Self-Noise in a Measurement Circuit

Estimating the ratio of signal to intrinsic noise (SNR) in the amplified and filtered output of a piezoresistive pressure sensor

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Though generally small compared to external noise, a signal conditioner's intrinsic or "self-noise" should be properly characterized so that an accurate SNR for low-level sensor measurements can be predicted. This requires a noise model for the circuit that can be verified by direct measurements. Precision Filters (PFI) employs a simple model to provide users of its signal conditioners with a consistent reference for SNR estimation.

Consider the measurement setup shown in Figure 1A. A high-sensitivity Kulite® piezoresistive pressure sensor (XCS-190-5D) with nominal output of 30 mV/PSID is connected to PFI's 28108 bridge conditioner. The programmable 28108 provides voltage excitation to the bridge and two gain stages placed on either side of a low-pass filter.

Of interest here is a quick and accurate assessment of the signal conditioner noise to determine its effect on the pressure sensor measurement.

Establishing a noise specification for quick SNR estimation at any gain and filter setting requires a noise model. PFI's model (Figure 1B-1D) assumes the sensor and signal conditioner act as independent noise sources, each described by their amplitude spectral density (units of $V_{rms}/\sqrt{Hz}$). Each source is dominated by a combination of 'pink' or '1/f' noise (i.e. inversely proportional to frequency) and white noise (i.e. independent of frequency). Though their generative mechanisms differ, both sources are stochastic and modeled as voltages that vary randomly with time.

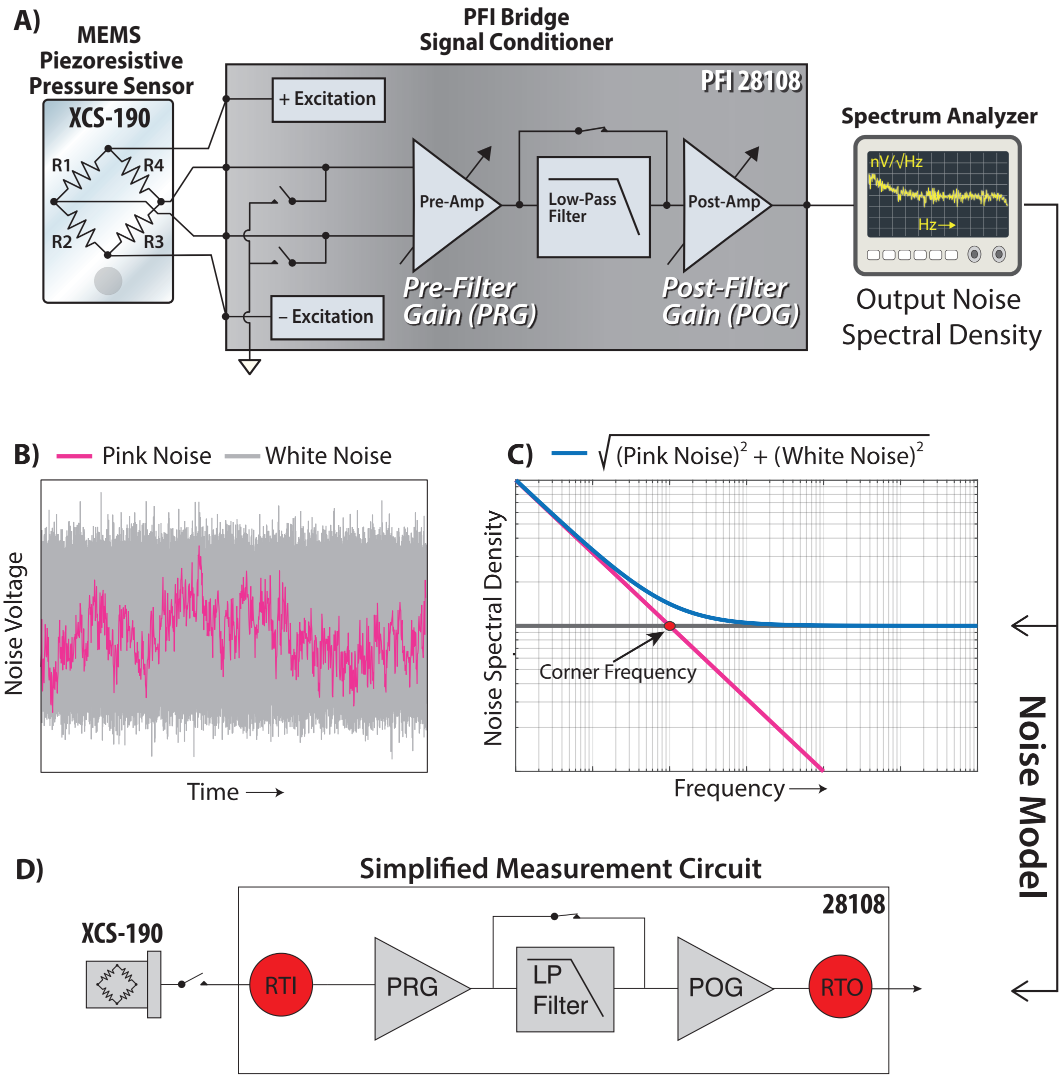

Figure 1

1A) Measurement Setup

Schematic showing the measurement setup for the analysis presented in this study. Kulite's XCS-190 pressure sensor is connected to PFI's 28108 signal conditioner, whose output is measured using a spectrum analyzer.

1B),1C) Modeling Noise Sources

B) Modeled time records of 'pink' and 'white' noise sources over a bandwidth of 0.1 Hz - 100 Hz and 0.1 Hz to 100 kHz, respectively. C) Corresponding noise spectral densities of pink and white noise sources and their combination. The sources are independent and combine in root-sum-square (RSS) fashion to produce a total noise spectral density (blue curve) that can be used to model the sensor + signal conditioner noise.

1D) Simplified Noise Model

Concept sketch describing the simplified circuit model used to estimate the self-noise for the purpose of SNR prediction.

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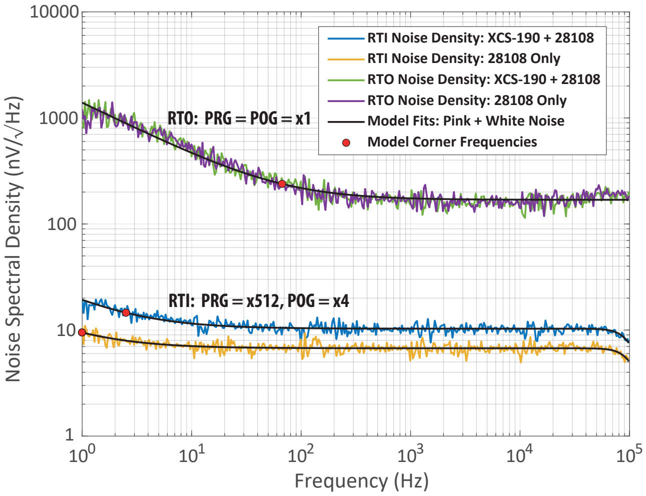

Figure 2) ***Measured noise spectral densities (see Figure 1A for setup) with model fits. See text for detailed discussion.***

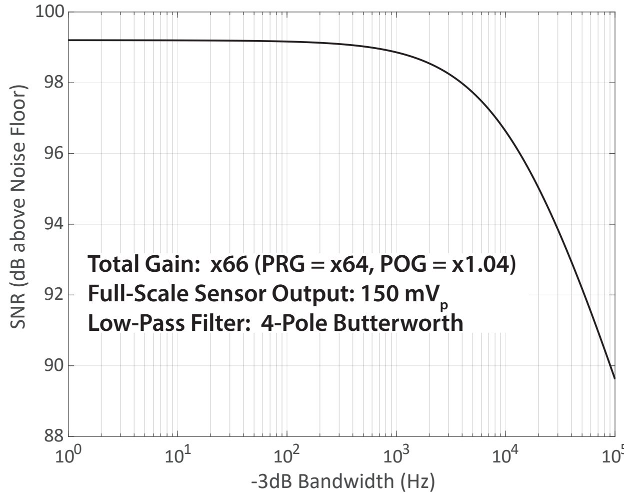

Figure 3) ***Estimated SNR vs. bandwidth for the setup in Figure 1A. The desired full-scale circuit output for A/D conversion is 10 V_p.***

Importantly, two or more uncorrelated random noise voltages combine via their root-sum-square (RSS). Here, the total noise contributed from each source (sensor and signal conditioner) represents an RSS combination of pink and white noise, and the total noise measured at the output represents the RSS combination of sensor noise and signal conditioner noise.

In addition, the noise generated within the 28108 is partitioned into two independent sources. A referred-to-input source (RTI) is assumed to represent the input-stage noise: it is (along with any sensor noise) amplified by both pre-filter (PRG) and post-filter (POG) gain stages, and is passed through the low-pass filter. A referred-to-output source (RTO) is assumed to represent the output-stage noise: it is downstream from the PRG, POG, and low-pass filter. Again, these sources are treated as independent and combine via their RSS. Though only approximate, this model is useful insofar as it can be constrained with a few basic benchtop measurements.

To proceed, a spectrum analyzer is connected to the output of the signal conditioner. Two pairs of noise spectral density curves are collected; each measurement is configured to isolate the noise sources (Figure 2). For the first pair of measurements (RTI Noise Density), the PRG is set to a maximum of x512 and the POG set to x4 to achieve a total gain of x2048. The low-pass filter is bypassed – the measurement band is 1 Hz to the 100 kHz upper limit of the 28108's amplifiers (note the high-frequency roll-off in each plot) – and the output noise spectral densities are divided by the total channel gain. The second pair of measurements (RTO Noise Density) are collected in the same way, except that both PRG and POG are set to one.

Each pair includes one measurement with the sensor in the signal path, and one measurement with the sensor shorted to ground. The combination can be used to effectively isolate the 28108 self-noise from that of the XCS-190.

But how does each pair differentiate the model-defined RTI and RTO noise? In an RSS combination, if one term is appreciably larger than the others (≥ x3), the total is approximately equal to that term. So the largest noise source will always dominate. Considering the results in Figure 2, we can make the following interpretation: (i) The RTO noise densities, measured with no gain applied, far exceed the gain-normalized RTI noise densities. This fact, along with the observation that shorting the sensor has no effect on the RTO measurement, suggests that the output-stage RTO noise dominates the RTI noise when no gain is applied; and (ii) With a large, PRG-dominated gain applied to the channel the input-stage noise becomes the dominant term. In fact, this setup – characterized by "input-stage-dominated noise" with a moderate amount of early-stage gain – is a common design goal for low-noise instrumentation.

How do we translate the noise summary in Figure 2 to an SNR estimate for the circuit in Figure 1 under various gain and filter settings? The full-scale output from the sensor is 150 mV_p (106.07 mV_{rms}). To record the pressure signal using an attached A/D converter with a 10 V_p full-scale range, a total gain of x66 is applied by the 28108 (with PRG = x64 and POG = x1.04). With the 28108's low-pass filter (here, a 4-pole Butterworth) now in the signal path, the modeled RTI and RTO spectral densities can be integrated to predict the total noise (in V_{rms}) over any bandwidth.

The result (plotted as SNR) is shown in Figure 3. It is desirable that the measured pressure signal is expected to be 90 dB or greater above the noise floor of the combined sensor and signal conditioner. The 10 dB reduction in SNR from 100 Hz to 100 kHz is due to the RTI noise being limited by the filter: the lower the filter's cutoff frequency, the narrower the bandwidth over which the RTI spectral density is integrated.

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