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Determining Sensor Resolution

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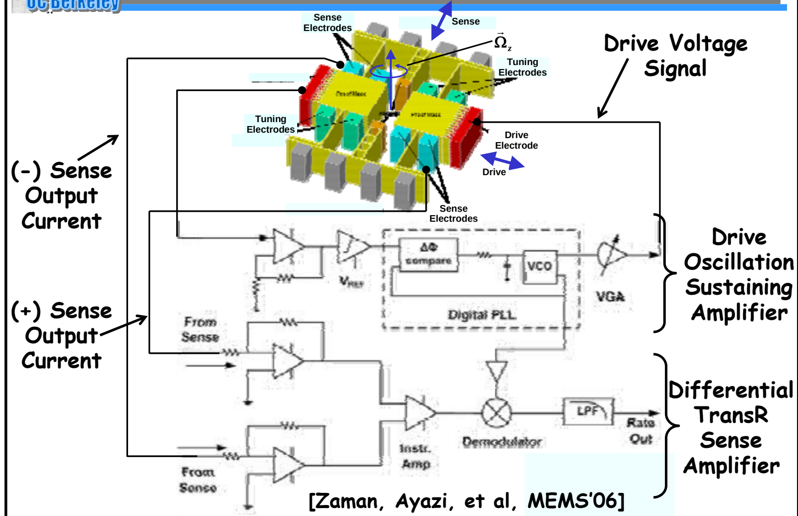
MEMS-Based Tuning Fork Gyroscope



[Zaman, Ayazi, et al, MEMS'06]

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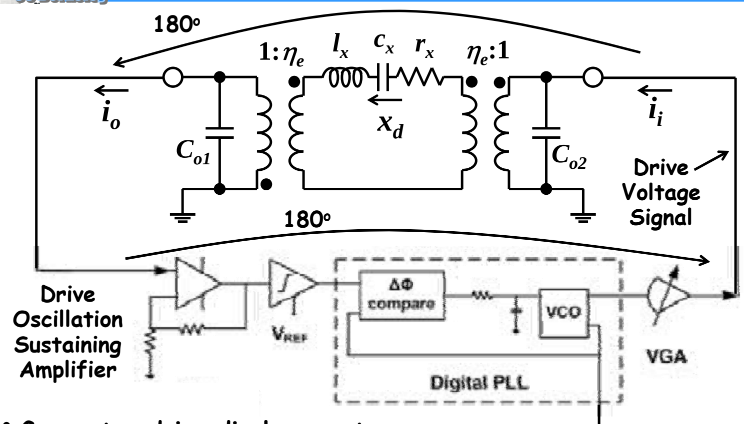
Drive Axis Equivalent Circuit



- Generates drive displacement velocity $\dot{x}_d$ to which the Coriolis force is proportional

To Sense Amplifier (for synchronization)

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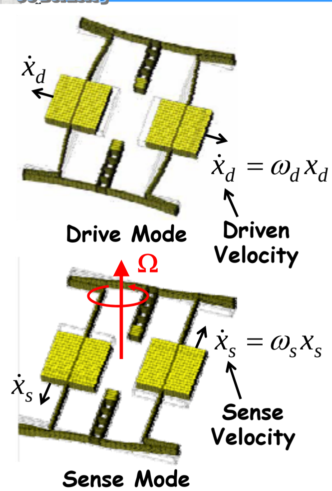
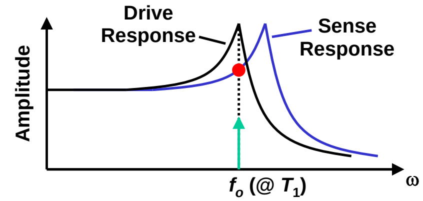
Drive-to-Sense Transfer Function



Drive/Sense Response Spectra:



Rotation-Induced Coriolis Force:

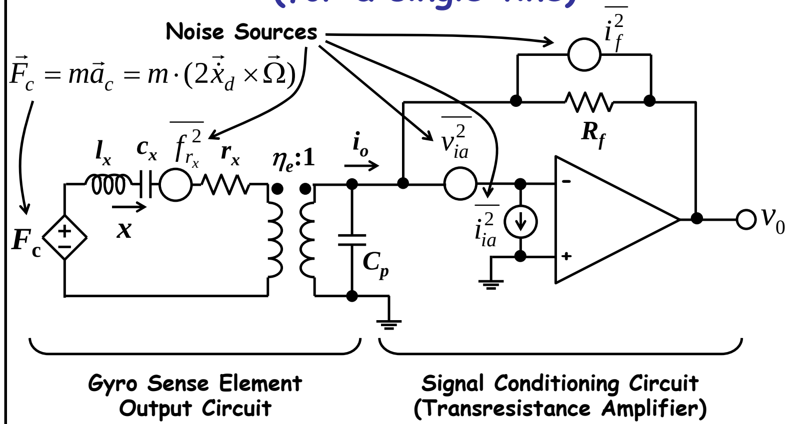
$\vec{a}_c = 2\dot{\vec{x}}_d \times \vec{\Omega} = 2\omega_d \vec{x}_d \times \vec{\Omega}$

⇒ Acts in the sense mode direction

$a_s = 2\omega_d x_d \Omega \sin 90°$

↪ $\boxed{a_s = 2\omega_d x_d \Omega}$

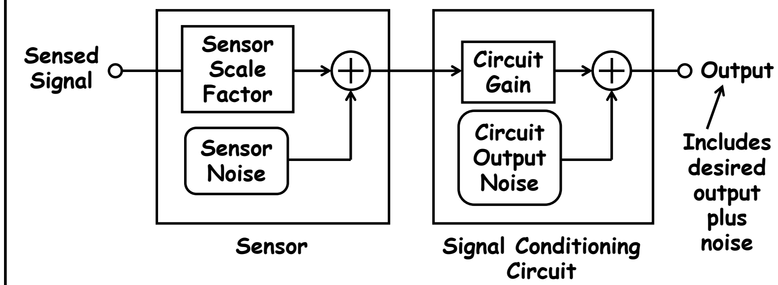
Gyro Readout Equivalent Circuit (for a single tine)



- Easiest to analyze if all noise sources are summed at a common node

Minimum Detectable Signal (MDS)

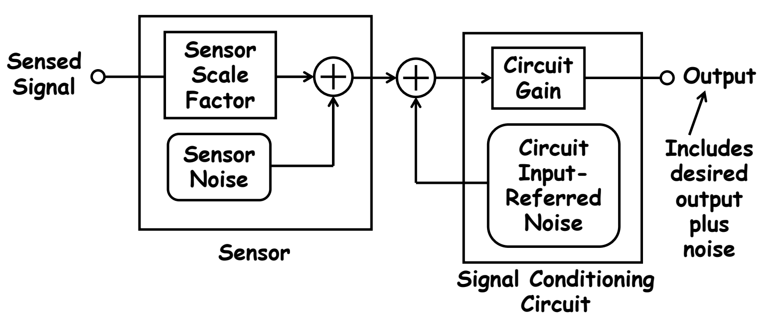
- Minimum Detectable Signal (MDS): Input signal level when the signal-to-noise ratio (SNR) is equal to unity



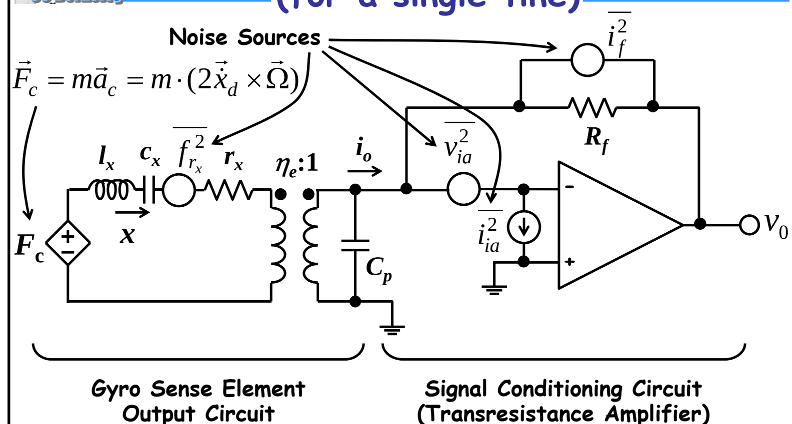
- The sensor scale factor is governed by the sensor type
- The effect of noise is best determined via analysis of the equivalent circuit for the system

Move Noise Sources to a Common Point

- Move noise sources so that all sum at the input to the amplifier circuit (i.e., at the output of the sense element)
- Then, can compare the output of the sensed signal directly to the noise at this node to get the MDS

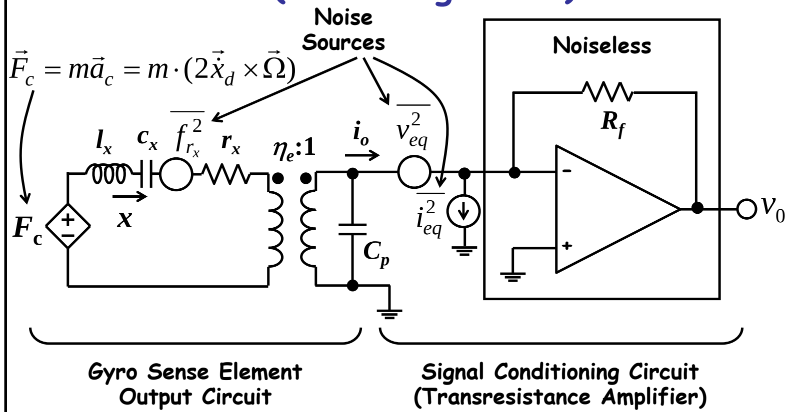


Gyro Readout Equivalent Circuit (for a single tine)



- Easiest to analyze if all noise sources are summed at a common node

Gyro Readout Equivalent Circuit (for a single tine)

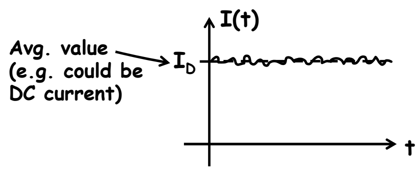


- Here, $\overline{v_{eq}^2}$ and $\overline{i_{eq}^2}$ are equivalent input-referred voltage and current noise sources

Noise

Noise

- Noise: Random fluctuation of a given parameter I(t)
- In addition, a noise waveform has a zero average value



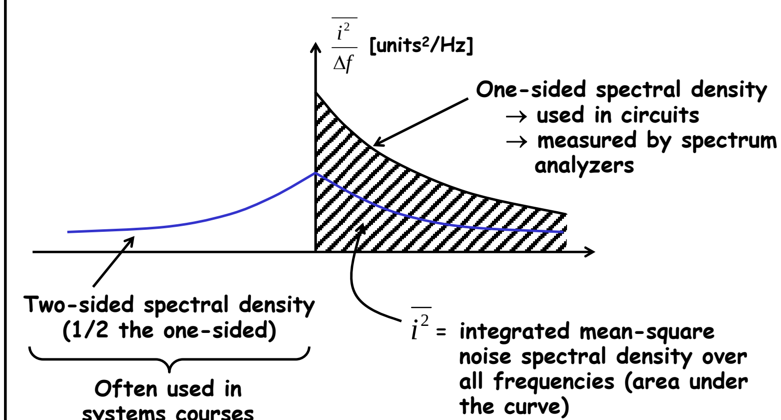
- We can't handle noise at instantaneous times
- But we can handle some of the averaged effects of random fluctuations by giving noise a power spectral density representation
- Thus, represent noise by its mean-square value:

Let $i(t) = I(t) - I_D$

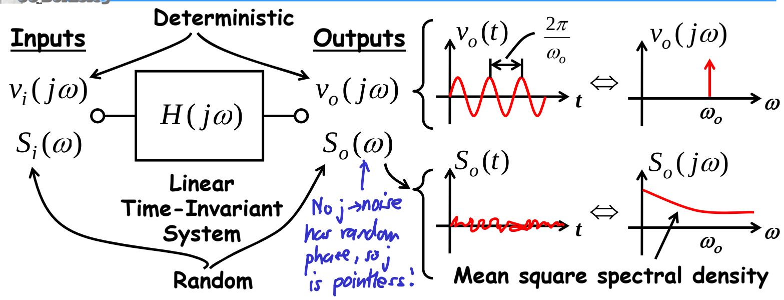
Then $\overline{i^2} = \overline{(I - I_D)^2} = \lim_{T\to\infty} \frac{1}{T}\int_0^T |I - I_D|^2 dt$

Noise Spectral Density

- We can plot the spectral density of this mean-square value:



Circuit Noise Calculations



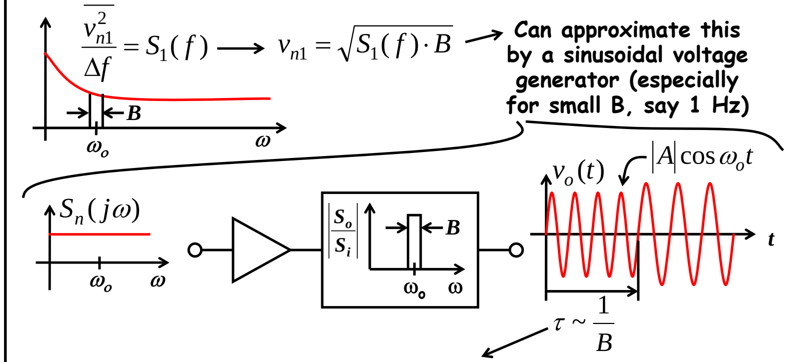
- **Deterministic:** $v_o(j\omega) = H(j\omega)v_i(j\omega)$
- **Random:** $S_o(\omega) = \left[H(j\omega)H^*(j\omega)\right]S_i(\omega) = \left|H(j\omega)\right|^2 S_i(\omega)$

$$\sqrt{S_o(\omega)} = \left|H(j\omega)\right|\sqrt{S_i(\omega)}$$ → How is it we can do this?

Root mean square amplitudes

Handling Noise Deterministically

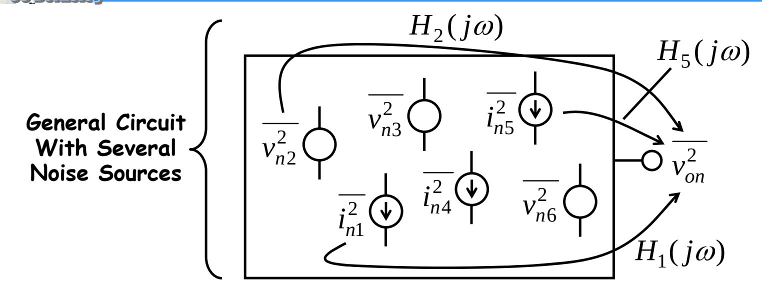
- Can do this for noise in a tiny bandwidth (e.g., 1 Hz)



[This is actually the principle by which oscillators work → oscillators are just noise going through a tiny bandwidth filter]

Why? Neither the amplitude nor the phase of a signal can change appreciably within a time period 1/B.

Systematic Noise Calculation Procedure



- Assume noise sources are uncorrelated

1. For $\overline{i_{n1}^2}$ replace w/ a deterministic source of value

$$i_{n1} = \sqrt{\frac{\overline{i_{n1}^2}}{\Delta f}\cdot(1\,\text{Hz})}$$

Systematic Noise Calculation Procedure

2. Calculate $v_{on1}(\omega) = i_{n1}(\omega)H(j\omega)$ (treating it like a deterministic signal)
3. Determine $\overline{v_{on1}^2} = \overline{i_{n1}^2}\cdot\left|H(j\omega)\right|^2$
4. Repeat for each noise source: $\overline{i_{n1}^2}, \overline{v_{n2}^2}, \overline{v_{n3}^2}$
5. Add noise power (mean square values)

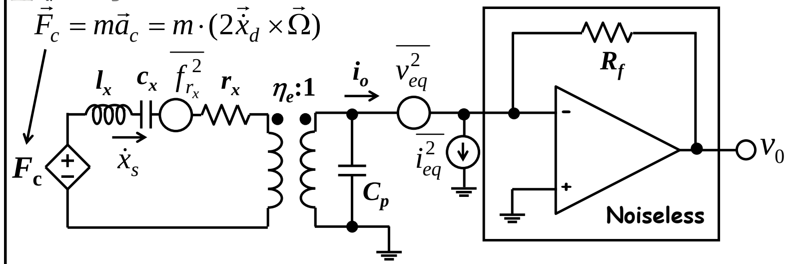
$$\overline{v_{onTOT}^2} = \overline{v_{on1}^2} + \overline{v_{on2}^2} + \overline{v_{on3}^2} + \overline{v_{on4}^2} + \cdots$$

$$v_{onTOT} = \sqrt{\overline{v_{on1}^2} + \overline{v_{on2}^2} + \overline{v_{on3}^2} + \overline{v_{on4}^2} + \cdots}$$

Total rms value

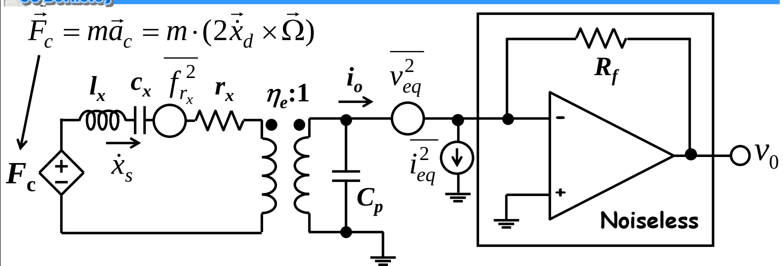
Determining Sensor Resolution

Example: Gyro MDS Calculation



- The gyro sense presents a large effective source impedance
  - Currents are the important variable; voltages are "opened" out
  - Must compare i_o with the total current noise i_{eqTOT} going into the amplifier circuit

Example: Gyro MDS Calculation (cont)



- First, find the rotation to i_o transfer function:

$$\dot{x}_s = \frac{\omega_s Q}{k_s}\,Ⓗ_s(j\omega_d)\,F_s = \frac{\omega_s Q}{k_s}\cdot 2\omega_d x_d \Omega m \cdot Ⓗ(j\omega_d)$$

$$\left[F_s = F_c = 2\omega_d x_d \Omega m\right] \qquad \frac{m}{k_s} = \frac{1}{\omega_s^2}$$

$$\dot{x}_s = 2\frac{\omega_d}{\omega_s} Q x_d\, Ⓗ(j\omega_d)\cdot\Omega$$

Example: Gyro MDS Calculation (cont)

$$i_o = \eta_e \dot{x}_s = \underbrace{2\frac{\omega_d}{\omega_s} Q x_d \eta_e Ⓗ(j\omega_d)}_{A \triangleq \text{scale factor}}\cdot\Omega \rightarrow \boxed{i_o = A\Omega \quad \text{where } A = 2\frac{\omega_d}{\omega_s} Q x_d \eta_e Ⓗ(j\omega_d)}$$

When $\Omega = \Omega_{min} \triangleq$ MDS, $i_o = i_{eqTOT}$ ← input-referred noise current entering the sense amplifier → in $pA/\sqrt{Hz}$

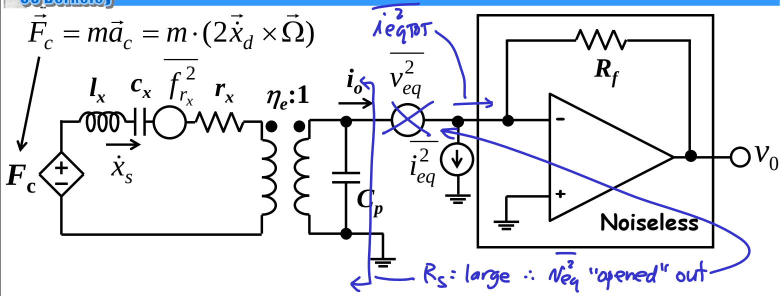
$$\therefore\ i_{eqTOT} = A\Omega_{min} \rightarrow \boxed{\Omega_{min} = \frac{i_{eqTOT}}{A}\left(\frac{3600s}{hr}\right)\left(\frac{180^\circ}{\pi}\right)\ \left[(^\circ/hr)/\sqrt{Hz}\right]}$$

$$\boxed{\text{Angle Random Walk} = \text{ARW} = \frac{1}{60}\Omega_{min}\ \left[^\circ/\sqrt{hr}\right]}$$

↳ Easier to determine directional error as a function of elapsed time.

Example: Gyro MDS Calculation (cont)

$\vec{F}_c = m\vec{a}_c = m \cdot (2\dot{\vec{x}}_d \times \vec{\Omega})$



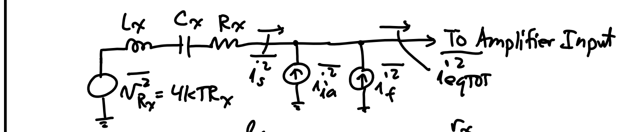
- Now, find the i_{eqTOT} entering the amplifier input:

$i_{eqTOT} = i_s + i_{eq} \rightarrow \overline{i_{eqTOT}^2} = \overline{i_s^2} + \overline{i_f^2} + \overline{i_{ia}^2} + \frac{\overline{v_{ia}^2}}{R_f^2}$ $\qquad \frac{\overline{f_{r_x}^2}}{\Delta f} = 4kTr_x$

↑ Brownian motion noise of the sense element → determined entirely by the noise in $r_x \rightarrow \overline{f_{r_x}^2}$

↳ easiest to convert to an all electrical equiv. ckt.

Example: Gyro MDS Calculation (cont)



where $L_x = \frac{l_x}{\eta_e^2}$, $C_x = \eta_e^2 c_x$, $R_x = \frac{r_x}{\eta_e^2}$

$\therefore \; i_s = v_{R_x}\left(\frac{1}{R_x}\right)\Theta(j\omega_d) \rightarrow \frac{\overline{i_s^2}}{\Delta f} = 4kTR_x\left(\frac{1}{R_x^2}\right)|\Theta(j\omega_d)|^2$

$$\Rightarrow \boxed{\frac{\overline{i_s^2}}{\Delta f} = \frac{4kT}{R_x}|\Theta(j\omega_d)|^2}$$

Thus:

$$\boxed{\frac{\overline{i_{eqTOT}^2}}{\Delta f} = \frac{4kT}{R_x}|\Theta(j\omega_d)|^2 + \frac{4kT}{R_f} + \frac{\overline{i_{ia}^2}}{\Delta f} + \frac{\overline{v_{ia}^2}}{\Delta f}\left(\frac{1}{R_f^2}\right)}$$

learn to get these from EE240.
↳ or just get them from a data sheet...

LF356 Op Amp Data Sheet

LF155/LF156/LF256/LF257/LF355/LF356/LF357
JFET Input Operational Amplifiers

General Description

These are the first monolithic JFET input operational amplifiers to incorporate well matched, high voltage JFETs on the same chip with standard bipolar transistors (BI-FET™ Technology). These amplifiers feature low input bias and offset currents/low offset voltage and offset voltage drift, coupled with offset adjust which does not degrade drift or common-mode rejection. The devices are also designed for high slew rate, wide bandwidth, extremely fast settling time, low voltage and current noise and a low 1/f noise corner.

Features

Advantages

- Replace expensive hybrid and module FET op amps
- Rugged JFETs allow blow-out free handling compared with MOSFET input devices
- Excellent for low noise applications using either high or low source impedance—very low 1/f corner
- Offset adjust does not degrade drift or common-mode rejection as in most monolithic amplifiers
- New output stage allows use of large capacitive loads (5,000 pF) without stability problems
- Internal compensation and large differential input voltage capability

Applications

- Precision high speed integrators
- Fast D/A and A/D converters
- High impedance buffers
- Wideband, low noise, low drift amplifiers
- Logarithmic amplifiers
- Photocell amplifiers
- Sample and Hold circuits

Common Features

- Low input bias current: 30pA
- Low Input Offset Current: 3pA
- High input impedance: $10^{12}\Omega$
- Low input noise current: 0.01 pA/√Hz
- High common-mode rejection ratio: 100 dB
- Large dc voltage gain: 106 dB

$\sqrt{\frac{\overline{i_{ia}^2}}{\Delta f}} = 0.01\ pA/\sqrt{Hz}$

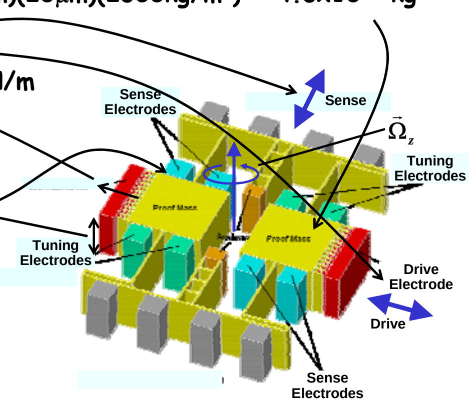
Uncommon Features

	LF155/ LF355	LF156/ LF256/ LF356	LF257/ LF357 (A_V=5)	Units
Extremely fast settling time to 0.01%	4	1.5	1.5	μs
Fast slew rate	5	12	50	V/μs
Wide gain bandwidth	2.5	5	20	MHz
Low input noise voltage	20	12	12	nV/√Hz

$\sqrt{\frac{\overline{v_{ia}^2}}{\Delta f}} = 12\ nV/\sqrt{Hz}$

Example ARW Calculation

- Example Design:
  - Sensor Element:
    - m = (100μm)(100μm)(20μm)(2300kg/m³) = 4.6x10⁻¹⁰kg
    - ω_s = 2π(15kHz)
    - ω_d = 2π(10kHz)
    - $k_s = \omega_s^2 m$ = 4.09 N/m
    - x_d = 20 μm
    - Q_s = 50,000
    - V_P = 5V
    - h = 20 μm
    - d = 1 μm
  - Sensing Circuitry:
    - R_f = 100kΩ
    - i_{ia} = 0.01 pA/√Hz
    - v_{ia} = 12 nV/√Hz



Example ARW Calculation (cont)

Get rotation rate to output current scale factor:

$$A = 2\frac{\omega_d}{\omega_s}Q_s x_d \eta_e |\Theta(j\omega_d)| = 2\left(\frac{10k}{15k}\right)(50K)(20\mu)(5)(2000\epsilon_o)(0.000024) = \underline{2.83\times10^{-12}C}$$

$$\Theta(j\omega_d) = \frac{(j\omega_d)(\omega_s/Q_s)}{-\omega_d^2 + \frac{j\omega_d\omega_s}{Q_s} + \omega_s^2} = \frac{j(10K)(15K)/(50K)}{(15K)^2 - (10K)^2 + \frac{j(10K)(15K)}{50K}} = \frac{j(3K)}{1.25\times10^8 + j(3K)}$$

$$\rightarrow |\Theta(j\omega_d)| = \frac{3K}{\sqrt{(1.25\times10^8)^2 + (3K)^2}} = 0.000024$$

$$\frac{\partial C}{\partial x} = \frac{C_o}{d} = \frac{\epsilon_o h W_p}{d} = \frac{\epsilon_o(20\mu)(100\mu)}{(1\mu)^2} = 2000\epsilon_o \rightarrow \eta_e = V_P\frac{\partial C}{\partial x} = 5(2000\epsilon_o)$$

($\uparrow$ Assume electrode covers the whole sidewall.) (ϵ_o = 8.854x10^{-12} F/m; $5(2000\epsilon_o)$ = 8.854x10^{-8} F/m)

Then, get noise:

$$\frac{\overline{i_{eqTOT}^2}}{\Delta f} = \frac{4kT}{R_x}|\Theta(j\omega_d)|^2 + \frac{4kT}{R_f} + \frac{\overline{i_{ia}^2}}{\Delta f} + \frac{\overline{v_{ia}^2}}{\Delta f}\left(\frac{1}{R_f^2}\right)$$

Example ARW Calculation (cont)

$$\left[R_x = \frac{\omega_s m}{Q_s\eta_e^2} = \frac{2\pi(15K)(4.6\times10^{-10})}{(50K)(8.854\times10^{-8})^2} = 110.6k\Omega\right]$$

$$\frac{\overline{i_{eqTOT}^2}}{\Delta f} = \underbrace{\frac{(1.66\times10^{-29})}{(110.6K)}(0.000024)^2}_{8.64\times10^{-35}A^2/Hz} + \underbrace{\frac{(1.66\times10^{-29})}{1M}}_{1.66\times10^{-26}A^2/Hz} + \underbrace{(0.01p)^2}_{1\times10^{-28}A^2/Hz} + \underbrace{\frac{(12n)^2}{(1M)^2}}_{1.44\times10^{-28}A^2/Hz}$$

(sensor element noise insignificant) (Noise from R_f dominates!)

$$\therefore \frac{\overline{i_{eqTOT}^2}}{\Delta f} = 1.68\times10^{-26}A^2/Hz \longrightarrow i_{eqTOT} = \sqrt{\frac{\overline{i_{eqTOT}^2}}{\Delta f}} = 1.30\times10^{-13}A/\sqrt{Hz}$$

$$\therefore \Omega_{min} = \frac{i_{eqTOT}}{A}\left(\frac{3600s}{hr}\right)\left(\frac{180^\circ}{\pi}\right) = \frac{1.30\times10^{-13}}{2.83\times10^{-12}}(3600)\left(\frac{180}{\pi}\right) = \underline{9448\ (^\circ/hr)/\sqrt{Hz}}$$

And finally:

$$ARW = \frac{1}{60}\Omega_{min} = \frac{1}{60}(9448) = \boxed{157\ ^\circ/\sqrt{hr} = ARW}$$

$\Rightarrow$ Almost turned around in 1 hour!

What if $\omega_d = \omega_s$?

If $\omega_d = \omega_s = 15KHz$, then $|\Theta(j\omega_d)| = 1$ and

$$A = 2\frac{\omega_d}{\omega_s}Q_s x_d \eta_e |\Theta(j\omega_d)| = 2Q_s x_d \eta_e = 2(50K)(20\mu)(5)(2000\epsilon_o) = \underline{1.77\times10^{-7}C}$$

$$\frac{\overline{i_{eqTOT}^2}}{\Delta f} = \underbrace{\frac{(1.66\times10^{-29})}{(110.6K)}(1)^2}_{1.51\times10^{-25}A^2/Hz} + \underbrace{\frac{(1.66\times10^{-29})}{1M}}_{1.66\times10^{-26}A^2/Hz} + \underbrace{(0.01p)^2}_{1\times10^{-28}A^2/Hz} + \underbrace{\frac{(12n)^2}{(1M)^2}}_{1.44\times10^{-28}A^2/Hz}$$

(Now, the sensor element dominates!)

$$\therefore \frac{\overline{i_{eqTOT}^2}}{\Delta f} = 1.67\times10^{-25}A^2/Hz \longrightarrow i_{eqTOT} = \sqrt{\frac{\overline{i_{eqTOT}^2}}{\Delta f}} = 4.08\times10^{-13}A/\sqrt{Hz}$$

$$\therefore \Omega_{min} = \frac{i_{eqTOT}}{A}\left(\frac{3600s}{hr}\right)\left(\frac{180^\circ}{\pi}\right) = \frac{4.08\times10^{-13}}{1.77\times10^{-7}}(3600)\left(\frac{180}{\pi}\right) = \underline{0.476\ (^\circ/hr)/\sqrt{Hz}}$$

And finally:

$$ARW = \frac{1}{60}\Omega_{min} = \frac{1}{60}(0.476) = \boxed{0.0079\ ^\circ/\sqrt{hr} = ARW}$$

$\Rightarrow$ Navigation grade!