BOSEM Noise Analysis

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Ⓥ => must verify ✓ => checked

Analysis of BOSEM Performance per "Sensors and Actuators for the Advanced LIGO Mirror Suspensions" P1100208

Ⓥ Per page 4, the BOSEM yields $3\times10^{-10}\frac{m}{\sqrt{Hz}}$ sensitivity from 0.1 → 10Hz

✓ TYPO Per figure 6, the BOSEM sensitivity should be:

$9\times10^{-10}\frac{m}{\sqrt{Hz}}$ @ 0.1Hz

$3\times10^{-10}\frac{m}{\sqrt{Hz}}$ @ 1Hz

$1\times10^{-10}\frac{m}{\sqrt{Hz}}$ @ 10Hz

Ⓥ Per page 6, the mean photocurrent at $\frac{1}{2}$ light is 62.5μA

↳ The PD responsivity is $0.55\frac{A}{W}$

✓ V_{OUT} at ½ light = ~8.5VDC per figure 6

Transimpedance was => 160kΩ × factor of 2 for diff driver = 320kΩ

$$\text{Photocurrent } (I_{PD}) = \frac{8.5\text{VDC}}{320\text{k}\Omega} = 26.6\mu A \ \underline{\text{NOT}}\ 62.5\mu A$$

However the <u>FULL</u> light photocurrent is $= 62.5\mu A = \frac{20V}{320\Omega}$

✓ Per page 6, measuring range = ~700μm, and the average slope of Voltage output vs position is $\sim 20\frac{kV}{m}$ $\left(\text{actual } \frac{16V}{700\times10^{-6}m} = 22.9\frac{kV}{m}\right)$

Ⓥ Per page 6, the BOSEM noise performance should be limited by Shot noise at $7\times10^{-11}\frac{m}{\sqrt{Hz}}$ for Freq > 10Hz. Freq < 10Hz, the performance should be limited by $1/f$ photo current noise in the LED

✓

$$\text{Shot noise at } 62.5\mu A = \sqrt{2eI_{PD}} = 4.47\,pA/\sqrt{Hz}$$

$$\text{Shot noise at } 26.6\mu A = \sqrt{2eI_{PD}} = 2.92\,pA/\sqrt{Hz}$$

$$\text{average slope in terms of current} = \frac{22.9\times10^{3}V}{m}\times\frac{1}{320k\Omega} = 7.16\times10^{-2}\frac{A}{m}$$

$$\text{So: } 4.47\frac{pA}{\sqrt{Hz}}\times\frac{m}{7.16\times10^{-2}A} = 6.24\times10^{-11}\,m/\sqrt{Hz}$$

$$2.92\frac{pA}{\sqrt{Hz}}\times\frac{m}{7.16\times10^{-2}A} = 4.07\times10^{-11}\frac{m}{\sqrt{Hz}}$$

Conclusion is that even at full light, shot noise equivalent displacement is $< 1\times10^{-10}\frac{m}{\sqrt{Hz}}$ @ 10Hz which is the requirement. This does not yet allow for the other noise terms in the overall sensor (LED current noise, PD electronics noise, ADC input noise)

From: P1100208

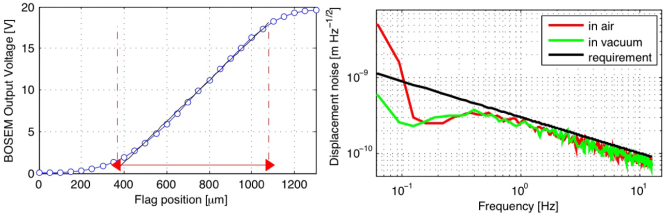

Figure 6. Typical performances of the BOSEMs displacement sensors. Left: response of BOSEM readout as function of position of the flag. Nominal measuring range (red lines), and fit in the linear region (black line) are also shown. Right: displacement sensitivity for a BOSEM unit, measured in-air and in-vacuum. The Advanced LIGO requirements, nominally 3×10^{-10} m Hz$^{-1/2}$ at 1 Hz and 1×10^{-10} m Hz$^{-1/2}$ at 10 Hz [24], are shown for comparison.

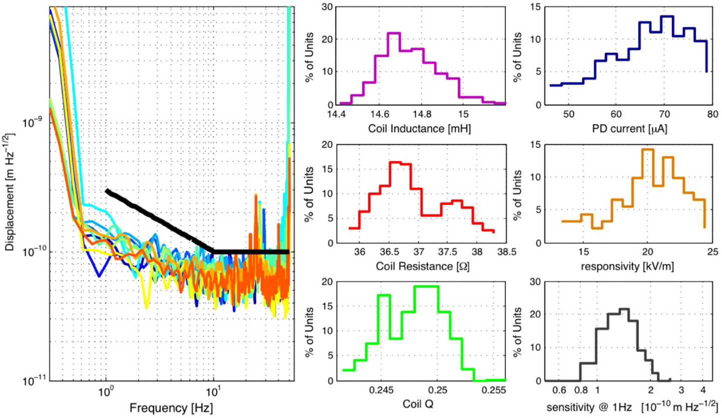

Figure 7. Typical performances of the BOSEM production articles. Left panel: displacement noise spectra of ten BOSEM samples, compared with the Advanced LIGO requirement (black line). The spikes between 20 Hz and 50 Hz are mains-related pick-up and are artefacts of the measurement system. Central column: some statistics on the reproducibility of the BOSEMs electrical properties for ∼ 600 BOSEM articles: inductance (nominal design value 14.7 mH), resistance (37.6 Ω) and electrical Q (243×10^{-3}), to be compared with ±5% tolerances from the requirements [17]. Right column: distribution of the PD currents measured from ∼ 600 units (nominal design value 62.5 μA, tolerance ±28%), and some statistics on responsivity and displacement noise at 1 Hz measured for the fully characterised BOSEM units (about ∼ 20% of the total).

Satellite Box Details (D0901284)

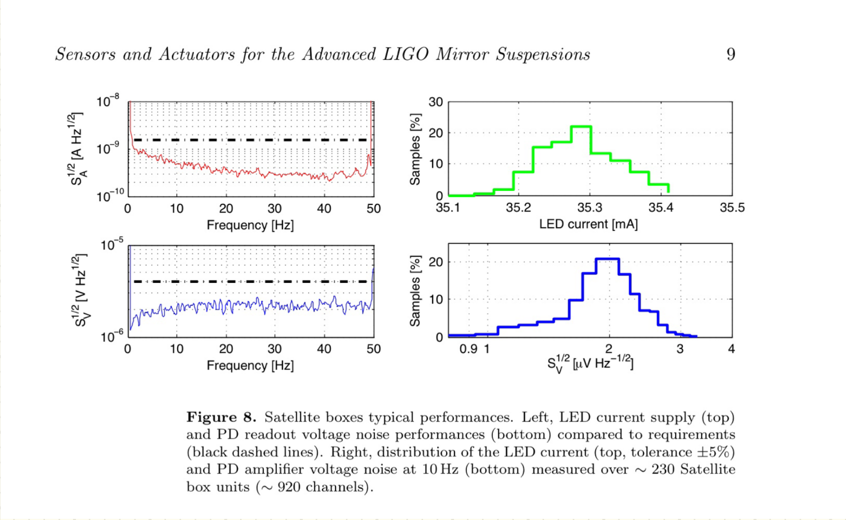

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Figure 8. Satellite boxes typical performances. Left, LED current supply (top) and PD readout voltage noise performances (bottom) compared to requirements (black dashed lines). Right, distribution of the LED current (top, tolerance ±5%) and PD amplifier voltage noise at 10 Hz (bottom) measured over ~ 230 Satellite box units (~ 920 channels).

Ⓥ Per page 9, the LED current source produces 35mA for each LED with $0.5\frac{nA}{\sqrt{Hz}}$ at 10Hz corresponding to $3\times10^{-11}\frac{m}{\sqrt{Hz}}$ which should be ~ 3X < the requirement

① Verified $I_{LED} = 35mA$

② Verified I_{LED} noise @ 10Hz per figure 8 is $\leq 0.5\, nA/\sqrt{Hz}$ @ 10Hz

✓ assume I_{LED} of 35mA produces 62.5μA => Gain $= \frac{62.5\times10^{-6}}{35\times10^{-3}} = 1.79\times10^{-3}$

So $0.5nA/\sqrt{Hz}$ becomes $\frac{0.5nA}{\sqrt{Hz}} \times 1.79\times10^{-3} = 8.95\times10^{-13}\frac{A}{\sqrt{Hz}}$

which equates to a displacement noise of $8.95\times10^{-13}A/\sqrt{Hz}\ \underbrace{\frac{m}{7.16\times10^{-2}A}}$

$= 1.25\times10^{-11}\, m/\sqrt{Hz}$

Gain of sensor in A/m based on slope = $22.86\frac{kV}{m}$ & $320\,k\Omega$

* measured aLIGO unit current noise to be $0.7\,nA/\sqrt{Hz}$ @ 10Hz
S1000276 Unit from LHO
BOSEM Pedigree unknown

Ⓥ Per page 9, the PD amplifier [Transimpedance amplifier signal chain] converts the PD current into a ±10V signal with intrinsic voltage noise [interpreted to mean electronics chain dark noise] $< 4\frac{\mu V}{\sqrt{Hz}}$ which equates to a displacement noise of $5\times10^{-11}\frac{m}{\sqrt{H}}$ at 10Hz

- Using the sensor slope of $7.16\times10^{-2}\frac{A}{m}$ =>

TIA opamp current noise - $0.2\,pA/\sqrt{Hz}$, 1/f corner ~ 400Hz

Voltage noise - $7.9\,nV/\sqrt{Hz}$ (negligable)

160kΩ feedback resistor $I_{noise} = 0.32\,pA/\sqrt{Hz}$

Input referred TIA electronics noise $= \sqrt{(0.2)^2 + (0.32)^2} = \sim 0.4\,pA/\sqrt{Hz}$

Equivalent displacement noise $= \frac{0.4pA}{\sqrt{Hz}} \cdot \frac{m}{7.16\times10^{-2}A} = \boxed{5.59\times10^{-12}\frac{m}{\sqrt{Hz}}}$

- If the shot noise at 62.5µA I_{PD} is included in the electronics noise, the shot noise ($4.47\,pA/\sqrt{Hz}$) will dominate over the TIA noise ($0.4\,pA/\sqrt{Hz}$) and yield an equivalent displacement noise of:

$$4.47\times10^{-12}\frac{A}{\sqrt{Hz}} \cdot \frac{m}{7.16\times10^{-2}A} = \boxed{6.24\times10^{-11}\,m/\sqrt{Hz}}$$

- If Ipd is taken at 1/2 light, then the equivalent displacement noise is:

$$2.92\times10^{-12}\frac{A}{\sqrt{Hz}} \cdot \frac{m}{7.16\times10^{-2}A} = \boxed{4.08\times10^{-11}\frac{m}{\sqrt{Hz}}}$$

- The quoted $4\frac{\mu V}{\sqrt{Hz}}$ is translated to $m/\sqrt{Hz}$ at 10Hz by knowing the whitening gain @ 10Hz (19) & the trans Z (320kΩ) ∴

$$4\times10^{-6}\frac{\cancel{V}}{\sqrt{Hz}} \times \frac{\cancel{A}}{320\times10^{3}\cdot19\,\cancel{V}} \cdot \frac{m}{7.16\times10^{-2}\cancel{A}} = \boxed{9.19\times10^{-12}\,m/\sqrt{Hz}}$$

Conclusion: We do not understand how $4\mu V/\sqrt{Hz}$ equates to $5\times10^{-11}\,m/\sqrt{Hz}$

The whitening gain consists of

Zero = 0.4 Hz
Pole = 10 Hz
DC Gain = −1

(ACTUAL
ZERO = 0.3835 Hz
Pole = 10.61 Hz)

$\therefore$ if one were to use the pole & zero to calculate the gain at 10 Hz, one would conclude:

$$\text{Gain @ 10 Hz} = \frac{10}{0.4} = 25$$

Now using this ⇒

Output noise quoted as $4\,\mu V/\sqrt{Hz}$, DC Gain of sensor $= \overset{\text{Quoted in note}}{\sim} 20\times10^{3}\,\frac{V}{m}$

$$\text{So:}\quad \frac{4\,\mu V}{\sqrt{Hz}}\cdot\frac{m}{20\times10^{3}\,V} \Rightarrow 2\times10^{-10}\,\frac{m}{\sqrt{Hz}}$$

Translating the 1 Hz & 10 Hz sensing noise specs to equivalent motion for inclusion in a noise budget presented in units of voltage noise:

at 1 Hz spec is $3\times10^{-10}\,m/\sqrt{Hz}$
10 Hz " " $1\times10^{-10}\,m/\sqrt{Hz}$

The DC gain from motion to output voltage is quoted in P as $700\,\mu m \Rightarrow 16\,VDC$ so

$$\frac{16\,VDC}{700e{-6}\,m} = 22.86\,\frac{kV}{m}$$

(Using 160kΩ TIA resistor & diff dr, gain = 2)

A shift from 160kΩ to 120kΩ for TIA ⇒

$$22.86\,\frac{kV}{m}\times\frac{120\,k\Omega}{160\,k\Omega} = \boxed{17.14\,\frac{kV}{m}}$$

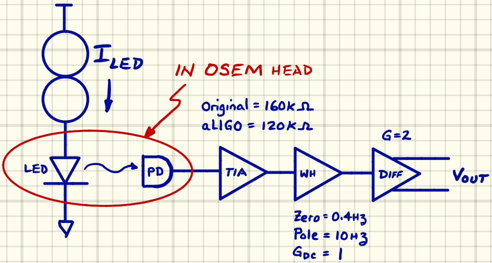
So to predict output voltage noise at 1 Hz & 10 Hz this slope in conjunction with the whitening gain (2.87 @ 1 Hz, 19 @ 10 Hz) is given by

1 Hz 120kΩ

$$3\times10^{-10}\,\frac{m}{\sqrt{Hz}}\times17.14\,\frac{kV}{m}\times2.87 = 1.48\times10^{-5}\,\frac{V}{\sqrt{Hz}}$$

10 Hz 120kΩ

$$1\times10^{-10}\times17.14\,\frac{kV}{m}\times19 = 3.26\times10^{-5}\,\frac{V}{\sqrt{Hz}}$$

I_LED
IN OSEM HEAD
LED
PD
Original = 160kΩ
aLIGO = 120kΩ
TIA
WH
Zero = 0.4Hz
Pole = 10Hz
G_DC = 1
G=2
DIFF
V_OUT