

Voltage Amplifier PD200 - Test Bench

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The goal of this test bench is to characterize the Voltage amplifier [PD200](#) from PiezoDrive.

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.

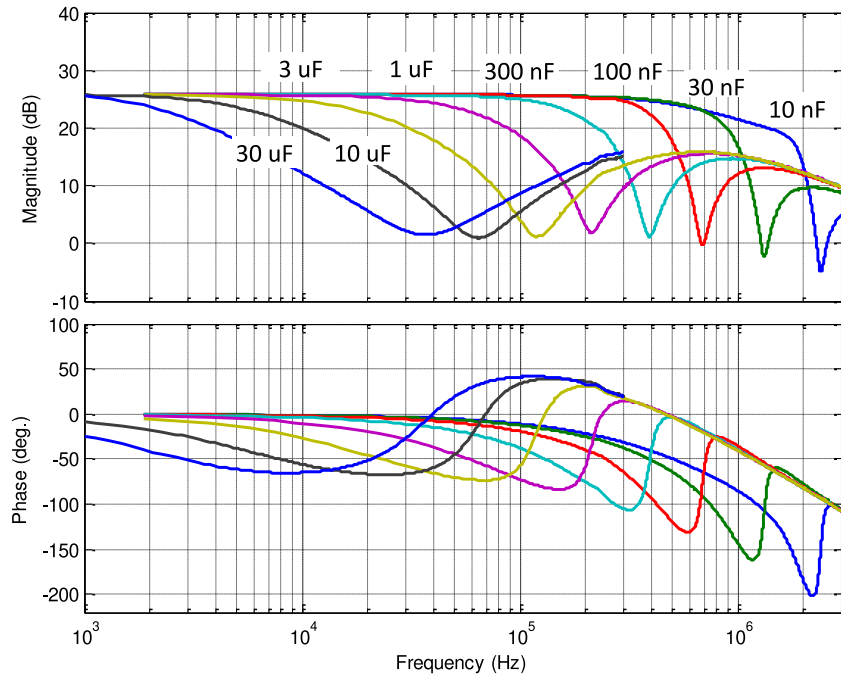


Figure 1.2: Expected small signal bandwidth

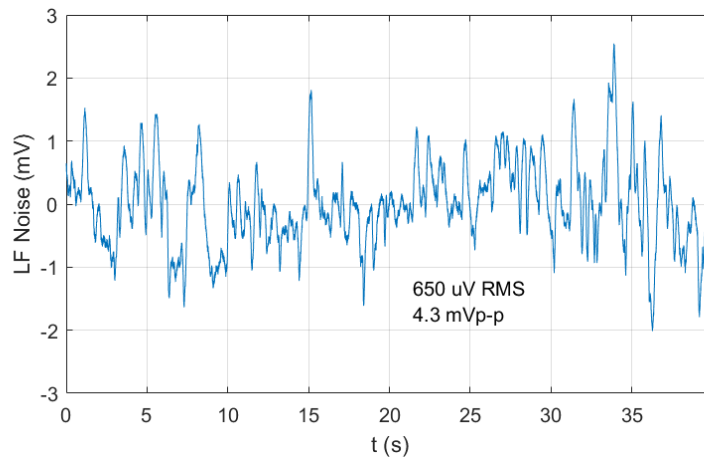


Figure 1.3: Expected Low frequency noise from 0.03Hz to 20Hz

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.

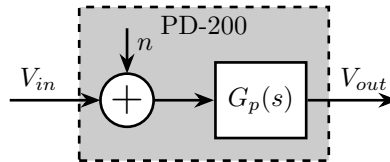


Figure 2.1: Model of the voltage amplifier

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:

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

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

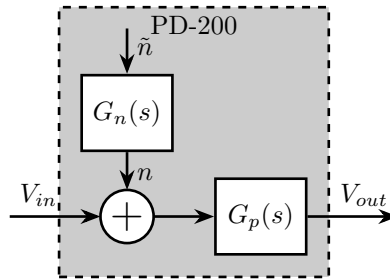


Figure 2.2: Model of the voltage amplifier with normalized noise input

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: a model of the small signal dynamics of the amplifier is obtained
- Section 3.5: 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.

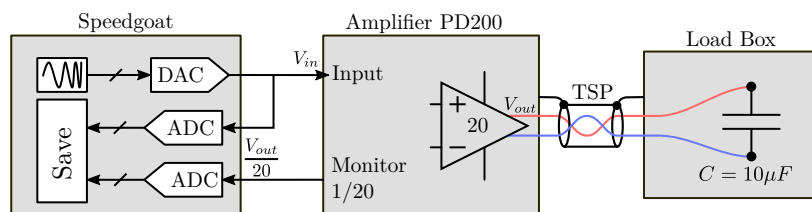


Figure 3.1: Schematic of the test bench to estimate the dynamics from voltage input V_{in} to voltage output V_{out}

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:

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

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

$$\omega_{max} = \frac{1}{20CV_{in}} I_{out,max} \quad (3.1)$$

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
- $I_{out,max}$ the specified maximum output current in Amperes

$\omega_{max}/2\pi$ 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

Here the small signal dynamics of all the 7 PD200 amplifiers are identified.

A (logarithmic) sweep sine excitation voltage is generated by the Speedgoat DAC with an amplitude of 0.1V and a frequency going from 1Hz up to 5kHz.

The output voltage of the PD200 amplifier is measured thanks to the monitor voltage of the PD200 amplifier. The input voltage of the PD200 amplifier (the generated voltage by the DAC) is measured

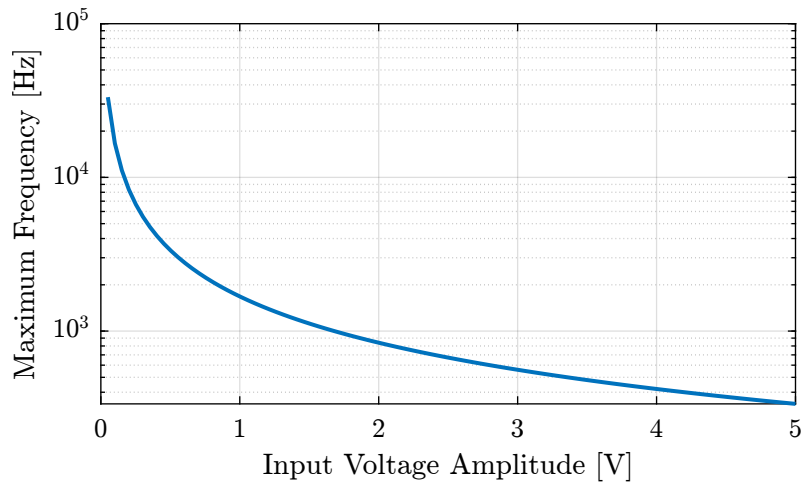


Figure 3.2: Maximum frequency as a function of the excitation voltage amplitude

with another ADC of the Speedgoat. This way, the time delay related to the ADC will not be apparent in the results.

The obtained transfer functions from V_{in} to V_{out} are shown in Figure 3.3.

We can see the very well matching between all the 7 amplifiers. The amplitude is constant over a wide frequency band and the phase drop is limited to less than 1 degree up to 500Hz.

3.4 Model of the amplifier small signal dynamics

The identified dynamics in Figure 3.3 can very well be modeled this dynamics with a first order low pass filter (even a constant could work fine).

Below is the defined transfer function $G_p(s)$.

```
Matlab
Gp = 20/(1 + s/2/pi/25e3);
```

Comparison of the model with the identified dynamics is shown in Figure 3.4.

And finally this model is saved.

```
Matlab
save('mat/pd200_model.mat', 'Gp');
```

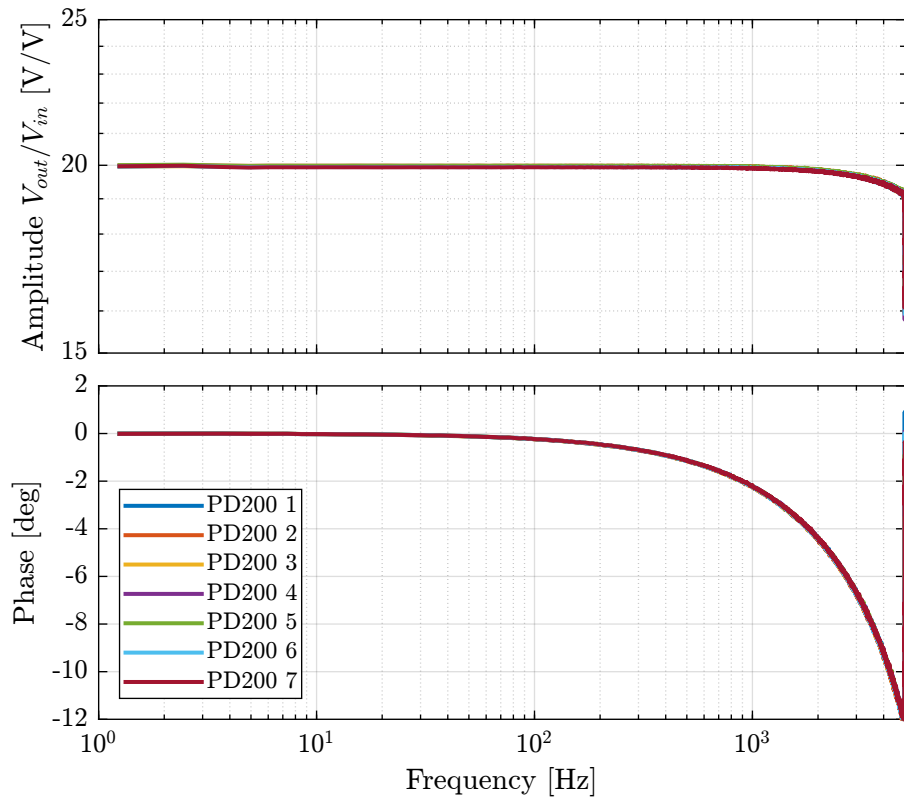


Figure 3.3: Identified dynamics from input voltage to output voltage

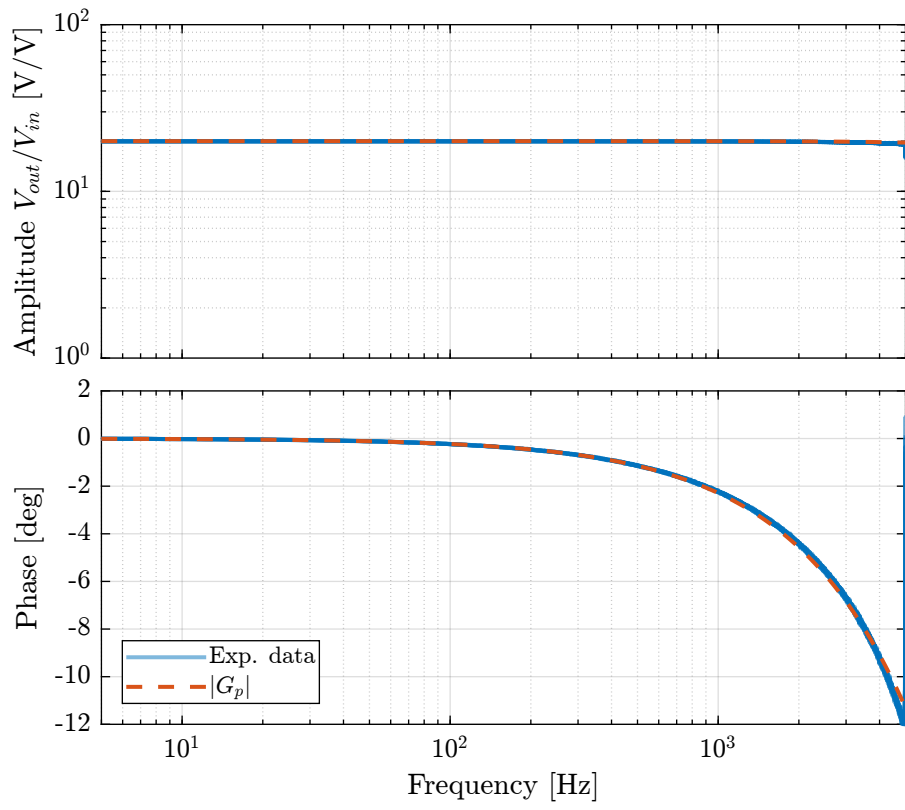


Figure 3.4: Bode plot of $G_d(s)$ as well as the identified transfer functions of all 7 amplifiers

3.5 Large Signal Bandwidth

The PD200 amplifiers will most likely not be used for large signals, but it is still nice to see how the amplifier dynamics is changing with the input voltage amplitude.

Several identifications using sweep sin were performed with input voltage amplitude ranging from 0.1V to 4V. The maximum excitation frequency for each amplitude was limited from the estimation in Section 3.2.

The obtained transfer functions for the different excitation amplitudes are shown in Figure 3.5. It is shown that the input voltage amplitude does not affect that much the amplifier dynamics.

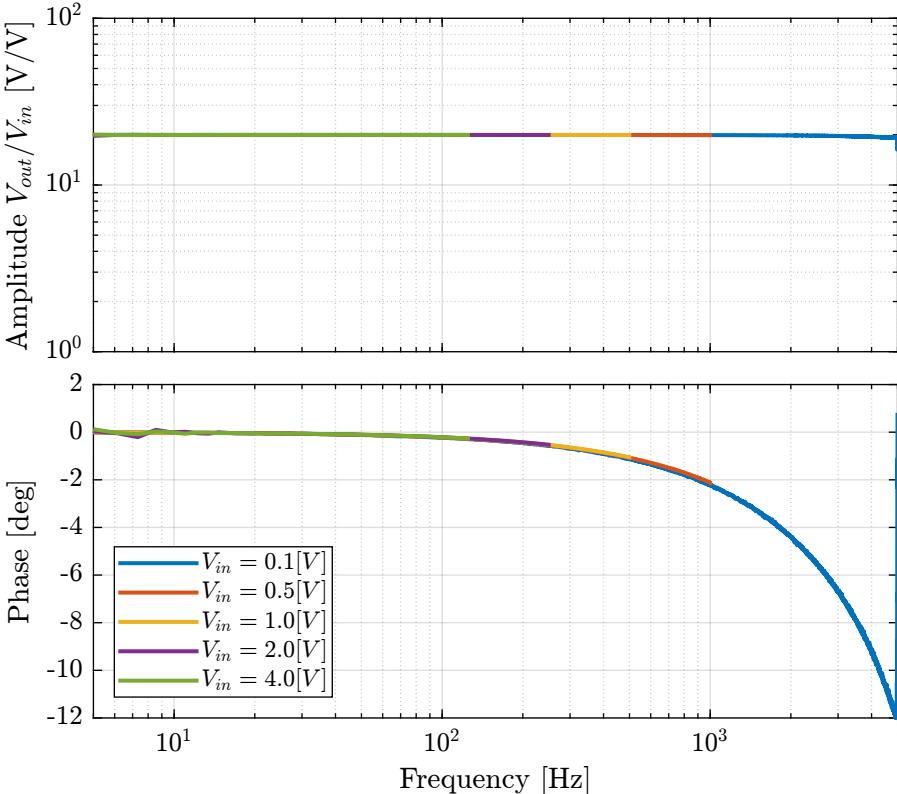


Figure 3.5: Amplifier dynamics for several input voltage amplitudes

4 Noise measurement

In this part, the goal is to measure the noise of the PD200 voltage amplifier. This noise can be separated into an input voltage noise and an input current noise. However, the input voltage noise has much larger effects than the input current noise and we will only try to measure the input voltage noise.

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
- Sections 4.6 and 4.7: the input voltage noise of the PD200 amplifier is estimated
- Section 4.8: the output noise of the DAC is measured
- Section 4.9: 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 4.10: the noise of an 20bits DAC is measured
- Section 4.11: it is shown if using the 20bits DAC could lower the overall noise of the setup

Finally in section 4.12, a model of the PD200 amplifier's noise is developed.

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](#)
- 16bits DAC: [IO313 Speedgoat card](#)
- 20bits DAC: [SSI2V](#)

4.1 Measurement Setup

As the output noise of the PD200 voltage amplifier is foreseen to be around 1mV rms in a bandwidth from DC to 1MHz, it is not possible to directly measure it with an ADC. We need to amplify the noise before digitizing the signal. To do so, we need to use a low noise voltage amplifier with a noise density much smaller than the measured noise of the PD200 amplifier.

Let's first estimate the noise density of the PD200 amplifier. If we suppose a white noise, this correspond to an amplitude spectral density:

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

The input noise of the instrumentation amplifier should be then much smaller than the output noise of the PD200. We will use either the amplifier EG&G 5113 that has a noise of $\approx 4nV/\sqrt{\text{Hz}}$ referred to its input or the Femto DLPVA amplifier with an input noise of $\approx 3nV/\sqrt{\text{Hz}}$.

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

A representation of the measurement bench is shown in Figure 4.1.

Note that it is quite important to load the amplifier with the "Load Box" including a $10 \mu\text{F}$ capacitor as the (high frequency) noise of the amplifier depends on the actual load being used.

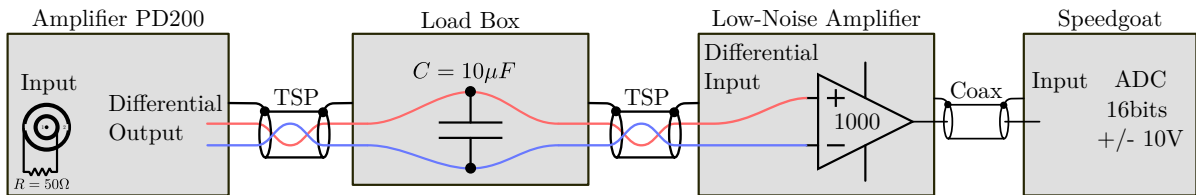


Figure 4.1: Schematic of the test bench to measure the Power Spectral Density of the Voltage amplifier noise n

4.2 Model of the setup

As shown in Figure 4.2, there are 4 elements 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

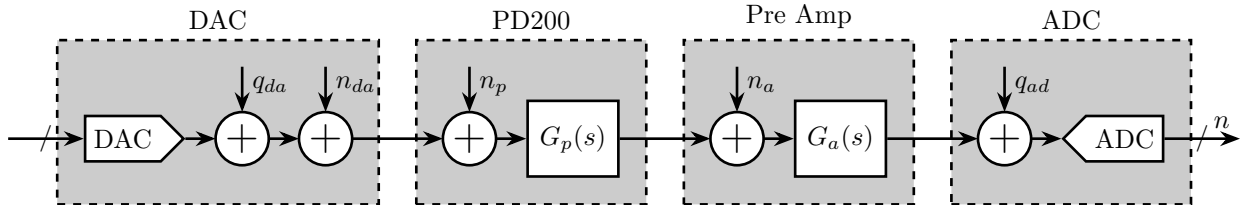


Figure 4.2: Sources of noise in the experimental setup

In the next sections, we wish to measure all these sources of noise and make sure that we can effectively characterize the noise n_p of the PD200 amplifier.

4.3 Quantization Noise of the ADC

The quantization noise is something that can be predicted from the sampling frequency and the quantization of the ADC. Indeed, the Amplitude Spectral Density of the quantization noise of an ADC/DAC is equal to:

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

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]

Let's estimate that with the ADC used for the measurements:

```

Matlab
-----
%% ADC Quantization noise
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

We now wish to measure the noise of the pre-amplifier. To do so, the input of the pre-amplifier is shunted with a 50Ohms resistor such that the pre-amplifier input voltage is just its input noise. Then, the gain of the amplifier is increased 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:

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

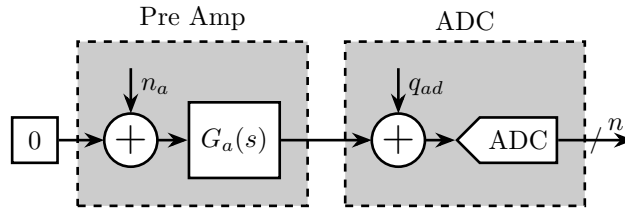


Figure 4.3: Sources of noise in the experimental setup

The gain of the low noise amplifier is set to **50000** for the measurement.

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.

It is also verified that the quantization noise of the ADC is much smaller and what we are measuring is indeed the noise of the pre-amplifier.

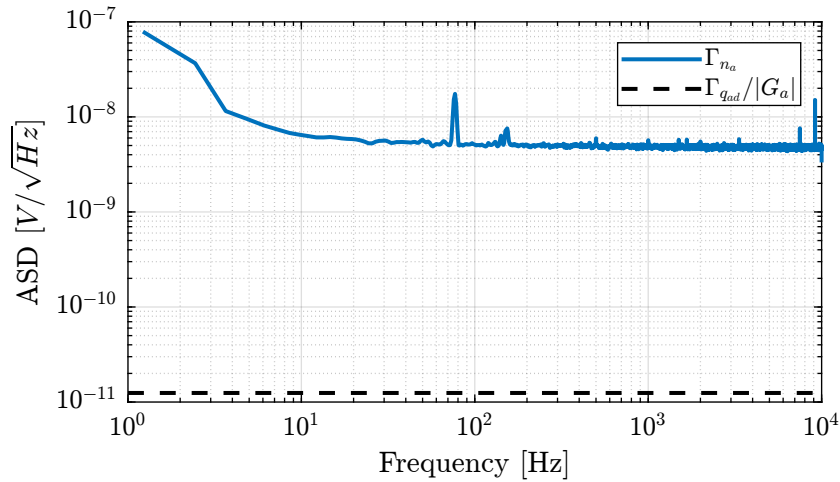


Figure 4.4: Obtained Amplitude Spectral Density of the EG&G Low Noise Voltage Amplifier

4.5 Femto - Amplifier noise measurement

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

The obtained Amplitude spectral density is shown in Figure 4.5.

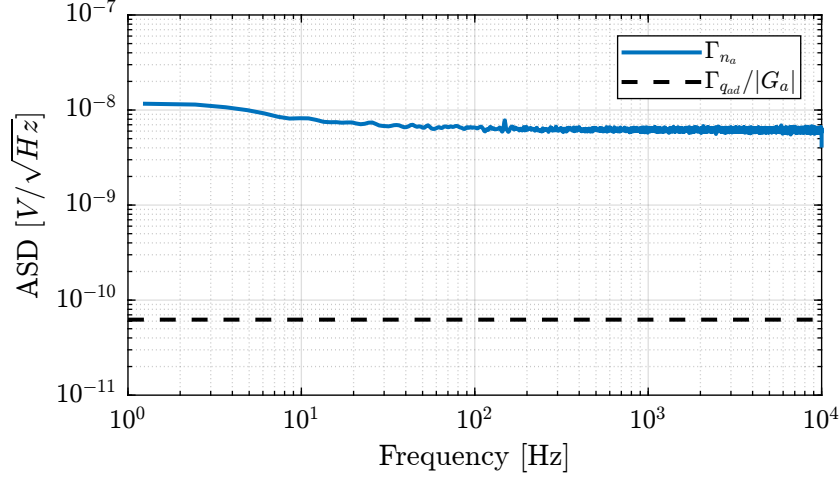


Figure 4.5: Obtained Amplitude Spectral Density of the Femto Low Noise Voltage Amplifier

4.6 PD200 - Low frequency noise measurement

The measurement setup is shown in Figure 4.6. The input of the PD200 amplifier is shunted with a 50 Ohm resistor such that there is no voltage input expected the PD200 input voltage noise. The gain of the pre-amplifier is increased in order to measure a signal much larger than the quantization noise of the ADC.

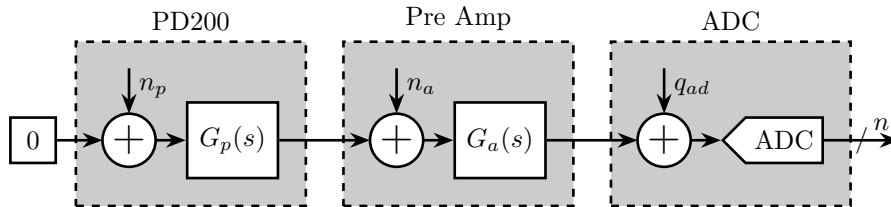


Figure 4.6: Sources of noise in the experimental setup

The measured low frequency (<20Hz) **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 and found to be very similar to the specified ones.

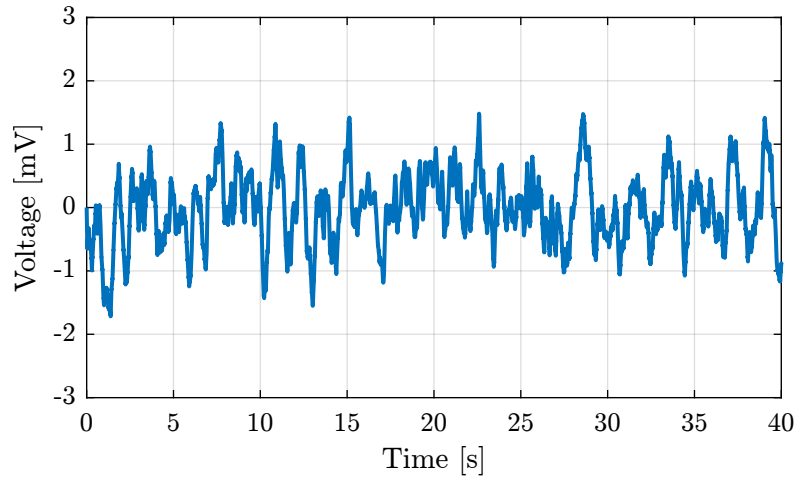


Figure 4.7: Measured low frequency noise of the PD200 from 0.01Hz to 20Hz

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

	RMS [μV]	Peak to Peak [mV]
Specification [$10 \mu F$]	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

4.7 PD200 - High frequency noise measurement

The measurement setup is the same as in Figure 4.6.

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

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

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

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

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

It is verified that the contribution of the PD200 noise is much larger than the contribution of the pre-amplifier noise of the quantization noise.

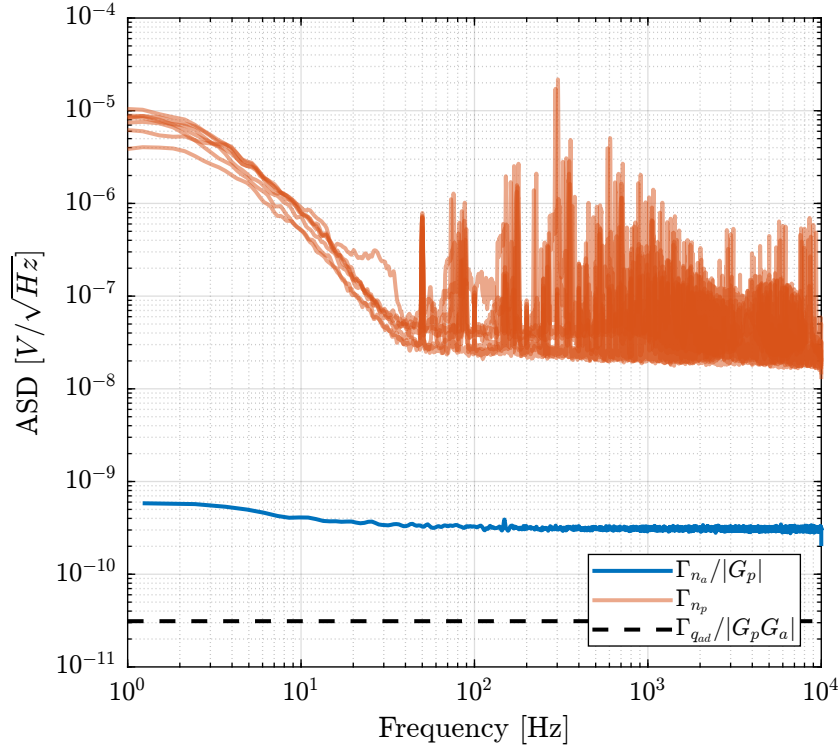


Figure 4.8: Amplitude Spectral Density of the measured input voltage noise of the PD200 amplifiers

Note

The Amplitude Spectral Density of the input noise of the PD200 amplifiers present sharp peaks. It is not clear yet what causes such peaks and if these peaks have high influence on the total

RMS noise of the amplifiers.

4.8 16bits DAC noise measurement

In order not to have any quantization noise and only measure the output voltage noise of the DAC, we “ask” the DAC to output a zero voltage.

The measurement setup is schematically represented in Figure 4.9. The gain of the pre-amplifier is adjusted such that the measured amplified noise is much larger than the quantization noise of the ADC.

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

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

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

$$\Gamma_{n_{da}} \gg \Gamma_{n_a} \quad (4.7)$$

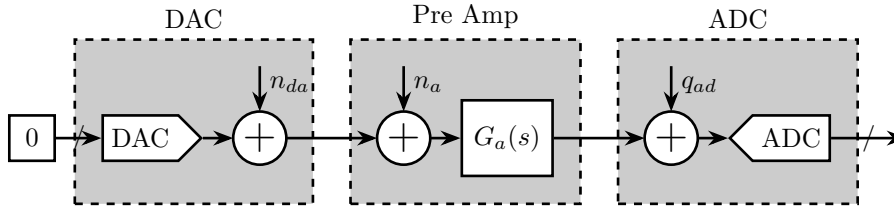


Figure 4.9: Sources of noise in the experimental setup

The obtained Amplitude Spectral Density of the DAC’s output voltage is shown in Figure 4.10.

4.9 Noise of the full setup with 16bits DAC

Let’s now measure the noise of the full setup in Figure 4.11 and analyze the results.

The Amplitude Spectral Density of the measured noise is computed and the shown in Figure 4.12.

We can very well see that to total measured noise is the sum of the DAC noise and the PD200 noise.

Important

The input noise of the PD200 amplifier is limited by the output voltage noise of the DAC. Having a DAC with lower output voltage noise could lower the overall noise of the setup. SSI2V 20bits

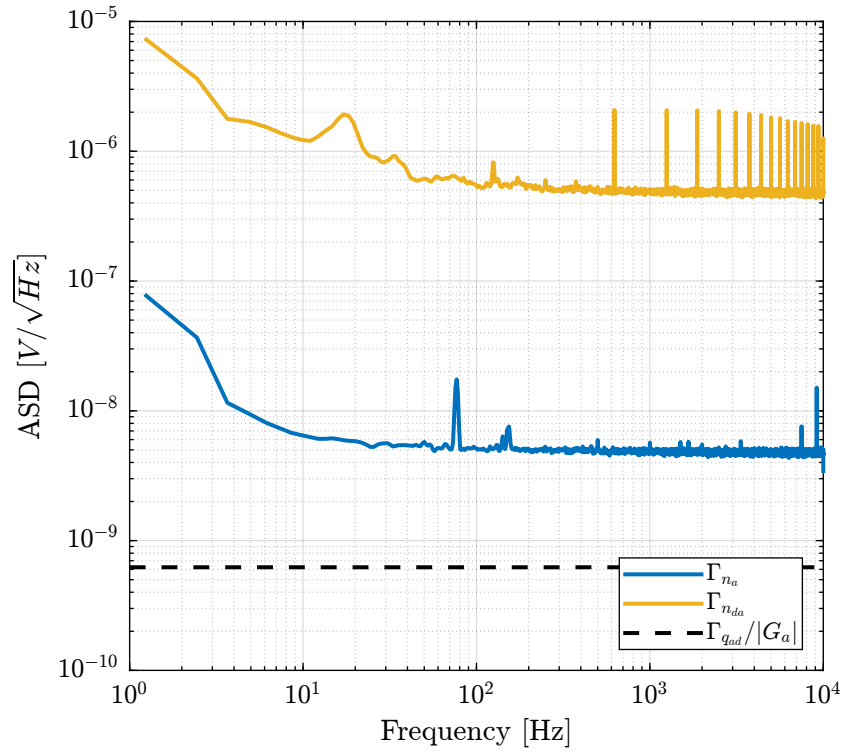


Figure 4.10: Amplitude Spectral Density of the measured output voltage noise of the 16bits DAC

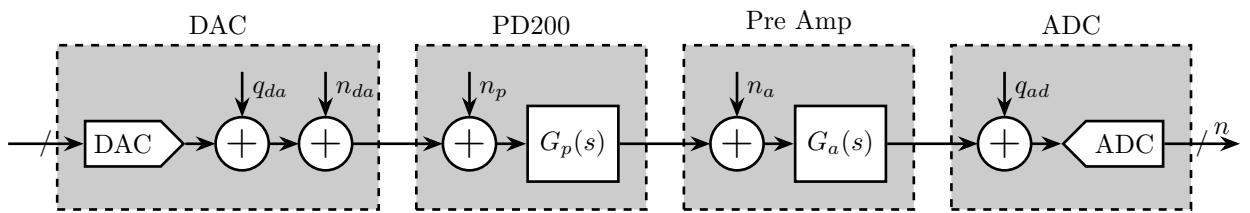


Figure 4.11: Sources of noise in the experimental setup

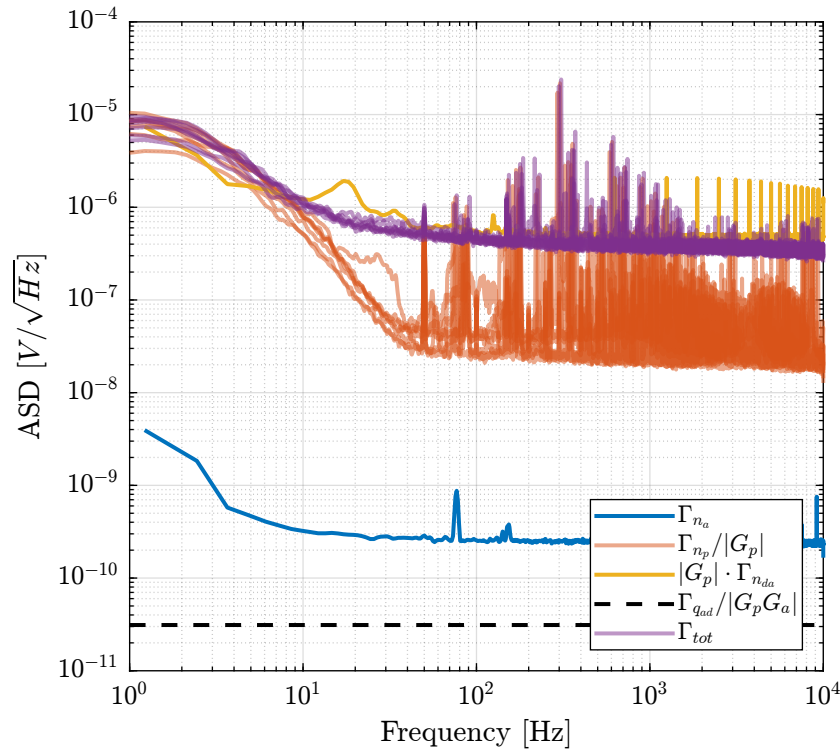


Figure 4.12: Amplitude Spectral Density of the measured noise and of the individual sources of noise

DACs are used in the next section to verify that.

4.10 20bits DAC noise measurement

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

The measurement setup is the same as the one in [Figure 4.9](#).

The obtained Amplitude Spectral Density of the output voltage noise of the SSI2V DAC is shown in [Figure 4.13](#) and compared with the output voltage noise of the 16bits DAC. It is shown to be much smaller (~1 order of magnitude).

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.

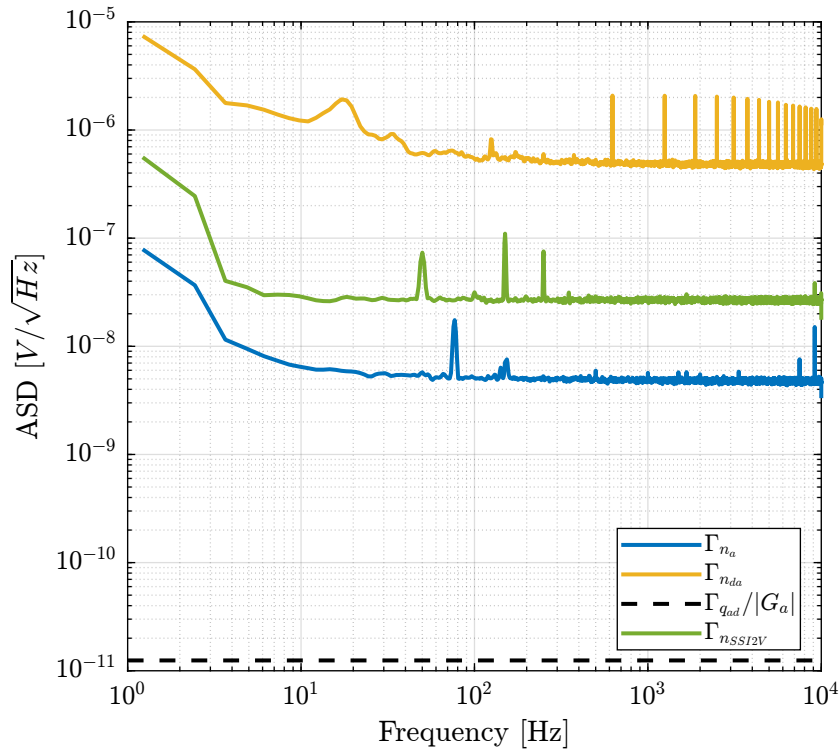


Figure 4.13: Amplitude Spectral Density of the SSI2V DAC's noise

4.11 Noise of the full setup with 20bits DAC

4.12 PD200 Amplifier noise model

Let's design a transfer function $G_n(s)$ whose norm represent the Amplitude Spectral Density of the input voltage noise of the PD200 amplifier as shown in Figure 4.14.

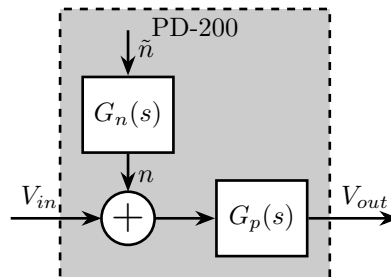


Figure 4.14: Model of the voltage amplifier with normalized noise input

A simple transfer function that allows to obtain a good fit is defined below.

```
Matlab
%% Model of the PD200 Input Voltage Noise
Gn = 1e-5 * ((1 + s/2/pi/20)/(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 4.15.

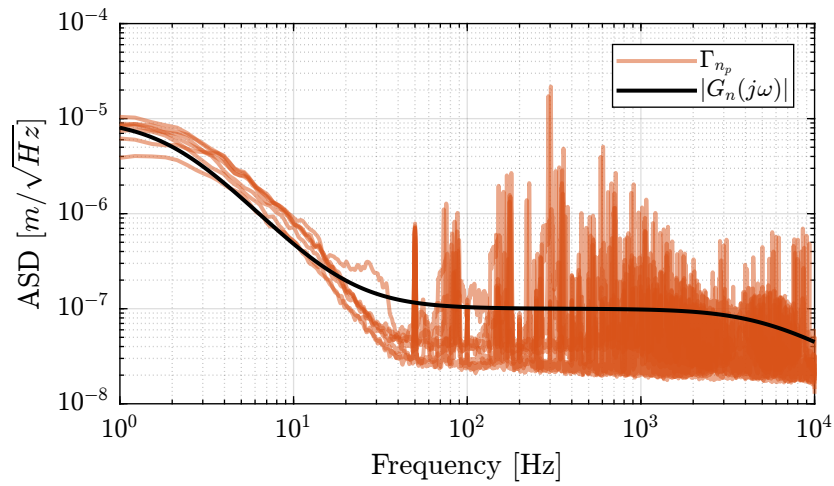


Figure 4.15: ASD of the measured input voltage noise and modeled noise using $G_n(s)$

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 4.16.

The fit between the model and the measurements is rather good considering the complex shape of the measured ASD and the simple model used.

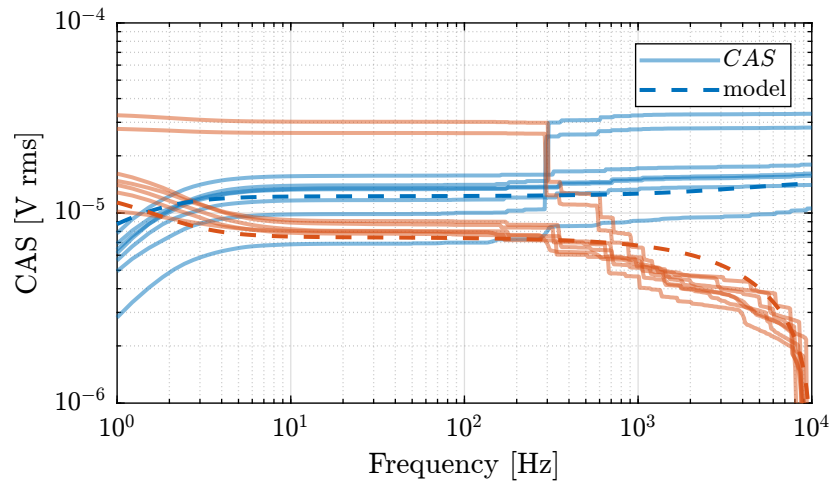


Figure 4.16: Cumulative Amplitude Spectrum of the measured input voltage noise and modeled noise using $G_n(s)$

The obtained RMS noise of the model is 286.74 μV RMS which is not that far from the specifications.

Finally the model of the amplifier noise is saved.


```
save('mat/pd200_model.mat', 'Gn', '-append');
```

5 Comparison to other commercial amplifiers

5.1 Introduction

In this section, three similar voltage amplifiers are compared:

- the [PD200](#) from PiezoDrive
- the [LA75B](#) from CedratTechnologies
- the [E-505.00](#) from PI

These are compared in term of dynamic from input voltage to output voltage for a load of $10\ \mu F$ in Section 5.2 and then in term of input voltage noise in Section 5.3.

The characteristics that I could find for the three amplifiers are summarized in Table 5.1.

Table 5.1: Characteristics of the three tested voltage amplifiers

Characteristics	PD200	LA75B	E-505
Gain	20 [V/V]	20 [V/V]	10 [V/V]
Maximum RMS current	0.9 [A]	0.4 [A]	
Maximum Pulse current	10 [A]	1 [A]	2 [A]
Slew Rate	150 [V/us]		
Noise (10uF load)	0.7 [mV RMS]	3.4 [mV RMS]	0.6 [mV RMS]
Small Signal Bandwidth	7.4 [kHz] (10uF)	30 [kHz] (unloaded)	

Note

The documentation for the three amplifiers can be found here: [PD200](#), [LA75B](#), [E-505.00](#).

5.2 Transfer functions

```
_____ Matlab _____  
la75 = load('tf_la75_10uF_small_signal.mat', 't', 'Vin', 'Vout');  
pd200 = load('tf_pd200_1_10uF_small_signal.mat', 't', 'Vin', 'Vout', 'notes');
```

5.3 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 characteristics 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]	-