Application Note

Analog Signal Chain for Particle Monitor in Cost Optimized Systems

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ABSTRACT

Particulate Matter (PM) refers to the solid and liquid particles suspended in air. PM Sensors are used to determine the PM2.5 and PM10 particle concentration in air. Optical PM sensors use light scattering principle to determine PM concentration in air. This application report looks into a single operational amplifier (Opamp) based analog front end (AFE) solution for Particulate Matter (PM) monitoring sensors. This application note discusses how the scattered light by the particles can be converted into an output voltage proportional to the intensity of light incident on the sensor. The voltage output can be processed using various algorithms to determine the concentration and size information.

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Trademarks

1 Introduction to Particulate Matter Sensors

Particulate Matter (PM) refers to the solid and liquid particles suspended in air. PM2.5 and PM10 refers to particulate matter having diameter less than 2.5 µm and 10 µm respectively. There are several methods to measure the Particulate Matter (PM) concentration in air based on gravitational, centrifugal and optical concepts.

1.1 Optical Particulate Matter Measurement Instruments

Optical based PM measurement techniques uses the concept of light scattered or light absorbed by the particles to estimate the size and concentration of the particle as shown in Figure 1-1. Light scattered by a particle depends upon the particle size, particle shape and refractive index of the particle. Apart from these parameters, optical chamber design, light source and detection angle influence the light scattering. Light scattering based PM measurement instruments can be of two types, Photometers and Optical Particle Counters.

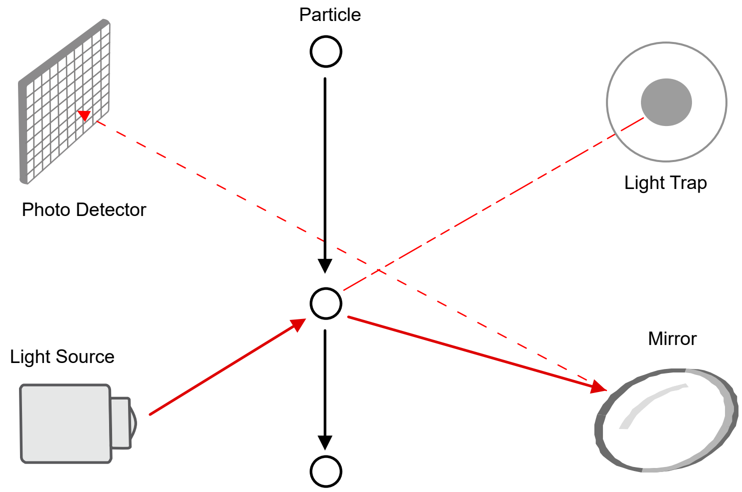

Figure 1-1. Light Scattering Concept of Optical PM Instruments

1.1.1 Photometer

A Photometer measures the light scattered by a group (cloud) of particles and directly correlates the output to the mass concentration. The output voltage is directly proportional to the concentration of particles in the optical chamber. Photometers can only provide concentration information and are useful in high particle concentrated environments.

1.1.2 Optical Particle Counter

An Optical Particle Counter (OPC), measures the light scattered by each individual particle in the sample stream, to get size and concentration information. OPC gives size information, but are preferred in low concentration environments to ensure that single particle is present in front of the light source at a given time.

1.1.2.1 Determination of Size and Concentration

1.1.2.1.1 Size

Smaller particles scatter less amount of light so the intensity of light falling onto the photo detector is low thus generating a lower photo current, while for larger particles more amount of light is scattered hence larger photo current is generated. Since this current is converted proportionally to voltage through the transimpedance amplifier (TIA), the output voltage of the analog front end is proportional to the particle size.

1.1.2.1.2 Concentration

The rate of pulses is used to measure concentration. More closely spaced the pulses are higher the concentration. So pulse count per second relates to particle count per second (pcs/s). The particle count per second can be converted to particle concentration (pcs/ml) using flow rate information (ml/s).

A similar analog front end can be used in photometer and optical particle counter. The functioning of sensor varies based on flow rate as flow rate is a critical parameter to ensure single particle presence at a time in sensing volume of the optical chamber. Tuning the circuit for desired flow rate is critical to ensure that a particle doesn’t dwell for longer duration in the sensing volume. The passband frequency range of the AFE should be able to support the flow rate requirement of optical PM measurement sensor.

1.2 Architecture of Optical PM Sensor

A light source directed at the aerosol particles, a photo detector (photo diode) to measure the light scattered by particles, an analog signal chain (AFE) to convert the photo current to voltage. The output voltage is processed using a microprocessor to get size and concentration information.

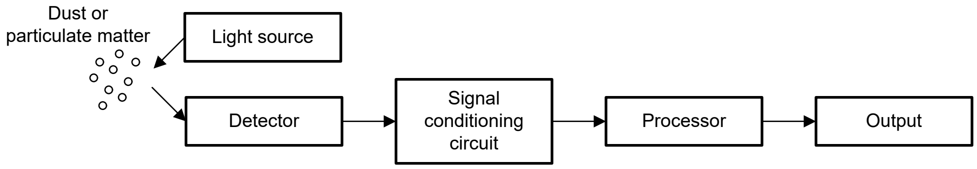

Figure 1-2. Block Diagram PM Sensor

2 Single Op Amp Based Analog Front End

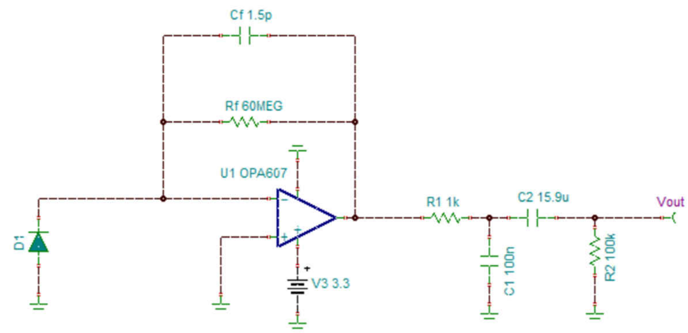

Figure 2-1. Block Diagram of Analog Front End (AFE)

The signal chain shown in Figure 2-1, is a single operational amplifier based analog front end solution for the particle monitoring sensors. The gain of the trans-impedance amplifier configuration is

$$G = \frac{V_{out}}{i_{in}} = R_f = 60\,x\,10^6\,(V/A) = 155.5dB\Omega \tag{1}$$

where I_{in} is the photo diode current and V_{OUT} is the filtered output.

This signal chain supports a huge measurement range from a minimum current of 50 pA to as high as 50 nA. The rail to rail output capability of OPA607 allows to maximize the dynamic range at the AFE output thereby achieving such huge measurement range. As the photo current generated due to falling light intensity will flow from cathode to anode of photo diode, the design focuses on measuring the positive peaks of photo current due to scattered light. The OPA607 input common mode range extends up to the negative supply rail allowing the ground referencing of TIA. Low input offset voltage and input bias current of OPA607, ground referenced circuit ensures that when there is no photo current, the op amp output is small enough to avoid any loss in dynamic range.

The high bandwidth of OPA607 allows high trans-impedance gain of 155.5 dBΩ and passband frequency range of 0.1 Hz to 1 kHz to be achieved with a single stage. The photo diode is zero biased to minimize noise as well as the leakage current of photo diode. The dark current of photo diode increases exponentially with increasing temperature, thereby a zero bias helps in minimizing the dark current and preventing operational amplifier saturation. In zero biased mode the variations of responsivity with temperature are lower. Low dark current and high photo sensitivity at zero bias are major considerations while choosing a photo diode for particle sensors.

2.1 Frequency Response

The filter response of this circuit is a bandpass filter composed of simple poles and zeroes. The passband frequency range of the signal chain is from 0.1 Hz to 1 kHz as shown in Figure 2-2. The upper cutoff frequency is important to restrict the noise bandwidth of the circuit. The lower cutoff frequency is required to remove DC offset.

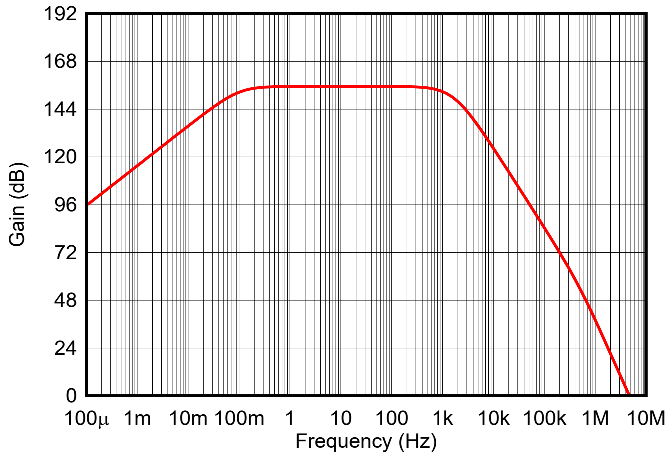

Figure 2-2. Frequency Response of AFE

The feedback capacitance (C_f = 1.5 pF) in parallel to the feedback resistor (R_f = 60 MΩ) is required to avoid any instability issues in the TIA. For details on stabilizing a TIA using feedback capacitance see What You Need To Know About Transimpedance Amplifiers – Part 1. The feedback network generates a pole given by,

$$p_1 = \frac{1}{2\pi R_f C_f} = \frac{1}{2\pi\ x\ 60\ x\ 10^6\ x\ 1.5\ x\ 10^{-12}} = 1.7\ kHz \quad (2)$$

The RC low pass filter placed at the output of operational amplifier increases the fall off rate to 40 dB/dec helping in reducing the output voltage noise thereby, improving the SNR. The RC low pass filter (roll-off filter) gives a pole at frequency given by,

$$p_2 = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi\ x\ 1\ x\ 10^3\ x\ 100\ x\ 10^{-9}} = 1.6\ kHz \quad (3)$$

The two poles around 1.6 kHz results in a 3 dB point around 1 kHz. Therefore, the upper cutoff frequency of the AFE settles to 1 kHz.

The high pass filter at the operational amplifier output end removes the DC offset due to diode dark current, input bias current and offset voltages of the operational amplifier. Thus only the photo current pulses due to the presence of particle are digitized using ADC. This helps in making the calibration algorithm independent of DC offsets.

A high pass RC filter, inserts a zero at origin and a pole at high pass cutoff frequency which can be adjusted using,

$$f_h = \frac{1}{2\pi R_2 C_2} = \frac{1}{2\pi\ x\ 100\ x\ 10^3\ x\ 15.9\ x\ 10^{-6}} = 0.1\ Hz \quad (4)$$

The particle flow rate range requirement of the PM sensor relates to passband frequency range of AFE. Maximum flow rate of particles sets limit for upper cutoff frequency and minimum flow rate sets the lower cutoff frequency,

2.2 Noise

Low voltage noise density and current noise density of OPA607 helps to minimize the noise in the signal chain.

The integrated output voltage noise of the signal chain is 130 μV_{RMS} which is equivalent to 2.15 pA input referred current noise. Figure 2-3 shows the integrated output noise of signal chain. The input referred current noise of the proposed chain is approximately 24 times smaller than the minimum measurable current, thereby assuring high signal fidelity.

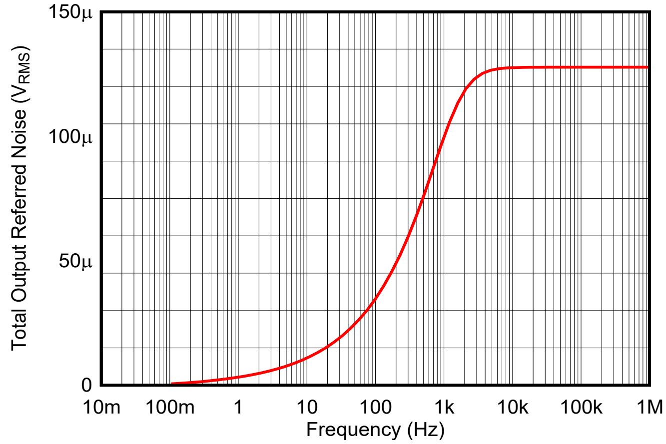

Figure 2-3. Integrated Noise of AFE

The net expression for input referred current spot noise of the signal chain (i_{n_TIA}) is given by,

$$i_{n\_TIA} = \sqrt{i_n^2 + \left(\frac{e_n}{R_f}\right)^2 + \frac{4KT}{R_f} + \frac{4KTR_1}{R_f^2} + \frac{4KTR_2}{R_f^2} + \frac{\left(e_n 2\pi f_{bw} C_{in}\right)^2}{3}} \tag{5}$$

Here, f_{bw} refers to the equivalent noise bandwidth of the signal chain and C_{in} refers to the net source capacitance. The net source capacitance (C_{in}) equals to the sum of diode capacitance, common mode and differential capacitance of the op amp. Equivalent noise bandwidth is 1.22 times the circuit bandwidth for a second order filter response.

The output voltage spot noise can be obtained by multiplying the input spot current noise with transimpedance gain R_f. The output spot noise can be multiplied by the square root of noise bandwidth to get the integrated noise. For more details, on noise analysis refer Noise analysis for High Speed Opamps.

For the discussed single operational amplifier based signal chain, current noise of the operational amplifier (i_n) is the dominant noise source as due to the high feedback resistance all other noise terms with a gain factor of $1/R_f$ becomes negligible.

From Equation 5 with increment in feedback resistance R_f, input referred current noise decreases. This implies a higher R_f results in higher SNR for a given input signal. The change is not very large though, due to the fact that current noise term is dominant which is independent of R_f. For more details on noise analysis of TIA refer Transimpedance Consideration of High Speed Amplifiers.

2.3 Data Acquisition

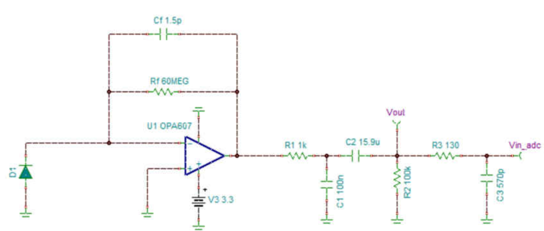

Figure 2-4. Block Diagram with Charge Bucket

It is assumed that the output voltage of the analog front end is acquired using a single-ended 10-bit ADC available on MSP430G2x53 microcontroller board. The voltage reference of the ADC is 3 V and analog signal sampled at a rate of 10 ksps (100 µs), satisfying the Nyquist criteria $f_{sample} \geq 2\ f_{max\_signal}$. ADC has an input capacitance of 27 pF, resistance of 1 kΩ, maximum conversion time of 3.5us. The sample and hold circuit can be modeled using RC low-pass filter during the sampling time t_{sample} (100 µs - 3.5 µs = 96.5 µs). It is calculated that a charge bucket of 130 Ω and 570 pF is required to provide enough charge at the input of ADC to match the input voltage. For more details on charge bucket see TI Precision Lab Videos on SAR ADC Input Driver Design.

The results show that the signal chain and charge bucket are able to drive the 10 bit ADC within 0.5 LSB accuracy.

The measurement range supported by the signal chain is dependent upon the ADC bit resolution and reference voltage as discussed in the following topics.

2.3.1 Minimum Current Calculations

The minimum measurable current is the photocurrent which generates an output voltage equal to the LSB of ADC. Thus, expression for minimum current is given by,

$$I_{in\_min} = \frac{V_{ref}}{2^N} \, x \, \frac{1}{R_f} = \frac{3}{2^{10}} \, x \, \frac{1}{60 \, x \, 10^6} = 50 \, pA \tag{6}$$

2.3.2 Maximum Current Calculations

The absolute maximum reading supported by the signal chain is given by the value of current which saturates the output of amplifier to supply voltage. So absolute maximum current (I_{abs}) is given by,

$$I_{abs} = \frac{V_{CC}}{R_f} = \frac{3.3}{60 \, x \, 10^6} = 55 \, nA \tag{7}$$

The AC current reading supported by TIA in such case is,

$$I_{in\_max} = \frac{V_{CC}}{R_f} - I_{offset} \tag{8}$$

where I_{offset} refers to the DC offset contributed by the diode dark current, offset voltage, input bias current and any other illumination current even in the absence of particle depending upon the optical chamber construction. For this simulation diode BWP34S was assumed, and it was considered that even with the exponential increase in current with rising temperature, the offset current (I_{offset}) would be below 1 nA.

Maximum AC current limit is related to ADC by the expression,

$$I_{in\_max} \le \frac{V_{ref}}{R_f} = \frac{3}{60 \, x \, 10^6} = 50 \, nA \tag{9}$$

as V_{ref} is the maximum input voltage which can be converted by the ADC.

3 Optimizing for Different Photodiode Currents

The signal chain can be modified for the desired current range and transimpedance gain, using the equations explained in Section 2. To modify the signal chain to measure values lower than 50 pA, R_f should be increased. The increment in R_f would result in a decrease the maximum measurable current supported by the signal chain with the same ADC. Table 3-1 mentions different measurement ranges supported by the signal chain with different feedback resistance for a 10-bit ADC at 3-V reference. The capacitance values in the Table 3-1 are for maintaining an upper cutoff frequency equal to 1 kHz.

Table 3-1. Suggested R_f-C_f Combinations for Different I_{In}

Feedback Resistor (MΩ)	Feedback Capacitor (pF)	Minimum Measurable Current (I_{in_min} in pA)	Maximum Measurable Current (I_{in_max} in nA)	Input Refereed Current Noise (pA)
300	0.3	10	10	1.8
60	1.5	50	50	2.14
30	3	100	100	2.5

Using a higher R_f with the same ADC enables to achieve a better resolution for detecting minimum change in the input current. For instance, if required range is 50 pA to 5 nA, measuring using R_f = 300 MΩ ensures that every 10 pA change is detectable. Also for the same current value, a larger R_f results in better SNR because increasing R_f reduces the input referred current noise. The graph in Figure 3-1 shows the increasing trend of SNR for 50 pA input signal with increasing feedback resistance.

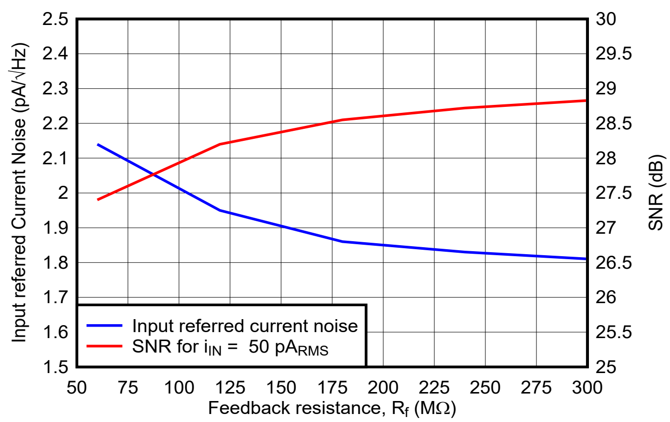

Figure 3-1. SNR vs. Feedback Resistance

4 Summary

Light Scattered by particles is dependent on particle's physical parameters like shape, size and refractive index. Optical PM Sensors uses light scattered by particles to estimate the PM2.5 and PM10 concentration in air. The light scattered by the particles is converted into an electrical signal using analog front end. This application note showed a method to design a single operational amplifier based analog front end for PM sensors using OPA607. The report discussed in detail the calculations of signal chain parameters like bandwidth, noise and sampling the output voltage using a SAR ADC.

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