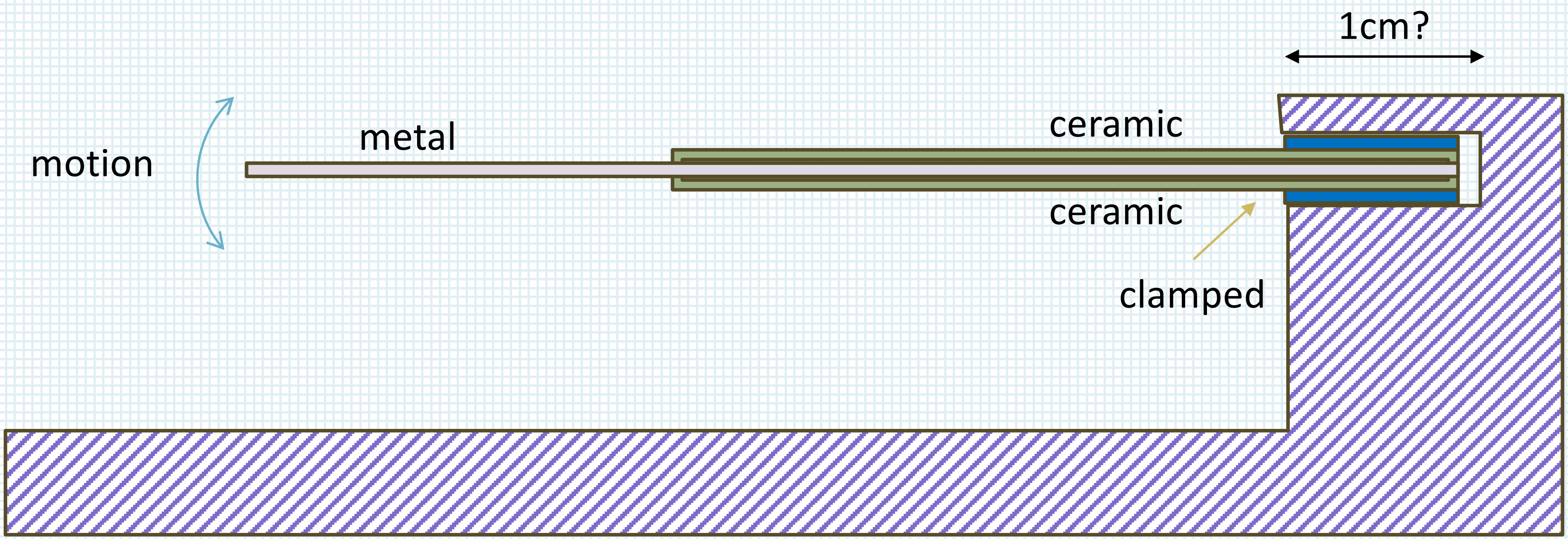
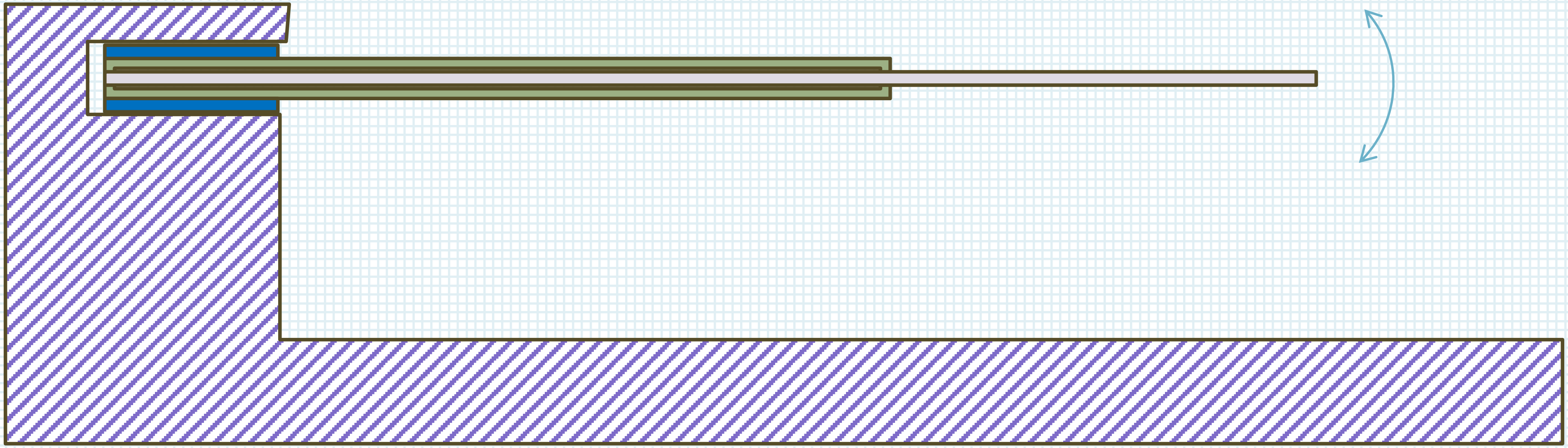
EH Characterisation

Experimental plans – LSBU project file
Potential Energy Group: PO 001
Our ref: ESQ1980
Nov 24-Dec 24

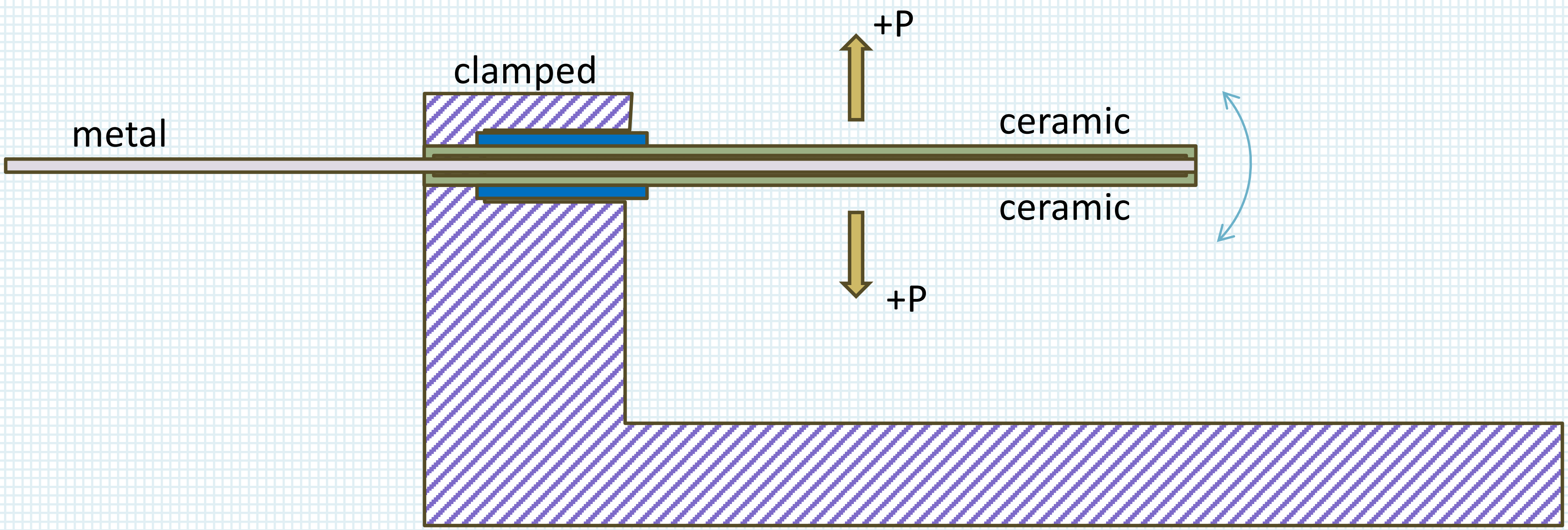
Schematic 1

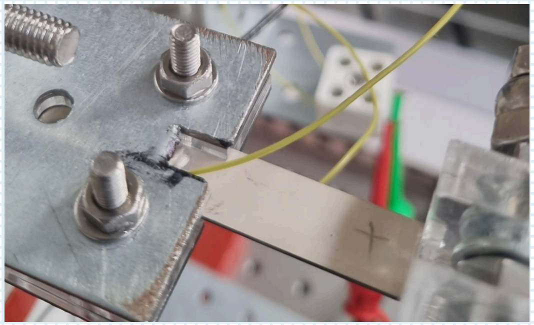


Schematic 2



Schematic 3





- Two ceramic layers are oppositely poled so positive polarisation pointing out.
- Metal shim central connecting electrode.
- SCD does not use the metal shim. Just connecting the two yellow wires to voltmeter

System Build

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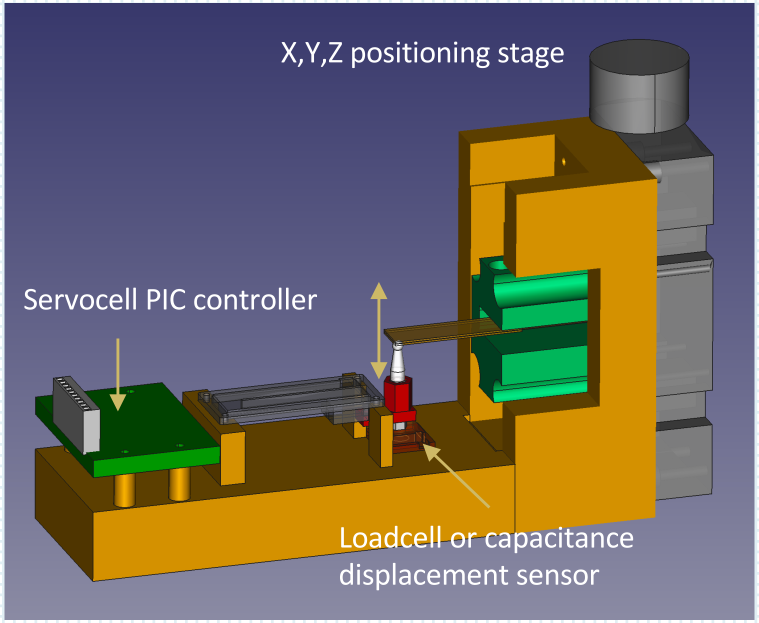
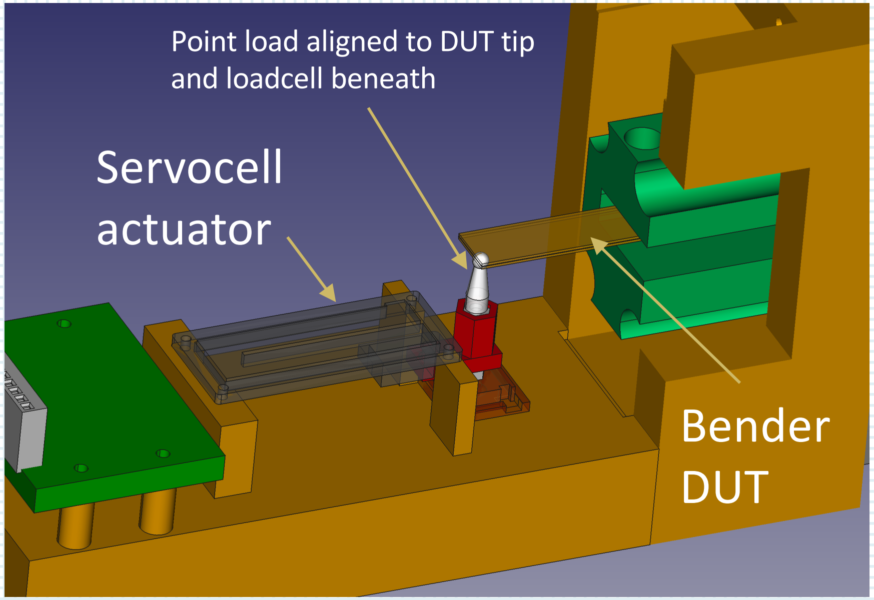
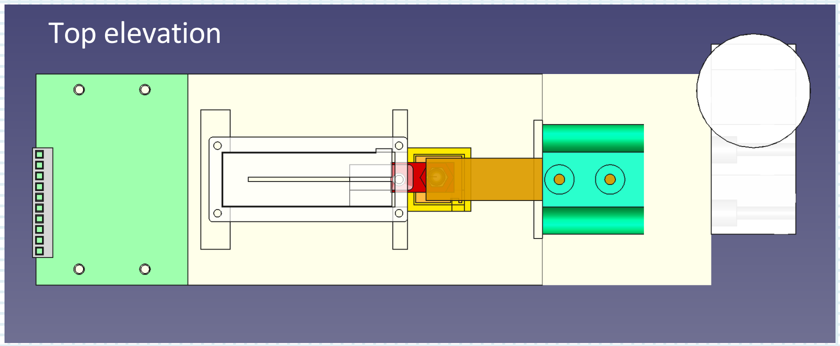
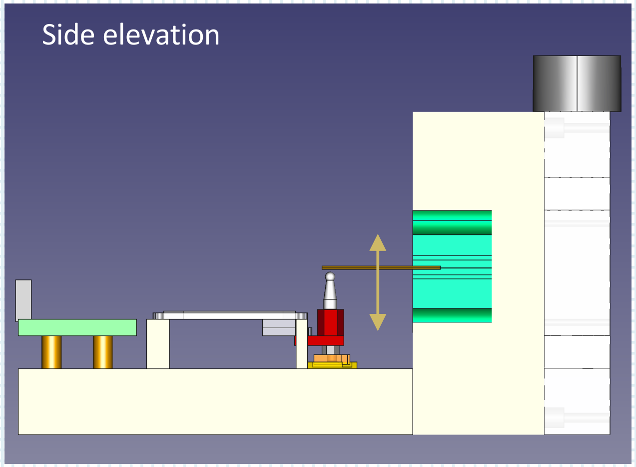
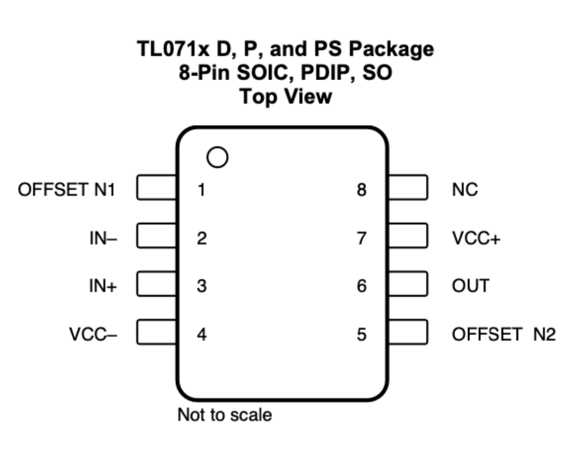




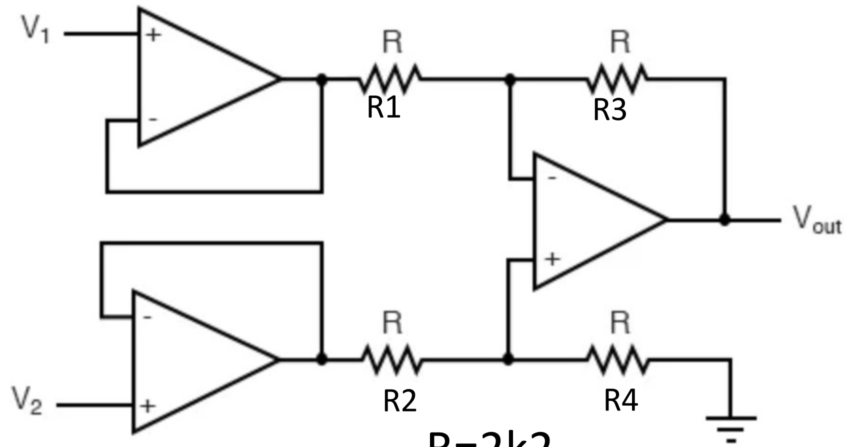




Electronics buffer



Differential IA



R=2k2

TL071 ±10V
Check: Gain: 1.6
INPUT: 200mV rms
OUTPUT: 323mV rms

Gain: unity:
Vout=(R3/R1) (V2-V1)

- R_L as load for bender element: can exceed the input resistance of modern ADC / input amplifiers / oscilloscopes. This changes the effective load on the bender.
- Solution: pass output of R_L loaded bender through a buffer (voltage follower) Differential Instrumentation amplifier: output impedance many hundreds MΩ

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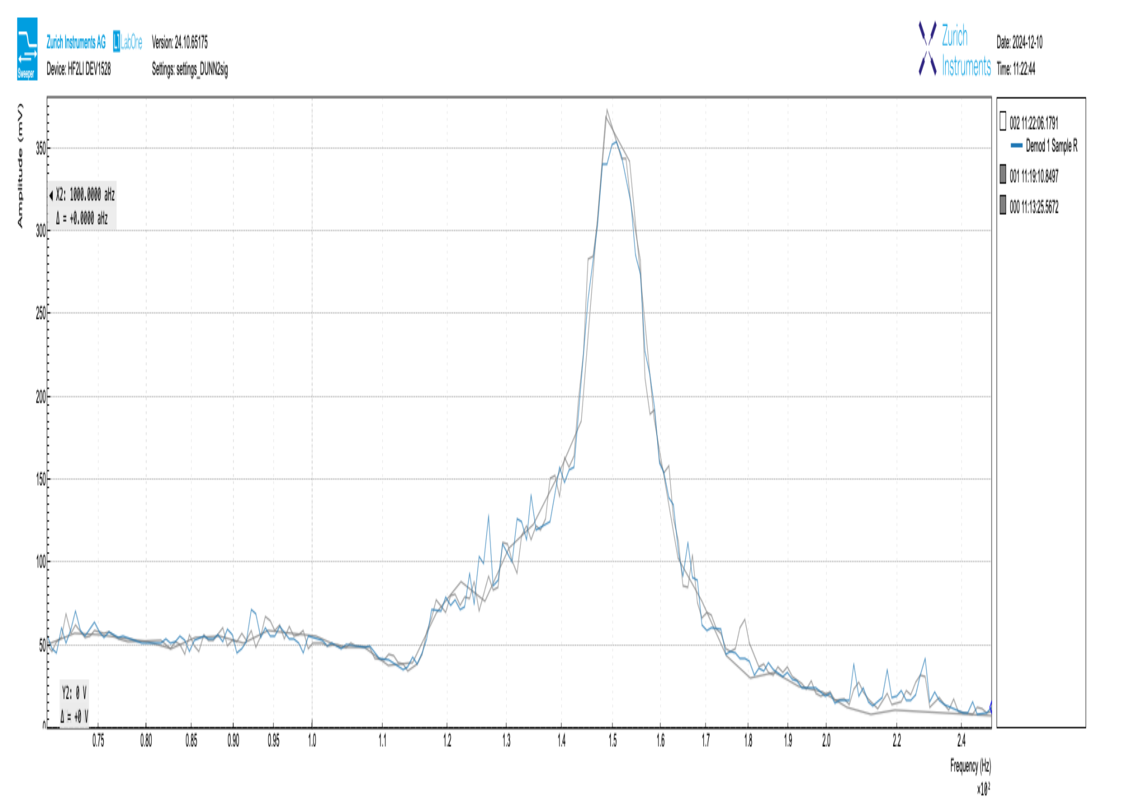
FRA Lock-In Initial analysis

- 4MOhm load on the piezo bender
- Use of 2 buffer amps for each lead from bender
- Buffer amps bipolar supply. TL071 JFET input very high input impedance >> 10^{12} Ohm
- Buffer chips feed to unity gain non-inverting amplifier.
- Power supply: ±10V
- Lock-In: Zurich Inst HF2LI
- (initially used the MOKU Go but the outputs had large offset)
- OSC 2 to sig o/p 2.
- Settings: saved DUNN, settings_DUNN2sig
- Inputs: DC, HighZ, single ended.
- Outputs: 2.5V, offset 2.5V sine ON.
- Resonance around 150Hz. This may be servocell resonance or sample.



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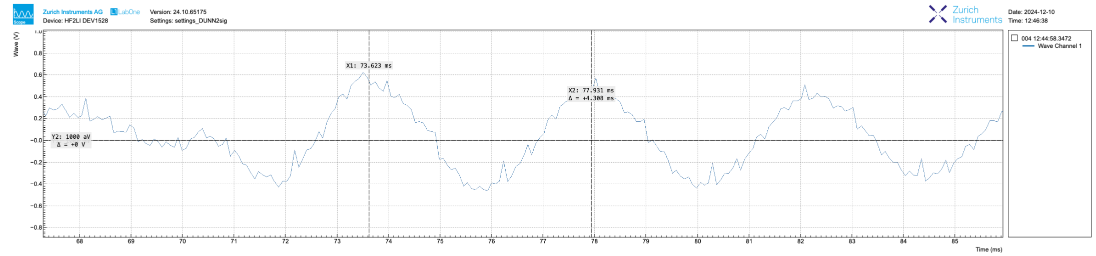
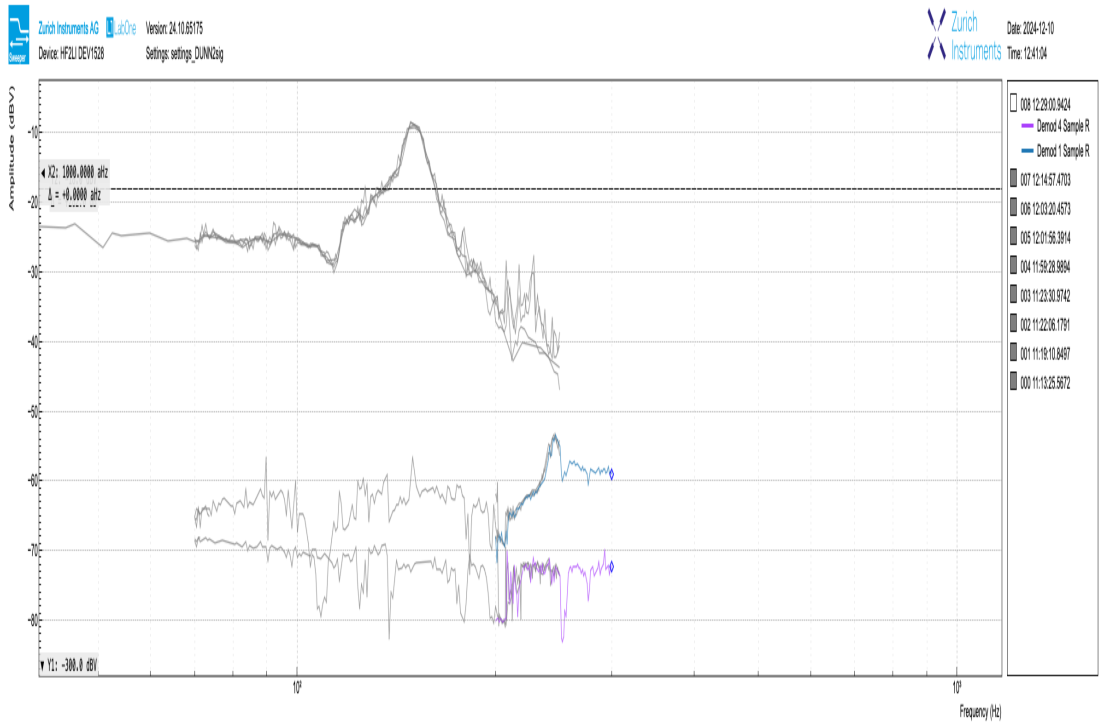
Loaded bender with loadcell: resonances

Free resonance 233Hz: Ping on bender



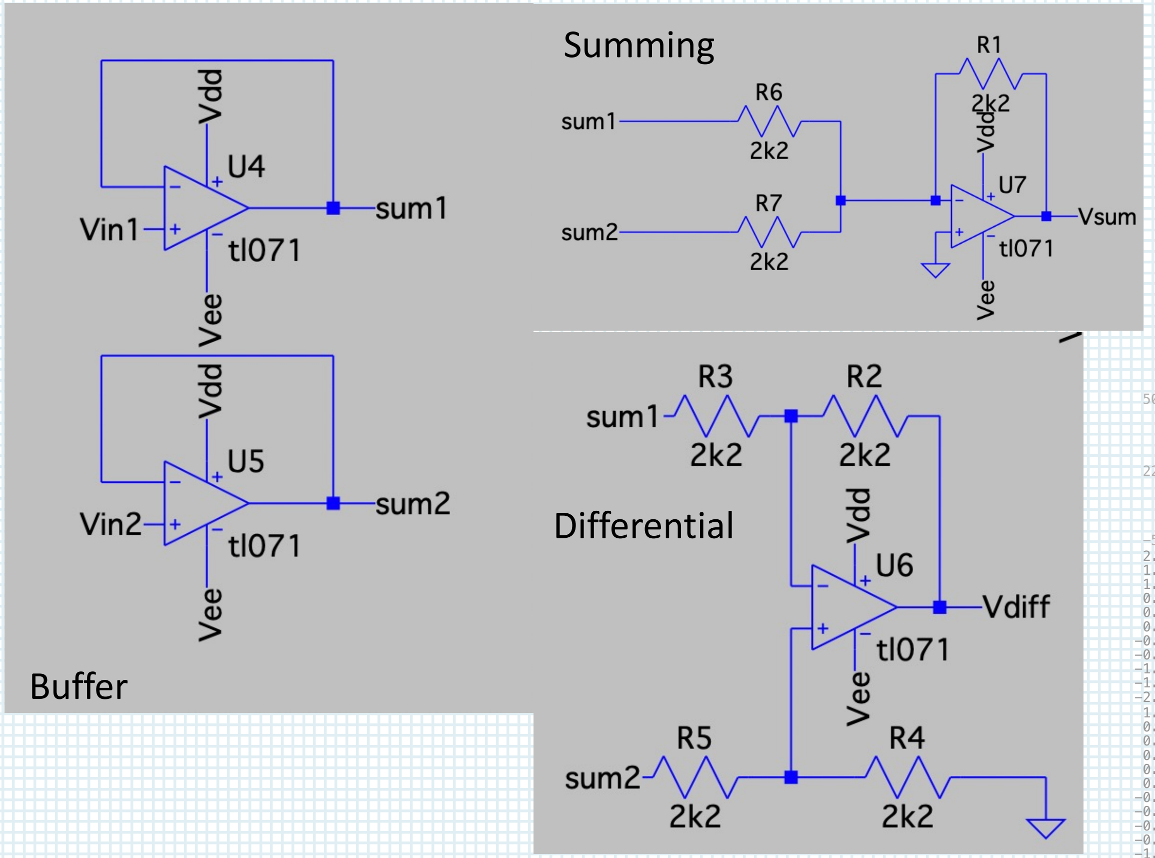
Freq scan with no loadcell: fr~150Hz

Loaded with loadcell: resonance peak around 246Hz



Buffer:

Difference and Summing instrumentation amplifier

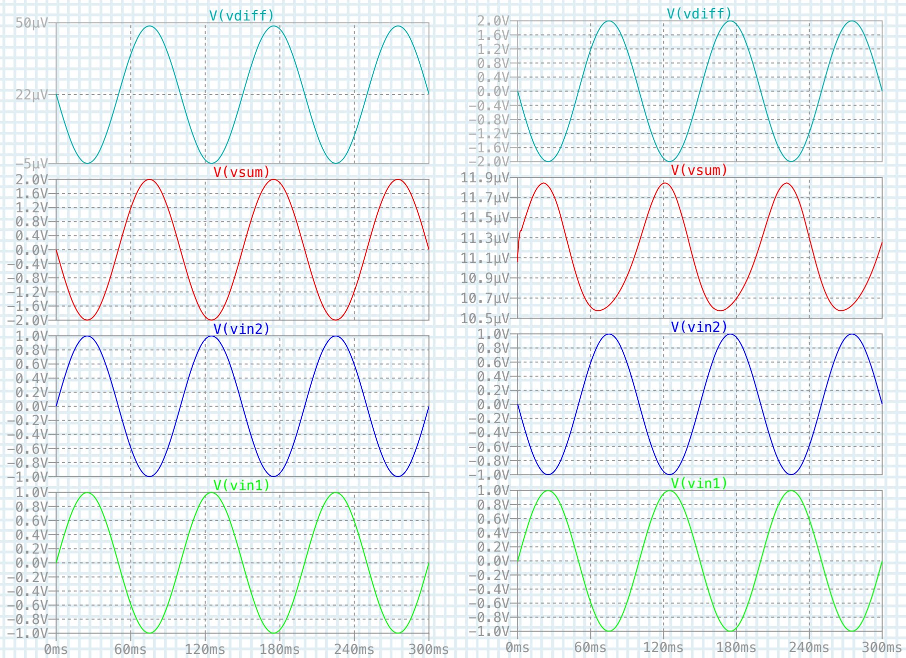


LTSpice: TL071 opamp: TL071.301

/Users/markyscain/Documents/Science_Programs/LTspice/Energy_Harvesting/EH_buffer1.asc

In Phase

180° out of Phase



Outcome:

- In Phase signals, we need SUM
- Out of-phase signals, we need DIFF

LTSpice circuit analysis and response

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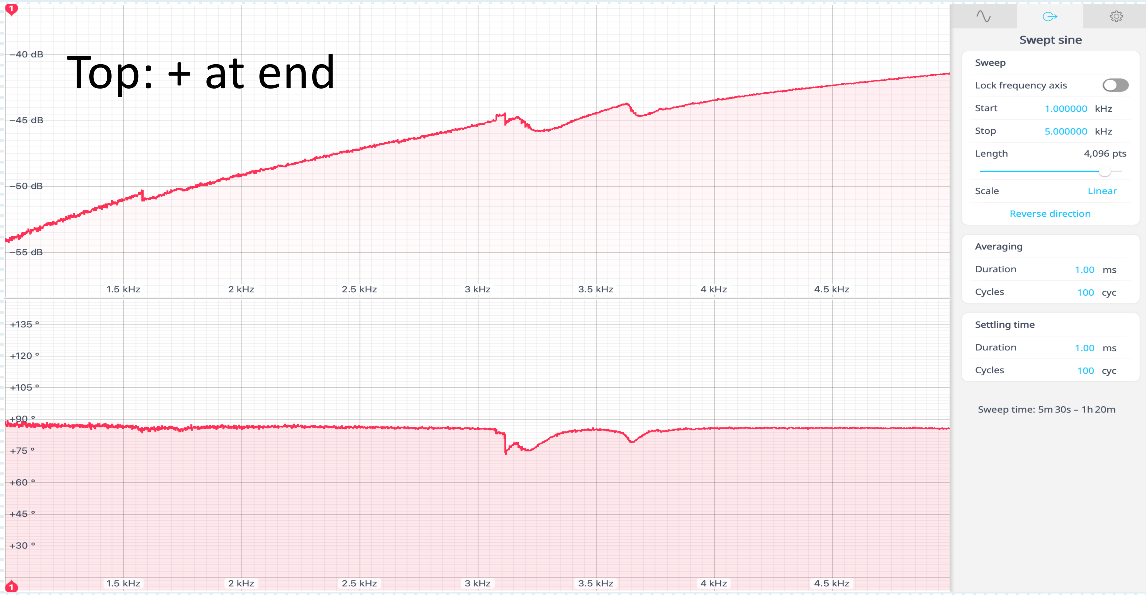
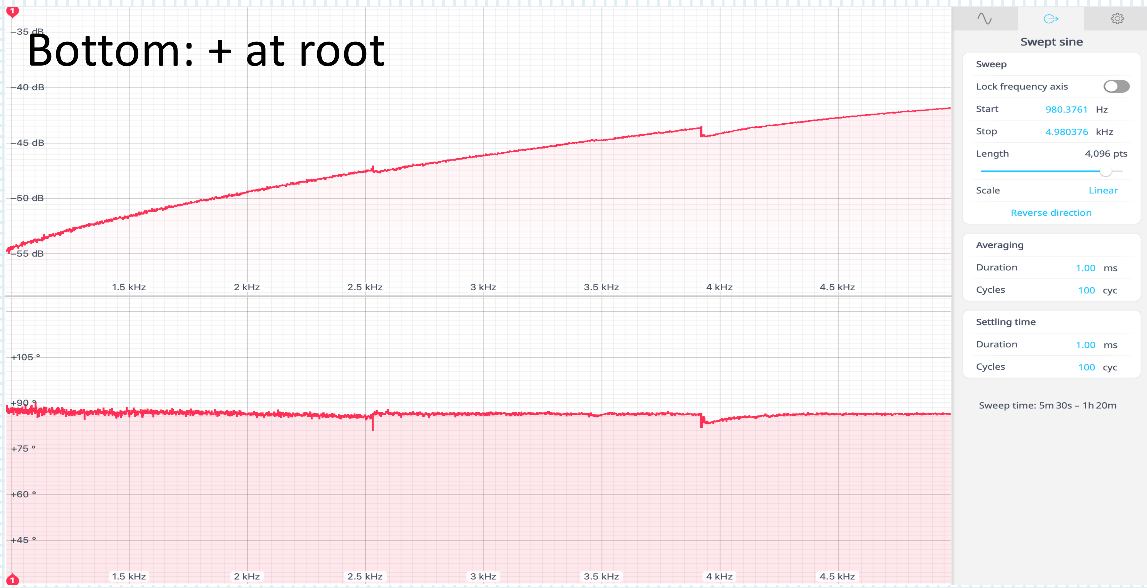
Electrical resonance of bender

- Individual addressed resonance of each ceramic plate
- Similar resonance behaviour
- (MOKU-GO –FRA). i/p: 50 ohm terminated.
- o/p: 200 ohm
- Positive (biased sine wave) to ceramic plate.
- Resonance of both plates different. Implies coupling or thickness of each plate is different – or material is different.
- Repeated in later slide.
- /Users/markyscain/Documents/Electrosciences/DUNN EH 2024/Experimental Research/FRA/





Electrical resonance

MOKU GO: FRA

Connections through top and bottom ceramic layers, through 2 yellow wires.

Excitation:

± 2V, 1V dc bias

Two examples.

Both ceramic sides driven together: current taken from metal shim

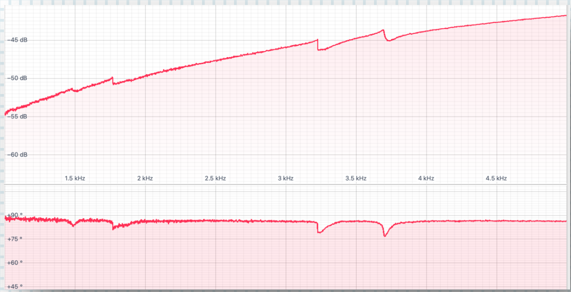
± 2V, 1V dc bias

Electrical resonance – separate ceramic sheets

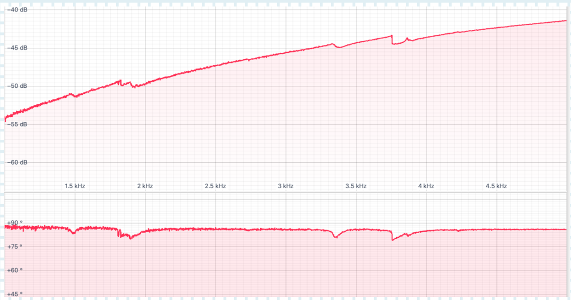
2Vpp, sine, 1V DC. Positive always to ceramic.
Metal shim return path to FRA Input 1.

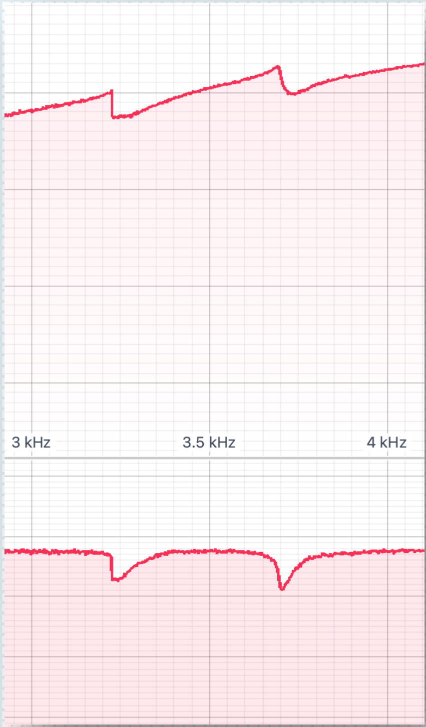
Similar, but not identical resonances.

Lower



Upper



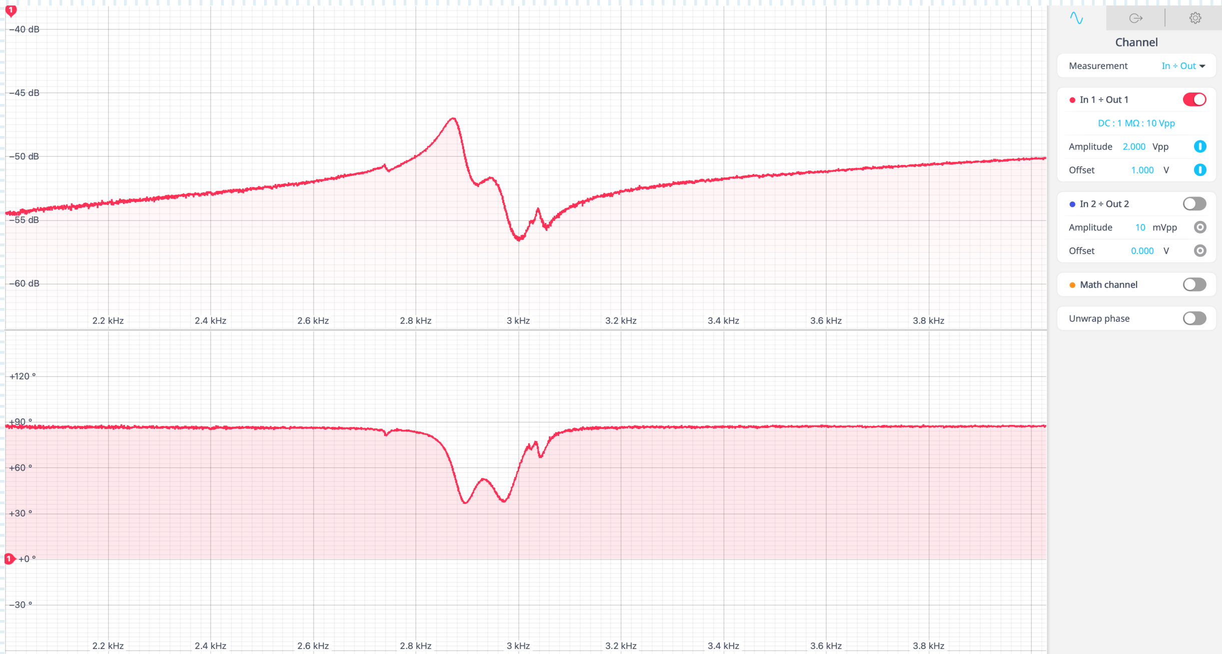


Lower

Upper

Electrical resonance FRA

- HPZ actuator free resonance. held by inner metal shim. Ceramic in air, not touching anything. yellow wire in, yellow wire out. No Rl load. Resonance different to when actuator resting on surface.
- Clean resonances – 2 off based on slight difference in top and bottom ceramic.
- 2.8702kHz
- 2.951kHz
- Tiny at 3.0399kHz and 2.7382kHz



'/Users/markyscain/Documents/Electrosciences/DUNN EH 2024/Experimental Research/FRA/MokuFrequencyResponseAnalyzerData_20241216_195612_Screenshot.png'

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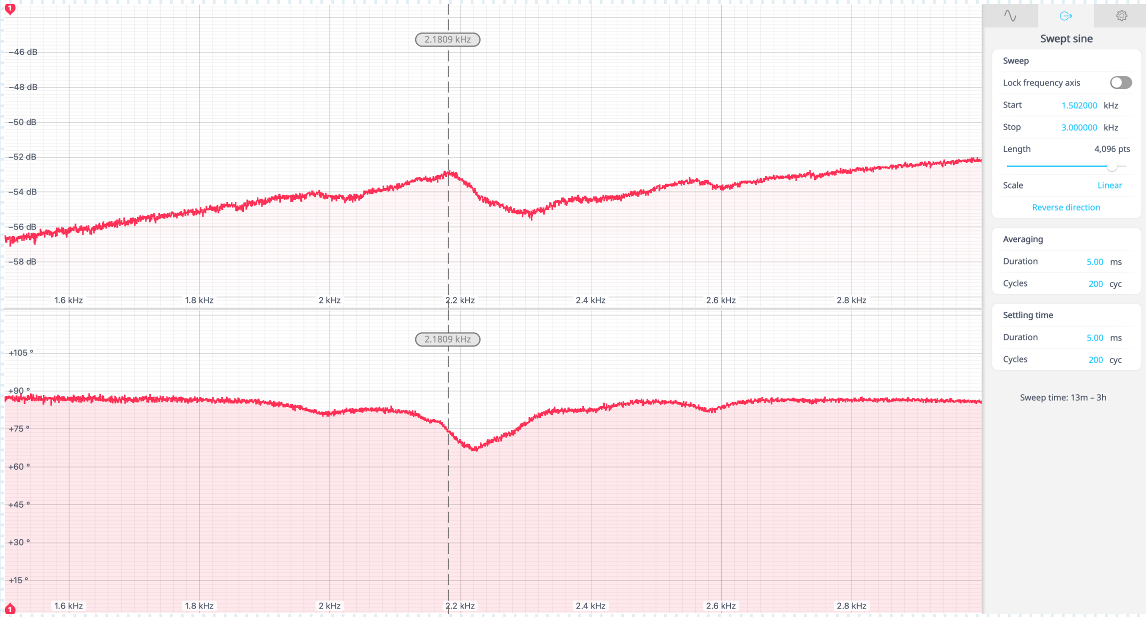
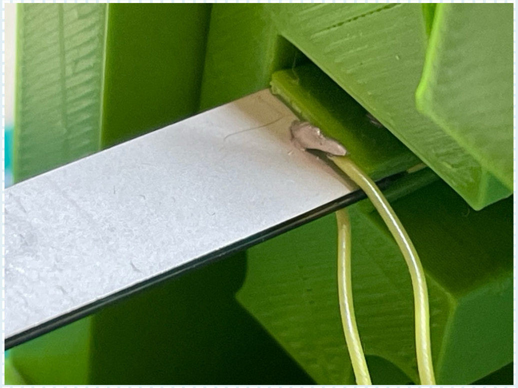
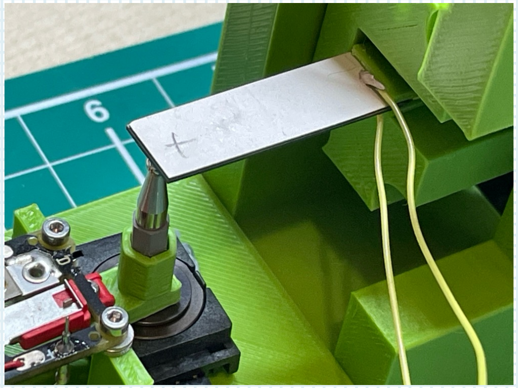
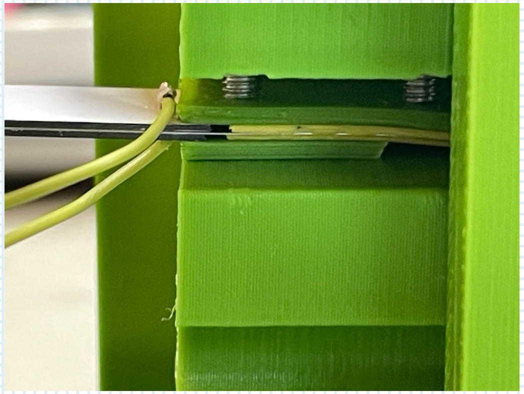
Clamped resonance

- Clamp bender using ABS packing pieces.
- Resonance for thickness mode.
- L_0=38mm
- F_r~2.2kHz
- Increase clamp Allen key bolt slightly: no change in fr.



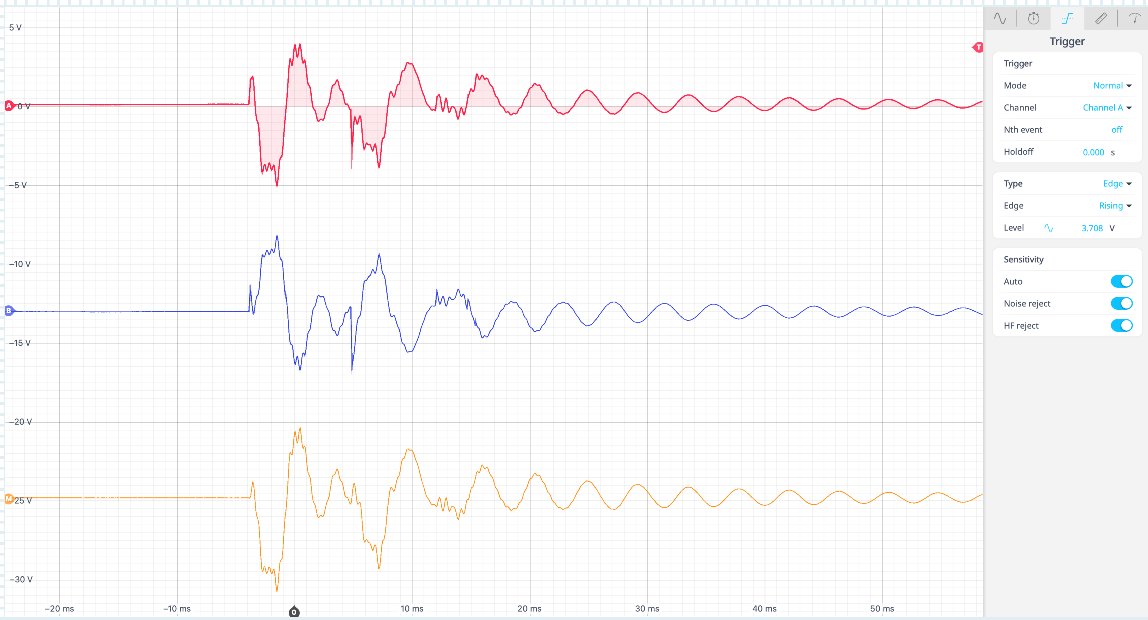






Bender resonance

- Bender resonance:
  - driven using FRA at ±3V dc offset: fr~242Hz.
  - Mechanical ping: oscilloscope capture: fr~241Hz
- Run at fr mechanical. 241 Hz



System : small signal excitation, R_L loading

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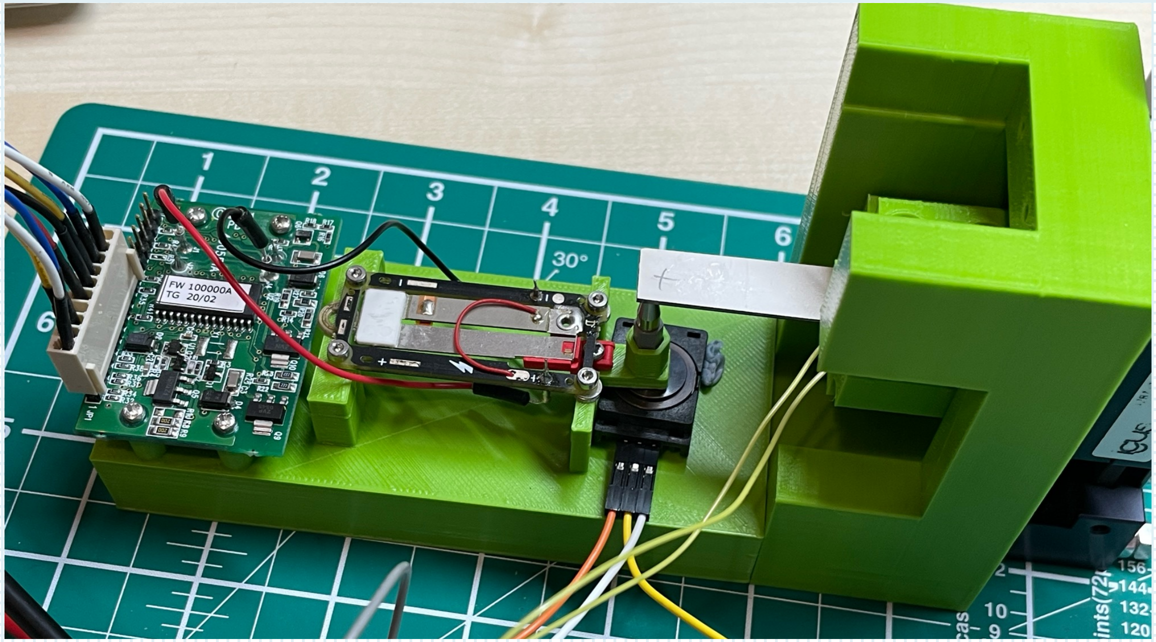
- Zurich Instruments: HF2LI lock-in(LI) amplifier.
- Excitation:±5V pkpk, 2.5V dc biased.
- Off resonant response.
- Bender and R_L (R_{load}) element routed through differential IA (buffer).
- Loadcell as second input to LI
- Lock-in data is recorded and logged as a function of R_L and operating frequency.

- Plot: power generated against RL and against force.
- Acceleration calculated from bender displacement via:
    - force, frequency, span length and PZT modulus.
    - Capacitance displacement sensor, micrometers.



Force:
Calibration mass: 100g
TE Connectivity load cell FS2050-0000-1500-G (RS 893-7225).
1500gF full range at 3V span (5V supply)
1500gF==14.7N
$F=((V_0-V_z)/3.0)x1500x9.81/1000$ [N]
$V_z=0.988V$

Calibration: 100gF (0.98N): $V_0=1.183V$: F=0.96N

Bender Voltage output: V_B
Lock-in voltage rms: V_{LI}
RL=ohms
G_1: Transfer through DIFF-IA: x1.6
G_2: Gain: LI set = +10
$V_B=V_{LI}/G_1G_2$

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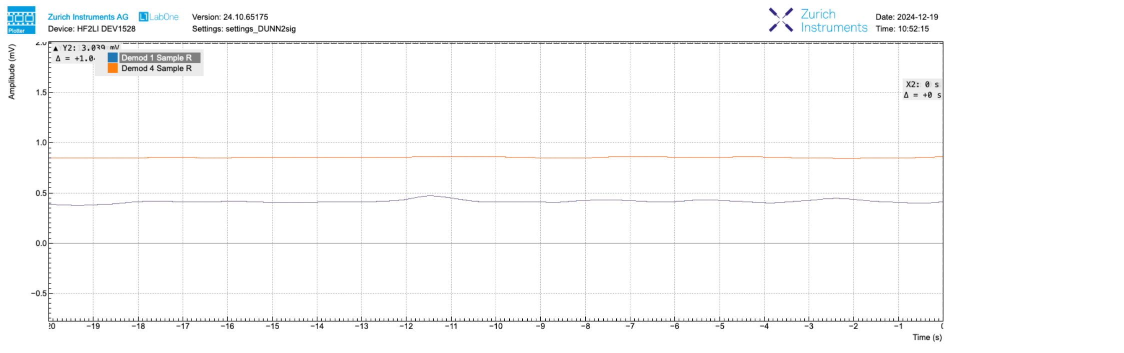
Calibration – offsets: capacitative pickup/induction from cantilever

- Bender element in vicinity of driving electronics (EMI)
- Bender not touching load probe.
- No flexure, SERVOCELL EM pickup at 35Hz: 2MOhm loading: 406 μV.
- Remove this offset on all data.



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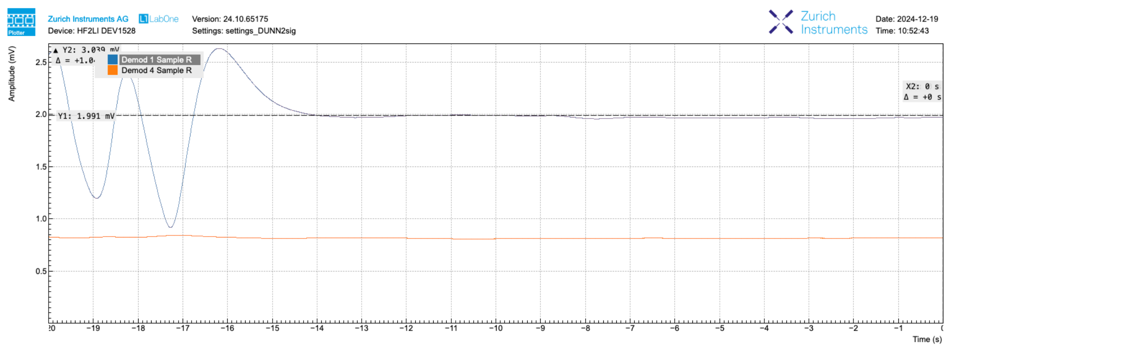
- Loading probe full contact with bender.
- Lock-in data very stable.
- Lock-In Bender V_{out} 5 times pickup.



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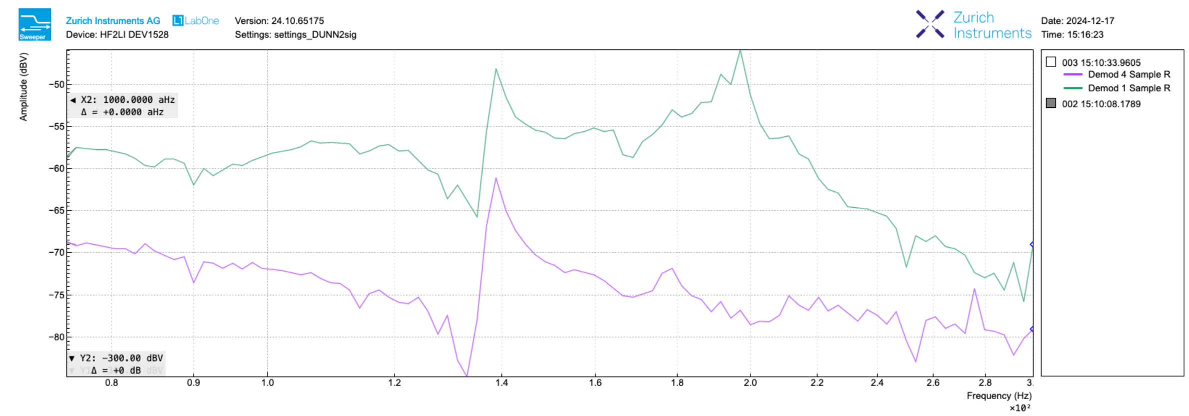
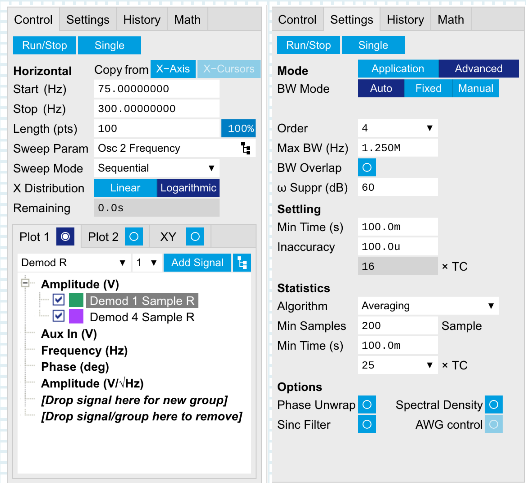
Small signal response

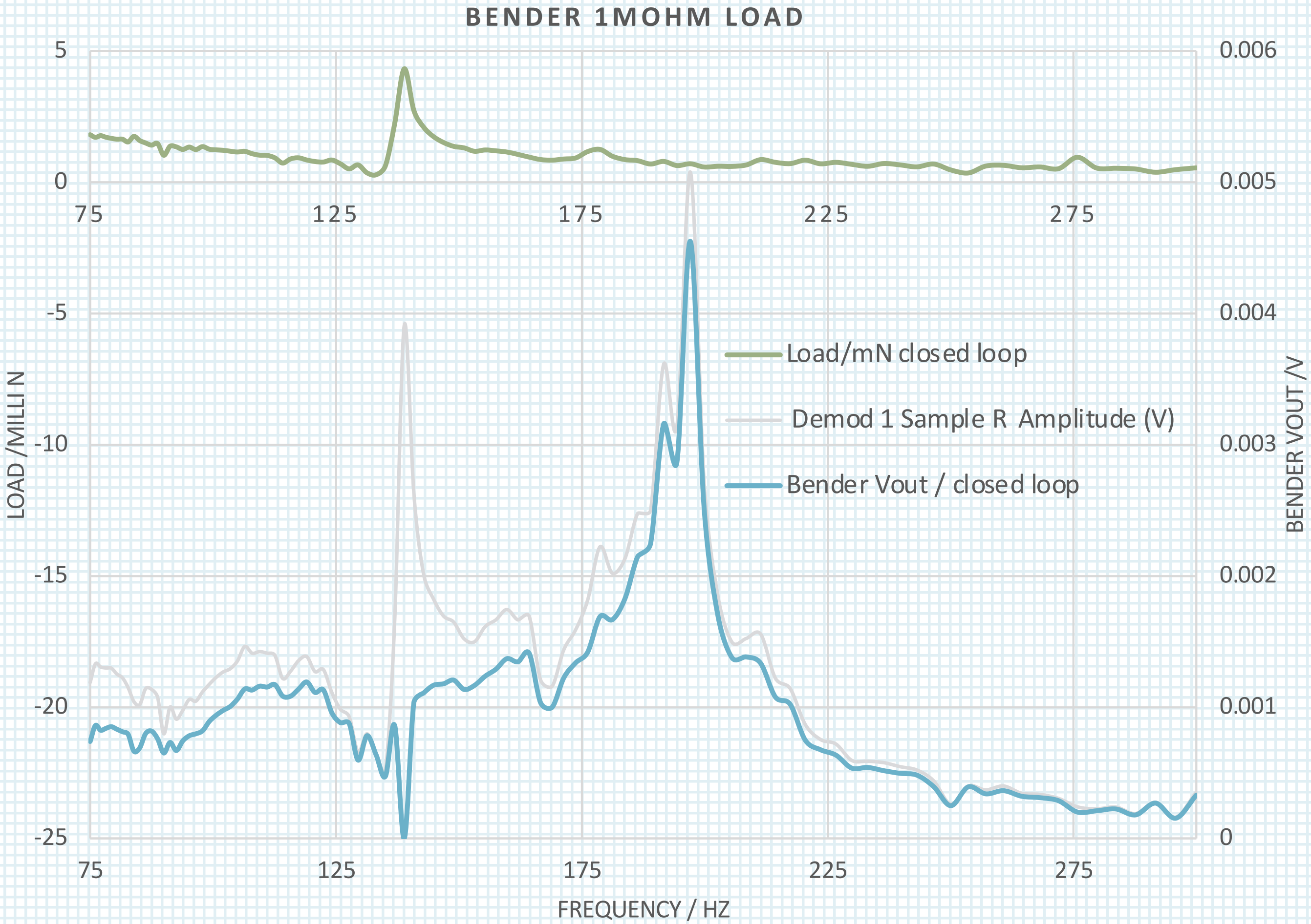
- HF2LI output: sweeper response. Freq. scan.
  - Green: Voltage output over 1MΩ load
  - Purple: Loadcell.
- Servocell input is voltage to the actuator. Open loop control. Nothing is controlled. Hence load is changing with bender response and with frequency.
  - We can use closed loop control to control force. Or to control displacement.
  - Or, we can normalise the output with changes in load with freq.





Normalised output

- Normalised Load (0-1) as normalisation ratio for VOUT
- First resonance – system Servocell response
- Normalised for constant load.
- We can see bender+loadcell resonance at ~ 200Hz
- Preload affects the f_r as expected



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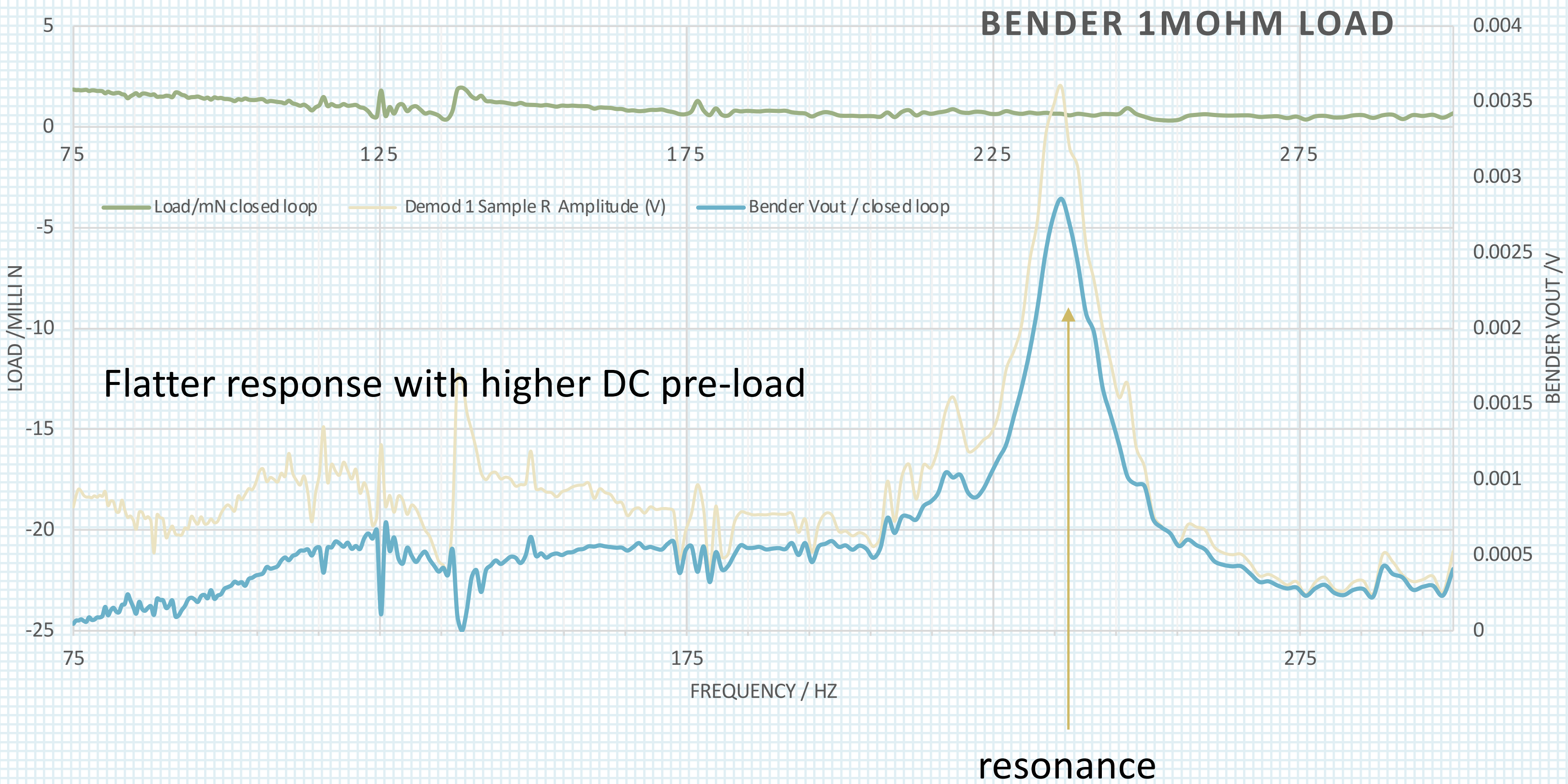
Bender excitation mechanical 2



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Strain calculations

5mN ac max load

Deflection: $\delta = PL^3/3EI$

L=length cantilever 34mm,

Point of load, a=1mm from end.

P=load in N, 0.6mN at resonance

E = modulus = 80 GPa (PZT)

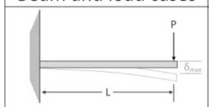
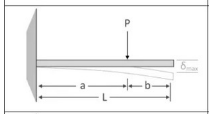
I = area moment of inertia: = $h.w^3/12$

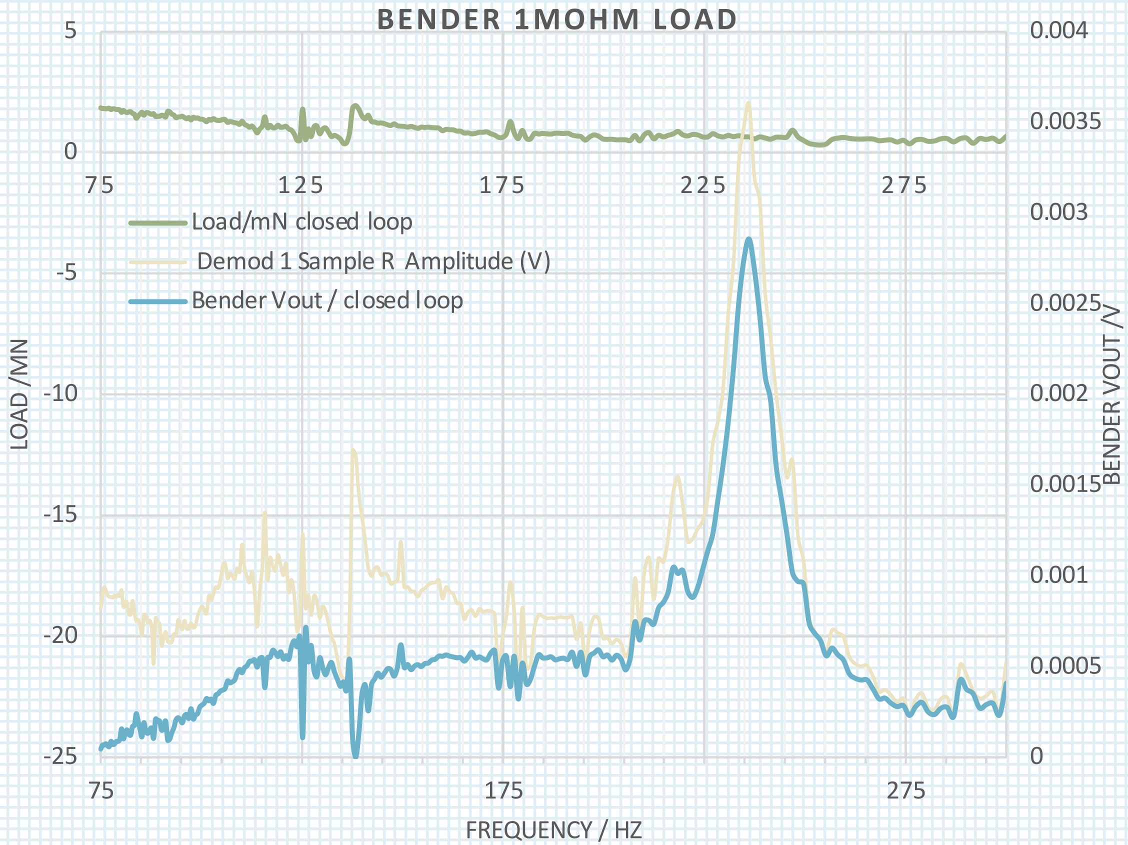
h=1.2mm, w=10mm

Max deflection: δ = 0.08767μm

Max voltage output: measured: 0.003V

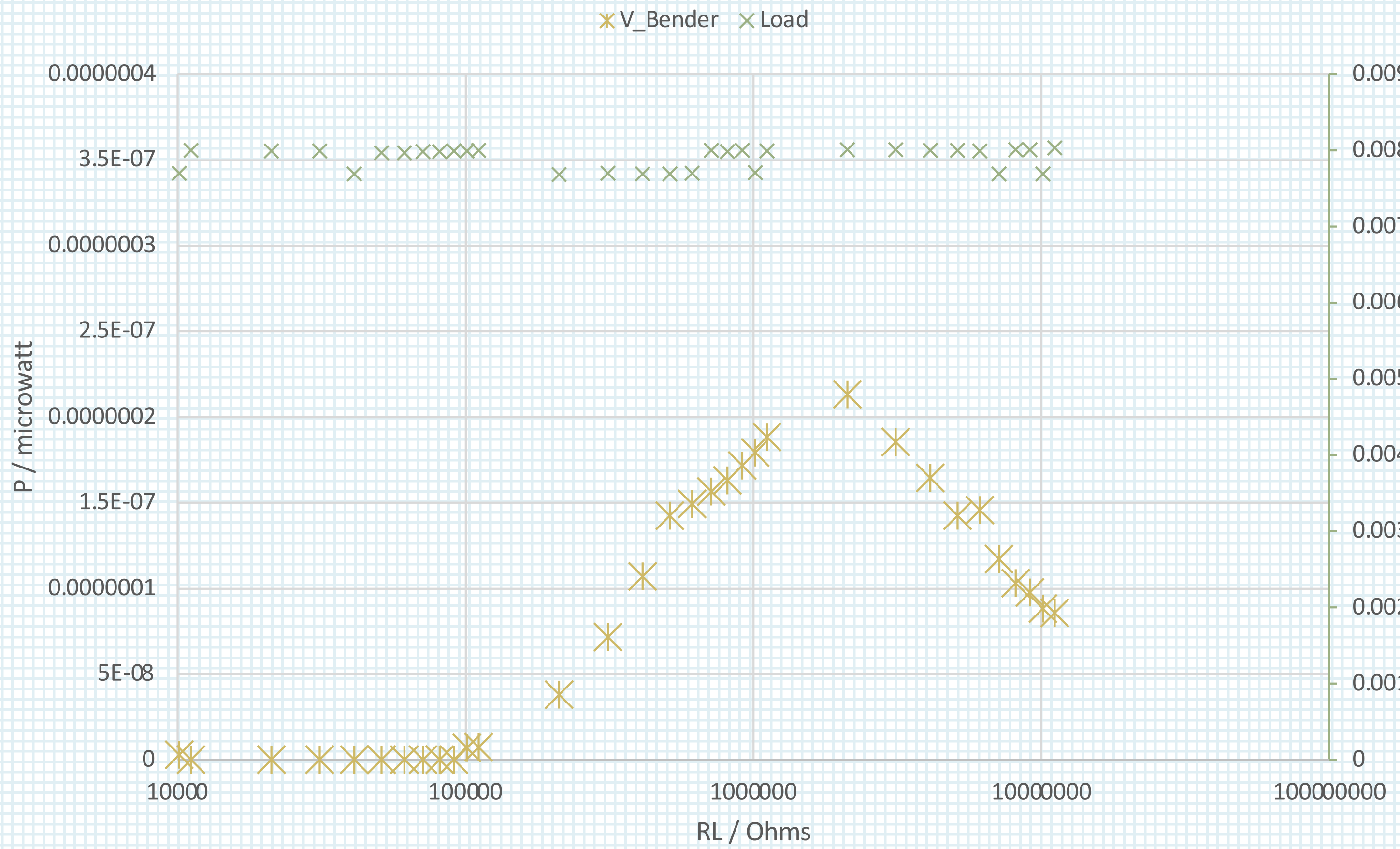
Typical 1000μm deflection indicates typical voltages 1MΩ shunt ~ 34V

Beam and load cases	Maximum Beam Deflection
	$\delta_{max} = \frac{PL^3}{3EI}$
	$\delta_{max} = \frac{Pa^2(3L-a)}{6EI}$



Matching Loads: Resistance Load

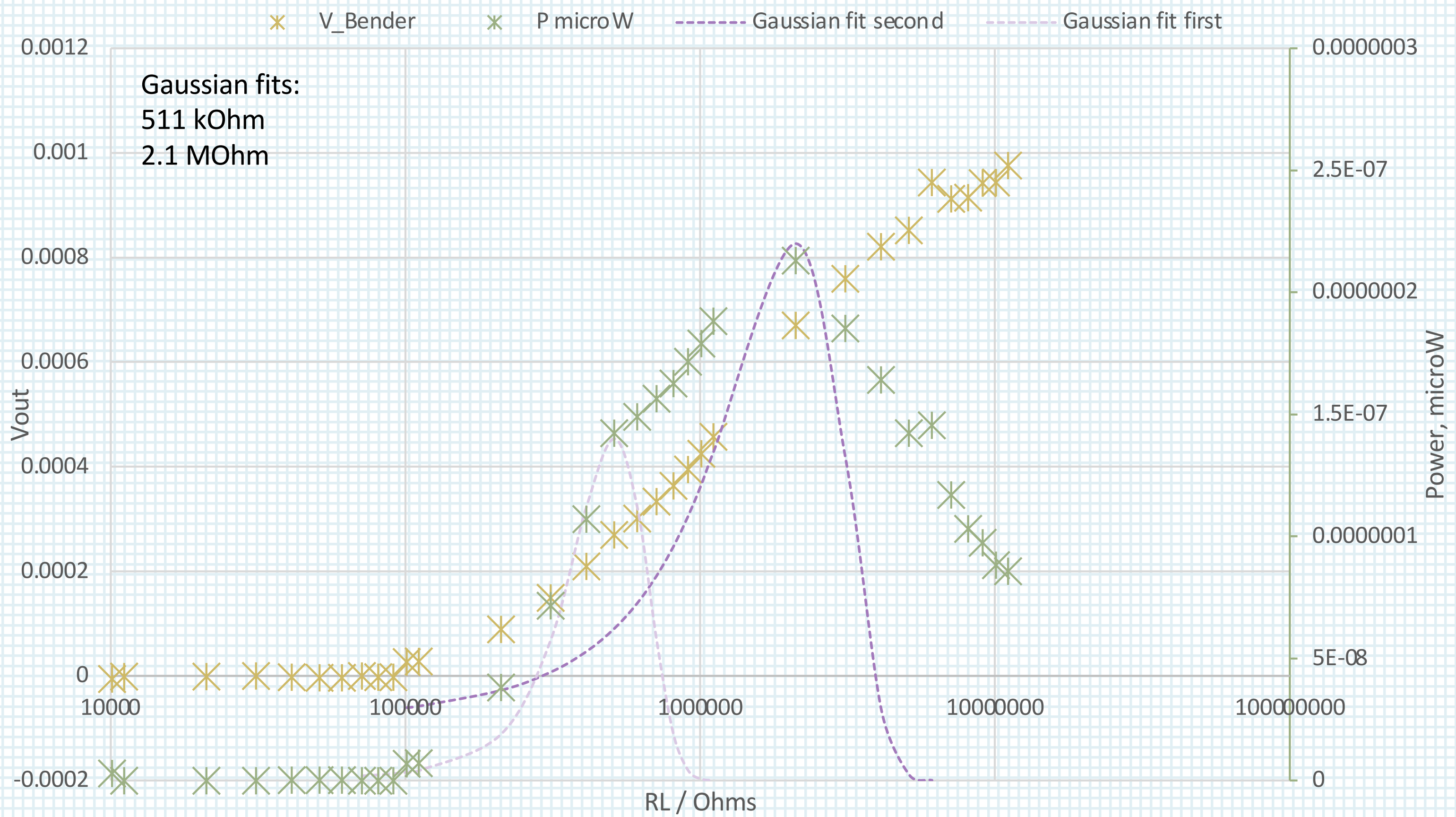
Outcome: Optimum power transfer into RL~ 2.1MΩ



- Set freq at resonance freq? No.
- Stay away from resonance? Flat insensitive to load at about 35Hz. Yes.
- Run freq sweeps for each RL. Explore the sensitivity of fr with frequency.
  - Minimal.
- Load the bender cantilever with R_L.
- Plot, $P=V^2/R_L$ against R_L

Resistive Loads

- Asymmetrical bender actuator: two distinct power load matches
- Points to the possibility for considering harvesting each element separately.
  - Phase is not exactly 180° between each element.
  - Difference amplifier does not then maximise output.



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Measurement Summary

Calibrated Energy Harvesting Rig

- Voltage-calibrated Lock-in amplifier
- Loadcell calibrated with NIST standard
- Resistance load decade box – calibrated at source
- DVM calibrated - Keysight calibration
- Buffer amplifier gain calibration via voltage source and calibrated DVM

- Bender loading conditions & assumptions
  - Composite modulus 80GPa
  - Sample dimensions using calibrated vernier callipers
  - Displacement at resonance calculated (~228Hz)
  - Acceleration: $a=dv/dt=d^2z/dt^2$
    - $a=|z_0|.(2.\pi.f)^2$ ~ $0.18ms^{-2}$ ~ 0.02g
  - Set acceleration: 1g
    - Thus, $|z|$ ~ 50 * $|z_0|$
    - Expect V ~ 0.2V
  - Increase acceleration $|z|$ ~ 1mm
    - a ~ 200g
    - V_{out} ~ 31V
  - Optimize output with matched R_L
    - V ~ experimental conditions ~ 7mV
    - Gain ~ 7/3
    - V_{out} ~ 7x31/3 ~ 72V pp.

- Errors and uncertainty analysis:
  - Approach: Use of partial differentials for compounding of individual errors through analysis of linear equations.
  - Largest error: calculation of displacement.

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Executive summary -Table

Parameter	Measured values	Displacement Calculated values ±10%	Acceleration /g ± 15%	V_{out} (± 0.01mV) measured	V_{out} ±15% expectation	Assumptions –at cantilever mechanical resonance
δ, displacement	Force, V_{out}	0.088 μm	0.02	3 mV		E~80GPa, resonance (228Hz), linear bending moment.
δ, displacement	-	1000 μm	200	-	31 V	Ratiometric output with deflection. R_L=1MΩ
V_{out}	-	1000 μm	200	-	72 V	R_L=2.2MΩ ideal matched. Gain increase=7/3
V_{out}	-	4.4 μm	1	-	0.4 V	R_L=2.2MΩ ideal matched. Gain increase=7/3