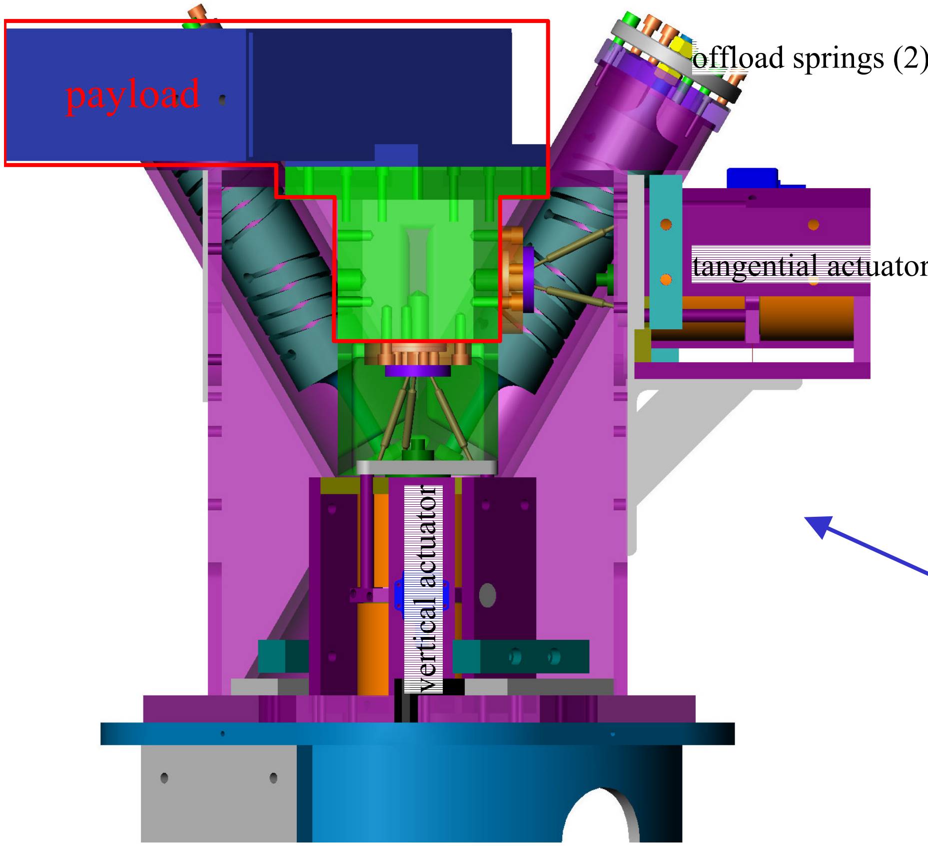


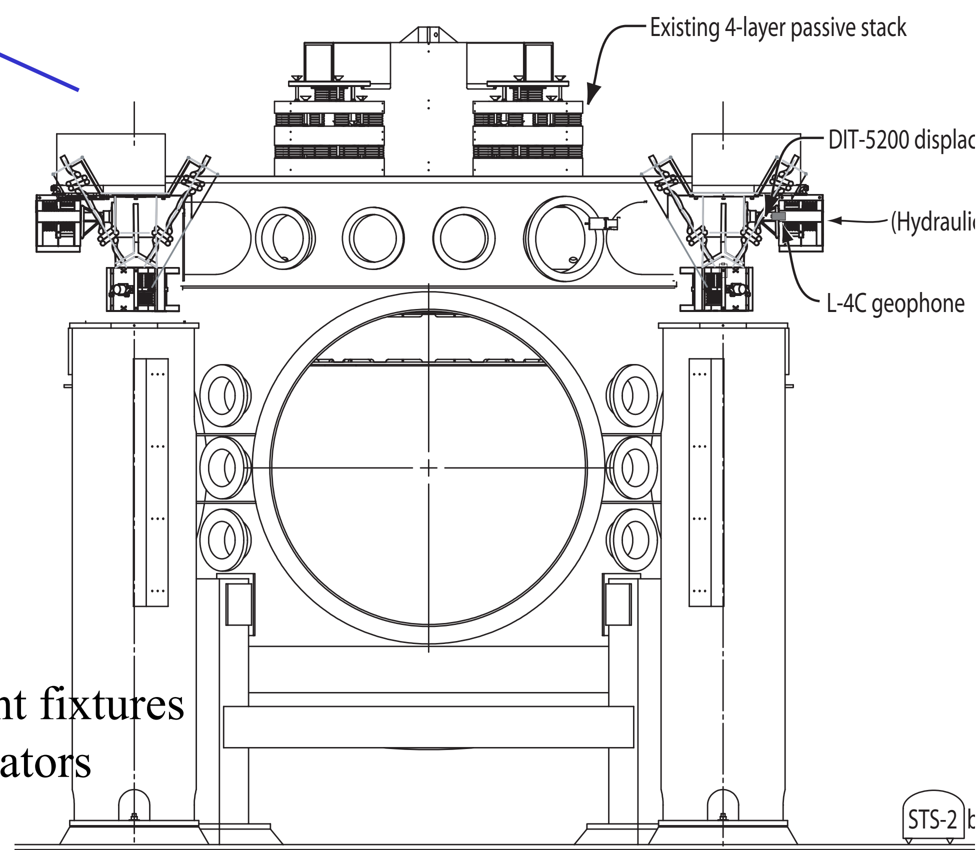
Placement of an External Isolation System

- Install an isolation and alignment system without opening the chambers.
- Replace the coarse and fine actuators which are currently between the pier and the cross beam weldment (which hold the support tubes and support table)
- New system will act to hold support table still in the presence of ground motion



Placement of the Actuators and Offload Springs





Drawings courtesy of Ken Mason

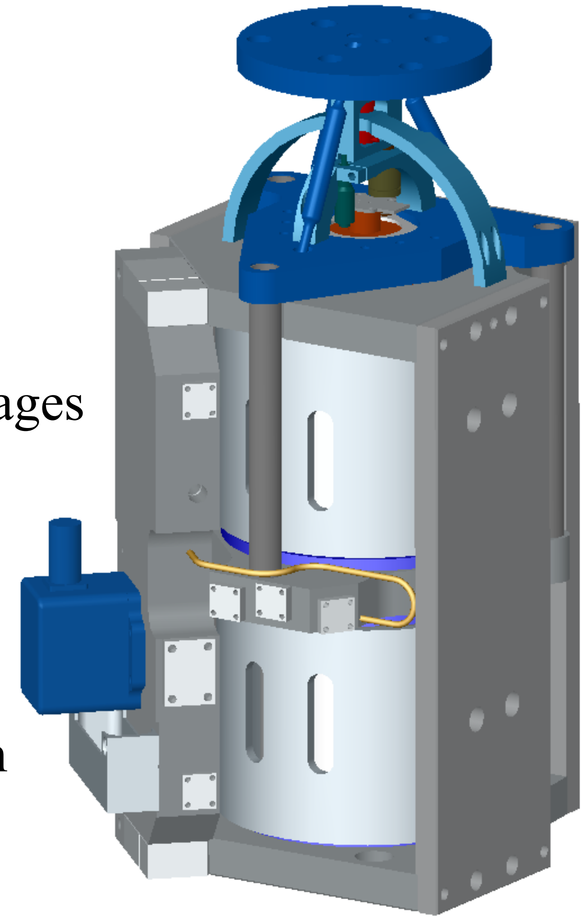
All the pier-top components are mounted into a frame

Frame holds:

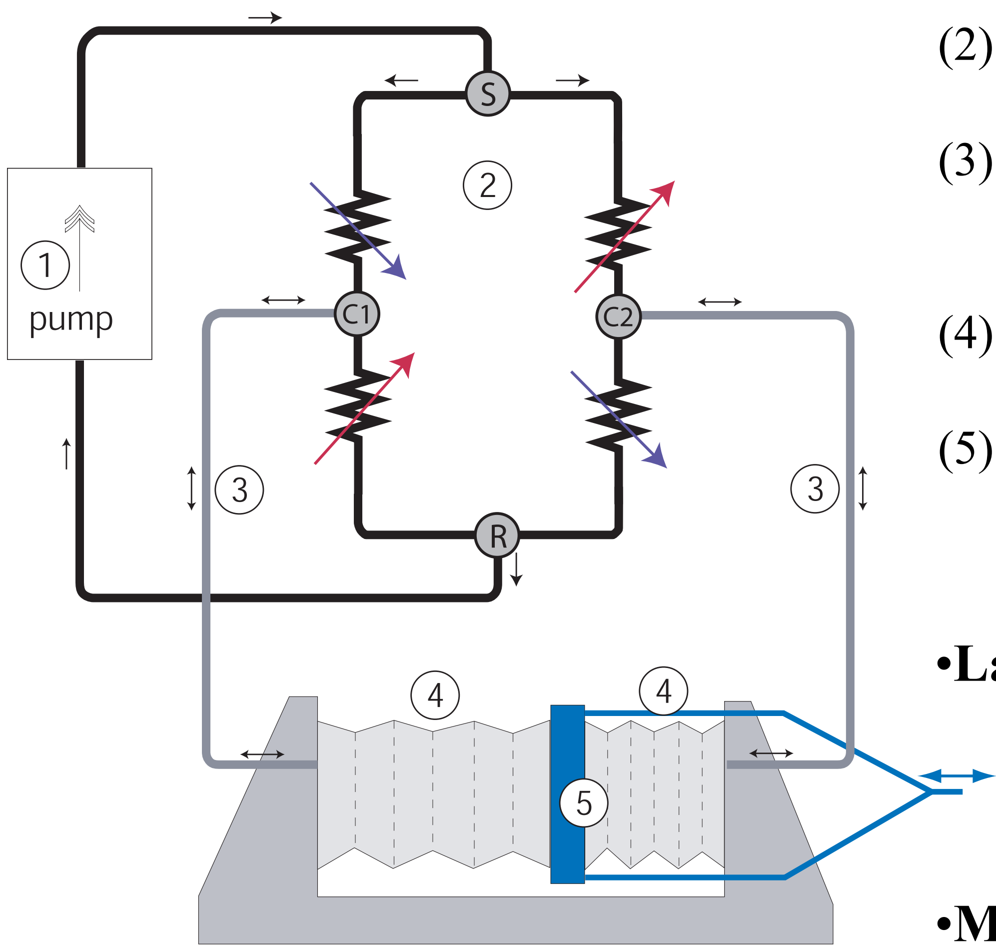
- 1 vertical and 1 tangential actuator,
  (isolation and alignment in 6 DOF)
- Pair of offload springs and initial alignment fixtures
- Sensors which are not included in the actuators

Motivation for Hydraulic Actuators

- Isolation
  - From the micro-seismic peak to 3 Hz
- Alignment
  - Seasonal Temperature and ground water changes
  - Tidal correction +/- 150 microns ~twice per day
- Control Reallocation (offload authority) from inner stages
  - minimize heat load
  - decrease noise from power supplies
  - maximize available authority
- High Impedance Support
  - Inner stages react against stiff, damped foundation



Hydraulic Actuator Basics



(1) Pump supplies a constant flow of fluid to the actuator.

(2) Fluid flows continuously through a hydraulic Wheatstone bridge.

(3) By controlling the resistance, one generates differential pressure across the bridge, which are connected to

(4) Differential bellows which act as a stiction-free piston.

(5) The actuator plate is between the bellows, and is connected to the payload with a flexure stiff in 1 DOF

- **Laminar flow**
  - high viscosity (.086 Pa-sec = 86 x water),
  - low velocity (80 microns/ sec.),
  - fluid path geometry.
- **Motion with flexures**
- **Offload springs to keep bridge balanced**
  - common mode rejection of pump noise

History of Valve Development

Oostman design for QH machine tools

1. HSC design
2. HSC with modified nozzles
3. Dynamic Valve to the rescue
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5. Performance
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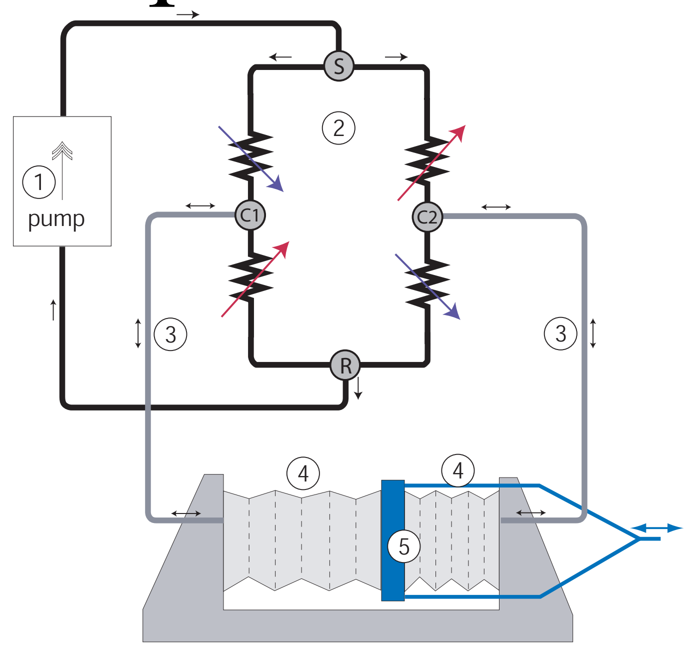
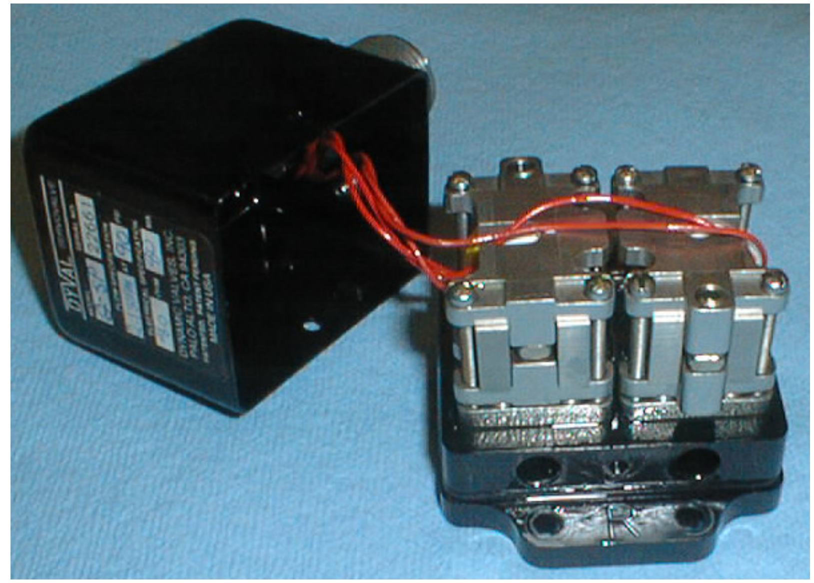


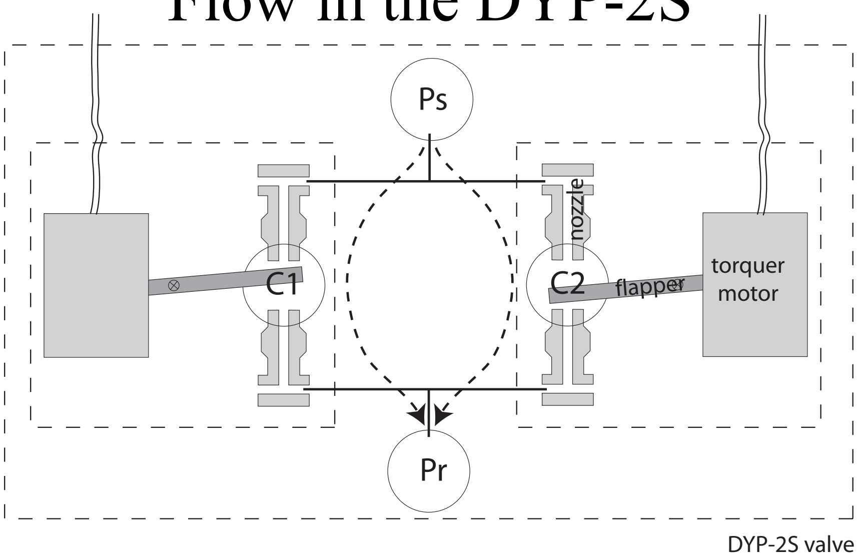
Hydraulic Valve forms the bridge

- Differential bridge in a single valve body
- 4 nozzles – one for each resistor in the bridge
- Original nozzles replaced with custom units shown below right.



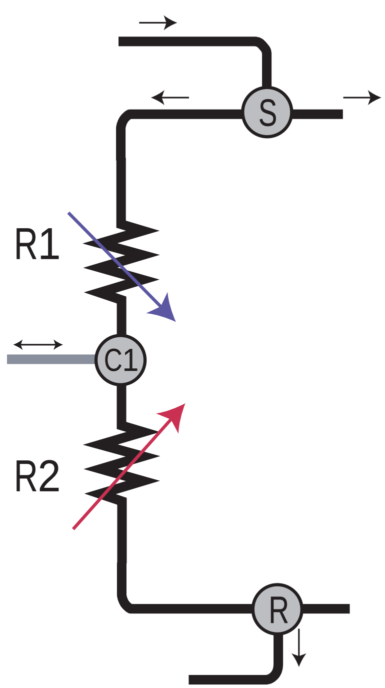
Parker DYP-2S valve

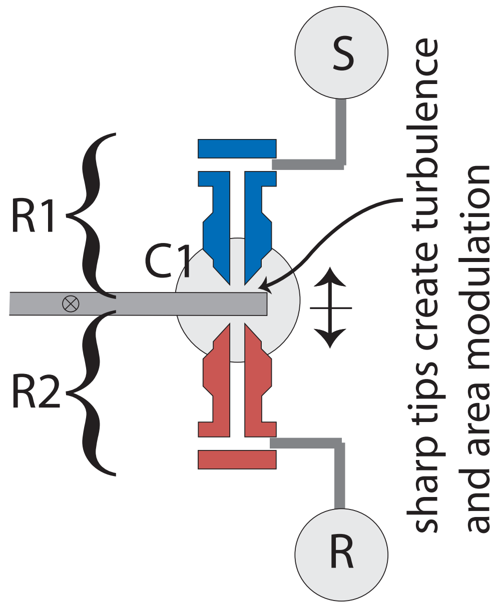
Flow in the DYP-2S



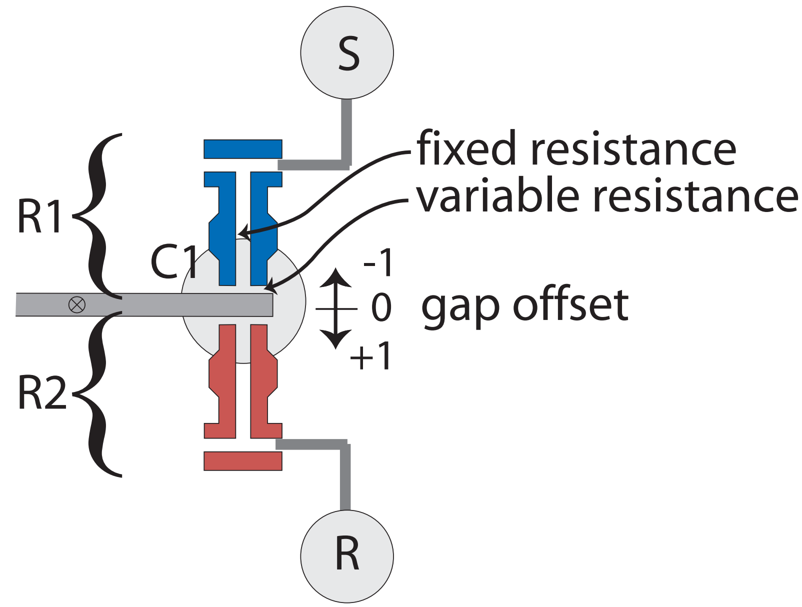
The new nozzle

Nozzles in the Control Valve



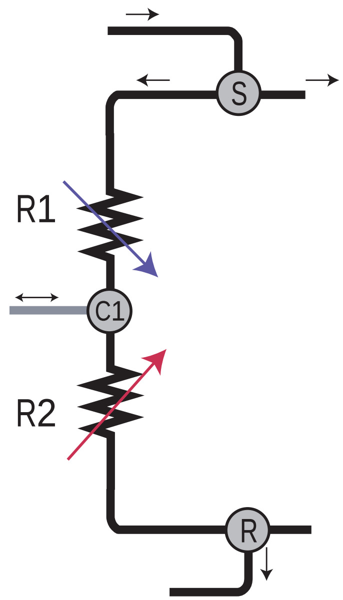


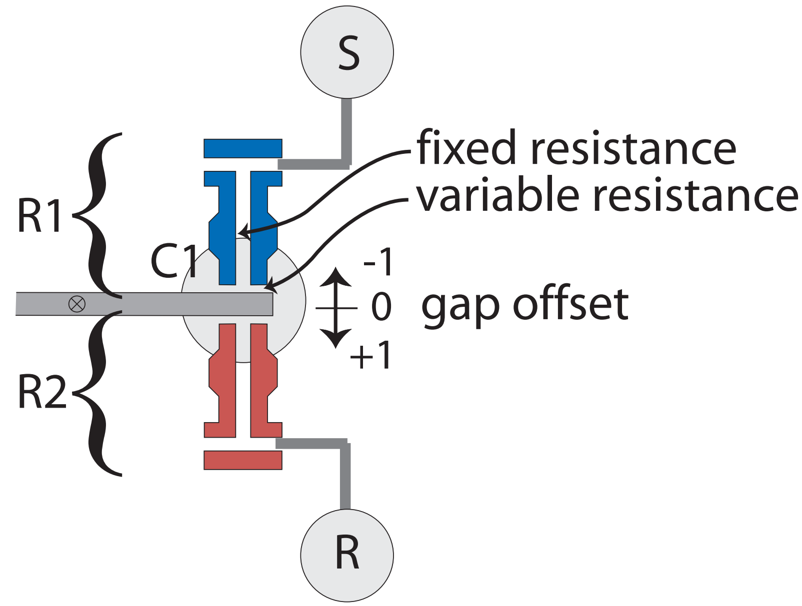
from Parker



Laminar flow

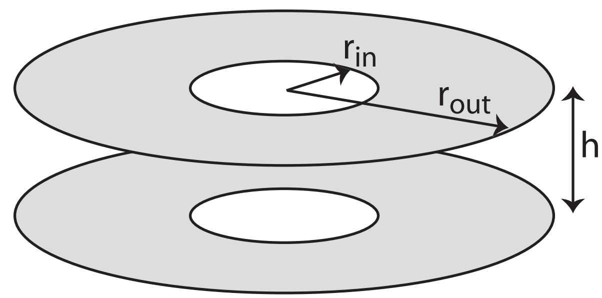
Nozzle Math





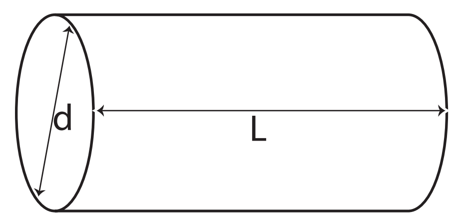
radial flow between parallel washers

$$R_{washers} = \frac{6\mu}{\pi \cdot h^3} \cdot \ln\left(\frac{r_{outer}}{r_{inner}}\right)$$

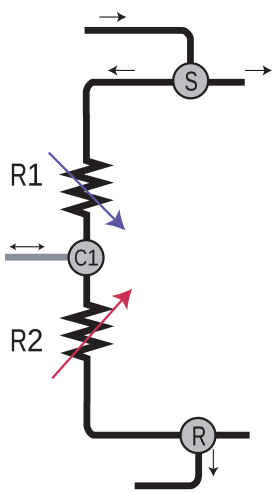


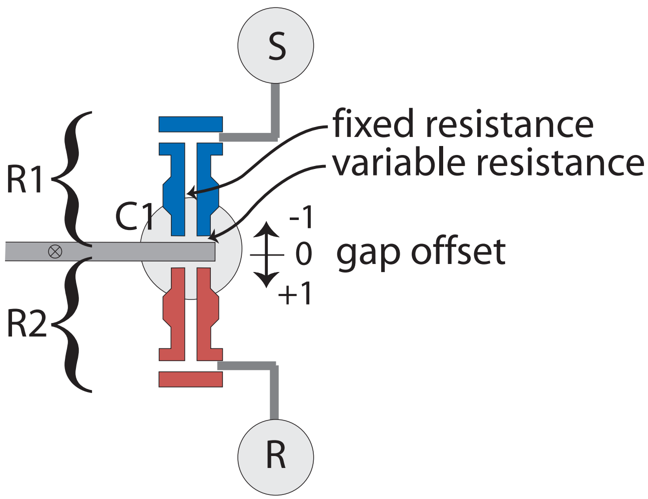
flow along a pipe

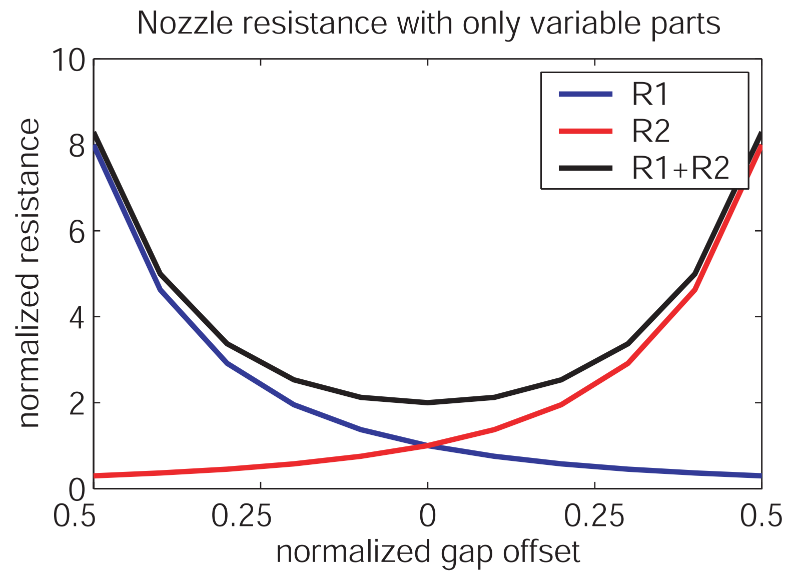
$$R_{pipe} = \frac{128\mu L}{\pi \cdot d^4}$$

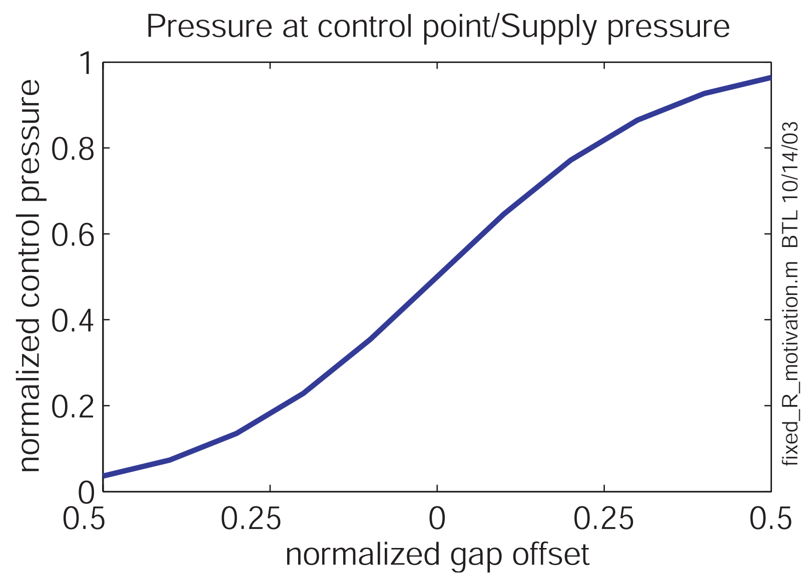


Nozzle with no fixed resistance

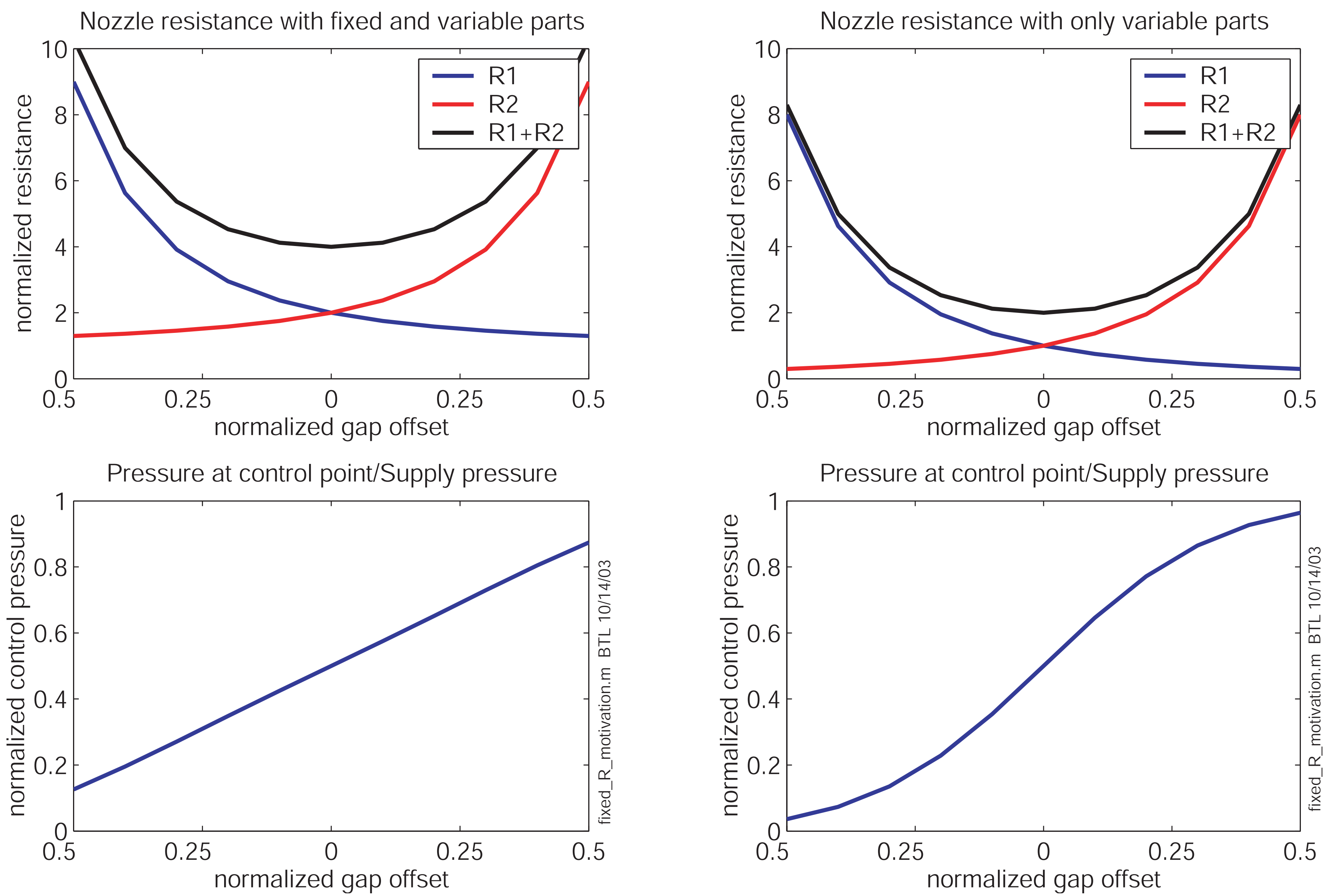








With and without fixed resistance



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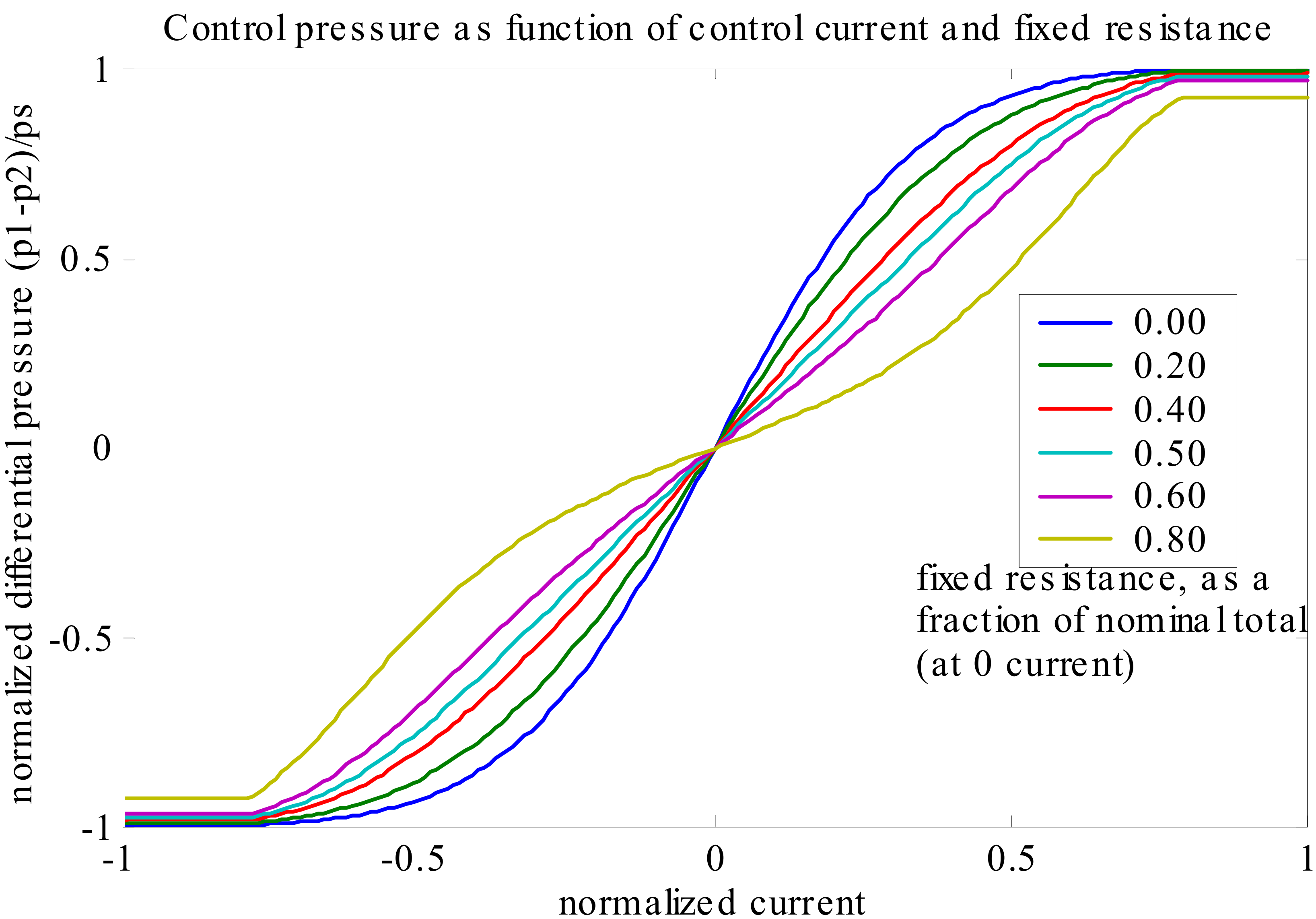
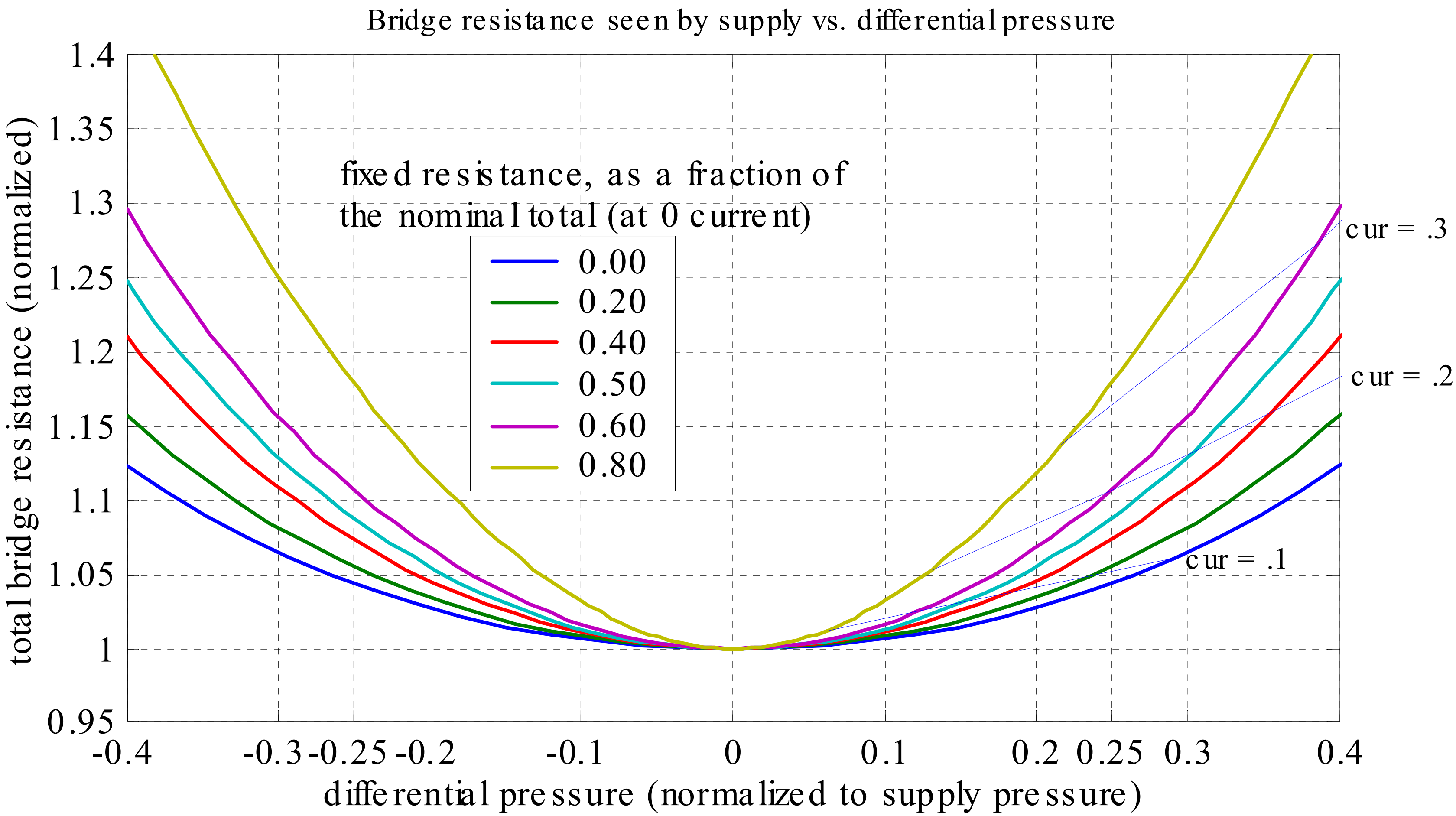
Choosing Nozzle Parameters



load impedance of actuator



Setup and Calibration of the Valve

Nozzles must be set to the correct offset from the flapper

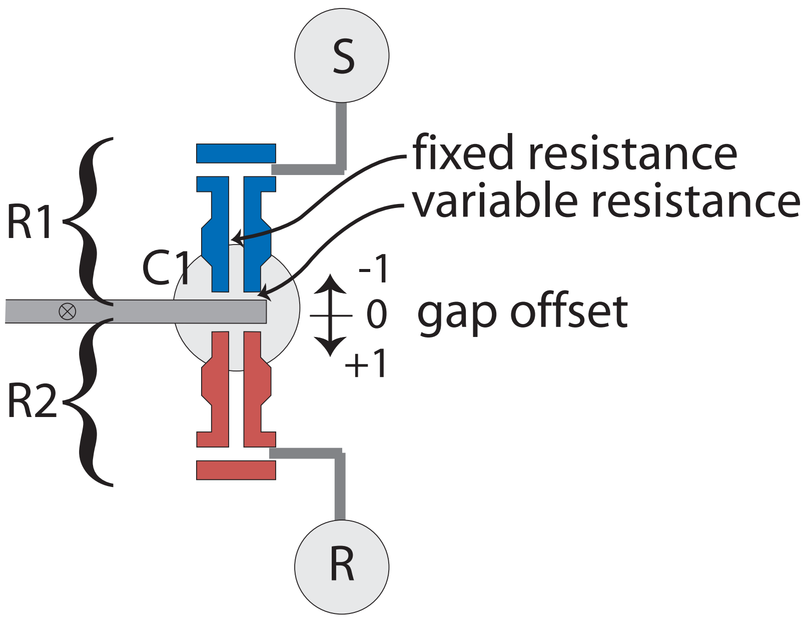
nozzles come have built-in 10-56 fine thread for adjustment in-situ

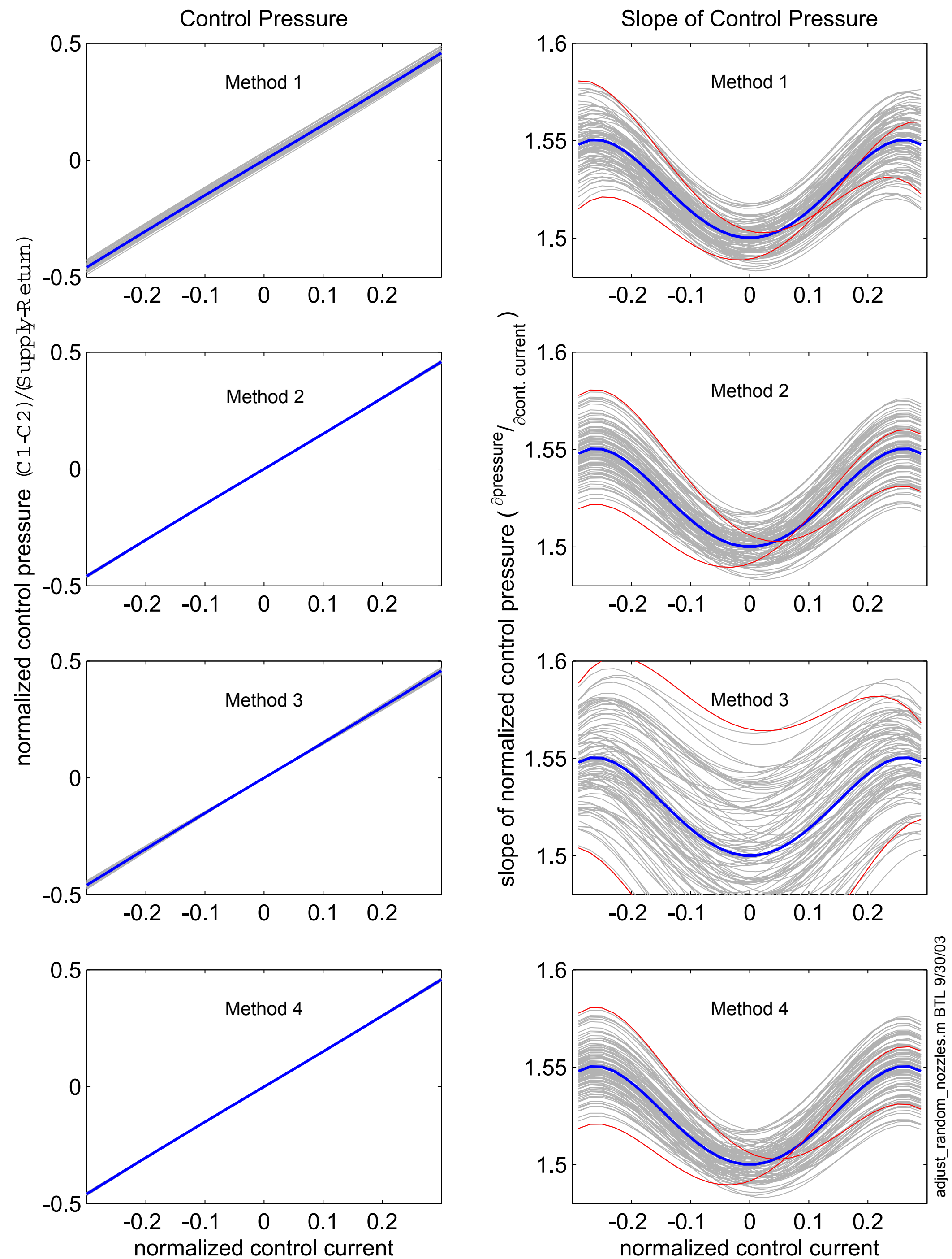
We are making a calibration station to do the nozzle setup, and measure the pressure recovery vs. control current (in the lab)

Matching the fixed resistance gives self-calibration immunity to viscosity changes.

We have developed a method to give the best response in the presence of small variations in the fixed resistance

Best Method



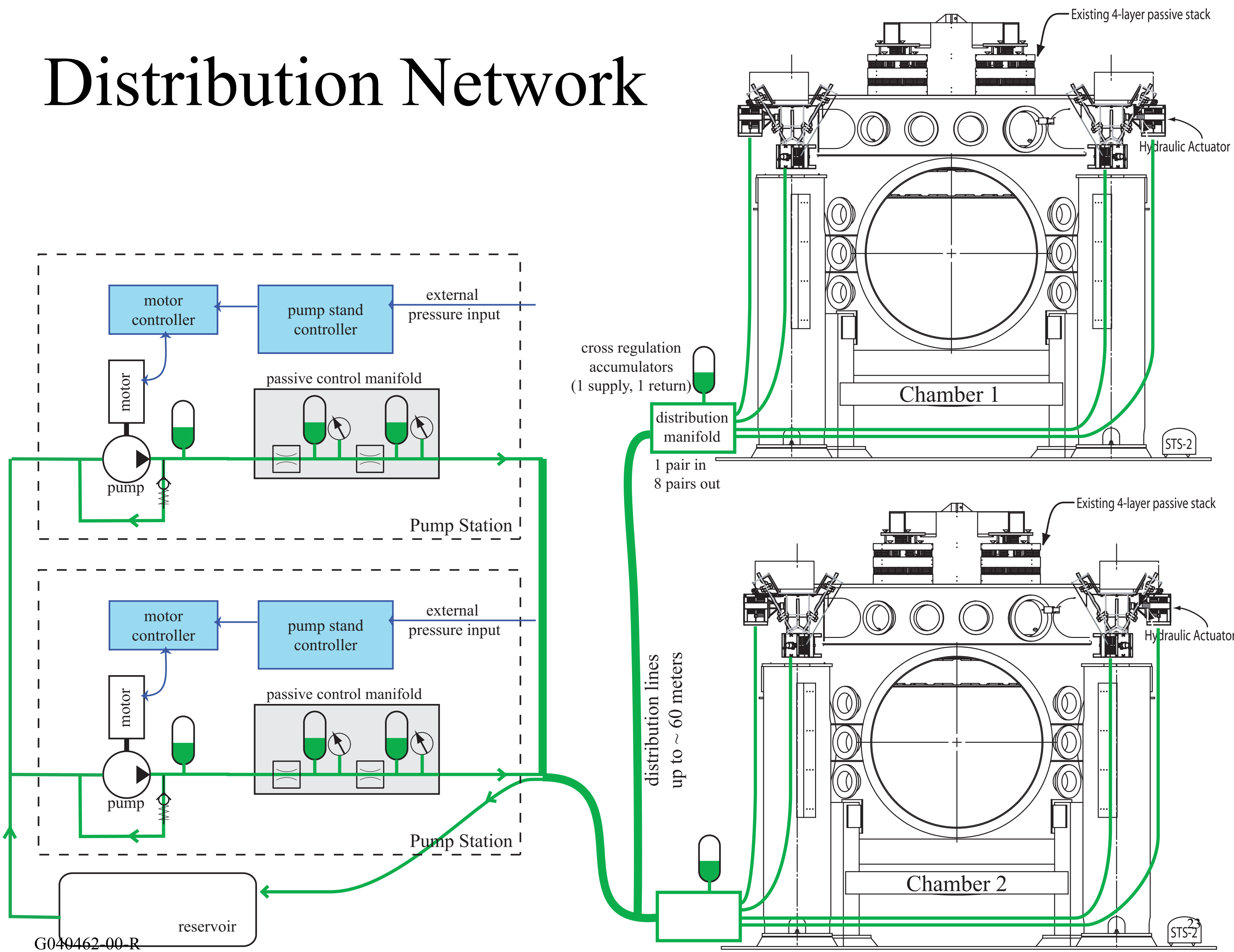


see *Calibration of the Modified DYP-2S Valves*, Brian Lantz

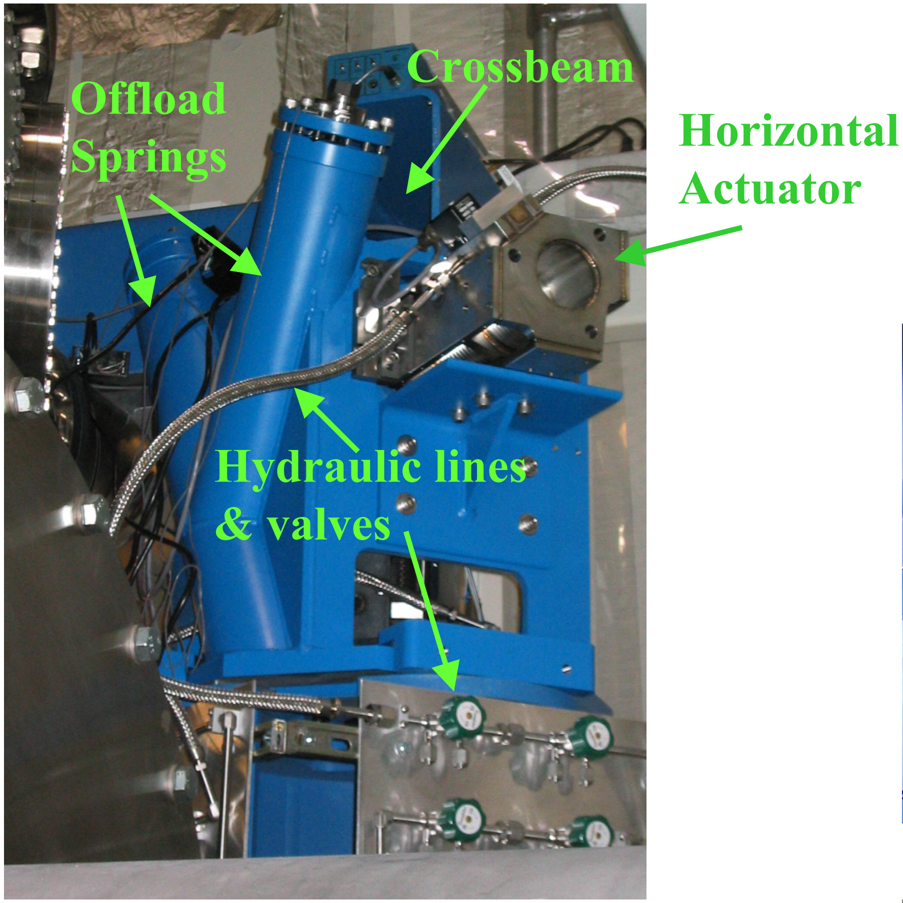
Valve conclusions

- Valve is a critical, non-standard part.
- Simple modification to existing valves can be done.
- New nozzles are:
  - quiet
  - linear
  - susceptible to temperature variations, but addressed by:
    1) temperature control of the room
    2) closed loop control of the actuator
    3) closed loop control of the pressure drop across actuator
- Custom nozzles require custom installation fixture

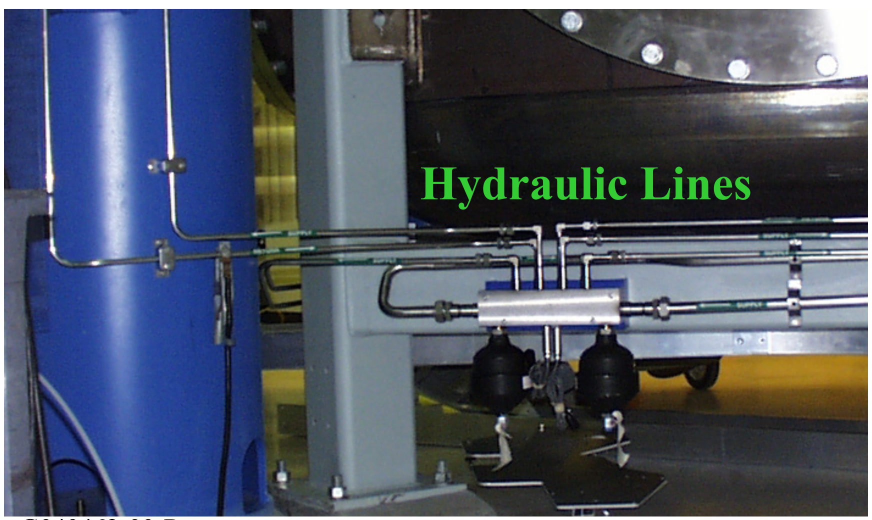
Distribution Network

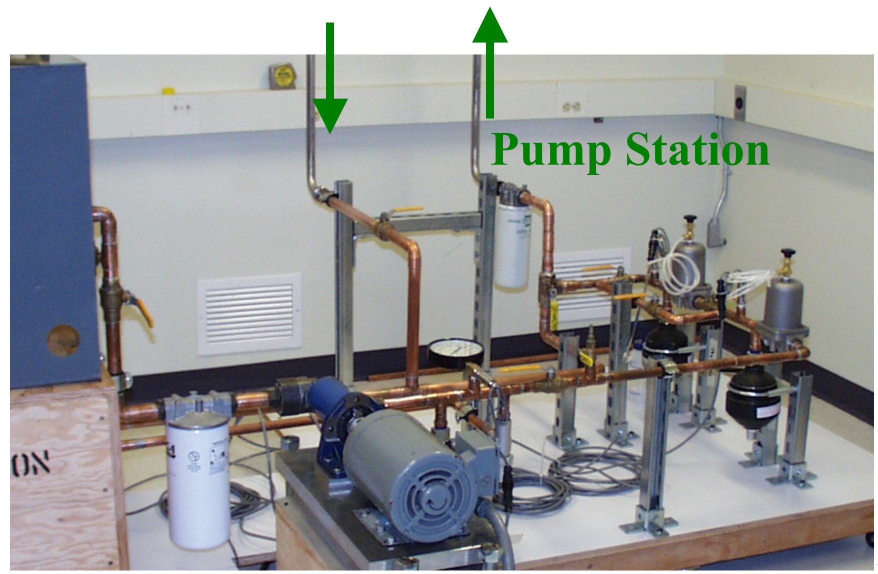


Hydraulic Installation

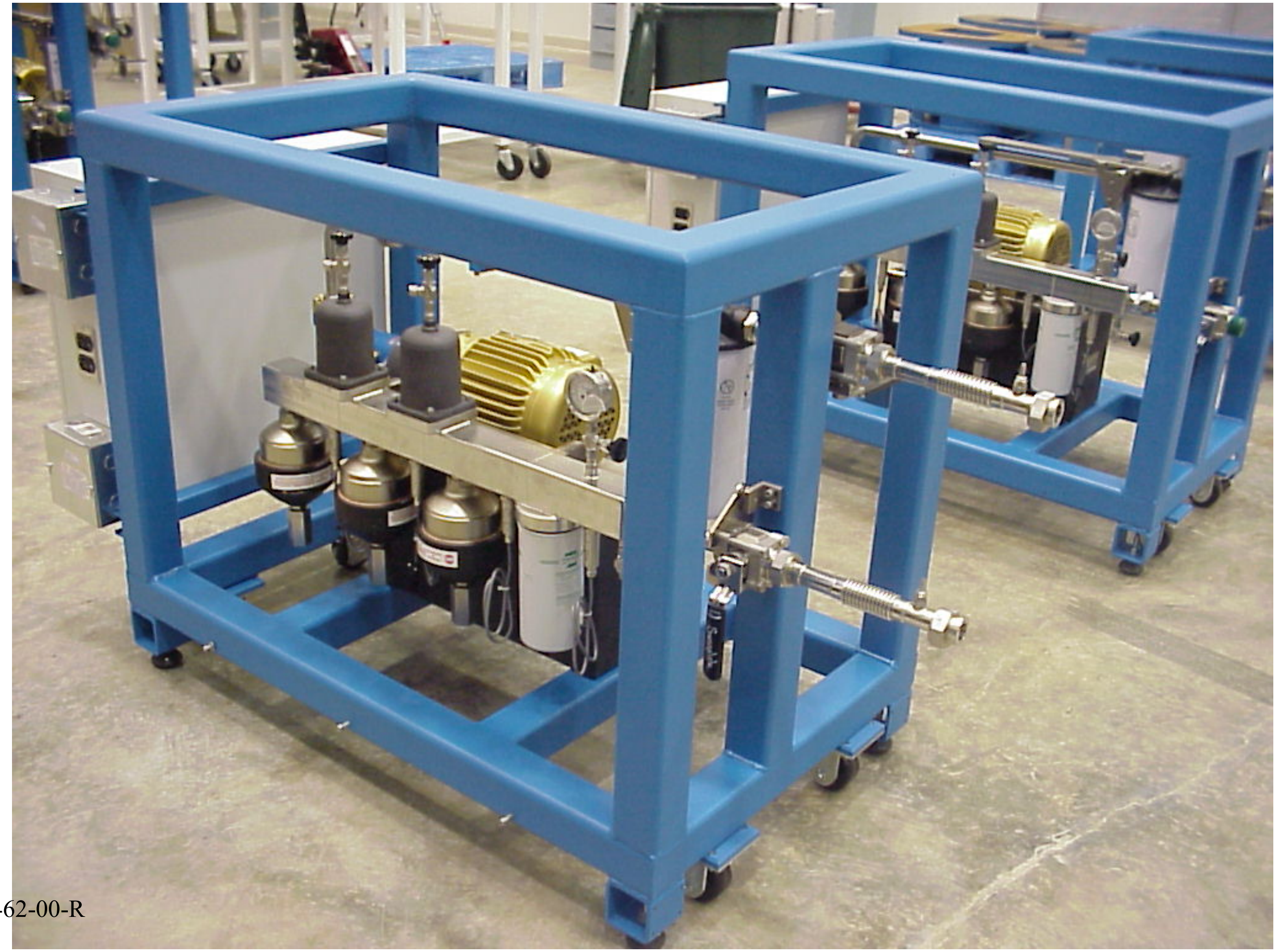


fun!





Pumps at LLO



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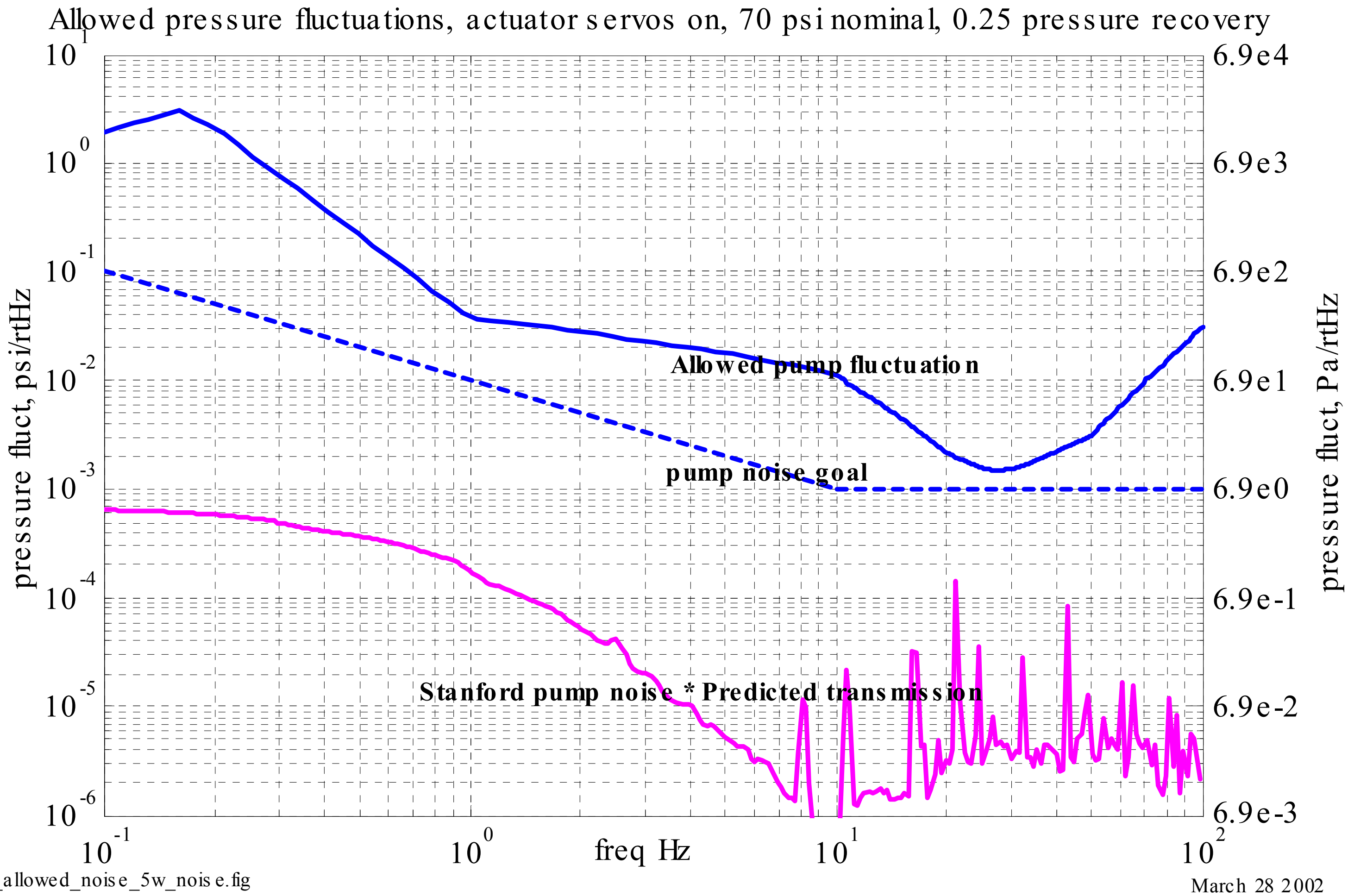
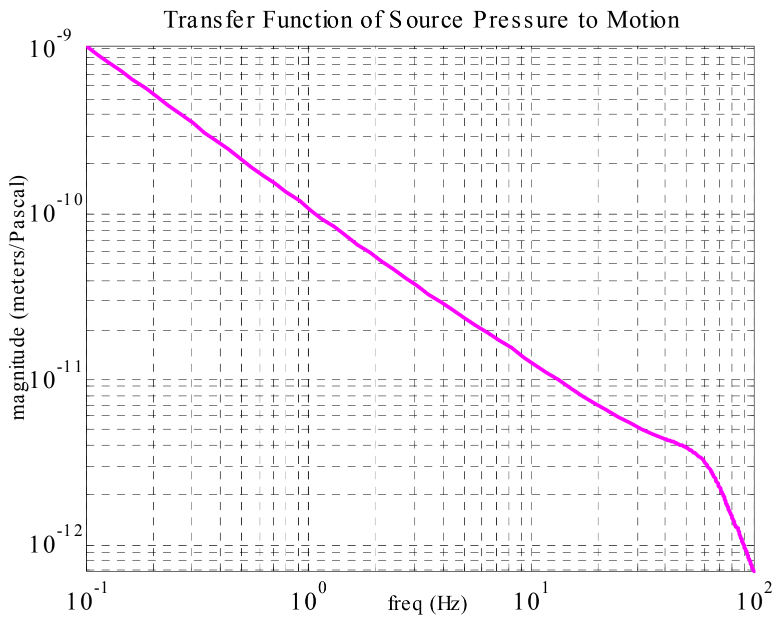
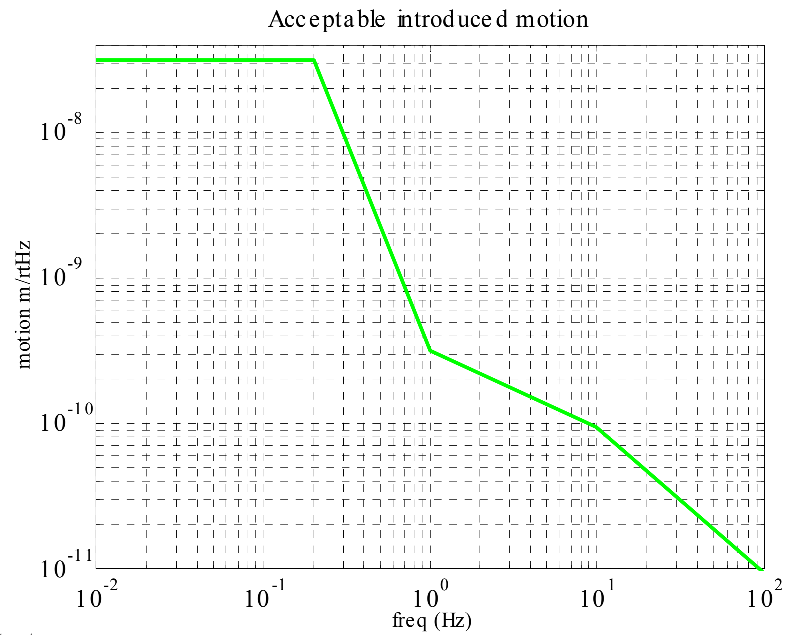
Allowed pump noise

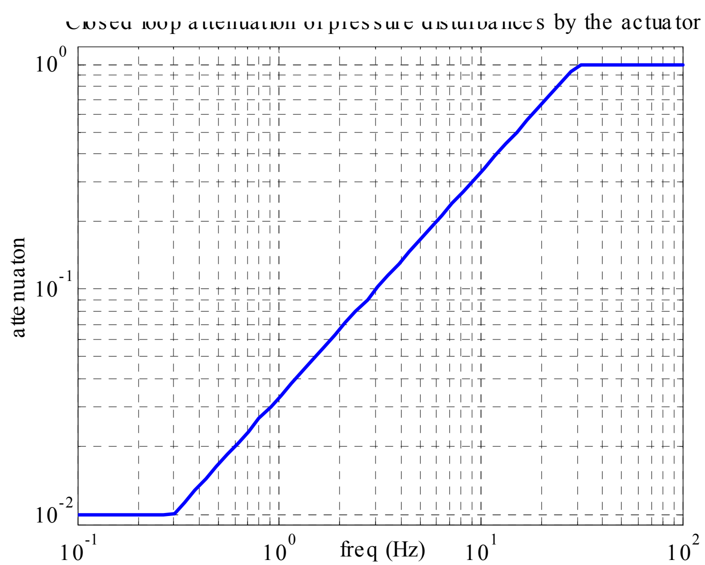
- Bridge offset couples pressure noise into actuator motion
- Active control reduces actuator noise
- Pressure noise * coupling * loop_attenuation <= acceptable motion



Calculating Allowed Pump Noise

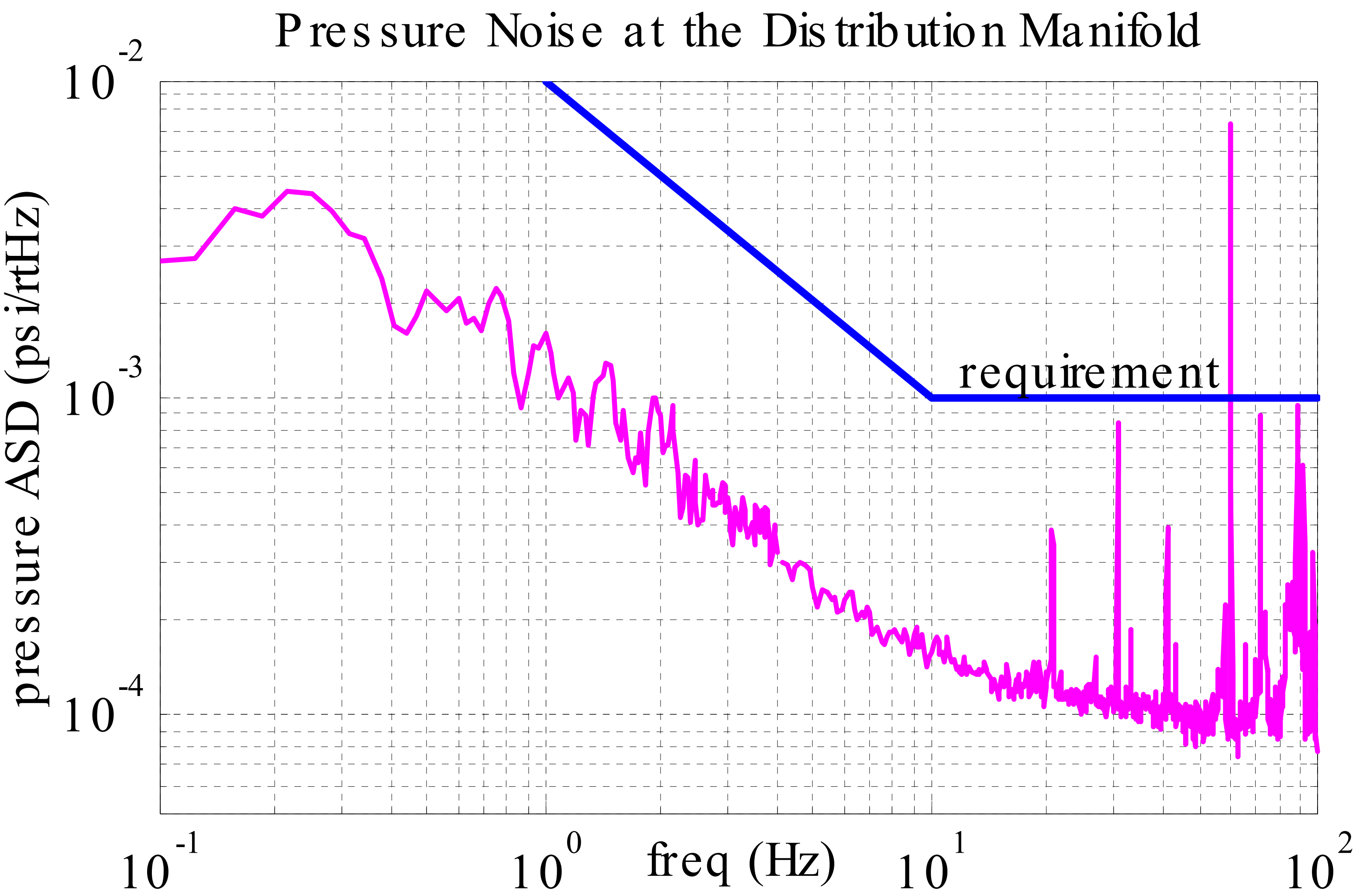






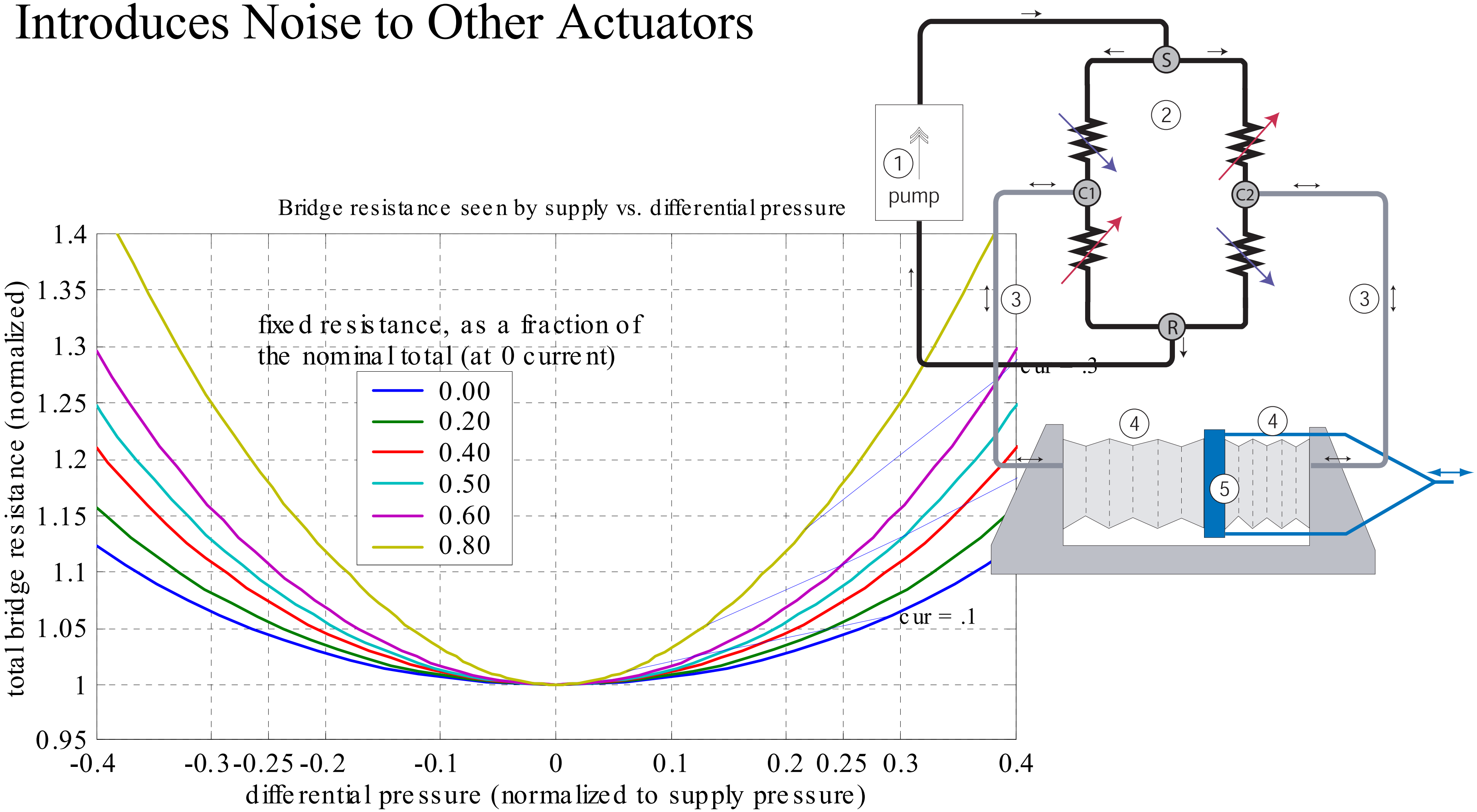
described in
Allowed Pump Noise,
Brian Lantz, Corwin Hardham,
Dan DeBra, Jan 31 2002.

Measured noise at LASTI

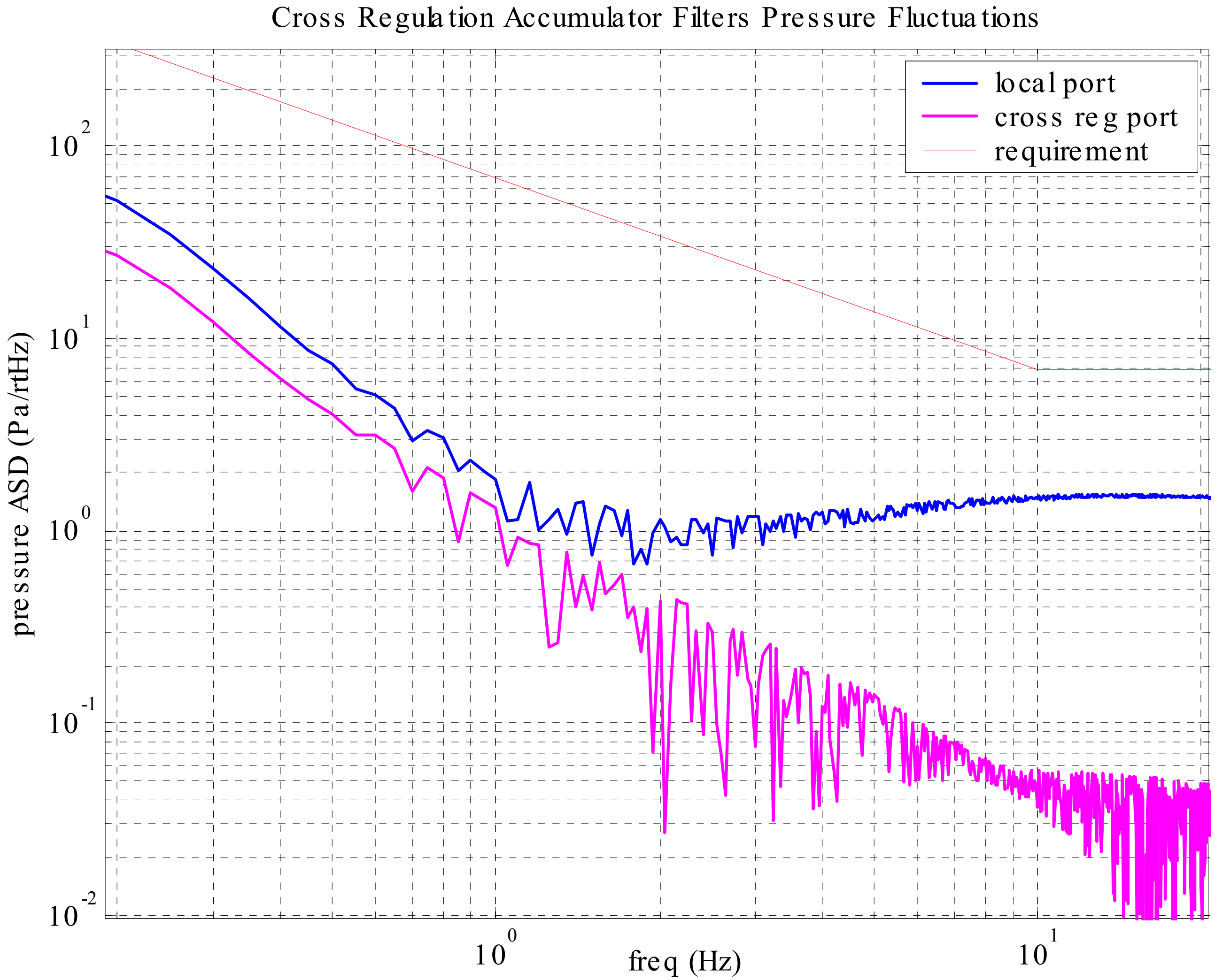


Cross Regulation Noise

- Bridge offset couples actuator drive into changing Load Resistance
- Load Change = flow & pressure change at Distribution Manifold
- Introduces Noise to Other Actuators



Modeled Effect of Cross-Regulation Accumulator



Comments on Distribution System

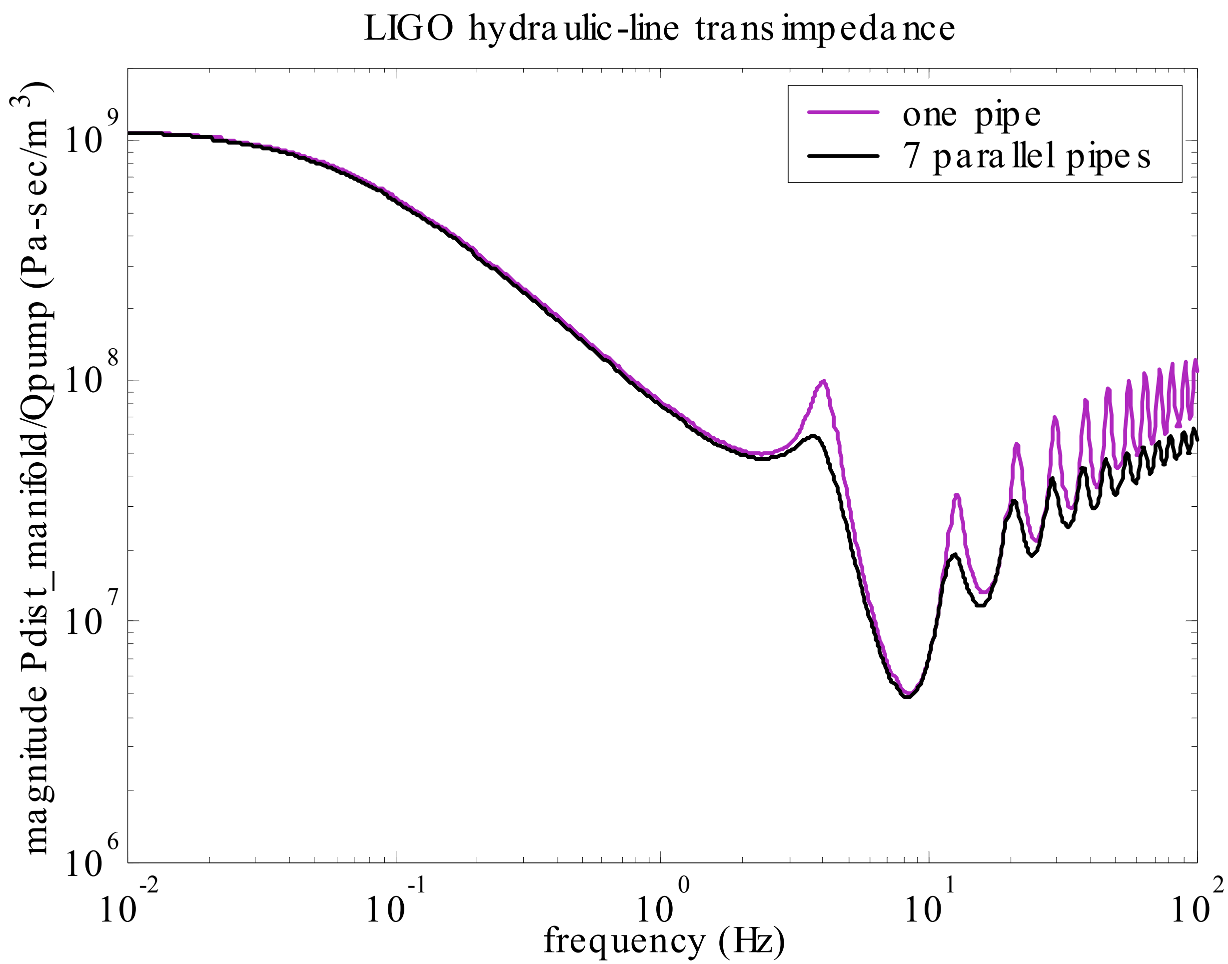
2 stages of passive filtering + pump speed control seems sufficient

Cross modulation between actuators controlled by manifold accumulators

pipe dynamics are interesting (and not discussed here)

pump station is all COTS, except laminar flow resistors

Pipeline dynamics are interesting



Sensors – our two types

Inertial Sensors

A class of commercial instruments called seismometers (geophones are a common type of seismometer)

Substantially more quiet than the ground between 0.1 and 100 Hz (and provide useful information at 0.01 Hz to 1000 Hz)

Relative Displacement Sensors

measure the distance between stages

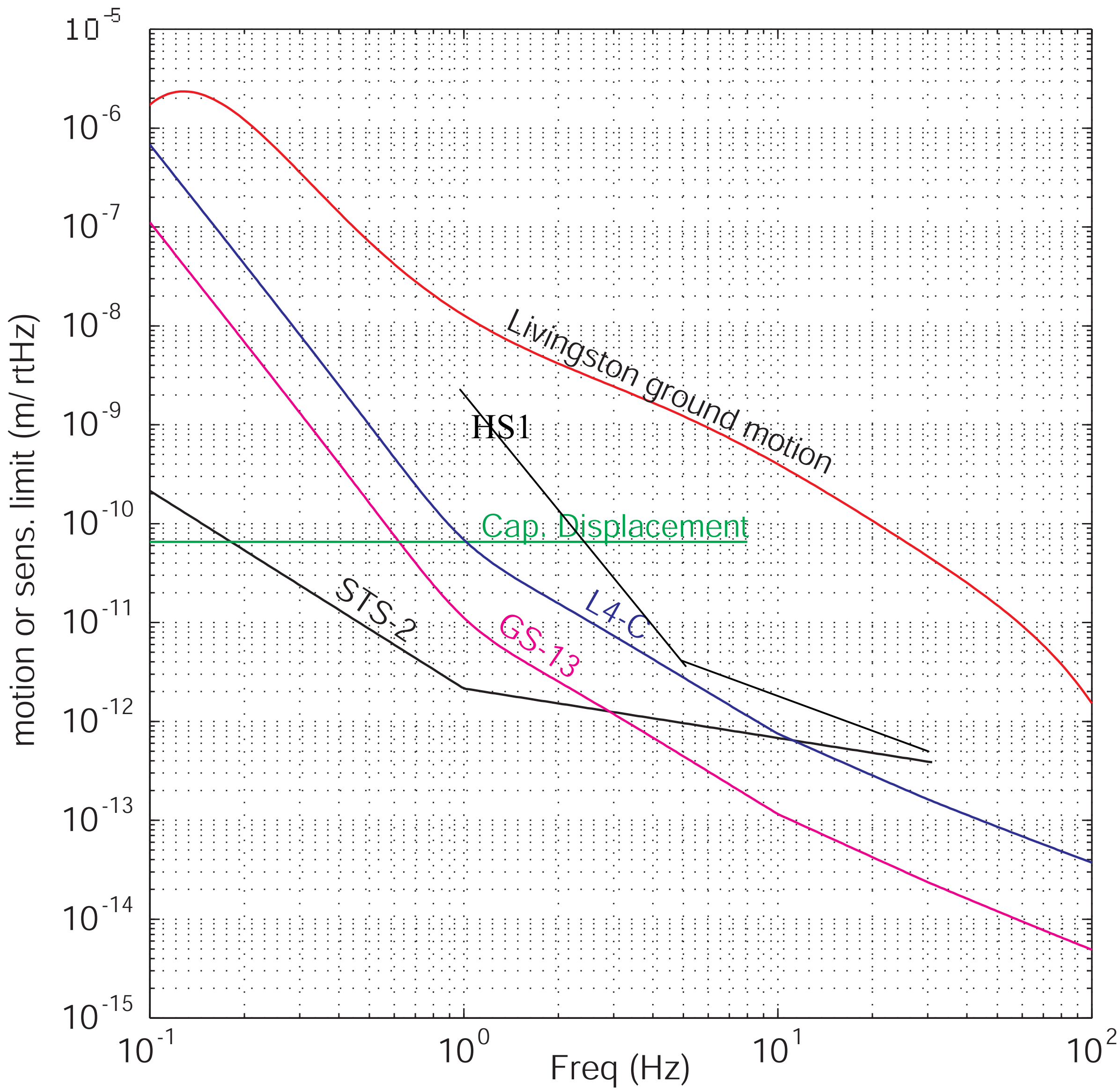
eliminate low frequency loop crossover (replace with blending)

provide alignment information

help with tilt control

relate inertial information between stages

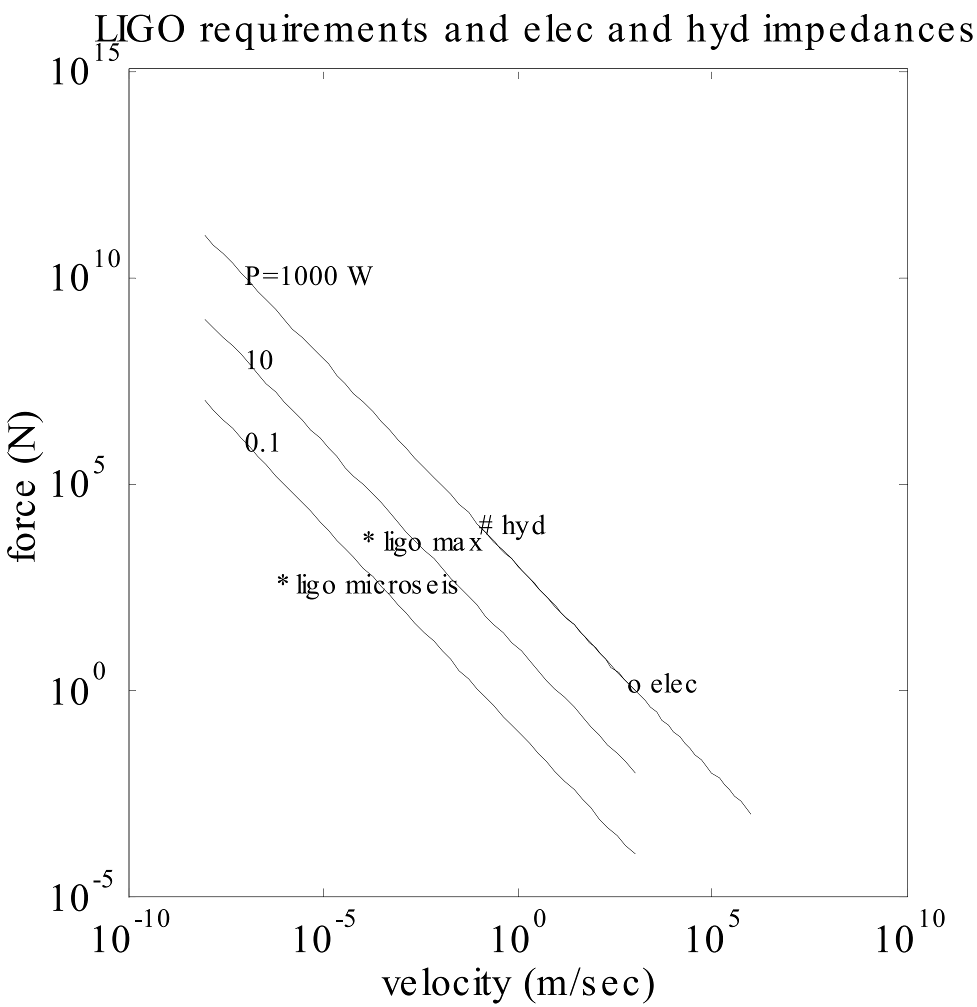
Sensor noise



A Few Inertial Sensors

Streckeisen STS-2	Geotech GS-13	Sercel L-4C	Geospace HS1
~$14k 3 DOF	~$6k 1 DOF	~$1.1k 1 DOF	~$70 1 DOF
120 sec period	1Hz	1 Hz	4.5 Hz
~26 cm x 23 cm d	~38 cm x 17 cm d	13 cm x 7.6 cm d	7.2 cm x 6.7 cm d
13 kg	10.4 kg	2.15 kg	1/4 kg
active force balance	passive w/ preamp	passive	passive

Actuators



Outer Stage

Laminar Flow Hydraulic

- Well matched to requirement (range and noise)
- easy to hold large offsets
- stiff and well damped

Inner Stages

Electromagnetic

- quiet
- force actuation is independent of position of support
- high bandwidth

Design Trades

Performance \ Parameter	Trend	Specification		Design					Related Parameter	
		δ=1mm	Δt=10 sec	Ps=5 bar	β=2e3 bar	R = 5e10 Pa-sec/m^3	A=.01 m^2	V=3e-4 m^3	m=1e3 kg	k=4e6 N/m
1) Hydraulic Resonance $\omega_n^2 = \frac{2A^2\beta}{mV}$	↑			↑	↑		↑	↓	↓	
2) Damping $\zeta = \frac{1}{RA}\sqrt{\frac{m\beta}{2V}}$	↑			↑	↑	↓	↓	↓	↑	
3) Bridge Power Dissipation $P_b = \frac{P_s^2}{R}$	↓			↓		↑				
4) Acquisition Power $P_{acq} = \frac{k\delta^2}{\Delta t}$	↓	↓	↑							↓
5) Microseism Power $P_\mu = k\delta\delta_s w_s$	↓	↓								↓
6) Microseism vs. Bridge $\frac{P_{acq}}{P_b} = \frac{k\delta\delta_s\omega_s R}{P_s^2}$	↓	↓		↑		↓				↓
7) Microseism vs. Acquisition $\frac{P_\mu}{P_{acq}} = \frac{\delta_s\omega_s\Delta t}{\delta}$	↓	↑	↓							

Candidate Actuators

	Force	Velocity	Stiffness	Displacement	Stiction	Hysteresis	Mechanical Noise
Hydraulic	High	Low	Med	Med	Low	Low	Low
Ball Screw	High	Low	High	High	High	Low	High
Linear Motor	Med	High	Low	High	Low	Low	Low
Piezo or Magnetostriction	High	High	High	Low	Low	High	Low

Organizational Responsibilities

Caltech: Administer the project, engineering staff, research.

MIT: Research, LASTI.

LASTI: LIGO vacuum system, user facility for Advanced LIGO final prototypes.

Stanford: Research for Advanced LIGO, LSC member, Engineering Test Facility.

LIGO Livingston Observatory (LLO): One of the two US observatories (see also Hanford, GEO, Virgo, TAMA, ACIGA), destination of system

LSU: Research for Advanced LIGO, LSC member, near LLO