Voltage Amplifier PD200 - Test Bench

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Contents

The goal of this test bench is to characterize the Voltage amplifier PD200 from PiezoDrive.

> **Note**
>
> The documentation of the PD200 is accessible here.

This document is organized as follows:

- Section 1: the requirements for the amplifiers and the characteristics of the PD200 amplifiers as advertise in the datasheet are listed.
- Section 2: a very simple amplifier model consisting of a transfer function and a noise source is described.
- Section 3: the transfer function from input voltage to output voltage is identified.
- Section 4: the power spectral density of the amplifier's noise is measured

- Section 5: the characteristics of the PD200 amplifier are compared to the E.505 amplifier from PI and to the LA75 from cedrat

- Section 6: the measured characteristics of the PD200 amplifier are compared with the requirements

1 Requirements PD200 Expected characteristics

A picture of the PD200 amplifier is shown in Figure 1.1.

Figure 1.1: Picture of the PD200 Voltage Amplifier

The specifications as well as the amplifier characteristics as shown in the datasheet are summarized in Table 1.1.

Table 1.1: Characteristics of the PD200 compared with the specifications

Characteristics	**Manual**	**Specification**
Input Voltage Range	+/- 10 [V]	+/- 10 [V]
Output Voltage Range	-50/150 [V]	-20/150 [V]
Gain	20 [V/V]	
Maximum RMS current	0.9 [A]	$>$ 50 [mA]
Maximum Pulse current	10 [A]	
Slew Rate	150 [V/us]	
Noise (10uF load)	0.7 [mV RMS]	$<$ 2 [mV rms]
Small Signal Bandwidth (10uF load)	7.4 [kHz]	$>$ 5 [kHz]
Large Signal Bandwidth (150V, 10uF)	300 [Hz]	

The most important characteristics are the large (small signal) bandwidth $>$ 5 [kHz] and the small noise ($<$ 2 [mV RMS]).

For a load capacitance of $10\,\mu F$, the expected $-3\,dB$ bandwidth is $6.4\,kHz$ (Figure 1.2) and the low frequency noise is $650\,\mu V$ rms (Figure 1.3).

These two characteristics are respectively measured in Section 3 and Section 4.

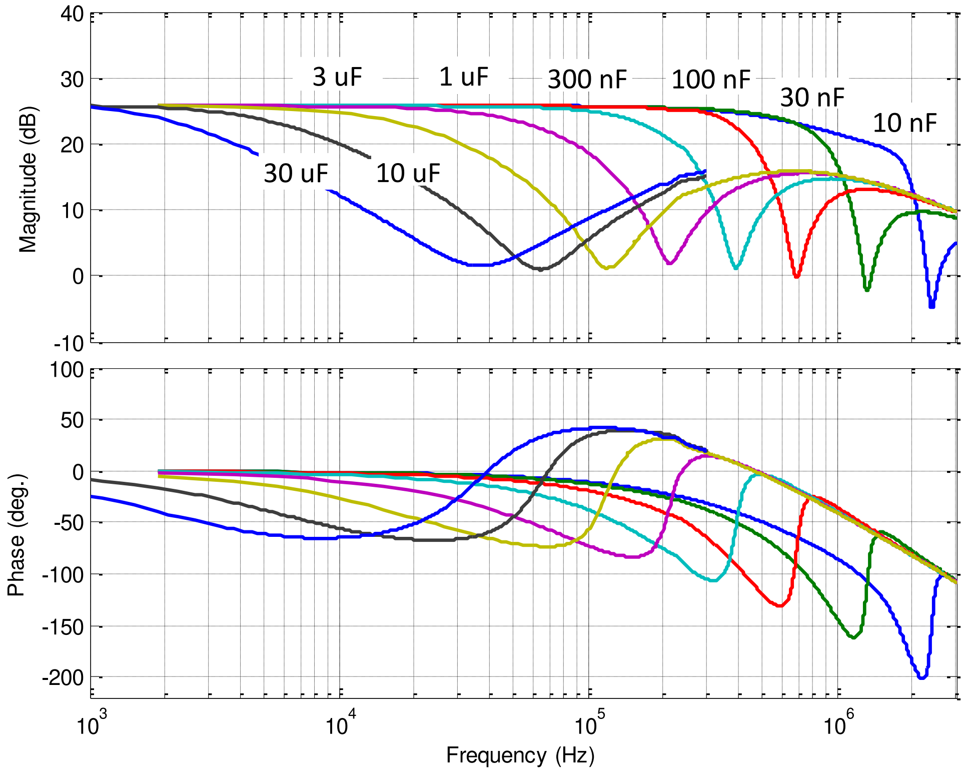


Figure 1.2: Expected small signal bandwidth

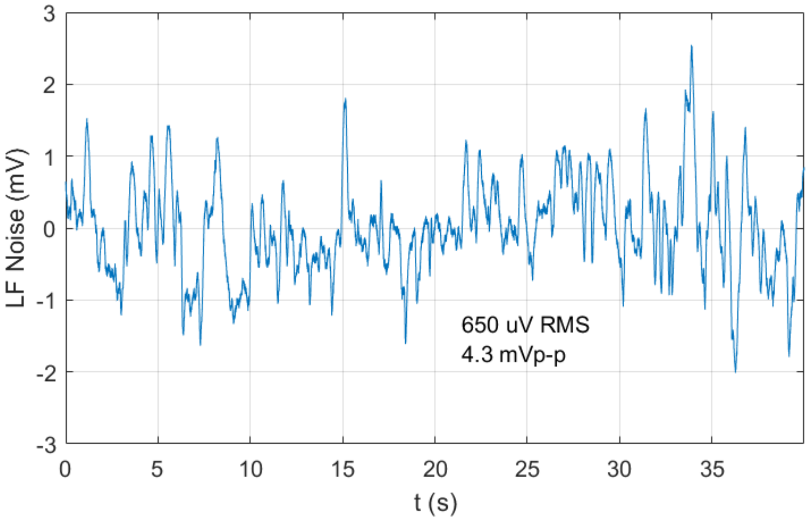


Figure 1.3: Expected Low frequency noise from 0.03Hz to 20Hz

2 Voltage Amplifier Model

The Amplifier is characterized by its dynamics $G_p(s)$ from voltage inputs V_{in} to voltage output V_{out}. Ideally, the gain from V_{in} to V_{out} is constant over a wide frequency band with very small phase drop.

It is also characterized by its **input** noise n.

The objective is therefore to determine the transfer function $G_p(s)$ from the input voltage to the output voltage as well as the Power Spectral Density $S_n(\omega)$ of the amplifier input noise.

As G_p depends on the load capacitance, it should be measured when loading the amplifier with a $10\,\mu F$ capacitor.

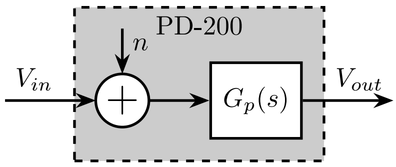


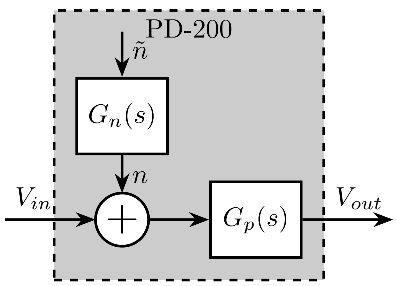
Figure 2.1: Model of the voltage amplifier

The input noise of the amplifier n can be further modeled by shaping a white noise with unitary PSD $\tilde{n}$ with a transfer function $G_n(s)$ as shown in Figure 3.1.

The Amplitude Spectral Density Γ_n is then:

$$\Gamma_n(\omega) = |G_n(j\omega)|\Gamma_{\tilde{n}}(\omega) \tag{2.1}$$

with $\Gamma_{\tilde{n}}(\omega) = 1$.



3 Transfer Function measurement

In this section, the transfer function of the PD200 amplifier is measured:

- Section 3.1: the measurement setup is described
- Section 3.2: the maximum sinusoidal excitation frequency is estimated in order to not overload the amplifier
- Section 3.3: the small signal bandwidth measurement results are shown
- Section 3.4: the amplifier's transfer function is estimated for several input amplitudes

3.1 Setup

In order to measure the transfer function from the input voltage V_{in} to the output voltage V_{out}, the test bench shown in Figure 3.1 is used.

Note

Here are the documentation of the equipment used for this test bench:

- Voltage Amplifier: PD200
- Load Capacitor: Film Capacitors 600V 10uF 5%
- DAC/ADC: IO313 Speedgoat Interface

For this measurement, the sampling frequency of the Speedgoat ADC should be as high as possible.

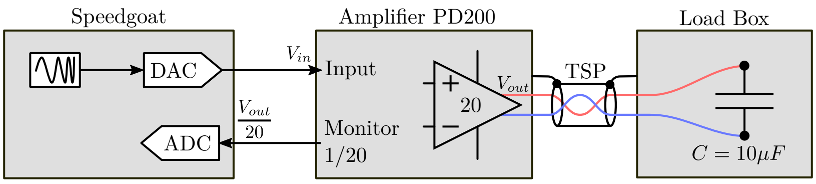


Figure 3.1: Schematic of the test bench to estimate the dynamics from voltage input V_{in} to voltage output V_{out}

3.2 Maximum Frequency/Voltage to not overload the amplifier

Then the maximum output current of the amplifier is reached, the amplifier automatically shuts down itself. We should then make sure that the output current does not reach this maximum specified current.

The maximum current is 1A [rms] which corresponds to 0.7A in amplitude of the sin wave.

The impedance of the capacitance is:

$$Z_C(\omega) = \frac{1}{jC\omega}$$

Therefore the relation between the output current amplitude and the output voltage amplitude for sinusoidal waves of frequency ω:

$$V_{out} = \frac{1}{C\omega} I_{out}$$

Moreover, there is a gain of 20 between the input voltage and the output voltage:

$$20 V_{in} = \frac{1}{C\omega} I_{out}$$

For a specified voltage input amplitude V_{in}, the maximum frequency at which the output current reaches its maximum value is:

$$\boxed{\omega_{\text{max}} = \frac{1}{20 C V_{in}} I_{out,\text{max}}} \tag{3.1}$$

with:

- ω_{max} the maximum input sinusoidal frequency in Radians per seconds
- C the load capacitance in Farads
- V_{in} the input voltage sinusoidal amplitude in Volts
- $I_{out,\text{max}}$ the specified maximum output current in Amperes

$\omega_{\text{max}}/2\pi$ as a function of V_{in} is shown in Figure 3.2.

When doing sweep sine excitation, we make sure not to reach this maximum excitation frequency.

3.3 Small Signal Bandwidth

Load Data

Compute Transfer Functions

Compare

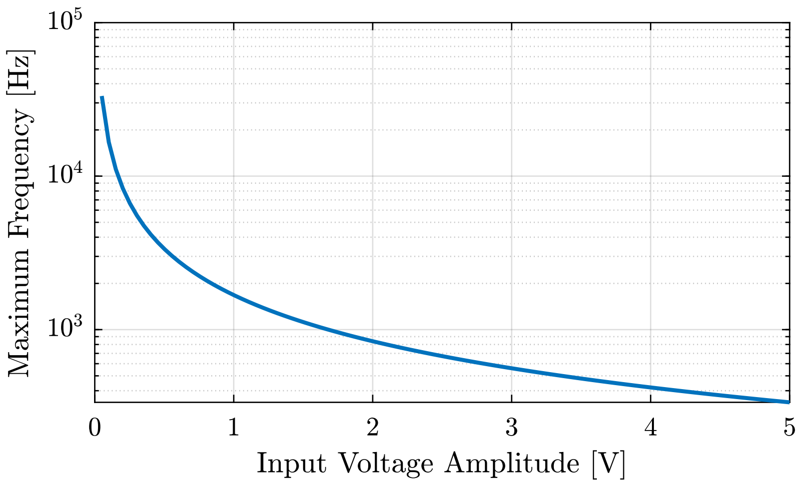


Figure 3.2: Maximum frequency as a function of the excitation voltage amplitude

Model

Save Model

3.4 Bandwidth for multiple excitation signals

Several identifications using sweep sin were performed with input voltage amplitude ranging from 0.1V to 4V.

Matlab
```
Iout_max = 0.57; % Maximum output current [A]
C = 10e-6; % Load Capacitance [F]

V_in = [0.1, 0.5, 1, 2, 4];
f_max = 0.8*Iout_max./(20*C*V_in/sqrt(2))/2/pi;
for i = 1:length(Vin_ampl)
    pd200{i}.notes.pd200.f_max = f_max(i);
    pd200{i}.notes.pd200.Vin = V_in(i);
end
```

4 Noise measurement

In section 4.1, the measurement setup is described and a model (block diagram) of the setup is given in section 4.2.

Then, the noise contribution of each element is measured:

- Section 4.3: the quantization noise of the ADC is estimated
- Sections 4.4 and 4.5: the noise of the low-noise amplifiers are estimated
- Section 4.6: the input voltage noise of the PD200 amplifier is estimated
- Section 4.7: the output noise of the DAC is measured
- Section 4.8: the noise of the full measurement chain (DAC to PD200 to pre-amplifier to ADC) is measured and it is found that the DAC is the main source of noise
- Section 4.9: the noise of an 20bits DAC is measured and it is shown if it could lowering the overall noise of the setup

Finally in section 4.10, a model of the PD200 amplifier's noise is developed.

4.1 Measurement Setup

Note

Here are the documentation of the equipment used for this test bench:

- Voltage Amplifier PD200
- Load Capacitor: Film Capacitors 600V 10uF 5%
- Low Noise Voltage Amplifiers EG&G 5113 and Femto DLPVA
- ADC: IO313 Speedgoat card

The output noise of the voltage amplifier PD200 is foreseen to be around 1mV rms in a bandwidth from DC to 1MHz. If we suppose a white noise, this correspond to an amplitude spectral density:

$$\Gamma_n(\omega) \approx \frac{1\,mV}{\sqrt{1\,MHz}} = 1\frac{\mu V}{\sqrt{Hz}} \tag{4.1}$$

The RMS noise being very small compare to the ADC resolution, we must amplify this noise before digitizing the signal.

The added noise of the instrumentation amplifier should be much smaller than the noise of the PD200. We use either the amplifier EG&G 5113 that has a noise of $\approx 4nV/\sqrt{Hz}$ referred to its input which is much smaller than the noise induced by the PD200.

The gain of the low-noise amplifier can be increased until the full range of the ADC is used. This gain should be around 1000 (60dB).

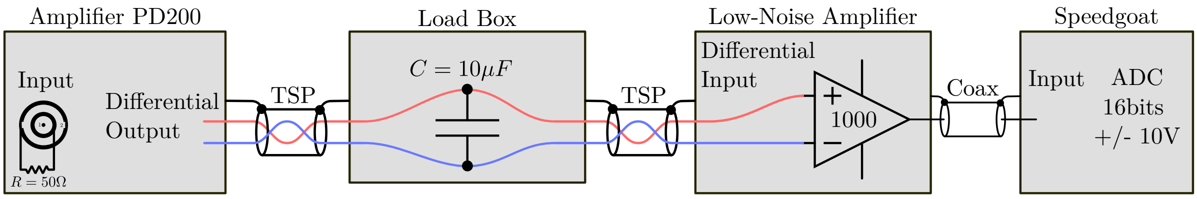


Figure 4.1: Schematic of the test bench to measure the Power Spectral Density of the Voltage amplifier noise n

A low pass filter at 10kHz can be included in the EG&G amplifier in order to limit aliasing. An high pass filter at low frequency can be added if there is a problem of large offset.

4.2 Model of the setup

As shown in Figure 4.2, there are 4 equipment involved in the measurement:

- a Digital to Analog Convert (DAC)
- the Voltage amplifier to be measured with a gain of 20 (PD200)
- a low noise voltage amplifier with a variable gain and integrated low pass filters and high pass filters
- an Analog to Digital Converter (ADC)

Each of these equipment has some noise:

- q_{da}: quantization noise of the DAC
- n_{da}: output noise of the DAC
- n_p: input noise of the PD200 (what we wish to characterize)
- n_a: input noise of the pre amplifier
- q_{ad}: quantization noise of the ADC

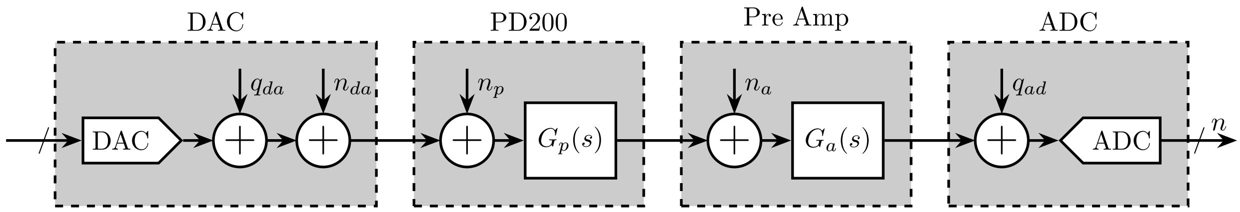


Figure 4.2: Sources of noise in the experimental setup

4.3 Quantization Noise

The quantization noise is something that can be predicted. The Amplitude Spectral Density of the quantization noise of an ADC/DAC is equal to:

$$\Gamma_q(\omega) = \frac{q}{\sqrt{12 f_s}} \tag{4.2}$$

with:

- $q = \frac{\Delta V}{2^n}$ the quantization in [V], which is the corresponding value in [V] of the least significant bit
- ΔV is the full range of the ADC in [V]
- n is the number of bits
- f_s is the sample frequency in [Hz]

Matlab

```
adc = struct();
adc.Delta_V = 20; % [V]
adc.n = 16; % number of bits
adc.Fs = 20e3; % [Hz]
adc.Gamma_q = adc.Delta_V/2^adc.n/sqrt(12*adc.Fs); % [V/sqrt(Hz)]
```

The obtained Amplitude Spectral Density is `6.2294e-07` $V/\sqrt{Hz}$.

4.4 EG&G - Amplifier noise measurement

First, we wish to measure the noise of the pre-amplifier. To do so, the input of the pre-amplifier is shunted such that there is 0V at its inputs. Then, the gain of the amplifier is increase until the measured signal on the ADC is much larger than the quantization noise.

The Amplitude Spectral Density $\Gamma_n(\omega)$ of the measured signal n is computed. Finally, the Amplitude Spectral Density of n_a can be computed taking into account the gain of the pre-amplifier:

$$\Gamma_{n_a}(\omega) \approx \frac{\Gamma_n(\omega)}{|G_a(\omega)|} \tag{4.3}$$

This is true if the quantization noise $\Gamma_{q_{ad}}$ is negligible.

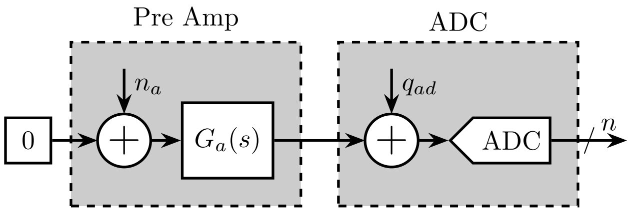


Figure 4.3: Sources of noise in the experimental setup

The gain of the low noise amplifier is set to `50000`.

The obtained Amplitude Spectral Density of the Low Noise Voltage Amplifier is shown in Figure 4.4. The obtained noise amplitude is very closed to the one specified in the documentation of $4nV/\sqrt{Hz}$ at 1kHZ.

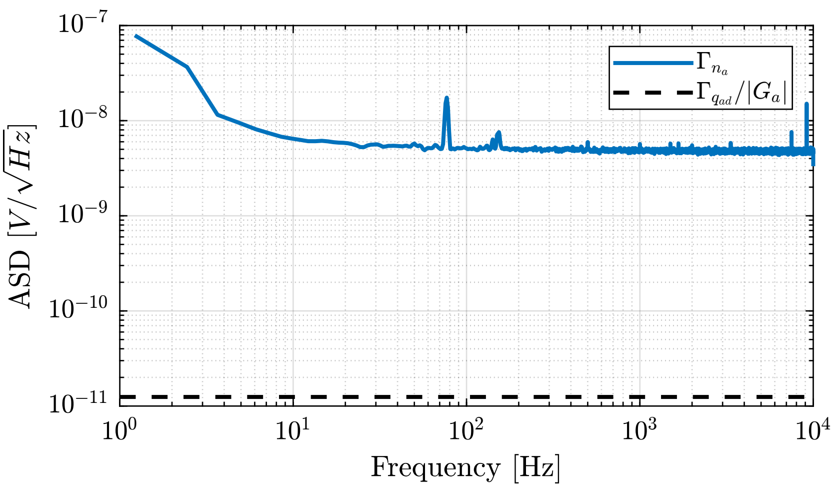


Figure 4.4: Obtained Amplitude Spectral Density of the EG&G Low Noise Voltage Amplifier

4.5 Femto - Amplifier noise measurement

Similarly to Section 4.4, the noise of the Femto amplifier is identified.

Matlab
```
% Hanning window
win = hanning(ceil(0.5/Ts));

% Power Spectral Density
[pxx, f] = pwelch(femto.Vout, win, [], [], Fs);

% Save the results inside the struct
femto.pxx = pxx;
femto.f = f;
```

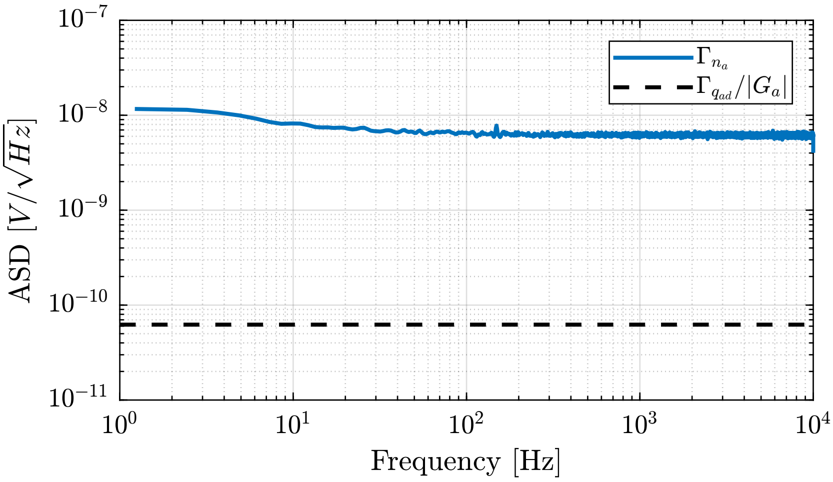


Figure 4.5: Obtained Amplitude Spectral Density of the Femto Low Noise Voltage Amplifier

4.6 PD200 noise measurement

The input of the PD200 amplifier is shunted with a 50 Ohm resistor. The gain of the pre-amplifier is increased in order to measure a signal much larger than the quantization noise of the ADC.

The Amplitude Spectral Density of the measured signal $\Gamma_n(\omega)$ is computed. The Amplitude Spectral Density of n_p is then computed taking into account the gain of the pre-amplifier and the can of the PD200 amplifier:

$$\Gamma_{n_p}(\omega) = \frac{\Gamma_n(\omega)}{|G_p(j\omega)G_a(j\omega)|} \tag{4.4}$$

And we verify that this is indeed the noise of the PD200 and not the noise of the pre-amplifier by checking that:

$$\Gamma_{n_p}(\omega)|G_p(j\omega)| \ll \Gamma_{n_a} \tag{4.5}$$

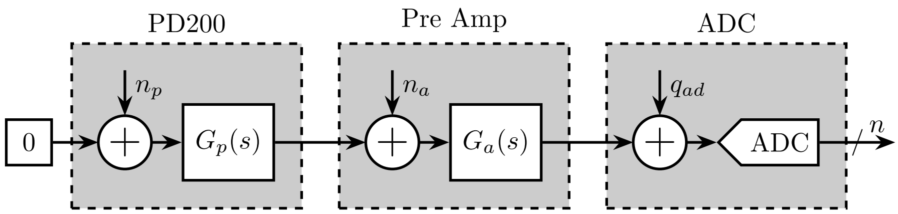


Figure 4.6: Sources of noise in the experimental setup

The measured low frequency **output** noise of one of the PD200 amplifiers is shown in Figure 4.7. It is very similar to the one specified in the datasheet in Figure 1.3.

The obtained RMS and peak to peak values of the measured **output** noise are shown in Table 4.1.

The Amplitude Spectral Density of the measured **input** noise is computed and shown in Figure 4.8.

The contribution of the PD200 noise is much larger than the contribution of the pre-amplifier noise of the quantization noise.

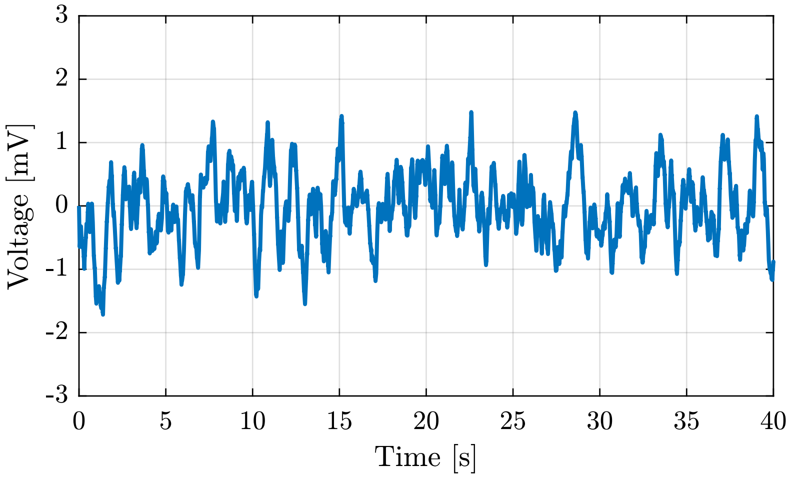


Figure 4.7: Measured low frequency noise of the PD200 from 0.01Hz to 20Hz

Table 4.1: RMS and Peak to Peak measured low frequency output noise (0.01Hz to 20Hz)

	RMS [uV]	**Peak to Peak [mV]**
Specification [10uF]	714.0	4.3
PD200_1	565.1	3.7
PD200_2	767.6	3.5
PD200_3	479.9	3.0
PD200_4	615.7	3.5
PD200_5	651.0	2.4
PD200_6	473.2	2.7
PD200_7	423.1	2.3

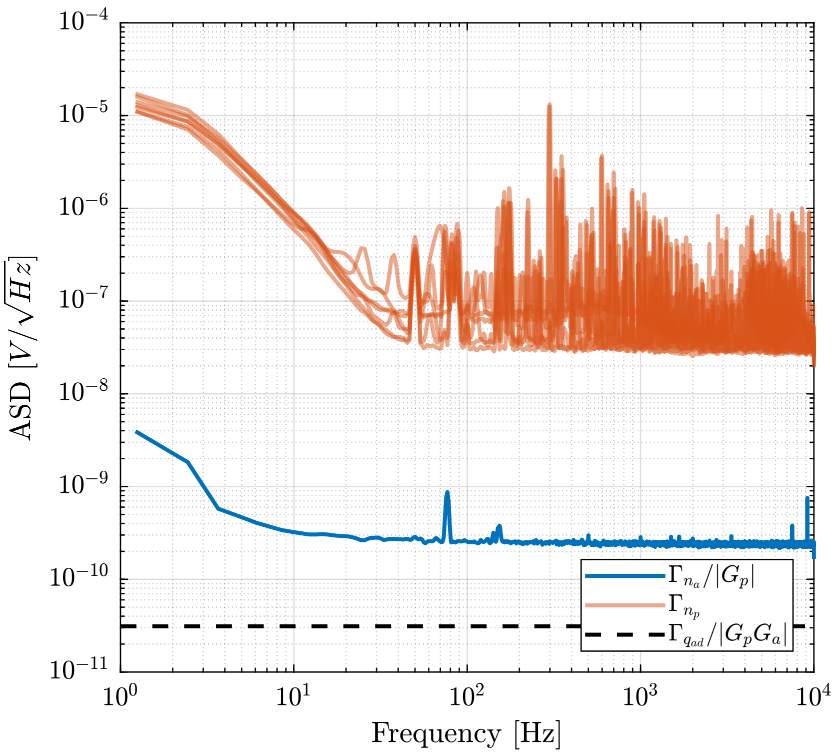


Figure 4.8: Amplitude Spectral Density of the measured noise

4.7 DAC noise measurement

In order not to have any quantization noise, we impose the DAC to output a zero voltage. The gain of the low noise amplifier is adjusted in order to have sufficient voltage going to the ADC.

The Amplitude Spectral Density $\Gamma_n(\omega)$ of the measured signal is computed. The Amplitude Spectral Density of n_{da} can be computed taking into account the gain of the pre-amplifier:

$$\Gamma_{n_{da}}(\omega) = \frac{\Gamma_m(\omega)}{|G_a(\omega)|} \tag{4.6}$$

And it is verify that the Amplitude Spectral Density of n_{da} is much larger than the one of n_a:

$$\Gamma_{n_{da}} \gg \Gamma_{n_a} \tag{4.7}$$

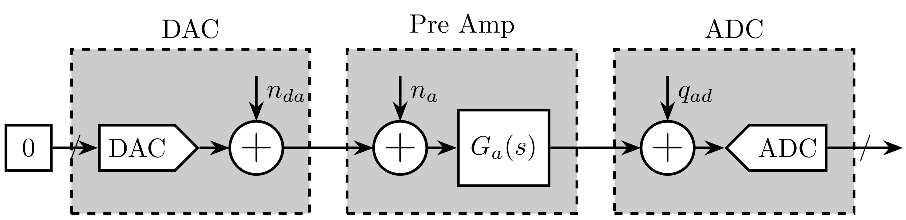
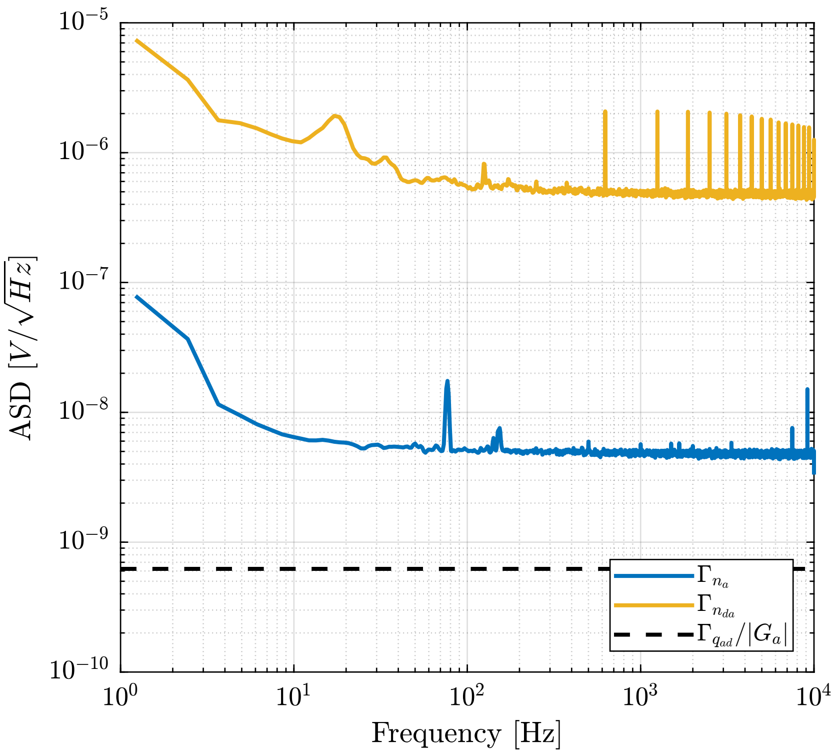


Figure 4.9: Sources of noise in the experimental setup



4.8 Total noise measurement

Let's now analyze the measurement of the setup in Figure 4.10.

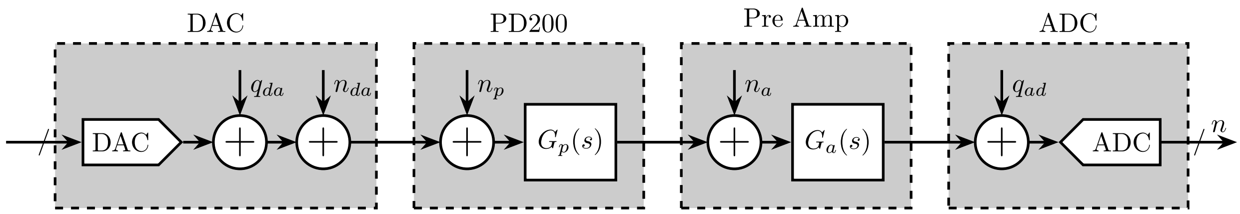


Figure 4.10: Sources of noise in the experimental setup

The PSD of the measured noise is computed and the ASD is shown in Figure 4.11.

Matlab
```
win = hanning(ceil(0.5/Ts));

for i = 1:7
    [pxx, f] = pwelch(pd200dac{i}.Vn, win, [], [], Fs);
    pd200dac{i}.f = f;
    pd200dac{i}.pxx = pxx;
end
```

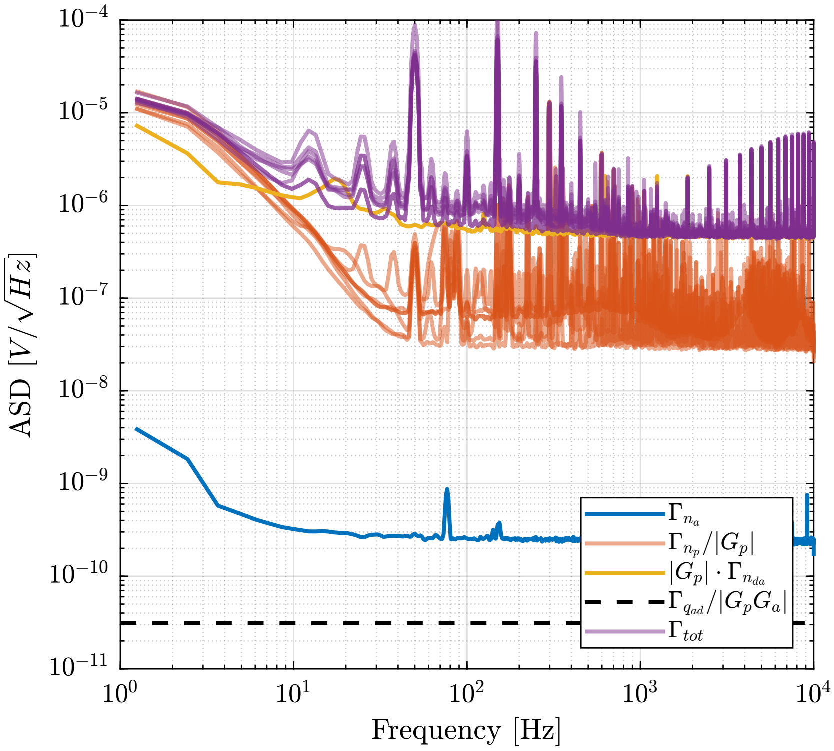


Figure 4.11: Amplitude Spectral Density of the measured noise and of the individual sources of noise

Important

The output noise of the PD200 amplifier is limited by the noise of the DAC. Having a DAC with lower noise could lower the output noise of the PD200. SSI2V DACs will be used to verify that.

4.9 20bits DAC noise measurement

Let's now measure the noise of another DAC called the "SSI2V" (doc). It is a 20bits DAC with an output of +/-10.48 V and a very low output noise.

The measurement setup is the same as the one in Figure 4.9.

Matlab
```
win = hanning(ceil(0.5/Ts));

[pxx, f] = pwelch(ssi2v.Vn, win, [], [], Fs);
ssi2v.pxx = pxx;
ssi2v.f = f;
```

The obtained noise of the SSI2V DAC is shown in Figure 4.12 and compared with the noise of the 16bits DAC. It is shown to be much smaller (~1 order of magnitude).

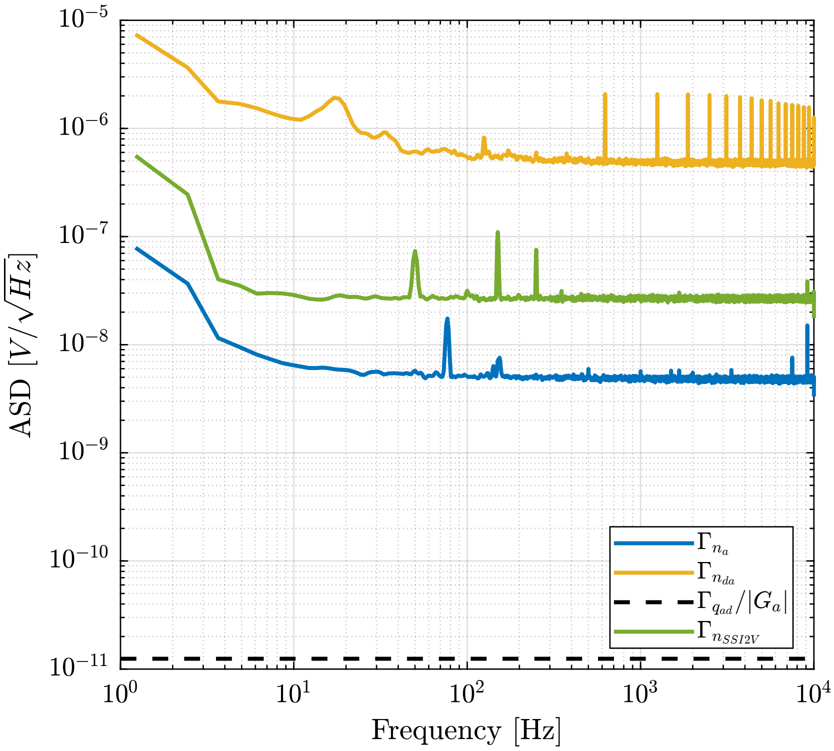


Figure 4.12: Amplitude Spectral Density of the SSI2V DAC's noise

> **Important**
>
> Using the SSI2V as the DAC with the PD200 should give much better noise output than using the 16bits DAC. The limiting factor should then be the noise of the PD200 itself.

4.10 PD200 Amplifier noise model

Let's design a transfer function whose norm represent the Amplitude Spectral Density of the input voltage noise of the PD200 amplifier.

Matlab
```
Gn = 2.5e-5 * ((1 + s/2/pi/30)/(1 + s/2/pi/2))^2 /(1 + s/2/pi/5e3);
```

The comparison between the measured ASD of the modeled ASD is done in Figure

Let's now compute the Cumulative Amplitude Spectrum corresponding to the measurement and the model and compare them.

The integration from low to high frequency and from high to low frequency are both shown in Figure

The obtained RMS noise of the model is `650.77` uV RMS which is the same as advertise.

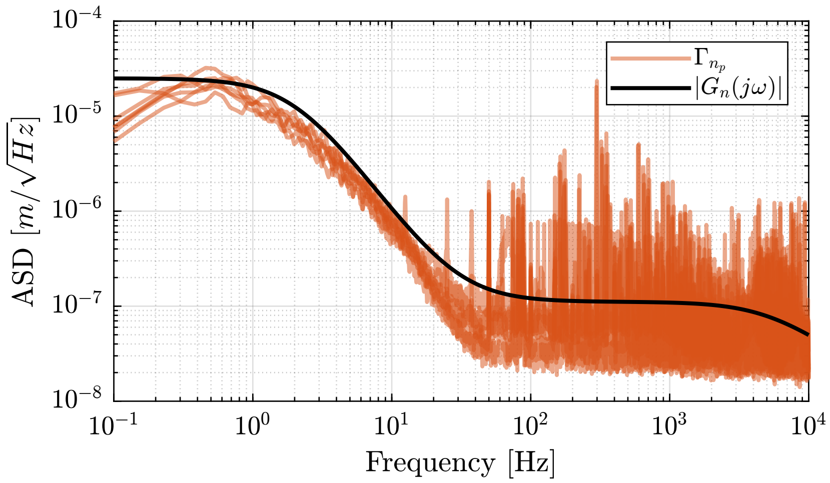


Figure 4.13: ASD of the measured input voltage noise and modeled noise using $G_n(s)$

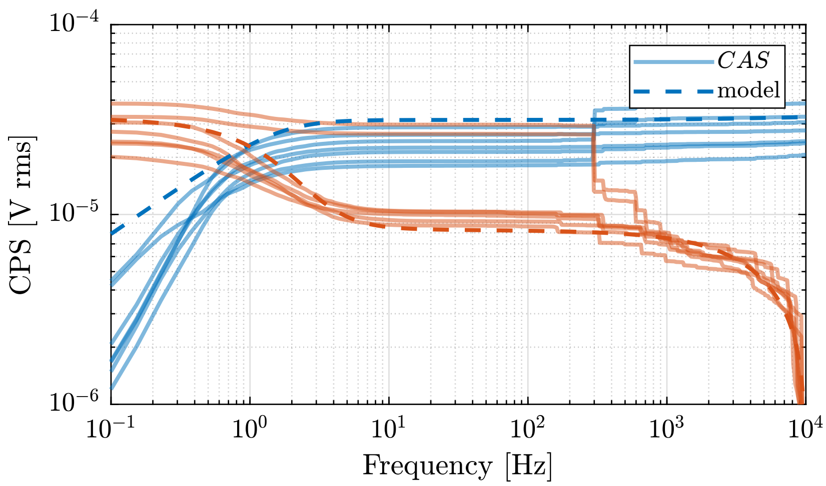


Figure 4.14: Cumulative Amplitude Spectrum of the measured input voltage noise and modeled noise using $G_n(s)$

5 Comparison to other commercial amplifiers

5.1 Transfer functions

5.2 Noise Characteristics

Matlab

```
pd200.Vout = pd200.Vout/pd200.notes.pre_amp.gain;
la75.Vout  = la75.Vout/la75.notes.pre_amp.gain;
```

Matlab

```
figure;
hold on;
plot(pd200.t, 1e3*pd200.Vout)
plot(la75.t, 1e3*la75.Vout)
hold off;
xlabel('Time [s]');
ylabel('Voltage [mV]');
% ylim([-3, 3]);
```

6 Conclusion

Table 6.1: Measured characteristics, Manual characterstics and specified ones

Characteristics	**Measurement**	**Manual**	**Specification**
Input Voltage Range	-	+/- 10 [V]	+/- 10 [V]
Output Voltage Range	-	-50/150 [V]	-20/150 [V]
Gain		20 [V/V]	-
Maximum RMS current		0.9 [A]	$>$ 50 [mA]
Maximum Pulse current		10 [A]	-
Slew Rate		150 [V/us]	-
Noise (10uF load)		0.7 [mV RMS]	$<$ 2 [mV rms]
Small Signal Bandwidth (10uF load)		7.4 [kHz]	$>$ 5 [kHz]
Large Signal Bandwidth (150V, 10uF)		300 [Hz]	-